Development and Testing of a Water Microresistojet

Master of Science Thesis Report

By Eng. R. A. Ferreira
# 1293613
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Acknowledgements

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<tbody>
<tr>
<td>$A$</td>
<td>Area [m²]</td>
</tr>
<tr>
<td>$Bo$</td>
<td>Bound number [-]</td>
</tr>
<tr>
<td>$C$</td>
<td>Specific heat [J/(kg K)]</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat at constant pressure, [J/(kg K)]</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Discharge coefficient [-]</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter [m]</td>
</tr>
<tr>
<td>DARTS</td>
<td>Delft Aerospace Rocket Test Stand</td>
</tr>
<tr>
<td>$De$</td>
<td>Dean number, $\frac{Re_a}{D}$ [-]</td>
</tr>
<tr>
<td>DUR</td>
<td>Delft University Resistojet</td>
</tr>
<tr>
<td>$F$</td>
<td>Friction factor</td>
</tr>
<tr>
<td>$G$</td>
<td>Mass flux, $\frac{4m}{\pi D^2}$ [m² kg/s]</td>
</tr>
<tr>
<td>$G_0$</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>$Gr$</td>
<td>Grashof number, $\frac{g_0 \beta \rho^2}{\mu^2} (T_v - T_{room}) \times X^3$ [-]</td>
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<tr>
<td>$H$</td>
<td>Enthalpy [J/kg]</td>
</tr>
<tr>
<td>$H$</td>
<td>Convection coefficient, $h = \frac{Nu_k \cdot k}{D}$ [W/(m² K)]</td>
</tr>
<tr>
<td>ICSC</td>
<td>International Chemical Safety Card</td>
</tr>
<tr>
<td>$I$</td>
<td>Current [A]</td>
</tr>
<tr>
<td>$Isp$</td>
<td>Specific impulse [s]</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal conductivity [W/(m K)]</td>
</tr>
<tr>
<td>$L$</td>
<td>Length [m]</td>
</tr>
<tr>
<td>$M$</td>
<td>Molar mass [kg/mol]</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass [Kg]</td>
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<tr>
<td>$\dot{m}$</td>
<td>Mass flow [kg/s]</td>
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<tr>
<td>$Nu_D$</td>
<td>Nusselt number [-]</td>
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<td>NFPA</td>
<td>National Fire Protection Association</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure [Pa]</td>
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<tr>
<td>$Pr$</td>
<td>Prandtl number, $Pr = \frac{\mu c_p}{k}$ [-]</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat power [W]</td>
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<td>$q''$</td>
<td>Heat flux [W/m²]</td>
</tr>
<tr>
<td>$R$</td>
<td>Electric resistance [Ω]</td>
</tr>
<tr>
<td>$Re_D$</td>
<td>Reynolds number, $\frac{4m}{\pi D \mu}$ [-]</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius [m]</td>
</tr>
<tr>
<td>$SCB$</td>
<td>Shield Connector Block</td>
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<tr>
<td>SS</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature [K]</td>
</tr>
<tr>
<td>$T_{film}$</td>
<td>Film temperature, $\frac{T_v + T_{room}}{2}$ [K]</td>
</tr>
<tr>
<td>TU-Delft</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness [m]</td>
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<td>$t$</td>
<td>Time [s]</td>
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<tr>
<td>$v$</td>
<td>Velocity [m/s]</td>
</tr>
<tr>
<td>$W$</td>
<td>Weber number [-]</td>
</tr>
<tr>
<td>$X$</td>
<td>Lockhart-Martinelli parameter, $\frac{(\rho \mu_x)^{1/2} (\mu \rho)^{1/2} (1-x)^{v_x}}{(\rho \mu_x)^{1/2} (\mu \rho)^{1/2} (1-x)^{v_\rho}}$ [-]</td>
</tr>
<tr>
<td>$x$</td>
<td>Gas quality [-]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency [-]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Specific heat ratio [-]</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Void fraction [-]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Coefficient of volumetric expansion, $\approx T_{film}^{-1}$ K⁻¹</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Coefficient of volumetric expansion, $\approx T_{film}^{-1}$ K⁻¹</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Misalignment angle [°]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density [kg/m³]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Circumferential stress [Pa]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant [W/(m² K⁴)]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Surface tension [mN/m]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Stabilization time [s]</td>
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### Greek symbol

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>Void fraction [-]</td>
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<tr>
<td>$\beta$</td>
<td>Coefficient of volumetric expansion, $\approx T_{film}^{-1}$ K⁻¹</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Variation</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Emissivity [-]</td>
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<tr>
<td>$\Gamma$</td>
<td>Vandenkerckhove function [-]</td>
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<tr>
<td>$\gamma$</td>
<td>Specific heat ratio [-]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency [-]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity [Pa s]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Misalignment angle [°]</td>
</tr>
</tbody>
</table>

### Subscripts

- 2ph: Two-phase or boiling
- $a$: Ambient
- $c$: Chamber
- insul: Insulation
- $l$: Liquid
- $m$: Mean in transversal section
<table>
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<tr>
<td>cr</td>
<td>Critical</td>
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<tr>
<td>e</td>
<td>Exit</td>
</tr>
<tr>
<td>eq</td>
<td>Equivalent</td>
</tr>
<tr>
<td>frict</td>
<td>Friction</td>
</tr>
<tr>
<td>g</td>
<td>Gas</td>
</tr>
<tr>
<td>mom</td>
<td>Momentum</td>
</tr>
<tr>
<td>st</td>
<td>Transient</td>
</tr>
<tr>
<td>t</td>
<td>Throat</td>
</tr>
<tr>
<td>w</td>
<td>Wall or surface</td>
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</table>
Chapter 1 – Introduction

Delft University of Technology (TU Delft) is been investigating the use of microthrusters for space purposes. Part of this research program is focused on the use of resistance heaters as a means to decrease propellant consumption of cold nitrogen gas thrusters. To this effect, it was developed, improved and characterized the Delft University Resistojet (DUR) with gas flow. Present interest though is in liquid propellants as to reduce the storage volume on board of a micro- and nano-sized spacecraft, without increasing the complexity of the system.

At TU Delft, there is still very few knowledge about heating liquid propellant for use in a thruster. Furthermore, thruster tests were never performed with liquid propellants. This thesis studies the use of liquid propellant in resistance heaters for use in space as a mean to increase the specific impulse and decrease storage volume. The primary goal of this research is to produce constant thrust with fully vaporized water exhaust, using a Resistojet. It is then possible to demonstrate the use of liquid propellants in a thruster. The experimental results are compared with the model prediction and theory.

This research is divided into 8 chapters:

1. **Introduction**: General questions about space propulsion, as the purpose and the different forms of propulsion in a spacecraft, giving emphases on resistojets. A summary of previous work is performed at the chair of Space Systems Engineering.

2. **Requirements and options**: List of requirements, theoretical models used in the past, analysis of possible propellants, conceptual designs, material and insulation methods for the heating chamber.

3. **Design of a Resistojet**: Design of a nozzle and heating chamber. Concepts for feed system, tank and insulation. Suitability of the design in relation to the pressure drop, tension and voltage.

4. **Analysis of a Resistojet**: Other DUR series are taken into account, with different ranges of temperature and mass flow. Analysis of the dynamical regime is performed. Final selection for Resistojet used for testing.

5. **Model for temperature and pressure loss prediction**: Heat loss model predictor. Model predictor for wall and flow temperature along the heater. Model predictor of the pressure drop in the heater.


7. **Test results and discussion**: Results, data elaboration and discussion of preparatory, heater and thruster tests.

8. **Conclusions and recommendations.**

1 Purpose of space propulsion

Depending on the mission, the spacecraft can have the need of a propulsion system. The propulsion system can then be used for attitude control, orbit control and orbit transfer. In most of scientific and engineering fields as aerospace field, there is an increase in the need of smaller systems. In the case of a micro- or nano-sized spacecraft, the propulsion system should be then scaled down, to a lower mass and volume [1].
2 Forms of space propulsion
The forms of space propulsion are mainly divided into two categories [73]:
- Rocket propulsion, when the thrust is generated by an expelled propellant;
- Non-rocket propulsion, when there is no expelled mass, and the thrust is generated by interaction with external entity, e.g., tethers, solar sail, plasma beam, etc.

Rocket propulsion can be again separated into two classes, chemical and non-chemical rocket. Chemical rockets are divided according to their propellant: solid, liquid, hybrid or cold gas. The non-chemical rockets are divided into thermal and electric rockets (ion thrusters, magnetoplasmadynamic thrusters, etc). Presently, the different thermal rockets are arcjets, resistojets, solar and laser thermal rockets and thermo-nuclear rockets.

![Figure 1 – Forms of space propulsion](image)

3 Definition of a resistojet
A resistojet is a form of thermal non-chemical rocket propulsion. It mainly consists on heating the propellant via a resistance element. The propellant is then expanded in a nozzle giving a certain thrust. The resistance element is heated by passing an electric current through it. This effect is described by Joule heating and, in other terms, the drop in electric potential along the resistance is converted to heat.

4 Rocket propulsion fundamentals
A certain body has a propulsion system when it is able to change its linear momentum, by applying a force on itself. A propulsion system is then a device that produces thrust to push the body. In case of a rocket system, that thrust is produced by expelling mass and can be expressed by the product of mass flow rate and exhaust velocity.

An important performance parameter frequently used in rocketry is the specific impulse. The higher this parameter is less mass it needs to expel for a certain thrust. It can be maximized increasing the exhaust velocity.

5 Previous work
The resistojet is investigated at the chair of Space Systems Engineering, already for some years. The study started with Hoole [12] and has being developed and improved by Giacobone [13], Bisi [14], Bolhuis [15], Rycek [16], Maas [17] and Tijsterman [18].
These studies were mainly focused in nitrogen as the propellant. A more detailed overview can be found in [19]. In the present moment, there are 3 different designs of Delft University Resistojet (DUR). DUR 1.0 was developed by Rycek, DUR 1.1 and DUR 2.0 was developed by Tijsterman.

![Figure 2 – DUR 1.0](image1)

![Figure 3 – DUR 1.1](image2)

![Figure 4 – DUR 2.0](image3)

Meanwhile, other works were indirectly related to the resistojet, as the development of Delft Aerospace Rocket Test Stand (DARTS), developed by Bolhuis and improved by Bisi, Rycek and Koopmans [20].

![Figure 5 – DARTS in November 2007](image4)

Also in the past, studies of the more suitable propellant have been performed at TU-Delft for a number of gaseous propellants including hydrogen, helium, methane, nitrogen, and carbon dioxide [13, 15, 16]. Furthermore, A. Janssens [29] started a research on the use of water as a propellant on solar thermal propulsion.
Chapter 2 – Requirements and options

In this chapter, the requirements are given for flight and test conditions. As a background, the previous theoretical models are referred to and a thermal boundary condition is chosen. It is given a brief description of boiling flow. Afterwards it is analysed and compared to the possible propellants and conceptual designs of the heating chamber for use in TU-Delft’s future thermal propulsion system, capable of propelling a small Cubesat[1] and thereby demonstrating the feasibility of thermal propulsion in space. A brief description of porous media is given followed by the analysis and comparison of different materials for heating chambers and the insulation methods. This chapter is concluded by the summary of the choices taken along this document.

1 Requirements and constraints

Requirements are separated into flight requirements, applied in case of space flight in a Cubesat, and into the test requirements, applied for test and first phase of research.

Flight requirements
For this low-thrust propulsion system, there is approximately only 1 W available from the Cubesat. This electric power is related to the maximum power that these satellites can collect with the solar panels at LEO[2] and use for the propulsion system [40]. The minimal thrust that is representative for attitude control on a Cubesat of 1 kg is 0.06 mN [25, 40]. To obtain low thrust with minimal power consumption, the mass flow should have a very low value, less than 1 mg/s. This propulsion system should have a tank with a maximum pressure of 5 bar. Furthermore, to decrease the large storage volume, typical from gas propellants, the propellant should be stored in liquid phase, as LH2 (liquid hydrogen) [1]. However, this liquid propellant should be intrinsically safe, as it is discussed in section 4.1.

Test requirements
To demonstrate the technology of a liquid resistojet, the exhaust shall be constant and in gas phase. To obtain gas exhaust the electric power can be increased to levels higher than 1 W. The maximum allowable temperature of the heater shall be lower than 1000 K. The tank pressure shall not be higher than 5 bar. The pressure just before the nozzle shall be around 2 bar.

Constraints
The propellant should be intrinsically safe for handling and testing, for that reason, water shall be used. Furthermore the voltage levels shall be lower than 35 V. The system shall be tested on the DARTS, in a laboratory environment. The level of mass flow shall be as lower as the minimum capability provided by the test equipment, around 20 mg/s. The thrust levels should be measurable by the equipment, higher than 5 mN. The maximum available current by the equipment is 20 A.

1 A Cubesat typically has a mass of 1 kg and measures 0.1m x 0.1m x 0.1m. A Cubesat belongs to Microspacecraft Class II
2 Low Earth Orbit
### Table 1 – Requirements for flight and test, and constraints

| Flight requirements                      | Pressure < 5 bar  
|                                       | Power < 1 W  
|                                       | Thrust > 0.06 mN  
|                                       | Propellant stored in liquid phase  
|                                       | Safe propellant  
| Test requirements                      | Constant gas exhaust  
|                                       | Chamber temperature < 1000 K  
|                                       | Chamber pressure ~ 2 bar  
|                                       | Tank pressure < 5 bar  
| Constraints                            | Test performed on the DARTS  
|                                       | Water as propellant  
|                                       | Mass flow around 20 mg/s  
|                                       | Thrust > 5 mN  
|                                       | Maximum current, 20 A  
|                                       | Voltage < 35 V  

2. **Theoretical models developed in the past**

Several theoretical models were developed at the chair of Space Systems Engineering. These models take into account the heat loss to the exterior and the heat transport to the flow. Some models assumed constant heat flux as thermal boundary condition [12, 17]. This is also found in some literature when applied in resistance heaters [3, 4]. However others assumed constant wall temperature, [13, 16, 18]. A more detailed overview can be found in [19]. The heat losses to the exterior were assumed by radiation, conduction and convection, while the heat transport to the flow was considered only by convection. However these models were developed for single-phase gas flow, and considering small properties variation of the propellant. It was then possible to consider mean properties and temperature, without adding great deviation between experimental and theoretical values [16, 18].

When the propellant enters at liquid phase and is exhausted at gas phase, passing by boiling phase, the propellant properties change greatly. In this case, taking mean properties of the propellant would give great deviation from the reality, since the propellant would have properties without any physical meaning (between liquid and gas). Separating the flow into three parts (liquid, boiling and gas), can solve part of the problem. Nevertheless, the propellant properties change still considerably near the boiling point to higher temperatures. Then, to avoid significant deviation, the local properties should be taken into account, requiring heavier computation.

There is still a doubt about which thermal boundary condition should then be taken: constant wall temperature or constant heat flux [33]. Constant wall temperature assumption seemed to match with experimental values in case of gas flow [16, 18]. For a flow going from liquid to gas, it is expected that the wall temperature will vary greatly. In liquid and boiling phase the temperature difference between flow and wall is small, when in gas phase that difference is much higher. Furthermore most correlation for boiling flow is for constant heat flux. For these reasons, constant heat flux is chosen for this purpose, since it should be closer to experiment.
Finally, any model took into account the dissociation of the propellant. Also in this research the dissociation of water at high temperatures is not taken into account. Since the dissociation is negligible at temperature range considered in this application. The dissociation of water starts to play a bigger role at temperatures higher than 2000 K [106] (at 2000 K dissociation is around 1%).

3 Brief description of boiling flow

From the requirements, the propellant shall be stored in liquid phase and the exhaust shall be in gas phase. This change from liquid phase to gas phase by increasing temperature, is called boiling flow (diabatic process), horizontal line on Figure 6. The vaporization can also be made by decreasing the pressure, vertical line on Figure 6. The latter is not studied in this research.

Boiling flow is then a two-phase flow of liquid and gas of the same species at boiling conditions, see [33] for more detailed information. It is also related to higher pressure drop than at a single phase flow in a same channel [1]. Two-phase flow has been deeply researched due to its important applications in rocketry but also in chemical engineering processes, heat exchangers, refrigeration systems, etc. However, due to the complexity of the flow, predictions are made in terms of empirical or semi-empirical correlations [5]. For boiling flow, the flow patterns and heat transfer regimes change during vaporization process, as shown in Figure 7 for vertical tube.

Figure 6 – Phase diagram of water [74]
Figure 7 – Flow and heat transfer regimes in a sufficiently long heated vertical tube [6]

From Figure 7, it is seen that the temperature is not perfectly constant, since near a flow quality (ration of mass flow rate of gas to mass flow rate of the mixture) of 0 and 1 the liquid and vapour bulk temperatures are different than the saturation temperature. Until the “Dryout” point (no liquid on the surface), the surface temperature is almost constant. After “Dryout” point, the region is deficient in liquid and the convection coefficient decreases, reason why the surface temperature abruptly increases. However, depending on the value of heat flux, the order of flow regimes can be different. When the vapour bubbles have dimensions close to the channel diameter (Taylor bubbles), there is then a slug flow [4, 6], with liquid at the surface and high oscillatory pressure [7, 8, 53]. In case of horizontal tube the regimes are slightly different, since the gravity plays an important role in the non-axisymmetry of the flow [6, 7, 8].
4 Possible propellants for low-thrust propulsion system

Here, it is first discuss the major requirements of importance to the propellant selection. Next the principal options for the propellant are listed. Thirdly, these propellants in relation to the requirements are assessed. A trade and rank the various options according to suitability is performed. According to the comparisons, a propellant is selected and evaluated.

4.1 Requirements for the propellants

Various requirements must be taken into account when selecting a propellant. A general list of requirements is given in [1]. Here not all requirements are considered, but only those that are considered most critical for demonstrating the fundamental use of thermal propulsion. It will be discussed specific impulse, storability, handling qualities (safety), and heating properties.

Of these, the two major requirements that need to be satisfied for this research purpose are: storability and handling qualities. Furthermore the system should be as simple as possible, avoiding pumps, cryogenic storage, complex piping system and if possible using self vaporized propellants. This simplicity results in a lower dry mass and a higher reliability of the propulsion system.

Specific impulse

The first requirement should be the propulsive performance in terms of specific impulse, since it is often used on rocket motors. This performance is directly connected with molar mass; a lower molar mass $M$ leads to a higher specific impulse $I_{sp}$ and vice versa. This relation can be found in the following formula [1]:

$$I_{sp} \propto \sqrt{\frac{R_A}{M}}$$

However, since microsatellites have low propellant mass compared to propulsion system dry mass [44], high specific impulse is not a major requirement.

Heating properties

Heating properties are an important requirement to select a propellant, since it determines the difficulty of heating it. However to demonstrate the feasibility of thermal propulsion in space, worst heating properties can be accepted. Only in a more advanced part of the project, this requirement should be taken into account to increase the efficiency of the propulsion system. A propulsion system is more efficient when less energy is needed to heat the propellant.

Storability

First main requirement is the storability characterised by the density and state of aggregation (phase) of the propellant. The conditions should be around the temperature and pressure in the tank of the propulsion system. The storability requirement is even more important for Cubesats where the available volume and mass are limited [43].
Safety
One of the most important requirements in this assessment is safety. Since this type of low-thrust propulsion system is mainly applied in piggy bag satellites, it should not pose any larger risk for the main satellite. Furthermore the propellant must pose little or no threat for fire, explosion, and detonation during all activities as during use, loading, unloading, storage, etc. A safer propellant avoids risk of accident and complexity in testing measures.

4.2 Propellant options
Many different substances can be use as a propellant in non-chemical thermal propulsion. However the list should have a restricted number of candidates so that a qualitative analysis is still possible. Some of the propellants already used or evaluated in the past for the same purpose (see references), are chosen as candidates. The candidates are given in the table 1.

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Reference</th>
<th>Propellant</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, H2O</td>
<td>[16, 40, 45, 88, 90]</td>
<td>Hydrogen fluoride, HF</td>
<td>[40]</td>
</tr>
<tr>
<td>Carbon Dioxide, CO2</td>
<td>[13, 15, 16, 22, 45, 90]</td>
<td>Freon 12, CCl2F2</td>
<td>[40]</td>
</tr>
<tr>
<td>Hydrogen, H2</td>
<td>[13, 16, 22, 47]</td>
<td>Ethyl methyl ether, C2H5OCH3</td>
<td>[40]</td>
</tr>
<tr>
<td>Nitrogen, N2</td>
<td>[13, 15, 16, 46, 48, 88]</td>
<td>Methylamine, CH3NH2</td>
<td>[40]</td>
</tr>
<tr>
<td>Helium, He</td>
<td>[13, 15, 16, 22, 48, 88]</td>
<td>Methane, CH4</td>
<td>[13, 16, 48]</td>
</tr>
<tr>
<td>Xenon, Xe</td>
<td>[46, 48]</td>
<td>Ethane, C2H8</td>
<td>[40]</td>
</tr>
<tr>
<td>Ammonia, NH3</td>
<td>[16, 40, 47, 48, 90]</td>
<td>Propane</td>
<td>[90]</td>
</tr>
<tr>
<td>Hydrazine, N2H4</td>
<td>[16, 45, 48]</td>
<td>Butane</td>
<td>[89]</td>
</tr>
<tr>
<td>Nitrous oxide, N2O</td>
<td>[16, 88, 90]</td>
<td>Methanol, CH3OH</td>
<td>[16, 40, 88]</td>
</tr>
<tr>
<td>Chloromethane, CH3Cl</td>
<td>[40]</td>
<td>Ethanol3, C2H5OH</td>
<td></td>
</tr>
<tr>
<td>Chloroethane, C2H5Cl</td>
<td>[40]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Candidates as propellant in non-chemical thermal propulsion

4.3 Propellant analysis
This section explains how to analyse a propellant. Most of the properties as molar mass, enthalpy change and density are taken from [75], however when it is not available some other references are used and indicated. For safety requirement NFPA 704 is used, most information can be found in [81, 83].

Storability
With respect to propellant density and phase, it is taken the conditions in the tank of the propulsion system. These conditions are laboratory temperature and maximum pressure of 5 bar.

Following the method outlined in [2], three different grades are given with respect to propellant density and phase:

- Green (adequate) = liquid around room temperature and storage pressure below 5 bar;
- Red (not acceptable) = only liquid below room temperature or at elevated pressure in excess of 5 bar.

3 Added as a curiosity but was not found in the literature
**Safety**

To be able to give a grade for safety requirement, a safety standard as International Chemical Safety Card (ICSC) should be used. However, even if the information is very complete, it consists mainly in standard phrases [83]. Another safety standard that is related to ICSC is the National Fire Protection Association (NFPA). They define the informal “fire diamond” (NFPA 704) used by emergency personnel that can identify quickly and easily the risks posed by some materials [87]. Even if it not so complete than ICSC it is easier to give a grade based on NFPA.

The NFPA 704 has 4 categories: health (blue), flammability (red), reactivity (yellow) and special (white). Excepting the special category, the others are scaled from 0 (no hazard) to 4 (highly hazardous). The more detailed description and analysis of these categories can be found in [26] and in Annexes.

Using NFPA rate, three different grades are given for the safety of the propellant: green (safe), yellow (precautions should be taken) and red (not safe). The grades are given by a combination of the safety in the 4 categories. The grades are:

- Green (adequate) = health and flammability 0 or 1; reactivity 0; no special characteristic
- Yellow (acceptable) = health 2; or flammability 2 or 3; reactivity 0; no special characteristic
- Red (not acceptable) = health 3 or 4; or flammability 4; or reactivity higher than 0; or special dangerous characteristic

**Final grade**

A final grade is given at the end of the qualitative analysis: GO (suitable) and NO GO (inappropriate). A propellant is suitable on a thermal propulsion system of a Cubesat when the major criteria of density and safety are fulfilled. There are only two possible results:

- GO = no red allowable
- NO GO = at least one red

Nevertheless, some of the NO GO propellants are used in propulsion system. This is the case when the requirements are different, and the use of cryogenics is allowable.

**Example**

Water is taken as an example to understand how to analyse a propellant. Molar mass, enthalpy and density are taken from [75]. To analyse the heating properties at constant pressure [1], the change of enthalpy is used. The temperature will go from 293 K to 1000 K at 2 bar. However, for others propellants, it is not always possible to find all chemical information at this pressure and temperature, in that case other conditions can be taken. The calculations performed for the enthalpy change, in the case of water, are:

To know the enthalpy change at 2 bar from 293 K to 1000 K some calculations are performed, using the following formula:

\[
\Delta H(293K \to 1000K) = \Delta H_{vap} + \Delta H_{\text{liq}}(293K \to T_{\text{boil}}) + \Delta H_{vap}(T_{\text{boil}} \to 1000K) = H(1000K) - H(293K)
\]

\[
\Delta H(293K \to 1000K) = 3990.1 - 83.473 = 3906.63kJ / kg
\]
At 5 bar and 293 K, conditions in the tank, it is found that water is in the liquid state with a density of 998.4 kg/m³. These properties indicate that this propellant is suitable for storage (green grade), since it is liquid at room temperature. For some propellants, due to lack of information, it will be taken the density available at other temperature or pressure. In case of liquid, it is considered as incompressible and for gas it is used the ideal gas law. If the propellant is gas around room temperature, then it has a red grade, not suitable. For safety it is found that water is inherently safe, having as NFPA rate: 0, 0, 0, no. These rates confirm that water is suitable and does not need special precautions, green grade. Since it has two green grades, water is suitable as propellant of a thermal propulsion system of a Cubesat.

### 4.4 Comparison between propellants

In this section, the principal and more interesting propellants are traded: water, nitrogen, butane, hydrogen fluoride and methanol. The complete trade-off table can be found in [26]. It is used as the two major requirements: density and safety. Considering these requirements, some propellants are not suitable. However it does not mean that these propellants cannot be used in the future. If a slightly less strict criterion is used some propellants can appear in the end as suitable, e.g. butane.

<table>
<thead>
<tr>
<th>Propellant option</th>
<th>Molar mass [kg/kmol]</th>
<th>Enthalpy change [kJ/kg]</th>
<th>Density (5 bar and 293 K [kg/m³], phase)</th>
<th>Safety: health, flammability, reactivity, special</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, H₂O</td>
<td>18.02</td>
<td>3886</td>
<td>998.4, liq. [75]</td>
<td>0, 0, 0, no [81]</td>
<td>GO</td>
</tr>
<tr>
<td>Nitrogen, N₂</td>
<td>28.01</td>
<td>772</td>
<td>5.75, gas [75]</td>
<td>0, 0, 0, no [81]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Butane, C₄H₁₀</td>
<td>58.12</td>
<td>649 (293 to 575K)</td>
<td>579.07, liq. [75]</td>
<td>1, 4, 0, no [84]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Hydrogen fluoride, HF</td>
<td>20.01</td>
<td>1031 (298 to 1000K at 1bar, gas phase)</td>
<td>959⁴, liq. [77]</td>
<td>3, 0, 2, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Methanol, CH₃OH</td>
<td>32.04</td>
<td>1766 (293 to 620K)</td>
<td>791.4, liq. [75]</td>
<td>1, 3, 0, no [83]</td>
<td>GO</td>
</tr>
</tbody>
</table>

Table 3 – Propellant trade-off summary table

From Table 3, the density and safety remove most of the propellants as a possible option for thermal propulsion. After the trade-off table there are 2 possible options for propellants: water and methanol. Other alcohols, as ethanol, can be suitable as propellant, see [26]. In contrary to water, alcohols have an inherent danger that should be taken into account during testing, handling, loading, unloading, storage, etc. Additionally, water has a lower molar mass.

---

⁴ Considering an incompressible liquid
and slightly higher density than the others propellants, therefore using water as propellant shows to be the ideal choice. However the energy needed to heat from 293K to a higher temperature is much higher for water. One inherent problem with water is the energy required to be vaporized (high value of enthalpy of vaporization).

4.5 Selection of the propellant

Different propellants were analysed but only water and alcohols, as methanol, fulfil the major requirements: density and safety. Finally water was chosen to be the “best” propellant to demonstrate the feasibility of thermal propulsion, since it greatly fulfils all major requirements, density and safety. However water is far from a perfect choice, i.e., it needs high heat energy. If methanol or ethanol or even butane, that are less safe, were used as propellants, the propulsion system would be more efficient, since they need less heat energy. Nevertheless since it is required to demonstrate a technology, it is more important to have a high density and better safety than lower heat energy, avoiding this propulsion system to be hindered.

5 Conceptual designs for heating chambers

A great many low-thrust propulsion systems for space application purposes exist. Many different designs are used, each design having its own advantages and disadvantages. Generally, an electro-thermal propulsion system has normally a pressurised tank, valves, a heating chamber and a nozzle. The purpose of this section is to give an overview and evaluation of different concepts for the heating chamber of an electro-thermal thruster. No thermal insulation to the environment is taken into account as well as electrical insulation.

Here, it is first discussed the important requirements for the selection. Next the various options for the conceptual design are listed. Thirdly, it is assessed these concepts in relation to the criteria and it is performed a trade of the various options and finally an option is selected.

5.1 Requirements for heating chambers

The requirements [1, 41] that must be taken into account to evaluate conceptual designs for the heating chamber are: availability, flexibility, heater efficiency, manufacturability and simplicity.

Other requirements, as required length, mass and pressure drop, cannot be evaluated without a theoretical background that is only performed in Chapter 3 and Chapter 4. For that reason they are not taken into account in the present section, although they can be decisive afterwards.

Availability

Availability is fundamental for a concept meaning how easy it is to obtain different parts. This requirement can be related to cost, since a lower availability is normally related to a higher cost.
**Flexibility**

Design flexibility is characterised by the capacity that a design inherently has to be easily modified if input parameters are changed: temperature, pressure, input power, mass flow and propellant.

**Heater efficiency**

Heater efficiency [1, 3] in the designs is characterized by the capacity to transport heat from the solid (tube, wires) to the flow and within the flow. The nature of the flow, laminar or turbulent plays a big role since the last one as more capacity to transport heat.

**Manufacturability**

A conceptual design should take into account the manufacturability meaning how difficult it is to produce different parts with the existing facilities. This requirement can also be related to cost, since a lower manufacturability is normally related to a higher cost.

**Simplicity**

Simplicity of a design is related to the amount of different parts, interactions between them and actions that should be performed to mount and remount. A higher simplicity generally brings to lower failure and sometimes to a higher understanding of the system.

### 5.2 Options for heating chambers

The heating chambers [95] can be divided into two main concepts: porous media [92, 93] and small diameter tube [53, 94]. Furthermore they can be heated in two different ways [16, 41, 45]: indirect heating and direct heating. In the case of indirect heating, the chamber is heated by a resistor wire, while in direct heating the chamber is itself heated by an electric current. For the indirect heating, the resistor wire can be in the inner or the outer surface of the heating chamber. In the case of small diameter tube, there is the possibility to have coiled tube or multi-channels. In the total there are 9 different conceptual designs, see Figure 8.

![Figure 8 – Conceptual designs’ tree](image-url)
**Concept 1**
Concept 1 is the porous media with direct heating. The porous media is represented by the dotted part. No electric contact can be done between the porous media and the solid tube around. The porous material should have a quite high electric resistance. The small arrows represent the direction of the flow, passing through the porous media.

**Concept 2**
Concept 2 is the porous media with an outer heater as indirect heating. The coil represents the resistor wire. The wire should have a small cross sectional area and long length, increasing the resistance. No electric contact can be done between the wire and the solid tube around the porous media. This concept is close to the previous one (1), however in this case the porous media is heated indirectly by a wire.

**Concept 3**
Concept 3 is the porous media with an inner heater as indirect heating. The heater is represented by a coil. The fluid passes through the porous media and no fluid enters in the central hole where the resistance is. No electric contact can be done between the resistor wire, the porous media and the solid cylinder. This concept was used at University of Surrey for the Mark-III Resistojet, [50, 88].
**Concept 4**
Concept 4 is the coiled tube with direct heating. The flow passes in the coiled tube where it is heated. This concept is commonly used for resistojet [49, 95]. At the chair of Space Systems Engineering, this concept, based in Hoole [12], was extensively used, in all the DUR series (DUR1.0, DUR1.1, DUR2.0).

**Concept 5**
Concept 5 is the coiled tube with an outer heater as indirect heating. The flow passes in the coiled tube where it is heated. This concept is a modified version of the DUR. No electric contact can be done between the coiled tube and the resistor wire.

**Concept 6**
Concept 6 is the coiled tube with an inner heater as indirect heating. The flow passes in the coiled tube where it is directly heated by the wire. This concept is a slightly different configuration than concept 5. Furthermore, no electric contact can be done between the coiled tube and the resistor wire.
Concept 7
Concept number 7 is the multi-channels with direct heating. The flow passes in the tubes, as indicated by the arrows. The cross sectional area should be as small as possible, to increase total electric resistance.

Figure 15 – Concept 7: Multi-channels with direct heating

Concept 8
Concept number 8 is the multi-channels with an outer heater as indirect heating. The flow passes in the tubes, as indicated by the arrows. For this design the cross sectional area of the channels is not of major importance, since the heat is produced by the wire.

Figure 16 – Concept 8: Multi-channels with an outer heater as indirect heating

Concept 9
Concept number 9 is the multi-channels with an inner heater as indirect heating. No electric contact can be done between the channels and the heater wire. This concept is often used in solar-thermal propulsion, however using direct solar radiation as heat source instead of electric power. It is being used for that purpose, at the chair of Space Systems Engineering, by Leenders [27].

Figure 17 – Concept 9: Multi-channels with an inner heater as indirect heating
5.3 Concept analysis
This section explains how to analyse different concepts regarding to the requirements.

Availability
With respect to the availability, different grades are given. From the highest to the lowest availability:
- 5 – within the chair of Space Systems Engineering;
- 4 – within the Delft University of Technology;
- 3 – in a regular shop;
- 2 – ordering by internet;
- 1 – directly to the manufacturer;
- 0 – not available.

Flexibility
With respect to the flexibility, different grades are given in relation to the total number $n$ of different design parameters that can be changed. The highest the better it is:
- $n$ – total number of design parameters that can be changed;

Heater efficiency
Heater efficiency has a secondary role to demonstrate a technology but has a primordial role for optimization. For that reason, the grades for heater efficiency have less weight than the other requirements. Furthermore there are many different ways to enhance the heat transport efficiency within a concept. Only 4 grades are given, depending on the flow regime, [1]:
- 3 – very good, highly turbulent flow;
- 2 – good, turbulent flow (near laminar);
- 1 – satisfactory, laminar flow (near turbulent);
- 0 – not acceptable, highly laminar flow.

Manufacturability
With respect to the manufacturability, different grades are given. From the highest to the lowest manufacturability:
- 5 – no special workmanship required, neither special tooling;
- 4 – no special workmanship required, but special tooling required;
- 3 – special workmanship required, can be performed in the workshop of aerospace faculty;
- 2 – special workmanship required, only performed in a specialized workshop;
- 1 – very special workmanship required, with highly specialised tooling;
- 0 – not manufacturable.
**Simplicity**  
With respect to the simplicity, different grades are given in relation of different parts existing in the concept. The bigger number of parts, the worse is the concept. For that reason the grades are given in negative values:  
• \(-n\) – total number different parts.

**Final grade**  
A final grade is given in the end of the qualitative analysis, adding all the grades. The concepts with higher final grade are more suitable for the purpose of demonstrator model of thermal rocket propulsion with liquid propellant. Furthermore 3 colour grades are given, to emphasis the more and less suitable concepts. The colour grades are:  
• Green (suitable) – grade higher than 10;  
• Yellow (acceptable) – grade higher than 5 and lower than 10;  
• Red (unsuitable) – grade of 5 or lower.

**Example**  
Concept 4 (coiled tube with direct heating) is taken as an example to understand how to analyse a concept.  
In terms of availability, since some coils are available within the chair of Space Systems Engineering, the grade is 5.  
For the flexibility, the coiled tube has the following main parameters that can be changed: tube diameter, coil diameter and length. This concept has then a grade of 3 in terms of flexibility.  
For the heater efficiency, the flow in a coil is characterized by secondary flows caused by centrifugal forces. These forces are responsible to an increase in heat transfer coefficient in the flow. However they also stabilise the flow, making the transition to turbulent happening at higher Reynolds numbers. For these reasons the flow can be laminar or turbulent, but always with a good thermal efficiency, [18, 32, 38, 39]. The grade given is then 2.  
For the manufacturability, most of the coils can be performed without special workmanship. However to avoid buckling, some special tooling is required. The manufacturability grade is then 4.  
In this concept, there is only one part: the coil. For that reason, the grade is -1.  
Adding all the grades, the final result is 13, with a green grade. This value is compared with the final result from other concepts, and the best concept is then chosen.
5.4 Comparison between concepts

In this section, the concepts from section 5.2 are traded. The requirements discussed in section 5.1 are used. Considering these requirements, some concepts are more suitable than others, for a technology demonstrator of heating chamber. However it does not mean directly that a concept is better than another, since most of the requirements are focused in the way to obtain the heating chamber. With other requirements, the result could be very different. In parenthesis, it is found the factors that influence the grade. Here d, L, n_channels and ε are respectively the diameter, length, number of channels and porosity (defined in section 6).

<table>
<thead>
<tr>
<th>Concept #</th>
<th>Availability</th>
<th>Flexibility</th>
<th>Requirements</th>
<th>Manufacturability</th>
<th>Simplicity</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (porous media)</td>
<td>4 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{pore}}, \varepsilon)</td>
<td>3 (highly turbulent)</td>
<td>2 (special)</td>
<td>-2 (porous media, tube)</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>1 (porous media)</td>
<td>5 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{pore}}, \varepsilon, L_{\text{wire}})</td>
<td>3 (highly turbulent)</td>
<td>2 (special)</td>
<td>-3 (porous media, outer tube, wire)</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>1 (porous media)</td>
<td>5 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{pore}}, \varepsilon, L_{\text{wire}})</td>
<td>3 (highly turbulent)</td>
<td>2 (special)</td>
<td>-4 (porous media, inner tube, outer tube, wire)</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>5 (coil)</td>
<td>3 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{coil}})</td>
<td>2 (turbulent)</td>
<td>4 (no special)</td>
<td>-1 (coil)</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>4 (wire)</td>
<td>4 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{coil}}, L_{\text{wire}})</td>
<td>2 (turbulent)</td>
<td>4 (no special)</td>
<td>-2 (coil, wire)</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>4 (wire)</td>
<td>4 (d_{\text{tube}}, L_{\text{tube}}, d_{\text{coil}}, L_{\text{wire}})</td>
<td>2 (turbulent)</td>
<td>3 (at workshop)</td>
<td>-2 (coil, wire)</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>1 (multi-channels)</td>
<td>3 (d_{\text{channels}}, L_{\text{channels}}, n_{\text{channels}})</td>
<td>1 (laminar)</td>
<td>3 (at workshop)</td>
<td>-3 (channels, distributor, outer tube)</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>1 (multi-channels)</td>
<td>4 (d_{\text{channels}}, L_{\text{channels}}, n_{\text{channels}}, L_{\text{wire}})</td>
<td>1 (laminar)</td>
<td>3 (at workshop)</td>
<td>-4 (channels, distributor, outer tube, wire)</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>1 (multi-channels)</td>
<td>4 (d_{\text{channels}}, L_{\text{channels}}, n_{\text{channels}}, L_{\text{wire}})</td>
<td>1 (laminar)</td>
<td>3 (at workshop)</td>
<td>-4 (channels, distributor, outer tube, wire)</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4 – Comparison and summary of different concepts
From Table 4, it is found that the availability plays an important role for the comparison. After the trade-off table, there are 9 possible options for concepts: 3 concepts of porous media and 6 concepts of small diameter tubes. From the table, it is found that coiled tube concepts are more attractive mainly due to the availability and manufacturability. However, from the literature, porous media can be very interesting due to the high heat transport efficiency. Furthermore, from the final results, the concepts with direct heating seem to be more attractive than with indirect heating.

5.5 Selection of the concept
Different concepts were analysed but only the porous media and coiled tube concepts were considered attractive to demonstrate the feasibility of thermal propulsion. Finally coiled tube with direct heating was chosen as the more suitable for this purpose. Porous media seems to be very attractive, and it was studied by [33]. This conceptual design is not manufactured and tested, to avoid this propulsion system to be hindered.

6 Different types of porous media
Coiled tubes have a good efficiency for heat transfer however porous media has an even higher efficiency.
There are three different main media to enhance the thermal efficiency with porous media: the sintered metal, packed beds with small metallic balls [100] and metal foams. The main difference between these mediums is the way that they are manufacture having then different porosities\(^5\). In sintered metals and metal foams, the pores are considered randomly distributed however for packed beds it can be uniformly distributed. Generally sintered metals have a lower porosity and a lower pore size followed by packed bed and finally metal foams. For metal foams the pores cannot be approximated to spherical shape but more to cylindrical shape [54]. For more detailed information, see [33]. Their appearance is shown in the figures below.

\(^5\) Ratio between pore volume and entire body volume
In the case of packed bed, there is mainly 3 different method of packing [33, 55, 100]: Cubic, rhombic and random packing.

![Cubic packing](image)
![Rhombic packing](image)

**Figure 26 – Schemes of packing: cubic (a), rhombic (b) [55]**

### 7 Materials for the heating chamber

Here, it is first discussed the major requirements of importance to the selection. Next the principal options for heating chamber materials are listed. Thirdly, these materials in relation to the requirements are assessed. It is performed a trade and rank the various options according to suitability. According to the comparisons, a material is selected and evaluated.
7.1 Requirements for the materials

Various requirements must be taken into account when selecting a material. A general list of requirements is given in [1]. Here it is not consider all requirements, but only those that are considered most critical for a heating chamber for use in a thermal propulsion system. Here, it is discussed heat capacity, resistivity, melting temperature, availability and special characteristic. Of these, the three major requirements that need to be satisfied for these purposes are: resistivity, melting temperature, availability and special characteristics. The definition of availability is given in section 5.1, but in this case it is related to material.

**Heat capacity**

The first requirement is the heating capacity, since it is fundamental to know how long the material will take to reach stable conditions. A higher value indicates higher energy stored in the material, making longer transient phases. This parameter is presented in order of magnitude, O[ ], taking into account the different grades in the alloy. However, since this document focuses on the development of a thruster, this parameter is not taken into account for the comparison. Furthermore it also depends on the power level and heater mass.

**Resistivity**

The electrical resistivity is very important for a resistojet, since this parameter indicates the facility that a certain material has to convert electric power into heat power. It should be as high as possible, allowing smaller electric current levels for the same electric power. However the electrical resistivity should be much smaller than the electric insulation, avoiding electric contact between the thruster and the satellite (or the test facility).

However this parameter is not considered as fundamental since capacity to convert electric power into heat power also depends on the geometry. Furthermore, if the heating chamber is heated indirectly, this parameter is no more important.

**Melting temperature**

Since the temperature in the heating chamber reaches high values, this parameter is crucial in the choice of a material. This avoids the maximum allowable temperature of the material to be a constraint.

**Special characteristics**

In some cases, there are special characteristics that should also be taken into account, as oxidation, machinability, etc. Some characteristics can make the choice of that material unacceptable.
7.2 Materials options

Many different materials can be used in a heating chamber of non-chemical thermal propulsion system. However the list should have a restricted number of candidates so that a qualitative analysis is still possible. Some of the materials already used for heating chamber or commonly used for other purposes are chosen as candidates. The materials can be pure or in alloy, where the other materials of a certain alloy are in lower percentage. The candidates are given in the Table 5:

<table>
<thead>
<tr>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium alloys</td>
</tr>
<tr>
<td>Copper alloys (including bronzes and brasses)</td>
</tr>
<tr>
<td>Nickel alloys</td>
</tr>
<tr>
<td>Stainless Steel alloys</td>
</tr>
<tr>
<td>Titanium alloys</td>
</tr>
<tr>
<td>Graphite</td>
</tr>
</tbody>
</table>

Table 5 – Candidates as material for heating chamber in non-chemical thermal propulsion system

7.3 Material analysis

This section explains how to analyse a material. Heat capacity, resistivity and melting temperature are taken from [103, 104].

Resistivity

With respect to material resistivity, the values are taken at room temperature (considered as reference temperature). Following the method outlined in [2], four different grades are given with respect to this parameter:

- Green (adequate) = $10^{-2}$ to $10^{-4}$;
- White (acceptable) = $10^{-5}$;
- Yellow (acceptable but with special configuration) = $10^{-6}$;
- Red (unacceptable) = lower than $10^{-6}$ and higher than $10^{-2}$.

Melting temperature

The melting temperature of a certain materials is considered at ambient pressure. Three grades are given:

- Green (adequate) = higher than 1300 K;
- Yellow (acceptable) = higher than 1000 K, lower than 1300 K;
- Red (unacceptable) = lower than 1000 K.

Availability

With respect to the availability, different grades are given. From the highest to the lowest availability:

- Green (adequate) = easily available at Delft University of Technology or a shop, high availability;
- Yellow (acceptable) = ordering by internet or directly to the manufacturer, moderate availability;
- Red (unacceptable) = hardly available.
**Special characteristics**
Some special characteristics of the materials can be crucial on the final choice.
- Green (adequate) = positive aspect;
- Yellow (acceptable) = negative aspect, but not critical;
- Red (unacceptable) = negative aspect, highly critical.

**Final grade**
A final grade is given in the end of the qualitative analysis: GO (suitable) and NO GO (inappropriate). A material is suitable for the heating chamber of a thermal propulsion system when the major criteria of density and safety are fulfilled. There are only two possible results:
- GO (suitable) = no red allowable
- NO GO (unsuitable) = at least one red

**Example**
Stainless steel is taken as an example to understand how to analyse a material. Heat capacity, resistivity, melting temperature and special remarks are taken from [103, 104].
The heat capacity does not enter as major criterion, and for that reason no grade is given.
The resistivity of stainless steel has an order of magnitude of $10^{-5} \ \Omega \text{cm}$, having then a White grade (acceptable).
The grade for melting temperature is Green (adequate), since it can have temperatures slightly higher than 1600 K.
Since stainless steel can be easily found at Delft University of Technology or even in a shop, the grade is Green (adequate).
Stainless steel has only one special characteristic, it has low machinability. However this remark is not critical, since the heating chamber can have by itself a high manufacturability.
Since there are no red grades, the final grade is a GO, meaning that this material is suitable for a heating chamber.
## 7.4 Comparison between materials

In this section, it is traded the materials analysed in section 7.2, and it is used the requirements discussed in section 7.1. Considering these requirements, some materials are more suitable than others, for a technology demonstrator of a heating chamber. However it does not mean directly that a material is better than another, but only that is more suitable for this specific application. Four major criteria are used for comparison: resistivity, melting temperature, availability, machinability and some special characteristics.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminium alloys</th>
<th>Copper alloys</th>
<th>Nickel alloys</th>
<th>Stainless steel alloys</th>
<th>Titanium alloys</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat capacity</strong> [kJ/(kgK)]</td>
<td>0.8 – 1.6</td>
<td>~ 0.4</td>
<td>0.3 – 0.7</td>
<td>0.4 – 0.5</td>
<td>0.45 – 0.65</td>
<td>~ 0.7</td>
</tr>
<tr>
<td><strong>Melting temperature</strong></td>
<td>800 – 1000 K</td>
<td>1000 – 1300 K</td>
<td>1200 – 1500 K</td>
<td>&gt; 1600 K</td>
<td>&gt; 1700 K</td>
<td>&gt; 3000 K</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>At TUDelft</td>
<td>At TUDelft</td>
<td>Ordering</td>
<td>At TUDelft</td>
<td>Ordering</td>
<td>Ordering</td>
</tr>
<tr>
<td><strong>Special Characteristics</strong></td>
<td>High machinability</td>
<td>High machinability</td>
<td>Outstanding oxidation and chemical resistance</td>
<td>Low machinability</td>
<td>• Very strong yet lightweight • Excellent corrosion resistance • Expensive</td>
<td>Dissolves in water • Low machinability</td>
</tr>
</tbody>
</table>

| Final Grade | NO GO | GO | GO | GO | NO GO | NO GO |

Table 6 – Material trade-off summary table, from [103] and [104]

From Table 6, the graphite, titanium and aluminium are not suitable for this purpose, since the graphite dissolves in water (propellant chosen for test and possible propellant for flight), titanium is expensive (avoided when the goal is to demonstrate a technology) and aluminium starts melting at temperatures lower than 1000 K (from test requirements). However for slightly different requirements, these three materials could be suitable for a heating chamber.

Three materials remain as suitable, copper, nickel and stainless steel. Depending mostly on the availability, the materials are chosen depending on the conceptual design of the heating chamber.
7.5 Selection of the material

Different materials were analysed and three of them remained as attractive for a heating chamber to demonstrate the feasibility of thermal propulsion. The final selection of the material depends on the conceptual design.

Stainless steel is chosen as the material for the concept of a coiled tube directly heated. Since, this material, more specifically SS304 and SS316, is already available for this concept and it was already used in the heating chambers of DUR [16, 18]: DUR 1.0, DUR 1.1 and DUR 2.0. Furthermore this choice avoids the propulsion system to be hindered.

For the concept of a porous media indirectly heated, the materials already available at space systems engineering chair for the porous media are brass (copper alloy) and nickel-chromium (nickel alloy). For the tube around the porous media, the material should be the same, avoiding oxidation and different thermal expansions.

8 Insulation method for the heating chamber

A crucial part of the design of the heating chamber is still not defined: the way to thermally insulate the heating chamber from the outside. This avoids very high levels of current and voltage (constraints from test equipment and safety). Furthermore the influence of the external conditions is reduced.

The method used is the same as in section 5.

8.1 Requirements for the insulation methods

The requirements [1] that must be taken into account to evaluate the different methods of insulation of the heating chamber are: availability, flexibility, heat loss and simplicity. Other requirements, as external dimensions and mass, are not evaluated, since it is not possible to give estimation at this point. For the heat loss, numerical values are not given, since a theoretical background is needed, see Chapter 5.

It is considered that the propellant used is water and the thruster is a resistojet, forbidding electric contact between the heater element and the insulation method.

The definition of availability, flexibility and simplicity are defined in section 5.1, but in this case it is related to insulation methods.

Heat loss

Heat loss [1, 3] in the insulation method is characterized by the capacity to decrease the heat transport from the heating chamber to the exterior. The influence of external conditions can play a major role in some cases, increasing the heat loss.

8.2 Options for insulation methods

Many different insulation methods can be used. Here the list has a restricted number of candidates so that a qualitative analysis is still possible. The insulation methods already used in heating chambers are chosen as candidates, Table 7.
### 8.3 Analysis of insulation methods

This section explains how to analyse different insulation methods regarding to the requirements. In case of simplicity, the grades definition is explained in section 5.3.

#### Availability

With respect to the availability, different grades are given. From the highest to the lowest availability:

- 3 – within the chair of Space Systems Engineering;
- 2 – within the Delft University of Technology;
- 1 – ordering in a shop or internet;
- 0 – not available.
**Flexibility**

With respect to the flexibility, different grades are given in relation to the total number $n$ of different design parameters that can be changed. The highest the better it is:

- 3 – nothing to change;
- 2 – one parameter to be changed;
- 1 – several parameters to be changed;
- 0 – not possible to be changed.

**Heat loss**

To analyse heat loss without calculations, it is seen how the external conditions (ambient temperature and pressure, humidity, air flow) influence the heat loss. The following grades are:

- 3 – negligible influence by the exterior;
- 2 – little influence by the exterior (Temperature);
- 1 – some influence by the exterior (Temperature and external air flow);
- 0 – highly influenced by external conditions (ambient temperature and pressure, humidity, air flow).

**Final grade**

A final grade is given in the end of the qualitative analysis, adding all the grades. The insulation methods with higher final grade are more suitable for the purpose of thermal rocket propulsion with liquid propellant. Furthermore 3 colour grades are given, to emphasise the more and less suitable concepts. The colour grades are:

- Green (suitable) – grade higher than 4;
- Yellow (acceptable) – grade of 3 or 4;
- Red (unsuitable) – grade of 2 or lower.

**Example**

The method of insulation taken as example is the vacuum chamber with radiation shield. This method was used with DUR1.1 with a small vacuum chamber as first test and, as second test, at hypersonic aerodynamic tunnel of aerospace faculty in the building of High Speed Laboratory [18].

For the availability, the difficulty is to find a vacuum chamber that as special vacuum pumps that can work with water vapour or even liquid water in case exhaust condensation or leakages. These pumps are not available at Delft University of Technology but need to be ordered. For that reason the grade for availability is 1.

For the flexibility of this method, in case of changing the dimensions of the heating chamber, the radiation shield and the electric insulation should be also modified. Furthermore, in the case of a vacuum chamber as done in the first test with DUR1.1, see Figure 29, the vacuum chamber also needs to be modified. There is then more than one parameter to be changed and for that reason the grade is 1.
The heat loss in this case is quite low, since it is only influenced by the surface temperature of the heat chamber. However the heat losses cannot be considered as negligible since there are still losses by the radiation shields and some remaining convection in case of small vacuum chamber as in Figure 29. For these reasons the grade for heat loss is 2.

For the simplicity, this method has 3 different parts, grade -3: vacuum facility, radiation shield and electric insulation.

Adding all the grades the final result is 1. Since it is lower than 2, the grade is RED, meaning that this method of insulation is not suitable for this purpose.

8.4 Comparison between insulation methods

In this section, it is traded the insulation methods analysed in section 8.2, and it is used the requirements discussed in section 8.1. Considering these requirements, some methods are more suitable than others, for an insulator for a technology demonstrator. However it does not mean directly that a method is better than another, since only one requirement (heat loss) is about the performance of the insulation method. Four major criteria are used for comparison: availability, flexibility, heat loss and simplicity. The parameter that makes the grade is in paranthesis.
From Table 8, at open air, the methods show to be more suitable for this purpose, since the methods with vacuum chamber have the handicap of the availability. Three methods remain as suitable: at open air, without insulation, with insulation and with regenerated flow.

### 8.5 Selection of insulation method

For the final selection, the regenerated flow is not taken for now, since it is more complex than the other options. Furthermore the goal is not to optimize a heating chamber, but to demonstrate a technology.

In case that no insulation is used, the system can be very simple, however is has high levels of heat loss. Since it is fundamental to vaporize the water and simultaneously keeping the system as safe as possible (low voltage levels), this configuration is only used to compare with the selected insulation method, see Chapter 5 and 7. The latter option is a good compromise between simplicity and heat loss.
9 Choices summary

Different options have been considered for propellant, conceptual design, material and insulation method for the heating chamber. The choice for the thermal boundary condition for the theoretical model is presented in section 2. A choice was made for each parameter with some possible alternative for testing or for future development. Table 9 shows the summary of the choices and the respective alternatives.

<table>
<thead>
<tr>
<th>General parameters</th>
<th>Choices</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>Water</td>
<td>Methanol (also ethanol and other alcohols) Butane</td>
</tr>
<tr>
<td>Conceptual Design</td>
<td>Coiled tube with direct heating (concept 4)</td>
<td>Porous media with an outer heater as indirect heating (concept 2)</td>
</tr>
<tr>
<td>Material for the heating chamber</td>
<td>Stainless steal alloy (SS304 and SS 316)</td>
<td>Nickel alloy (Nickel chromium for porous media) Copper alloy (Brass for porous media)</td>
</tr>
<tr>
<td>Insulation method for the heating chamber</td>
<td>Insulation material at open air</td>
<td>No insulation (for comparison) Regenerated flow at open air (for optimization)</td>
</tr>
<tr>
<td>Boundary condition of theoretical model</td>
<td>Constant heat flux</td>
<td>Constant wall temperature</td>
</tr>
</tbody>
</table>

Table 9 – Summary of the choices and alternatives for different general parameters
Chapter 3 – Design of a Resistojet

This chapter is focused in the design of different parts of a resistojet: nozzle and heating chamber. The feed system, tank and insulation are given only as a concept. The levels of pressure drop, tension and voltage are also studied to confirm the suitability of the design. The requirements and constraints are found in Chapter 2.

1 Nozzle design

The ideal rocket motor theory is used in this section, allowing a reasonable approximation of propulsive characteristics of a real rocket motor [1, 9]. To apply ideal rocket motor theory, it is required to have sonic conditions \( M_{throat} = 1 \) at the throat. The nozzle design will take into account a very small expansion. The convergent angle is determined by the drill bit angle. These two options design decrease greatly the manufacture complexity, influencing directly the manufacturing time and price of the nozzle.

1.1 Critical conditions

Most of the equations used in this section are only for critical conditions in the nozzle, when Mach number \( M_{throat} \) is 1 at the throat. The critical conditions appear only when the critical pressure ratio \( \frac{p_i}{p_c} \) is obtained [106]. If the critical conditions are not reached, then the exhaust velocity is smaller as well as all the parameters related to it, as the thrust.

For a certain nozzle (with certain throat area \( A_t \)), using a specified propellant at a certain chamber temperature \( T_c \) (K) and chamber pressure \( p_c \) (Pa), it is possible to know the mass flow \( \dot{m} \), see equation (3.1).

\[
\dot{m} = \frac{A_t p_c \Gamma}{\sqrt{RT_c}}, \text{ with } R = \frac{R_A}{M} \text{ [kg/s]}
\]

(3.1)

Where the ideal gas constant is \( R_A = 8.314472 \text{ J/(molK)} \) and \( M \) is the molar mass (kg/mol). \( \Gamma \) is the Vandenkerckhove function that depends on the propellant characteristics and temperature:

\[
\Gamma = \sqrt{\gamma} \cdot \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \text{ [-]}
\]

(3.2)

Where \( \gamma \) is the specific heat ratio that depends on the propellant temperature [75]. It was considered that the critical conditions (choked flow) happen in the throat. However if earlier in the thruster there is an orifice smaller than the throat, the flow would be choked at that point. This is only applied when at that orifice the flow is in gas phase. Consequently the chamber pressure would be smaller and the thruster would have a very low performance [56].
1.2 Non-critical conditions

When the critical pressure ratio $\frac{p_t}{p_c}$ is not obtained, the critical conditions are not reached, having only a subsonic flow along the nozzle. In space environment this is never a problem, since the ambient pressure is always much lower than the throat pressure. In standard atmosphere, the minimal chamber pressure with choked flow is computed using [102]. This reference also shows if there is any shock wave in the nozzle, in case of choked flow. If a shock wave is present then the thrust is smaller, see [30].

1.3 Thruster characteristics

Taking the mass flow obtained for a certain throat area $A_t$. In this configuration, the resulting thrust $F$ is calculated using:

$$F = \dot{m}U_{eq} \text{ [N]}$$  \hspace{1cm} (3.3)

Where $\dot{m}$ is the mass flow in kg/s. Assuming sonic conditions in the throat the equivalent velocity $U_{eq}$ of an ideal rocket motor is computed by:

$$U_{eq} = U_e + \frac{p_e - p_a}{\dot{m}} A_e \text{ [m/s]}$$  \hspace{1cm} (3.4)

The ambient pressure $p_a$ is assumed for test at 1 bar and vacuum environment at 0 bar. It is considered that the exit area $A_e$ is almost inexistent, to decrease the manufacturing complexity.

Flow separation occurs only when $\frac{p_e}{p_a}$ is below 0.25 or 0.35 [1]. In that case the exhaust velocity would be severely affected. Obviously, in vacuum (flight environment), there is no flow separation.

$U_e, A_e, p_e$ are the exhaust velocity, the exit area and exit pressure, respectively. The exit velocity $U_e$ is computed by:

$$U_e = \sqrt{\frac{2}{\gamma - 1} \cdot \frac{R_A}{M} \cdot T_c \cdot \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma - 1}{\gamma}}\right)} \text{ [m/s]}$$  \hspace{1cm} (3.5)

Where the ideal gas constant is $R_A = 8.314472 \text{ J/(molK)}$, $M$ is the molar mass (kg/mol), $p_c$ is the chamber pressure (Pa), $T_c$ is the chamber temperature (K) and $\gamma$ is the specific heat ratio that depends on the propellant temperature [75].

The value of exit pressure $p_e$ and the respective pressure ratio $\frac{p_c}{p_e}$ is still unknown. Then equation (3.6) is used.
The equation (3.6) is computed in the following way to know the pressure ratio \( \frac{p_e}{p_i} \):

1. Create vector for \( \frac{p_e}{p_i} \) from 1 to 100 or 1000;
2. With equation (3.6), compute the vector \( \frac{A_e}{A_i} \);

Since \( \frac{A_e}{A_i} \) is known, to obtain \( \frac{p_e}{p_i} \), interpolate this value with the two vectors: \( \frac{p_e}{p_i} \) and \( \frac{A_e}{A_i} \).

An important parameter for the performance of a rocket motor is the specific impulse \( Isp \). The higher this parameter, the lower expelled mass is needed for a certain thrust \( F \). It can be maximized increasing the exhaust velocity \( U_e \). The specific impulse \( Isp \) is defined as:

\[
Isp = \frac{U_{eq}}{g_0} \quad [s]
\]  

(3.7)

With \( g_0 = 9.80665 \text{ m/s}^2 \) as the gravitational acceleration at sea level.

The parameter to know the kinetic power in the jet is the jet power \( P_j \), calculated by:

\[
P_j = \frac{1}{2} FU_{eq} \quad [W]
\]  

(3.8)

The thrust efficiency \( \eta_{thrust} \) is estimated by:

\[
\eta_{thrust} = \frac{P_j}{P_{in}} \quad [-]
\]  

(3.9)

Here the power input \( P_{in} \) is considered to be the heat power \( P_{heat} \). This is considering the system without heat losses to the exterior. This approximation is done since the power losses are still unknown. Nevertheless, the approximated value of thrust efficiency will still be representative of the propulsion system. For the thrust efficiency, a higher value brings to a lower required power for a propulsion system with a certain jet power.

The power input is computed using equation (3.10).
\[ P_{in} = P_{heat} = \dot{m} \cdot \Delta H = \dot{m} \left( H(T_{final}) - H(T_{room}) \right) \text{ [W]} \] (3.10)

Here \( \dot{m} \) is the mass flow, \( \Delta H \) is the change of enthalpy, and \( H(T_{room}) \) and \( H(T_{final}) \) is the enthalpy at room temperature \( T_{room} \) and final temperature \( T_{final} \).

The power input is not only important for determining the thrust efficiency, but also to compute temperatures in the heating chamber, heat loss and heat efficiency. These parameters are analysed in other sections.

### 1.4 Design dimensions

The dimensions of the nozzle are established in accordance to the requirements and constraints. Some other requirements are in accordance with previous nozzles designed at the chair of Space Systems Engineering, as Nozzle C [23]. These dimensions are not optimized, since the primordial objective of this research are not the thruster characteristics, but the heater characteristics.

<table>
<thead>
<tr>
<th>Material</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber diameter [mm]</td>
<td>3.1</td>
</tr>
<tr>
<td>Outer diameter [mm]</td>
<td>6.0</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>10.0</td>
</tr>
<tr>
<td>Throat diameter, ( D_t ) [m]</td>
<td>0.40</td>
</tr>
<tr>
<td>Exit diameter, ( D_e ) [m]</td>
<td>0.41</td>
</tr>
<tr>
<td>Chamber Temperature, ( T_c ) [K]</td>
<td>1000</td>
</tr>
<tr>
<td>Chamber pressure, ( p_c ) [bar]</td>
<td>2.0</td>
</tr>
<tr>
<td>Critical mass flow, ( \dot{m} ) [mg/s]</td>
<td>24</td>
</tr>
<tr>
<td>Thrust, ( F ) [mN]</td>
<td>19</td>
</tr>
<tr>
<td>Specific impulse, ( I_{sp} ) [s]</td>
<td>79</td>
</tr>
<tr>
<td>Jet power, ( P_J ) [W]</td>
<td>7</td>
</tr>
<tr>
<td>Power input, ( P_{in} ) [W]</td>
<td>95</td>
</tr>
<tr>
<td>Thrust efficiency, ( \eta_{thrust} ) [%]</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 10 – Nozzle and thrust parameters
Figure 30 shows the nozzle designed for this purpose. The nozzle is named in accordance to the throat diameter, Nozzle Ø 0.4 mm. The smaller side holes are for thermocouple, the biggest is for pressure tube, as in Nozzle C. For the technical drawing see Annexes of Technical Drawings.

2 Heater design

From Chapter 2, the conceptual design of a helically coiled tube was chosen. The objective of this section is to be able to give a proper tube inner diameter, $D$, constant along all the tube, tube length, $L$, and mean coil diameter, $D_c$. Furthermore, the pressure drop along the heater needs to be checked to ensure that the pressure requirements are fulfilled.

The flow analysis of a propellant as water through a heated tube is divided into three parts. The first part is the liquid phase, where the propellant enters at ambient temperature until reaching the boiling temperature. The second part is the boiling flow, where the temperature remains around constant at critical temperature. The last part is the gas phase, where the propellant is fully evaporated and remains only gas. It is considered that fluid properties are not constant with temperature, and change considerably with a different phase. For water, the fluid properties as enthalpy, $H$, density, $\rho$, viscosity, $\mu$, thermal conductivity, $k$ and specific heat capacity, $C_p$ can be found in [75].

2.1 Tube diameter

As first estimation, it is important to know what should be the minimum inner diameter of the tube in case of a certain mass flow of a substance at a certain pressure and temperature. This estimation should avoid high levels of pressure drop along the channels. However the boiling flow and coiled effects are not taken into account, since it is only a first estimation. It is then used equation (3.11) to determine the minimum admissible inner diameter of the tube.

$$D = \sqrt[4]{\frac{m}{\pi \nu \rho}} \text{[m]}$$ (3.11)
A smaller diameter has a high speed flow that brings a high pressure drop and the compressibility starts to be relevant. For that reason the flow velocity in liquid, $v_l$, and vapour, $v_g$, are limited by the following formulas [1]:

$$v_l < 7 - 15 \text{ [m/s]}$$  \hspace{1cm} (3.12)

$$v_g < 175 \left( \frac{1}{P_g} \right)^{0.43} \text{ [m/s]}$$  \hspace{1cm} (3.13)

A larger diameter has a low speed flow but the mass flow can be insufficient to fill all the volume available by the tube. Additionally a larger diameter will have less capacity to heat the flow, as it will be seen later.

For the final design, the inner diameter should be chosen avoiding high pressure drop. A minimum tube inner diameter of 0.53 mm was computed. Since the minimum available tube diameter is 1.3 mm, it is then chosen for the design. However, the definitive choice can be made only after fixing the length and coil diameter.

<table>
<thead>
<tr>
<th>Design</th>
<th>Inner diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>New DUR coiled tube</td>
<td>$&gt; 0.53 \Rightarrow 1.3$</td>
</tr>
</tbody>
</table>

Table 11 – Chosen diameter for the new DUR

### 2.2 Length and coil diameter

To compute the minimum length $L$, it is required to fix the final conditions of the flow and wall just before the throat (final pressure $p$, final flow temperature $T_{m,final}$ and final wall temperature $T_{w,final}$). Furthermore it is also important to fix a boundary condition for the flow, see Chapter 2. In this case, resistive heater, it is chosen constant heat flux $q''$, equation (3.14).

$$\frac{q}{\pi DL} = q'' = h_j(T_{w,j} - T_{m,j}) = \text{const} \quad \text{[W/m}^2\text{]}$$  \hspace{1cm} (3.14)

Here $h_j$ is the local convection coefficient and the subscribe $j$ is for local condition.

To obtain the heat power $q$ equation (3.10) is used:

$$P_{\text{heat}} = q = \dot{m} \cdot \Delta H = \dot{m} \left( H(T_{m,final}) - H(T_{\text{room}}) \right) \quad \text{[W]}$$  \hspace{1cm} (3.10)

The total length for the heating chamber is then:

$$L_{\text{total}} = \frac{q}{\pi D h_{f,final} (T_{w,final} - T_{m,final})} \quad \text{[m]}$$  \hspace{1cm} (3.15)

The convection coefficient at final conditions is still missing. Several correlations exist to estimate this value however it is normally related to a dimensionless parameter, the Nusselt number, $N_{\text{ Nu D}}$. This parameter can be seen as the ratio between the transmitted
energy by convection with the transmitted energy by conduction on the fluid thickness, \( D \). The heat transfer coefficient is related to Nusselt number \( Nu_D \) by the equation (3.16).

\[
h = \frac{Nu_D \cdot k}{D} \quad [\text{W/m}^2\text{K}]
\]  

(3.16)

Here \( k \) is the thermal conductivity in W/(mK).

Several correlations exist for the Nusselt number depending on the type of tube: for straight tube, helically coiled tube, tube with porous media, etc; also depending on the flow regime: laminar and turbulent; and depending on the boundary condition: constant wall temperature and constant heat flux.

For boiling flow, special correlations are used, but normally they depend on the vertical or horizontal flow, level of constant heat flux and type of tube (some also depend on the roughness of the tube surface for bubbles production). It is also important to remark that some correlations for two-phase flow are not for boiling flow but for liquid and gas from different species (adiabatic flow).

For the estimation of the tube length, it is only important to know the final conditions of the gas flow. For that reason, the correlations for boiling flow are not used.

Most of the correlations also use another dimensionless parameter, Prandtl number \( Pr \), equation (3.17).

\[
Pr = \frac{\mu c_p}{k} \quad [-]
\]  

(3.17)

Here \( \mu \) is the dynamic fluid viscosity in Pa.s and \( c_p \) is the specific heat in J/(kgK).

<table>
<thead>
<tr>
<th></th>
<th>Liquid</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>298.15 K</td>
<td>Boiling temperature</td>
</tr>
<tr>
<td>( Pr )</td>
<td>6.130</td>
<td>1.438</td>
</tr>
</tbody>
</table>

Table 12 – Prandtl number for water boiling flow at 2 bar
2.2.1 Flow regime characterization

The flow regime is fundamental to understand if the flow is at laminar or turbulent regime. It is characterized by the Reynolds number \( \text{Re}_D \) and depends on the tube diameter \( D \), mass flow \( \dot{m} \) and dynamic fluid viscosity \( \mu \). It also can depend on the flow velocity \( v \) and the density \( \rho \).

\[
\text{Re}_D = \frac{\rho v D}{\mu} = \frac{4\dot{m}}{\pi D \mu} \quad [-]
\] (3.18)

For straight tube, the critical Reynolds number (transition from laminar to turbulent flow) is 2300 [3, 4] or 2320 [1]. However in helically coiled tube, the transition is also dependent on the coil diameter. To be able identify the transition from laminar to turbulent Srinivasan et al. proposes to use [4]:

\[
\text{Re}_{crit} = 2100 \left[ 1 + 12 \left( \frac{D_{tube}}{D_{coil}} \right)^{0.5} \right] \quad [-]
\] (3.19)

According to Ito, the critical Reynolds number is [24, 18]:

\[
\text{Re}_{crit} = 20000 \left( \frac{D_{tube}}{D_{coil}} \right)^{0.32} \quad [-]
\] (3.20)

Both relations give close values close to each other. However the relation from Srinivasan et al. is more conservative for heat transfer since it assumes that the transition occurs at higher Reynolds numbers. A more detailed comparison is done in [33], with the choice of Srinivasan et al. relation.

2.2.2 Nusselt number

For helically coiled tube, several correlations exist, but only most famous and less rigid formulas are used [1]. Two formulas are given for laminar flow, (3.21) and (3.22), and are used depending on the Prandtl number. Two other formulas are used for turbulent flow, where the last correlation (3.24) is used to fill the gap for transition flow. However that formula could also be used for laminar flow if more information was available. All the correlations are for constant heat flux, even if some of them can also be used for constant wall temperature. For comparison between correlations, see [33].
<table>
<thead>
<tr>
<th>Correlations</th>
<th>Conditions</th>
<th>References</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Nu_D = \left(0.76 + 0.65 \text{Re}_D^{0.5} \left(\frac{D}{D_c}\right)^{0.25}\right) \text{Pr}^{0.175}$</td>
<td>Laminar flow $5 &lt; \text{Pr} &lt; 175$ $50 &lt; \text{Re}(D/D_c)^{1/2} &lt; 2000^6$</td>
<td>[1, 18, 57]</td>
<td>(3.21)</td>
</tr>
<tr>
<td>Kalb correlation: $Nu_D = 0.913 \left(\text{Re}_D \left(\frac{D}{D_c}\right)^{0.5} \text{Pr}^{0.2}\right)$</td>
<td>Laminar flow $0.7 \leq \text{Pr} \leq 5$ $80 &lt; \text{Re}(D/D_c)^{1/2} &lt; 1200$</td>
<td>[1, 58]</td>
<td>(3.22)</td>
</tr>
<tr>
<td>Seban-McLaughlin correlation: $Nu_D = 0.023 \text{Re}_D^{0.85} \text{Pr}^{0.4} \left(\frac{D}{D_c}\right)^{0.1}$</td>
<td>Turbulent Flow $6000 &lt; \text{Re}_D &lt; 100000^7$ (Error of $\pm 10%$)</td>
<td>[1, 18, 59]</td>
<td>(3.24)</td>
</tr>
<tr>
<td>Mori correlation: $Nu_D = \frac{\text{Re}_D^{0.8} \text{Pr} \left(\frac{D}{D_c}\right)^{0.1}}{26.2(\text{Pr}^{2/3} - 0.074)} \left(1 + \left(\frac{0.098}{\text{Re}_D \left(\frac{D}{D_c}\right)^2}\right)^{1/5}\right)$</td>
<td>Laminar to turbulent flow $\text{Pr} \approx 1$ $\text{Re}_D(D/D_c)^2 &gt; 0.1$</td>
<td>[18, 60, 61]</td>
<td>(3.24)</td>
</tr>
</tbody>
</table>

Table 13 – Nusselt number correlations for helically coiled tube

Here $D$ is the inner tube diameter and $D_c$ is the mean coil diameter. The value of 0.32 m is obtained when the output temperature of the flow and wall is 1000 K and 1100 K, respectively, and with coil diameter of 25 mm. The coil diameter comes by trial and error explained afterwards. However, if the final flow temperature is lower than 1000 K, the critical mass flow is then higher, for a constant chamber pressure. Then, the minimum length should be higher when the output flow temperature is lower.

---

6 Some references have 200 as upper limit
7 Depending on the references: $6000 < \text{Re}_D < 65600$ or $10000 < \text{Re}_D < 100000$. It is chosen both limits to include a wider range of values.
The final wall temperature is assumed to be 10% higher than the flow. Since the required tube length increases at lower temperatures, it is taken the length of 0.7 m computed at 700 K. This temperature is the mean temperature between range of temperatures (from 500 K to 1000 K) and range of required length (from 0.3 m to 1.1 m). Then, if the temperature is higher than 700 K, the difference between wall and flow will be lower, and vice versa.

The value of 25 mm coil diameter comes by trial and error with the required tube length and the number of loops of the helically coiled tube. For that, the aspect ratio between coil diameter and coil length should be between 0.5 and 1. If the aspect ratio is smaller than 0.5, the coil diameter would be smaller but the coil length would be longer, increasing significantly the difficulty in manufacturing without bringing an decrease in volume.

<table>
<thead>
<tr>
<th>Design</th>
<th>Length [m]</th>
<th>Coil diameter [mm]</th>
<th>Number of loops</th>
</tr>
</thead>
<tbody>
<tr>
<td>New DUR coiled tube</td>
<td>&gt; 0.32 ⇒ 0.70</td>
<td>25</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 14 – Chosen diameter for the new DUR

### 2.3 Pressure Drop for a helically coiled tube

From section 2.1 it was clear that the choice of a minimal tube diameter is fundamental to avoid high pressure drop along the channel. However, it was not more than a first estimation. Now, it is important to know if the actual tube diameter with its respective length is acceptable, quantifying the pressure drop along the tube. The tube is divided into 3 parts: liquid flow, boiling flow and vapour flow. It is fundamental to separate the flow into these three parts, since the properties and the characteristics depend heavily on the type of flow.

Furthermore, the pressure drop is divided into three parts: gravitational pressure loss, frictional pressure loss and pressure loss due to momentum change (acceleration pressure loss). For a horizontal flow or in space conditions, the gravitational pressure loss is
negligible. The acceleration pressure loss is present when the flow is diabatic (heat added to the flow) or when the cross-sectional area changes. This term is not relevant for single phase flow, but for boiling flow during vaporization, this term can be significant.

The total frictional pressure drop $\Delta p_{\text{total}}$ in a boiling flow has the pressure drop in liquid phase $\Delta p_{\text{liquid}}$, in two-phase $\Delta p_{\text{1-2-ph}}$ and in gas phase $\Delta p_{\text{gas}}$.

$$\Delta p_{\text{total}} = \Delta p_{\text{liquid}} + \Delta p_{\text{1-2-ph}} + \Delta p_{\text{gas}} \quad [\text{Pa}]$$  \hspace{1cm} (3.26)

Here the length of each part comes directly from assuming constant heat flux, see Chapter 5.

To obtain the total pressure drop $\Delta p_{\text{total}}$, the total frictional pressure loss and the momentum term $\Delta p_{\text{mom}}$ are added, (3.27).

$$\Delta p_{\text{total}} = \Delta p_{\text{total}} + \Delta p_{\text{mom}} \quad [\text{Pa}]$$  \hspace{1cm} (3.27)

For all the cases, the chamber pressure is fixed to 2 bar. However during test, since the chamber pressure is not directly controlled, the chamber pressure can have a value from 1 to 2 bar. Nevertheless, for heat chamber design, the worst case is at higher pressure.

### 2.3.1 Single-phase flow

To calculate the pressure drop in single flow, the Darcy-Weisbach relation [1, 3], equation (3.28), is used. The relations found to be with Fanning are converted to Darcy using $f_{\text{Darcy}} = 4 \times f_{\text{Fanning}}$. The velocity $\bar{v}$, the density $\bar{\rho}$ and the friction factor $\bar{f}$ are mean values computed by the sum of small parts divided by the number of the parts.

$$\Delta P_f = \frac{1}{2} \bar{f} \rho \bar{v}^2 \frac{L}{D} \quad [\text{Pa}]$$  \hspace{1cm} (3.28)

The friction factor $\bar{f}$ is based on the Reynolds number and in friction factor of a equivalent straight tube. There are many correlations, however, in this document, only the most common and more conservative are used [1, 3, 18, 24, 62]. For coiled tube, Ito correlation for friction factor for laminar and turbulent flow is used, since it presents the more reasonable values (not too conservative, not too optimistic [33]). Furthermore this correlation is more often used for friction factor in coiled tubes.
Friction factor

| f = \frac{64}{Re_D} | (Poiseuille) | Straight tube | Laminar flow | Re < 2320 | (3.29) |
| f = 0.316 \left( \frac{1}{Re_D} \right)^{0.25} | (Blasius) | Straight tube | Turbulent flow | 2320 < Re < 10^5 | (3.30) |
| f = 0.0032 + 0.221 Re_D^{-0.237} | (Nikuradse) | Straight tube, turbulent flow | 10^5 < Re < 10^7 | (3.31) |
| f_{coil} = f_{straight} \frac{21.5 De}{(1.56 + \log_{10} De)^{5/3}} | (Ito) | Coiled tube | Laminar flow | (3.32) |
| f_{coil} = 0.304 \left( Re_D \right)^{-0.25} + 0.029 \left( \frac{D}{D_c} \right)^{0.5} | (Ito) | Coiled tube | Turbulent flow | (3.33) |

Table 15 – Summary of friction factors [1, 3, 18, 24]

Here \( De \) is Dean number:

\[
De = Re_D \sqrt{\frac{D}{D_c}} [-]
\]

To know if the flow is at laminar or turbulent regime equation (3.19) is used (see section 2.2.1).

2.3.2 Boiling flow

The pressure drop for boiling tube flow is the sum of three different contributions: static pressure drop \( \Delta p_{\text{static}} \), momentum pressure drop \( \Delta p_{\text{mom}} \) and frictional pressure drop \( \Delta p_{\text{frict}} \) as:

\[
\Delta p_{\text{total}} = \Delta p_{\text{static}} + \Delta p_{\text{mom}} + \Delta p_{\text{frict}} \quad [\text{Pa}]
\]

The static pressure drop is given by:

\[
\Delta p_{\text{static}} = \rho_p g H \sin \theta \quad [\text{Pa}]
\]

Here \( g \) is the acceleration due to gravity, \( H \) is the static head, \( \theta \) is the angle with the horizontal and \( \rho_p \) is the density for two phase flow. For horizontal tubes, this
contribution is zero, since \( H = 0 \) and \( \theta = 0 \). For coiled tubes in horizontal position, this contribution is assumed as zero. This contribution is also zero for space conditions, since \( g \) is zero.

The density for two phase flow is defined as:

\[
\rho_p = \rho_l (1 - \alpha) + \rho_g \alpha \quad [\text{kg/m}^3]
\]  

(3.37)

The void fraction \( \alpha \) (ration of the gas volume in the mixture with total volume of gas and liquid) varies depending on the model. For separated flow model (see explanation below eq. (3.41)) the void fraction \( \alpha \) is defined by equation (3.38).

Steiner version of the drift flux model of Rouhani and Axelsson:

\[
\alpha = \frac{x}{\rho_g} \left[ (1 + 0.12(1-x))(\frac{x}{\rho_g} + 1-x) + \frac{1.18(1-x)}{G^2 \rho_g \rho_l^{0.5}} \right]^{-1}
\]  

(3.38)

Here \( \sigma \) is the surface tension of water (see [65]) and \( x \) is the gas quality (see (3.44)). \( G \) is the mass flux defined by equation (3.39).

\[
G = \frac{4 m}{\pi D^2} \quad [\text{kg/(m}^2\text{s})]
\]  

(3.39)

Generally, momentum pressure drop is defined by [33]:

\[
\frac{dp}{dz}_{\text{mom}} = G^2 \left[ \frac{1-x}{\rho_l} + \frac{x}{\rho_g} \right] \Rightarrow \Delta p_{\text{mom}} = G^2 \left[ \frac{(1-x)^2}{\rho_l (1-\alpha)} + \frac{x^2}{\rho_g \alpha} \right] - \left[ \frac{(1-x)^2}{\rho_l (1-\alpha) \rho_g \alpha} \right] \quad [\text{Pa}]
\]  

(3.40)

At inlet conditions \( \text{in} \), when the flow enters at boiling temperature, the gas quality \( x = 0 \) and the void fraction is 0. At outlet conditions \( \text{out} \), in the end of two-phase flow, the gas quality \( x = 1 \) and the void fraction is 1, (3.38). Then the momentum pressure loss is reduced to equation (3.41).

\[
\Delta p_{\text{inout}} = G^2 \left( \frac{1}{\rho_g} - \frac{1}{\rho_l} \right) \quad [\text{Pa}]
\]  

(3.41)

For the frictional pressure loss in two-phase there are mainly two different models. The homogeneous flow model is a simplified model averaging the properties of the liquid and vapour phase, assuming that the two phases are well mixed and that the velocities of both phases are equal [5]. This model cannot be used for boiling flow, since the velocity of liquid and gas phase are different in two or three orders of magnitude.

The separated flow model is a more complex model that artificially separates the liquid and gas phases into two streams. The main difference is in the way to compute the void
fraction $\alpha$ and the friction factor $f$ or the frictional pressure drop $\Delta p|_{\text{frict}}$. In case of separated flow models, there are several different correlations [63]. However, it is not given a clear range for using each correlation, instead only recommendations, barely followed, are given. Furthermore, it is important to choose a correlation that is not dependent on unknown parameters, e.g., the roughness of the tube. Furthermore, some correlations are for total pressure drop and others assume separately frictional pressure drop and momentum pressure drop (for non-horizontal flow also gravitational pressure drop). Generally, for two-phase flow the pressure drop is calculated using a correlation that is related to the pressure drop when considering liquid phase in the two-phase flow [63, 64, 5, 53], for straight or for coiled tube.

For boiling two-phase flow (gas and liquid from the same species) in a straight or coiled tube, the predicted pressure drop has still a great deviation from the experimental values. The disagreement between them can be easily $\pm 50\%$ or sometimes even more [33, 63, 62]. Due to this disagreement, a very frequent correlation for boiling flow in a straight tube is also used, the Lockhart-Martinelli correlation (3.42).

For boiling flow, since the gas quality $x$ goes from 0 to 1, the mean gas quality is considered as 0.5 [62].

It is also found, that the orientation of coiled tube influences significantly the results. Many correlations exist for horizontal and vertical helically coiled tubes. However some of them are for a very specific case or are too sophisticated to be practically used (refrigerants, high mass flow, high working pressure, etc) [62]. Other correlations are only for adiabatic two-phase flow (e.g. air and water) and not for boiling flow. It is then important to use a general correlation for boiling flow as Guo’s correlation, which can be use independently of the orientation of the helically coiled tube.
<table>
<thead>
<tr>
<th>Tube type</th>
<th>Pressure Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Lockhart-Martinelli correlation</strong></td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{ph} = \Delta P_{l} \left( 1 + \frac{C}{X} + \frac{1}{X^2} \right) ) [Pa]</td>
</tr>
<tr>
<td></td>
<td>( C = 30 ), for turbulent liquid and turbulent gas flows ( (\text{small tubes})^8 )</td>
</tr>
<tr>
<td></td>
<td>( C = 20 ), for turbulent liquid and turbulent gas flows ( (\text{large tubes}) )</td>
</tr>
<tr>
<td></td>
<td>( C = 12 ), for laminar liquid and turbulent gas flows</td>
</tr>
<tr>
<td></td>
<td>( C = 10 ), for turbulent liquid and laminar gas flows</td>
</tr>
<tr>
<td></td>
<td>( C = 5 ), for laminar liquid and laminar gas flows</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{l} ) is the frictional pressure drop assuming the two-phase</td>
</tr>
<tr>
<td></td>
<td>flow to be in liquid flow for a straight tube</td>
</tr>
<tr>
<td></td>
<td><strong>Lockhart-Martinelli parameter</strong></td>
</tr>
<tr>
<td></td>
<td>( X = \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( \frac{\mu_l}{\mu_g} \right)^{0.1} \left( 1 - \frac{x}{x} \right)^{0.9} )</td>
</tr>
<tr>
<td></td>
<td>(3.43)</td>
</tr>
<tr>
<td></td>
<td><strong>Mean gas quality ( x )</strong></td>
</tr>
<tr>
<td></td>
<td>( x = \frac{x_{in} + x_{out}}{2} ) (x = 0.5 for boiling flow)</td>
</tr>
<tr>
<td></td>
<td>(3.44)</td>
</tr>
<tr>
<td></td>
<td><strong>Guo’s correlation</strong></td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{ph} = \Delta P_{l} \psi \left[ 1 + x \left( \frac{\rho_l}{\rho_g} - 1 \right) \right] ) [Pa]</td>
</tr>
<tr>
<td></td>
<td>(3.45)</td>
</tr>
<tr>
<td></td>
<td>( \Delta P_{l} ) is the frictional pressure drop assuming the two-phase</td>
</tr>
<tr>
<td></td>
<td>flow to be in liquid flow for a helically coiled tube</td>
</tr>
<tr>
<td></td>
<td>( \psi = 1 + \frac{x(1-x)(1000/G - 1)(\rho_l/\rho_g)}{1 + x(\rho_l/\rho_g - 1)} )</td>
</tr>
<tr>
<td></td>
<td>(3.46)</td>
</tr>
<tr>
<td></td>
<td>For ( G \leq 1000 \text{ kg/(m}^2\text{s}) )</td>
</tr>
<tr>
<td></td>
<td>( \psi = 1 + \frac{x(1-x)((1000/G - 1)(\rho_l/\rho_g)}{1+(1-x)((\rho_l/\rho_g - 1)} )</td>
</tr>
<tr>
<td></td>
<td>(3.47)</td>
</tr>
<tr>
<td></td>
<td>For ( G &gt; 1000 \text{ kg/(m}^2\text{s}) )</td>
</tr>
<tr>
<td></td>
<td>( \psi_t = 142.2 \left( \frac{P}{P_{cr}} \right)^{0.62} \left( \frac{D_{tube}}{D_{coil}} \right)^{1.04} )</td>
</tr>
<tr>
<td></td>
<td>(3.48)</td>
</tr>
<tr>
<td></td>
<td>For water ( p_{cr} = 22.115 \times 10^6 ) Pa</td>
</tr>
</tbody>
</table>

Table 16 – Frictional pressure drop for boiling flow in a straight and in a helically coiled tube

---

\(^8\) There is no clear definition of small and large tube. It is used \( C = 20 \), since it is used often in tubes of mm of inner diameter
Now that the pressure drop in boiling flow is introduced, it is possible to check if the dimensions from the new design would not have a too high pressure drop. The Lockhart-Martinelli correlation is also added for additional information and for a second check.

### 2.3.3 Total pressure drop

To know the total frictional pressure drop for a helically coiled tube, the pressure drop in liquid phase, two-phase and gas phase, are added, (3.26). The total pressure drop is the total frictional pressure loss with the momentum term, (3.27). For additional check, a second column is added with the boiling flow in a straight tube.

<table>
<thead>
<tr>
<th>Frictional pressure drop</th>
<th>Liquid flow [Pa]</th>
<th>0.00012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas flow [Pa]</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>Boiling flow [Pa]</td>
<td>1.401</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.177</td>
</tr>
<tr>
<td>Total frictional pressure drop [Pa]</td>
<td>1.478</td>
<td>0.254</td>
</tr>
<tr>
<td>Momentum pressure drop [Pa]</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Total pressure drop [Pa]</td>
<td>1.481</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.257</td>
<td></td>
</tr>
</tbody>
</table>

Table 17 – Pressure drop in a helically coiled tube with single and boiling flow

In both cases, the pressure drop for this design is acceptable. The first case has a pressure drop much higher than the second case. This also means a higher efficiency to transport heat through the flow, see Stanton number [1, 33].

### 2.4 Structural properties of the heating chamber

Yield strength is an important parameter for strength capabilities of the heating chamber. That parameter is exposed in Table 18.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 316</td>
<td>~ 205 At room temperature</td>
</tr>
</tbody>
</table>

Table 18 – Yield strength of SS 316 for the heating chamber, from [18], [103] and [107]

Since yield strength decreases with temperature, as shown in Figure 32, the most critical part is at higher temperature, 1000 K.
From Figure 32, at 1000 K the yield strength is around 105 MPa. Assuming the same inclination of the curve, for 1100 K the yield strength will be 95 MPa. With the value of yield strength, and using equation (3.49) of internal pressure in thin wall [10, 18, 16], it is possible to compute the maximum allowable pressure, using equation (3.49).

Criterion for thin wall with internal pressure:

\[ p = \frac{\sigma t}{jr_{int}} \]  

(3.49)

Where \( j \) is the safety-factor, \( r_{int} \) is the inner tube radius, \( t \) is the tube thickness, \( \sigma \) is the circumferential stress [Pa] and \( p \) is the net internal pressure. Safety factor will be 3 as Rycek [16] did to DUR 1.0. The tube taken for the design of the heat chamber is commercially available with standard dimensions, see Table 19.

<table>
<thead>
<tr>
<th>Outer diameter [mm]</th>
<th>Inner diameter [mm]</th>
<th>Wall thickness [mm]</th>
<th>Safety factor [-]</th>
<th>Yield strength [MPa]</th>
<th>Maximum pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.3</td>
<td>0.35</td>
<td>3</td>
<td>95 (1100 K)</td>
<td>170</td>
</tr>
</tbody>
</table>

Table 19 – Tube dimensions and characteristics

The maximum pressure allowed by this tube is much higher than the required pressures. This means that the tube could have a much thinner wall and being still safe. A thinner wall would decrease the mass of the thruster system and would increase the resistance of the heater, as it will be shown in section 2.5.

Since the maximum allowed pressure is much higher than the working pressures, for the analysis, this parameter will not be taken into account. There are also equations for thicker walls, as suggested by [18 or 10]. These equations show values at the same order of magnitude, meaning that they are still far from the required pressures.
Another structural parameter that was not taken into account is the fatigue. This analysis shows the number of cycles that a material can support before being damaged. Since the resistance to fatigue decreases with increasing temperature, this parameter is important for the heat chamber of the Resistojet. Here this parameter is not studied since the cycles expected for testing are orders of magnitude lower than the maximum allowable (\( \gg 10^5 \)). This parameter can be more deeply studied using [10].

2.5 Electric properties of the heating chamber

The electric properties of the heater are fundamental to know the amount of electric current needed to obtain a certain electric power. The voltage can also be known, being fundamental for safety reasons. The electric power is then converted to heat and transferred to the propellant as input power. The heater resistance is also needed, since a higher resistance with the same level of electric current has a higher power, (3.50). However the resistance is temperature dependent and can be approximated by a polynomial, equation (3.51).

\[
P = RI^2 \tag{3.50}
\]

\[
R = R_0 \left( 1 + \alpha \Delta T + \beta \Delta T^2 + \ldots \right) \tag{3.51}
\]

\[
R_0 = \frac{P_0 L}{A} \tag{3.52}
\]

Here \( \alpha \ (1/K) \) and \( \beta (1/K^2) \) are temperature coefficients, \( R_0 \) is the heater resistance (\( \Omega \)) at reference temperature, \( \Delta T \) is the temperature difference, \( L \ (m) \) and \( A \ (m^2) \) is the length and cross sectional area of the heater, respectively.

For smaller temperature ranges, the polynomial expression (3.51) can be approximated to a linear relation [12, 16, 18].

\[
R = R_0 \left( 1 + \alpha \Delta T \right), \text{ where } \alpha \text{ is the temperature coefficient} \tag{3.53}
\]

Normally, the temperature coefficients have positive values, meaning that at higher temperatures the resistance increases. The current can be decreased in order to keep the same level of electric power.

In the case of a tube, the cross sectional area is computed by equation (3.54).

\[
A = \pi \left( r_{\text{ext}}^2 - r_{\text{int}}^2 \right) \tag{3.54}
\]
In the case of the heating chamber from the design as well from DUR series the properties are shown in Table 20.

<table>
<thead>
<tr>
<th>Material</th>
<th>Theoretical values (273 K – 700 K)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electrical resistivity [nΩm]</td>
<td>Temperature coefficient [K⁻¹]</td>
</tr>
<tr>
<td></td>
<td>@ 298 K</td>
<td>(273 – 700 K)</td>
</tr>
<tr>
<td>SS 316</td>
<td>740</td>
<td>0.820×10⁻³</td>
</tr>
</tbody>
</table>

Table 20 – Electric and heat properties of SS 316, [18], [103] and [107]

These values will be compared with tests in order to have a better estimation of the power input.

To estimate the electric power needed, it is assumed for now heat losses about 50 %, as found in standard atmosphere in case of DUR 1.0 and DUR 1.1 [16, 18]. Table 21 shows an estimation of the current and voltage needed for the new design of DUR using Nozzle ∅ 0.4 mm.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle ∅ 0.4 mm</td>
<td>1000</td>
<td>24</td>
<td>95</td>
<td>95×(1+50%) = 143</td>
<td>0.451</td>
<td>17.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 21 – Summary of electric parameters using new design of DUR

With the values estimated in Table 21, the check on the safety levels are fulfilled. This is due to low levels of electric voltage around 8 V. With this level it is even possible to read directly the heater voltage during test, since most of the voltmeters⁹ work until 10 V.

---

⁹ This is the case of SCB (see Chapter 6).
2.6 Design dimensions

The dimensions of the heat chamber are established in accordance to the requirements and constraints. Some other constraints are related to the availability and a better efficiency for other temperature ranges. These dimensions are not optimized but in contrary take into account the availability. Other shapes can also be taken into account, however this shape as a high manufacturability with good thermal efficiency, see Chapter 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>SS316</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Helically coiled tube</td>
</tr>
<tr>
<td>Inner diameter [mm]</td>
<td>1.3</td>
</tr>
<tr>
<td>Outer diameter [mm]</td>
<td>2.0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>0.70</td>
</tr>
<tr>
<td>Number of loops [-]</td>
<td>8.5</td>
</tr>
<tr>
<td>Distance between loops [mm]</td>
<td>~ 2.0</td>
</tr>
<tr>
<td>Mass [Kg]</td>
<td>~ 0.01</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Strength characteristics</td>
<td>good</td>
</tr>
<tr>
<td>Voltage safety</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 22 – Heat chamber dimensions and characteristics

Figure 33 – Heat chamber for DUR H2O
3 Design of a feed system and tank

After designing the heat chamber and nozzle, it is still missing two important parts of a Resistojet, the feed system and the tank. There are two different configurations, for test at standard atmospheric conditions, and in flight, at space conditions. This section will not go deep in detail, since it is not part of this research. Furthermore, the test model of the propulsion system should take as priority the availability and the simplicity. The feed system and the tank do not need to be optimized in dimensions, but only with reasonable dimensions. It is important to use materials that do not react with the propellant. In case of valves, in the first levels of design they do not need to be automated, they can simply be controlled manually. A more detailed description is given in Chapter 6.

For space conditions, the feed system and the tank should be optimized in dimensions and mass, using space qualified materials that do not react with the propellant. In this case, the valves should be completely automated as well as the rest of the system. For that it is chosen the Lee® valve [18, 110]. The feed system has the particularity to be electrically insulated from the heater. That material should support temperatures at least until 500 K, should not be porous and be space qualified. As recommendation, Delrin® could be a good material for this purpose. The feed system is also leak tight, for that it uses o-rings, see Chapter 6 for more detailed information.

![Figure 34 – Concept for the feed system (with Lee® valve)](image)

Since the Lee® valve has a relatively small diameter but it is relatively long, it is important to use the free volume. To take that volume into account, the concept of a toroidal tank came into consideration. Here again, the dimensions were not taken into account neither the material.
4 Insulation design

As discussed in Chapter 2, the use of insulation around the heater increases significantly the thermal efficiency (see Chapter 5 for numerical values). Furthermore, at space conditions, an insulator as a blanket has even lower conductivity than at atmosphere conditions. In this particular case, the use of it would also damp the shocks during launch. This is an additional reason why a blanket is chosen instead of a multi-layer radiation shield. However, to give structural strength being encapsulated, a radiation shield is added. Adding this part, the thermal losses should reduce even more. It is important for safety reasons, that the radiation shield is electrically insulated from the heater. For that, electrical and thermal insulators are added (one in each side of the thruster).
5 Final design

From previous section, the dimensions of the heat chamber and nozzle were calculated for a better performance and more suitable for liquid propellants. Furthermore in the previous chapter, it was seen the best method to insulate the heat chamber. Taking all this in consideration a final conceptual design of an entire resistojet is given.

For space flight, the nozzle should have and expansion to increase the thrust efficiency. In that case, the central part of the heating chamber can be used to insert the nozzle, see Figure 39.
6 Conclusions from design

A nozzle was designed specially to be used at standard atmospheric conditions. The throat diameter of 0.4 mm was chosen to work with a chamber temperature of 1000 K at 2 bar, having a critical mass flow around 24 mg/s. The expected thrust performances are: thrust of 19 mN, Isp of 79 s. For the design of the heater, it was chosen:

- The tube inner diameter of 1.3 mm, with a length of 0.70 m.
- Coil diameter of 25 mm.
- The pressure drop, voltage levels and strength are acceptable.
Chapter 4 – Analysis of a Resistojet

In the previous chapter, the design of a heat chamber was done for optimization. However an already available DUR is used for testing. This avoids having the system hindered around 3 month on the manufacturing of a new heat chamber. Furthermore, the main objective of this research is the technology demonstration and not the optimization. Finally, it is possible to focus more on the testing and results than on the manufacturing.

Now, it is important to see which DUR shall be used during testing: DUR 1.0, DUR 1.1 and DUR 2.0. Furthermore, the levels of mass flow and temperature can be different than designed in the previous chapter. The new design is still analyzed to understand the performance under different conditions.

1 Nozzle analysis

In this section, the thrust, the specific impulse, the jet power, power input and thrust efficiency are analysed. It is considered two different configurations of the nozzle:

- TUDelft Nozzle C ($\varnothing_{\text{throttle}}$ 0.66 mm, $\varnothing_{\text{exit}}$ 0.77 mm), for standard atmosphere.
- TUDelft Nozzle $\varnothing$ 0.4 mm, for standard atmosphere.

Finally both configurations are analysed and compared, for different temperatures and pressures. With the analysis it is possible to demonstrate the advantage to use Nozzle $\varnothing$ 0.4 mm instead of Nozzle C.

The ranges taken into account for chamber pressure and temperature are from 1.7 bar to 2.0 bar and from 500 K to 1000 K, respectively.

1.1 Dimensions of the nozzles

The main dimensions are shown in Table 23, with these dimensions, it is possible to analyse the different nozzles.

<table>
<thead>
<tr>
<th>Nozzle type</th>
<th>Main dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle C</td>
<td>Exit diameter: $D_e = 0.77$ mm</td>
</tr>
<tr>
<td></td>
<td>Throat diameter: $D_t = 0.66$ mm</td>
</tr>
<tr>
<td>Nozzle $\varnothing$ 0.4 mm</td>
<td>Exit diameter: $D_e = 0.41$ mm</td>
</tr>
<tr>
<td></td>
<td>Throat diameter: $D_t = 0.40$ mm</td>
</tr>
</tbody>
</table>

Table 23 – Main dimensions of Nozzle C and Nozzle $\varnothing$ 0.4 mm
1.2 Critical mass flow

Here, it is analysed the dependency of critical mass flow with chamber pressure and chamber temperature, for both nozzles. The propellant species is assumed constant, as the ambient properties. See Annexes of Chapter 3 for the 3D graphic.

![Critical mass flow versus chamber pressure for two different nozzles, for water flow at 1000 K in the chamber](image1)

![Critical mass flow versus chamber temperature for two different nozzles, for water flow at 2 bar in the chamber](image2)
In Figure 40, it can be seen that the critical mass flow increases with chamber pressure. In Figure 41 the critical mass flow decreases with chamber temperature. For both cases the Nozzle C presents higher values of mass flow than Nozzle \( \varnothing 0.4 \) mm. The critical mass flow for both nozzles and for different ranges of chamber temperature and chamber pressure are shown in Table 24.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Temperature and pressure range</th>
<th>Mass flow [mg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle C</td>
<td>500 K – 1000 K (@ 2 bar)</td>
<td>95 – 66</td>
</tr>
<tr>
<td></td>
<td>1.7 bar – 2.0 bar (@ 1000 K)</td>
<td>56 – 66</td>
</tr>
<tr>
<td>Nozzle ( \varnothing 0.4 ) mm</td>
<td>500 K – 1000 K (@ 2 bar)</td>
<td>35 – 24</td>
</tr>
<tr>
<td></td>
<td>1.7 bar – 2.0 bar (@ 1000 K)</td>
<td>21 – 24</td>
</tr>
</tbody>
</table>

Table 24 – Critical mass flow depending on the nozzle and pressure and temperature range

Using a smaller throat diameter, the critical mass flow can be smaller. This will decrease the power needed to vaporize the water, since this is the primordial goal of the research.

1.3 Thruster analysis

Thrust levels

Both nozzles are studied for a range of chamber pressure. The chamber temperature is not taken into account, since thrust is independent to it, as it can be seen in equation (3.3).

![Thrust versus chamber pressure, with H2O mass flow](image)

Figure 42 – Thrust depending on chamber pressure, for both nozzles, with water flow

This figure shows that thrust increases with chamber pressure. Here Nozzle C has higher levels of thrust than Nozzle \( \varnothing 0.4 \) mm. It is presented a pressure range from 1.7 to 2 bar, however in case of exhaust of water gas, only at 1.8 bar the flow is choked [106]. Here 1.7 bar is given as additional information, since, experimentally, the effective throat area
is smaller (due to boundary layer on the throat). This would bring to choked flow at lower chamber pressure than theoretically expected. Since in this case it is used water as propellant, condensation should be avoided in the heat chamber and in the exhaust. Otherwise, the thrust decreases abruptly. In case of standard atmosphere \( (p_a = 1 \text{ bar}) \), flow separation should be avoided, then the separation pressure ratio \( (p_{e}/p_a) \) between exhaust and ambient pressure should the always higher than 0.25 to 0.35 [1]. Since both nozzles, have a very small expansion, this is not a problem.

**Specific impulse**
The specific impulse \( Isp \) depends on the chamber temperature and pressure, see equation (3.7).

![Figure 43 – Specific impulse depending on chamber temperature, nozzle, with water flow](image1)

![Figure 44 – Specific impulse depending on chamber pressure, nozzle, with water flow](image2)
For both nozzles, the specific impulse increases with chamber temperature and pressure. Nozzle $\varnothing$ 0.4 mm presents higher values than Nozzle C, meaning that the consumption is lower for the same thrust level.

**Power input**

Power input is computed in a range of chamber pressure and temperature, using equation (3.10).

![Power input versus chamber temperature, with H2O mass flow, at 2 bar](image1)

**Figure 45 – Power input depending on the chamber temperature, for water flow**

![Power input with Chamber pressure with H2O flow for a chamber pressure of 1000 K](image2)

**Figure 46 – Power input depending on the chamber pressure, for water flow**

Here, the power input slightly decreases with chamber temperature, and increases with chamber pressure. Nozzle C presents higher values than Nozzle $\varnothing$ 0.4 mm, meaning that
the second nozzle needs less energy. This is important to ensure a proper vaporization of the flow.

**Thrust efficiency**

Now that power input is known and using equation (3.8) to determine the jet power, the thrust efficiency can be determined, using relation (3.9).

![Graph showing thrust efficiency versus chamber temperature and pressure](image)

**Figure 47 – Thrust efficiency depending on the chamber temperature, for water flow**

![Graph showing thrust efficiency with chamber pressure](image)

**Figure 48 – Thrust efficiency depending on the chamber pressure, for water flow**

From above figures, it is find that thrust efficiency increases with chamber temperature and pressure. Nozzle ∅ 0.4 mm presents higher thrust efficiency than Nozzle C, being in
range of 0.04 o 0.08. Notice that the efficiency is very low, meaning that the input power is much higher than the output power. However if the ambient pressure is decreased, being zero at flight operation, the efficiency would increase significantly. In these conditions, using a nozzle with a large expansion, the efficiency would increase even more. This parameter has then small meaning for these nozzles at standard atmosphere. Furthermore, with a higher chamber pressure and temperature, the thrust efficiency is also higher.

1.4 Thrust parameters summary

Table 25 presents the summary of the minimum and maximum values obtained using both nozzles, and considering the range of chamber pressure and temperature, from 1.5 bar to 2.0 bar and 500 K to 1000 K.

<table>
<thead>
<tr>
<th>Range</th>
<th>Nozzle C</th>
<th>Nozzle Ø 0.4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow [mg/s]</td>
<td>56 – 95</td>
<td>21 – 35</td>
</tr>
<tr>
<td>Thrust [mN]</td>
<td>33 – 47</td>
<td>14 – 19</td>
</tr>
<tr>
<td>Specific impulse [s]</td>
<td>41 – 72</td>
<td>48 – 79</td>
</tr>
<tr>
<td>Thrust efficiency [-]</td>
<td>0.029 – 0.064</td>
<td>0.04 – 0.076</td>
</tr>
</tbody>
</table>

Table 25 – Summary of thruster parameter

2 Heat chamber analysis

For the heat chamber analysis, it is chosen all series of DUR. The main dimensions are shown in Table 26. Furthermore the analysis will be done at different ranges of mass flow and temperature. With this analysis, it should be possible to select the most appropriate DUR for testing in a first phase of research. This avoids the waiting time for a new heat chamber (DUR H2O), even with lost in efficiency.

<table>
<thead>
<tr>
<th>DUR series</th>
<th>Inner diameter [mm]</th>
<th>Outer diameter [mm]</th>
<th>Length [m]</th>
<th>Coil diameter [mm]</th>
<th>Number of loops</th>
</tr>
</thead>
<tbody>
<tr>
<td>New design (DUR H2O)</td>
<td>1.3</td>
<td>2.0</td>
<td>0.70</td>
<td>25</td>
<td>~ 8.5</td>
</tr>
<tr>
<td>DUR 1.0</td>
<td>2.5</td>
<td>3.0</td>
<td>0.95</td>
<td>40</td>
<td>~ 7</td>
</tr>
<tr>
<td>DUR 1.1</td>
<td>2.5</td>
<td>3.0</td>
<td>2.00</td>
<td>40</td>
<td>~ 15.5</td>
</tr>
<tr>
<td>DUR 2.0</td>
<td>1.3</td>
<td>2.0</td>
<td>0.12</td>
<td>~ 13</td>
<td>~ 3</td>
</tr>
</tbody>
</table>

Table 26 – Main dimensions of DUR series

<table>
<thead>
<tr>
<th>Mass flow range [mg/s]</th>
<th>Output temperature range [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 100</td>
<td>500 – 1000</td>
</tr>
</tbody>
</table>

Table 27 – Studied ranges
2.1 Minimum tube diameter
To compute the minimum tube diameter, it is used equation (3.11).

![Minimum diameter with H2O mass flow at 2 bars](image)

Figure 49 – Minimum diameter depending on the mass flow and output temperature

Figure 49 shows that the minimum tube diameter increases with mass flow, and output flow temperature. The minimum required diameters are still smaller than the inner diameters of the DUR series, meaning that in principle the levels of pressure drop should be admissible.

2.2 Minimum Length
Before computing the required minimal length for the heat chamber, it is important to know in which regime is the output flow. For that, it is used equations (3.18) and (3.19).

![Reynolds number with H2O mass flow](image)

Figure 50 – Reynolds number depending on the mass flow, tube diameter and temperature

In the considered range of mass flow and temperature, the values of Reynolds number are always below 6000. In these helicoidally coiled tubes, the critical Reynolds number is around 8000, meaning that the regime is laminar.
To compute the minimum length of the heat chamber, it is used equation (3.15). The same method from previous chapter is applied for this case. It is presented the variation of the minimum length with mass flow for three main designs: DUR 1.0/1.1, DUR 2.0 and DUR H2O. Furthermore, it is presented for two output temperatures with more 100 K for wall temperature than the output temperature.

From Figure 51 and Figure 52, the required minimum length increases with mass flow. However it decreases with higher output temperature, for the same difference between wall and flow temperature. DUR 2.0 presents the lowest required length, followed by DUR H2O and finally DUR 1.0/1.1. The reason for a lower value is due to a lower coil diameter and tube diameter. From these figures, it is concluded that DUR 2.0 can only work for very small mass flow, since it has a length of 0.12 m. For higher mass flow, this heat chamber should have a wall temperature much higher than the flow temperature. It is then highly inefficient for higher mass flow. DUR H2O and DUR 1.0 are suitable for
mass flow lower than 50 mg/s to 90 mg/s, depending on the flow temperature. For DUR 1.1, the studied mass flows are suitable, having a very small difference between wall and flow temperature. As example, for better understanding the problem of a tube shorter or longer than required, it is taken the mass flow where DUR 1.0 fulfils the conditions (difference between wall and flow temperature), 85.2 mg/s. It is found that at that mass flow, DUR 2.0 and DUR 1.1 need a wall temperature of 1520 K and 1050 K respectively to obtain the same output flow temperature. In case of DUR 2.0, since it is too short, the high value of wall temperature can be a major problem. However, for DUR 1.1, the wall temperature is not a problem, performing even better than DUR 1.0.

2.3 Pressure drop analysis

Here the pressure drop of the tube flow is analysed for different heat chambers, mass flow and output temperature. It is only presented the total pressure drop using equation (3.27). For more information of the different pressure drop, see Chapter 3.

![Figure 53 – Pressure drop depending on the mass flow for different DUR, at 1000 K](image)
From Figure 53 and Figure 54, the total pressure drop increases with increase on mass flow at constant temperature (increase on chamber pressure). It also increases with the decrease on the output temperature. This is due to an increase on the length of boiling flow, part where the pressure drop is the highest, see Chapter 3. DUR 1.0 and DUR 2.0 have relatively low pressure drop, followed by DUR 1.1 and finally the new design (DUR H2O) has the highest pressure drop. However the values are considered still admissible taking into account the requirements. Furthermore, the correlations for boiling flow have a deviation that can go to ± 50%, meaning a much lower or much higher pressure drop than expected. For that reason, DUR 1.0 should be used for testing on the first part of the research, avoiding very high levels of pressure drop.
3 Electric analysis

For the electric analysis, it is chosen all series of DUR. The main dimensions are shown in Table 26. With this analysis, it should be possible to confirm which DUR is the most appropriate, in a first phase of research.

As done in the previous chapter, to estimate the electric power needed, it is assumed for now heat losses about 50 %, as found in standard atmosphere in case of DUR 1.0 and DUR 1.1[16, 18]. This is a conservative estimation even more when insulation is used (lower heat losses). Table 28 shows an estimation of the current and voltage needed for the DUR series, using Nozzle $\varnothing$ 0.4 mm and Nozzle C. The difference between the nozzles is important in this case, since they have different levels of mass flow, and then different required power input.

Two grades are given to help selecting the proper heat chamber:

- Green (adequate): Current < 20 A, Voltage < 10 V;
- Yellow (precautions and modifications should be taken): Current > 20 A, Voltage < 10 V.
- Red (unsuitable): voltage > 35 V.

The current levels are chosen as the maximum available by a power supply of the DARTS. The voltage levels as the maximum measurable by the data acquisition system. See Chapter 6 for further information.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle $\varnothing$ 0.4 mm</td>
<td>New design (DUR H2O)</td>
<td>500</td>
<td>99</td>
<td>99×1.5 = 149</td>
<td>0.334</td>
<td>21.1</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>DUR 1.0</td>
<td></td>
<td></td>
<td></td>
<td>0.380</td>
<td>19.8</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>DUR 1.1</td>
<td></td>
<td></td>
<td></td>
<td>0.800</td>
<td>13.6</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>DUR 2.0</td>
<td></td>
<td></td>
<td></td>
<td>0.057</td>
<td>51.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Nozzle C</td>
<td>New design (DUR H2O)</td>
<td>269</td>
<td>269×1.5 = 404</td>
<td></td>
<td>0.334</td>
<td>34.8</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>DUR 1.0</td>
<td></td>
<td></td>
<td></td>
<td>0.380</td>
<td>32.6</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>DUR 1.1</td>
<td></td>
<td></td>
<td></td>
<td>0.800</td>
<td>22.5</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>DUR 2.0</td>
<td></td>
<td></td>
<td></td>
<td>0.057</td>
<td>84.2</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 28 – Summary of electric parameters using Water Nozzle and DUR 1.0

From Table 28, the only fully adequate heat chamber is DUR 1.0 with Nozzle $\varnothing$ 0.4 mm. In case of DUR 2.0, the required current can be difficult to obtain even conjugating power supplies, see Chapter 6.
4 Dynamical regime

When applying a liquid propellant on a rocket motor in space environment, the propulsion system can be exposed to a dynamical regime not usually encountered in terrestrial conditions [36]. For that reason, it is important to analyse in which dynamical regime is the liquid flow, avoiding completely different regimes in space than in Earth. In Earth orbit the order of magnitude of gravity acceleration, $g$, is $O(10^{-6} g_0)$. The parameters of the liquid as the density $\rho$, velocity $V$ and surface tension $\sigma$ (for water see [65])are taken in a range of temperature (295 K to 393 K) and a mean value is calculated. The regime is defined depending on Bond number or Eötvos $Bo$ (ratio between gravity forces and surface tension forces), and on Weber number, $We$ (ratio between inertia forces and surface tension forces).

$$Bo = \frac{\rho D^2 g}{\sigma} \quad [-]$$

$$We = \frac{\rho V^2 D}{\sigma} \quad [-]$$

Here $D$ is the tube inner diameter. There are three different regimes for forces applied on liquids:

- Capillary dominated, $Bo, We < 1$;
- Inertia dominated, $We > 1, Bo < We$;
- Gravity dominated, $Bo > 1, Bo > We$.

In the following figures, the Bond and Weber numbers are shown at different flow temperatures and at different mass flow.

![Figure 55 – Bond and Weber number in Earth and space using DUR 1.0 or DUR 1.1](image)

Using a tube of 2.5 mm (DUR1.0/1.1), the Bond number at Earth conditions, $1g_0$, is always higher than Weber number. Furthermore the Weber number is always smaller than 1 and from 375 K to boiling temperature the Bond number is higher than 1. The flow at Earth conditions goes from capillarity dominated to gravity dominated. In space, the
Bond and Weber number are always smaller than 1, the flow is then fully capillarity dominated.

It is then expected that the behaviour of DUR 1.0 and DUR 1.1, using liquid propellant, will be different in Earth or space. For that reason, on a more advanced part of the research, a microgravity test should be considered for understanding these differences.

![Graph showing Bond and Weber number in Earth and space](image)

**Figure 56 – Bond and Weber number in Earth and space using DUR H2O**

Using the DUR H2O configuration (same as DUR 2.0), there are no differences in the dynamical regime between Earth and space, since the flow is always dominated by capillarity. This configuration is then more reliable to use in space environment, avoiding microgravity testing.

<table>
<thead>
<tr>
<th>D [mm]</th>
<th>Bo [-] Earth</th>
<th>Bo [-] Space</th>
<th>$W_{\text{max}}$ [-]</th>
<th>Regime in Earth</th>
<th>Regime in space</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.8 – 1.1</td>
<td>$10^6$</td>
<td>0.02</td>
<td>Capillarity – Gravity</td>
<td>Capillarity</td>
</tr>
<tr>
<td>(DUR1.0 and DUR1.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>0.2 – 0.3</td>
<td>$10^7$</td>
<td>0.15</td>
<td>Capillarity</td>
<td>Capillarity</td>
</tr>
<tr>
<td>(DUR H2O and DUR 2.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 29 – Summary of the dynamic regime in Earth and space**
5 Final trade-off summary

The nozzle used is Nozzle $\phi 0.4$ mm, since it needs lower levels of power input. It is then easier to vaporize the water flow, since this is the primordial test objective of the research.

The selection of the proper heat chamber for testing, on the first part of the research is fundamental to avoid major failures. Three grades are given for the trade-off:

- Green (adequate):
  - Minimum mass flow $> 40$ mg/s;
  - Pressure drop, $\Delta p$, $< 1$ bar;
  - Current $< 20$ A;
  - Voltage $< 10$ V.

- Yellow (precautions and modifications should be taken):
  - Mass flow $> 30$ mg/s;
  - Pressure drop, $\Delta p$, $< 3$ bar;
  - Current $> 20$ A;
  - Voltage $< 35$ V.

- Red (Inadequate):
  - Mass flow $< 30$ mg/s;
  - Pressure drop, $\Delta p$, $> 3$ bar;
  - Voltage $> 35$ V.

Table 30 presents the results obtained from the trade-off.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DUR 1.0</td>
<td>$&lt; 50 - 90$</td>
<td>0.5 – 1</td>
<td>19.8</td>
<td>7.5</td>
<td>Adequate</td>
</tr>
<tr>
<td>DUR 1.1</td>
<td>$&gt;&gt; 100$</td>
<td>1 – 3</td>
<td>13.6</td>
<td>10.9</td>
<td>Precautions and modifications should be taken</td>
</tr>
<tr>
<td>DUR 2.0</td>
<td>$&lt; 10$</td>
<td>0.5 – 1</td>
<td>51.1</td>
<td>2.9</td>
<td>Inadequate</td>
</tr>
<tr>
<td>New design (DUR H2O)</td>
<td>$&lt; 50 - 90$</td>
<td>1 – 2</td>
<td>21.1</td>
<td>7.0</td>
<td>Precautions and modifications should be taken</td>
</tr>
</tbody>
</table>

Table 30 – Final trade-off of DUR series

For testing, DUR 1.0 is chosen, since it has low pressure drop and admissible levels of current and voltage. The pressure drop is primordial factor here, since the correlations for boiling flow have an important deviation with experiment. Furthermore, since testing is performed at standard atmosphere, it is more suitable to use DUR 1.0 already fully oxidised, than DUR 1.1 that is almost not oxidised. This avoids ruining DUR 1.1 that can be still used on a vacuum chamber. DUR 2.0 is inadequate for this purpose, since it can work only at very low mass flow without high temperature difference between flow and wall.
Chapter 5 – Model for temperature and pressure loss prediction

In this chapter, three models are described: Heat loss model, model for wall and flow temperature along the heater, model of pressure drop in the heater.

The first model is the most complex and simulates the heat losses, power input and temperatures of the heat chamber. Depending on the insulation, on the dry or wet operation, and on different correlations, different heat losses and temperatures are computed. The simulation uses numerical equilibrium equations with some approximations to decrease the complexity of them. Afterwards, the results are shown and compared between cases.

The model of temperature along heater is in reality a simplification of the first model, taking much shorter computational time. However, in this case, the surrounding environment is not taken into account.

The last model presented is for pressure drop along the heater. Here again, the computational time is much shorter than the first model.

1 Heat losses Model

In the previous chapters, the heat losses to the surrounding environment were not taken into account. These heat losses can be greatly decreased using insulation and radiation shields. With this assumption, it can be considered that all the electric power was mainly going to the flow and a negligible part to the environment. However, this is not completely true at standard atmosphere, where the tests are performed.

It is important to predict the temperature and power expected for the test, with required input parameters. These parameters are: geometric dimensions, heater resistance, ambient temperature, electric current and mass flow (at wet operation). All these parameters are fundamental for the equilibrium equation that predicts the heat losses, see section 1.4.

In a control volume there is conservation of energy: the input energy $Q_{in}$ is equal to the output energy $Q_{out}$ and variation of energy accumulated in the control volume $Q_{st}$:

$$Q_{in} = Q_{out} + Q_{st} \ [W]$$

The output energy $Q_{out}$ is the heat losses to the exterior and the heat to the flow $Q_{flow}$. For the heat losses, it is considered only from the heat chamber to the exterior and not from the cabling, neither nozzle nor feed system. The heat losses are divided into conduction $Q_{cond}$ (can be reduced to convection and radiation), convection $Q_{conv}$ and radiation $Q_{rad}$.

These together with the heat to the flow $Q_{flow}$ are the output energy $Q_{out}$:

$$Q_{out} = Q_{cond} + Q_{conv} + Q_{rad} + Q_{flow} \ [W]$$

The difference using insulation is a higher heater temperature, and a longer time to reach stable conditions for a constant input power. In this case, at stable conditions with
constant power input \( Q_{in} \), the heat losses are the same without flow, and are lower with flow.
However, during testing, the power input \( Q_{in} \) is not directly controlled. Instead of that, the electric current is controlled.

\[
Q_{in} = R(T_s)I^2 \quad [W]
\]  

(5.3)

Here \( R \) is the resistance of the heater that depends on the heater temperature, see section 3:

\[
R = R_0 (1 + \alpha \Delta T), \text{ where } \alpha \text{ is the temperature coefficient } [\Omega]
\]  

(3.53)

Then, using insulation, a higher temperature will also have a higher input power. Then at dry conditions, the heat losses will be also higher.

**1.1 Heat loss by natural convection**

The heat losses by convection \( Q_{conv} \) are defined as:

\[
Q_{conv} = Ah(T_s - T_{amb}) = \frac{AkNuD}{D_{tube}}(T_s - T_{amb}) \quad [W]
\]  

(5.4)

Here \( A \) is the surface area of the heater, \( h \) is the convection coefficient that is related to Nusselt number \( Nu \) by (3.16), \( T_s \) is the surface temperature of the heater, \( T_{amb} \) is the ambient temperature and \( D_{tube} \) is the tube diameter (it also can be diameter of the coil \( D_{coil} \) or total diameter with insulation \( D_{insulation} \)).
The surface area depends on the geometry of the heater. For helicoidal coil and short cylinder see equations (5.5) and (5.6). For other geometries see annexes and [4].

For helicoidal coil:

\[
A = \pi D_{tube}L_{tube} \quad [m^2], \text{ with } L_{tube} = N\pi D_{coil} \quad [m]\text{ and } N \text{ the number of loops}
\]  

(5.5)

For short cylinder of insulation:

\[
A_{insul} = \frac{\pi D_{insul}^2}{2} \left(1 + \frac{2L_{insul}}{D_{insul}}\right) \quad [m^2]
\]  

(5.6)

The geometry taken into account is the DUR 1.0 with and without insulation.
For a heater working in air, without forced flow, there is then natural convection. The natural convection does not depend only on the heater geometry but also on the properties
of the surrounding air, as temperature and humidity. Nevertheless it is possible to give a range of natural convection: $5^{10}$ W/m²K to 25 W/m²K.

To give a more precise estimation of convection, some correlations for natural convection are available depending on the geometry of the heater. Two correlations that are taken into account are for short cylinder (5.7) and for helicoidal coil (5.8). There are other correlations than can be found in the annexes and in [4].

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Equation</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>For short isothermal cylinder</td>
<td>$N_{D} = \left[ N_{cond} + \left( G \bar{C}_v Ra^{1/4} \right)^n \right]^{m/n} + \left( \bar{C}_v Ra^{1/3} \right)^m$</td>
<td>for $1 &lt; Ra &lt; 10^{7}$</td>
</tr>
<tr>
<td></td>
<td>$\bar{C}_v = \frac{0.671}{\left[1 + (0.492 / Pr)^{9/16} \right]^{4/9}}$</td>
<td>[-] (Churchill-Usagi)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5.7)</td>
</tr>
<tr>
<td></td>
<td>$Nu_{cond}$, $G$, $\bar{C}_v$, $n$ and $m$ are constants, see Table 32</td>
<td></td>
</tr>
<tr>
<td>For helicoidal coil</td>
<td>$N_{D} = 0.318 Ra^{0.293}$</td>
<td>[-], for $5 \times 10^3 &lt; Ra &lt; 10^5$</td>
</tr>
<tr>
<td>Rayleigh number: $Ra = Gr Pr$</td>
<td></td>
<td>(5.9)</td>
</tr>
<tr>
<td>Grashof number: $Gr = \frac{g_0 \beta \rho^2 (T_s - T_{amb}) X^3}{\mu^2}$</td>
<td>$X$ is the characteristic dimension can be $D_{coil}$ or $D_{insulation}$ or $D_{tube}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta \approx \frac{1}{T_{film}}$ (coefficient of volumetric expansion) and $T_{film} = \frac{T_s + T_{amb}}{2}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$g_0 = 9.81$ m/s², $\rho$ is the density [kg/m³] at film temperature $T_{film}$ [K]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu$ is the dynamic viscosity [Pa.s]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5.10)</td>
<td></td>
</tr>
</tbody>
</table>

Table 31 – Correlations for natural convection in cylinder and helicoidal coil

For (5.7) several constants are needed. These values come from the interpolation of the tabled values in [4].

---

10 In controlled environments, without any source of small forced convection (air conditioning, moving people, etc) the value can be 2 W/m²K [3]
For the helicoidal heater at standard atmosphere, a comparison can be done, using all correlations, on the influence of helicoidal geometry with cylindrical geometry. For the configuration of insulated heater, all correlations can be used except the correlation for coils. It is then possible to compare the correlations for long and short cylinder. These comparisons are shown in the Annexes.

In the end, it is chosen the most conservative correlations, the ones that give lower temperature for the same input parameters, see annexes. In section 1.5 it is only presented the chosen correlation for better understanding.

Additionally, after performing a dry test, it is possible to obtain a mean convection coefficient at stable conditions that can be compared with the values obtained using the correlations. For that the equilibrium equation for steady state is used, see (5.11) and section 0.

\[
h = \frac{P_{\text{in}}}{A} = \frac{F_{x,\text{amb}} \varepsilon_s \sigma (T_{\text{test}}^4 - T_{\text{amb}}^4)}{F_{x,\text{amb}} (1 - \varepsilon_s) + \varepsilon_s} \quad [\text{W}]
\]  

(5.11)

Here \( F \) is the view factor, \( \varepsilon \) is the emissivity and \( \sigma \) is the Stefan–Boltzmann constant.

### 1.2 Heat loss by radiation

The losses by radiation \( Q_{\text{rad}} \) are:

\[
Q_{\text{rad}} = \frac{\sigma (T_s^4 - T_{\text{amb}}^4)}{1 - \varepsilon_s + \frac{1}{A_s F_{x,\text{amb}}} + \frac{1 - \varepsilon_{\text{amb}}}{\varepsilon_{\text{amb}} A_{\text{amb}}}} = \frac{F_{x,\text{amb}} \varepsilon_s A_s \sigma (T_s^4 - T_{\text{amb}}^4)}{F_{x,\text{amb}} (1 - \varepsilon_s) + \varepsilon_s} \quad [\text{W}]
\]  

(5.12)

When considering the ambient emissivity \( \varepsilon_{\text{amb}} = 1 \) or considering \( A_{\text{amb}} > A_s \) the slashed term is zero.

---

11 RMS – root mean square

12 Error defined as the difference between data and equation (5.7)
When the heater is insulated the view factor $F_{s,\text{amb}} = 1$, the emissivity $\varepsilon_s$, the surface temperature $T_s$ and the surface area $A_s$ are from the insulation.

### 1.2.1 View factors

The view factor from one surface to another surface is the fraction of radiation that leaves the first surface and is intercepted by the second surface.

When the heater is insulated the view factor is 1, since all the radiation from the insulation is intercepted by the environment.

When the heater is a helicoidal coil some radiation is intercepted by the coil itself instead of the environment, increasing then the surface temperature.

To compute the view factor of a helicoidal coil the method used is inspired by [34] with some corrections. The general idea of the method is to know what certain half loop sees from other half loops of the coil, and it is related to the view factor of infinitely long parallel cylinders of the same diameter [109]. The method is dependent on coil diameter, tube diameter and distance between loops. The last parameter should be as small as possible to decrease the heat loss to the exterior but also to decrease the size of the heater.

The most important part of this method is the separation between different view factors. The view factor from a half loop $i$ to the half loop $j$ just on the side is called view factor order 0. The view factor from a half loop $i$ to the half loop $k$ just under it is called view factor order 1. When the loop is on the side of that loop $k$ then is called view factor order 1, and so on [34]. This is done for each half loop. The difference between the orders is the distance from a half loop to another, giving different view factor. Afterwards, a mean view factor is calculated.

A view factor was calculated for DUR1.0, see Table 33.

<table>
<thead>
<tr>
<th>Heat chamber</th>
<th>View factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUR 1.0</td>
<td>0.79</td>
</tr>
</tbody>
</table>

### Table 33 – View factor of DUR 1.0 without insulation

#### 1.3 Conduction through insulation

When there is insulation around the heat chamber the heat loss comes from the outer surface. $T_s$ and $A_s$ are the temperature and area of the insulation, and $T_{\text{heat}}$ and $A_{\text{heat}}$ are the temperature and area of the heater. It is then fundamental to find a relation between $T_{\text{insul}}$ and $T_{\text{heat}}$. Equation (5.13) is found, equalizing the equation for conduction through the insulation with convection and radiation from the outer insulation surface to the environment. This equation does not take into account the time dependence of heat transport through the insulation. For that reason, the transient regime will be shorter in theoretical model than experimentally.

\[
T_{\text{heat}} = \left( A_{\text{insul}} h (T_{\text{insul}} - T_{\text{amb}}) + \frac{F_{s,\text{amb}} \varepsilon_s A_{\text{insul}} \sigma (T_{\text{insul}}^4 - T_{\text{amb}}^4)}{F_{s,\text{amb}} (1 - \varepsilon_s) + \varepsilon_s} \right) \log \left( \frac{r_{\text{insul}}}{r_{\text{heat}}} \right) + T_{\text{insul}} \text{ [K]} \quad (5.13)
\]

\[
L_{\text{corr}} = L_{\text{insul}} + \frac{D_{\text{insul}}}{2} \quad \text{(5.14)}
\]
Using the corrected length $L_{corr}$, the loss by the extremes of the insulation are taken into account. This is done adding the factor of the sides and then they can be considered as isolated, see Figure 57 and equation (5.14). This is normally performed on fins.

\[ L \]

\[ L_{corr} \]

**Figure 57 – Corrected length of the insulation cylinder**

### 1.4 Energy equilibrium equation

The energy equilibrium equation (5.1) can be written as:

\[
R I^2 = h A (T_s - T_{amb}) + \frac{F_{s,amb} \varepsilon_s A_s \sigma (T_s^4 - T_{amb}^4)}{F_{s,amb} (1 - \varepsilon_s) + \varepsilon_s} + \dot{m} (H_{out} - H_{in}) + m_{heater} c_{ss316} \frac{dT}{dt} \tag{5.15}
\]

[W]

In case of insulation, $T_s$ is the insulation outer surface temperature and without insulation is simply the heater temperature. Here $c_{ss316}$ is the heat capacity of the heater material (assumed constant) and $m_{heater}$ is the mass of the heater.

In case of dry operation, without mass flow, the third term of the right part of equation (5.15), $\dot{m} (H_{out} - H_{in})$, is then zero.

Figure 58 shows the model block diagram, with the time loop ($i$) incrementing the heater mean temperature $T_{heater}(i)$.

**Figure 58 – Model block diagram**
A more detailed explanation about the Heat loss model can be found in the next section, 1.4.1.

1.4.1 Numeric computation

To simplify the computation the analytical equilibrium equation is written in numerical form. For that it is important to assume the initial conditions at \( i = 0 \). Here \( T_i \) is heater temperature \( T_2 \) is insulation temperature, when present.

\[
T_i(i=0) = T_2(i=0) = T_{amb} \ [K]
\] (5.16)

As said previously the simplifications of this model are:
- Heat losses to the feed system and nozzle are not taken into account.
- The time dependence of heat transport trough the insulation (if present) is not taken into account.
- In dry operation, the axial direction is not taken into account.
- In wet operation, the axial direction is considered for final flow temperature, but for heat losses a mean value is computed.

Without mass flow, dry operation

The main question is how to compute the heater temperature \( T_1 \). The increase in the surface temperature \( \Delta T_1 \) is replaced by the heat loss by convection \( Q_{conv} \) and radiation \( Q_{rad} \) and by the input power \( Q_{in} \), (5.17).

\[
T_i(i+1) = T_i(i) + \Delta T_i(i)
\]
\[
T_i(i+1) = T_i(i) + \frac{\Delta t}{c_s x_316 \cdot m \cdot cont \cdot vol.} (Q_{in}(i) - Q_{conv}(i) - Q_{rad}(i)) \ [K]
\] (5.17)

In case of insulation the heat loss by convection \( Q_{conv} \) and radiation \( Q_{rad} \) depend on the insulation outer surface temperature \( T_2 \) instead of \( T_1 \). First step is to create a vector for \( T_2 \) from ambient temperature \( T_{amb} \) to \( T_1 \). The vector \( T_i \) is computed in function of \( T_2 \), and finally interpolating (Interpol) both vectors with the already known value of \( T_1 \) to obtain the value of \( T_2 \).

\[
\tilde{T}_2(i+1) = [T_{amb}, \ldots, T_1(i+1)]
\]
\[
\tilde{T}_1(i+1) = (\tilde{Q}_{conv}(i) + \tilde{Q}_{rad}(i)) \frac{\log \frac{\tilde{r}_2}{\tilde{r}_1}}{2\pi L_{conv} \cdot k} + \tilde{T}_2(i+1) \ [K]
\] (5.18)
\[
T_2(i+1) = \text{Interpol} \left( \tilde{T}_1(i+1), \tilde{T}_2(i+1), T_1(i+1) \right)
\]

Equation (5.18) is not used in case of convection and radiation directly from the heater to the ambient.
With mass flow, wet operation
The equilibrium equation takes now into account the mass flow. In case of insulation, the equilibrium equation between $T_1$ and $T_2$, (5.18), remains the same. The heater mean temperature is computed by equation (5.19).

$$T_1(i+1) = T_1(i) + \Delta T_1(i)$$

$$T_1(i+1) = T_1(i) + \frac{\Delta t}{c_{ss316} m_{cont.vol.}} (Q_{in}(i) - Q_{conv}(i) - Q_{rad}(i) - m\Delta H(i)) \text{[K]}$$

(5.19)

With $\Delta H(i) = H(T_{flow,\text{out}}(i)) - H(T_{amb})$

Here $\Delta t$ is the time step that can be taken as 1 s or 0.1 s for shorter steps. Using bigger steps, the computational time is shorter, but some oscillations appear with the possibility to diverge. These oscillations have no physical meaning.

At dry operation and in wet operation, the true meaning of $T_1$ is the mean temperature of the heater surface. In dry operation the highest temperature is in the middle, where the losses are lower. However, this is not relevant since the difference is small and can be simplified by a mean temperature, without increasing significantly the model inaccuracy.

In case of wet operation the situation is clearly different. The highest temperature is located in the final part of the heater, and it is significantly higher than the initial part or even it can be much higher than the mean value (due to boiling flow). It is then important to define the highest temperature in relation to the mean value. Furthermore, the equations for the inner forced convection require the value of the final wall temperature, and final flow temperature.

In this case, the initial conditions of the flow and wall final temperature are not at $i = 0$ but when the flow starts at $i = n$. The sub-program works in the following order:

- The mean heater temperature $T_1$ is an input coming from the main program.
- A vector of final flow temperature is created going from ambient temperature $T_{amb}$ to maximum available temperature $T_{max}$ (from properties of matlab-files).

$$\tilde{T}_{flow,\text{final}}(i) = [T_{amb}...T_{max}] \text{[K]}$$

(5.20)

- For each vector entrance $i$:
  - A length of each phase of the flow is computed (the situation of $T_{flow,\text{final}} < T_{boil}$ is also taken into account). For boiling part, the length is divided into 2 parts, before and after “Dryout” point (typically at gas quality $x$ between 0.5 and 0.9 [37]).

$$\begin{cases}
L_{\text{total}} = L_{\text{liq}}(i) + L_{\text{boil}}(i) + L_{\text{gas}}(i) \text{[m]} \\
Q_{flow,\text{total}}(i) = Q_{flow,\text{liq}} + Q_{flow,\text{boil}} + Q_{flow,\text{gas}}(i) \Rightarrow \Delta H_{\text{total}}(i) = \Delta H_{\text{liq}} + \Delta H_{\text{boil}} + \Delta H_{\text{gas}}(i)
\end{cases}$$

(5.21)
\[
\begin{align*}
\Delta H_{\text{total}}(i) &= H(T_{\text{flow,final}}(i)) - H(T_{\text{room}}) \\
\Delta H_{\text{liq}} &= H(T_{\text{boil,liq}}) - H(T_{\text{room}}) \\
\Delta H_{\text{boil}} &= H(T_{\text{boil,gas}}) - H(T_{\text{boil,liq}}) \\
\Delta H_{\text{gas}}(i) &= H(T_{\text{flow,final}}(i)) - H(T_{\text{boil,gas}})
\end{align*}
\]

\[\text{[J/kg]} \quad (5.22)\]

Constant heat flux:
\[
q^*(i) = \frac{Q_{\text{flow,total}}(i)}{\pi DL_{\text{total}}} = \text{const.}(i) = \frac{Q_{\text{flow,liq}}}{\pi DL_{\text{liq}}(i)} = \frac{Q_{\text{flow,boil}}}{\pi DL_{\text{boil}}(i)} = \frac{Q_{\text{flow,gas}}}{\pi DL_{\text{gas}}(i)} \text{ [W/m}^2\text{]} \quad (5.23)
\]

\[
\begin{align*}
L_{\text{liq}}(i) &= \frac{Q_{\text{flow,liq}}}{Q_{\text{flow,total}}(i)} L_{\text{total}} = \frac{H(T_{\text{boil,liq}}) - H(T_{\text{room}})}{H(T_{\text{flow,final}}(i)) - H(T_{\text{room}})} L_{\text{total}} \\
L_{\text{boil}}(i) &= \frac{Q_{\text{flow,boil}}}{Q_{\text{flow,total}}(i)} L_{\text{total}} = \frac{H(T_{\text{boil,gas}}) - H(T_{\text{boil,liq}})}{H(T_{\text{flow,final}}(i)) - H(T_{\text{room}})} L_{\text{total}} \quad \text{[m]} \quad (5.24)
\end{align*}
\]

\[
\begin{align*}
L_{\text{gas}}(i) &= \frac{Q_{\text{flow,gas}}}{Q_{\text{flow,total}}(i)} L_{\text{total}} = \frac{H(T_{\text{flow,final}}(i)) - H(T_{\text{boil,gas}})}{H(T_{\text{flow,final}}(i)) - H(T_{\text{room}})} L_{\text{total}} \\
L_{\text{boil before-dryout}}(i) &= \frac{H(T_{\text{boil,gas}}) - H(T_{\text{boil,liq}})}{H(T_{\text{flow,final}}(i)) - H(T_{\text{room}})} L_{\text{total}} x_{\text{dryout}} \\
L_{\text{boil after-dryout}}(i) &= \frac{H(T_{\text{boil,gas}}) - H(T_{\text{boil,liq}})}{H(T_{\text{flow,final}}(i)) - H(T_{\text{room}})} L_{\text{total}} (1 - x_{\text{dryout}})
\end{align*}
\]

\[\text{[5.25]}\]

For the equations above, the liquid and boiling phases are also dependent on \(i, T_{\text{flow,final}} < T_{\text{boil}}\).

\[\text{o} \quad \text{A new vector is made for the local flow temperature on the axial direction. The last term of this vector is the final flow temperature } T_{\text{flow,final}}(i) \text{. This vector is divided into liquid part } T_{\text{flow,liquid}}(i, j) \text{ and gas part } T_{\text{flow,gas}}(i, j). \]

\[
T_{\text{flow,liquid}}(j) = [T_{\text{amb}}, \ldots, T_{\text{boil}}] \\
\text{or } T_{\text{flow,liquid}}(i, j) = [T_{\text{amb}}, \ldots, T_{\text{flow,liquid,final}}(i)] \text{ [K], if } T_{\text{flow,final}} < T_{\text{boil}} \quad (5.26)
\]

\[
T_{\text{flow,gas}}(i, j) = [T_{\text{boil}}, \ldots, T_{\text{flow,final}}(i)] \text{ [K]} \quad (5.27)
\]

\[\text{o} \quad \text{For each entrance } j \text{ of these vectors:} \]

\[\text{i. The local convection coefficient } h(j) \text{ is computed.} \]

\[\text{ii. The local wall temperature } T_w(i, j) \text{ is computed, including final wall temperature } T_{w,\text{final}}(i). \]
From here a mean wall temperature is computed for different phases.

A mean heater temperature $\bar{T}(i)$ is computed from the weighted mean temperature of each phase.

$$T(i) = T_{w,\text{liq}}(i) \frac{L_{\text{liq}}(i)}{L_{\text{total}}} + T_{w,\text{liq},o}(i) \frac{L_{\text{liq},o}(i)}{L_{\text{total}}} \chi_{\text{dryout}} + T_{w,\text{gas}}(i) \frac{L_{\text{gas}}(i)}{L_{\text{total}}} (1 - \chi_{\text{dryout}}) + T_{w,\text{gas}}(i) \frac{L_{\text{gas}}(i)}{L_{\text{total}}} \quad [K] \quad (5.28)$$

Here $T_{w,\text{liq},o}$ and $T_{w,\text{gas}}$ are the wall temperature of the final part of liquid and initial part of gas, respectively.

Interpolation is performed in order to give the final flow temperature $T_{\text{flow,final}}$ taking the vector of mean heater temperature $\bar{T}(i)$ and the vector of final flow temperature $\bar{T}_{\text{flow,final}}(i)$, and the input value of heater mean temperature $T_1$.

$$T_{\text{flow,final}} = \text{interpolation} \left( \bar{T}(i), \bar{T}_{\text{flow,final}}(i), T_1 \right) \quad [K] \quad (5.29)$$

Interpolation is performed in order to give the final wall temperature $T_{w,\text{final}}$ taking the vector of mean heater temperature $\bar{T}(i)$ and the vector of final wall temperature $\bar{T}_{\text{wall,final}}(i)$, and the input value of heater mean temperature $T_1$.

$$T_{\text{wall,final}} = \text{interpolation} \left( \bar{T}(i), \bar{T}_{\text{wall,final}}(i), T_1 \right) \quad [K] \quad (5.30)$$

This sub-program gives a short peak on final flow temperature, when passing from dry operation to wet operation. That peak takes only few seconds to converge, and has no physical meaning. This is due to a wrong value of mean heater temperature taken the first time in the loop. It can be decreased with a shorter step.
1.5 Results from the Heat loss model

In this section, the results from the Heat loss model are presented with and without insulation, dry and wet operation. This model has also the possibility to easily change the correlations for convection, for different geometries (view factor should be reviewed and values from Table 32) and propellant species (when boiling is not present, need to be checked). These results have as objective to show that the model is consistent with the respective changes. The accuracy of the model compared with the experimental values is compared in Chapter 7.

The settings for the example are shown in Table 34.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Dry operation</th>
<th>Dry and wet (combined) operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>Without</td>
<td></td>
<td>8 min with</td>
<td>8 min with 0 A</td>
</tr>
<tr>
<td>insulation</td>
<td></td>
<td>10 A</td>
<td>0 A</td>
</tr>
<tr>
<td>With</td>
<td></td>
<td>20 min with</td>
<td>20 min with 0 A</td>
</tr>
<tr>
<td>insulation</td>
<td></td>
<td>10 A</td>
<td>0 A</td>
</tr>
</tbody>
</table>

Table 34 – Current and time for different configurations

1.5.1 Dry operation

At dry operation, without inner flow, the results are different depending if there is or not insulation. See Annexes, for the comparison between correlations. Here only the most conservative correlation will be taken. For power and natural convection coefficient, see Annexes.

Without insulation

![Figure 59 – Heater temperature for DUR1.0, without insulation, dry operation](image-url)
Here it is seen that:
- When current is inserted, temperature immediately increases.
- Temperature takes around 3 min to stabilize, with current applied. However takes around 6 minutes to reach again ambient temperature, when there is no current applied.

**With insulation**

![Figure 60 – Heater temperature for DUR1.0, with insulation, dry operation](image1.png)

Most of the comments are also applied for this case. However, even with the same input parameters but with insulation, the maximum temperature is much higher, taking also more time to stabilize.

![Figure 61 – Insulation temperature for DUR1.0, dry operation](image2.png)

For the insulation temperature, the temperature increase is slightly longer and different shape. Obviously, the maximum temperature is much lower.
1.5.2 Combined operation

At combined operation, without inner flow and then inserting flow, the results are different depending if there is or not insulation. For the comparison between correlations, see Annexes. Here only the most conservative correlation will be taken. For power input, power loss and natural convection coefficient, see Annexes. Here the “Dryout” point is at gas quality \( x \) of 0.7, since is the mean value between 0.5 and 0.9. The mass flow is set at 30 mg/s.

Without insulation

![Figure 62](image-url)  
**Figure 62** – Heater mean temperature for DUR1.0, without insulation, combined operation

![Figure 63](image-url)  
**Figure 63** – Final temperature of the heater for DUR1.0, without insulation, combined operation
Final flow temperature variation in the heat chamber, for 5 A to 18 A, without insulation, with H2O flow at 30 mg/s

Coil [Tjisterman]

Figure 64 – Final temperature of the flow for DUR1.0, without insulation, combined operation

From Figure 62, Figure 63 and Figure 64, it can be seen that the flow decreases the mean temperature of the heater as expected. When more current is applied, the temperatures increase. The final wall temperature is higher than the mean and final flow temperature, as expected. At minute 10, the peak temperature at final wall temperature has no physical meaning. A smaller numerical step could remove the peak, but increases significantly the computational time. When flow is present, the transient phases are shorter than at dry operation. Slightly near minute 18, it is observed, more clearly in Figure 64, a different slope. This is due to the phase changing from liquid to gas, passing by the boiling temperature. Afterwards, the slope comes from gas flow.

**With insulation**

Heater temperature, for 5 A to 16 A, with insulation, with H2O flow at 30 mg/s

Short cylinder [Rohsenow]

Figure 65 – Heater mean temperature for DUR1.0, with insulation, combined operation
In case of insulation, Figure 65, Figure 66 and Figure 67, the same remarks can be done than without insulation. However, here the transient time is longer and the temperatures are almost the same but with a lower current. This means a lower power loss, see Annexes. Here again, the peak just after minute 20, has no physical meaning.
The behaviour of insulation temperature, see Figure 68, follows heater mean temperature, but at much lower level. The transient part has the same extension, but has explained previously, the experimental values will take much longer time to stabilize.

2 Model of temperature along heater

As said previously, the model of heat losses does not have completely the axial direction. Then, the variation of temperature along the heater is only taken to compute a mean temperature and final temperatures. Indeed, the model can provide values for local temperatures. However, in order to decrease the time of computation, from 5 to 6 hours to few minutes, an additional program was made. Here, the environment is not taken into account, but only the flow in the heater. The input parameters are:

- Mean temperature of the heater;
- Species of the propellant;
- Initial temperature of the propellant;
- Mass flow;

The pressure of the flow is limited to 2 bar. For other pressures, the program should be improved. The heater mean temperature is taken as an input, as a way to confirm the model. However, if wanted the input temperature can be the local flow or wall temperature.

This model uses the same method than explained previously from equation (5.20) to equation (5.30).
2.1 Results from the model of temperature along heater

From Figure 69, it can be seen that:
- In liquid part, the both temperatures increase, with the flow temperature following the wall temperature.
- In boiling part, both temperatures are constant, until the “Dryout” point where the wall temperature is much higher than the flow temperature.
- In gas part, the trend is similar with the liquid part, but with a higher difference between wall and flow temperatures.

3 Model of pressure drop along heater

This model computes the pressure drop along the heater. For that, the input parameters are:
- Propellant species, and mass flow;
- Geometric dimensions;
- Initial and final temperature.

The friction factor is computed using Ito correlation for helically coiled tubes, see Chapter 3. However other correlations can be chosen.

The length of each phase is done as indicated in equation (5.24). Here again the boundary thermal condition plays an important role. This part of program could be easily added to the main heat loss mode. However in this way, the computational time decreases significantly.
4 Transient regime

Due to the complexity of the equations, there is no analytical equation considering convection and radiation at the surface. Since convection plays the biggest role in the heat loss for lower temperatures, the analytical equation for transient regime will not take into account radiation in the surface. It is then possible to write as:

\[
T - T_{amb} = (T_i - T_{amb}) \exp \left( \frac{hA}{\rho V_{c_{sr316}}} t \right) + \frac{P_{in}}{hA_s} \left( 1 - \exp \left( -\frac{hA_s}{\rho V_{c_{sr316}}} t \right) \right) [W]
\]

\[
t = -\frac{\rho V_{c_{sr316}}}{hA_s} \log \left( 1 - \frac{hA}{P_{in}} (T - T_{amb}) \right) [s]
\]

In (5.31) the first term of the right side is zero, since the initial conditions are at ambient temperature.

<table>
<thead>
<tr>
<th></th>
<th>(T_{surface, final} [K])</th>
<th>(t [s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUR1.0 without insulation</td>
<td>427 – 560</td>
<td>65 – 70</td>
</tr>
<tr>
<td>DUR1.0 with insulation</td>
<td>350 – 485</td>
<td>30 – 60</td>
</tr>
</tbody>
</table>

Table 35 – Final surface temperature and required time to reach stable conditions, with convection and power input

As expected, the relation (5.31) cannot be applied in case of insulation, giving completely wrong values of required time to stabilize. Without insulation, the required time from analytical equations is still lower than the time from the numerical equations.

5 Conclusion of the theoretical models

The model of heat losses is divided into four parts: with/without insulation, dry/combined operation. Numerical equations depending on time are used, since an analytical formulation is not possible without doing major simplifications. The results seem to be coherent when input parameters are changed or when there is insulation or flow. Nevertheless, it was not taken into account the axial direction for the heat loss, neither the time dependence of the temperature along the insulation. These two simplifications can be the reason for some deviation when compared with experimental values. The model for temperature along heater and pressure drop are much less complex and require much less computational time. For that reason they were not added to the main program of heat losses, avoiding an even longer computational time.
Chapter 6 – Test plan and preparation

This chapter presents: the test item description, test objectives, resources, software, interfaces, test setup, preparation test description, final tests, general test procedure and risk assessment. This test plan and preparation is related to the test campaign on the Microresistojet DUR 1.0H2O, using water as propellant.

1 Test item description

DUR 1.0 H2O is a microresistojet based on DUR1.0 thruster developed by Rycek but adapted for use for use with liquid water. It consists of:
- Heating chamber, DUR 1.0, see Figure 70, including:
  - 3 thermocouples K, beginning, T1, middle, T2, and end, T3;
  - 1 thermocouple K, on the insulation, $T_{insul}$, see Figure 71;
- Axi-symmetric nozzle, Nozzle $\varnothing$ 0.4 mm:
  - 1 pressure measurement point, $p_n$;
  - 1 thermocouples K, $T_n$;

Specific parameters are given in the Table 36.

![Figure 70 – Test Item, with Nozzle $\varnothing$ 0.4 mm on the right](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea level thrust</td>
<td>Up to 20 mN</td>
</tr>
<tr>
<td>Hot gas temperature</td>
<td>Up to 700 K</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>Up to 5 bar absolute</td>
</tr>
<tr>
<td>Propellant</td>
<td>Demineralised water</td>
</tr>
<tr>
<td>Propellant mass flow</td>
<td>Up to 35 mg/s</td>
</tr>
<tr>
<td>Length</td>
<td>130 mm</td>
</tr>
<tr>
<td>Diameter (without/with insulation)</td>
<td>43/90 mm</td>
</tr>
</tbody>
</table>

*Table 36 – Thruster parameters*
The nozzle and heater parameters are given in Table 37 and Table 38, see Annexes of Technical drawings for the nozzle dimensions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throat diameter</td>
<td>0.40 mm</td>
</tr>
<tr>
<td>Exit diameter</td>
<td>0.40 mm</td>
</tr>
<tr>
<td>Chamber inner diameter</td>
<td>3.1 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>Length</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Copper</td>
</tr>
</tbody>
</table>

Table 37 – Nozzle parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature</td>
<td>1000 K</td>
</tr>
<tr>
<td>Maximum internal pressure</td>
<td>5 bar</td>
</tr>
<tr>
<td>Electrical resistance</td>
<td>0.315 Ω</td>
</tr>
<tr>
<td>Mass</td>
<td>18 g</td>
</tr>
<tr>
<td>Configuration</td>
<td>Helically coiled tube</td>
</tr>
<tr>
<td></td>
<td>7 full 360° with 2 90° bend at the ends</td>
</tr>
<tr>
<td>Length</td>
<td>0.95 m</td>
</tr>
<tr>
<td>Mean coil diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>Inner tube diameter</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Outer tube diameter</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>Material</td>
<td>SS 316</td>
</tr>
</tbody>
</table>

Table 38 – Heater parameters
The configuration of the heater with insulation and with nozzle thermocouple and nozzle pressure tube is shown in Figure 71.

Figure 71 – Thruster with insulation, thermocouple in the nozzle and on the insulation, with coiled tube for pressure measurement

2 Test objectives

The main objectives of the tests are:
- To verify the theoretical model at dry and wet operations, with and without insulation.
- To compare between the experimental and theoretical pressure drop along the heater.
- To compare between the experimental and theoretical critical mass flow and thrust.
- To verify the temperature variation along the heater at wet operation.

Other objectives are:
- To qualify the system to be possible to use it in the clean room.
- To verify test procedures.
- To decrease heat losses to the exterior (it is then easier to vaporize the propellant).
- To measure the heater resistance and the nozzle dimensions.
- To validate the use of the thruster with water as propellant.
3 Resources

3.1 Measurement equipment

The following measurement equipments are required for the test campaign.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Model</th>
<th>Range</th>
<th>Inaccuracy (instrument + DAQ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td><em>Delta Electronika</em></td>
<td>0 – 5 V</td>
<td>0.5 % - 20 mA/0 A ± 6.48 mA</td>
</tr>
<tr>
<td></td>
<td>SM7020-D</td>
<td>0 – 5 V</td>
<td>0.5 % - 35 mV/0 V ± 11.34 mV</td>
</tr>
<tr>
<td>Multimeter</td>
<td>TENMA72 - 7770</td>
<td>0 – 20 V</td>
<td>± 0.005 V</td>
</tr>
<tr>
<td>Voltmeter (heater and power supply voltage)</td>
<td>SCB-68</td>
<td>0 – 10 V</td>
<td>± 0.32 mV</td>
</tr>
<tr>
<td>Thermocouples</td>
<td>Type-K</td>
<td>-150 – 1370 °C</td>
<td>1 % ± 4 °C</td>
</tr>
<tr>
<td>Thermistor (ambient temperature)</td>
<td>SCB-68</td>
<td>0 – 110 °C</td>
<td>± 1 °C</td>
</tr>
<tr>
<td>Pressure gauge (before and after control valve)</td>
<td>PX181-200G5V</td>
<td>0 – 13.79 bar gauge (0 – 200 psig)</td>
<td>± 0.042 bar (± 0.608 psi)</td>
</tr>
<tr>
<td>Pressure gauge (in the nozzle)</td>
<td>PX181B-100G5V</td>
<td>0 – 6.89 bar gauge (0 – 100 psig)</td>
<td>± 0.021 bar (± 0.304 psi)</td>
</tr>
<tr>
<td>Ambient pressure gauge</td>
<td>144SC0811BARO</td>
<td>800 – 1100 mbar</td>
<td>0.56 mbar</td>
</tr>
<tr>
<td>Mass flow meter</td>
<td>F &amp; P co. Tube No 02-08-3/37</td>
<td>0 – 2.5 [-]</td>
<td>± 0.01 [-]</td>
</tr>
<tr>
<td>Weight scale (only for calibration)</td>
<td>KERN 442-512N</td>
<td>0 – 4000 g</td>
<td>± 0.5 g</td>
</tr>
<tr>
<td>Load cell</td>
<td><em>Futek LSB 200</em></td>
<td>0 – 1 N</td>
<td>± 0.3 mN</td>
</tr>
</tbody>
</table>

Table 39 – Measurement equipment, model, range and inaccuracy [66]
3.2 Thrust stand (DARTS)

To measure thrust, the Delft Aerospace Rocket Test Stand (DARTS) is used, see Figure 72. Its feeding system is not used, instead it is used the feeding system described in section 6. The inaccuracy of DARTS is not less than ± 1 mN (see Chapter 7).
4 Software

4.1 Program description

A dedicated control software and data acquisition system is developed operating in Labview 8.5 environment. The control parameter is the electric current. The data acquired is:
- Electric current;
- Heater voltage;
- Power supply voltage;
- Coil temperature (3 different points);
- Insulation temperature (if insulation is present);
- Wall temperature near control valve;
- Ambient temperature;
- Flow temperature in the nozzle;
- Pressure before and after control valve;
- Pressure in the nozzle;
- Ambient pressure;
- Thrust;

Raw data is directly recorded into test files then to Excel files or Matlab files for further processing. The records are organized as followed:
- K:\deos\sse\sse-shared\5. Personal Directories\Rodrigo\Documents & excel &Thesis\Test Plans & Test Reports\Final tests
- Classification by date or by test case.

The Labview programs are listed in the Table 40.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Program name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve and mass flow calibration</td>
<td>Test valve DUR10_H2O</td>
</tr>
<tr>
<td>Test power loss</td>
<td>Test power loss-2 DUR10_H2O</td>
</tr>
<tr>
<td>Final test with Thrust, Temperature and Pressure(^\text{13})</td>
<td>Test ThTePr DUR10_H2O v2.vi</td>
</tr>
</tbody>
</table>

\(^\text{13}\) The block diagram is shown in the Annexes of LABVIEW Files
5 Interfaces

5.1 Mechanical interfaces

The thruster is installed, in the inlet side, to a brass interface mounted in the modified side plate. In the outlet, a Monolux interface is installed to avoid electrical contact with the bench. The technical drawing of the brass interface and modified side plate are in Annexes of Technical Drawings.

Figure 73 – Mechanical brass interface for the inlet, with modified side plate

Figure 74 – Mechanical Monolux interface for the outlet

Figure 75 – Thruster with mechanical interface for the inlet (right) and for the outlet (left)
5.2 Electrical interfaces
The cables from the power supply and the cables that measure the heater voltage should be suitable for higher currents and temperatures. For that reason, it is used cables insulated with kapton, near the heater. Furthermore, the power cables should have at least 1.5 mm². If not, several cables should then be used.
To decrease the influence of these cables on the thrust measurement, they are sustained by a rope connected to the ceiling. This connection should be as flexible as possible.

6 Test setup
A schematic of the test setup is shown in Figure 76.
The setup is composed of a feed system, a power supply, Delta Electronika SM7020-D and the thruster itself, see section 1. The feed system consists of:

- Air pump, with pressure gauge, see Figure 80;
- Water tank, with inlet and outlet, for storing water at ambient temperature, see Figure 80;
- Fill/drain valve, see Figure 82;
- Shutoff valve, see Figure 82;
- Flow meter, see Figure 79;
- Control/metering valve, Swagelok S Series metering valve, for more details, see Figure 77;
- 2 pressure measurement points, before and after the metering valve, connected to 2 pressure transducers PX181;
- 1 thermocouple type K, near control valve;
- Electrical and thermal insulator disc, see Figure 83;

The general view of the system in the clean room is shown in the Figure 72.

6.1 Feed system items description

**Flow control valve**

The control valve is a manually controlled by manually adjusting the knob, see Figure 77.

![Figure 77 – Control/metering valve](image)

By adjusting the valve, the friction coefficient $C_v$ is adapted and hence the mass flow $\dot{m}$. The friction coefficient as the number of turns is given by the manufacturer [67] and varies between 0 and 0.004, see Annexes. From [68], the mass flow is computed using:

$$\dot{V} = N_1 C_v \sqrt{\frac{\Delta p [bar]}{G_f}} \quad [L/min] \quad \Leftrightarrow \dot{m} [g/min] = \dot{V} [L/min] \times \rho [g/L]$$

Here $N_1 = 14.42$, $G_f = 1$ (for water) and $\Delta p = p_1 - p_2$ is the pressure drop through the valve. The water density $\rho [g/L]$ varies with temperature, see Annexes. This equation is similar to the equation found in [1]. The control valve goes from 0 to 1400 mg/s depending on the flow coefficient, see Figure 78.
From Table 36, we learn that propellant mass flow rate for DUR1.0 is up to 35 mg/s. Only a small range of the valve will be used.

**Flow meter**
The flow meter (*Rotameter*) is read directly from the value indicated by the little ball inside, see Figure 79. The scale is dimensionless and needs to be calibrated, see section 7.2.

The inlet is at the bottom part, where the ruined valve is. The outlet is at the top part. The measurable water mass flow rate is from 10 mg/s to 200 mg/s.
**Air pump and water tank**
The air pump (*Gazelle* pump) works manually, having an analogue pressure gauge. The air pump can go until 12 bar.
The water tank (*Daalderop Close-up 10*) has an inlet and an outlet and a heater (is not used), see Figure 80. The inlet tube goes only until the very top of the tank, and the outlet tube goes to the very bottom. The maximum pressure is 8 bar with 10 litre of capacity.

![Figure 80 – Tank on the left side and air pump on the right side](image1)

**Shut-off valve and fill valve**
The shut-off and fill valve are a needle and a ball valve respectively. Both of them are suitable to work with water.

![Figure 82 – Shutoff valve (green) on the left side and fill valve (blue) on the right side](image2)

Ball valve: *Festo* ball valve: Typ QH – ¼ Serie Q 9541 0 – 30 bar
Needle valve: *Nupro* Company valve SS-6H-MM
Electrical/thermal insulator disc
To avoid electrical contact between the heater and the feed system, an electrical insulator disc was designed, see Figure 75 and Figure 83. The non-conductive material used is Delrin, with o-rings to avoid leaks [9, 69, 70]. The Screws have non-conductive washers and the metal parts are in SS316 to avoid oxidation by the water. The side discs are hard soldered to the Ø 3 mm tubes. This assembly is composed by 4 M3 bolts, 2 o-rings, 2 metal discs and 1 insulation disc, see Figure 84. The technical drawing can be found in the Annexes of Technical Drawings.

Figure 83 – Electrical/thermal insulator disc (Delrin) in the middle

Figure 84 – Electrical/thermal insulator disc, exploded view
7 Preparation tests description
Preparation tests have been done for safety, system integrity and better accuracy. Some preparation tests need to be performed each time, and some only once.

7.1 Every time preparation test

Electrical contact
Electrical contact between the heated and the cold part of the system (from the right side to the left side of the insulator) is not acceptable just like between the heater and the insulation or radiation shield (if electrically conductive). For that, it is used a multimeter in sound configuration. If there is any sound, then electrical contact is present. The mounting shall be reviewed, until there is no electrical contact.

Leakage in the system
Since water propellant is used, the leakage test is easily performed. For that the shutoff valve is open as the metering valve, with 8 turns. To check the leakages, there is only need to detect if there is water in different location than the exhaust. If there are leakages, close valves and repair them. If there is no leakage, fully open the metering valve and check again if there are leakages. All the system shall be checked since water leakage is not allowed.

Mass flow test
To check if the mass flow meter is giving acceptable values: open with 8 turns the metering valve, check if the value is consistent with the calibration performed, see Chapter 7. Open with one more turn (9 open turns) and check if the value increased and if it is coherent.

Check power and Shield Connector Block switches
Before running the labview program, the switches from the power supply and from the shield connector block (SCB) should be checked, see facility documentation [66].

Check labview program and instruments
Run labview program, and check if the temperatures have a value around room temperature. For that, an external thermometer as the RSDual Thermometer is used or the ambient thermistor in the SCB. Check if the current input is the same than the measured current, typing 1 A and 2 A. If an offset is present, the input current should take that into account.
**Pressure test**  
Check if the pressure after valve and in the nozzle has the same value, around ambient pressure.  
The pressure transducers give a relative value of pressure, with a certain drift. To have them in absolute values without drift, add the value from the ambient transducer, 144SC0811BARO, and cancel the difference between both.

\[
P_{px181,\text{absolute}} = P_{px181,\text{relative}} + P_{144SC,\text{absolute}} - \text{Drift}
\]

\[
\text{Drift} = P_{px181,\text{relative}} (1\text{bar}) \quad \text{[bar]}
\]

**Thrust test**  
The load cell of the DARTS is calibrated in accordance to calibration section of the facility documentation, [66].  
With low levels of thrust (near the inaccuracy of the bench), the thrust tests should be performed after 13 PM, when the ambient temperature is more stable, see annexes and [20].  
When touching the metering valve, some noise appears in the thrust output. However no drift was seen afterwards due to side forces. After calibration avoid touching cables and tubes that are connected to the DARTS. If not, some thrust drift can appear.

### 7.2 Single time preparation and qualification test

These tests have as objective to prepare the use of the new system that uses water as a propellant. A new propellant storage is used, as well as, a completely new feed system including pipes, valves, DARTS interface and electrical insulation. A thermal insulator around the heater is also used to increase the efficiency of the system. Since they were never used before, they need to be tested. The final objective of these tests is to qualify the current water resistojet for use in the clean-room of Delft University of Technology.

**Material selection**  
All the parts that are in direct contact with water should not corrode. Furthermore, the propellant shall not be contaminated by the different parts. All parts in brass and in copper are suited for this purpose. Moreover, some stainless steels are also suited for water, as SS314 and SS316. To confirm if the stainless steel is the desired one, check if it has very small magnetic properties, using a magnet. If the magnet attach to the part, then the stainless steel is not the desired one.

**Water tank**  
Test performed in order to check if there is no leakage in the tank, and to check the best location for inlet (compressed air) and outlet (compressed water). The leakages are checked from 1 bar to 7 bar. If there is no water coming from the tank, then the tank is leak tight.
**Shutoff valve**
Test carried out to check if the valve fully closes at 6 bar, and to check the order of magnitude of minimum mass flow, that can still be controlled by the valve. Measure for 1 to 2 minutes the weight of water for a certain valve opening. It was found that the valve was able to fully close and the minimal mass flow was around 300 mg/s depending on the tank pressure.

**Filling method and fill valve**
Ensure during filling, if there is no contact between the person and the propellant. Check if the fill valve does not leak when at close position with a pressurized tank. This preparatory test was performed during the preparation tests: test DUR H2O #1 to #3, see annexes. To fill the tank the following order should be followed:
- Unscrew slowly and partially the inlet connector.
- Wait for the pressure in the tank to drop until 1 bar.
- Unscrew totally the inlet connector.
- Open slowly the fill valve.
- Using a funnel, fill the tank with water.
- Close the fill valve.
- Screw again the inlet connector with new Teflon tape.
- Pressurize the tank.

**Control valve and flow meter**
To calibrate the metering valve and mass flow meter, water is allowed to flow from a reservoir during some time at different valve setting. To obtain the mass flow \( \dot{m} \), mass \( m \) is measured and divided with the time \( t \):

\[
\dot{m} = \frac{m}{t} \frac{[g]}{[min]} \frac{[g/min]}{}
\]  

(6.3)

To obtain a conservative estimation of the mass flow inaccuracy, the relative inaccuracies are added [11]:

\[
\dot{m} \pm \Delta \dot{m} = \frac{m \pm \Delta m}{t \pm \Delta t} \approx \frac{m}{t} \left( 1 \pm \frac{\Delta m}{m} + \frac{\Delta t}{t} \right)
\]  

(6.4)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fully open</td>
<td>2.0</td>
<td>0.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fully open – 2</td>
<td>2.0</td>
<td>0.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fully open – 4</td>
<td>2.0</td>
<td>0.0</td>
<td>10.0</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Fully open – 6</td>
<td>2.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Fully open – 8</td>
<td>2.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Fully open – 5</td>
<td>2.0</td>
<td>0.0</td>
<td>20.0</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Fully open – 8</td>
<td>3.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Fully open – 5</td>
<td>3.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fully open – 6</td>
<td>3.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Fully open – 4</td>
<td>3.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Fully open – 5</td>
<td>4.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Fully open – 8</td>
<td>4.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Fully open – 4½</td>
<td>4.0</td>
<td>0.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Fully open – 3.5</td>
<td>2.0</td>
<td>0.0</td>
<td>5.0</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>Fully open – 4.5</td>
<td>2.0</td>
<td>0.0</td>
<td>10.0</td>
<td>X</td>
</tr>
<tr>
<td>16</td>
<td>Fully open – 4½</td>
<td>2.0</td>
<td>0.0</td>
<td>5.0</td>
<td>X</td>
</tr>
</tbody>
</table>

**Table 41 – Settings for test series 1**

The procedure of this test can be found in annex.

**Thermal insulation**

Check if the thermal insulation around the heater can support temperatures around 1000 K, without burning, melting or smoking. This pre-test was performed during test DUR H2O #1 and #2, see Annexes. The ordinary rock wool used as insulation was not suitable since it started to burn, see Figure 85. Ceramic ficer blanket (*Fiberfrax Durablanket S*) [111] was chosen as insulator, showing stable behaviour during tests, Figure 86.

![Figure 85 – Heater and alumina blanket insulation after test](image-url)
Nevertheless some smoke was observed when starting the test. When opening the insulation, it was found that the smoke did not come from Fiberfrax Durablanket S insulation but from the first brown layer of the thermocouples insulation. After the brown layer is burnt, a reddish layer remains, see in Figure 86. This layer is more easily detachable but does not burn.

**Electrical/Thermal insulator**

This insulator is not only electrical but it also works as a thermal insulator, decreasing the heat transport to the non-heated part. A first design was done with the particularity to have high manufacturability and simplicity, the Cube, see Annexe of Technical Drawings. However, during mounting, this part showed to be too fragile. Furthermore, major leakages appeared, since the material had some porosity. See Annexes for more detailed information. A new electrical/thermal insulator was then made, Figure 83 and Figure 84.
**High temperature adhesive**
In order to fix the thermocouple in the nozzle, without electrical contact, an adhesive shall be used. Check the temperature that the adhesive can support and if it does not dissolve with water.
Most of the ceramic glues that withstand temperatures higher than 1100 K dissolve in water. For that reason a high temperature silicone [112] was chosen, withstanding around 700 K without any noticeable modification in its structure. At around 800 K, the silicone was ruined.
Since the silicone has a high viscosity, it is difficult to apply on the thermocouple. For that reason it is used a thinner, like turpentine, highly volatile, that does not modify the structure of the silicone. Isopropanol was also tested, being a failure, since it deteriorated the structure of the silicone, see Figure 88.

![Image](image.png)

**Figure 88** – Left: silicone with isopropanol; Right: silicone with turpentine

**Interface with Darts**
Check if the interface can fit correctly with DARTS. Check if there is no leakage in the brass interface, see Figure 73.
**Pressure tube connections**

It is observed that the pressure tube connections were frequent points of leakage. To avoid that problem a tube with smaller diameter is used. In some cases the tube needs to be slightly enlarged, in that case, an ice pick is used. Since tubes available with smaller diameter were fragile, it was still used the larger tube with the smaller tube in the tips.

![Figure 89 – Alternative pressure tube connection](image)

These connections are not enough when the pressure point is in a hot part, as at the nozzle (the most critical point). Two different occurrences happen: the tube is plastically deformed and is not leak tight anymore; the tube is literally ruined. It was also found heat conduction was not the only problem. The high temperature flow entering the pressure tube was also one of the reasons for the higher temperatures. As first solution with high manufacturability and simplicity, a cooling tube with water was mounted around the pressure tube, see Figure 90.

![Figure 90 – Pressure tube with cooling water tube](image)

However this solution showed not to be enough for the high temperature flow. Furthermore it was highly unreliable, with some cases failing and others not. An alternative solution was found, the coiled cooling tube, see Figure 91. This solution showed to be highly reliable during testing.
**Thermocouple connections**

As done previously in Resistojet research [18], the thermocouples are welded to the point of measurement. This type of connection gives very little temperature reading inaccuracy, however it is very fragile. To give more rigidity, ceramic glue is added in the welded connections, see Figure 92.

For the thermocouple in the nozzle (critical point) it is used a different technique. Two thin wires of the thermocouple K are welded together (done by Hans Weerheim), seeming only one thin wire. Since this thermocouple cannot have electrical contact with the nozzle, a layer of silicone/thinner mixture coats the thermocouple. Ceramic glue can also be used if water is not used. When the layer is dried, insert carefully the thermocouple through the nozzle, until the weld point is in the middle of the nozzle chamber. Attach it with silicone and let it dry. Add ceramic glue around the silicone and the thermocouple wire to avoid the wire to slip. The positive and negative part of the small thermocouple can be found connecting it with a thermocouple. When touching the junction between thermocouples the temperature should remain almost the same. If the temperature increases significantly, then connections should be the opposite. Verify again to check if the connection is then correct. The junction between the thermocouples can be done simply using Kapton tape (light and easily redone), see Figure 93. This operation takes around 4 days to be done, due to the drying time.
Figure 93 – Nozzle thermocouples with Kapton tape in the tips and fixed with silicone.

**Tube house for pressure transducer**
The tube house for pressure transducers were designed by [16]. A new one was designed and manufactured for the new pressure transducer, using almost the same dimensions but in brass instead of stainless steel, see Annexes of Technical Drawings.

**Behaviour of boiling flow**
It is important to monitor the behaviour of boiling flow as temperature variation and pressure variation. The basic understanding of boiling flow will allow more controllable final tests. This preparation test was performed during *test DUR H2O #1, #2 and #3*, see Annexes. A final preparation test is performed to confirm this behaviour. The test is performed with a mass flow of 20 - 30 mg/s that is set by the number of open turns. The electric power input is calculated using the current provided by the power supply and the heater voltage measured separately by a voltmeter. It is fundamental to measure the heater temperature in 3 different points and then a weighted mean temperature is computed, see Chapter 7. The pressure before the valve is measured to keep a constant pressure in the tank. The pressure drop is measured by the difference between the pressure before and after the control valve. It is then possible to associate with a certain mass flow.
This test is divided into 3 parts:
- Dry operation, at 10 A;
- With water flow 20 - 30 mg/s, and increasing current until reaching vapour exhaust;
- Constant current with vapour exhaust.

This test has a secondary role to validate the theoretical pre-model of the effect of natural convection and radiation in the heater, at constant electric current, during transient and stationary regime, at dry operation. This test was performed in *test DUR H2O #3*.

**Final clean room qualification tests**
To finally qualify the water resistojet, no water leakage can be tolerable. The filling method should be done in a controllable way and smoke from thermal insulation is not acceptable. This qualification test was performed during *test DUR H2O #1 and #2*, see Annexes.
**Measurement of the throat dimensions**
Check the minimum and maximum diameter of the nozzle throat. The microscope brightfield reflection with monitor projection, from Delft Aerospace Structures & Materials Laboratory, is used. To confirm the measurement, insert in the nozzle a small rod with the minimum dimensions measured previously. The results are showed in Chapter 7.

**Measurement of the heater resistance with temperature**
This test can be performed with a multimeter in the resistance configuration. However the contact resistance gives a high inaccuracy and low repeatability. Some resistance test were done by [16, 18], but for lower temperature ranges. For these reasons, a different method is used, explained in Chapter 7.

8 Final tests description
To perform the final test, it is needed at least one week: 2 days to mount, 1 day for preparatory tests, 1 day for testing, 1 day to dismount. However if some problem occurs, this week can easily go to 1 or 2 months, depending on the problem.

8.1 Heater test
This test is performed to validate the Heat loss model. Here the effect of natural convection and radiation in the heater, at constant electric current, without flow, during transient and stationary regime is analyzed. Afterwards, the heater configuration with and without insulation are compared. Furthermore, this test is important for higher accuracy, and wider temperature range, on the heater resistance, which influences the total power input.
To obtain the electric power that is converted to heat, by Joule heating effect, it is important to know the heater resistance at constant electric current. The current is provided by the power supply and the voltage in the heater is measured separately by voltmeter. This 4-wire measurement method avoids measuring the voltage along the cables, giving then the right value. Since the heater resistance is dependent on the temperature, the temperature is measured in 3 different points and then an arithmetic mean temperature is computed. However the temperature is not controlled directly but indirectly by increase in electric current.
The following test conditions and configurations are shown in Table 42.
<table>
<thead>
<tr>
<th>Current levels</th>
<th>Insulation method</th>
<th>Expected temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>without insulation</td>
<td>~300 K</td>
</tr>
<tr>
<td>5 A</td>
<td>with and without insulation</td>
<td>400 - 700 K (depending on the insulation)</td>
</tr>
<tr>
<td>10 A</td>
<td>with and without insulation</td>
<td>500 K or 1000 K (depending on the insulation)</td>
</tr>
</tbody>
</table>

Table 42 – Test conditions for the effect of insulation on power loss and heater resistance characterization

The effect of the thermal insulation around the heating chamber provides higher and more stable temperatures, insulating from the environment. As a result, for higher temperatures, a longer period of time is required to obtain stable conditions. All configurations are used for verification and validation of the theoretical model in transient and stable conditions at dry operation, with and without insulation. For these configurations, 5\(^{14}\) measurements per second should be the maximum to be used, since it is important to register the transient pattern. If the test is longer than 1 hour for a certain configuration, 2 measurements per second should then be used as a maximum.

8.2 Thruster test

This test is performed to validate the Heat loss model with the effect of water flow on the heater temperature and pressure drop, at stationary conditions. Furthermore, the thrust levels will be measured for a critical chamber pressure and mass flow. With these measurements, the heat loss to the exterior and the thermal efficiency of the heater are computed, see chapter 4. The electric power input is calculated measuring the current provided by the power supply and the heater voltage measured directly by the SCB. The heater temperature is measured in 3 different points to observe the variation of temperature along the heater. At dry operation and wet operation, the heater mean temperature is calculated from the current input and heater voltage and then related to heater resistance at a certain mean temperature. The pressure drop is calculated measuring the pressure before and after the heater. Pre-heating is essential to prevent liquid exhaust and to prevent longer transient period. Pressure in the tank is assumed to be equal to the pressure before the valve, P1, this measurement increases the accuracy of the tank pressure in relation to the air pump pressure gauge. The mass flow is read directly from the mass flow meter once per minute (if possible). To have better thrust signal, all the cables and tubes are fixed to the DARTS with high flexibility. Furthermore the test is performed after 13 PM to avoid higher drifts from the load cell.

\[^{14}\text{5(measurements)} \times 60(\text{min}) \times 60(\text{test time}) = 18000 \text{ points} < 32000 \text{ points (maximum from Excel)}\]
The following test conditions are planned:

- Pre-heating at 8 A during 2 – 4 min;
- Open control valve with a mass flow of around 30 mg/s, wait for stable conditions;
- Increase current to 15 A, open more the control valve to keep around 30 mg/s;
- Increase current to 16 A and to 17 A, opening more the control valve;
- Increase current to 17.5 A with mass flow that gives a chamber pressure around 2 bar.
  - Keep this configuration until reaching stable conditions, at least 10 minutes;
- Close valve;
- Set current to 0 A. Wait to reach ambient temperature in the heater.

To be able to reach high temperatures and avoiding temperature fluctuations due to convection, the heater is thermally insulated from the environment. To be able to register the oscillatory behaviour of a boiling flow, the measurements should be taken 1 to 2 times per second. Since the test takes 2 to 3 hours, more measurements per second give a heavy data files, difficult to work.

During the test, the system is pressurized by slightly opening the control valve. Avoid increasing the tank pressure, since the heater pressure equalizes the tank pressure at unstable conditions.
## General test procedure

The following test procedure describes a general test step by step.

<table>
<thead>
<tr>
<th>Task</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do the preparation tests</td>
<td>(1 day)</td>
</tr>
<tr>
<td>If combined operation:</td>
<td></td>
</tr>
<tr>
<td>Open shutoff valve</td>
<td></td>
</tr>
<tr>
<td>Open metering valve with 3 (no flow)</td>
<td></td>
</tr>
<tr>
<td>Start the Labview program</td>
<td></td>
</tr>
<tr>
<td>Wait for reference values</td>
<td>(1 – 2 min)</td>
</tr>
<tr>
<td>Start heating with the required current</td>
<td></td>
</tr>
<tr>
<td>If dry operation:</td>
<td></td>
</tr>
<tr>
<td>Wait until the temperature is stable</td>
<td>1K/5min</td>
</tr>
<tr>
<td>Wait until the temperature at T3 is</td>
<td>(10 – 40 min)</td>
</tr>
<tr>
<td>between 600 K to 650 K</td>
<td></td>
</tr>
<tr>
<td>Open metering valve with value of 0.2</td>
<td></td>
</tr>
<tr>
<td>to 0.3 [-]</td>
<td></td>
</tr>
<tr>
<td>Wait until reaching stable temperatures</td>
<td></td>
</tr>
<tr>
<td>Open more the metering valve until</td>
<td></td>
</tr>
<tr>
<td>reaching the desired pressure at P-n</td>
<td></td>
</tr>
<tr>
<td>Wait for stable conditions (2.5 K/min)</td>
<td></td>
</tr>
<tr>
<td>If required, repeat the 2 previous</td>
<td></td>
</tr>
<tr>
<td>steps for different pressures</td>
<td></td>
</tr>
<tr>
<td>Close control valve</td>
<td></td>
</tr>
<tr>
<td>If combined operation:</td>
<td></td>
</tr>
<tr>
<td>Stop heating, no current</td>
<td></td>
</tr>
<tr>
<td>Wait until reaching room temperature</td>
<td>+10 K than $T_{\text{room}}$ is</td>
</tr>
<tr>
<td>in the heater</td>
<td>acceptable</td>
</tr>
<tr>
<td>(5 min – 1 hour)</td>
<td></td>
</tr>
<tr>
<td>Stop program and close shutoff valve</td>
<td></td>
</tr>
</tbody>
</table>

*Table 43 – General test procedure for dry or combined operation*
10 Risk assessment

10.1 High current
DUR1.0 H2O is driven by a current up to 20A. If the voltage is lower than 35 V, no appropriate precautions for handling and operating shall be observed. Nevertheless, the test engineer should not touch heated part of the propulsion system.

10.2 Other risks
The maximum allowable temperature of the thermocouples has not to be surpassed. If this happens, the temperature of the thruster has to be decreased, decreasing the current. The maximum voltage measured by the DAQ is 10 V. If the power supply is near to that value, the current has to be decreased.
Chapter 7 – Test results and discussion

This chapter presents the main results from the preparatory test, heater test and thruster test. The test results are elaborated to obtain extraordinary information and to focus in more relevant parts. After each section, the results are compared with the theory and then discussed.

This chapter is divided into two parts:
- Preparatory test:
  - Calibration of a control valve and mass flow meter;
  - Measurement of throat dimensions;
  - Heater resistance characterization;
- Final test:
  - Heater test;
  - Thruster test.

1 Preparatory test

1.1 Calibration of a control valve and mass flow meter

From Chapter 6, the different settings can be found as well as the formulas used.

<table>
<thead>
<tr>
<th>Test #</th>
<th># of turns</th>
<th>Mass flow meter value [-]</th>
<th>Mass flow rate [mg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fully open</td>
<td></td>
<td>1203.3</td>
</tr>
<tr>
<td>2</td>
<td>Fully open – 2</td>
<td></td>
<td>353.3</td>
</tr>
<tr>
<td>3</td>
<td>Fully open – 4</td>
<td></td>
<td>51.7</td>
</tr>
<tr>
<td>3 V2</td>
<td>Fully open – 4</td>
<td>0.51</td>
<td>60.0</td>
</tr>
<tr>
<td>3 V3</td>
<td>Fully open – 4</td>
<td>0.99</td>
<td>79.6</td>
</tr>
<tr>
<td>3 V4</td>
<td>Fully open – 4</td>
<td>1.08</td>
<td>90.0</td>
</tr>
<tr>
<td>4</td>
<td>Fully open – 6</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>Fully open – 8</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>Fully open – 5</td>
<td></td>
<td>11.7</td>
</tr>
<tr>
<td>6 V2</td>
<td>Fully open – 5</td>
<td>0.27</td>
<td>15.0</td>
</tr>
<tr>
<td>6 V3</td>
<td>Fully open – 5</td>
<td>0.23</td>
<td>18.3</td>
</tr>
<tr>
<td>6 V4</td>
<td>Fully open – 5</td>
<td>0.19</td>
<td>24.0</td>
</tr>
<tr>
<td>7</td>
<td>Fully open – 8</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>Fully open – 5</td>
<td></td>
<td>23.8</td>
</tr>
<tr>
<td>9</td>
<td>Fully open – 6</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>Fully open – 4</td>
<td></td>
<td>136.7</td>
</tr>
<tr>
<td>11</td>
<td>Fully open – 5</td>
<td></td>
<td>26.4</td>
</tr>
<tr>
<td>12</td>
<td>Fully open – 8</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>13</td>
<td>Fully open – 4</td>
<td></td>
<td>152.1</td>
</tr>
<tr>
<td>14</td>
<td>Fully open – 3.5</td>
<td>1.72</td>
<td>163.0</td>
</tr>
<tr>
<td>15</td>
<td>Fully open – 4.5</td>
<td>0.39</td>
<td>38.3</td>
</tr>
<tr>
<td>16</td>
<td>Fully open – 4½</td>
<td>0.61</td>
<td>66.7</td>
</tr>
</tbody>
</table>

Table 44 – Results from calibration of control valve and mass flow meter
As indicated in Table 44, for the same turn the mass flow is quite inconsistent, giving only an order of magnitude. For that reason, the use of number of turns cannot be used to accurately estimate mass flow, being also difficult to reproduce. To increase the reproducibility of valve setting, a more precise handle should be used (Vernier Handle [67]).

The dimensionless values of the mass flow meter are calibrated, giving the mass flow in the desired units. Figure 94 presents the relation between the dimensionless and calibrated values. For a wider range, see Annexes.

Using this calibration, the dependency on pressure drop and ambient temperature will not bring additional errors. Furthermore it is possible to have a direct reading during a test.

<table>
<thead>
<tr>
<th>Range</th>
<th>Calibration equation</th>
<th>Inaccuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[g/s]</td>
<td>[g/s]</td>
</tr>
<tr>
<td>0.2 – 0.5</td>
<td>0.015 – 0.060</td>
<td>0.1269x^2 + 0.0519x</td>
</tr>
</tbody>
</table>

Table 45 – Calibration equations depending on the desired range
1.2 Measurement of throat dimensions

From Chapter 3 the dimensions of the nozzle are given. The main dimension is the throat diameter with 0.4 mm. However, this value has a certain inaccuracy.

The minimum and maximum diameter of the nozzle throat is measured by the microscope brightfield reflection with monitor projection, from Delft Aerospace Structures & Materials Laboratory. The confirmation of the measurement is done by inserting in the nozzle a small rod with the minimum dimensions measured previously, see annexes.

The value given by inserting the small rods shows a value with a maximum of 0.42 mm. However, from the picture taken by the microscope the value is higher. This is due to small protuberances in the throat that do not allow inserting circular rods. For that reason, the values from the microscope are the ones taken into account. For the exit diameter, the expansion should be very small, and the value considered is 0.450 mm. This value comes from half of the maximum measured value. The final dimensions of the throat diameter and inaccuracy are shown in Table 46.
<table>
<thead>
<tr>
<th>Nozzle ∅0.4mm (Water nozzle)</th>
<th>Minimum diameter [μm]</th>
<th>Maximum diameter [μm]</th>
<th>Mean diameter and error [μm]</th>
<th>Exit diameter [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>407.36</td>
<td>469.58</td>
<td>440 ± 30</td>
<td>450</td>
</tr>
</tbody>
</table>

*Table 46 – Mean throat diameter and error of Nozzle ∅0.4mm*

1.3 **Heater resistance characterization**

This test was performed in order to obtain values of the heater resistance at higher temperatures.

The resistance of DUR1.0 was measured indirectly by measuring the heater voltage and current, at a certain mean temperature. The heater mean temperature $T_{heater}$ is discussed in section 2.2. For this test, the data used is the same as used for the heater test, section 2.

\[
y = -1.478 \times 10^{-7} x^2 + 3.394 \times 10^{-4} x + 3.150 \times 10^{-1}
\]

\[
R^2 = 9.994 \times 10^{-1}
\]

*Figure 96 – Heater resistance with temperature, for DUR1.0*

The measurement accuracy at ambient temperature is ± 5 mΩ and at higher temperatures is ± 1 mΩ.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$\alpha$ [1/K]</th>
<th>$\beta$ [1/K]</th>
<th>$R_0$ [Ω]</th>
<th>$T_{ref}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3.394 \times 10^4$/$0.315$</td>
<td>$-1.478 \times 10^7$/$0.315$</td>
<td>0.315</td>
<td>295</td>
</tr>
</tbody>
</table>

*Table 47 – Temperature coefficients and resistance of DUR1.0*
Data elaboration and discussion

Due to the difference with theoretical values, Rycek [16] and Tijsterman [18] developed their own relations, given in Table 48. However, these relations were for shorter ranges of temperature than required for the final test.

<table>
<thead>
<tr>
<th></th>
<th>$R_0$ [Ω]</th>
<th>$T_{ref}$ [K]</th>
<th>$R(T)$ [Ω]</th>
<th>Range of $\bar{T}_{heater}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rycek [16+p.76]</td>
<td>0.320</td>
<td>293</td>
<td>$R_0 \left(1 + 1.00 \times 10^{-3} \Delta T \right)$</td>
<td>293 – 600</td>
</tr>
<tr>
<td>Tijsterman [18]</td>
<td>0.318</td>
<td>294</td>
<td>$R_0 \left(1 + 1.009 \times 10^{-3} \Delta T \right)$</td>
<td>294 – 700</td>
</tr>
<tr>
<td>Ferreira</td>
<td>0.315</td>
<td>295</td>
<td>$R_0 - 1.478 \times 10^{-7} \Delta T^2 + 3.394 \times 10^{-4} \Delta T$</td>
<td>295 – 900</td>
</tr>
</tbody>
</table>

Table 48 – Different relations for resistance with different ranges

The temperature difference $\Delta T$ is defined as the difference between heater mean temperature $\bar{T}_{heater}$ and reference temperature, $T_{ref}$.

![Resistance of DUR1.0 with temperature variation](image)

Figure 97 – Resistance of DUR1.0 depending on the heater temperature

The relations of resistance are only plotted in valid ranges. Using the new relation from the test, Ferreira relation, the main difference with the other correlations is a lower resistance for higher temperatures. This relation shows slightly lower values of resistance comparing with the other two relations. This difference goes from - 2 % for lower temperatures to -3 % for higher temperatures, where all the relations are still valid.
2 Heater test

At dry operation, the effect of insulation on the heater temperature is analyzed and compared with the model predictor. This section is divided into test results, data elaboration and discussion.

2.1 Test results

Test results have been obtained for a current setting of 5A and 10 A. Here the results are only presented for 10 A, since the results for 5 A are quite similar. For the full results, see annexes. For the complete data files see folder: Rodrigo\Documents & Tests & Thesis\Test Plans & Test Reports\Test Power loss - no flow.

![Heater temperature, 10 A, without insulation](image)

Figure 98 –Heater temperature depending on location, for DUR1.0, at 10 A, without insulation
Figure 99 – Heater temperatures depending on location, for DUR1.0, at 10 A, with insulation

The power input at 10 A without insulation is showed as an example. For other values and configurations, see annexes.

Figure 100 – Heater temperatures depending on the location, for DUR1.0, at 10 A, with insulation
The figures on the temperature show:

- Temperature increases in time and after some period stabilizes. The highest temperature is measured in the middle of the heater, and the lowest in the extremes: \(T_3 < T_1 < T_2\). This is independent of the heater configuration with or without insulation.
- Temperatures with insulation are always higher than the temperatures without insulation, taking longer time to achieve stable temperatures.
- Signal shows a low noise level (to be quantified later) and noise level decreases in case of insulation.
- There is no drift in the temperature, since before and after the test the temperature is at 295 K.
- The insulation temperature is much lower than the heater temperatures, but showing the same behaviour.

From the Figure 100, it is seen:

- The power follows same trend as temperature increasing in time until it stabilizes at the same time the temperature stabilizes.

### 2.2 Data elaboration

For each test the values of temperature and power at stable conditions have been determined. Stable conditions are defined as conditions under which the change in temperature is less than 1K/min. The temperature oscillations at stable conditions are calculated subtracting the maximum and the minimum value at that period. The values are presented in Table 49.

The heater mean temperature is obtained averaging the temperatures measured at the locations 1, 2 and 3. However, the relation used for the heater mean temperature gives a higher weight to the value measured in the middle, see equation (7.1).

\[
\bar{T}_{\text{heater}} = \frac{T_1 + 2T_2 + T_3}{4} \quad [\text{K}]
\]  

(7.1)

This weighted mean temperature should be closer to the real value than the arithmetic mean temperature. This is known, since the temperature distribution along the heater is close to parabolic distribution.

The stabilization time is computed taking 95 % of the final value, see equation (7.2).

\[
\tau = t\left(\left(T_{\text{stable}} - T_{\text{initial}}\right) \times 95\% - T_{\text{initial}}\right) \quad [\text{s}]
\]  

(7.2)

The elaborated data is presented in Table 49. Figure 101 shows the evolution of mean temperature and how the stabilization time and the stable value of temperature are calculated.
Figure 101 – Heater mean temperature, for DUR1.0, at 10 A, without insulation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5 A No</td>
<td>341</td>
<td>352</td>
<td>337</td>
<td></td>
<td>8</td>
<td>140</td>
<td></td>
<td>345</td>
<td>± 4</td>
</tr>
<tr>
<td>5 A Yes</td>
<td>547</td>
<td>580</td>
<td>526</td>
<td>326</td>
<td>10</td>
<td>1550</td>
<td></td>
<td>558</td>
<td>± 1</td>
</tr>
<tr>
<td>10 A No</td>
<td>448</td>
<td>468</td>
<td>434</td>
<td></td>
<td>36</td>
<td>100</td>
<td></td>
<td>455</td>
<td>± 4</td>
</tr>
<tr>
<td>10 A Yes</td>
<td>942</td>
<td>977</td>
<td>920</td>
<td>394</td>
<td>47</td>
<td>900</td>
<td></td>
<td>954</td>
<td>± 1</td>
</tr>
</tbody>
</table>

Table 49 – Measured heater temperature, insulation temperature and power input, for DUR1.0

Furthermore, it is found that:
- The maximum temperature difference along the heater is relatively small, not more than 60 K.
- The temperature difference, between having insulation or not, increases with current, from 213 K at 5 A to 499 K to 10 A. The same occurs with power difference, from 2 W at 5 A to 11 W at 10 A.

2.3 Discussion

Effect of current setting
From the Table 6, it is found that the main differences using a lower current level are:
- Lower heater temperature and insulation temperature if present.
- Lower power input.
- Longer stabilization time.
Comparison with theory
Here the experimental results are compared with the results obtained from the theoretical model, described in Chapter 4. The discussion is performed in the final part of this section.

It is only presented the heater mean temperature at 10 A with insulation. For other configuration and settings of the heater mean temperature, as well as, for insulation temperature and power input, see annexes.

![Graph of Comparison between test and theory, for DUR1.0, at 10 A, with insulation](image)

**Figure 102 – Comparison between test and theory, for DUR1.0, at 10 A, with insulation**

In the case of insulated heater:
- The stabilized value of the heater mean temperature predicted by the model is higher than the measured temperature.
- The model has a much shorter transient phase than the experimental values, having then a bigger slope. This is directly related to the time dependence of heat transport through the insulation, which is not taken into account in the model.
- The deviation\(^{15}\) of the predicted stabilization time is high. In practice, the heating takes more time than predicted.

In the case of non-insulated heater:
- The behaviour at stable conditions is essentially the same.
- The slope of the transient phase predicted is nearly the same than in practice.
- The deviation\(^{15}\) of the predicted stabilization time is low. In practice, the heating takes less time than predicted. This is directly related to a higher predicted temperature.

---

\(^{15}\) Model deviation or offset is defined as: \[ \frac{X_{\text{theory}}}{X_{\text{exp.}}} - 1 \] , where X is a defined parameter.
The theoretical values for power, with and without insulation are also computed. They essentially showed the same behaviour than the respective mean temperatures of the heater, being always slightly higher than in practice.

Table 50 presents the values from the test and from the model with the respective deviation\textsuperscript{15}.

<table>
<thead>
<tr>
<th>Current input [A]</th>
<th>5</th>
<th>5</th>
<th>10</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Heater mean temperature from test [K]</td>
<td>345</td>
<td>558</td>
<td>455</td>
<td>954</td>
</tr>
<tr>
<td>Heater mean temperature from model [K]</td>
<td>352</td>
<td>591</td>
<td>471</td>
<td>969</td>
</tr>
<tr>
<td>Model deviation\textsuperscript{15}</td>
<td>+ 2%</td>
<td>+ 6%</td>
<td>+ 4%</td>
<td>+ 2%</td>
</tr>
<tr>
<td>Measured insulation temperature [K]</td>
<td></td>
<td>327</td>
<td></td>
<td>395</td>
</tr>
<tr>
<td>Insulation temperature from model [K]</td>
<td></td>
<td>338</td>
<td></td>
<td>446</td>
</tr>
<tr>
<td>Model deviation\textsuperscript{15}</td>
<td></td>
<td>+ 3%</td>
<td></td>
<td>+ 13%</td>
</tr>
<tr>
<td>Stabilization time from test [s]</td>
<td>120</td>
<td>1500</td>
<td>90</td>
<td>840</td>
</tr>
<tr>
<td>Stabilization time from model [s]</td>
<td>150</td>
<td>680</td>
<td>110</td>
<td>290</td>
</tr>
<tr>
<td>Model deviation\textsuperscript{15}</td>
<td>+ 25%</td>
<td>- 54%</td>
<td>+ 22%</td>
<td>- 65%</td>
</tr>
<tr>
<td>Power from test [K]</td>
<td>8.2</td>
<td>9.8</td>
<td>36.2</td>
<td>47.4</td>
</tr>
<tr>
<td>Power from model [K]</td>
<td>8.3</td>
<td>10.1</td>
<td>37.0</td>
<td>47.8</td>
</tr>
<tr>
<td>Model deviation\textsuperscript{15}</td>
<td>+ 1%</td>
<td>+ 3%</td>
<td>+ 2%</td>
<td>+ 1%</td>
</tr>
</tbody>
</table>

Table 50 – Measured and theoretical values with and without insulation, for DUR1.0

The model predicts reasonably well the stationary mean temperatures of the heater. Nevertheless, the model gives slightly higher temperatures than measured, since it assumes lower levels of power loss. The transient phase is better predicted in case of heater without insulation. In case of insulation, the model does not take into account the time dependence of heat transport through the insulation. Instead the model only takes equations of stationary conduction along the insulation. This can be clearly seen in the significant deviation to predict the transient behaviour of the insulation temperature. Furthermore, the deviation to predict the insulation temperature at stable condition is relevant. However since it was measured only one point, the error can be smaller than measured. The power levels are well predicted by the model with only minor deviation, being directly related to the predicted heater mean temperature.
3 Thruster test

To perform the test, the water is heated to a high temperature, while achieving the desired pressure. The maximum allowed temperature for the nozzle is 700 K. The controlled parameters are the heater current and flow valve setting. These were stepwise adapted to achieve the desired state:

1. Heat the heater to about 700 K without propellant flow.
2. Start propellant flow at reduced rate; heater temperature will drop due to the flow.
3. Increase current to bring flow temperature to 700 K.
4. Increase mass flow rate to increase pressure.
5. Wait for some time (5-10 minutes) to establish if temperature and pressure reach the desired (stable) values.
6. Continue steps 3 to 5 until the desired conditions are reached.
7. End test (switch off propellant flow and current).

The resulting adaptations in the controlled parameters are shown in Figure 103.

![Figure 103 – Settings of heater current and flow valve, with DUR 1.0H2O](image)

The desired conditions were reached from 1200 s to 1750 s and from 4000 s to 5300 s. After that time, difficulties in maintaining the proper conditions were experienced (see section 3.1).

The complete data file can be found in: Rodrigo\Documents & Tests & Thesis\Test Plans & Test Reports\Final tests\Final Test 04-06-2008.xls.
3.1 Test results

The different signals were measured: mass flow, heater temperature, insulation temperature, ambient temperature, pressure, ambient pressure, voltage and current. See test plan in Chapter 6 for more details.

The ambient conditions during the test are shown in Table 51.

<table>
<thead>
<tr>
<th>Ambient temperature [K]</th>
<th>Ambient pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>296.5 ± 0.3</td>
<td>1.013 ± 0.0005</td>
</tr>
</tbody>
</table>

Table 51 – Ambient conditions during test

The current measurements follow the desired current settings with a minor offset and inaccuracy: - 0.03 A ± 0.07 A.

During the test, the various valve settings did not have the initial set value of mass flow. As it can be seen in Figure 104, after a valve setting, the mass flow decreases until a stable value. Furthermore an increase in current gives an oscillatory behaviour until reaching a new equilibrium. At 5200 s and at 6800 s, with a constant setting, the mass flow started to increase. For that reason, the settings were changed to obtain the previous conditions.

![Mass flow and valve setting](image)

Figure 104 – Flow valve setting and respective mass flow measurement, with DUR 1.0H2O

During the test, it was possible to distinguish between vapour (liquid and water mixture) and gas exhaust. The first is clearly visible and audible, when the last one is only audible.

Vapour exhaust was observed during the test at:
- Phase 2, propellant at reduced rate (600 s to 900 s).
- 5200 s and 6800 s, when the mass flow was higher than the desired value.
**Temperature**
The figure for temperature variation is split into two figures for better understanding.

*Figure 105 – Temperature of the heater, with DUR 1.0H2O*

*Figure 106 – Flow temperature, insulation and ambient at the nozzle, with DUR 1.0H2O*

Here $T_{\text{nozzle}}$ represents the temperature of the flow in the nozzle, and $T_{\text{insulation}}$ is the temperature of the insulation on the outer surface.
From Figure 105 and Figure 106, it is found that:

- Heater and nozzle temperature increase when current is increased, and vice versa.
- Heater and nozzle temperature decrease when mass flow is increased, and vice versa.
- Highest temperature is measured in the end of the heater, and the lowest in the beginning: $T_1 < T_2 < T_3$. Except at dry operation, where the order is the same than in section 2.
- Insulation temperature, $T_{\text{insulation}}$, remains near a constant value, except during pre-heating or in the cooling part. $T_{\text{insulation}}$ is higher than ambient temperature but significantly lower than the other temperatures.
- Maximum temperature variation along the heater is important, at wet operation.
- At wet operation, $T_2 < T_{\text{nozzle}}$, except when power input is high enough (900 s to 1800 s), then $T_2 > T_{\text{nozzle}}$. $T_2 \approx T_{\text{nozzle}}$ if both are at boiling temperature.
- Most of the time, $T_2$ is at boiling temperature, $T_1$ measures the liquid part of the flow and $T_3$ the gas part.
- $T_{\text{nozzle}}$ and $T_2$ follow $T_3$, except after 5400 s where $T_2$ does not follow $T_3$.
- It was observed that, when water droplets are expelled from the nozzle, $T_{\text{nozzle}}$ drops instantly for a very short period. This explains the big oscillations of $T_{\text{nozzle}}$. When vapour exhaust is observed, $T_{\text{nozzle}}$ is at boiling temperature.
- Periods with small variation were observed: 1300 s to 1800 s, and 4000 s to 4700 s.
- At 5200 s and at 6200 s the temperature decreases, with constant setting.
- There is no drift in the temperature, since before and after the test the temperature is at 296 K.

**Power**

![Power variation for DUR1.0](image)

**Figure 107 – Power from heater and from power supply , with DUR 1.0H2O**
From above figure, it is found that:

- Power increases with increasing current and decreases increasing mass flow, and vice versa.
- Power from the power supply is always higher than the power that goes to the heater.
- Difference between both powers increases significantly with current. The power losses in the cables are then significant.
- From 1200 s to 1750 s and 4000 s to 5100 s, both powers are nearly constant.
- No drift in power.

**Pressure and mass flow**

![Pressure variation of tank, heater and ambient for DUR1.0](image)

Figure 108 – Various pressure measurements, with DUR 1.0H2O

Here, it is seen that:

- P1 and ambient pressure ($P_{ambient}$) are almost constant. $P_1 = 2.60 \pm 0.02$ bar.
- P2 and $P_{nozzle}$ increase until 3600 s with increase in the control settings.
- P2 and $P_{nozzle}$ decrease from 5100 s until the end, even at constant settings.
- The pressure order is: $P_{ambient} < P_{nozzle} < P_2 < P_1$.
- P2 and $P_{nozzle}$ have a significant oscillation. The bigger oscillations appear with changing settings, taking some time to decrease. Except at 5200 s, when a considerable oscillation appeared with constant settings.
- In general, the big oscillations are more significant at higher setting levels. The highest peak of 3.2 bar was measured at 3900 s, here $P_1 < P_{nozzle} < P_2$.
- From 1200 s to 1800 s, 4000 s to 5100 s and 5800 s to 6200 s the pressure is around 1.5 bar, 2 bar and 1.7 bar respectively. During these periods the oscillations are smaller than 0.5 bar.
- A drift of 0.03 bar in P2 is present, comparing initial to final conditions.
• No drift present in $P_{\text{nozzle}}$, $P_1$ and $P_{\text{ambient}}$.

**Thrust**

In case of thrust measurement, see annexes, it is found that:

- Signal is quite noisy:
  - The noise is about ± 100 mN.
  - Some peaks of ± 200 mN to ± 1000 mN are present, when setting the manual control valve.
- It is not possible to analyse this thrust signal, without data elaboration, since the maximum theoretical thrust expected is around 20 mN.
- More details about the thrust are given by data elaboration, see section 3.2.

### 3.2 Data elaboration

In this section, the data from the test is elaborated following this order: average data with drift correction (pressure and pressure drop), filter data (thrust), Fourier analysis (pressure and thrust), and heater mean temperature from power.

**Nozzle pressure and pressure drop**

Since the pressure signal in the heater is highly oscillatory, the average will give additional information. The pressure in the nozzle $P_{\text{nozzle}}$ is presented with mass flow and current settings, Figure 109. The averaged pressure drop along the heater is presented in Figure 110, also with mass flow and current settings. The pressure drop along the heater is calculated by equation (7.3), and the correction for the drift in equation (7.4). See annexes for non-corrected pressure drop:

$$\Delta P_{\text{heater}} = P_2 - P_{\text{nozzle}} \text{ [bar]} \quad (7.3)$$

$$\Delta P_{\text{heater,correct}} = \Delta P_{\text{heater}} - Drift \text{ [bar]}, \text{ with } Drift = 0.032 \text{ bar} \quad (7.4)$$
From Figure 109 and Figure 110, it is found that:

- Average value of $P_{\text{nozzle}}$ increases set by step until 5100 s.
- After 5100 s, no clear steps are present, with a general tendency to decrease pressure.
• Steps in pressure are directly related to increase in flow valve setting.
• When longer and higher pressure oscillations are present (2100 s, 2700 s, 3800 s), the mass flow is also highly oscillatory. Generally, it happens when current setting is changed.
• There are clearly 2 constant steps that can be used for further analysis: 1300 s to 1750 s and 4000 s to 4600 s.
• At 5100 s and from 6000 s to the end, with constant settings, the pressure decreases with increase in mass flow.
• Averaged pressure drop is small, going from 0 to 0.04 bar.
• Pressure drop does not vary significantly with mass flow.
• From 1200 s to 1800 s and from 4000 s to 4600 s, the pressure drop does not vary considerably.

Filtered thrust
Thrust signal has levels of noise comparable with the expected theoretical thrust. For that reason it is primordial to use filtered\textsuperscript{16} or averaged data, see [35]. Moving average (of 255) shows the same trend than low-pass filter (omega at 8), keeping information about oscillations in the thrust. Using Matlab Smooth (smooth range 900) and Savitzky-Golay (range 0.03), the oscillations are averaged and the peaks smoothed. When looking in the entire test, moving average is used. When looking in particular periods where the properties are more constant, Matlab Smooth is used, since it gives smoother values, easier to compare with the model, see Annexes.

Using moving average and low-pass filter, a drift of + 2 mN was observed. With Matlab Smooth and Savitzky-Golay, the drift was + 4 mN. The first value is the one taken into account, since the last two filters smooth too much the data.

Some horizontal misalignment\textsuperscript{17} was observed, about 21° ± 2.5°. However vertical misalignment was not possible to measure.

Table 52 indicates the corrections done to obtain the final thrust from the initial raw value, \( F_{\text{raw}} \).

<table>
<thead>
<tr>
<th>Drift</th>
<th>+ 2 mN</th>
<th>( F_{\text{drift}} = F_{\text{raw}} - \text{Drift} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal misalignment, ( \theta )</td>
<td>21°</td>
<td>( F_{\text{hor.,mis.}} = \frac{F_{\text{raw}}}{\cos(\theta)} )</td>
</tr>
<tr>
<td>Final corrected thrust, ( F_{\text{corrected}} )</td>
<td>+ 2 mN</td>
<td>21°</td>
</tr>
</tbody>
</table>

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|}
\hline
Drift                  & + 2 mN                           & \( F_{\text{drift}} = F_{\text{raw}} - \text{Drift} \) \\
\hline
Horizontal misalignment, \( \theta \) & 21°                              & \( F_{\text{hor.\,mis.}} = \frac{F_{\text{raw}}}{\cos(\theta)} \) \\
\hline
Final corrected thrust, \( F_{\text{corrected}} \) & + 2 mN 21°                      & \( F_{\text{corrected}} = \frac{F_{\text{raw}} - \text{Drift}}{\cos(\theta)} \) \\
\hline
\end{tabular}
\caption{Drift and misalignment corrections for thrust}
\end{table}

\textsuperscript{16} Some parameters are characteristics of the filters: low-pass filter – omega; Matlab Smooth – smooth range; Savitzky-Golay – range.

\textsuperscript{17} Horizontal misalignment is computed by measuring the distance in x and y axis from expelled water droplets: \( x = 1.3 \text{ m } \pm\ 0.05 \text{ m } y = 0.5 \text{ m } \pm\ 0.05 \text{ m } \)
Figure 111 – Mass flow, current settings and averaged thrust, for DUR1.0

Here, it is found that:

- Thrust starts and finishes at 0 mN.
- Until 5100 s, when mass flow increases, thrust increases.
- After 5100 s, when mass flow increases, thrust decreases.
- Big peaks are present when setting the manual control valve. And should not be taken into account.
- From 600 s to 900 s, the negative values have no interest, since at that time liquid water was accumulated in the mechanical support, and after taken out.
- At 5100 s, with constant settings, the thrust drops abruptly and mass flow increases in the opposite direction.
- When flow is present, the minimal thrust is around 0 mN, at 1000 s. The maximum thrust is 13.5 mN, at 4500 s.
Fourier analysis for thrust and pressure

Taking the thrust raw data from the test, it is possible to find the natural frequency of the system. Knowing that the sampling frequency during the test was 5 Hz, the Nyquist frequency is then 2.5 Hz [35, 72]. It is then fundamental to have the higher signal peaks at lower frequency than the Nyquist frequency, see Figure 112.

![Figure 112 – Amplitude of original thrust data in frequency domain, for DUR1.0](image)

Here, it is possible to see that the natural frequency of the system is around 1.4 Hz. For shorter periods during the test, it is found the same, see annexes.

Analysing the nozzle pressure in frequency domain, like for thrust, it is found that the peaks have very low amplitude with frequency near 0 Hz (around 0.02 Hz to 0.2 Hz), see annexes. Then for pressure, there is no relevant characteristic frequency.

Heater mean temperature

In wet operation, it is also important to calculate a heater mean temperature, to be able to compare with theory. The heater mean temperature $\bar{T}$ is calculated by the voltage $V$ and current $I$ in the heater with its resistance that depends on temperature, see equations (7.8) and (7.9).

\[
P = VI = I^2 R(\bar{T}) \quad [W] \tag{7.8}
\]

\[
\bar{T} = \frac{2\beta R_0 T_{ref} I + \sqrt{\alpha^2 I^2 - 4\beta R_0 (I^2 R_0 - P) - \alpha R_0 I}}{2\beta R_0 I} \quad [K] \tag{7.9}
\]

Here, $P$ is the power input in the heater. $\alpha$, $\beta$ and $R_0$ are the temperature coefficients and heater resistance at reference temperature from section 1.3. This way does not permit to know the mean temperature when current is not applied.

The result of heater mean temperature can be found in Annex. It is found that this temperature follows perfectly T3 along the test, but at lower levels.
**Thermal efficiency**

Thermal efficiency $\eta_{\text{thermal}}$ is defined as:

$$
\eta_{\text{thermal}} = \frac{\dot{m} \left( H(T_{\text{out}}) - H(T_{\text{in}}) \right)}{P_{\text{in}}}
$$

(7.10)

Here $T_{\text{in}}$, $T_{\text{out}}$, $P_{\text{in}}$ and $\dot{m}$ are respectively room temperature, nozzle flow temperature, power input and mass flow. These values were obtained experimentally during test. The values of enthalpy $H$ are taken directly from [75].

**Stable periods**

The complexity of the transient behaviour, during test, makes difficult to compare with the theory (oscillatory behaviour in boiling flow). Then, only the stable periods ($\bar{T} \leq 2.5$ K/min) are compared with theory, see Table 53. During the stable periods, the variation of the measured parameters is lower or even negligible for some parameters, see Table 54.

<table>
<thead>
<tr>
<th>Period</th>
<th>Current</th>
<th>Temperature increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410 s to 1710 s</td>
<td>15.0 A</td>
<td>$\bar{T} = 2.4$ K/min</td>
</tr>
<tr>
<td>4000 s to 4600 s</td>
<td>17.5 A</td>
<td>$\bar{T} = 2.5$ K/min</td>
</tr>
</tbody>
</table>

*Table 53 – Stable periods of the test*
### Summary of the Elaborated parameters

The oscillations registered are not taken into account, since they are not simulated by the model. Instead an averaged value is given. In the last 30 s of the first period (1410 s to 1710 s), the thrust is not taken into account, since the flow valve was set at that moment. For other parameters this is not a problem, since the change takes around 30 s to 90 s to occur.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1410 s to 1710 s</th>
<th>4000 s to 4600 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat power [W]</td>
<td>89.5 ± 0.5</td>
<td>117 ± 1</td>
</tr>
<tr>
<td>Flow temperature at nozzle, T_{nozzle} [K]</td>
<td>615 ± 15</td>
<td>653 ± 24</td>
</tr>
<tr>
<td>Maximum wall temperature, T3 [K]</td>
<td>817 ± 6</td>
<td>791 ± 18</td>
</tr>
<tr>
<td>T2 [K]</td>
<td>681 ± 14</td>
<td>455 ± 45</td>
</tr>
<tr>
<td>T1 [K]</td>
<td>377 ± 3</td>
<td>363 ± 3</td>
</tr>
<tr>
<td>Mean heater temperature [K]</td>
<td>573 ± 6</td>
<td>514 ± 14</td>
</tr>
<tr>
<td>Insulation temperature [K]</td>
<td>323 ± 2</td>
<td>314 ± 1</td>
</tr>
<tr>
<td>Nozzle pressure [bar]</td>
<td>1.48 ± 0.10</td>
<td>1.98 ± 0.17</td>
</tr>
<tr>
<td>Heater pressure drop [bar]</td>
<td>0.023 ± 0.002</td>
<td>0.031 ± 0.004</td>
</tr>
<tr>
<td>Mass flow [mg/s]</td>
<td>21.4 ± 1.2</td>
<td>31.9 ± 2.5</td>
</tr>
<tr>
<td>Filtered thrust [mN]</td>
<td>2.5 ± 2</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Thermal efficiency [%]</td>
<td>73.5 ± 0.5</td>
<td>85.5 ± 0.5</td>
</tr>
</tbody>
</table>

Table 54 – Summary of different signals during constant period, with DUR 1.0H2O
3.3 Discussion

In this section, the experimental and theoretical values, from test and model respectively, are compared.

Mass flow comparison

Both periods, in the conditions presented in Table 55, have choked flow, see [102]. It is then possible to use the equation for critical mass flow presented in Chapter 3.

<table>
<thead>
<tr>
<th>Temperature and pressure</th>
<th>Mass flow from theory [mg/s]</th>
<th>Measured mass flow from test [mg/s]</th>
<th>Test deviation(^{18})</th>
</tr>
</thead>
<tbody>
<tr>
<td>615 K, 1.48 bar</td>
<td>28.2</td>
<td>21.4 ± 1.3</td>
<td>- 24 % ± 4 %</td>
</tr>
<tr>
<td>653 K, 1.98 bar</td>
<td>36.6</td>
<td>31.9 ± 2.5</td>
<td>- 13 % ± 7 %</td>
</tr>
</tbody>
</table>

Table 55 – Expected and measured mass flow at 2 different properties, with respective inaccuracy and deviation

From Table 55, the averaged mass flow \( \dot{m}_{\text{real}} \) from the test is lower than the ideal mass flow from ideal rocket motor theory, \( \dot{m}_{\text{ideal}} \). This difference between test and theory is expected, since in the test, the effective throat area is smaller. Furthermore, the flow temperature measured by the thermocouple is lower than the real value.

The difference is higher for the first case, at 1.48 bar and 615 K, than for the second period. This is due to higher inaccuracy for lower values and eventually shock waves in the divergent part of the nozzle expected for the first period, see [102]. The discharge coefficient \( C_d \) and the critical Reynolds number in the throat \( \text{Re}_{D_t}^* \) (for sonic conditions at the throat) are defined by [71] as:

\[
C_d = \frac{\dot{m}_{\text{real}}}{\dot{m}_{\text{ideal}}} \\
\text{Re}_{D_t}^* = \frac{4\dot{m}_{\text{ideal}}}{\pi D_t \mu}
\]  \hspace{1cm} (7.11)

Here \( D_t \) is the throat diameter of the nozzle and \( \mu \) is the dynamic viscosity\(^{19}\).

Table 56 indicates the discharge coefficient, the critical Reynolds number in the throat and the linearization parameter, using the method used by [71].

\(^{18}\) In this case the deviation is obtained by: \( (X_{\text{test}} - X_{\text{theo}})/X_{\text{theo}} \)

\(^{19}\) \( \mu \) (1.48 bar, 615 K) = 22.03 \( \mu \)Pa*s, \( \mu \) (1.98 bar, 653 K) = 23.61 \( \mu \)Pa*s
As expected, the discharge coefficient for the first case is lower than the second case, due to the reason already referred previously. Still the second discharge coefficient is slightly lower than founded in [71] for different gaseous species ($C_d \approx 0.94$, not found for water). There are several reasons for a smaller discharge coefficient:
- Throat area smaller than measured.
- The thermocouple in the nozzle presents slightly lower temperature than the real temperature of the flow (the ideal mass flow would decrease, increasing the discharge coefficient).
- Small calibration errors from the mass flow meter.
- The non ideal shape of the nozzle used during test.
- Water droplets in the exhaust, producing oscillatory behaviour in various parameters, making difficult to give a mean value.

**Thrust comparison**
The filtered thrust signal, with misalignment correction is compared with the theoretical thrust, at measured mass flow.

<table>
<thead>
<tr>
<th>chamber temperature [K]</th>
<th>615</th>
<th>653</th>
</tr>
</thead>
<tbody>
<tr>
<td>chamber pressure [bar]</td>
<td>1.48</td>
<td>1.98</td>
</tr>
<tr>
<td>Theoretical thrust [mN]</td>
<td>12.8</td>
<td>22.5</td>
</tr>
<tr>
<td>Elaborated thrust signal from test [mN] (test deviation$^{18}$)</td>
<td>$2.5 \pm 2$ ($-80% \pm 16%$)</td>
<td>$12 \pm 2$ ($-47% \pm 10%$)</td>
</tr>
</tbody>
</table>

From Table 57, the theoretical thrust is higher than from the test. This difference is higher in the first case, high inaccuracy reading. The nozzle is then highly inefficient with an efficient throat area much smaller than the geometric throat area. Furthermore, the water droplets are an additional reason for lower thrust. Since when the droplet is at the throat, the flow velocity is much lower, and then the thrust is also much lower.

<table>
<thead>
<tr>
<th>Averaged values from test</th>
<th>Discharge coefficient, $C_d$ [-]</th>
<th>Critical Reynolds number in the throat, $Re_{D_t}^*$ [-]</th>
<th>$\frac{1}{(Re_{D_t}^*)^{1.25}}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.4 mg/s, 1.48 bar, 615 K</td>
<td>0.76</td>
<td>3704</td>
<td>0.016</td>
</tr>
<tr>
<td>31.9 mg/s, 1.98 bar, 653 K</td>
<td>0.87</td>
<td>4486</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 56 – Comparison between test and theory with discharge coefficient, critical Reynolds number
Comparison of the temperature increase along the heater

The wall and flow temperatures along the heater obtained in the experiment are compared with the theoretically determined values, under the same conditions: mass flow, room temperature, heater mean temperature and pressure (the model is restricted at 2 bar). See annexes for the respective figure.

| Mass flow: 31.9 mg/s; heater mean temperature: 514 K; ambient temperature: 296.5 K |
|-------------------------------------------------|---------------------------------|--------------------------|
| T1 [K]                                           | Experiment                      | Theory                  | Model deviation$^{21}$ |
| 363                                              | 347                             | - 4 %                   |
| T2 [K]                                           | 410 (liq.) | 500 (gas)         | 408 (liq.) | 492 (gas) | - 0.5 % (liq.) | - 1.6 % (gas) |
| T3 [K]                                           | 791                             | 888                     | + 12 %                  |
| T$_{nozzle}$ [K]                                | 653                             | 871                     | + 33 %                  |

Table 58 – Comparison between experimentally and theoretically determined temperatures along the heater, using the short model

From Table 58, the following points can be seen and discussed:

- The values from the model show the same trend than during the test: T1 < T2 < T3, and T1 << T3. This shows that, the boundary condition of constant heat flux goes in agreement with test. Furthermore, the boundary condition of constant wall temperature cannot be applied, since the difference in temperature is large.
- From the model, it is expected that T1 measures the liquid part, T2 the boiling part (around ‘Dryout’ point) and T3 the gas part. This is confirmed with the experimentally measured values.
- T2 is clearly in the boiling part having a high temperature variation. This variation is directly related to the oscillation in pressure and mass flow, changing the boiling temperature and the localization of the ‘Dryout’ point.
- T1 and T2 have a negligible difference with the theory. T3 has a small difference with the theory, and T$_{nozzle}$ has an important difference.
- The higher deviation in T3 is due to higher heat losses in the last part of the heater. These losses are by convection and radiation through the last part of insulation, and by conduction to the nozzle. Here, the boundary condition of constant heat flux applied to the flow has some deviation. The constant heat flux from the heater goes also to the surroundings (losses), which are not insignificant anymore, like in the first part of the heater.
- The previous point also explains the difference in T$_{nozzle}$. However here there are additional events: temperature measured by the thermocouple reads lower temperature than the real value; the wall is heated by the flow, increasing even more the heat losses.
- The difference between the experimentally measured T3 and T$_{nozzle}$ is much higher than for the theoretically determined values. This difference is explained in

$^{20}$ The theoretical model used is not the full one, to avoid very high time of computation from few minutes to around 10 hours.

$^{21}$ In this case the deviation is obtained by: $(X_{theo} - X_{test})/X_{test}$
the previous point, with another factor: flow pattern is in straight tube for the last part of DUR1.0, and not only helically coiled tube as modelled. As result, the difference between wall temperature and flow temperature is higher than modelled, presenting also a higher heater mean temperature. Since this parameter is an input, the final temperatures theoretically determined are then higher. In this case, the full theoretical model should be used, see temperature and power comparison.

<table>
<thead>
<tr>
<th>Mass flow: 21.4 mg/s; heater mean temperature: 573 K; ambient temperature: 296.5 K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T1 [K]</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>T2 [K]</strong></td>
</tr>
<tr>
<td><strong>T3 [K]</strong></td>
</tr>
<tr>
<td><strong>Tnozzle [K]</strong></td>
</tr>
<tr>
<td><strong>Table 59 – Comparison between experimentally and theoretically determined temperatures along the heater</strong></td>
</tr>
</tbody>
</table>

Same comments than for Table 58 can be done for Table 59. However there are still some differences:

- In this case, the deviation is higher since the model is restricted to 2 bar when the flow is at 1.48 bar. Furthermore T3 is higher, having more losses and increasing the deviation of the constant heat flux boundary condition.
- From the theory, T2 should be at boiling part. However the experientially measured value indicates that T2 is already in the gas part.
- The difference between the experimentally measured T3 and T\textit{nozzle} is much higher than for the theoretically determined values, since in the model the flow temperatures are restricted to 1000 K.

As recommendation, the improvement in the theoretical model should take into account the axial direction and the heat losses to the nozzle. Furthermore, the model should be improved taking into account different flow pressures and flow patterns (from straight to coiled and ending in straight, see geometry of DUR1.0, chapter 6).
Temperature and power comparison

Here, the experimentally determined values are compared with the theory, for both periods (1410 s to 1710 s shown in annexes and 4000 s to 4600 s). These values are: power input, final flow temperature ($T_{\text{nozzle}}$) and final wall temperature ($T_3$), heater mean temperature and insulation temperature. The numerical values are in the following tables of this sub-section, including temperature and power comparison with theory. Furthermore, the theoretical model with flow is compared with the test assuming straight and coiled tube. Here, the final flow temperature ($T_{\text{nozzle}}$) and final wall temperature ($T_3$) are again compared, but now using the complete theoretical model. In this model, the input parameters are: current, mass flow, flow pressure and ambient temperature. The geometric dimensions of the heater are fixed, but can be changed for a different geometry.

![Figure 113 – Final wall and flow temperatures, at 17.5 A and 31.9 mg/s, for DUR1.0, with insulation](image)

From above figure, it is found that:
- Both temperatures are higher in the theoretical model than in the test.
- The temperatures from the test are closer to the theoretical ones in the end of the studied time.
- The temperature drops in the flow temperature, due to expelled droplets (clearly visible during test), are not modelled by the theory.
- The difference between the experimentally measured final wall temperature and nozzle flow temperature is higher than for the theoretically determined values.

These differences are due to extraordinary heat losses in the final part of the heater in which the model predictor does not take into account. These losses are by convection and radiation of the last part of the heater to the environment and conduction to the nozzle. For the flow temperature in the nozzle these effects are even higher, as the difference
between final wall temperature and nozzle flow temperature. This is explained in previous section, *Comparison of the temperature increase along the heater*.

![Graph showing heater mean temperature and insulation temperature](image)

**Figure 114** – Heater mean temperature and insulation temperature, at 17.5 A and 31.9 mg/s, for DUR1.0, with insulation

From Figure 114, it is found that:

- Insulation temperature is slightly higher in the theoretical model than in the test.
- The heater mean temperature from the model has a lower value than from the test.
- The tested heater mean temperature is still increasing, and the difference with theory is then more significant.

The difference in the heater mean temperature is due to higher heat losses (mainly in the final part) and due to the assumption of flow in a helically coiled tube. In DUR1.0 there are some parts are straight: beginning and the final part of the heater. As a result, the experimentally determined heater mean temperature is higher, with a higher difference between flow and wall as discussed in *Comparison of the temperature increase along the heater*.
Here, it is seen that:

- The power input from test is lower than from the model;
- The difference between the test and the model increases with time, since experimentally measured values are not completely constant.

Since power input is directly related with the heater mean temperature, this difference is then due to the difference in heater mean temperature. This final reason is explained in the previous discussion.

The numerical values and comparison between experimentally and theoretically determined values are presented in Table 60, for different periods. Furthermore, the flow pattern in straight tube is added as indication of its influence on the theoretical values, since, in the previous discussions, this parameter was considered to be one of the causes for the differences between model and test, see Table 61.
Experimental values

<table>
<thead>
<tr>
<th>Flow pattern: Helically coiled tube</th>
<th>Experimental values</th>
<th>Theoretical model</th>
<th>Model deviation(^2), from mean values</th>
<th>Model deviation(^2), from maximum values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean values</td>
<td>Maximum values</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation temperature [K]</td>
<td>323</td>
<td>325</td>
<td>325</td>
<td>+ 1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 %</td>
</tr>
<tr>
<td>Heater mean temperature [K]</td>
<td>573</td>
<td>579</td>
<td>512</td>
<td>- 10 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 12 %</td>
</tr>
<tr>
<td>Final flow temperature [K]</td>
<td>615</td>
<td>630</td>
<td>921</td>
<td>+ 50 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 46 %</td>
</tr>
<tr>
<td>Final wall temperature [K]</td>
<td>817</td>
<td>823</td>
<td>964</td>
<td>+ 18 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 17 %</td>
</tr>
<tr>
<td>Power input [W]</td>
<td>89.5</td>
<td>90.0</td>
<td>86</td>
<td>- 4 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 4 %</td>
</tr>
</tbody>
</table>

1st period

| Insulation temperature            | 314                 | 315              | 319                                    | + 2 \%                                 |
|                                   |                     |                  |                                        | + 1 \%                                 |
| Heater mean temperature           | 514                 | 528              | 480                                    | - 7 \%                                 |
|                                   |                     |                  |                                        | - 9 \%                                 |
| Final flow temperature            | 653                 | 677              | 785                                    | + 20 \%                                |
|                                   |                     |                  |                                        | + 16                                    |
| Final wall temperature            | 791                 | 809              | 842                                    | + 6 \%                                 |
|                                   |                     |                  |                                        | + 4\%                                   |
| Power input                       | 117                 | 118              | 114                                    | - 3 \%                                 |
|                                   |                     |                  |                                        | - 3 \%                                 |

2nd period

Table 60 – Comparison between experimentally and theoretically determined temperatures and power, using Heat loss model (flow pattern in a helically coiled tube)

From Table 60, the following points can be seen and discussed:

- The model has a little deviation, except for final flow temperature. These deviations are explained in previous discussions.
- The deviation is, in some cases, positive and in other cases, negative. This discrepancy is related to the assumption of a helical flow pattern, when the real geometry of DUR1.0 is not purely helical.
- In general, the theoretical determined values are closer to the maximum values than for the mean values of the test. However the transient pattern was not analysed since it was not possible to compare with the test. During the test, transient phases with flow are highly unstable in pressure, mass flow and temperature (typical from boiling flow).
• The first period has more deviation than the second period. The cause is the higher temperatures and higher heat losses.

As an example, Table 61 presents the predicted values when considering straight tube.

<table>
<thead>
<tr>
<th>Flow pattern: Straight tube (2\textsuperscript{nd} period)</th>
<th>Experimental values</th>
<th>Theoretical model</th>
<th>Model deviation\textsuperscript{21}, from mean values</th>
<th>Model deviation\textsuperscript{21}, from maximum values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean values</td>
<td>Maximum values</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation temperature [K]</td>
<td>314</td>
<td>315</td>
<td>329</td>
<td>+ 5 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 4%</td>
</tr>
<tr>
<td>Heater mean temperature [K]</td>
<td>514</td>
<td>528</td>
<td>537</td>
<td>+ 4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 2%</td>
</tr>
<tr>
<td>Final flow temperature [K]</td>
<td>653</td>
<td>677</td>
<td>820</td>
<td>+ 26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 21%</td>
</tr>
<tr>
<td>Final wall temperature [K]</td>
<td>791</td>
<td>809</td>
<td>937</td>
<td>+ 18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 16%</td>
</tr>
<tr>
<td>Power input [W]</td>
<td>117</td>
<td>118</td>
<td>119</td>
<td>+ 2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ 1%</td>
</tr>
</tbody>
</table>

Table 61 – Comparison between experimentally and theoretically determined temperatures and power, using Heat loss model (flow pattern in a straight tube)

Using a flow pattern in a straight tube the same is observed than the previous case. However there are some differences:

• The deviation is always positive. Some inaccuracies are lower and some higher than for the previous case. This is a good indication that the flow is not totally in helically coiled tube neither in a straight tube.

• All the theoretical determined values are closer to the maximum values than for the mean values of the test.

**Pressure drop comparison**

During the test, it was observed a pressure drop much lower than expected by the theory. Here, the experimentally and the theoretically determined pressure loss are compared. Since the first method of coiled tube in single and two-phase flow does not follow the test, other methods are added:

- Flow in helically coiled tube, during all the phases;
- Flow in straight tube, during all the phases;
- Flow in helically coiled tube in single phase parts and flow in straight tube in the two-phase part (combined tube).

The theory uses as input in final flow temperature, \( T_{\text{nozzle}} \), ambient temperature and mass flow. For the length of each part comes from the theory and is showed in the annexes of *comparison of the temperature increase along the heater*.
First period
\[ \dot{m} = 21.4 \text{ mg/s}, \]
\[ T_{\text{flow,o}} = 615 \text{ K} \]
Second period
\[ \dot{m} = 31.9 \text{ mg/s}, \]
\[ T_{\text{flow,o}} = 653 \text{ K} \]

<table>
<thead>
<tr>
<th>Heater pressure drop from test [bar]</th>
<th>0.023 ± 0.002</th>
<th>0.031 ± 0.004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater pressure drop from theoretical model [bar]</td>
<td>Helically coiled tube</td>
<td>0.729</td>
</tr>
<tr>
<td></td>
<td>Straight tube</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>Combined tube</td>
<td>0.022</td>
</tr>
</tbody>
</table>

| Model deviation | Helically coiled tube | 31× | 23× |
| | Straight tube | - 9 % | 0 % |
| Combined tube | - 4 % | + 6 % |

**Table 62 – Comparison between experimentally and theoretically determined heater pressure drop, using different methods**

From Table 62, the following points can be seen and discussed:

- The increase in pressure drop from the first period to the second period is observed in experimentally and theoretically determined values.
- The values given by flow in helically coiled tube is completely out. Since the bigger contribution in pressure drop comes from two-phase flow, it can be concluded that the correlation used cannot be applied for this case. This correlation was initially obtained for much higher mass flux (236 – 943 kg/m²s) [59, 62] than during the test (~ 6 kg/m²s). This correlation should then be avoided.
- The methods of flow in straight tube and flow in combined tube present theoretical values very close to the experimental values.
- As an advice, the method of flow in combined tube should be used, since the deviation is smaller and more conservative than the straight tube method.
**Thermal efficiency**

The experimental thermal efficiency is computed using the measured values in equation (7.10). The theoretical thermal efficiency is computed using the measured ambient temperature and mass flow. The final flow temperature and power input come from the model predictor.

<table>
<thead>
<tr>
<th>Power input [W]</th>
<th>Final temperature [K]</th>
<th>Experimental thermal efficiency(^{22}) [-]</th>
<th>Theoretical thermal efficiency [-]</th>
<th>Model deviation(^{21})</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.4 mg/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean values</td>
<td>89.5</td>
<td>615</td>
<td>0.73</td>
<td>0.93</td>
</tr>
<tr>
<td>Maximum values</td>
<td>90.0</td>
<td>630</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>31.9 mg/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean values</td>
<td>117</td>
<td>653</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>Maximum values</td>
<td>118</td>
<td>677</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Table 63 – Thermal efficiency of the thruster

In reality, the experimental thermal efficiency is slightly higher, since the temperature measured by the thermocouple in the flow presents a slightly lower value than the actual flow temperature. The higher thermal efficiency for the higher value of mass flow (second period), indicates a lower heat losses to the environment. This goes in accordance with the earlier discussions.

To increase the thermal efficiency, the heat losses mainly in the last part of the heater should be reduced. This can be done heating also the nozzle and covering it with insulation (at this moment, the thermocouple in the nozzle is hardly usable due to the high temperatures). As last optimization, the heater tube should have a smaller diameter. This will decrease the difference between the wall and flow temperature and will decrease the wall temperature (decreasing also the heat losses) for the same outflow temperature.

### 4 Conclusions of test results and comparison

**Heat test (dry operation):**

- In both configurations (with and without insulation) the highest temperature is in the middle of the heater and the lowest at the extremes.
- Higher current levels have higher temperatures and lower stabilization time.
- With insulation the heater temperature is significantly higher than without insulation, with longer transient period.
- The heat power increases with temperature and current.
- The theoretical model:
  - Gives slightly higher stable temperatures than during test, up to + 13 %.
  - Without insulation simulates the transient phase with a considerable deviation, lower than + 25 %.

\(^{22}\) The values using the definition from Hoole [12] give almost the same efficiency (+ 1%).
With insulation has a much shorter transient phase than during test, with a deviation lower than -65%.

Generally, the model predicts relatively well the experimental values, with exception to the transient phase with insulation.

**Thruster test (wet operation, with insulation):**

- The highest temperature is at the end of the heater and the lowest is in the beginning of the heater. The difference between these two temperatures is very high.
- The wall temperature goes in conformity with the boundary condition of constant heat flux to the flow.
- The temperature related to boiling flow has high oscillations due to the change in position of the “dryout” part.
- The insulation temperature has little variation during test, around 315 K.
- The flow temperature in the nozzle has big oscillations, with small water droplets at the exhaust.
- The power input increases with temperature and current, as in dry operation.
- The pressure in the heater is highly oscillatory in transient phases with peaks that can be even higher than the tank pressure. These oscillations are followed by a high oscillation in the mass flow.
- At more stable conditions, the pressure and mass flow have still some oscillations.
- The pressure drop along the heater is highly oscillatory, and the mean value is well predicted by the correlation of boiling of flow in straight tube. The correlation of boiling flow in helically coiled tube was highly deviated from the value obtained in test. For that reason, this correlation should not be used in the future.
- Due to the high oscillatory behaviour in transient phase, only the stable conditions can be compared with theory.
- The thrust measurement is extremely noisy and filtering is then required.
- The mass flow is lower than in theory, with a discharge coefficient up to 0.87.
- The nozzle is highly inefficient, since the expected thrust using the mass flow of the test is almost twice the value found during test. The efficient throat area is then smaller much smaller than the geometric throat area.
- Comparing the temperatures and the power from the theoretical model and from the test, it is found that:
  - The expected temperatures are higher than the test, from +2% to +26%, except for heater mean temperature.
  - Depending on the correlation used for internal flow (straight or coiled) the heater mean temperature and the power input can be lower or higher depending, –7% to +4% temperature, -3% to +2% for power input.
- The measurement points in the coldest part and in the middle part are close to the expected values, being in the liquid and two-phase part.
- The measurement points in the hottest part and in the flow at the nozzle are significantly lower than expected.
- In general, the model predicts relatively well the temperatures and power levels, with exception on the nozzle point.
- The thermal efficiency of the heater is up to 86%.
Chapter 8 – Conclusion and recommendations

1 Conclusion
Fully vaporized water exhaust was obtained. However an oscillatory behaviour was always present and stable conditions were difficult to reach.
The Heat loss model for temperature prediction at stable conditions showed relatively small deviation with the experimental results.
The prediction of pressure drop was much higher than experimentally obtained. For that reason, other correlations were taken into account.
The heat loss was dramatically reduced with use of insulation, as predicted by the Heat loss model. A thermal efficiency up to 86 % was obtained.
Finally, the research was a success, since the main goal was accomplished: demonstrate the use of liquid propellant in a thruster. This research increased significantly the knowledge and experience in liquid propellants and boiling flow, for TU-Delft.

2 Recommendations
Several recommendations for further developments are as follows:
- The new design of the heat chamber should be used to increase the efficiency of the heater.
- A more efficient nozzle with blunt angles in the convergent part should be used to avoid flow separation and condensation in the nozzle.
- The technique to install the nozzle thermocouple should be review.
- A mass flow meter compatible with liquids shall be used and connected to the data acquisition system to increase accuracy at stable and oscillatory conditions.
- A smaller tube connecting the mass flow meter to the DARTS should be used, to avoid load drifts.
- Instead of using thick power cables, multi thinner cables should be used to avoid load drifts and to decrease the heat losses in the cables.
- The theoretical model can be improved taking into account the axial direction, the time dependence of the temperature along the insulation, and heat losses in the nozzle.
- The program of Heat loss model should be friendly user.
- A finite element program as ANSYS® should be used instead of a program made from scratch. This can give more reliable and accurate values, being also less time consuming.
- The boiling flow pressure drop in a helically coiled tube should be further investigated.

For a final flight model the recommendations are:
- The full new design for flight should be taken into account, with space qualified materials. A new nozzle with a high area ratio should be used.
- The Lee® valve or equivalent should be used as a control valve.
- A new tank should be manufactured for this purpose.
- For higher efficiency, other liquid propellants should be used.
References

[15] Michiel F. van Bolhuis, *Design, development and construction of a rocket engine test facility for thrust levels up to 1 N*, TUDelft, June 2004
[23] B.T.C. Zandbergen, *50 mN motor nozzle design*, TUDelft

[48] Clayton H. Bader, Potential Propulsion Storage and Feed system for Space Station Resistojet Propulsion Options, NASA, January 1987


[52] Stewart Bennett, K. F. Connors, Ken E. Clark, Development of a 3-Kilowatt Resistojet, AVCO Corporation, AIAA 64-672, 1964

[53] Satish G. Kandlikar, Two-phase patterns, pressure drop and heat transfer during boiling in minichannels and microchannels flow passages of compact evaporators, Mechanical Engineering Department, Rochester Institute of Technology


[57] Paisarn Naphon, Somchai Wongwises, A review of flow and heat transfer characteristics in curved tubes, FUTURE, King Mongkut’s University of Technology Thonburi, Bangmod, 2004

[58] C. E. Kalb, J. D. Seader, Heat and Mass Transfer Phenomena for viscous flow in curved circular tubes, University of Utah, 1971

[59] Liang Zhao, Liejin Guo, Bofen Bai, Yucheng Hou, Ximin Zhang, Convective boiling heat transfer and two-phase flow characteristics inside a small horizontal helically coiled tubing once-through steam generator, Xi’an Jiaotong University, 2003


[61] Yasuo Mori, Wataru Nakayama, Study on Forced Convective Heat Transfer in curved pipes (3rd report, Theoretical analysis under the condition of uniform wall temperature and practical formulae), Int. J. Heat Mass Transfer, 1967


[64] Weizhong Zhang, Takashi Hibiki, Kaichiro Mishima, Correlation for flow boiling heat transfer at low liquid Reynolds number in small diameter channels, ASME, 2005

[65] J.R. Cooper, Dr. R.B. Dooley, IAPWS Release on Surface Tension of Ordinary Water Substance, International Association for the properties of Water and Steam, September 1994
[69] Dichtomatik o-ring handbook, Section two - O-ring Gland Design Guidelines, Dichtomatik
[70] Precisie O-ringen - afdichtingen, ERIKS
[88] Resistojet Research at the University of Surrey, http://www.ee.surrey.ac.uk/SSC/CSER/UOSAT/research/resisto.htm
[95] Resistojet, http://www.lr.tudelft.nl/live/pagina.jsp?id=353bb7e5-d814-4a1f-9565-6ee7e9481b06&lang=en
[96] www.stoneman.co.uk
[97] www.scielo.cl
[99] www.meyerinst.com
[106] NASA-GLENN chemical equilibrium program CEA2
[109] http://www.me.utexas.edu/~howell/sectionc/C-68.html
Annexes of Chapter 2

Possible propellants for low-thrust thermal propulsion system

1 Introduction
The purpose of this document is to select the “best” propellant for use in TU-Delft’s future solar-thermal propulsion system capable of propelling a small Cubesat\(^{23}\) [21] and thereby demonstrating the feasibility of solar-thermal propulsion in space. In the past such studies have been performed at TU-Delft for a number of gaseous propellants including hydrogen, helium, methane, nitrogen, and carbon dioxide [13, 15, 16]. Present interest though is in liquid propellants as to reduce the storage volume on board of the Cubesat. Furthermore, next to the above mentioned propellants a great many other propellants are used, each propellant having its own advantages and disadvantages [28, 31].

2 Analysis
This section explains how to analyse a propellant. Most of the properties as molar mass, enthalpy change and density are taken from [75], however when it is not available some other references should be used and indicated. For safety requirement using NFPA 704, most information can be found in [81 or 83].

Description of NFPA categories
Health category is defined by the severity of injuries in function of exposure time. Since rate 3 and 4 are related to at least serious temporary or residual injury they will be considered as not safe. It will be considered as safe rates 0 and 1 where not more than minor residual injury can happen in case of exposure. For rate 4 some precautions should be taken.
Flammability category is defined by the flash point. This parameter is not related to the temperature of ignition source, which is much higher. For that reason this category will be considered safe with rates 0 and 1 (heated before occurring ignition), and not safe with a rate of 4 (burn very easily). For 2 and 3 some precautions should be taken.
Reactivity category is defined by the stability of the substance at a certain temperature and pressure and the reaction in contact with water. The last aspect is not relevant for the purpose of this document. Since we want a propellant that can stand high pressure (~5 bar) and high temperatures (~1000 K) without any change on the stability only the minimum rate, 0, will be suitable. Even if reactivity category is in safety requirement, in the case of a propulsion system it means that a certain propellant is suitable or not.
Last category is the special characteristic that a substance can have. When a substance has a special characteristic, it will be unsuitable.

23 A Cubesat typically has a mass of 1 kg and measures 0.1m x 0.1m x 0.1m. A Cubesat belongs to Microspacecraft Class II
## 3 Comparison

In this section, it is traded the various propellants. It is used two major requirements: density and safety. Considering these requirements, some propellants are not suitable. However it does not mean that this propellant cannot be used in the future. If a slightly less strict criterion is used some propellant can appear in the end as suitable, e.g. butane.

<table>
<thead>
<tr>
<th>Propellant option</th>
<th>Molar mass [kg/kmol]</th>
<th>Enthalpy change [75] from 293 to 1000 K (at 2 bar) [kJ/kg]</th>
<th>Criterion</th>
<th>Safety: health, flammability, reactivity, special</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, H$_2$O</td>
<td>18.02</td>
<td>3886</td>
<td>998.4, liq. [75]</td>
<td>0, 0, 0, no [81]</td>
<td>GO</td>
</tr>
<tr>
<td>Carbon Dioxide, CO$_2$</td>
<td>44.01</td>
<td>765</td>
<td>9.28, gas [75]</td>
<td>1, 0, 0, no [84]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Hydrogen, H$_2$</td>
<td>2.02</td>
<td>10238 (298 to 1000K at 1bar)</td>
<td>0.41, gas [75]</td>
<td>0, 4, 0, no [84]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Nitrogen, N$_2$</td>
<td>28.01</td>
<td>772</td>
<td>5.75, gas [75]</td>
<td>0, 0, 0, no [81]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Helium, He</td>
<td>4.00</td>
<td>3671</td>
<td>0.82, gas [75]</td>
<td>0, 0, 0, no [81]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Xenon, Xe</td>
<td>131.29</td>
<td>73 (293 to 750K)</td>
<td>27.71, gas [75]</td>
<td>0, 0, 0, no [82]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Ammonia, NH$_3$</td>
<td>17.03</td>
<td>1022 (293 to 700K)</td>
<td>3.71, gas [75]</td>
<td>3, 1, 0, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Hydrazine, N$_2$H$_4$</td>
<td>32.05</td>
<td>1713 (298 to 1000K at 1bar, gas phase)</td>
<td>1004$^{24}$, liq. [1]</td>
<td>3, 3, 2, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Nitrous oxide, N$_2$O</td>
<td>44.013</td>
<td>775 (298 to 1000K at 1bar)</td>
<td>9.03$^{25}$, gas [77]</td>
<td>0,0,0, no [81]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Chloromethane, CH$_3$Cl</td>
<td>50.49</td>
<td>869 (298 to 1000K at 1bar, gas phase)</td>
<td>1003$^{24}$, liq. [77]</td>
<td>2, 4, 0, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Chloroethane, C$_2$H$_2$Cl</td>
<td>64.51</td>
<td>TBD$^{26}$</td>
<td>921$^{24}$, liq. [79]</td>
<td>2, 4, 0, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Hydrogen fluoride, HF</td>
<td>20.01</td>
<td>1031 (298 to 1000K at 1bar, gas phase)</td>
<td>959$^{24}$, liq. [77]</td>
<td>3, 0, 2, no [83]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Freon 12, CCl$_2$F$_2$</td>
<td>120.91</td>
<td>161 (293 to 525K)</td>
<td>27.83, gas [75]</td>
<td>1, 0, 0, no [84]</td>
<td>NO GO</td>
</tr>
<tr>
<td>Ethyl methyl ether, C$_2$H$_5$OCH$_3$</td>
<td>60.10</td>
<td>TBD</td>
<td>720$^{24}$, liq[77]</td>
<td>2, 4, 1, no [85]</td>
<td>NO GO</td>
</tr>
</tbody>
</table>

$^{24}$ Considering an incompressible liquid  
$^{25}$ Using ideal gas law  
$^{26}$ To Be Determined
Table 64 – Trade-off summary table

Table 64, the density and safety remove most of the propellants as a possible option for solar-thermal propulsion.

After the trade-off table there are 3 possible options for propellants: water, methanol and ethanol. In contrary to water, both alcohols have an inherent danger that should be taken into account during testing, handling, loading, unloading, storage, etc. Additionally, water has a lower molar mass and slightly higher density than the others propellants, therefore using water as propellant shows to be the ideal choice. However the energy needed to heat from 293K to a higher temperature is much higher for water (see annexes). One inherent problem with water is the energy required to vaporize it, high value of enthalpy of vaporization.

**Liquid propellant heating**

This section describes how to determine the energy needed to heat a liquid propellant from laboratory temperature to a high temperature. Only three propellants were taken: water, methanol and ethanol; since they were the only ones to obtain GO as final result. In the end, some comparisons are made between them. Unfortunately not all data is available for the required conditions, 2 bar from 293 K to 1000 K. For that reason, other pressure and temperatures are taken. These propellants have a small difference between enthalpy changes from 2 bar to 1 bar (from negligible difference at low temperature until around +10% at higher temperatures) and then we take the last pressure, since more data is available. In the case of specific heat at constant pressure, $C_p$, the difference of values for these 2 different pressures can be negligible or around 5% for boiling temperature. For the temperature the data available goes until 620 K, for methanol. Since we want to do a comparison between these three propellants, they will have a temperature range from 293 K to 600 K.

To determine the energy needed, method taken from [1], we should know the heat needed to change from liquid to vapour at constant pressure and temperature, heat of vaporization $\Delta H_{vap}$, as well as the energy needed to raise the temperature at constant pressure, specific heat at constant pressure $C_p$. 
Starting with the heat of vaporization $\Delta H_{vap}$ of the three substances at 1 bar, the values are:

Heat of vaporization for water [75]: $\Delta H_{vap} = 2257kJ / kg$

Heat of vaporization for methanol [75]: $\Delta H_{vap} = 1102kJ / kg$

Heat of vaporization for ethanol [1]: $\Delta H_{vap} = 854kJ / kg$

As we can see the heat of vaporization for the water is much larger than for methanol and even more than for ethanol. This is even more important when we know that the heat of vaporization takes at least half of the total energy required.

For the specific heat at constant pressure $c_p$ at 1 bar, the results are [75]:

Water in liquid phase: $c_p \approx 4.19 \text{ kJ/kg.k}$ (from 293 K to boiling point, 372.76 K)

Water in vapour phase: $c_p = 2.0784 - 1.9746 \text{ kJ/kg.k}$ (from boiling point, 372.76 K, to 460.3 K); $c_p = 1.9746 - 2.0268 \text{ kJ/kg.k}$ (from 460.3 K to 600 K)

Methanol in liquid phase: $c_p = 2.5037 - 2.8229 \text{ kJ/kg.k}$ (from 293 K to boiling point, 337.3 K)

Methanol in vapour phase: $c_p = 4.4277 - 1.6868 \text{ kJ/kg.k}$ (from boiling point, 337.3 K to 389.7 K); $c_p = 1.6868 - 2.1048 \text{ kJ/kg.k}$ (from 389.7 K to 600 K)

Ethanol in liquid phase: $c_p \approx 2.44 \text{ kJ/kg.k}$ (laboratory temperature)

Ethanol in vapour phase: $c_p = 1.5970 - 3.9120 \text{ kJ/kg.k}$ (from boiling point, 351.5 K to 600 K)

As we can see, water has a higher specific heat at constant pressure in liquid phase, but in vapour phase they are close to each other. For a better evaluation between the three substances, we will compare the energy needed to heat them.

The following first formula will be used for water and methanol. The second formula will be used for ethanol, since there is less information available.

\[
\Delta H = \Delta H_{vap} + \Delta H_{liq}(293K \to T_{boil}) + \Delta H_{vap}(T_{boil} \to 600K)
\]

\[
\Delta H \approx \Delta H_{vap} + \frac{C_{p,liq}(T_{boil} - 293)}{M} + \frac{C_{p,vap}(600 - T_{boil})}{M}
\]

For water the enthalpies at different temperatures at 1 bar are [75]:

\[
\begin{align*}
H_{liq}(293K) &= 83.378kJ / kg \\
H_{liq}(T_{boil} = 372.76K) &= 417.5kJ / kg \\
H_{vap}(T_{boil} = 372.76K) &= 2674.9kJ / kg \\
H_{vap}(600K) &= 3128.8kJ / kg
\end{align*}
\]

The energy needed to heat water from 293 K to 600 K is:

\[
\Delta H = 2257 + (417.5 - 83.378) + (3128.8 - 2674.9) = 3045.0kJ / kg
\]

For methanol the enthalpies at different temperatures at 1 bar are [75]:

\[
\begin{align*}
H_{liq}(293K) &= -118.48kJ / kg \\
H_{liq}(T_{boil} = 337.3K) &= -0.945kJ / kg \\
H_{vap}(T_{boil} = 337.3K) &= 1100.8kJ / kg \\
H_{vap}(600K) &= 1605.8kJ / kg
\end{align*}
\]

The energy needed to heat methanol from 293 K to 600 K is:

\[
\Delta H = 1102 + (-0.945 + 118.1) + (1605.8 - 1100.8) = 1724.2kJ / kg
\]
For ethanol the specific heats at constant pressure at 1 bar are [75]:
\[
\begin{align*}
C_{p,\text{liq}}(351.5K) &= 112.4J/mol.K \\
C_{p,\text{g}}(351.5K) &= 73.6J/mol.K \\
C_{p,\text{v}}(600K) &= 104.88J/mol.K \\
C_{p,\text{v}}(351.5K \to 600K) &= 89.2J/mol.K
\end{align*}
\]

The energy needed to heat ethanol from 293 K to 600 K is:
\[
\Delta H = 854 + \frac{112.4 \times (351.5 - 293)}{46.07} + \frac{89.2 \times (600 - 351.5)}{46.07} = 1477.9kJ/kg
\]

The following table summarizes the values for heat of vaporization and energy needed to heat from 293 K to 600 K of water, methanol and ethanol.

<table>
<thead>
<tr>
<th></th>
<th>heat of vaporization $\Delta H_{\text{vap}}$ [kJ/kg]</th>
<th>Total heat from 293 K to 600 K [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2257</td>
<td>3045</td>
</tr>
<tr>
<td>Methanol</td>
<td>1102</td>
<td>1724</td>
</tr>
<tr>
<td>Ethanol</td>
<td>854</td>
<td>1478</td>
</tr>
</tbody>
</table>

Table 65 – Heat of vaporization and energy to heat for water, methanol and ethanol

As we can see water needs almost 80% and 110% more of energy than methanol and ethanol respectively. This shows that at identical power input, the mass flow of water that can be heated to a certain temperature is less than for Methanol and Ethanol. If the final temperature is lower than the required heat is also lower and vice versa. However the enthalpy of vaporization has a large contribution for the increase of the required heat needed, as we can see in the following figure.
Annexes of Chapter 3

For a required pressure ratio

In this case that it is required a certain pressure ratio \( \frac{P_e}{p_c} \) with a certain throat area for thrust optimization. Using directly equation (3.6) the exit area can be computed. This nozzle should be only for vacuum conditions, since at ambient conditions the effect of separations would be significant, since the exhaust pressure \( p_e \) is much lower than the ambient pressure.

Annexes of Chapter 4

Analysis of critical mass flow

Figure 117 shows the evolution of critical mass flow, in a certain range of chamber pressure and temperature.

![Critical mass flow with H2O mass flow](image)

Figure 117 – Critical mass flow depending on output temperature and chamber pressure
Dynamical regime

As we can see, the Weber number for DUR H2O/2.0 is always higher than for DUR1.0/1.1.

**Annexes of Chapter 5**

**Heat losses**

For short cylinder:

\[ A_{\text{cyl}} = \frac{\pi D_{\text{cyl}}^2}{2} \left( 1 + \frac{2L_{\text{cyl}}}{D_{\text{cyl}}} \right) \text{[m}^2\text{]} \]  \hspace{1cm} (4.13)

For long cylinder:

\[ A_{\text{cyl}} = \pi D_{\text{cyl}} L_{\text{cyl}} \text{[m}^2\text{]}, \quad L_{\text{cyl}} \text{is the length of the cylinder} \]  \hspace{1cm} (4.14)

For long cylinder with insulation:

\[ A_{\text{insul}} = \pi D_{\text{insul}} L_{\text{insul}} \text{[m}^2\text{]}, \quad L_{\text{insul}} \text{is the length of the cylinder} \]  \hspace{1cm} (4.15)
Churchill and Chu correlation\(^{27}\):

\[
Nu_D = 0.6 + \left( \frac{0.387 Ra^{1/6}}{1 + \left( \frac{0.559 \, \Pr^{9/16}}{8/27} \right)^{9/16}} \right)^2
\]

for \(10^{-5} < Ra < 10^{12}\)  

(4.16) \[3\]

Morgan correlation:

\[Nu_D = 0.47 Ra^{0.25} [-], \text{ for } 10^4 < Ra < 10^9\]  

\[Nu_D = 0.1 Ra^{1/3} [-], \text{ for } Ra > 10^9\]  

[3, 18, 16] (4.17)

Table 66 – Nusselt number correlations for natural convection in a long isothermal cylinder

Comparing Correlations

Dry operation

Without insulation

Using DUR1.0 without insulation, the correlations used are:

- **Long cylinder [Coelho], (4.16), [3];**
- **Long cylinder [Tijsterman], (4.17), [18];**
- **Short cylinder [Rohsenow], (5.7), [4];**
- **Coil [Rob], (5.8), [18];**
- **Minimum natural convection coefficient, \(h = 5 \text{ W/(m}^2\text{K)};**
- **Maximum natural convection coefficient, \(h = 25 \text{ W/(m}^2\text{K).****

In case of cylinders, it is assumed that the DUR1.0 will have approximately the same behaviour than a cylinder. In this case, the surface area for convection is considered to be the cylinder with the external dimensions of the coil.

\(^{27}\) More correlations from Churchill and Chu are available for smaller range and then more precise [4]
Figure 119 – Convection coefficient for different correlations in case of DUR1.0, without insulation, dry operation

In this figure, excepting the constant values for minimum and maximum convection, the convection coefficient increases with time until it stabilizes, around minute 3. At minute 8, it decreases since the current is at 0A. The Coil [Tijsterman] correlation has the closest result from the Maximum natural convection. Other correlations are closer to Minimum natural convection, being close to each other.
Figure 120 – Surface temperature for different correlations in case of DUR1.0, without insulation, dry operation

Here, the curves have the same behaviour than in Figure 120, with the difference that it takes between 4 to 5 minutes to stabilize. The cylinder correlations present a surface temperature close to the Minimum natural convection. The Coil [Tijsterman] correlation has a more conservative result, closer to the Maximum natural convection.

Figure 121 – Power input for different correlations in case of DUR1.0, without insulation, dry operation
Since the power input is dependent on the heater resistance that depends on the temperature. Then a higher surface temperature brings to a higher power input.

**With insulation**
Using DUR1.0 with insulation, the correlations used are:
- Long cylinder [Coelho], (4.16), [3];
- Long cylinder [Tijsterman], (4.17), [18];
- Short cylinder [Rohsenow], (5.7), [4];
- Minimum natural convection coefficient, \( h = 5 \);
- Maximum natural convection coefficient, \( h = 25 \).

![Convection coefficient for different correlations in case of DUR1.0, with insulation, dry operation](image)

**Figure 122 – Convection coefficient for different correlations in case of DUR1.0, with insulation, dry operation**

In this figure, excepting the constant values for minimum and maximum convection, the convection coefficient increases with time until it stabilizes after 8 minutes. At minute 20, it decreases since the current is at 0A. All correlations are closer to Minimum natural convection than Maximum natural convection. Furthermore, they are very close to each other.
These curves present the same behaviour than in Figure 120, but with much higher values. The difference between minimum and maximum natural convection is, in this case, almost negligible. This concludes that with insulation, the surrounding environment has little influence in the heater temperature. This effect is even more evident when comparing the correlations, and for that reason it is needed a closer view. Here the most conservative relation is the Short cylinder [Rohsenow].

Figure 123 – Heater temperature for different correlations in case of DUR1.0, with insulation, dry operation

Figure 124 – Close view of heater temperature for different correlations in case of DUR1.0, with insulation, dry operation
With a closer view, it is evident the negligible difference of the result using different correlations for cylinders. As in section 1.5.1, the *Short cylinder* [Rohsenow] correlation presents slightly more conservative values.

![Surface temperature of the insulation, for 10 A, with insulation](image)

**Figure 125 – Surface insulation temperature for different correlations in case of DUR1.0, with insulation, dry operation**

In the case of temperature at the insulation surface, the convection plays a more important role. Here again, the correlations have very little differences between them, but still they are close to the *Minimum natural convection* case.

![Power input in the heat chamber, for 10 A, with insulation](image)

**Figure 126 – Power input for different correlations in case of DUR1.0, with insulation, dry operation**
For all the correlations and convection coefficient assumptions, the value of power input has almost the same value. Since the heater temperature is similar in all cases.

**Combined operation**

**Without insulation**
The correlations used for the forced convection in the inner flow for coiled tube. It is possible to use for straight tube. In that case, the correlations used are Dittus-Boelter and Dittus-Boelter with Pethukov high temperature correction.

![Convection coefficient graph](image)

**Figure 127 – Convection coefficient for different correlations in case of DUR1.0, without insulation, combined operation**

The natural convection is influenced by the mass flow and power input. All correlations are between the expected minimum and maximum convection coefficient.
The surface mean temperature increases during the pre-heating. When the flow is inserted, the temperature drops significantly. When the current is increased, the temperature increases until it stabilizes. Here, the influence of convection plays an important on the temperature.
The final wall and flow temperature start close to the final wall temperature followed by a decrease until stabilizing. When input power is added, the temperatures increase until reaching stable temperatures. The difference between correlations is enormous, meaning that the outer convection plays a fundamental role in the final wall and flow temperature.
During the pre-heating part, the power input and loss increase with temperature, reaching values. With mass flow the power input and loss decrease and increase again with higher level of power input.

**With insulation**
The correlations used for the forced convection in the inner flow are for coiled tube.
Figure 133 – Heater mean temperature for different correlations in case of DUR1.0, with insulation, combined operation

Figure 134 – Final heater temperature for different correlations in case of DUR1.0, combined operation

During pre-heating the heater mean and final temperatures increase until reaching almost stable values. When the mass flow is inserted, at minute 20, the temperature drops suddenly until reaching a new stable temperature. At minute 25, the power is increased and the mean heater and final wall temperature increase significantly, until reaching a new equilibrium.
When the flow is inserted, the final flow temperature is around the heater temperature, decreasing both suddenly. The step just after minute 20 has no true meaning, coming from the non convergence of the equilibrium equation. At minute 25, more current is inserted with the final flow temperature increasing. The difference between correlations is minimal.

The surface temperature of the insulation increases in the pre-heating phase, until it almost stabilizes. The correlations for natural convection coefficient have an important role on this temperature. When the flow is inserted, the temperature decreases until a new equilibrium point. With higher power input, the temperature slightly increases. Here the difference between correlations for natural convection coefficient has lower difference than during dry-operation.
Power input has 3 stable parts, dry-operation, and two with mass flow. The transient part is directly related to the heater temperature change.

The power loss increases with temperature, at dry operation, equalizing the power input. When the flow is inserted, the losses to the surrounding environment are almost negligible, even when the current is increased, minute 25.
Figure 139 – Convection coefficient for different correlations in case of DUR1.0, with insulation, combined operation

Figure 140 – Close view of heater mean temperature for different correlations in case of DUR1.0, dry operation

Here, it is clear than the correlations for short cylinder from Rohsenow is the most conservative one.
Annexes of Chapter 6

Water properties

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>ρ [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>998.80</td>
</tr>
<tr>
<td>295</td>
<td>997.91</td>
</tr>
<tr>
<td>300</td>
<td>996.56</td>
</tr>
</tbody>
</table>

Table 67 – Water density with temperature [75]

Control valve parameters

![Flow coefficient graph]

Figure 141 – Flow coefficient depending on the open turns of the control valve
1. Preparation tests description

1.1 Every time preparation test

Thrust test

![Thrust test graph](image1)

During morning (from 7h to 11h) the ambient temperature increases significantly. From 11h05m until 17h05m, the temperature increases only from 294.8 K to 295.4 K. This difference is more significant in sunny days.

**Test DUR H2O #1**

1. Introduction

Some experiments are needed to understand how DUR 1.0 and DUR 1.1 can work with boiling flow. Previous small tests were performed to check the water tank and valves with liquid water, but also to see the behaviour of DUR 1.0 in these conditions. Some problems mainly related to leakage and air bubbles could be solved. However heating was never applied and lot of issues were still open.

The present experiment was performed with DUR 1.0, electrically heated and with water flow. The main objective of this test was to understand some open issues, as the behaviour with boiling flow, the temperature distribution and the electric power required. No pressure measurements were done and during the test the mass flow was unknown. No inaccuracy analysis was done for this test.
The structure of this test is as follows. In section 3 the setup is described including the tank, feeding system and heating chamber. In section 4 the procedure employed during testing is described, followed in section 5 by the test results, where they are discussed in section 6. The report is concluded in section 8.

2. Background
The background can be found in Chapter 7 on the data elaboration. In this test, the thermal efficiency is assumed to be between 0.5 and 0.9. Then the thermal power is estimated.

3. Setup
For this heater test the setup used is the same than described in Chapter 6 with the following difference:
- Thermal insulator: Glass wool with a thickness of 80 mm around the heater and 40 mm on the caps; normal aluminium foil around the glass wool;
- Axisymmetrical nozzle without pressure neither temperature measurement point;

The test was performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology.

![Test setup](image)

**Figure 143 – Test setup**

Legend:

<table>
<thead>
<tr>
<th>1 – Air pump</th>
<th>7 – Pressure measurement point, after metering valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – Fill Valve</td>
<td>8 – Electrical and heat insulator</td>
</tr>
<tr>
<td>3 – Water tank</td>
<td>9 – Heating chamber with insulation</td>
</tr>
<tr>
<td>4 – Shutoff valve</td>
<td>10 – Thermocouple just after metering valve, T-valve</td>
</tr>
</tbody>
</table>
Table 68 – Test setup legend

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – Metering valve</td>
<td>11 – Power lines to the power supply</td>
</tr>
<tr>
<td>6 – Pressure measurement point, before metering valve</td>
<td>12 – Thermometers</td>
</tr>
</tbody>
</table>

Legend:
- A: ammeter
- P-n: pressure near the nozzle
- P-p: pressure of the air pump
- T-n: temperature near the nozzle
- T-v: temperature near the metering valve
- V: voltmeter

Figure 144 – Schematic of the test setup

P-1, P-2, P-n and T-n are not used for this test.

Figure 145 – Heating chamber, DUR 1.0, with thermocouples and nozzle
In Figure 145, we can see the heating chamber, DUR 1.0, with 3 thermocouples type K. The first Thermocouple, T-1, is in the first loop, the second thermocouple, T-2, is more or less in the middle and the third thermocouple, T-3, is in the last loop.

In Figure 146, we can see the insulation around the heating chamber, consisting in glass wool and aluminium foil.

4. Procedure
As said before, the test was performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology. With the system already in place, the thermocouples are connected to the thermometers. The power cables are connected to the power supply still switched off. After confirming that the knobs are at zero (fully at counter-clockwise), switch on the power supply. Increase slightly the voltage, and start to increase the current to a desired value. Open the metering valve to the sixth turn, wait 3-5 min and then fully open the shutoff valve.

After experiment, turn the knobs to the zero position and switch off the power supply. After waiting around 5 min, turn the metering valve to fully open and close the shutoff valve, for a faster cooling to ambient temperature. At this point the experiment is concluded.

5. Results
Only after one minute, when the temperature was around 500 K, the insulation started to brun. It was visible some smoke with a strong smell. For that reason after some minutes, the window was opened. At this point, it was clearly visible that the thermocouple T-1 was not working properly. To avoid further melting of the insulation the metering valve was opened, 6 turns, and then the smoke gradually stopped. For that reason the window was closed, furthermore the temperature in the preparation room was decreasing significantly. With the metering valve open, a vapour exhaust started to appear. Some small leakage appeared in the second pressure tube, P-2, however the experiment proceeded since the problem was minor.
Before opening the shutoff valve, the current was increased to 10 A. When the temperature of the heater was again around 700 K, the shutoff valve was fully opened. It was clearly visible the switching in temperature between T-2 and T-3, with T-3 being now the highest temperature. Even if the exhaust was vapour, it appeared once or twice per minute an exhaust peak, during no more than 3 seconds. The increase of vapour exhaust was not only visible but also audible.

After some time, the power supply was switched off however the valves stayed at the same position. The vapour exhaust continued for about one minute and gradually came to stop. However to speed up to room temperature and to close the system, the metering valve was fully opened and the shutoff valve closed. The temperature decreased to ambient temperature the exhaust was now liquid water. The metering valve was turn to close position. At this point, the test was considered as concluded. During the test, no pressure measurements were done, except the tank pressure that stayed almost constant at 4 bars gauge, corresponding to 5 bars absolute. During the test, the tank pressure decreased not more than 0.1 bars and was for two times increased again to 4 bars gauge.

The following table shows the data obtained during the test, taken once per minute. The data obtained directly from the thermometers and power supply, was the temperature of the thermocouples and the current and voltage. Some remarks were written down with the corresponding time.
Annexes of Chapter 2

Possible propellants for low-thrust thermal propulsion system

1 Introduction
The purpose of this document is to select the “best” propellant for use in TU-Delft’s future solar-thermal propulsion system capable of propelling a small Cubesat23 [21] and thereby demonstrating the feasibility of solar-thermal propulsion in space. In the past such studies have been performed at TU-Delft for a number of gaseous propellants including hydrogen, helium, methane, nitrogen, and carbon dioxide [13, 15, 16]. Present interest though is in liquid propellants as to reduce the storage volume on board of the Cubesat. Furthermore, next to the above mentioned propellants a great many other propellants are used, each propellant having its own advantages and disadvantages [28, 31].

2 Analysis
This section explains how to analyse a propellant. Most of the properties as molar mass, enthalpy change and density are taken from [75], however when it is not available some other references should be used and indicated. For safety requirement using NFPA 704, most information can be found in [81 or 83].

Description of NFPA categories
Health category is defined by the severity of injuries in function of exposure time. Since rate 3 and 4 are related to at least serious temporary or residual injury they will be considered as not safe. It will be considered as safe rates 0 and 1 where not more than minor residual injury can happen in case of exposure. For rate 4 some precautions should be taken.

Flammability category is defined by the flash point. This parameter is not related to the temperature of ignition source, which is much higher. For that reason this category will be considered safe with rates 0 and 1 (heated before occurring ignition), and not safe with a rate of 4 (burn very easily). For 2 and 3 some precautions should be taken.

Reactivity category is defined by the stability of the substance at a certain temperature and pressure and the reaction in contact with water. The last aspect is not relevant for the purpose of this document. Since we want a propellant that can stand high pressure (~5 bar) and high temperatures (~1000 K) without any change on the stability only the minimum rate, 0, will be suitable. Even if reactivity category is in safety requirement, in the case of a propulsion system it means that a certain propellant is suitable or not.

Last category is the special characteristic that a substance can have. When a substance has a special characteristic, it will be unsuitable.

---

23 A Cubesat typically has a mass of 1 kg and measures 0.1m x 0.1m x 0.1m. A Cubesat belongs to Microspacecraft Class II
3 Comparison

In this section, it is traded the various propellants. It is used two major requirements: density and safety. Considering these requirements, some propellants are not suitable. However it does not mean that this propellant cannot be used in the future. If a slightly less strict criterion is used some propellant can appear in the end as suitable, e.g. butane.

<table>
<thead>
<tr>
<th>Propellant option</th>
<th>Molar mass [kg/kmol]</th>
<th>Enthalpy change [kJ/kg] from 293 to 1000 K (at 2 bar)</th>
<th>Criterion</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, H$_2$O</td>
<td>18.02</td>
<td>3886</td>
<td>998.4, liq [75]</td>
<td>0, 0, 0, no [81]</td>
</tr>
<tr>
<td>Carbon Dioxide, CO$_2$</td>
<td>44.01</td>
<td>765</td>
<td>9.28, gas [75]</td>
<td>1, 0, 0, no [84]</td>
</tr>
<tr>
<td>Hydrogen, H$_2$</td>
<td>2.02</td>
<td>10238 (298 to 1000K at 1bar)</td>
<td>0.41, gas [75]</td>
<td>0, 4, 0, no [84]</td>
</tr>
<tr>
<td>Nitrogen, N$_2$</td>
<td>28.01</td>
<td>772</td>
<td>5.75, gas [75]</td>
<td>0, 0, 0, no [81]</td>
</tr>
<tr>
<td>Helium, He</td>
<td>4.00</td>
<td>3671</td>
<td>0.82, gas [75]</td>
<td>0, 0, 0, no [81]</td>
</tr>
<tr>
<td>Xenon, Xe</td>
<td>131.29</td>
<td>73 (293 to 750K)</td>
<td>27.71, gas [75]</td>
<td>0, 0, 0, no [82]</td>
</tr>
<tr>
<td>Ammonia, NH$_3$</td>
<td>17.03</td>
<td>1022 (293 to 700K)</td>
<td>3.71, gas [75]</td>
<td>3, 1, 0, no [83]</td>
</tr>
<tr>
<td>Hydrazine, N$_2$H$_4$</td>
<td>32.05</td>
<td>1713 (298 to 1000K at 1bar, gas phase)</td>
<td>1004$^{24}$, liq [1]</td>
<td>3, 3, 2, no [83]</td>
</tr>
<tr>
<td>Nitrous oxide, N$_2$O</td>
<td>44.013</td>
<td>775 (298 to 1000K at 1bar)</td>
<td>9.03$^{25}$, gas [77]</td>
<td>0,0,0, no [81]</td>
</tr>
<tr>
<td>Chloromethane, CH$_3$Cl</td>
<td>50.49</td>
<td>869 (298 to 1000K at 1bar, gas phase)</td>
<td>1003$^{24}$, liq [77]</td>
<td>2, 4, 0, no [83]</td>
</tr>
<tr>
<td>Chloroethene, C$_2$H$_5$Cl</td>
<td>64.51</td>
<td>TBD$^{26}$</td>
<td>921$^{24}$, liq [79]</td>
<td>2, 4, 0, no [83]</td>
</tr>
<tr>
<td>Hydrogen fluoride, HF</td>
<td>20.01</td>
<td>1031 (298 to 1000K at 1bar, gas phase)</td>
<td>959$^{24}$, liq [77]</td>
<td>3, 0, 2, no [83]</td>
</tr>
<tr>
<td>Freon 12, CCl$_2$F$_2$</td>
<td>120.91</td>
<td>161 (293 to 525K)</td>
<td>27.83, gas [75]</td>
<td>1, 0, 0, no [84]</td>
</tr>
<tr>
<td>Ethyl methyl ether, C$_2$H$_5$OCH$_3$</td>
<td>60.10</td>
<td>TBD$^{26}$</td>
<td>720$^{24}$, liq [77]</td>
<td>2, 4, 1, no [85]</td>
</tr>
</tbody>
</table>

$^{24}$ Considering an incompressible liquid
$^{25}$ Using ideal gas law
$^{26}$ To Be Determined
Table 64 – Trade-off summary table

Table 64, the density and safety remove most of the propellants as a possible option for solar-thermal propulsion.
After the trade-off table there are 3 possible options for propellants: water, methanol and ethanol. In contrary to water, both alcohols have an inherent danger that should be taken into account during testing, handling, loading, unloading, storage, etc. Additionally, water has a lower molar mass and slightly higher density than the others propellants, therefore using water as propellant shows to be the ideal choice. However the energy needed to heat from 293K to a higher temperature is much higher for water (see annexes). One inherent problem with water is the energy required to vaporize it, high value of enthalpy of vaporization.

**Liquid propellant heating**

This section describes how to determine the energy needed to heat a liquid propellant from laboratory temperature to a high temperature. Only three propellants were taken: water, methanol and ethanol; since they were the only ones to obtain GO as final result. In the end, some comparisons are made between them. Unfortunately not all data is available for the required conditions, 2 bar from 293 K to 1000 K. For that reason, other pressure and temperatures are taken. These propellants have a small difference between enthalpy changes from 2 bar to 1 bar (from negligible difference at low temperature until around +10% at higher temperatures) and then we take the last pressure, since more data is available. In the case of specific heat at constant pressure, C_p, the difference of values for these 2 different pressures can be negligible or around 5% for boiling temperature. For the temperature the data available goes until 620 K, for methanol. Since we want to do a comparison between these three propellants, they will have a temperature range from 293 K to 600 K.

To determine the energy needed, method taken from [1], we should know the heat needed to change from liquid to vapour at constant pressure and temperature, heat of vaporization $\Delta H_{vap}$, as well as the energy needed to raise the temperature at constant pressure, specific heat at constant pressure $C_p$. 

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Molecular Mass (M)</th>
<th>Minimum Temperature (T, K)</th>
<th>Maximum Temperature (T, K)</th>
<th>Density (ρ, kg/m³)</th>
<th>Safety (1, 2, 3, 4, no)</th>
<th>Final Result</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methylamine, CH₃NH₂</td>
<td>31.06</td>
<td>TBD</td>
<td>694⁴⁷⁴, liq. [77]</td>
<td>3, 4, 0, no [83]</td>
<td>NO GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane, CH₄</td>
<td>16.04</td>
<td>2380 (298 to 1000K at 1bar)</td>
<td>3.32, gas [75]</td>
<td>1, 4, 0, no [83]</td>
<td>NO GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethane, C₂H₆</td>
<td>30.07</td>
<td>804 (293 to 625K)</td>
<td>6.43, gas [75]</td>
<td>1, 4, 0, no [83]</td>
<td>NO GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propane, C₃H₈</td>
<td>44.10</td>
<td>438.09 (293 to 500K)</td>
<td>9.94, gas [75]</td>
<td>1, 4, 0, no [84]</td>
<td>NO GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butane, C₄H₁₀</td>
<td>58.12</td>
<td>649 (293 to 575K)</td>
<td>579.07, liq. [75]</td>
<td>1, 4, 0, no [84]</td>
<td>NO GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol, CH₃OH</td>
<td>32.04</td>
<td>1766 (293 to 620K)</td>
<td>791.4, liq. [75]</td>
<td>1, 3, 0, no [83]</td>
<td>GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol, C₂H₅OH</td>
<td>46.07</td>
<td>1477.9 (293 to 600K at 1 bar)</td>
<td>789⁴⁷⁴, liq. [78]</td>
<td>0, 3, 0, no [83]</td>
<td>GO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Starting with the heat of vaporization $\Delta H_{vap}$ of the three substances at 1 bar, the values are:

Heat of vaporization for water [75]: $\Delta H_{vap} = 2257 \, kJ / kg$

Heat of vaporization for methanol [75]: $\Delta H_{vap} = 1102 \, kJ / kg$

Heat of vaporization for ethanol [1]: $\Delta H_{vap} = 854 \, kJ / kg$

As we can see the heat of vaporization for the water is much larger than for methanol and even more than for ethanol. This is even more important when we know that the heat of vaporization takes at least half of the total energy required.

For the specific heat at constant pressure $c_p$ at 1 bar, the results are [75]:

Water in liquid phase: $c_p \approx 4.19 \, kJ/kg.k$ (from 293 K to boiling point, 372.76 K)

Water in vapour phase: $c_p = 2.0784 - 1.9746 \, kJ/kg.k$ (from boiling point, 372.76 K, to 460.3 K); $c_p = 1.9746 - 2.0268 \, kJ/kg.k$ (from 460.3 K to 600 K)

Methanol in liquid phase: $c_p = 2.5037 - 2.8229 \, kJ/kg.k$ (from 293 K to boiling point, 337.3 K)

Methanol in vapour phase: $c_p = 4.4277 - 1.6868 \, kJ/kg.k$ (from boiling point, 337.3 K to 389.7 K); $c_p = 1.6868 - 2.1048 \, kJ/kg.k$ (from 389.7 K to 600 K)

Ethanol in liquid phase: $c_p \approx 2.44 \, kJ/kg.k$ (laboratory temperature)

Ethanol in vapour phase: $c_p = 1.5970 - 3.9120 \, kJ/kg.k$ (from boiling point, 351.5 K to 600 K)

As we can see, water has a higher specific heat at constant pressure in liquid phase, but in vapour phase they are close to each other. For a better evaluation between the three substances, we will compare the energy needed to heat them.

The following first formula will be used for water and methanol. The second formula will be used for ethanol, since there is less information available.

$$\Delta H = \Delta H_{vap} + \Delta H_{liq}(293K \rightarrow T_{boil}) + \Delta H_{vap}(T_{boil} \rightarrow 600K)$$

$$\Delta H \approx \Delta H_{vap} + \frac{C_{p,liq}(T_{boil} - 293)}{M} + \frac{C_{p,vap}(600 - T_{boil})}{M}$$

For water the enthalpies at different temperatures at 1 bar are [75]:

$$\begin{align*}
H_{liq}(293K) &= 83.378 \, kJ / kg \\
H_{liq}(T_{boil} = 372.76K) &= 417.5 \, kJ / kg \\
H_{vap}(T_{boil} = 372.76K) &= 2674.9 \, kJ / kg \\
H_{vap}(600K) &= 3128.8 \, kJ / kg
\end{align*}$$

The energy needed to heat water from 293 K to 600 K is:

$$\Delta H = 2257 + (417.5 - 83.378) + (3128.8 - 2674.9) = 3045.0 \, kJ / kg$$

For methanol the enthalpies at different temperatures at 1 bar are [75]:

$$\begin{align*}
H_{liq}(293K) &= -118.48 \, kJ / kg \\
H_{liq}(T_{boil} = 337.3K) &= -0.945 \, kJ / kg \\
H_{vap}(T_{boil} = 337.3K) &= 1100.8 \, kJ / kg \\
H_{vap}(600K) &= 1605.8 \, kJ / kg
\end{align*}$$

The energy needed to heat methanol from 293 K to 600 K is:

$$\Delta H = 1102 + (-0.945 + 118.1) + (1605.8 - 1100.8) = 1724.2 \, kJ / kg$$
For ethanol the specific heats at constant pressure at 1 bar are [75]:

\[
\begin{align*}
C_{p,\text{liq}}(351.5K) &= 112.4 J/molK \\
C_{p,\text{vap}}(351.5K) &= 73.6 J/molK \\
C_{p,\text{vap}}(600K) &= 104.88 J/molK \\
C_{p,\text{vap}}(351.5K \rightarrow 600K) &= 89.2 J/molK
\end{align*}
\]

The energy needed to heat ethanol from 293 K to 600 K is:

\[
\Delta H = 854 + \frac{112.4 \times (351.5 - 293)}{46.07} + \frac{89.2 \times (600 - 351.5)}{46.07} = 1477.9 J/kg
\]

The following table summarizes the values for heat of vaporization and energy needed to heat from 293 K to 600 K of water, methanol and ethanol.

<table>
<thead>
<tr>
<th></th>
<th>heat of vaporization ( \Delta H_{\text{vap}} ) [kJ/kg]</th>
<th>Total heat from 293 K to 600 K [kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2257</td>
<td>3045</td>
</tr>
<tr>
<td>Methanol</td>
<td>1102</td>
<td>1724</td>
</tr>
<tr>
<td>Ethanol</td>
<td>854</td>
<td>1478</td>
</tr>
</tbody>
</table>

Table 65 – Heat of vaporization and energy to heat for water, methanol and ethanol

As we can see water needs almost 80% and 110% more of energy than methanol and ethanol respectively. This shows that at identical power input, the mass flow of water that can be heated to a certain temperature is less than for Methanol and Ethanol. If the final temperature is lower than the required heat is also lower and vice versa. However the enthalpy of vaporization has a large contribution for the increase of the required heat needed, as we can see in the following figure.

![Required Heat vs Temperature](image)

Figure 116 – Required heat to reach a certain temperature for water
Annexes of Chapter 3

For a required pressure ratio

In this case that it is required a certain pressure ratio $\frac{p_c}{p}$ with a certain throat area for thrust optimization. Using directly equation (3.6) the exit area can be computed. This nozzle should be only for vacuum conditions, since at ambient conditions the effect of separations would be significant, since the exhaust pressure $p_c$ is much lower than the ambient pressure.

Annexes of Chapter 4

Analysis of critical mass flow

Figure 117 shows the evolution of critical mass flow, in a certain range of chamber pressure and temperature.

Figure 117 – Critical mass flow depending on output temperature and chamber pressure
Dynamical regime

Figure 118 – Comparison of Weber number between DUR 1.0-1.1 and DUR H2O depending on the water mass flow

As we can see, the Weber number for DUR H2O/2.0 is always higher than for DUR 1.0/1.1.

Annexes of Chapter 5

Heat losses

For short cylinder:

$$A_{cyl} = \frac{\pi D_{coil}^2}{2} \left( 1 + \frac{2L_{cyl}}{D_{coil}} \right) \text{[m}^2\text{]} \quad (4.13)$$

For long cylinder:

$$A_{cyl} = \pi D_{coil}L_{cyl} \text{[m}^2\text{]}, \ L_{cyl} \text{ is the length of the cylinder} \quad (4.14)$$

For long cylinder with insulation:

$$A_{insul} = \pi D_{insul}L_{insul} \text{[m}^2\text{]}, \ L_{insul} \text{ is the length of the cylinder} \quad (4.15)$$
Churchill and Chu correlation\textsuperscript{27}:
\[
N_u_D = \left(0.6 + \frac{0.387 Ra^{1/6}}{1 + \left(\frac{0.559}{Pr}\right)^{9/16}}\right)^2
\]
for \(10^{-5} < Ra < 10^{12}\) \[3\] (4.16)

Morgan correlation:
\[
N_u_D = 0.47 Ra^{0.25} \quad [-], \quad \text{for } 10^4 < Ra < 10^9
\]
\[
N_u_D = 0.1 Ra^{1/3} \quad [-], \quad \text{for } Ra > 10^9
\] \[3, 18, 16\] (4.17)

Table 66 – Nusselt number correlations for natural convection in a long isothermal cylinder

Comparing Correlations

Dry operation

Without insulation

Using DUR1.0 without insulation, the correlations used are:
- Long cylinder [Coelho], (4.16), [3];
- Long cylinder [Tijsterman], (4.17), [18];
- Short cylinder [Rohsenow], (5.7), [4];
- Coil [Rob], (5.8), [18];
- Minimum natural convection coefficient, \(h = 5 \text{ W/(m}^2\text{K)}\);
- Maximum natural convection coefficient, \(h = 25 \text{ W/(m}^2\text{K)}\).

In case of cylinders, it is assumed that the DUR1.0 will have approximately the same behaviour than a cylinder. In this case, the surface area for convection is considered to be the cylinder with the external dimensions of the coil.

\textsuperscript{27} More correlations from Churchill and Chu are available for smaller range and then more precise [4]
In this figure, excepting the constant values for minimum and maximum convection, the convection coefficient increases with time until it stabilizes, around minute 3. At minute 8, it decreases since the current is at 0A. The Coil [Tijsterman] correlation has the closest result from the Maximum natural convection. Other correlations are closer to Minimum natural convection, being close to each other.
Here, the curves have the same behaviour than in Figure 120, with the difference that it takes between 4 to 5 minutes to stabilize. The cylinder correlations present a surface temperature close to the *Minimum natural convection*. The *Coil [Tijsterman]* correlation has a more conservative result, closer to the *Maximum natural convection*. 

---

**Figure 120** – Surface temperature for different correlations in case of DUR1.0, without insulation, dry operation

**Figure 121** – Power input for different correlations in case of DUR1.0, without insulation, dry operation
Since the power input is dependent on the heater resistance that depends on the temperature. Then a higher surface temperature brings to a higher power input.

**With insulation**

Using DUR1.0 with insulation, the correlations used are:

- **Long cylinder [Coelho]**, (4.16), [3];
- **Long cylinder [Tijsterman]**, (4.17), [18];
- **Short cylinder [Rohsenow]**, (5.7), [4];
- **Minimum natural convection coefficient,** \( h = 5 \);
- **Maximum natural convection coefficient,** \( h = 25 \).

![Figure 122 – Convection coefficient for different correlations in case of DUR1.0, with insulation, dry operation](image)

In this figure, excepting the constant values for minimum and maximum convection, the convection coefficient increases with time until it stabilizes after 8 minutes. At minute 20, it decreases since the current is at 0A. All correlations are closer to *Minimum natural convection* than *Maximum natural convection*. Furthermore, they are very close to each other.
These curves present the same behaviour than in Figure 120, but with much higher values. The difference between minimum and maximum natural convection is, in this case, almost negligible. This concludes that with insulation, the surrounding environment has little influence in the heater temperature. This effect is even more evident when comparing the correlations, and for that reason it is needed a closer view. Here the most conservative relation is the Short cylinder [Rohsenow].
With a closer view, it is evident the negligible difference of the result using different correlations for cylinders. As in section 1.5.1, the Short cylinder [Rohsenow] correlation presents slightly more conservative values.

![Figure 125 – Surface insulation temperature for different correlations in case of DUR1.0, with insulation, dry operation](image)

In the case of temperature at the insulation surface, the convection plays a more important role. Here again, the correlations have very little differences between them, but still they are close to the Minimum natural convection case.

![Figure 126 – Power input for different correlations in case of DUR1.0, with insulation, dry operation](image)
For all the correlations and convection coefficient assumptions, the value of power input has almost the same value. Since the heater temperature is similar in all cases.

**Combined operation**

**Without insulation**

The correlations used for the forced convection in the inner flow for coiled tube. It is possible to use for straight tube. In that case, the correlations used are Dittus-Boelter and Dittus-Boelter with Pethukov high temperature correction.

![Convection coefficient for different correlations](image)

**Figure 127** – Convection coefficient for different correlations in case of DUR1.0, without insulation, combined operation

The natural convection is influenced by the mass flow and power input. All correlations are between the expected minimum and maximum convection coefficient.
The surface mean temperature increases during the pre-heating. When the flow is inserted, the temperature drops significantly. When the current is increased, the temperature increases until it stabilizes. Here, the influence of convection plays an important role on the temperature.

Figure 128 – Surface mean temperature for different correlations in case of DUR1.0, without insulation, combined operation

Figure 129 – Final wall temperature for different correlations in case of DUR1.0, without insulation, combined operation
The final wall and flow temperature start close to the final wall temperature followed by a decrease until stabilizing. When input power is added, the temperatures increase until reaching stable temperatures. The difference between correlations is enormous, meaning that the outer convection plays a fundamental role in the final wall and flow temperature.
During the pre-heating part, the power input and loss increase with temperature, reaching values. With mass flow the power input and loss decrease and increase again with higher level of power input.

**With insulation**
The correlations used for the forced convection in the inner flow are for coiled tube.
During pre-heating the heater mean and final temperatures increase until reaching almost stable values. When the mass flow is inserted, at minute 20, the temperature drops suddenly until reaching a new stable temperature. At minute 25, the power is increased and the mean heater and final wall temperature increase significantly, until reaching a new equilibrium.
When the flow is inserted, the final flow temperature is around the heater temperature, decreasing both suddenly. The step just after minute 20 has no true meaning, coming from the non convergence of the equilibrium equation. At minute 25, more current is inserted with the final flow temperature increasing. The difference between correlations is minimal.

The surface temperature of the insulation increases in the pre-heating phase, until it almost stabilizes. The correlations for natural convection coefficient have an important role on this temperature. When the flow is inserted, the temperature decreases until a new equilibrium point. With higher power input, the temperature slightly increases. Here the difference between correlations for natural convection coefficient has lower difference than during dry-operation.
Power input has 3 stable parts, dry-operation, and two with mass flow. The transient part is directly related to the heater temperature change.

The power loss increases with temperature, at dry operation, equalizing the power input. When the flow is inserted, the losses to the surrounding environment are almost negligible, even when the current is increased, minute 25.
Convection coefficient around the heat chamber, for 5 A to 16 A, with insulation, with H2O flow at 30 mg/s

Minimum natural convection
Maximum natural convection
Long cylinder [Tijsterman]
Long cylinder [Coelho]
Short cylinder [Rohsenow]

Figure 139 – Convection coefficient for different correlations in case of DUR1.0, with insulation, combined operation

Heater temperature, for 5 A to 16 A, with insulation, with H2O flow at 30 mg/s

Minimum natural convection
Maximum natural convection
Long cylinder [Tijsterman]
Long cylinder [Coelho]
Short cylinder [Rohsenow]

Figure 140 – Close view of heater mean temperature for different correlations in case of DUR1.0, dry operation

Here, it is clear than the correlations for short cylinder from Rohsenow is the most conservative one.
Annexes of Chapter 6

Water properties

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>ρ [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>998.80</td>
</tr>
<tr>
<td>295</td>
<td>997.91</td>
</tr>
<tr>
<td>300</td>
<td>996.56</td>
</tr>
</tbody>
</table>

Table 67 – Water density with temperature [75]

Control valve parameters

![Diagram of Flow coefficient vs. Number of open turns]

Figure 141 – Flow coefficient depending on the open turns of the control valve
1. Preparation tests description

1.1 Every time preparation test

Thrust test

![Drift of the thrust signal and ambient temperature from [20]](image)

During morning (from 7h to 11h) the ambient temperature increases significantly. From 11h05m until 17h05m, the temperature increases only from 294.8 K to 295.4 K. This difference is more significant in sunny days.

Test DUR H2O #1

1. Introduction

Some experiments are needed to understand how DUR 1.0 and DUR 1.1 can work with boiling flow. Previous small tests were performed to check the water tank and valves with liquid water, but also to see the behaviour of DUR 1.0 in these conditions. Some problems mainly related to leakage and air bubbles could be solved. However heating was never applied and lot of issues were still open.

The present experiment was performed with DUR 1.0, electrically heated and with water flow. The main objective of this test was to understand some open issues, as the behaviour with boiling flow, the temperature distribution and the electric power required. No pressure measurements were done and during the test the mass flow was unknown. No inaccuracy analysis was done for this test.
The structure of this test is as follows. In section 3 the setup is described including the tank, feeding system and heating chamber. In section 4 the procedure employed during testing is described, followed in section 5 by the test results, where they are discussed in section 6. The report is concluded in section 8.

### 2. Background

The background can be found in Chapter 7 on the data elaboration. In this test, the thermal efficiency is assumed to be between 0.5 and 0.9. Then the thermal power is estimated.

### 3. Setup

For this heater test the setup used is the same than described in Chapter 6 with the following difference:
- Thermal insulator: Glass wool with a thickness of 80 mm around the heater and 40 mm on the caps; normal aluminium foil around the glass wool;
- Axisymmetrical nozzle without pressure neither temperature measurement point;

The test was performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology.

![Test setup](image)

**Figure 143 – Test setup**

<table>
<thead>
<tr>
<th>Legend</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Air pump</td>
<td>7 – Pressure measurement point, after metering valve</td>
</tr>
<tr>
<td>2 – Fill Valve</td>
<td>8 – Electrical and heat insulator</td>
</tr>
<tr>
<td>3 – Water tank</td>
<td>9 – Heating chamber with insulation</td>
</tr>
<tr>
<td>4 – Shutoff valve</td>
<td>10 – Thermocouple just after metering valve, T-valve</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>5 – Metering valve</td>
<td>11 – Power lines to the power supply</td>
</tr>
<tr>
<td>6 – Pressure measurement point, before metering valve</td>
<td>12 – Thermometers</td>
</tr>
</tbody>
</table>

**Table 68 – Test setup legend**

![Diagram of test setup](image)

**Figure 144 – Schematic of the test setup**

P-1, P-2, P-n and T-n are not used for this test.

![Heating chamber with thermocouples and nozzle](image)

**Figure 145 – Heating chamber, DUR 1.0, with thermocouples and nozzle**
In Figure 145, we can see the heating chamber, DUR 1.0, with 3 thermocouples type K. The first Thermocouple, T-1, is in the first loop, the second thermocouple, T-2, is more or less in the middle and the third thermocouple, T-3, is in the last loop.

![Figure 146 – Insulation of the heating chamber, DUR 1.0](image)

In Figure 146, we can see the insulation around the heating chamber, consisting in glass wool and aluminium foil.

4. Procedure

As said before, the test was performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology. With the system already in place, the thermocouples are connected to the thermometers. The power cables are connected to the power supply still switched off. After confirming that the knobs are at zero (fully at counter-clockwise), switch on the power supply. Increase slightly the voltage, and start to increase the current to a desired value. Open the metering valve to the sixth turn, wait 3-5 min and then fully open the shutoff valve.

After experiment, turn the knobs to the zero position and switch off the power supply. After waiting around 5 min, turn the metering valve to fully open and close the shutoff valve, for a faster cooling to ambient temperature. At this point the experiment is concluded.

5. Results

Only after one minute, when the temperature was around 500 K, the insulation started to brun. It was visible some smoke with a strong smell. For that reason after some minutes, the window was opened. At this point, it was clearly visible that the thermocouple T-1 was not working properly. To avoid further melting of the insulation the metering valve was opened, 6 turns, and then the smoke gradually stopped. For that reason the window was closed, furthermore the temperature in the preparation room was decreasing significantly. With the metering valve open, a vapour exhaust started to appear. Some small leakage appeared in the second pressure tube, P-2, however the experiment proceeded since the problem was minor.
Before opening the shutoff valve, the current was increased to 10 A. When the temperature of the heater was again around 700 K, the shutoff valve was fully opened. It was clearly visible the switching in temperature between T-2 and T-3, with T-3 being now the highest temperature. Even if the exhaust was vapour, it appeared once or twice per minute an exhaust peak, during no more than 3 seconds. The increase of vapour exhaust was not only visible but also audible. After some time, the power supply was switched off however the valves stayed at the same position. The vapour exhaust continued for about one minute and gradually came to stop. However to speed up to room temperature and to close the system, the metering valve was fully opened and the shutoff valve closed. The temperature decreased to ambient temperature the exhaust was now liquid water. The metering valve was turn to close position. At this point, the test was considered as concluded. During the test, no pressure measurements were done, except the tank pressure that stayed almost constant at 4 bars gauge, corresponding to 5 bars absolute. During the test, the tank pressure decreased not more than 0.1 bars and was for two times increased again to 4 bars gauge. The following table shows the data obtained during the test, taken once per minute. The data obtained directly from the thermometers and power supply, was the temperature of the thermocouples and the current and voltage. Some remarks were written down with the corresponding time.
<table>
<thead>
<tr>
<th>Time</th>
<th>T-3</th>
<th>T-2</th>
<th>T-1</th>
<th>T-valve</th>
<th>Electric</th>
<th>Voltage</th>
<th>Power</th>
<th>Resistance</th>
<th>Heater power</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>[min]</td>
<td>[K]</td>
<td>[K]</td>
<td>[K]</td>
<td>[K]</td>
<td>[A]</td>
<td>[V]</td>
<td>[W]</td>
<td>[Ω]</td>
<td>[W]</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>295</td>
<td>294.8</td>
<td>295.4</td>
<td>294.8</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.025</td>
<td>14.448</td>
<td>Burning insulation</td>
</tr>
<tr>
<td>1</td>
<td>443</td>
<td>248.8</td>
<td>294.8</td>
<td>8.4</td>
<td>3.4</td>
<td>28.8</td>
<td>0.225</td>
<td>14.400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>512</td>
<td>553</td>
<td>294.7</td>
<td>8.0</td>
<td>3.4</td>
<td>27.2</td>
<td>0.238</td>
<td>15.200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>563</td>
<td>608</td>
<td>294.8</td>
<td>8.0</td>
<td>3.5</td>
<td>26.9</td>
<td>0.249</td>
<td>15.132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>604</td>
<td>649</td>
<td>294.8</td>
<td>7.8</td>
<td>3.5</td>
<td>27.3</td>
<td>0.250</td>
<td>15.132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>637</td>
<td>683</td>
<td>293.5</td>
<td>8.0</td>
<td>3.6</td>
<td>28.8</td>
<td>0.250</td>
<td>16.000</td>
<td>Open window</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>661</td>
<td>709</td>
<td>291.4</td>
<td>8.6</td>
<td>3.6</td>
<td>31.0</td>
<td>0.219</td>
<td>16.168</td>
<td>Open metering valve (6 turns), vapour flow</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>615</td>
<td>669</td>
<td>291.4</td>
<td>8.7</td>
<td>3.6</td>
<td>31.3</td>
<td>0.214</td>
<td>16.162</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>611</td>
<td>616</td>
<td>292.1</td>
<td>8.6</td>
<td>3.6</td>
<td>31.0</td>
<td>0.219</td>
<td>16.168</td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>616</td>
<td>629</td>
<td>290.3</td>
<td>8.7</td>
<td>3.6</td>
<td>31.3</td>
<td>0.214</td>
<td>16.162</td>
<td></td>
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<tr>
<td>10</td>
<td>610</td>
<td>626</td>
<td>289.5</td>
<td>8.7</td>
<td>3.6</td>
<td>31.3</td>
<td>0.214</td>
<td>16.162</td>
<td>Not constant vapour flow</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>611</td>
<td>631</td>
<td>289.3</td>
<td>8.5</td>
<td>3.6</td>
<td>30.6</td>
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<td></td>
<td></td>
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<td>8.5</td>
<td>3.6</td>
<td>30.6</td>
<td>0.224</td>
<td>16.150</td>
<td>Not constant flow</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>637</td>
<td>684</td>
<td>289.8</td>
<td>10.0</td>
<td>4.3</td>
<td>43.0</td>
<td>0.230</td>
<td>23.000</td>
<td>Increase current</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>676</td>
<td>705</td>
<td>290.6</td>
<td>10.0</td>
<td>4.3</td>
<td>43.0</td>
<td>0.230</td>
<td>23.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>594</td>
<td>706</td>
<td>291.0</td>
<td>10.2</td>
<td>4.3</td>
<td>43.9</td>
<td>0.222</td>
<td>23.052</td>
<td>Open shutoff valve, more flow</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>684</td>
<td>667</td>
<td>290.4</td>
<td>10.2</td>
<td>4.3</td>
<td>43.9</td>
<td>0.222</td>
<td>23.052</td>
<td></td>
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<tr>
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<td>639</td>
<td>290.4</td>
<td>10.4</td>
<td>4.3</td>
<td>44.7</td>
<td>0.213</td>
<td>23.088</td>
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<td>291.1</td>
<td>10.5</td>
<td>4.3</td>
<td>45.2</td>
<td>0.210</td>
<td>23.100</td>
<td>Close window, constant vapour flow</td>
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</tr>
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<td>0.210</td>
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<td>4.3</td>
<td>45.2</td>
<td>0.210</td>
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<td>4.3</td>
<td>45.2</td>
<td>0.210</td>
<td>23.100</td>
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<td>618</td>
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<td>10.5</td>
<td>4.3</td>
<td>45.2</td>
<td>0.210</td>
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<td>4.3</td>
<td>45.2</td>
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<td>23.088</td>
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<td>44.7</td>
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<td>44.3</td>
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<td>4.3</td>
<td>44.3</td>
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<td>10.3</td>
<td>4.3</td>
<td>44.3</td>
<td>0.217</td>
<td>23.072</td>
<td>Peaks in the outflow</td>
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<td>Still vapour flow</td>
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</tr>
<tr>
<td>31</td>
<td>562</td>
<td>549</td>
<td>291.8</td>
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<td>Switch off power supply</td>
<td></td>
</tr>
<tr>
<td>32</td>
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<td>380</td>
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<td>Still vapour flow</td>
<td></td>
</tr>
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<td>33</td>
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<td>373</td>
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<td>35</td>
<td>363</td>
<td>368</td>
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<td>0</td>
<td>0.0</td>
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<td>0.0</td>
<td>No flow</td>
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</tr>
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<td>0</td>
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<td>Close shutoff valve, fully open metering valve</td>
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<tr>
<td>37</td>
<td>297</td>
<td>296</td>
<td>292.8</td>
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<td>Liquid outflow</td>
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<td>298</td>
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<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Liquid outflow</td>
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</tr>
<tr>
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<td>292.5</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Liquid outflow</td>
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</tr>
<tr>
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<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Close metering valve</td>
<td></td>
</tr>
</tbody>
</table>

Table 69 – Data and remarks of the test #1

Figure 148 and Figure 149 show the evolution of the temperature during the test. However the temperature of the thermocouple near the valve had small variations and for that reason Figure 149 shows more clearly the evolution of the temperature in that point.
Figure 148 – Heater temperature T2 and T3 and temperature near valve

Figure 149 – Thermocouple temperature near valve

Figure 150 shows the evolution of the electric current during the test. However the current was not constant contrasting with the almost constant electric voltage.
Figure 150 – Electric current in case of voltage control

Figure 151 shows the evolution of the electric power during the test. It was mainly 3 different powers: 0 W, around 30 W and around 45 W.

Figure 151 – Electric power

Figure 152 shows the evolution of the electric resistance of the heater. The resistance of the cables were taken into account and the value measured was around 0.1 Ω for each
cable. It was assumed that the temperature in the cables was constant, then a constant resistance along the test.

![Figure 152 – Electric resistance](image)

**6. Discussion**

This test showed that it is possible to obtain an exhaust of water vapour with 30 to 45 W. It showed that with mass flow, the temperature in the heater decreased. Without mass flow the highest temperature in the coil was in the middle, where the heat losses are lower. However, with mass flow the situation changes, the highest temperature is then closer to the final part of the heater. This change can be seen in minute 15, where T-3 starts to be higher than T-2. The reason of the decrease in temperature is because the heat of the coil is taken by the flow. Unfortunately it is not possible to know precisely the mass flow, since there is no mass flow meter and pressure drop measurement in the valve. From other tests of the metering valve, we expected to have a mass flow between 0.004 to 1 g/s. Unfortunately, this range is far too wide and cannot give a correct estimation of the heat power, neither the characteristics of the flow and of the thermal rocket motor.

**7. Data elaboration**

With the electric power of the heater, around 23 W, and assuming a thermal efficiency\(^{28}\) between 0.5 to 0.9, we obtain a thermal power between 12 to 21 W. Without any pressure measurement we can only assume a constant pressure of 2 bars in the heating chamber, since this value was also taken in the modelling. At 2 bars the enthalpy change is around 400 kJ/kg from liquid at room temperature to boiling temperature. The enthalpy

\[ \varepsilon = \frac{P_{\text{heat}}}{P_{\text{electric}}} \]

---

\(^{28}\) Thermal efficiency is defined by: \(\varepsilon = \frac{P_{\text{heat}}}{P_{\text{electric}}}\)
of vaporization is 2205 kJ/kg and the change of enthalpy is around 412 kJ/kg in vapour phase from boiling temperature to a flow temperature of 650 K [75]. The temperature of the flow at the end is unknown and it was assumed to be 650 K, however it can be also much lower as 440 or 450 K slightly higher than the boiling temperature. For that reason we assumed both conditions and in the end we have 4 different combinations as shown in Table 70.

<table>
<thead>
<tr>
<th>Total enthalpy [kJ/kg]</th>
<th>Thermal efficiency (thermal power)</th>
<th>0.5 (12 W)</th>
<th>0.9 (21 W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2602 (from 298 to 393.4 K)</td>
<td>4.4 mg/s</td>
<td>8.0 mg/s</td>
<td></td>
</tr>
<tr>
<td>3014 (from 298 to 650 K)</td>
<td>3.8 mg/s</td>
<td>6.9 mg/s</td>
<td></td>
</tr>
</tbody>
</table>

Table 70 – Different mass flows depending on the efficiency and the enthalpy

These values give a narrower range of mass flow, between 4 to 8 mg/s.

<table>
<thead>
<tr>
<th>Heating chamber</th>
<th>DUR 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank pressure [bar]</td>
<td>5</td>
</tr>
<tr>
<td>Electric power [W]</td>
<td>(~45)</td>
</tr>
<tr>
<td>Heater electrical resistance [Ω]</td>
<td>(~0.2 - 0.25)</td>
</tr>
<tr>
<td>Heat power [W]</td>
<td>(~12 – 21 \text{(e)})</td>
</tr>
<tr>
<td>Mass flow [mg/s]</td>
<td>(~4 – 8 \text{(e)})</td>
</tr>
<tr>
<td>Surface temperature [K]</td>
<td>End (T-3) 650 - 675</td>
</tr>
<tr>
<td>Gas temperature [K]</td>
<td>Not calculated</td>
</tr>
<tr>
<td>Thrust</td>
<td>Not calculated</td>
</tr>
<tr>
<td>Number of turns of metering valve</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 71 – Summarized values

(e) = estimated

8. Conclusion

The test was mainly a success, since it was possible to obtain vapour flow in the exhaust and reaching a wall temperature of 700 K with mass flow. Furthermore, the mass flow could remain low making possible to vaporize it with a lower electric power than expected.

Some failures appeared during the test. A minor failure was a small leakage in the pressure tube P-2. Major failures were the melting of the insulation, producing smoke and the malfunctioning of the thermocouple T-1.

Improvements for the test #2:
- Use a new insulation material that does not melt;
- Repair the thermocouple T-1;
- Repair the leakage in the tube;
- Use a more detailed test plan, to avoid errors during the test

Improvements for future tests:
- Use the test facility in the clean room, DARTS;
- Use pressure measurements, along the metering valve and near the nozzle;
- Use the data acquisition system;
- Measure the temperature just before the nozzle;
- Perform an inaccuracy analysis;
- Use DUR 1.1 with around 10 thermocouples, to understand the behaviour of the flow;
- Comparison between the thermal model of the heater and the tests;
- Connect the water tank and Nitrogen bottle, for more accurate constant pressure.

**Test DUR H2O #2**

1. **Introduction**

The present experiment was performed with DUR 1.0, electrically heated and with water flow. The main objective of this test was to reach 1000 K, to test the new insulation material and to understand the temperature distribution along the heater. No pressure measurements were done, except the constant pressure from the tank, and during the test the mass flow was unknown. No inaccuracy analysis was performed for this test. The structure of this test is the same than for Test DUR H2O #1.

2. **Background**

The resistance of the heater is obtained subtracting the resistance of the power cables. From that resistance we can obtain the electric power in the heater, $P_{electric}$.

3. **Setup**

For this heating test the setup was the same than Test DUR H2O #1 but using a different thermal insulation: Fiberfrax Durablanket S 128 kg/m³ of 25.4 mm, and normal aluminium foil.

The test was performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology.

4. **Procedure**

The data that should be written down, once per minute is: electric current, voltage, temperature of the thermocouples T-1, T-2, T-3 and T-valve. The pressure P-p needs to be checked every 5 minutes. The value of the pressure gauge should stay around 4 bar gauge.

As said before, the test is performed in the preparation room, 8.01, in aerospace faculty of Delft University of Technology. With the system already in place, the thermocouples are connected to the thermometers. The power cables are connected to the power supply still switched off.

<table>
<thead>
<tr>
<th>Step</th>
<th>Time [min]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>switch on the power supply</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Knobs at zero</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Press the button “Display cv/cc setting”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotate the current knob until 10 A</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Increase the voltage, until 10 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Voltage around 4 to 5 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature increases</td>
</tr>
<tr>
<td>If</td>
<td></td>
<td>Temperature is more than 320 K near the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature decreases</td>
</tr>
</tbody>
</table>
Then | valve or Insulation is burning  
Fully open the shutoff valve and open with 6 turns the metering valve |  
---|---
4 | Fully open the shutoff valve and open with 6 turns the metering valve | Temperature decreases  
5 | Press the button “Display cv/cc setting”  
Rotate the knob of the current until having 15 A | Temperature increases  
Voltage around 6 V  
If | Temperature is more than 320 K near the valve or Insulation is burning  
Highest temperature is higher than 1300 K  
Open with more 2 turns the metering valve | Temperature decreases  
6 | Turn the knobs to the zero position | Concluding the test  
7 | Close shutoff valve  
Fully open metering valve | Temperature decreases to ambient temperature  
8 | Experiment concluded |  

Table 72 – Procedure for test #2

**5. Results and discussion**

Until the minute 5, the experiment was going as expected. However some smoke appeared from the insulation. For that reason the shutoff valve was fully opened and the metering valve tuned with maximum turns minus 5 turns (8 turns). This action was enough to stop the smoke and some water vapour exhaust started to appear. The exhaust was more or less constant during 2 minutes followed by 1 minute with irregular exhaust and returning to constant exhaust afterwards. This behaviour still needs to be understood.

As planned, in minute 30 the current was increased, however not with 15 A, but with 14 A. After 1 minute the current was increased again to 15 A. The temperature increased significantly, reaching more than 1000 K. However some smoke appeared again in a different part of the insulation. A significant leakage appeared in electrical and thermal insulator, *The Cube*. In minute 34, the metering valve was open with one more turn, the temperature decreased but the leakage increased even more. Due to this situation the test was aborted in minute 37, fully opening the metering valve and switching off the power supply. In minute 42, the valves were closed since the temperature of the heater was already at almost ambient temperature.

During the test, the tank pressure was constant as well as the temperature near the valve. The temperature near the valve increased slightly when the thermocouple was wetted by the leakage.

Afterwards, the insulation of the heater was opened and we discovered that the smoke did not come from the *Fiberfrax Durablanket S* insulator but from the first brown layer of the thermocouples insulation. After the burning of that brown layer, it remains a reddish layer, as we can see in Figure 86.

The following table shows the data obtained during the test, taken once per minute. The data, obtained directly from the thermometers and the power supply, was the temperature of the thermocouples and the current and voltage. Some remarks were written down with the corresponding time.
### Table 73 – Data and remarks of the test #1

<table>
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<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>493</td>
<td>370</td>
<td>295.2</td>
<td>10</td>
<td>4.2</td>
<td>42</td>
<td>0.22</td>
<td>22.00</td>
</tr>
<tr>
<td>22</td>
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<td>370</td>
<td>295.2</td>
<td>10</td>
<td>4.2</td>
<td>42</td>
<td>0.22</td>
<td>22.00</td>
</tr>
<tr>
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<td>624</td>
<td>543</td>
<td>376</td>
<td>295.0</td>
<td>10</td>
<td>4.3</td>
<td>43</td>
<td>0.23</td>
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<tr>
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<td>631</td>
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<td>377</td>
<td>295.0</td>
<td>10</td>
<td>4.3</td>
<td>43</td>
<td>0.23</td>
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<tr>
<td>25</td>
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<td>562</td>
<td>380</td>
<td>295.0</td>
<td>10</td>
<td>4.3</td>
<td>43</td>
<td>0.23</td>
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</tr>
<tr>
<td>26</td>
<td>637</td>
<td>569</td>
<td>379</td>
<td>295.0</td>
<td>10</td>
<td>4.3</td>
<td>43</td>
<td>0.23</td>
<td>23.00</td>
</tr>
<tr>
<td>27</td>
<td>642</td>
<td>562</td>
<td>388</td>
<td>295.0</td>
<td>10</td>
<td>4.3</td>
<td>43</td>
<td>0.23</td>
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</tr>
<tr>
<td>28</td>
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<td>612</td>
<td>388</td>
<td>295.0</td>
<td>10</td>
<td>4.4</td>
<td>44</td>
<td>0.24</td>
<td>24.00</td>
</tr>
<tr>
<td>29</td>
<td>654</td>
<td>622</td>
<td>391</td>
<td>295.0</td>
<td>10</td>
<td>4.4</td>
<td>44</td>
<td>0.24</td>
<td>24.00</td>
</tr>
<tr>
<td>30</td>
<td>658</td>
<td>628</td>
<td>394</td>
<td>295.0</td>
<td>10</td>
<td>4.9</td>
<td>49</td>
<td>0.29</td>
<td>29.00</td>
</tr>
<tr>
<td>31</td>
<td>760</td>
<td>593</td>
<td>483</td>
<td>295.0</td>
<td>14</td>
<td>6.9</td>
<td>97</td>
<td>0.29</td>
<td>57.40</td>
</tr>
<tr>
<td>32</td>
<td>884</td>
<td>917</td>
<td>513</td>
<td>295.1</td>
<td>15</td>
<td>7.7</td>
<td>116</td>
<td>0.31</td>
<td>70.50</td>
</tr>
<tr>
<td>33</td>
<td>955</td>
<td>996</td>
<td>819</td>
<td>295.0</td>
<td>15</td>
<td>8</td>
<td>120</td>
<td>0.33</td>
<td>75.00</td>
</tr>
<tr>
<td>34</td>
<td>703</td>
<td>769</td>
<td>463</td>
<td>295.0</td>
<td>15</td>
<td>8</td>
<td>120</td>
<td>0.33</td>
<td>75.00</td>
</tr>
<tr>
<td>35</td>
<td>903</td>
<td>912</td>
<td>514</td>
<td>294.9</td>
<td>10</td>
<td>5</td>
<td>50</td>
<td>0.30</td>
<td>30.00</td>
</tr>
<tr>
<td>36</td>
<td>827</td>
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<td>295.0</td>
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<td>4.8</td>
<td>48</td>
<td>0.28</td>
<td>28.00</td>
</tr>
<tr>
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<td>366</td>
<td>299.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>No power</td>
</tr>
<tr>
<td>38</td>
<td>340</td>
<td>327</td>
<td>329</td>
<td>295.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
<td>39</td>
<td>326</td>
<td>317</td>
<td>319</td>
<td>294.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>Liquid exhaust</td>
</tr>
<tr>
<td>40</td>
<td>317</td>
<td>311</td>
<td>313</td>
<td>295.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>Forced convection (window opened)</td>
</tr>
<tr>
<td>41</td>
<td>311</td>
<td>307</td>
<td>309</td>
<td>294.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>307</td>
<td>305</td>
<td>306</td>
<td>294.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Thermocouples temperature vs Time

**Figure 153 – Heater temperature during test**
When the current was set at 10 A, the temperature started to increase instantaneously. Some water vapour exhaust appeared due to some remains in the heater. At minute 2, we can see a strange behaviour in the thermocouple T-1, probably due to detachment from the heater. Since in the beginning of the test it was attached and at the end it was not. Initially it was planned to keep the valves closed until the minute 10, being closer to the equilibrium temperature. However some smoke appeared and the valves were open at 7m50s. Without mass flow the highest temperature was in the middle of the heater, where the heat losses are lower. With mass flow the situation changes, the temperatures decreased and the highest temperature was then closer to the final part. The reason of this behaviour is due to the heat taken by the water flow. At the final part of the heater, the flow takes less heat and then the temperature can be higher. Until minute 30, the temperature T-2 converges to T-3 and T-1 is almost constant. However the values given by T-2 were highly oscillatory, with variations 20 or even 100 K in less than a second. The reason can be in bad twisting of that thermocouple. At minute 30, the current was increased to 14 A, and not to 15 A as expected, due to human error. After 1 minute, the current was increased to 15 A. At minute 34 the temperatures T-2 and T-3 reached more than 1000 K. They could not increase even more due to the decrease in electric current, since major leakage and some smoke appeared. The test was aborted due to an increase in leakage and the power supply was switched off.

From this figure, we can relate directly the increase in electrical resistance to an increase of temperature. Nevertheless, the resistance comes from the entire heater and the temperature is only of one point. Some discrepancies as at minute 8, 10 and 17 are related to that. When T-3 is around 600 K, the resistance is at 0.22 Ω – 0.23 Ω. The highest resistance of 0.33 Ω is at 1004 K and the lowest at 358 K with 0.2 Ω.
It is considered that the temperature at T-3 is around the heater output temperature. The electric power had values around 40 W – 50 W and increased obviously at minute 30 when the current was increased to 14 A and after to 15 A. The highest electric power was 120 W when the temperature was a 1004 K and the current at 15 A.

6. Data elaboration
In this section, it is analysed only when the electric current was at 10 A, since at 15 A it did not have enough time to reach equilibrium.

With the electric power in the heater around 22 W and assuming a thermal efficiency\(^{29}\) between 0.5 to 0.9, we obtain a thermal power between 11 to 20 W. Without any pressure measurement we can only assume a constant pressure of 2 bars in the heating chamber, since this value was also taken in the modelling. Nevertheless the total enthalpy change is nearly constant with pressure, then no other pressure will be taken into account. At 2 bars the enthalpy change is around 400 kJ/kg from liquid at room temperature to boiling temperature. The enthalpy of vaporization is 2205 kJ/kg and the change of enthalpy is around 412 kJ/kg in vapour phase from boiling temperature to a flow temperature of 650 K [75]. The temperature of the flow at the end is unknown and it was assumed to be 650 K, however it can be also much lower as 440 or 450 K slightly higher than the boiling temperature. For that reason we assumed both conditions and in the end we have 4 different combinations as shown in Table 70.

---

\(^{29}\) Thermal efficiency is defined by: \(\eta = \frac{P_{\text{heat}}}{P_{\text{electric}}}\)
7. Conclusion and recommendations

The main objectives of the test were fulfilled. The heater could reach 1000 K, the insulation material was successfully tested and the temperature behaviour along the heater was more deeply analysed. As the test #1, we obtained water vapour exhaust and the temperature near the valve was around ambient temperature. Some failures appeared during the test, mainly when the current was at 15 A. After some minutes, some smoke appeared from the thermocouples insulation. In further tests, to avoid some undesirable smoke, the brown layer shall be removed, keeping the reddish layer.

The electrical and thermal insulator, The cube, was ruined after the test. For the next test, the gasket seal will be used, since it is compatible with water and elastic, avoiding to be destroyed during mounting and testing.

Test DUR H2O #3

1. Introduction

The present experiment was performed with DUR 1.0, electrically heated with a first part without flow and a second part with flow. The main objective of this test was to try to reach 1000 K without insulation and to take pressure measurements. No measurements
were done in the nozzle, and during the test the mass flow was unknown. No inaccuracy analysis was performed for this test. However the range of the data was taken into account to perform estimations. The structure of this test is the same than for Test DUR H2O #1.

2. Background
To compute the electric power, electric resistance, heat power and mass flow, we need to know the temperature, voltage and electric current.

The electric power input, \( P_{\text{total,electric}} \), is determined knowing the voltage, \( V_{\text{tot}} \), and the current input, \( I \), provided by the power supply. The formula used is \( P_{\text{total,electric}} = V_{\text{tot}}I \). However some electric power is lost in the electricity supply cables and then the heater has a lower value: \( P_{\text{electric}} = V_{\text{tot}}I - R_{\text{cab}}I^2 \), where \( R_{\text{cab}} \) is the resistance of the power cables.

Two ways are used to know this resistance, measuring directly at room temperature and then assuming a constant value. Or measuring the voltage of the heater during test and then \( R_{\text{cab}} = \frac{V_{\text{tot}} - V_{\text{heater}}}{I} \). Since the heater voltage was not taken simultaneously, the values can be used only as confirmation of the measured value of the resistance.

The total resistance was computed by \( R = \frac{V}{I} \). We obtain the resistance of the heater, \( R_{\text{heater}} \), subtracting the resistance of the power cables. From the heater resistance we can obtain the electric power in the heater, \( P_{\text{electric}} = R_{\text{heater}}I^2 \).

To compute the mass flow the method is shown in Chapter 7.

3. Setup
For this heating test the setup was the same than Test DUR H2O #2 but using Multimeter, TENMA 72-7770.
The test was performed in the clean room, 8.01, in aerospace faculty of Delft University of Technology.
Legend:

| 1 – Water collector          | 5 – Voltmeter   |
| 2 – Heating chamber, DUR 1.0 | 6 – Fill/drain valve |
| 3 – Electrical and heat insulator, *The cube* | 7 – Shutoff valve |
| 4 – Metering valve           | 8 – Water tank |

Table 76 – Test setup legend
P-n and T-n are not used for this test. The ammeter is given by the power supply *Delta Electronika* SM7020-D. The voltage is given also from the power supply but also from the multimeter TENMA 72 – 7770. The following measurement instruments used are:

4. Procedure
The only data that should be written down, once per minute is the voltage. The pressure P-p needs to be checked every 5 minutes. The value of the pressure gauges P-p and P-1 should stay around 4 bar gauge.

As said before, the test is performed in the clean room, 8.01, in aerospace faculty of Delft University of Technology. With the system already in place, the thermocouples, the pressure transducers, current and voltage monitoring and current control are connected to SCB-68 dev0 and dev1 as shown in Figure 158 and Figure 159. The data cables of the pressure transducers can also be connected to the SCB-68 dev1, without BIAS resistor, since it is not a floating source but a grounded signal source. In that case, the computer and the power supply of the pressure transducer should be connected to the same plug. If
it is not possible, then it should be connected to the SCB-68 dev0, to avoid different grounds. In this case, some noise, related to the BIAS resistor, will appear.

![Figure 158 – SCB-68 dev0 with thermocouples and pressure transducers connection](image1)

The power cables are connected to the output terminals of the power supply still switched off. Since the current is controlled by labview, the switches are in Program for I and Manual for V (see back part of the power supply).

![Figure 159 – SCB-68 dev1 with current and voltage monitor and current control](image2)
Figure 160 – Back view of the power supply

<table>
<thead>
<tr>
<th>Step</th>
<th>Time [min]</th>
<th>Action</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Switch on the power supply</td>
<td>Knobs at zero</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Rotate voltage knob until the maximum</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Type in labview program 10 A</td>
<td>Voltage around 4 to 5 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If Temperature is more than 320 K near the valve</td>
<td>Temperature increases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Then Fully open the shutoff valve and open the metering valve with maximum - 5 turns</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Fully open the shutoff valve</td>
<td>Temperature decreases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fully open the metering valve and then close with 5 turns (8 open turns)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>If Temperature is more than 320 K near the valve</td>
<td>Temperature decreases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Then Fully open the metering valve with maximum - 5 turns</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>60 (1h)</td>
<td>Increase the current to 11 A</td>
<td>Temperature increases</td>
</tr>
<tr>
<td>6</td>
<td>65 (1h05)</td>
<td>Increase the current to 12 A</td>
<td>Temperature increases</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Increase current 1 A per 5 minutes until reaching 1000 K</td>
<td>Temperature increases (15 A should be enough to reach 1000 K)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If Temperature is more than 320 K near the valve</td>
<td>Temperature decreases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Then Fully open the metering valve with maximum - 5 turns</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Stay during 10 min at 1000 K with constant current</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Type 0 A in labview program and turn the voltage knob to the zero position</td>
<td>Concluding the test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fully close valves</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Fully open the metering valve</td>
<td>Temperature decreases to ambient temperature</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Experiment concluded</td>
<td></td>
</tr>
</tbody>
</table>

Table 77 – Procedure for test #3
5. Results and discussion

The first 10 minutes there was no water flow. It was possible to see temperature variations around +/- 20 K due to certain forced convection when closing doors or people around it. After the minute 10, the valves were opened and liquid water exhaust appeared. In minute 12, it was possible to see that the liquid exhaust was not completely stable. Around minute 18 the exhaust was periodically a mixture between liquid and vapour. When increasing the current the periods of two-phase exhaust became longer, but some clear pressure fluctuations started to appear in the pressure transducer, P-2. Around minute 64, some leakage appeared in the thermal and electrical insulator. During the test, the temperature near the valve was almost constant, T-v = 295 K. P-1 was kept at around 3.8 – 3.9 bar gauge, pumping if lower than 3.8 bar gauge. Some videos of the testing are available in the directory S:\Gezamenlijk\Personal Directories\Rodrigo\Pictures & Movies\Test n3.

[Figure 161 – Heater temperature during test]

When the current was set at 10 A, the temperature started to increase instantaneously. Some water vapour exhaust appeared due to some remains in the heater. After 10 minutes the valves were opened and the temperatures decreased almost instantaneously almost to room temperature. This is due to fully open the valve and then starting to close it. At this point T-3 is the highest measured temperature. When increasing the power, T-2 was then the highest temperature. Some irregular behaviour in the temperatures appeared, however it was more evident when increasing the current to 17 A. The oscillatory behaviour of the temperatures will be explained afterwards. At 18 A the exhaust was more constant as well as the temperature in T-3. As we can see, the temperature of 1000 K was not obtained, having a maximum of 590 K. Since it was more evident that the system was too far to be able to reach 1000 K, the current was not increased more than 18 A. Afterwards the power was switched off and the temperature decreased instantaneously.
It was considered that the temperature at T-3 was around the heater output temperature. The measured resistance of the cables as well as the resistance coming from the heater voltage had values around 0.075 Ω, independently of the current. As we can see, with the same amount of current, the output wall temperature decreased almost 40 k with flow. Even increasing the electric power, the output temperature did not increase considerably. This was due to the vaporization that starts to take place in the tube, between 370 K and 390 K. When the power reached a value around 100 W, the temperature had then higher values but highly unstable. At 120 W, the instability decreased and the mean output temperature increased.
As we can see the pressure drop along the metering valve was around 3.9 bar. The pressure after metering valve, P-2, increased with higher electric power, and started to have unstable behaviour. The pressure before valve, P-1, dropped slightly along the test as well as the pressure in the water tank, P-p. For that reason, the pressure in the tank needs to be increased to 4 bar gauge. There is no evidence of dependency between P-1 and P-2, however the mass flow decreased with lower pressure drop (higher pressure in P-2).

In Figure 164 we can see a clear relation between the unstable behaviour of the temperature and of the pressure. When the current was set at 18 A, the output temperature had a more stable behaviour, however the pressure had still high oscillations. From previous figures we see that, even when the output temperature, T-3, was more stable, T-1 and T-2 were even more unstable. This was due to the vaporization, when it takes place near T-3, then it has high oscillations. When the power increases, the vaporization takes place earlier in the tube, T-3 is then in vapour zone, with more stable behaviour.
In this figure, we can see more clearly the relation between output temperature and pressure. When the temperature increases, the pressure starts to increase and then the temperature decreases followed by a decrease in pressure. This behaviour stops with the output temperature when the power is increased.

The oscillation behaviour of the temperature and pressure can now be explained. When the temperature is near to the vaporization temperature, some vapour is produced. Due to lower density (3 orders of magnitude lower), the pressure drop along the heater, $\Delta P$, increases considerably. At that point, $P_2 - \Delta P \approx P_{\text{exhaust}} = P_{\text{amb}}$, and then the mass flow decreases, making an increase of temperature in the heater and decreasing $\Delta P$. With higher temperatures, $P_2$ increases (as all the pressure in the heater) and then the mass flow increases. The temperature decreases and $\Delta P$ increases. Again, $P_2$ decreases reaching the first condition $P_2 - \Delta P \approx P_{\text{exhaust}} = P_{\text{amb}}$. 

Summarizing, the oscillations happen as the following way:

\[
\begin{align*}
\text{if } P_2 - \Delta P &\approx P_{\text{exhaust}} = P_{\text{amb}} \\
\Rightarrow \dot{m} &\Rightarrow \Delta P \uparrow, T \downarrow \Rightarrow P_2 \uparrow \Rightarrow \\
\Rightarrow \dot{m} &\Rightarrow \Delta P \uparrow, T \downarrow \Rightarrow P_2 \downarrow \Rightarrow \\
\Rightarrow P_2 - \Delta P &\approx P_{\text{exhaust}} \Rightarrow ...
\end{align*}
\]

5.1 Without flow

For the coil heating without flow, the current was set at 10 A.
As we can see, not all the power supplied goes to the heater. There is around 7 – 8 W lost in cabling. The mean coil temperature is also not stable, having variations around 10 K.

From Figure 167, we see that the modified theory of the coil follows the power variation in time. For the mean coil temperature, the curve shows a similar behaviour, however there are still some differences. During transient phase, some water was still in the coil, decreasing the temperature of it. In stable phase, the temperature has some variation comparing to the theory due to variations of convection, since the environment is not completely quiet.
6. Data elaboration

From the formula that the valve’s manufacturer provides, we can compute the mass flow. Since the relation between the number of open turns of the metering valve and $C_v$ is still not completely known (the total number of turns are different), we consider that $C_v$ has a value between 0.0002 and 0.00125.

During liquid flow, at 10 A:

\[ \Delta P_{\text{valve}} = 3.88 \pm 0.01 \text{ bar} \]

\[ \dot{V} = 0.00568 - 0.03551L / \text{min or } \dot{m} = 0.0945 - 0.5905g / s. \]

With calibration test performed with the metering valve [67, we have the mass flow at 5 close turns: \( \dot{m} = 0.025 \pm 0.005g / s \)

Considering the change of enthalpy from 295 K to 340 K or 360 K, we have $\Delta H = 188.185 - 272.075 \text{ kJ/kg [75]. With } P_{\text{electric}} = 33 \pm 0.4 \text{ W we can estimate the thermal efficiency as shown in Table 78.}\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>188.185 - 272.075</td>
<td>0.0946</td>
<td>17.8 – 25.7</td>
<td>53.2 % – 78.9 %</td>
</tr>
<tr>
<td>(from 295 to 340 K or 360 K)</td>
<td>0.5925</td>
<td>111.1 – 160.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.02 - 0.03</td>
<td>3.8 – 8.2</td>
<td>11.3 % – 25.0 %</td>
</tr>
</tbody>
</table>

Table 78 – Estimated thermal efficiency depending on the electric and heat power for 10 A

The second assumption with higher mass flow was not correct, since it was giving values higher than the input electric power. Even the lower mass flow expected by the manufacturer is more than 3 times larger than the expected mass flow expected. As a result, the efficiency is much higher than with a lower mass flow.

For vapour exhaust flow, at 18 A:

Since the pressure is highly oscillatory, we consider a mean value of the pressure drop in the valve, then $\Delta P_{\text{valve}} = 2$ bar.

\[ \dot{V} = 0.00408 - 0.02549L / \text{min or } \dot{m} = 0.0678 - 0.4240g / s \]

Considering the change of enthalpy from 295 K to 400 K (near boiling temperature) or 570 K, we have $\Delta H = 2638.655 - 2976.455 \text{ kJ/kg [75]. With } P_{\text{electric}} = 119 \pm 2 \text{ W we can estimate the thermal efficiency as shown in Table 79.}\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2638.655 - 2976.455</td>
<td>0.0678</td>
<td>179 – 201.9</td>
<td>117 - 121</td>
</tr>
<tr>
<td>(from 295 to 400 K or 570 K)</td>
<td>0.4240</td>
<td>1118.7 – 1261.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.01 – 0.02</td>
<td>26.4 – 59.5</td>
<td>21.8 % - 50.9 %</td>
</tr>
</tbody>
</table>

Table 79 – Estimated thermal efficiency depending on the electric and heat power for 18 A
As we can see, the flow estimated by the manufacturer’s formula cannot correspond to the reality. The heat power associated to them is higher than the electric power and that cannot happen. The estimation given in Chapter 7 provides acceptable values of mass flow, but still too wide. It is not clear the real thermal efficiency however we can assume for now a range of 22 % - 51 % with a mass flow of 0.01 – 0.02 g/s.

<table>
<thead>
<tr>
<th>Heating chamber</th>
<th>DUR 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank pressure [bar]</td>
<td>5</td>
</tr>
<tr>
<td>Electric power [W]</td>
<td></td>
</tr>
<tr>
<td>At 10 A</td>
<td>33 ± 0.4</td>
</tr>
<tr>
<td>At 18 A</td>
<td>119 ± 2</td>
</tr>
<tr>
<td>Heater electrical resistance [Ω]</td>
<td></td>
</tr>
<tr>
<td>Around 300 K</td>
<td>0.316</td>
</tr>
<tr>
<td>Around 430 K</td>
<td>0.368 ± 0.005</td>
</tr>
<tr>
<td>Heat power [W]</td>
<td>26.4 – 59.5 (e)</td>
</tr>
<tr>
<td>Mass flow [g/s]</td>
<td>0.01 – 0.02 (e)</td>
</tr>
<tr>
<td>Surface temperature at 18 A [K]</td>
<td></td>
</tr>
<tr>
<td>End (T-3)</td>
<td>560 – 580</td>
</tr>
<tr>
<td>Middle (T-2)</td>
<td>400 – 420 (peaks at ~ 490 K)</td>
</tr>
<tr>
<td>Start (T-1)</td>
<td>330 – 390</td>
</tr>
<tr>
<td>Gas temperature [K]</td>
<td>Not calculated</td>
</tr>
<tr>
<td>Thrust</td>
<td>Not calculated</td>
</tr>
<tr>
<td>Number of close turns of metering valve</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 80 – Summarized values

(e) = estimated

7. Conclusion and recommendations

Most objectives of the test were fulfilled, as pressure measurements and testing without insulation. However, the heater could not reach 1000 K, since the heat losses by convection were too significant. In the Test DURH2O #1 and Test DURH2O #2, it was possible to obtain vapour exhaust with 10 A, since insulation was used. In the current test, it was only possible to obtain constant vapour exhaust with 18 A. The temperature near the valve remained around ambient temperature, during the entire test. Some small leakage appeared in the insulation when the pressure increased around 2 bars. The electrical and thermal insulator, The cube, was partially ruined after the test.

In further tests, to avoid undesirable leakage, another insulation device should be used. For next tests, the insulation used in Test DURH2O #2 should be used to be able to have higher temperatures with same electrical power.
Anomaly Report

Problem reported by:
Name: Rodrigo A. Ferreira Supervisor: B.T.C. Zandbergen
Date: 23-01-08

Problem handled by:
Name: Rodrigo A. Ferreira Supervisor: B.T.C. Zandbergen
Date: 28-01-08

Item of interest

Malfunction of the electrical and thermal insulator of DURH2O.

Anomaly description

Leakages due to the porosity of the insulator.
Damages of the insulator due to the forces applied on it.
Improvements could not completely solve the leakages and a clear misalignment of the insulator was evident.

Anomaly analysis and improvement

Anomaly analysis was performed and improvements were taken to solve the problems.
The analysis and improvements are reported in Chapter 6.

Conclusion

The new design should be able to end with these problems.
Annexes of Chapter 7

Preliminary tests

Calibration of a control valve and mass flow meter

Setup
In test series 1 mass flow will be determined from weighing mass of water. In test series two a slow meter will be used to increase the accuracy of the measurement. The test is performed in the SSE clean room in aerospace faculty of Delft University of Technology. Figure 144 shows the schematic of the test setup.

![Figure 168 – Schematic of the test setup](image)

P-1 and P-2 is the pressure before and after the metering valve.

Results and discussion
The values computed for low mass flows are almost one order of magnitude greater than the real mass flow. The calibration of the metering valve is then inevitable.
The pressure drop was kept within ± 0.5 – 1 % of the desired value. During all the tests, the temperature was in the range 294 K to 295 K.

For the tests, the turns’ inaccuracy of the metering valve was ±1/16 of a turn. The reading inaccuracy of the mass flow meter was 0.010 [-]. The inaccuracies of the mass flow were almost negligible, as we can see in the following figures.

![Figure 169 – Comparison between tested and theoretical water mass flow from the manufacturer’s formula, at 295 K](image1.png)

![Figure 170 – Closer view of the mass flow depending on the turns for 3 different pressure drops](image2.png)
The evolution of the mass flow has an almost exponential increase with the decrease of the close turns. The maximum flow at 2 bar pressure drop is around 1.2 g/s and the minimum mass flows is in the order of 10 mg/s, see excel file. The increase in pressure drop, from 2 bar to 3 bar, increases the mass flow. However, from 3 to 4 bar of pressure drop, the increase is smaller. The number of turns is important to fix an order of magnitude of the desired mass flow.

Nevertheless the calibration of the metering valve does not allow having a direct measurement of the mass flow, but only an estimation of it. With the change in pressure drop, the estimation is then more inaccurate, around 50%. Adding to that, the variation of the ambient temperature can play a role in the mass flow. For these reasons it is important to have a calibrated mass flow meter, to ensure a higher accuracy of the measurements.

For the calibration of the dimensionless values of the mass flow meter with real values of mass flow, two curves are obtained: for full range and for short range. The curve for shorter range is more accurate and more useful for the tested mass flows.

Using this calibration, the dependency on pressure drop and ambient temperature will not bring additional errors. Furthermore it is possible to have a direct reading.

<table>
<thead>
<tr>
<th>Range</th>
<th>Calibration equation</th>
<th>Inaccuracy [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[mg/s]</td>
<td>[g/s]</td>
<td></td>
</tr>
<tr>
<td>0.2 – 1.8</td>
<td></td>
<td>0.01 (worst case)</td>
</tr>
<tr>
<td>0.2 – 0.5</td>
<td></td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 81 – Calibration equations depending on the desired range
**Conclusion and recommendations**

To have a more accurate value with direct reading of the mass flow, the mass flow meter should be calibrated and used. After that the regression formulas should be used, for full scale or shorter scale.

The accuracy of the formulas can increase with further investigation in other mass flows. The mass flow accuracy and reading can be improved using a more accurate mass flow meter with voltage output to a data acquisition system. However water flow meters for mass flow in the range 0.01 g/s to 0.1 g/s are quite expensive, around 4000 €.

**Measurement of throat dimensions**

**Objective**

To determine and verify the throat diameter.

**Design dimensions**

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Water Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>Chamber diameter</td>
<td>3.1 mm</td>
</tr>
<tr>
<td>Throat Diameter</td>
<td>0.40 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Remarks</td>
<td>No divergent part in the nozzle</td>
</tr>
</tbody>
</table>

Table 82 – Nozzle dimensions from the design

**First measurement method**

It was used small wires and rods with different diameters, to see if they pass through the nozzle.

**Test measurements**

<table>
<thead>
<tr>
<th>Wire diameter [mm]</th>
<th>Passing or not</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>Yes</td>
</tr>
<tr>
<td>0.56</td>
<td>No</td>
</tr>
<tr>
<td>0.34</td>
<td>Yes</td>
</tr>
<tr>
<td>0.50</td>
<td>No</td>
</tr>
<tr>
<td>0.38</td>
<td>Yes</td>
</tr>
<tr>
<td>0.46</td>
<td>No</td>
</tr>
<tr>
<td>0.42</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 83 – Test measurements

**Test results and inaccuracy**

<table>
<thead>
<tr>
<th>Wire diameter [mm]</th>
<th>Passing or not</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>Yes</td>
</tr>
<tr>
<td>0.42</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 84 – Test results and inaccuracy

<table>
<thead>
<tr>
<th>Final dimensions and inaccuracy [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40 ± 0.02</td>
</tr>
</tbody>
</table>
Second measurement method

It was used the microscope brightfield reflection with monitor projection, from Delft Aerospace Structures & Materials Laboratory.

Test measurements

<table>
<thead>
<tr>
<th>Measured diameter [μm]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>415.04</td>
<td>Used a low magnification lens</td>
</tr>
<tr>
<td></td>
<td>No extreme values taken</td>
</tr>
<tr>
<td>422.76</td>
<td>No extreme values taken</td>
</tr>
<tr>
<td>407.36 to 469.58 = 438.47</td>
<td>Extreme values taken, mean value calculated</td>
</tr>
</tbody>
</table>

Table 85 – Second test measurements
Test results and inaccuracy

<table>
<thead>
<tr>
<th>Final dimensions and inaccuracy [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44 ± 0.03</td>
</tr>
</tbody>
</table>

Table 86 – Test results and inaccuracy

Final tests

Effect of insulation on power loss, without flow

Difference in temperature along the heater

![Figure 174](image1)

Figure 174 – Heater temperatures depending on the location, for DUR1.0, at 1 A, without insulation

![Figure 175](image2)

Figure 175 – Heater temperatures depending on the location, for DUR1.0, at 5 A, without insulation
Heater temperature, 5 A, with insulation

Figure 176 – Heater temperatures depending on the location, for DUR1.0, at 5 A, with insulation

Heater mean temperature and power

Figure 177 – Heater mean temperature and power, for DUR1.0, at 5 A, without insulation
Heater temperature and power at 5 A with insulation

Figure 178 – Heater mean temperature and power, for DUR1.0, at 5 A, with insulation

Heater temperature and power at 10 A with insulation

Figure 179 – Heater mean temperature and power, for DUR1.0, at 10 A, with insulation
Data elaboration and comparison

**Figure 180** – Comparison between test and theory, for DUR1.0, at 5 A, without insulation

**Figure 181** – Comparison between test and theory, for DUR1.0, at 5 A, with insulation
Figure 182 – Comparison between test and theory of insulation temperature, for DUR1.0, at 5 A, with insulation

Figure 183 – Comparison between test and theory, for DUR1.0, at 10 A, without insulation
Power input

Figure 184 – Comparison between test and theory, for DUR1.0, at 5 A, without insulation

Figure 185 – Comparison between test and theory, for DUR1.0, at 5 A, with insulation
Figure 186 – Comparison between test and theory, for DUR1.0, at 10 A, with insulation

Effect of insulation on power loss, wet operation

2.1.1 Test results
2.1.2 Data elaboration

**Pressure drop**

![Pressure drop along heater, raw and averaged data, for DUR1.0](image)

*Figure 188 – Pressure drop along heater, raw and averaged data, for DUR1.0*

**Heater mean temperature**

![Heater mean temperature from power, DUR1.0](image)

*Figure 189 – Pressure and mass flow, for DUR1.0, at 17.5 A, with insulation*
Thrust

Filtered thrust, depending on filter method, for DUR1.0

Figure 190 – Filtered and averaged thrust signal, for DUR1.0

Final thrust drift, depending on filter method, for DUR1.0

Figure 191 – Drift on filtered and averaged thrust signal, for DUR1.0
Figure 192 – Filtered and averaged thrust signal, at 17.5 A, for DUR1.0, with insulation

Fourier analysis for thrust and pressure

Figure 193 – Amplitude of original thrust data in frequency domain (from 4000 s to 4600 s), for DUR1.0

Natural frequency of the DARTS is around 1.4 HZ. The pressure at nozzle location has no natural frequency. The method used for both cases is the same.
2.1.3 Discussion

Critical conditions

Mass flow with pressure, at critical conditions, with DUR1.0

Figure 194 – Averaged mass flow and theoretical mass flow for different conditions, for DUR1.0

Comparison of the temperature increase along the heater

Variation of wall and flow temperature along DUR1.0, with a heater mean temperature of 514 K, with insulation, with H2O flow at 31.9 mg/s and at 2 bar

Figure 195 – Power input, at 17.5 A and 31.9 mg/s, for DUR1.0
Figure 197 – Brass DARTS interface
Figure 198 – Modified side plate for DARTS interface
Figure 199 – Electrical/thermal insulator disc, disc insulation
Figure 200 – Electrical/thermal insulator, disc metal
Figure 201 – Old insulator, The Cube
Figure 202 – New tube house for pressure transducer
Annexes of Labview Files
Since the Labview files are all related, only the most complex is shown.

Figure 203 – Block diagram of Test ThTePr DUR10_H2O v2

Annexes of Matlab Files

1 Files of properties

function h = computeEnthalpy(species, T, p);
    h = computeEnthalpy(species, T);
    Determine enthalpy w.r.t. 298.15 K
    h: enthalpy [J / mol]
    T: temperature of species [K]
    Data obtained from NIST Chemistry WebBook http://webbook.nist.gov/chemistry/
    The values for H2O are for 2bar
    Data for air from CRC Handbook of Chemistry and Physics, section 6

    Determine coefficients corresponding to species
    if(strcmp(species, 'N2') == true)
        A = 26.09200;
        B = 8.218801;
        C = -1.976141;
        D = 0.159274;
        E = 0.044434;
        F = -7.989230;
        H = 0.000000;
elseif(strcmp(species, 'O2') == true)
    A = 29.65900;
    B = 6.137261;
    C = -1.186521;
    D = 0.095780;
    E = -0.219663;
    F = -9.861391;
    H = 0.000000;
elseif(strcmp(species, 'Ar') == true)
    A = 20.78600;
    B = 2.825911E-7;
    C = -1.464191E-7;
    D = 1.092131E-8;
    E = -3.661371E-8;
    F = -6.197350;
    H = 0.000000;
elseif(strcmp(species, 'Air') == true)
    h_matrix = [98.3 199.7 300.3 503.4 1046.6] * 1E3; % [J/kg]
    T_matrix = [100 200 300 500 1000];
    A = 0; B = 0; C = 0; D = 0; E = 0; H = 0;
    F = interp1(T_matrix, h_matrix, T) * computeM('Air'); % [J/mol]
    F = F/1000;
elseif(strcmp(species, 'H2O') == true)
    A = 0; B = 0; C = 0; D = 0; E = 0; H = 0;
% p = 1 bar
    h_matrix = ([70.822 154.45 238.07 321.84 405.89 417.50 2674.9 2710.3 2750.4 2829.7 2928.9 3128.8 3334.4 3546.3 3756.5 3990.7 4223.4 4463.0 4585.4])* 1E3; % [J/kg];
    T_matrix = [290 310 330 350 370 372.76-1e-6 372.76+1e-6 390 410 450 500 600 700 800 900 1000 1100 1200 1250];
    F1 = interp1(T_matrix, h_matrix, T) * computeM('H2O'); % [J/mol]
% p = 1.5 bar
    h_matrix = ([70.870 196.29 321.88 448.11 467.13 2693.1 2746.2 2926.6 3127.7 3333.7 3545.8 3764.6 3990.4 4223.2 4462.8 4585.2])* 1E3; % [J/kg];
    T_matrix = [290 320 350 380 384.5-1e-6 384.5+1e-6 410 500 600 700 800 900 1000 1100 1200 1250];
    F2 = interp1(T_matrix, h_matrix, T) * computeM('H2O'); % [J/mol]
% p = 2 bar
    h_matrix = ([70.918 105.01 112.75 196.31 280.01 363.90 448.14 490.45 504.70 2529.1 2720.6 2824.0 2924.7 3025.3 3126.6 3229.1 3333.0 3438.3 3545.3 3653.9 3764.3 3876.3 3990.1 4223.0 4462.7 4646.9])* 1E3; % [J/kg];
    T_matrix = [290 298.15 300 320 340 360 380 390 393.36-1e-6 393.36+1e-6 400 450 500 550 600 650 700 750 800 850 900 950 1000 1100 1200 1275];
    F3 = interp1(T_matrix, h_matrix, T) * computeM('H2O'); % [J/mol]
    hvec = [F1 F2 F3];
    pvec = [1 1.5 2];
    F = interp1(pvec, hvec, p, 'linear');
    F = F/1000; % [J / Kmol]
else
    'Unknown gas'
    A = 0;
    B = 0;
    C = 0;
    D = 0;
    E = 0;
    F = 0;
end

T = T/1E3;
H = A*t + B*t^2/2 + C*t^3/3 + D*t^4/4 - E/t + F - H;
H = H * 1000; % [J / mol]

function Cp = computeCp(species, T)
% computeCp(species, T) Compute specific heat (J/mol/K) as a function of 
% gas 'species' and temperature (T [K])
% Admissible 'species' are:
%   'N2', 'O2', 'Ar', 'Air', 'H2O'
% The values for H2O are for 2bars
% Determine coefficients corresponding to species
if(strcmp(species, 'N2') == true)
    A = 26.09200;
    B = 8.218801;
    C = 0;
    D = 0;
    E = 0;
    F = 0;
end

function h = t(1E3);
    h = A*t + B*t^2/2 + C*t^3/3 + D*t^4/4 - E/t + F - H;
    h = h * 1000; % [J / mol]
elseif(strcmp(species, 'O2') == true)
    A = 29.65900;
    B = 6.137261;
    C = -1.186521;
    D = 0.095780;
    E = -0.219663;
elseif(strcmp(species, 'Ar') == true)
    A = 20.78600;
    B = 2.825911E-7;
    C = -1.464191E-7;
    D = 1.092131E-8;
    E = -3.661371E-8;
elseif(strcmp(species, 'Air') == true)
    cp_matrix = [1006 1006 1006 1006 1006 1008 1011 1025 1045 1093 1185]; % [J/(kg*K)] [Bejan]
    T_matrix = [223.15 273.15 283.15 293.15 303.15 333.15 373.15 473.15 573.15 773.15 1273.15]; %[K]
    A = interp1(T_matrix, cp_matrix, T) * computeM('Air');
    B = 0;
    C = 0;
    D = 0;
    E = 0;
elseif(strcmp(species, 'H2O') == true)
    cp_matrix = [75.674 75.310 75.309 75.449 75.702 76.095 76.454 39.240 38.53 36.53 36.18 36.34 36.70 37.17 37.69 38.25 38.84 39.44 40.06 40.69 41.318 42.572 43.795]; %[J/(mol*K)] [NIST]
    T_matrix = [280 300 320 340 360 380 393.36-1e-6 393.36+1e-6 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050]; %[K]
    A = interp1(T_matrix, cp_matrix, T);
    B = 0;
    C = 0;
    D = 0;
    E = 0;
else
    'Unknown gas';
    A = 0;
    B = 0;
    C = 0;
    D = 0;
    E = 0;
end

Cp = A + B.*t + C.*t.^2 + D.*t.^3 + E./t.^2; % [J/mol*K]

function k = computeK(species, T)
% computeK(species, T) Compute conductivity [W/m/K] as a function of
% 'species' and temperature (T [K]) (for Fiberfrax is
% the mean temperature)
% Admissible 'species' are:
% 'N2' 'Air' 'H2O' 'Fiberfrax'
% The values for H2O are for 2bars
if(strcmp(species, 'N2') == true)
    k_matrix = [9.8 18.7 25.8 32.3 38.5 44.5 50.5 56.3 62.0 67.7 93.3]* 1E-3;
    T_matrix = [100 200 300 400 500 600 700 800 900 950 1000 1050]; %[K]
    k = interp1(T_matrix, k_matrix, T, 'linear');
elseif(strcmp(species, 'Air') == true)
    k_matrix = [9.4 18.4 26.2 33.3 39.7 45.7 56 76]* 1E-3; %[W/(m*K)] [Rob] and [Bejan]
    T_matrix = [100 200 300 400 500 600 500+273.15 1000+273.15]; %[K]
    k = interp1(T_matrix, k_matrix, T, 'linear');
elseif(strcmp(species, 'H2O') == true)
    k_matrix = [0.57414 0.61037 0.63979 0.66063 0.67383 0.68104 0.68321 0.027493 0.027915 0.031677 0.036167 0.041150 0.046504 0.052153 0.058048 0.064155 0.070450 0.076912 0.083524 0.090271 0.097139];
    T_matrix = [280 300 320 340 360 380 393.36-1e-6 393.36+1e-6 400 450 500 550 600 650 700 750 800 850 900 950 1000]; %[NIST]
    k = interp1(T_matrix, k_matrix, T, 'linear');
elseif(strcmp(species, 'Fiberfrax') == true)
    k_matrix = [0.02 0.02 0.025 0.0375 0.05 0.075 0.1 0.12 0.15 0.18 0.28];
    T_matrix = [0 50 100 200 250 400 500 600 700 800 1000+273.15]; % This is the mean temperature
    k = interp1(T_matrix, k_matrix, T, 'linear');
else
    'Unknown gas';
end

k = interp1(T_matrix, k_matrix, T, 'linear');

function M = computeM(species)
% computeM(species) Determine molar mass [kg/mol] of 'species'
% Admissible 'species' are:
% 'Air', 'N2', 'H2O'
if(strcmp(species, 'Air') == true)
    M = 29.0e+3;
elseif(strcmp(species, 'N2') == true)
M = 28.01e-3;
elseif(strcmp(species, 'H2O') == true)
    M = 18.02e-3;
else
    'Unknown gas'
    M = 0;
end

function mu = computeMu(species, T)
% computeMu(species, T) Compute dynamic viscosity [Pas] as a function of
% 'species' and temperature (T [K])
% Admissible 'species' are:
% 'Air', 'NH3', 'CO2', 'CO', 'H2', 'N2', 'O2',
% 'H2O'
% The values for H2O are for 2 bars
if(strcmp(species, 'H2O') == true)
    muvec = [1433.4E-6 890.06E-6 577.05e-6 422.01e-6 262.71e-6 236.78e-6
             231.62e-6 1.2963e-5 1.322E-05 1.3538E-05 1.4318E-05 1.5485E-05
             1.725E-05 1.931E-05 2.140E-05 2.348E-05 2.556E-05 2.763E-05
             2.967E-05 3.169E-05 3.369E-05 3.566E-05 3.7596E-05 3.956E-05
             4.1387E-05 4.3237E-05 4.5058E-05];
    Tvec = [280 298.15 300 320 340 360 380 390 393.36-1e-6 393.36+1e-6
             400 450 500 550 600 650 700 750 800 850 900 950 1000 1050
             1100 1150 1200]; %[NIST]
    mu = interp1(Tvec, muvec, T, 'linear');
elseif(strcmp(species,'Air') == true)
    muvec = [1.71 1.76 1.81 1.86 2.00 2.18 2.58 2.95 3.58 4.82]*10^-5;%[kg/(ms)]=[Pas]
    Tvec = [273.15 283.15 293.15 303.15 333.15 373.15 473.15 573.15
             773.15 1273.15]; %[Bejan]
    % C = 120;
    T0 = 291.15;
    mu0 = 18.27E-6;
    % Determine coefficients corresponding to species
    else
        if(strcmp(species,'NH3') == true)
            C = 370;
            T0 = 283.15;
            mu0 = 9.82E-6;
        elseif(strcmp(species,'CO2') == true)
            C = 240;
            T0 = 293.15;
            mu0 = 14.8E-6;
        elseif(strcmp(species,'CO') == true)
            C = 118;
            T0 = 288.15;
            mu0 = 17.2E-6;
        elseif(strcmp(species,'H2') == true)
            C = 72;
            T0 = 293.85;
            mu0 = 8.76E-6;
        elseif(strcmp(species,'N2') == true)
            C = 111;
            T0 = 300.55;
            mu0 = 17.81E-6;
        elseif(strcmp(species,'O2') == true)
            C = 127;
            T0 = 292.25;
            mu0 = 20.18E-6;
        end
        a = 0.555*T0 + C;
        b = 0.555*T + C;
        mu = mu0 * (a/b) * (T/T0)^((3/2));
    end
end

function rho = computeRho(species,T,p)
% computeRho(species, T) Compute density [Pas] as a function of
% 'species', temperature (T [K]) and pressure (p[bar])
% Admissible 'species' are:
% 'Air', 'NH3', 'CO2', 'CO', 'H2', 'N2', 'O2',
% 'H2O'
% The values for H2O are only for 2 bars
if(strcmp(species, 'H2O') == true)
    %p = 1 bar
    rhovec1 = [999.91 996.56 989.43 979.54 967.40 958.63 0.59034 0.57824
                0.54761 0.43514 0.36185 0.30988 0.27102 0.24085 0.21673];
    Tvec1 = [280 300 320 340 360 372.76-1e-6 372.76+1e-6 380 400 450
             500 550 600 650 700 750 800 850 900 950 1000]; %[NIST]
    rho1 = interp1(Tvec1, rhovec1, T, 'linear');
elseif(strcmp(species,'Air') == true)
    %p = 2 bar
    rhovec1 = [999.91 996.56 989.43 979.54 967.40 958.63 0.59034 0.57824
                0.54761 0.43514 0.36185 0.30988 0.27102 0.24085 0.21673];
    Tvec1 = [280 300 320 340 360 372.76-1e-6 372.76+1e-6 380 400
             450 500 550 600 650 700 750 800 850 900 950 1000]; %[NIST]
    rho1 = interp1(Tvec1, rhovec1, T, 'linear');
rhovec2 = [999.96 997.09 996.60 989.47 979.58 967.45 953.36 945.63 942.94 1.1291 1.1081 0.97558
0.87394 0.79239 0.72518 0.66868 0.62046 0.57879 0.54241 0.51035 0.48189 0.45645 0.43357];
Tvec2 = [280 298.15 300 320 340 360 380 390 393.36-1E-6 393.36+1E-6 400 450 500 550 600 650 700
750 800 850 900 950 1000];%
[link]
rho2 = interp1(Tvec2, rhovec2, T, 'linear');

rhototalvec = [rho1 rho2];
pvec = [1 2];
rho = interp1(pvec, rhototalvec, p, 'linear');

else
% Determine rho for gasous species
M = computeM(species);  %[kg/mol]
R = 8.314 / M;          %[J/(kg K)]
rho = p / (R * T);      %[kg/m^3]
end

function surf_tens = computeSurf_tens(species, T)

if(strcmp(species, 'H2O') == true)
    surf_tens_matrix = [74.94 74.23 73.49 72.74 71.98 71.19 70.41 69.59 68.78 67.93 67.09 66.24 65.36
64.47 63.57 62.68 61.76 60.82 59.88 58.92 57.95 56.97 55.98 54.97 54.93]*10^-3; %[N/m] [IAPWS release
1994]
    T_matrix = [5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 120.21
+273.15]; %[K]
    surf_tens = (interp1(T_matrix, surf_tens_matrix, T))';
else
    surf_tens = 0;
end

2 Files of design and analysis

The plots are not included.

function MinTh = computeThrust (species)
clc
clear
close all
g0 = 9.80665;
% Specific heat [J/kg/K]
j = 1;
species = 'H2O';
for Tc_vect = [500 600 700 800 900 920 1000]

% Nozzle C
pc = 2;
pa = 1;
De = 0.77*10^-3; %[m] From drawing of nozzle
Dt = 0.66*10^-3;
A_t = pi*Dt^2/4;%[m^2]
Cp = computeCp(species, Tc_vect);    %[J/mol/K]
M = computeM(species); %[kg/mol]
cp = Cp/M;
RA = 8.314472; %[J/(molK)]
gama = Cp/(Cp-RA);
Gama = (gama)^(1/2)*(2/(gama+1))^((gama+1)/(2*(gama-1)));
p_ratio = 1 : 0.01 :100;
A_ratio = Gama./(2*gama/(gama-1)).^((gama-1)/(2*gama-1))
    p_r = interp1(A_ratio, p_ratio, A_r);
A_e = pi*De^2/4;%[m^2]
pe = pc/p_r;
p_sep(j) = pe/pc;
U_e = (2*gama/(gama-1))*(1/(2*(gama+1)))^((gama+1)/(2*(gama-1)));
% figure(j)
% plot(p_ratio, A_ratio)
% xlabel('Pressure ratio [-]');
% ylabel('Area ratio [-]');
m_Nozz(j) = pi*Dt^2/4*pc*10^5*gama/(RA/M*Tc_vect)^1/2;
pe_Nozz = pe*10^5;
pe_NozzAll(j) = pe_Nozz;
pa_Nozz=pa*10^5;
Ueq_Nozz = U_e+(pe_Nozz-pa_Nozz)/m_Nozz(j)*A_e;
Th_Nozz(j) = m_Nozz(j)*Ueq_Nozz;
Isp_Nozz(j) = Ueq_Nozz/g0;
\( P_{j\_\text{Nozz}}(j) = \frac{1}{2} Th_{\text{Nozz}}(j) \cdot U_{\text{eq\_Nozz}}; \)

\[
m_{\text{vec}} = 0:0.3\times10^{-3}/1000:0.3\times10^{-3} \text{[kg/s]}
\]
\[
T_i = 295 \text{ [K]}
\]
\[
H_{\text{in}} = \text{computeEnthalpy} \text{(species, } T_i, pc) / M; \text{ [J/kg]}
\]
\[
T_{o\_\text{out}} = \text{computeEnthalpy} \text{(species, } T_o, pc) / M; \text{ [J/kg]}
\]
\[
\text{Pin}(j,:) = m_{\text{vec}} \cdot (H_{\text{out\_w\_in}});
\]
\[
\text{Pin}_{\text{Nozz}}(j) = m_{\text{Nozz}}(j) \cdot (H_{\text{out\_w\_in}});
\]
\[
\text{Effic}_{\text{Nozz}}(j) = \frac{P_{j\_\text{Nozz}}(j)}{\text{Pin}_{\text{Nozz}}(j)};
\]
\[
\text{water} \text{ Nozzle}
\]
\[
\text{Dt}_w = 0.4\times10^{-3};
\]
\[
\text{De}_w = 0.4\times10^{-3};
\]
\[
\text{pc} = 1.48;
\]
\[
\text{pc} = 1.98;
\]
\[
\text{Dt}_w = 0.44\times10^{-3};
\]
\[
\text{De}_w = 0.45\times10^{-3};
\]
\[
A_{t\_w} = \pi \cdot (\text{Dt}_w)^2/4; \text{[m}^2\text{]}
\]
\[
\text{p\_ratio} = 1:0.01:100;
\]
\[
\text{A}_{r\_w} = \text{De}_w^2/\text{Dt}_w^2;
\]
\[
\text{p\_w} = \text{pc} / \text{p\_ratio};
\]
\[
U_{e\_w} = (2 \cdot gama/(gama-1) \cdot \text{RA} / \text{M} \cdot T_{\text{c\_vect}} \cdot (1-(\text{pc} / \text{pc})^{(gama-1)/gama})); \text{[(1/2);}
\]
\[
\text{figure}(j);
\]
\[
\text{p\_ratio2} = 100^{-1};
\]
\[
U_{e\_2} = (2 \cdot gama/(gama-1) \cdot \text{RA} / \text{M} \cdot T_{\text{c\_vect}} \cdot (1-(\text{p\_ratio2} \cdot ((\text{gama-1)/gama}))); \text{[(1/2);}
\]
\[
\text{A\_ratio2} = \text{Gama} / (2 \cdot gama/(gama-1) \cdot (\text{p\_ratio2}) \cdot ((\text{gama-1)/gama})); \text{[(1/2);}
\]
\[
\text{De}_2 = (\text{A\_ratio2} \cdot \text{Dt\_2}^2)/1.228;\]
\[
\text{Ae}_2 = \text{A\_ratio2} \cdot \pi \cdot \text{Dt\_2}^2/4;\]
\[
\text{pe}_2 = \text{pc} / \text{p\_ratio2} \cdot \text{10}^5;\]
\[
\text{pa}_2 = 0;\]
\[
\text{Th}_2(j) = \text{m\_Nozz}(j) \cdot U_{e\_2} + (\text{pe}_2 - \text{pa}_2) \cdot \text{Ae}_2;\]
\[
\text{Th\_vec\_All\_2}(j,:) = \text{Th\_vec2};\]
\[
\text{isp\_2}(j) = \text{Th}_2(j)/g0;\]
\[
\text{Pj\_2}(j) = 1/2 \cdot \text{Th}_2(j) \cdot \text{U\_eq\_2};\]
\[
\text{Effic\_2}(j) = \text{Pj\_2}(j)/\text{Pin\_Nozz}(j);\]
\[
\text{Flight condition} \text{ pa = 0;}\]
\[
\text{pa = 0};\]
\[
\text{Th\_Vac\_w\_j} = \text{m\_Nozz}(j) \cdot U_{\text{eq\_Vac\_w\_j}};\]
\[
\text{Th\_Vac\_w\_j} = \text{m\_Nozz}(j) \cdot U_{\text{eq\_Vac\_w\_j}};\]
\[
\text{Isp\_Vac\_w\_j} = \text{U\_eq\_Vac\_w\_j} / g0;\]
\[
\text{Pj\_Vac\_w\_j} = 1/2 \cdot \text{Th\_Vac\_w\_j} \cdot \text{U\_eq\_Vac\_w\_j};\]
\[
\text{Effic\_Vac\_w\_j} = \text{Pj\_Vac\_w\_j}/\text{Pin\_Nozz\_w\_j};\]
\[
\text{Water Nozzle}
\]
\[
\text{Ueq\_Vac\_w\_j} = \text{U\_eq\_w \_w} + (\text{pe\_Nozz\_w} - \text{pa}) \cdot \text{Ae}_w;\]
\[
\text{Th\_Vac\_w\_j} = \text{m\_Nozz\_w}(j) \cdot \text{U\_eq\_Vac\_w\_j};\]
\[
\text{Isp\_Vac\_w\_j} = \text{U\_eq\_Vac\_w\_j} / g0;\]
\[
\text{Pj\_Vac\_w\_j} = 1/2 \cdot \text{Th\_Vac\_w\_j} \cdot \text{U\_eq\_Vac\_w\_j};\]
\[
\text{Effic\_Vac\_w\_j} = \text{Pj\_Vac\_w\_j}/\text{Pin\_Nozz\_w\_j};\]
\[
\text{Throat diameter}
\]
\[ \text{Att} = \text{m}_\text{vec} \cdot (\text{RA}/\text{MT}_\text{vect}) \cdot (1/2) \cdot (\text{pc} \cdot 10^5 \cdot G_\text{ama}) \]

\[ \text{Dtt}(j,:) = (\text{Att} \cdot 4/\pi)^{1/2} \]

\% No sonic conditions at the throat of Nozzle C
\%
\%
\% Rho = computeRho(species,Tc_vect,pc);% Assuming pe=pc, incompressible flow
\% i=1;
\% ii=1;
\% for m_vec2 = 0 : m_Nozz(j)/1000 : m_Nozz(j)
\% m_Vec2(j,i) = m_vec2;
\% pa = 1; %[bar]
\%
\% Dc = 3 \cdot 10^{-3};
\%
\% A_c = pi \cdot Dc^2/4;
\%
\% p_chamber = (p_exit+(p_exit^2-4*(1/2*RA/MT_vec)^2-(m_vec2/A_c)^2)^1/2))/2;
\%
\% T_exit = Tc_vect*p_exit/p_chamber;
\%
\% Mach = V_exit/(gama*RA/MT_exit)^1/2;
\%
\% Th_exit = m_vec2*V_exit;
\%
\% if Mach > 0.3
\% m_Vec3(j,ii) = m_vec2;
\%
\% Th_exit3(j,ii)=Th_exit(j,i);
\%
\% i=i+1;
\%
\% end
\%
\% i=1;
\%
\% l=1;
\%
\% for m_vec2 w = 0 : m_Nozz_w(j)/1000 : m_Nozz_w(j)
\% m_Vec2_w(j,i) = m_vec2_w;
\%
\% Dc_w = 3.1 \cdot 10^{-3};
\%
\% A_c_w = pi \cdot Dc_w^2/4;
\%
\% p_chamber_w = (p_exit+(p_exit^2-4*(1/2*RA/MT_vect)^2-(m_vec2_w/A_c_w)^2))^{1/2}/2;
\%
\% T_exit_w = Tc_vect*p_exit/p_chamber_w;
\%
\% V_exit_w = m_vec2_w/(A_e_w*Rho_e_w);
\%
\% Mach_w = V_exit_w/(gama*RA/MT_exit)^1/2;
\%
\% if Mach_w > 0.3
\% m_Vec3_w(j,l) = m_vec2_w;
\%
\% Th_exit3_w(j,l)=Th_exit_w(j,i);
\%
\% i=i+1;
\%
\% end
\%
\% j=j+1;
\%
\% end
\%
\% Different chamber pressure
\%
\% Cp and H are taken at 2 bars, since the difference is minimal
\%
\% For better prediction, Cp and H should also include the respective values
\%
\% for 1 bar. Afterwards an interpolation can be done to obtain intermediate
\%
\% values.
\%
\% jj=0;
\%
\% pc_vec = 1.7:0.05:2;
\%
\% for jj=1:length(pc_vec)
\% for jjj=1:length(Tc_pvec)
\%
\% p_r_pvec = interp1(A_ratio_pvec, p_ratio, A_r);
\%
\% p_sep_pvec(jj,jjj) = pc_vec(jj)/p_r_pvec;
\[ U_{e \_pvec} = \left( \frac{2 \cdot \gamma_{pvec}}{(\gamma_{pvec} - 1) \cdot RA/M \cdot Tc_{pvec}(jjj)} \right)^{\frac{1}{2}} \cdot \left( 1 - \left( \frac{pe_{pvec}(jjj)}{pc_{vec}(jj)} \right)^{\frac{(\gamma_{pvec} - 1)}{\gamma_{pvec}}} \right)^{\frac{1}{2}}; \]

\[ m_{Nozz \_pvec}(jj, jjj) = \pi \cdot Dt^2/4 \cdot pc_{vec}(jj) \cdot 10^5 \cdot Gama_{pvec}/(RA/M \cdot Tc_{pvec}(jjj))^{\frac{1}{2}}; \]

\[ pe_{Nozz \_pvec}(jj, jjj) = pe_{pvec}(jjj) \cdot 10^5; \]

\[ pe_{NozzAll \_pvec}(jj, jjj) = pe_{Nozz \_pvec}(jj, jjj); \]

\[ pa_{Nozz \_pvec} = pa \cdot 10^5; \]

\[ U_{eq \_Nozz \_pvec} = U_{e \_pvec} + \frac{pe_{Nozz \_pvec} - pa_{Nozz \_pvec}}{m_{Nozz \_pvec}(jj, jjj) \cdot A_e}; \]

\[ Th_{Nozz \_pvec}(jj, jjj) = m_{Nozz \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_pvec}; \]

\[ Isp_{Nozz \_pvec}(jj, jjj) = \frac{U_{eq \_Nozz \_pvec}}{g_0}; \]

\[ P_{j \_Nozz \_pvec}(jj, jjj) = \frac{1}{2} \cdot Th_{Nozz \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_pvec}; \]

\[ P_{in \_Nozz \_pvec}(jj, jjj) = m_{Nozz \_pvec}(jj, jjj) \cdot (H_{out \_pvec} - H_{in}); \]

\[ Effic_{Nozz \_pvec}(jj, jjj) = \frac{P_{j \_Nozz \_pvec}(jj, jjj)}{P_{in \_Nozz \_pvec}(jj, jjj)}. \]

\[ p_{r \_w \_pvec} = \text{interp1}(A_{ratio \_pvec}, p_{ratio}, A_{r \_w}); \]

\[ pe_{w \_pvec} = pc_{vec}(jj) / p_{r \_w \_pvec}; \]

\[ p_{sep \_w \_pvec}(jj, jjj) = pe_{w \_pvec} / pa; \]

\[ U_{e \_w \_pvec} = \left( \frac{2 \cdot \gamma_{pvec}}{(\gamma_{pvec} - 1) \cdot RA/M \cdot Tc_{pvec}(jjj)} \right)^{\frac{1}{2}} \cdot \left( 1 - \left( \frac{pe_{w \_pvec}(jjj)}{pc_{vec}(jj)} \right)^{\frac{(\gamma_{pvec} - 1)}{\gamma_{pvec}}} \right)^{\frac{1}{2}}; \]

\[ m_{Nozz \_w \_pvec}(jj, jjj) = \pi \cdot Dt_{w}^2/4 \cdot pc_{vec}(jj) \cdot 10^5 \cdot Gama_{pvec}/(RA/M \cdot Tc_{pvec}(jjj))^{\frac{1}{2}}; \]

\[ pe_{Nozz \_w \_pvec}(jj, jjj) = pe_{w \_pvec}(jjj) \cdot 10^5; \]

\[ pe_{NozzAll \_w \_pvec}(jj, jjj) = pe_{Nozz \_w \_pvec}(jj, jjj); \]

\[ pa_{Nozz \_w \_pvec} = pa \cdot 10^5; \]

\[ U_{eq \_Nozz \_w \_pvec} = U_{e \_w \_pvec} + \frac{pe_{Nozz \_w \_pvec} - pa_{Nozz \_w \_pvec}}{m_{Nozz \_w \_pvec}(jj, jjj) \cdot A_{e \_w}}; \]

\[ Th_{Nozz \_w \_pvec}(jj, jjj) = m_{Nozz \_w \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_w \_pvec}; \]

\[ Isp_{Nozz \_w \_pvec}(jj, jjj) = \frac{U_{eq \_Nozz \_w \_pvec}}{g_0}; \]

\[ P_{j \_Nozz \_w \_pvec}(jj, jjj) = \frac{1}{2} \cdot Th_{Nozz \_w \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_w \_pvec}; \]

\[ P_{in \_Nozz \_w \_pvec}(jj, jjj) = m_{Nozz \_w \_pvec}(jj, jjj) \cdot (H_{out \_pvec} - H_{in}); \]

\[ Effic_{Nozz \_w \_pvec}(jj, jjj) = \frac{P_{j \_Nozz \_w \_pvec}(jj, jjj)}{P_{in \_Nozz \_w \_pvec}(jj, jjj)}. \]

\[ p_{throat}(jj, jjj) = pc_{vec}(jj) \cdot (1+(\gamma_{pvec}-1)/2)^{-\gamma_{pvec}/(\gamma_{pvec}-1)}. \]

```matlab
function computeMinD(species, T)
    % function Dtube = computeMinD(species, T)
    %   Compute the minimum diameter for a tube
    %     species:        'H2O'
    %     T:         Final flow temperature       [K]
    %     species:        'H2O'
    % Rodrigo A. Ferreira
    % 2007
    %
    p = 2; %pressure [bar]
    epsilon_1 = 0.2595;
    epsilon_2 = 0.4764;
    for T_vec = [500 600 700 800 900 1000]
        rho = computeRho(species, T_vec, p);
        m_vec = 0 : 0.1*10^-3/1000: 0.1*10^-3; %mass flow [kg/s]
        if rho < 100
            vp = 175*(1/rho)^0.43;
        else
            vp = 175;
        end
        Dtube(:,j) = sqrt(4*m_vec/(rho*pi*vp))*1000; %[mm]
        Dtube_PM1(:,j) = sqrt(4*m_vec/(rho*pi*vp*epsilon_1))*1000;
        Dtube_PM2(:,j) = sqrt(4*m_vec/(rho*pi*vp*epsilon_2))*1000;
        j=j+1;
    end
    m_vec = m_vec*10^6; %[mg/s]
end
```

\[ p_{r \_w \_pvec} = \text{interp1}(A_{ratio \_pvec}, p_{ratio}, A_{r \_w}); \]

\[ pe_{w \_pvec} = pc_{vec}(jj) / p_{r \_w \_pvec}; \]

\[ p_{sep \_w \_pvec}(jj, jjj) = pe_{w \_pvec} / pa; \]

\[ U_{e \_w \_pvec} = \left( \frac{2 \cdot \gamma_{pvec}}{(\gamma_{pvec} - 1) \cdot RA/M \cdot Tc_{pvec}(jjj)} \right)^{\frac{1}{2}} \cdot \left( 1 - \left( \frac{pe_{w \_pvec}(jjj)}{pc_{vec}(jj)} \right)^{\frac{(\gamma_{pvec} - 1)}{\gamma_{pvec}}} \right)^{\frac{1}{2}}; \]

\[ m_{Nozz \_w \_pvec}(jj, jjj) = \pi \cdot Dt_{w}^2/4 \cdot pc_{vec}(jj) \cdot 10^5 \cdot Gama_{pvec}/(RA/M \cdot Tc_{pvec}(jjj))^{\frac{1}{2}}; \]

\[ pe_{Nozz \_w \_pvec}(jj, jjj) = pe_{w \_pvec}(jjj) \cdot 10^5; \]

\[ pe_{NozzAll \_w \_pvec}(jj, jjj) = pe_{Nozz \_w \_pvec}(jj, jjj); \]

\[ pa_{Nozz \_w \_pvec} = pa \cdot 10^5; \]

\[ U_{eq \_Nozz \_w \_pvec} = U_{e \_w \_pvec} + \frac{pe_{Nozz \_w \_pvec} - pa_{Nozz \_w \_pvec}}{m_{Nozz \_w \_pvec}(jj, jjj) \cdot A_{e \_w}}; \]

\[ Th_{Nozz \_w \_pvec}(jj, jjj) = m_{Nozz \_w \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_w \_pvec}; \]

\[ Isp_{Nozz \_w \_pvec}(jj, jjj) = \frac{U_{eq \_Nozz \_w \_pvec}}{g_0}; \]

\[ P_{j \_Nozz \_w \_pvec}(jj, jjj) = \frac{1}{2} \cdot Th_{Nozz \_w \_pvec}(jj, jjj) \cdot U_{eq \_Nozz \_w \_pvec}; \]

\[ P_{in \_Nozz \_w \_pvec}(jj, jjj) = m_{Nozz \_w \_pvec}(jj, jjj) \cdot (H_{out \_pvec} - H_{in}); \]

\[ Effic_{Nozz \_w \_pvec}(jj, jjj) = \frac{P_{j \_Nozz \_w \_pvec}(jj, jjj)}{P_{in \_Nozz \_w \_pvec}(jj, jjj)}. \]
Dtube_DUR1 = 2.5+m_vec*0; %[mm]
Dtube_DUR2 = 1.3+m_vec*0; %[mm]
m_in = input(‘\ Mass flow, in g/s: ‘);
T_in = input(‘\ Flow temperature, in K: ‘);
if isempty(m_in)
    m_in = 12 % mass flow in g/s
    sprintf(‘Mass flow of, g/s: %.4f’, m_in)
end
if isempty(T_in)
    T_in = 1000; % mass flow in g/s
    sprintf(‘Flow temperature, K: %.4f’, T_in)
end
rho_in = computeRho(species,T_in,p);
if rho < 100 % Vapour
    vp_in = 175*(1/rho_in)^0.43;
else
    vp_in = 7;
end
Dtube_in = sqrt(4*m_in*10^-3/(rho_in*pi*vp_in))*1000; %[mm]
sprintf(‘Minimum inner diameter, mm: %.4f’, Dtube_in)

% function MinL = computeMinL (m,dtube,Dcoil, Ti, To, Two, species, correlation)
% computeMinL (m,dtube,Dcoil, Ti, To, Two, species, correlation)
% Compute the length for liquid part
% m:         mass flow                    [g/s]
% dtube:         Diameter of the tube         [m]
% Dcoil:         Diameter of the coil         [m]
% Ti:        initial bulk temperature     [K]
% To:        final bulk temperature       [K]
% Two:        final wall temperature       [K]
% (+10% than To)
% species:        ‘H2O’
% Correlation:    ‘coil’ for coiled tube
% ‘straight’ for straight tube
%
% Rodrigo A. Ferreira
% 2007-2008
% m =24.36*10^-3;
dtube = 1.3*10^-3;
Dcoil=25*10^-3;
Ti =295;
To= 1000;
Two= 1100;
species= ‘H2O’;
correlation='coil';
p = 2;
m = m/1000;
W = computeM(species); %[kg/mol]
H_in = computeEnthalpy(species, Ti,p)/M; % [J/kg]
H_out = computeEnthalpy(species, To,p)/M; % [J/kg]
qin = m*(H_out-H_in) % [W]
%
% Density [kg/m^3]
rho = computeRho(species,To,p);
%
% Viscosity [Pas]
mu = computeMu(species, To);
uwo = computeMu(species, Two);
%
% Specific heat [J/kg/K]
Cp = computeCp(species, To); %[J/mol/K]
M = computeM(species);
cp = Cp/M;
%
% Thermal conductivity [W/m/K]
k = computeK(species, To);
Pr = m*cp/k
Re = 4*m/(pi*dtube*mu)
if(strcmp(correlation, ‘coil’) == true)
    Re_crit = 2100*(1+12*(dtube/Dcoil)^0.5)
end
if(strcmp(correlation, ‘straight’) == true)
if Re < 2300
    Nu = 4.364
else
    if abs(To-Two)>56
        if (Re>10^4) && (Pr >= 0.5) && (Pr <= 16700)
            Nu3 = 0.027*Re^(-4/5)*Pr^(-1/3)*(mu/mu_w)^0.14
        else
            Nu = 0.023*Re^(-4/5)*Pr^(-0.4)*(To/Two)^0.36
        end
    end
end
\[ Nu_2 = 0.023*Re^{4/5}*Pr^{0.4}*(To/Two)^{0.47} \]

else
\[ Nu = 0.023*Re^{4/5}*Pr^{0.4} \]
end

elseif(strcmp(correlation, 'coil') == true)
if Re < Re_crit
  if (Pr > 5) && (Pr < 175)
    Nu = 0.76*0.65*Re^{0.5}*(dtube/Dcoil)^{0.25}*Pr^{0.175}
  else
    Nu = 0.913*(Re*(dtube/Dcoil)^{0.5})*0.476*Pr^{0.2}
  end
else
  if (Re>6000) && (Re<100000)
    Nu = 0.023*Re^{0.85}*Pr^{0.4}*(dtube/Dcoil)^{0.1}
  else
    if (Re*(dtube/Dcoil)^2) > 0.1 && Pr > 0.9 && Pr < 1.1
      Nu = Re^{0.8}*Pr^{0.4}*(dtube/Dcoil)^{0.1}*(26.2*(Pr^{2/3})-0.074)^{-1}(1+0.098/(Re^{2}(dtube/Dcoil)^{2})^{-1/3})
    end
  end
end
end

\[ h = Nu*k/dtube \]
\[ L = qin/(pi*dtube*h*(Two-To)) \]

% Vectors for plots
% Straight tube
m_vec = 0 : 0.1*10^{-3}/1000: 0.1*10^{-3};
qin_s = m_vec*(H_out-H_in);
Re_s = 4*m_vec/(pi*dtube*mu);
Nu_s = zeros(1,length(m_vec));
Nu2_s = zeros(1,length(m_vec));
Nu3_s = zeros(1,length(m_vec));
for i=1:length(m_vec)
  if Re_s(i) < 2300
    Nu_s(i) = 4.364;
    Nu2_s(i) = 4.364;
    Nu3_s(i) = 4.364;
  else
    if (abs(To-Two))>56
      if (Re_s(i)>10^4) && (Pr>=0.5) && (Pr<=16700)
        Nu_s(i) = 0.027*Re_s(i)^{4/5}*Pr^{1/3}*(mu/mu_wo)^{0.14}; % Sieder and Tate
        Nu2_s(i) = 0.027*Re_s(i)^{4/5}*Pr^{1/3}*(mu/mu_wo)^{0.14};
        Nu3_s(i) = 0.027*Re_s(i)^{4/5}*Pr^{1/3}*(mu/mu_wo)^{0.14};
      elseif Re_s(i)*(dtube/Dcoil)^2 > 0.1 && Pr > 0.9 && Pr < 1.1
        Nu_s(i) = 0.027*Re_s(i)^{4/5}*Pr^{1/3}*(mu/mu_wo)^{0.14}; % Sieder and Tate
      end
    end
  end
end

h_s = Nu_s.*k/dtube;
h2_s = Nu2_s.*k/dtube;
h3_s = Nu3_s.*k/dtube;
L_s = qin_s./(pi.*dtube.*h_s.*(Two-To));
L2_s = qin_s./(pi.*dtube.*h2_s.*(Two-To));
L3_s = qin_s./(pi.*dtube.*h3_s.*(Two-To));

% Coiled tube
m_vec = 0 : 0.1*10^{-3}/1000: 0.1*10^{-3};
qin_c = m_vec*(H_out-H_in);
Re_c = 4*m_vec/(pi*dtube*mu);
Re_crit = 2100*(1+12*(dtube/Dcoil)^0.5);
Nu_c = zeros(1,length(m_vec));
Nu2_c = zeros(1,length(m_vec));
for i=1:length(m_vec)
  if Re_c(i) < Re_crit
    if Pr > 5 && Pr < 175
      Nu_c(i) = (0.76+0.65*Re_c(i)^{0.5}*(dtube/Dcoil)^{0.25})*Pr^{0.175}; % Naphon correlation
    elseif (Re_c(i)^{2} > 0.1 && Pr > 0.9 && Pr < 1.1
      Nu_c(i) = 0.913*(Re_c(i)^{2})*(dtube/Dcoil)^{0.5})*0.476*Pr^{0.2}; % Kalb correlation
    else
      Nu_c(i) = Re_c(i)^{0.8}*(dtube/Dcoil)^{0.1}*(26.2*(Pr^{2/3})-0.074)^{-1}(1+0.098/(Re_c(i)^{2})*(dtube/Dcoil)^{2})^{-1/3}; % Mori correlation
    end
  end
end

% Vectors for plots
Nu_c(i) = 0.913.*(Re_c(i)*(dtube/Dcoil)^0.5)^0.476*Pr^0.2;% Kalb correlation
Nu2_c(i) = Re_c(i)^0.8*Pr*(dtube/Dcoil)^0.1/(26.2*(Pr^2/3)-0.074)\*(1+0.098/(Re(i)*(dtube/Dcoil)^2)^1/3));% Mori correlation
end
else
if Re_c(i)*(dtube/Dcoil)^2 > 0.1 \&\& Pr > 0.9 \&\& Pr < 1.1
Nu_c(i) = Re_c(i)^0.8*Pr*(dtube/Dcoil)^0.1/(26.2*(Pr^2/3)-0.074)\*(1+0.098/(Re_c(i)*(dtube/Dcoil)^2)^1/3));% Mori correlation
Nu2_c(i) = Re_c(i)^0.8*Pr*(dtube/Dcoil)^0.1/(26.2*(Pr^2/3)-0.074)\*(1+0.098/(Re_c(i)*(dtube/Dcoil)^2)^1/3));
else
Nu_c(i) = 0.023*Re_c(i)^0.85*Pr^0.4*(dtube/Dcoil)^0.1%;% Seban-McLaughlin correlation
Nu2_c(i) = 0.023*Re_c(i)^0.85*Pr^0.4*(dtube/Dcoil)^0.1;
end
end
end
h_c = Nu_c.*k/dtube;
h2_c = Nu2_c.*k/dtube;
L_c = qin_c./(pi.*dtube.*h_c.*(Two-To));
L2_c = qin_c./(pi.*dtube.*h2_c.*(Two-To));

% Porous media
d_p = 1*10^-3;%[m]
qin_p = m_vec*(H_out-H_in);
Dtube_p = 8.9*10^-3;
v_s = 4*m_vec/(pi.*Dtube_p^2*rho);
Re_books = d_p*rho/mu.*v_s;
Nu_p=zeros(1,length(m_vec));
Nu1_p=zeros(1,length(m_vec));
Nu2_p=zeros(1,length(m_vec));
for i=1:1:length(m_vec)
if (Re_books(i)^0.6*Pr^(1/3))^2 < 10^5
if Re_books(i) < 10 \&\& rho > 100
Nu_p(i) = 0.16*Re_books(i)^1.6*Pr^(1/3);%Levenspiel
Nu1_p(i) = 2+1.1*Re_books(i)^0.6*Pr^(1/3);%Wakao and Kaguei
Nu2_p(i) = 1.82*Re_books(i)^0.49*Pr^(1/3);%Balmer1
else
Nu_p(i) = 0.012*Re_books(i)^1.6*Pr^(1/3);%Rosenhow and Levenspiel
Nu1_p(i) = 2+1.1*Re_books(i)^0.6*Pr^(1/3);%Wakao and Kaguei
Nu2_p(i) = 1.82*Re_books(i)^0.49*Pr^(1/3);%Balmer1
else
Nu_p(i) = 2+1.8*Re_books(i)^1/2*Pr^(1/3);%Rosenhow and Levenspiel
Nu1_p(i) = 2+1.1*Re_books(i)^0.6*Pr^(1/3);%Wakao and Kaguei
Nu2_p(i) = 0.989*Re_books(i)^0.5*Pr^(1/3);%Balmer2
end
% Nu_p(i) = 0.012*Re_books(i)^1.6*Pr^(1/3);%Rosenhow and Levenspiel
Nu_p(i) = 2+1.1*Re_books(i)^0.6*Pr^(1/3);%Wakao and Kaguei
Nu2_p(i) = 0.989*Re_books(i)^0.5*Pr^(1/3);%Balmer2
end
end
h_p = Nu_p.*k/d_p;
h1_p = Nu1_p.*k/d_p;
h2_p = Nu2_p.*k/d_p;
L_p = qin_p./(pi.*Dtube_p.*h_p.*(Two-To));
L1_p = qin_p./(pi.*Dtube_p.*h1_p.*(Two-To));
L2_p = qin_p./(pi.*Dtube_p.*h2_p.*(Two-To));

% For DUR10 and DUR11
dtube1 = 2.5*10^-3;
Dcoil1 = 40*10^-3;
qin_c = m_vec*(H_out-H_in);
Re_c1 = 4*m_vec/(pi.*dtube1*mu);
Re_crit1 = 2100*(1+12*(dtube1/Dcoil1)^0.5);
Nu_c1=zeros(1,length(m_vec));
for i=1:1:length(m_vec)
if Re_c1(i) < Re_crit1
if Pr > 5 \&\& Pr < 175
Nu_c1(i) = (0.76+0.65*Re_c1(i)^0.5*(dtube1/Dcoil1)^0.25)*Pr^0.175;% Naphon correlation
else
Nu_c1(i) = 0.913.*(Re_c1(i)*(dtube1/Dcoil1)^0.5)^0.476*Pr^0.2;% Kalb correlation
end
else
if Re_c1(i)*(dtube1/Dcoil1)^2 > 0.1 \&\& Pr > 0.9 \&\& Pr < 1.1
Nu_c1(i) = Re_c1(i)^0.8*Pr*(dtube1/Dcoil1)^0.1/(26.2*(Pr^2/3)-0.074)\*(1+0.098/(Re_c1(i)*(dtube1/Dcoil1)^2)^1/3));% Mori correlation
else
Nu_c1(i) = 0.023*Re_c1(i)^0.85*Pr^0.4*(dtube1/Dcoil1)^0.1;
else
    \( \text{Nu}_{c1}(i) = 0.023 \times \text{Re}_{c1}(i)^{0.85} \times \text{Pr}^{0.4} \times (\text{dtube1}/\text{Dcoil1})^{0.1} \);
end
end
end

\( \text{h}_c_{D25} = \text{Nu}_{c1} \times k/\text{dtube1} ; \)
\( \text{L}_{D25} = \text{qin}_{\text{C}} \times (\pi \times \text{dtube1} \times \text{h}_c_{D25} \times (\text{Two}-\text{To})) ; \)

% For DUR2
\( \text{dtube2} = 1.3 \times 10^{-3} ; \)
\( \text{Dcoil2} = 13 \times 10^{-3} ; \ % \text{main loops} \)
\( \text{qin}_c = \text{m}_{\text{vec}} \times (\text{H}_{\text{out}}-\text{H}_{\text{in}}) ; \)
\( \text{Re}_{c2} = 4 \times \text{m}_{\text{vec}} / (\pi \times \text{dtube2} \times \mu) ; \)
\( \text{Re}_{\text{crit2}} = 2100 * (1+12 \times (\text{dtube2}/\text{Dcoil2})^{0.5}) ; \)
\( \text{Nu}_{c2} = \text{zeros}(1, \text{length}(\text{m}_{\text{vec}})) ; \)
for i=1:1:length(\text{m}_{\text{vec}})
if \( \text{Re}_{c2}(i) < \text{Re}_{\text{crit2}} \)
    if \( \text{Pr} > 5 \ % \& \text{Pr} < 175 \)
        \( \text{Nu}_{c2}(i) = (0.76+0.65 \times \text{Re}_{c2}(i)^{0.5} \times (\text{dtube2}/\text{Dcoil2})^{0.25}) \times \text{Pr}^{0.175} ; \)
    else
        \( \text{Nu}_{c2}(i) = 0.913 \times (\text{Re}_{c2}(i) \times (\text{dtube2}/\text{Dcoil2})^{0.5})^{0.476} \times \text{Pr}^{0.2} ; \)
    end
else
    if \( \text{Re}_{c2}(i) \times (\text{dtube2}/\text{Dcoil2})^2 > 0.1 \ % \& \text{Pr} < 0.9 \ % \& \text{Pr} < 1.1 \)
        \( \text{Nu}_{c2}(i) = (\text{Re}_{c2}(i)^{0.8} \times \text{Pr} \times (\text{dtube2}/\text{Dcoil2})^{0.1} / (26.2 \times (\text{Pr}^{(2/3)}-0.074))) \times (1+0.098 / \text{Re}_{c2}(i) \times (\text{dtube2}/\text{Dcoil2})^2)^{(1/3)} ; \)
    else
        \( \text{Nu}_{c2}(i) = 0.023 \times \text{Re}_{c2}(i)^{0.85} \times \text{Pr}^{0.4} \times (\text{dtube2}/\text{Dcoil2})^{0.1} ; \)
    end
end
end

\( \text{h}_c_{D13} = \text{Nu}_{c2} \times k/\text{dtube2} ; \)
\( \text{L}_{D13} = \text{qin}_{\text{C}} / (\pi \times \text{dtube2} \times \text{h}_c_{D13} \times (\text{Two}-\text{To})) ; \)

% For New design
\( \text{qin}_c = \text{m}_{\text{vec}} \times (\text{H}_{\text{out}}-\text{H}_{\text{in}}) ; \)
\( \text{Re}_{c3} = 4 \times \text{m}_{\text{vec}} / (\pi \times \text{dtube} \times \mu) ; \)
\( \text{Re}_{\text{crit3}} = 2100 \times (1+12 \times (\text{dtube}/\text{Dcoil})^{0.5}) ; \)
\( \text{Nu}_{c3} = \text{zeros}(1, \text{length}(\text{m}_{\text{vec}})) ; \)
for i=1:1:length(\text{m}_{\text{vec}})
if \( \text{Re}_{c3}(i) < \text{Re}_{\text{crit3}} \)
    if \( \text{Pr} > 5 \ % \& \text{Pr} < 175 \)
        \( \text{Nu}_{c3}(i) = (0.76+0.65 \times \text{Re}_{c3}(i)^{0.5} \times (\text{dtube}/\text{Dcoil})^{0.25}) \times \text{Pr}^{0.175} ; \)
    else
        \( \text{Nu}_{c3}(i) = 0.913 \times (\text{Re}_{c3}(i) \times (\text{dtube}/\text{Dcoil})^{0.5})^{0.476} \times \text{Pr}^{0.2} ; \)
    end
else
    if \( \text{Re}_{c3}(i) \times (\text{dtube}/\text{Dcoil})^2 > 0.1 \ % \& \text{Pr} < 0.9 \ % \& \text{Pr} < 1.1 \)
        \( \text{Nu}_{c3}(i) = (\text{Re}_{c3}(i)^{0.8} \times \text{Pr} \times (\text{dtube}/\text{Dcoil})^{0.1} / (26.2 \times (\text{Pr}^{(2/3)}-0.074))) \times (1+0.098 / \text{Re}_{c3}(i) \times (\text{dtube}/\text{Dcoil})^2)^{(1/3)} ; \)
    else
        \( \text{Nu}_{c3}(i) = 0.023 \times \text{Re}_{c3}(i)^{0.85} \times \text{Pr}^{0.4} \times (\text{dtube}/\text{Dcoil})^{0.1} ; \)
    end
end
end

\( \text{h}_c_{\text{new}} = \text{Nu}_{c3} \times k/\text{dtube} ; \)
\( \text{L}_{\text{new}} = \text{qin}_{\text{C}} / (\pi \times \text{dtube} \times \text{h}_c_{\text{new}} \times (\text{Two}-\text{To})) ; \)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\[ RA = 8.314472; \quad [J/(molK)] \]
\[ gama = Cp/(Cp-RA); \]
\[ Gama = (gama)^{(1/2)}*2/(gama+1)^{((gama+1)/(2*(gama-1)))}; \]
\[ m_Nozz(j) = \pi*Dt_w^2/4*p*10^5*Gama/(RA/M*Tc_vect(j))^{(1/2)}; \]
\[ H_in = computeEnthalpy(species, Ti_p)/M; \quad [J/kg] \]
\[ H_out = computeEnthalpy(species, Tc_vect(j),p)/M; \quad [J/kg] \]
\[ qin_N(j) = m_Nozz(j)*(H_out-H_in); \]
\[ % Straight tube \]
\[ Re_sN(j) = 4*m_Nozz(j)/(\pi*dtube_sc*mu); \]
if \[ Re_sN(j) < 2300 \]
\[ Nu_sN(j) = 4.364; \]
\[ Nu2_sN(j) = 4.364; \]
\[ Nu3_sN(j) = 4.364; \]
else
if \[ abs(Tc_vect-Tc_w) > 56 \]
if \[ (Re_sN(j) > 10^4) && (Pr >= 0.5) && (Pr <= 16700) \]
\[ Nu_sN(j) = 0.027*Re_sN(j)^{(4/5)}*Pr^{(1/3)}*(mu/mu_wo)^{0.14}; \quad %Sieder and Tate \]
\[ Nu2_sN(j) = 0.027*Re_sN(j)^{(4/5)}*Pr^{(1/3)}*(mu/mu_wo)^{0.14}; \]
\[ Nu3_sN(j) = 0.027*Re_sN(j)^{(4/5)}*Pr^{(1/3)}*(mu/mu_wo)^{0.14}; \]
else
\[ Nu_sN(j) = 0.023*Re_sN(j)^{(4/5)}*Pr^{0.4}*(Tc_vect(j)/Tc_w(j))^{0.36}; \quad % Dittus Boelter and \]
CHEMSOURCE
\[ Nu2_sN(j) = 0.023*Re_sN(j)^{(4/5)}*Pr^{0.4}*(Tc_vect(j)/Tc_w(j))^{0.47}; \quad % Dittus Boelter \]
and Pethukov
\[ Nu3_sN(j) = 0.027*Re_sN(j)^{(4/5)}*Pr^{(1/3)}*(mu/mu_wo)^{0.14}; \quad %Sieder and Tate \]
end
end
\[ h_sN(j) = Nu_sN(j)*k/dtube_sc; \]
\[ h2_sN(j) = Nu2_sN(j)*k/dtube_sc; \]
\[ h3_sN(j) = Nu3_sN(j)*k/dtube_sc; \]
\[ L_sN(j) = qin_N(j)/(\pi*dtube_sc*h_sN(j)*(Tc_w(j)-Tc_vect(j))); \]
\[ L2_sN(j) = qin_N(j)/(\pi*dtube_sc*h2_sN(j)*(Tc_w(j)-Tc_vect(j))); \]
\[ L3_sN(j) = qin_N(j)/(\pi*dtube_sc*h3_sN(j)*(Tc_w(j)-Tc_vect(j))); \]
% Coiled tube
\[ Re_cN(j) = Re_sN(j); \]
if \[ Re_cN(j) < Re_critN \]
if \[ Pr > 5 \quad && \quad Pr < 175 \]
\[ Nu_cN(j) = (0.76+0.65*Re_cN(j)^0.5*(dtube_sc/Dcoil)^0.25)*Pr^{0.175}; \quad %Naphon correlation \]
\[ Nu2_cN(j) = (0.76+0.65*Re_cN(j)^0.5*(dtube_sc/Dcoil)^0.25)*Pr^{0.175}; \quad %Naphon correlation \]
else
\[ Nu_cN(j) = 0.913*(Re_cN(j)^0.8*Pr^{0.4}*(dtube_sc/Dcoil)^0.1)/(26.2*(Pr^{(2/3)}-0.074)^{(1.0+0.998*(Re_cN(j)^7*(dtube_sc/Dcoil)^2)^{1/3})}); \quad % Mori correlation \]
\[ Nu2_cN(j) = 0.913*(Re_cN(j)^0.8*Pr^{0.4}*(dtube_sc/Dcoil)^0.1)/(26.2*(Pr^{(2/3)}-0.074)^{(1.0+0.998*(Re_cN(j)^7*(dtube_sc/Dcoil)^2)^{1/3})}); \quad % Mori correlation \]
else
\[ Nu_cN(j) = 0.023*Re_cN(j)^0.85*Pr^{0.4}*(dtube_sc/Dcoil)^0.1; \quad % Seban-McLaughlin correlation \]
\[ Nu2_cN(j) = 0.023*Re_cN(j)^0.85*Pr^{0.4}*(dtube_sc/Dcoil)^0.1; \]
end
\[ h_cN(j) = Nu_cN(j)*k/dtube_sc; \]
\[ h2_cN(j) = Nu2_cN(j)*k/dtube_sc; \]
\[ L_cN(j) = qin_N(j)/(\pi*dtube_sc*h_cN(j)*(Tc_w(j)-Tc_vect(j))); \]
\[ L2_cN(j) = qin_N(j)/(\pi*dtube_sc*h2_cN(j)*(Tc_w(j)-Tc_vect(j))); \]
% Porous media
\[ d_p = 1*10^{-3}; \quad [m] \]
\[ Dtube_p = 8.5*10^{-3}; \quad % From packed bed available at Space systems eng. \]
\[ v_s = 4*m_Nozz(j)/(\pi*Dtube_p^2*rho); \]
\[ Re_booksN(j) = d_p*rho/mu.*v_s; \]
if \[ (Re_booksN(j)^0.6*Pr^{(1/3)})^2 > 10^5 \]
if \[ Re_booksN(j) < 10 \quad && \quad rho > 100 \quad % for liquids \]
\[ Nu_pN(j) = 0.16*Re_booksN(j)^{1.6}*Pr^{(1/3)}; \quad %Levenspiel \]
\[ Nu1_pN(j) = 2+1.1*Re_booksN(j)^{0.6}*Pr^{(1/3)}; \quad %Wakao and Raguil \]
Nu2_pN(j) = 1.82*Re_booksN(j)^0.49*Pr^(1/3);%Balmer1

elseif Re_booksN(j) < 100 && rho < 100
%for gases
Nu_pN(j) = 0.012*Re_booksN(j)^1.6*Pr^(1/3);%Rosenhow and Levenspiel
Nu1_pN(j) = 2+1.1*Re_booksN(j)^0.6*Pr^(1/3);%Wakao and Kaguei
Nu2_pN(j) = 1.82*Re_booksN(j)^0.49*Pr^(1/3);%Balmer1

else
Nu_pN(j) = 2+1.8*Re_booksN(j)^0.59*Pr^(1/3);%Balmer2
end

h_pN(j) = Nu_pN(j)*k/d_p;

% For DUR10 and DUR11
dtube1 = 2.5*10^-3;
Dcoil1 = 40*10^-3;
Re_cN1(j) = 4*m_Nozz(j)/(pi*dtube1*mu);
Re_critN1 = 2100*(1+12*(dtube1/Dcoil1)^0.5);
Nu_cN1 = zeros(1,length(Tc_vect));
for i=1:length(Tc_vect)
if Re_cN1(j) < Re_critN1
if Pr > 5 && Pr < 175
Nu_cN1(j) = (0.76+0.65*Re_cN1(j)^0.5)*(dtube1/Dcoil1)^0.25*Pr*0.175;% Naphon correlation
else
Nu_cN1(j) = 0.913.*(Re_cN1(j)^0.5)*(dtube1/Dcoil1)^0.1; % Kalb correlation
end
else
if Re_cN1(j)>(dtube1/Dcoil1)^2 > 0.1 && Pr > 0.9 && Pr < 1.1
Nu_cN1(j) = (dtube1/Dcoil1)^0.1/(26.2*(Pr^(2/3))-0.074+0.098/(Re_cN1(j)^2)*(dtube1/Dcoil1)^2)^0.5;
else
Nu_cN1(j) = 0.023*Re_cN1(j)^0.85*Pr*0.4*(dtube1/Dcoil1)^0.1;
end
end

h_c_D25_N(j) = Nu_cN1(j)*k/dtube1;
L_D25_N(j) = qin_N(j)/(pi*dtube1*h_c_D25_N(j)*(Tc_w(j)-Tc_vect(j)));

% For DUR2
dtube2 = 1.3*10^-3;
Dcoil2 = 13*10^-3;
Re_cN2(j) = 4*m_Nozz(j)/(pi*dtube2*mu);
Re_critN2 = 2100*(1+12*(dtube2/Dcoil2)^0.5);
Nu_cN2 = zeros(1,length(Tc_vect));
for i=1:length(Tc_vect)
if Re_cN2(j) < Re_critN2
if Pr > 5 && Pr < 175
Nu_cN2(j) = (0.76+0.65*Re_cN2(j)^0.5)*(dtube2/Dcoil2)^0.25*Pr*0.175;
else
Nu_cN2(j) = 0.913.*(Re_cN2(j)^0.5)*(dtube2/Dcoil12)^0.1; % Kalb correlation
end
else
if Re_cN2(j)>(dtube2/Dcoil2)^2 > 0.1 && Pr > 0.9 && Pr < 1.1
Nu_cN2(j) = (dtube2/Dcoil2)^0.1/(26.2*(Pr^(2/3))-0.074+0.098/(Re_cN2(j)^2)*(dtube2/Dcoil2)^2)^0.5;
else
Nu_cN2(j) = 0.023*Re_cN2(j)^0.85*Pr*0.4*(dtube2/Dcoil2)^0.1;
end
end

h_c_D13_N(j) = Nu_cN2(j)*k/dtube2;
L_D13_N(j) = qin_N(j)/(pi*dtube2*h_c_D13_N(j)*(Tc_w(j)-Tc_vect(j)));

% For New design
Re_cN3(j) = 4*m_Nozz(j)/(pi*dtube2*mu);
for i=1:1:length(Tc_vect)
    if Re_cN3(j) < Re_critN3
        if Pr > 5 && Pr < 175
            Nu_cN3(j) = (0.76 + 0.65*Re_cN3(j)^0.5*(dtube/Dcoil)^0.25)*Pr^0.175;
        else
            Nu_cN3(j) = 0.913*(Re_cN3(j)*((dtube/Dcoil)^0.5)^0.476*Pr^0.2;
        end
    else
        if Re_cN3(j)*((dtube/Dcoil)^2 > 0.1 && Pr > 0.9 && Pr < 1.1
            Nu_cN3(j) = Re_cN3(j)^0.8*Pr*(dtube/Dcoil)^0.1/(26.2*(Pr^2/3)-
            0.074)**(1+0.098*(Re_cN3(j)*((dtube/Dcoil)^2)*(1/3));
        else
            Nu_cN3(j) = 0.023*Re_cN3(j)^0.85*Pr^0.4*(dtube/Dcoil)^0.1;
        end
    end
end

end

for j=1:1:length(Tc_vect)
    mu = computeMu(species, Tc_vect(j));
    Re_vec_1(:,j) = 4*m_vec/(pi*dtube1*mu);
    Re_vec_2(:,j) = 4*m_vec/(pi*dtube2*mu);
end

% L_DUR10 = 0.95*m_vec*0; %[m]
L_DUR11 = 2.00+m_vec*0; %[m]
L_DUR20 = 0.12+m_vec*0; %[m]
L_DUR10_N = 0.95*Tc_vect*0; %[m]
L_DUR11_N = 2.00*Tc_vect*0; %[m]
L_DUR20_N = 0.12*Tc_vect*0; %[m]

m_vec = m_vec*10^6;

% function DP = computeMinDP(species, Ltotal, D, Dcoil, Ti, To, correlation_l, correlation_g)

% Input parameters
Ti=295;
To=500;
% p = 1.98; %[bar]
p = 2;

Ltotal=0.70;
% Ltotal=0.95;
% D=2.5*10^-3;
D=1.3*10^-3;
Dcoil=40*10^-3;
Dcoil=25*10^-3;

% correlation_l='ito'; %coiled tube
% correlation_g='ito';

A = pi * D^2 / 4;
Tboil_l = 393.36-1e-6;%[K]
Tboil_g = 393.36+1e-6;%[K]

% m_vec = 0.3*10^-3/30 : 0.3*10^-3/30: 0.3*10^-3; %[kg/s]
m_vec = 10^-6:90*10^-6/25:100*10^-6;

M = computeM(species);
H_in = computeEnthalpy(species, Ti,p)/M; % [J/kg]
H_out = computeEnthalpy(species, To,p)/M; % [J/kg]
H_boil_l = computeEnthalpy(species, Tboil_l,p)/M; % [J/kg]
H_boil_g = computeEnthalpy(species, Tboil_g,p)/M % [J/kg]

q_total = m_vec.*(H_out-H_in); %[W]
q_1 = m_vec.*(H_boil_l-H_in); %[W]
if To < Tboil_l
    q_2ph = 0; %[W]
    q_g = 0; %[W]
else
    q_2ph = m_vec.*(H_boil_l-H_boil_g); %[W]
    q_g = m_vec.*(H_out-H_boil_g); %[W]
end
\[ L_l = L_{total} \cdot q_{l}/q_{total} \; \text{[m]} \]
\[ L_{2ph} = L_{total} \cdot q_{2ph}/q_{total} \; \text{[m]} \]
\[ L_g = L_{total} \cdot q_{g}/q_{total} \; \text{[m]} \]

% Liquid part
if \( T_0 < T_{boil_l} \)
    \( T_{l_vec} = T_i:0.1:T_{boil_l} \);
else
    \( T_{l_vec} = T_i:0.1:T_{boil_l} \);
end
\( \rho_{l_vec} = zeros(1, length(T_{l_vec})) \);
for \( j = 1:length(T_{l_vec}) \)
    \( \rho_{l_vec}(j) = computeRho(species, T_{l_vec}(j), p) \);
end
\( \rho_{l_mean} = mean(\rho_{l_vec}); \)
\( v_{l_vec} = zeros(length(m_vec), length(T_{l_vec})) \);
\( f_{l_vec} = zeros(length(m_vec), length(T_{l_vec})) \);
\( v_{l_mean} = zeros(1, length(m_vec)) \);
\( f_{l_mean} = zeros(1, length(m_vec)) \);
\( \delta P_{l_mean} = zeros(1, length(m_vec)); \)
\( \delta P_{l_mean_s} = zeros(1, length(m_vec)); \)
for \( j = 1:length(m_vec) \)
    \( v_{l_vec}(j,:) = m_vec(j)/A .* \rho_{l_vec}(j)^{-1}; \)
    \( f_{l_vec}(j,:) = computeF(species, D, Dcoil, T_{l_vec}, m_vec(j), \text{correlation}_l); \)
end
\( \delta P_{l_mean}(j) = 1/2 * f_{l_mean}(j) * L_l(j)/D * \rho_{l_mean} \cdot v_{l_mean}(j)^2; \)
\( \delta P_{l_mean_s}(j) = 1/2 * f_{l_mean_s}(j) * L_l(j)/D * \rho_{l_mean} \cdot v_{l_mean}(j)^2; \)

% Vapour part
if \( T_0 > T_{boil_g} \)
    \( T_{g_vec} = T_{boil_g}:0.1:T_0; \)
    \( \rho_{g_vec} = zeros(1, length(T_{g_vec})) \);
for \( j = 1:length(T_{g_vec}) \)
    \( \rho_{g_vec}(j) = computeRho(species, T_{g_vec}(j), p) \);
end
\( \rho_{g_mean} = mean(\rho_{g_vec}); \)
\( v_{g_vec} = zeros(length(m_vec), length(T_{g_vec})) \);
\( f_{g_vec} = zeros(length(m_vec), length(T_{g_vec})) \);
\( v_{g_mean} = zeros(1, length(m_vec)) \);
\( f_{g_mean} = zeros(1, length(m_vec)) \);
\( \delta P_{g_mean} = zeros(1, length(m_vec)); \)
\( \delta P_{g_mean_s} = zeros(1, length(m_vec)); \)
for \( j = 1:length(m_vec) \)
    \( v_{g_vec}(j,:) = m_vec(j)/A .* \rho_{g_vec}(j)^{-1}; \)
    \( f_{g_vec}(j,:) = computeF(species, D, Dcoil, T_{g_vec}, m_vec(j), \text{correlation}_g); \)
end
\( \delta P_{g_mean}(j) = 1/2 * f_{g_mean}(j) \cdot L_g(j)/D * \rho_{g_mean} \cdot v_{g_mean}(j)^2; \)
\( \delta P_{g_mean_s}(j) = 1/2 * f_{g_mean_s}(j) \cdot L_g(j)/D * \rho_{g_mean} \cdot v_{g_mean}(j)^2; \)
else
    \( \delta P_{g_mean} = zeros(1, length(m_vec)); \)
    \( \delta P_{g_mean_s} = zeros(1, length(m_vec)); \)
end

% Two-phase flow
if \( T_0 > T_{boil_g} \)
    \( \rho_{lo} = computeRho(species, T_{boil}_l, p); \)
    \( \rho_{gi} = computeRho(species, T_{boil}_g, p); \)
    \( \mu_l = computeMu(species, T_{boil}_l); \)
    \( \mu_g = computeMu(species, T_{boil}_g); \)
    \( x = 0.5; \) % mean quality \( x = (x_i + x_o)/2 \)
    \( \eta = \arctan(\mu_l/\rho_{lo}) * 0.5 \cdot \mu_{gi}/\rho_{gi} \cdot 0.1 \cdot (1-x)^{0.9}; \)
    \( v_{lo} = zeros(1, length(m_vec)); \)
    \( f_{lo} = zeros(1, length(m_vec)); \)
    \( \delta P_{lo} = zeros(1, length(m_vec)); \)
    \( \delta P_{lo_s} = zeros(1, length(m_vec)); \)
end
deltaP_lo_c = zeros(1,length(m_vec));
ReD_l = zeros(1,length(m_vec));
deltaP_2ph = zeros(1,length(m_vec));
deltaP_2ph_s = zeros(1,length(m_vec));
deltaP_2ph_cl = zeros(1,length(m_vec));
deltaP_2ph_c2 = zeros(1,length(m_vec));
deltaPm = zeros(1,length(m_vec));
G = zeros(1,length(m_vec));
Psi = zeros(1,length(m_vec));

for j=1:1:length(m_vec)
    v_lo(j) = m_vec(j)/(rho_lo* A);
    f_lo(j) = computeF(species, D, Dcoil, Tboil_l, m_vec(j), correlation_l);
    f_lo_s(j) = computeF(species, D, Dcoil, Tboil_l, m_vec(j), 'straight');
    f_lo_c(j) = computeF(species, D, Dcoil, Tboil_l, m_vec(j), correlation_l);
    deltaP_lo(j) = 1/2*f_lo(j)*L2ph(j)/D*rho_lo*v_lo(j)^2;
    deltaP_lo_s(j) = 1/2*f_lo_s(j)*L2ph(j)/D*rho_lo*v_lo(j)^2;
    deltaP_lo_c(j) = 1/2*f_lo_c(j)*L2ph(j)/D*rho_lo*v_lo(j)^2;
    ReD_l(j) = 4*m_vec(j)/(pi*D*mu_l);
    ReD_g(j) = 4*m_vec(j)/(pi*D*mu_g);
    if ((ReD_l(j) < 2320) && (ReD_g(j) < 2320))
        C = 5; % laminar liquid and gas flows
    elseif ((ReD_l(j) >= 2320) && (ReD_g(j) < 2320))
        C = 10; % turbulent liquid, laminar gas flows
    elseif ((ReD_l(j) < 2320) && (ReD_g(j) >= 2320))
        C = 12; % laminar liquid, turbulent gas flows
    else
        C = 20; % turbulent liquid and gas flows
    end
    deltaP_2ph_s(j) = deltaP_lo_s(j) * (1 + C/X + 1/X^2); % 2-phase pressure drop straight tube,
    Lockhart-Martinelli correlation
    deltaP_2ph_cl(j) = deltaP_lo_s(j) * (1 + C/X + 1/X^2);
    if (strcmp(species, 'H2O') == true)
        Pcr = 22.115*10^6;
    else
        Pcr = 0; % For other species, another value should be found
    end
    Psi1 = 142.2*(p*10^5/Pcr)^0.62*(D/Dcoil)^1.04;
    G(j)=4*m_vec(j)/(pi*D^2); % Mass flow rate [kg/(m²s)]
    if G(j) <=1000
        Psi(j) = 1 + (x*(1-x)*(1000/G(j)-1)*(rho_lo/rho_gi))/(1+x*(rho_lo/rho_gi-1));
    else
        Psi(j) = 1 + (x*(1-x)*(1000/G(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
    end
    deltaP_2ph_cl(j) = deltaP_lo_c(j) * Psi(j) * Psi1 * (1 + x*(rho_lo/rho_gi-1)); % 2-phase pressure drop coiled tube, Guo's correlation
    deltaP_2ph_c(j) = deltaP_lo_c(j) * (1 + (4.25-2.55*x^1.5)*G(j)^0.34); % 2-phase pressure drop coiled tube, Guo’s first correlation

User input
if (strcmp(correlation_l, 'straight') == true) || (strcmp(correlation_g, 'straight') == true)
    if ((ReD_l(j) < 2320) && (ReD_g(j) < 2320))
        C = 5; % laminar liquid and gas flows
    elseif ((ReD_l(j) >= 2320) && (ReD_g(j) < 2320))
        C = 10; % turbulent liquid, laminar gas flows
    elseif ((ReD_l(j) < 2320) && (ReD_g(j) >= 2320))
        C = 12; % laminar liquid, turbulent gas flows
    else
        C = 20; % turbulent liquid and gas flows
    end
    deltaP_2ph(j) = deltaP_lo(j) * (1 + C/X + 1/X^2);
else
    if (strcmp(species, 'H2O') == true)
        Pcr = 22.115*10^6;
    else
        Pcr = 0;
    end
    Psi1 = 142.2*(p*10^5/Pcr)^0.62*(D/Dcoil)^1.04;
    G(j)=4*m_vec(j)/(pi*D^2); % Mass flow rate [kg/(m²s)]
    if G(j) <=1000
        Psi(j) = 1 + (x*(1-x)*(1000/G(j)-1)*(rho_lo/rho_gi))/(1+x*(rho_lo/rho_gi-1));
    else
        Psi(j) = 1 + (x*(1-x)*(1000/G(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
    end
    deltaP_2ph(j) = deltaP_lo(j) * Psi(j) * Psi1 * (1 + x*(rho_lo/rho_gi-1));
end
deltaPf_total_c = deltaP_l_mean.*10^-5+deltaP_2ph_c1.*10^-5+deltaP_g_mean.*10^-5;
deltaP_total_c = deltaPf_total_c + deltaPm.*10^-5;
deltaPf_total_s = deltaP_l_mean_s.*10^-5+deltaP_2ph_s.*10^-5+deltaP_g_mean_s.*10^-5;
deltaP_total_s = deltaPf_total_s + deltaPm.*10^-5;

% For DUR10
D_10 = 2.5*10^-3;
Dcoil_10 = 40*10^-3;
L_Total_10 = 0.095; %[m]
L1_10 = L_Total_10*q_1./q_total; %[m]
L2ph_10 = L_Total_10*q_2ph./q_total; %[m]
A_10 = pi * D_10 ^ 2 / 4;
L_total_10 = 0.95; %[m]

% Liquid part
v_l_vec_10 = zeros(length(m_vec),length(T_l_vec));
f_l_vec_10 = zeros(length(m_vec),length(T_l_vec));
v_l_mean_10 = zeros(1,length(m_vec));
f_l_mean_10 = zeros(1,length(m_vec));
deltaP_l_mean_10 = zeros(1,length(m_vec));
for j=1:1:length(m_vec)
    v_l_vec_10(j,:) = m_vec(j)/A_10.*rho_l_vec.^(-1);
f_l_vec_10(j,:) = computeF(species, D_10, Dcoil_10, T_l_vec, m_vec(j), correlation_l);
v_l_mean_10(j) = mean(v_l_vec_10(j,:));
f_l_mean_10(j) = mean(f_l_vec_10(j,:));
deltaP_l_mean_10(j) = 1/2*f_l_mean_10(j)*Ll_10(j)/D_10*rho_l_mean*v_l_mean_10(j)^2;
end

% Vapour part
if To > Tboil_g
    v_g_vec_10 = zeros(length(m_vec),length(T_g_vec));
f_g_vec_10 = zeros(length(m_vec),length(T_g_vec));
v_g_mean_10 = zeros(1,length(m_vec));
f_g_mean_10 = zeros(1,length(m_vec));
deltaP_g_mean_10 = zeros(1,length(m_vec));
for j=1:1:length(m_vec)
    v_g_vec_10(j,:) = m_vec(j)/A_10.*rho_g_vec.^(-1);
f_g_vec_10(j,:) = computeF(species, D_10, Dcoil_10, T_g_vec, m_vec(j), correlation_g);
v_g_mean_10(j) = mean(v_g_vec_10(j,:));
f_g_mean_10(j) = mean(f_g_vec_10(j,:));
deltaP_g_mean_10(j) = 1/2*f_g_mean_10(j)*Lg_10(j)/D_10*rho_g_mean*v_g_mean_10(j)^2;
end
else
    deltaP_g_mean_10 = zeros(1,length(m_vec));
end

% Two-phase flow
if To >= Tboil_g
    v_lo_10 = zeros(1,length(m_vec));
f_lo_10 = zeros(1,length(m_vec));
deltaP_lo_10 = zeros(1,length(m_vec));
ReD_l_10 = zeros(1,length(m_vec));
ReD_g_10 = zeros(1,length(m_vec));
deltaP_2ph_10 = zeros(1,length(m_vec));
G_10 = zeros(1,length(m_vec));
Psi_10 = zeros(1,length(m_vec));
for j=1:1:length(m_vec)
    v_lo_10(j) = m_vec(j)/(rho_lo* A_10);
f_lo_10(j) = computeF(species, D_10, Dcoil_10, Tboil_l, m_vec(j), correlation_l);
deltaP_lo_10(j) = 1/2*f_lo_10(j)*L2ph_10(j)/D_10*rho_lo*v_lo_10(j)^2;
ReD_l_10(j) = 4*m_vec(j)/(pi*D_10*mu_l);
ReD_g_10(j) = 4*m_vec(j)/(pi*D_10*mu_g);
    if strcmp(correlation_l, 'straight') == true || strcmp(correlation_g, 'straight') == true
        if (ReD_l_10(j) < 2320) && (ReD_g_10(j) < 2320)
            C = 5; % laminar liquid and gas flows
        elseif (ReD_l_10(j) >= 2320) && (ReD_g_10(j) < 2320)
            C = 10; % turbulent liquid, laminar gas flows
        elseif (ReD_l_10(j) < 2320) && (ReD_g_10(j) >= 2320)
            C = 12; % laminar liquid, turbulent gas flows
        else
            C = 10; % turbulent liquid, turbulent gas flows
    end
end

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else
    C = 20; % turbulent liquid and gas flows
end
deltaP_2ph_10(j) = deltaP_lo_10(j) * (1 + C/X + 1/X^2);
elseif ((strcmp(correlation_l, 'straight') == false) || (strcmp(correlation_g, 'straight') == false ))
    if (strcmp(species, 'H2O') == true)
        Pcr = 22.115*10^6;
    else
        Pcr = 0;
    end
    Psi1_10 = 142.2*(p*10^5/Pcr)^0.62*(D_10/Dcoil_10)^1.04;
    G_10(j)=4*m_vec(j)/(pi*D_10^2);
    deltaPm_10(j) = G_10(j)^2*(1/rho_gi-1/rho_lo); % Momentum pressure loss
    if G_10(j) <=1000
        Psi_10(j) = 1+ (x*(1-x)*(1000/G_10(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
    else
        Psi_10(j) = 1+ (x*(1-x)*(1000/G_10(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
    end
    deltaP_2ph_10(j) = deltaP_lo_10(j) * Psi_10(j) * Psi1_10 * (1 + x*(rho_lo/rho_gi-1));
end
else
deltaP_2ph_10 = zeros(1,length(m_vec));
end
deltaPf_total_10 = deltaP_l_mean_10.*10^-5+deltaP_2ph_10.*10^-5+deltaP_g_mean_10.*10^-5;
deltaP_total_10 = deltaPf_total_10 + deltaPm_10.*10^-5;

% For DUR1.1
D_11 = 2.5*10^-3;
Dcoil_11 = 40*10^-3;
A_11 = pi * D_11 ^ 2 / 4;
Ltotal_11 = 2; %[m]
Ll_11 = Ltotal_11*q_l./q_total; %[m]
L2ph_11 = Ltotal_11*q_2ph./q_total; %[m]
Lg_11 = Ltotal_11*q_g./q_total; %[m]

% Liquid part
v_l_vec_11 = zeros(length(m_vec),length(T_l_vec));
f_l_vec_11 = zeros(length(m_vec),length(T_l_vec));
v_l_mean_11 = zeros(1,length(m_vec));
f_l_mean_11 = zeros(1,length(m_vec));
deltaP_l_mean_11 = zeros(1,length(m_vec));
for j=1:1:length(m_vec)
    v_l_vec_11(j,:) = m_vec(j)/A_11.*rho_l_vec.^(-1);
    f_l_vec_11(j,:) = computeF(species, D_11, Dcoil_11, T_l_vec, m_vec(j), correlation_l);
    v_l_mean_11(j) = mean(v_l_vec_11(j,:));
    f_l_mean_11(j) = mean(f_l_vec_11(j,:));
    deltaP_l_mean_11(j) = 1/2*f_l_mean_11(j)*Ll_11(j)/D_11*rho_l_mean*v_l_mean_11(j)^2;
end
% Vapour part
if To >= Tboil_g
    v_g_vec_11 = zeros(length(m_vec),length(T_g_vec));
f_g_vec_11 = zeros(length(m_vec),length(T_g_vec));
v_g_mean_11 = zeros(1,length(m_vec));
f_g_mean_11 = zeros(1,length(m_vec));
deltaP_g_mean_11 = zeros(1,length(m_vec));
for j=1:1:length(m_vec)
    v_g_vec_11(j,:) = m_vec(j)/A_11.*rho_g_vec.^(-1);
    f_g_vec_11(j,:) = computeF(species, D_11, Dcoil_11, T_g_vec, m_vec(j), correlation_g);
    v_g_mean_11(j) = mean(v_g_vec_11(j,:));
    f_g_mean_11(j) = mean(f_g_vec_11(j,:));
    deltaP_g_mean_11(j) = 1/2*f_g_mean_11(j)*Lg_11(j)/D_11*rho_g_mean*v_g_mean_11(j)^2;
end
else
deltaP_g_mean_11 = zeros(1,length(m_vec));
end
% Two-phase flow
if To >= Tboil_g
    v_lo_11 = zeros(1,length(m_vec));
f_lo_11 = zeros(1,length(m_vec));
deltaP_lo_11 = zeros(1,length(m_vec));
ReD_l_11 = zeros(1,length(m_vec));
ReD_g_11 = zeros(1,length(m_vec));
deltaP_2ph_11 = zeros(1,length(m_vec));
deltaPm_11 = zeros(1,length(m_vec));
G_11 = zeros(1,length(m_vec));
Psi_11 = zeros(1,length(m_vec));
for j=1:length(m_vec)
    v_lo_11(j) = m_vec(j)/(rho_lo* A_11);
    f_lo_11(j) = computeF(species, D_11, Dcoil_11, Tboil_l, m_vec(j), correlation_l);
    deltaP_lo_11(j) = 1/2*f_lo_11(j)*L2ph_11(j)/D_11*rho_lo*v_lo_11(j)^ 2;
    ReD_l_11(j) = 4*m_vec(j)/(pi*D_11*mu_l);
    ReD_g_11(j) = 4*m_vec(j)/(pi*D_11*mu_g);
    if ((strcmp(correlation_l, 'straight') == true) || (strcmp(correlation_g, 'straight') == true))
        if ((ReD_l_11(j) < 2320) && (ReD_g_11(j) < 2320))
            C = 5; % laminar liquid and gas flows
        elseif ((ReD_l_11(j) >= 2320) && (ReD_g_11(j) < 2320))
            C = 10; % turbulent liquid, laminar gas flows
        elseif ((ReD_l_11(j) < 2320) && (ReD_g_11(j) >= 2320))
            C = 12; % laminar liquid, turbulent gas flows
        else
            C = 20; % turbulent liquid and gas flows
        end
        deltaP_2ph_11(j) = deltaP_lo_11(j) * (1 + C/X + 1/X^2);
    elseif ((strcmp(correlation_l, 'straight') == false) || (strcmp(correlation_g, 'straight') == false ))
        if (strcmp(species, 'H2O') == true)
            Pcr = 22.115*10^6;
        else
            Pcr = 0;
        end
        Psi1_11 = 142.2*(p*10^5/Pcr)^0.62*(D_11/Dcoil_11)^1.04;
        G_11(j)=4*m_vec(j)/(pi*D_11^2);
        deltaPm_11(j) = G_11(j)^2*(1/rho_gi-1/rho_lo); % Momentum pressure loss
        if G_11(j) <=1000
            Psi_11(j) = 1+ (x*(1-x)*(1000/G_11(j)-1)*(rho_lo/rho_gi))/(1+x*(rho_lo/rho_gi-1));
        else
            Psi_11(j) = 1+ (x*(1-x)*(1000/G_11(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
        end
        deltaP_2ph_11(j) = deltaP_lo_11(j) * Psi1_11(j) * Psi_11(j) * (1 + x*(rho_lo/rho_gi-1));
    end
    end
    else
        deltaP_2ph_11 = zeros(1,length(m_vec));
    end
    deltaPf_total_11 = deltaP_l_mean_11.*10^-5+deltaP_2ph_11.*10^-5+deltaP_g_mean_11.*10^-5;
    deltaP_total_11 = deltaPf_total_11 + deltaPm_11.*10^-5;
end

% For DUR20
D_20 = 1.3*10^-3;
Dcoil_20 = 13*10^-3; % main loops
A_20 = pi * D_20 ^ 2 / 4;
Ltotal_20 = 0.12; %[m]
Ll_20 = Ltotal_20*q_l./q_total; %[m]
L2ph_20 = Ltotal_20*q_2ph./q_total; %[m]
Lg_20 = Ltotal_20*q_g./q_total; %[m]
Lg_20;
% Liquid part
v_l_vec_20 = zeros(length(m_vec),length(T_l_vec));
for j=1:length(m_vec)
    v_l_vec_20(j,:) = m_vec(j)/A_20.*rho_l_vec.^(-1);
end
v_l_mean_20 = zeros(1,length(m_vec));
for j=1:length(m_vec)
    v_l_mean_20(j) = mean(v_l_vec_20(j,:));
end
deltaP_l_mean_20 = zeros(1,length(m_vec));
% Vapour part
if To >= Tboil g
    v_g_vec_20 = zeros(length(m_vec),length(T_g_vec));
    for j=1:length(m_vec)
        v_g_vec_20(j,:) = m_vec(j)/A_20.*rho_g_vec.^(-1);
    end
    v_g_mean_20 = zeros(1,length(m_vec));
    for j=1:length(m_vec)
        v_g_mean_20(j) = mean(v_g_vec_20(j,:));
    end
end
else

deltaP_g_mean_20 = zeros(1,length(m_vec));

end

% Two-phase flow
if To >= Tboil_g
    v_lo_20 = zeros(1,length(m_vec));
    f_lo_20 = zeros(1,length(m_vec));
    deltaP_lo_20 = zeros(1,length(m_vec));
    ReD_l_20 = zeros(1,length(m_vec));
    ReD_g_20 = zeros(1,length(m_vec));
    deltaP_2ph_20 = zeros(1,length(m_vec));
    deltaPm_20 = zeros(1,length(m_vec));
    G_20 = zeros(1,length(m_vec));
    Psi_20 = zeros(1,length(m_vec));
    for j=1:1:length(m_vec)
        v_lo_20(j) = m_vec(j)/(rho_lo* A_20);
        f_lo_20(j) = computeF(species, D_20, Dcoil_20, Tboil_l, m_vec(j), correlation_l);
        deltaP_lo_20(j) = 1/2*f_lo_20(j)*L2ph_20(j)/D_20*rho_lo*v_lo_20(j)^ 2;
        ReD_l_20(j) = 4*m_vec(j)/(pi*D_20*mu_l);
        ReD_g_20(j) = 4*m_vec(j)/(pi*D_20*mu_g);
        if ((strcmp(correlation_l, 'straight') == true) || (strcmp(correlation_g, 'straight') == true))
            if ((ReD_l_20(j) < 2320) && (ReD_g_20(j) < 2320))
                C = 5; % laminar liquid and gas flows
            elseif ((ReD_l_20(j) >= 2320) && (ReD_g_20(j) < 2320))
                C = 10; % turbulent liquid, laminar gas flows
            elseif ((ReD_l_20(j) < 2320) && (ReD_g_20(j) >= 2320))
                C = 12; % laminar liquid, turbulent gas flows
            else
                C = 20; % turbulent liquid and gas flows
            end
        % C = 20; % turbulent liquid and gas flows
        end
        deltaP_2ph_20(j) = deltaP_lo_20(j) * (1 + C/X + 1/X^2);
        elseif ((strcmp(correlation_l, 'straight') == false) || (strcmp(correlation_g, 'straight') == false ))
            if (strcmp(species, 'H2O') == true)
                Pcr = 22.115*10^6;
            else
                Pcr = 0;
            end
            Psi1_20 = 142.2*(p*10^5/Pcr)^0.62*(D_20/Dcoil_20)^1.04;
            G_20(j)=4*m_vec(j)/(pi*D_20^2);
            deltaPm_20(j) = G_20(j)^2*(1/rho_gi-1/rho_lo); % Momentum pressure loss
            if G_20(j) <=1000
                Psi_20(j) = 1+ (x*(1-x)*(1000/G_20(j)-1)*(rho_lo/rho_gi))/(1+x*(rho_lo/rho_gi-1));
            else
                Psi_20(j) = 1+ (x*(1-x)*(1000/G_20(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
            end
        end
        deltaP_2ph_20(j) = deltaP_lo_20(j) * Psi_20(j) * Psi1_20 * (1 + x*(rho_lo/rho_gi-1));
    end
    deltaP_2ph_20 = zeros(1,length(m_vec));
end
deltaPf_total_20 = deltaP_l_mean_20.*10^-5 + deltaP_2ph_20.*10^-5 + deltaP_g_mean_20.*10^-5;
deltaP_total_20 = deltaPf_total_20 + deltaPm_20.*10^-5;

% For temperature variation
Tc_vect = 400 : 10 : 1050;
t1 = 295; %[K]
Dw = 0.4*10^-3; %Water Nozzle
% Liquid part
T_L_vec = T1:0.1:Tboil_l;
rho_L_vec_Nozz = zeros(1,length(T_L_vec));
for i=1:1:length(T_L_vec)
    rho_L_vec_Nozz(i) = computeRho(species, T_L_vec(i), p);
end
rho_L_mean_Nozz = mean(rho_L_vec_Nozz);
% Two-phase flow
rho_lo = computeRho(species, Tboil_l, p);
rho_gi = computeRho(species, Tboil_g, p);
mu_l = computeMu(species, Tboil_l);
mu_g = computeMu(species, Tboil_g);
x = 0.5; % mean quality x=(xi+xo)/2
x = (rho_gi/rho_lo)^0.5 * (mu_l/mu_g)^0.1 *( (1-x)/x)^0.9;
for j=1:1:length(Tc_vect)
    Tc_w(j) = Tc_vect(j)+1.1;
    % Density [kg/m^3]
    rho = computeRho(species, Tc_w(j), p);
    % Viscosity [Pa's]
mu = computeMu(species, Tc_vect(j));
% mu_w = computeMu(species, Tc_w(j));
% Specific heat [J/kg/K]
Cp = computeCp(species, Tc_vect(j)); % [J/mol/K]
M = computeM(species);
cp = Cp/M;
% Thermal conductivity [W/m/K]
k = computeK(species, Tc_vect(j));
Pr = mu*cP/k;
M = computeM(species); % [kg/mol]
% cp = Cp/M;
RA = 8.314472; % [J/(molK)]
gama = Cp/(Cp-RA);
Gama = (gama)^(1/2)*(2/(gama+1))^((gama+1)/(2*(gama-1)));
m_Nozz(j) = pi*D_t_w^2/4*p*10^5*Gama/(RA*M*Tc_vect(j))^1/2;
q_total_Nozz(j) = m_Nozz(j)*(H_out-H_in); % [W]
q_L_Nozz(j) = m_Nozz(j)*(H_boil-H_in); % [W]
q_2ph_Nozz(j) = m_Nozz(j)*(H_boil-H_boil_g); % [W]
Ll_Nozz(j) = Ltotal*q_L_Nozz(j)/q_total_Nozz(j); % [m]
L2ph_Nozz(j) = Ltotal*q_2ph_Nozz(j)/q_total_Nozz(j); % [m]
Lg_Nozz(j) = Ltotal*q_g_Nozz(j)/q_total_Nozz(j); % [m]
% Liquid part
v_l_vec_Nozz(j,:) = m_Nozz(j)/A.*rho_l_vec_Nozz.^(-1);
f_l_vec_c_Nozz(j,:) = computeF(species, D, Dcoil, T_l_vec, m_Nozz(j), correlation_l);
f_l_vec_s_Nozz(j,:) = computeF(species, D, Dcoil, T_l_vec, m_Nozz(j), 'straight');
v_l_mean_Nozz(j) = mean(v_l_vec_Nozz(j,:));
f_l_mean_c_Nozz(j) = mean(f_l_vec_c_Nozz(j,:));
f_l_mean_s_Nozz(j) = mean(f_l_vec_s_Nozz(j,:));
deltaP_l_mean_c_Nozz(j) = 1/2*f_l_mean_c_Nozz(j)*Ll_Nozz(j)/D*rho_l_mean_Nozz*v_l_mean_Nozz(j)^2;% [Pa]
deltaP_l_mean_s_Nozz(j) = 1/2*f_l_mean_s_Nozz(j)*Ll_Nozz(j)/D*rho_l_mean_Nozz*v_l_mean_Nozz(j)^2;% [Pa]
% Vapour part
T_g_vec_Nozz = Tboil_g:0.1:Tc_vect(j);
rho_g_vec_Nozz = zeros(1,length(T_g_vec_Nozz));
for i=1:1:length(T_g_vec_Nozz)
    rho_g_vec_Nozz(i) = computeRho(species,T_g_vec_Nozz(i),p);
end
rho_g_mean_Nozz = mean(rho_g_vec_Nozz(:));
v_g_vec_Nozz = m_Nozz(j)/A.*rho_g_vec_Nozz.^(-1);
f_g_vec_c_Nozz = computeF(species, D, Dcoil, T_g_vec_Nozz, m_Nozz(j), correlation_g);
f_g_vec_s_Nozz = computeF(species, D, Dcoil, T_g_vec_Nozz, m_Nozz(j), 'straight');
v_g_mean_Nozz(j) = mean(v_g_vec_Nozz(j,:));
f_g_mean_c_Nozz(j) = mean(f_g_vec_c_Nozz(j,:));
f_g_mean_s_Nozz(j) = mean(f_g_vec_s_Nozz(j,:));
deltaP_g_mean_c_Nozz(j) = 1/2*f_g_mean_c_Nozz(j)*Lg_Nozz(j)/D*rho_g_mean_Nozz*v_g_mean_Nozz(j)^2;% [Pa]
deltaP_g_mean_s_Nozz(j) = 1/2*f_g_mean_s_Nozz(j)*Lg_Nozz(j)/D*rho_g_mean_Nozz*v_g_mean_Nozz(j)^2;% [Pa]
% Two-phase flow
v_lo_Nozz(j) = m_Nozz(j)/(rho_lo* A);
f_lo_c_Nozz(j) = computeF(species, D, Dcoil, Tboil_l, m_Nozz(j), correlation_l);
f_lo_s_Nozz(j) = computeF(species, D, Dcoil, Tboil_l, m_Nozz(j), 'straight');
deltaP_lo_s_Nozz(j) = 1/2*f_lo_s_Nozz(j)*L2ph_Nozz(j)/D*rho_lo*v_lo_Nozz(j)^2;
deltaP_lo_c_Nozz(j) = 1/2*f_lo_c_Nozz(j)*L2ph_Nozz(j)/D*rho_lo*v_lo_Nozz(j)^2;
ReD_l_Nozz(j) = 4*m_Nozz(j)/(pi*D*mu_l);
ReD_g_Nozz(j) = 4*m_Nozz(j)/(pi*D*mu_g);
if (ReD_l_Nozz(j) < 2320) && (ReD_g_Nozz(j) < 2320)
    C = 5; % laminar liquid and gas flows
elseif (ReD_l_Nozz(j) >= 2320) && (ReD_g_Nozz(j) < 2320)
    C = 10; % turbulent liquid, laminar gas flows
elseif (ReD_l_Nozz(j) < 2320) && (ReD_g_Nozz(j) >= 2320)
    C = 12; % laminar liquid, turbulent gas flows
else
    C = 20; % turbulent liquid and gas flows
end
deltaP_2ph_s_Nozz(j) = deltaP_lo_s_Nozz(j) * (1 + C/X + 1/X^2); % 2-phase pressure drop straight tube, Lockhart-Martinelli correlation
if strcmp(species, 'H2O') == true
    Pcr = 22.115*10^6;
else
    Pcr = 0;%For other species, another value should be found
end
Psial = 142.2*p*10^5/Pcr - 0.62*D(Dcoil)
G_Nozz(j) = m_Nozz(j)/(psial*D^2); % Mass flow rate [kg/m^2s]
deltaPm_Nozz(j) = G_Nozz(j) * 2*(1/rho_gi1/rho_lo)*momentum pressure loss
if G_Nozz(j) < 1000
    Psi_Nozz(j) = 1*(x*(1-x)*(1000/G_Nozz(j)-1)*(rho_lo/rho_gi1)/(1+x*(rho_lo/rho_gi1)));%2
else
    Psi_Nozz(j) = 1*(x*(1-x)*(1000/G_Nozz(j)-1)*(rho_lo/rho_gi1)/(1+x*(rho_lo/rho_gi1)));%2
end
deltaP_2ph_c1_Nozz(j) = deltaP_lo_c_Nozz(j) * Psi_Nozz(j) * Psi1 * (1 + x*(rho_lo/rho_gi-1));%2-phase pressure drop coiled tube, Guo's correlation
deltaP_2ph_c2_Nozz(j) = deltaP_lo_c_Nozz(j) * (1+(4.25-2.55*x^1.5)*G_Nozz(j)^0.34);%2-phase pressure drop coiled tube, Guo's first correlation
deltaPf_total_c_Nozz = deltaP_l_mean_c_Nozz.*10^-5 + deltaP_2ph_c1_Nozz.*10^-5 + deltaP_g_mean_c_Nozz.*10^-5;%[bar]
deltaPf_total_s_Nozz = deltaP_l_mean_s_Nozz.*10^-5 + deltaP_2ph_s_Nozz.*10^-5 + deltaP_g_mean_s_Nozz.*10^-5;%[bar]
deltaP_total_c_Nozz = deltaPf_total_c_Nozz + deltaPm_Nozz.*10^-5;%[bar]
deltaP_total_s_Nozz = deltaPf_total_s_Nozz + deltaPm_Nozz.*10^-5;%[bar]

% For DUR1.1
D_11 = 2.5*10^-3;
Dcoil_11 = 40*10^-3;
A_11 = pi * D_11 ^ 2 / 4;
Ltotal_11 = 2; %[m]
Ll_11_Nozz(j) = Ltotal_11*q_l_Nozz(j)./q_total_Nozz(j); %[m]
L2ph_11_Nozz(j) = Ltotal_11*q_2ph_Nozz(j)./q_total_Nozz(j); %[m]
Lg_11_Nozz(j) = Ltotal_11*q_g_Nozz(j)./q_total_Nozz(j); %[m]
% Liquid part
v_l_vec_11_Nozz(j,:) = m_Nozz(j)/A_11.*rho_l_vec_Nozz.^(-1);
f_l_vec_11_Nozz(j,:) = computeF(species, D_11, Dcoil_11, T_l_vec, m_Nozz(j), correlation_l);
v_l_mean_11_Nozz(j) = mean(v_l_vec_11_Nozz(j,:));
f_l_mean_11_Nozz(j) = mean(f_l_vec_11_Nozz(j,:));
deltaP_l_mean_11_Nozz(j) = 1/2*f_l_mean_11_Nozz(j)*Ll_11_Nozz(j)/D_11*rho_l_mean_Nozz*v_l_mean_11_Nozz(j)^2;
% Vapour part
v_g_vec_11_Nozz = m_Nozz(j)/A_11.*rho_g_vec_Nozz.^(-1);
f_g_vec_11_Nozz = computeF(species, D_11, Dcoil_11, T_g_vec_Nozz, m_Nozz(j), correlation_g);
v_g_mean_11_Nozz(j) = mean(v_g_vec_11_Nozz(j,:));
f_g_mean_11_Nozz(j) = mean(f_g_vec_11_Nozz(j,:));
deltaP_g_mean_11_Nozz(j) = 1/2*f_g_mean_11_Nozz(j)*Lg_11_Nozz(j)/D_11*rho_g_mean_Nozz*v_g_mean_11_Nozz(j)^2;
% Two-phase flow
v_lo_11_Nozz(j) = m_Nozz(j)/(rho_lo* A_11);
f_lo_11_Nozz(j) = computeF(species, D_11, Dcoil_11, Tboil_l, m_Nozz(j), correlation_l);
deltaP_lo_11_Nozz(j) = 1/2*f_lo_11_Nozz(j)*L2ph_11_Nozz(j)/D_11*rho_lo*v_lo_11_Nozz(j)^2;
ReD_l_11_Nozz(j) = 4*m_Nozz(j)/(pi*D_11*mu_l);
ReD_g_11_Nozz(j) = 4*m_Nozz(j)/(pi*D_11*mu_g);
if (strcmp(species, 'H2O') == true)
Pcr = 22.115*10^6;
else
Pcr = 0;
end
Psi1_11_Nozz = 142.2*(p*10^5/Pcr)^0.62*(D_11/Dcoil_11)^1.04;
G_11_Nozz(j)=4*m_Nozz(j)/(pi*D_11^2);
deltaPm_11_Nozz(j) = G_11_Nozz(j)^2*(1/rho_gi-1/rho_lo); %Momentum pressure loss
if G_11_Nozz(j) <=1000
Psi_11_Nozz(j) = 1+ (x*(1-x)*(1000/G_11_Nozz(j)-1)*(rho_lo/rho_gi))/(1+(1-x)*(rho_lo/rho_gi-1));
else
Psi_11_Nozz(j) = 1+ (x*(1-x)*(1000/G_11_Nozz(j)-1)*(rho_lo/rho_gi))/((1-x)*(rho_lo/rho_gi-1));
end
deltaP_2ph_11_Nozz(j) = deltaP_lo_11_Nozz(j) * Psi_11_Nozz(j) * Psi1_11_Nozz(j) * (1 + x*(rho_lo/rho_gi-1));
deltaPf_total_11_Nozz = deltaP_l_mean_11_Nozz.*10^-5+deltaP_2ph_11_Nozz.*10^-5+deltaP_g_mean_11_Nozz.*10^-5;%[bar]
deltaP_total_11_Nozz = deltaPf_total_11_Nozz + deltaPm_Nozz.*10^-5;%[bar]
\[
\text{f}_{g\_vec\_11\_Nozz} = \text{computeF}(\text{species, } D_{11}, \text{Dcoil}_{11}, T_{g\_vec\_Nozz}, m_{Nozz(j)}),
\] 
\text{correlation}_g);
\]
\[
\text{v}_{g\_mean\_11\_Nozz}(j) = \text{mean}(\text{v}_{g\_vec\_11\_Nozz}(:,j));
\]
\[
\text{f}_{g\_mean\_11\_Nozz}(j) = \text{mean}(\text{f}_{g\_vec\_11\_Nozz}(j));
\]
\[
\text{deltaP}_{g\_mean\_11\_Nozz}(j) = 1/2*\text{f}_{g\_mean\_11\_Nozz}(j)^2 - \text{L}_{g\_11\_Nozz}(j)/\text{D}_{11}\times \text{rho}_{g\_mean\_Nozz}\times \text{v}_{g\_mean\_11\_Nozz}(j)^2;
\]
\% Two-phase flow
\[
\text{v}_{lo\_11\_Nozz}(j) = m_{Nozz(j)}/(\rho_{lo}\times A_{11});
\]
\[
\text{f}_{lo\_11\_Nozz}(j) = \text{computeF}(\text{species, } D_{11}, \text{Dcoil}_{11}, T_{boil\_l}, m_{Nozz(j)}, \text{correlation}_l);
\]
\[
\text{deltaP}_{l\_11\_Nozz}(j) = 1/2*\text{f}_{lo\_11\_Nozz}(j)^2 - \text{L}_{2ph\_11\_Nozz}(j)/\text{D}_{11}\times \text{rho}_{lo}\times \text{v}_{lo\_11\_Nozz}(j)^2;\]
\]% Momentum pressure loss
\[
\text{if}\ G_{11\_Nozz}(j) < 1000
\]
\[
\text{Psi}_{11\_Nozz}(j) = 1 + (x*(1-x)*(1000/G_{11\_Nozz}(j) - 1)*(\text{rho}_{lo}/\text{rho}_{gi})/(1+(1-x)\times (\text{rho}_{lo}/\text{rho}_{gi})));\]
\[
\text{psi}_{11\_Nozz}(j) = 1 + (x*(1-x)*(1000/G_{11\_Nozz}(j) - 1)*\text{psi}_{11\_Nozz}(j) * \text{psi}_{11\_Nozz} * (1 + x*(\text{rho}_{lo}/\text{rho}_{gi})));\]
\[
\text{deltaP}_{2ph\_11\_Nozz}(j) = \text{deltaP}_{l\_11\_Nozz}(j) * \text{psi}_{11\_Nozz}(j) * \text{psi}_{11\_Nozz} * (1 + x*(\text{rho}_{lo}/\text{rho}_{gi})));\]
\[
\text{deltaP}_{total\_11\_Nozz} = \text{deltaP}_{l\_mean\_11\_Nozz} + \text{deltaP}_{2ph\_11\_Nozz} + \text{deltaP}_{g\_mean\_11\_Nozz};\]
\% For DUR20
\[
\text{D}_{20} = 1.3*10^{-3}; \qquad \text{Dcoil}_{20} = 13*10^{-3}; \quad \% \text{main loops}
\]
\[
\text{A}_{20} = \pi \times \text{D}_{20}^2/4; \quad \text{L}_{total\_20} = 0.12; \quad \% [m]
\]
\[
\text{L}_{l\_20\_Nozz} = \text{L}_{total\_20}\times q_{l\_Nozz}/q_{total\_Nozz}; \quad \% [m]
\]
\[
\text{L}_{2ph\_20\_Nozz} = \text{L}_{total\_20}\times q_{2ph\_Nozz}/q_{total\_Nozz}; \quad \% [m]
\]
\[
\text{L}_{g\_20\_Nozz} = \text{L}_{total\_20}\times q_{g\_Nozz}/q_{total\_Nozz}; \quad \% [m]
\]
\% Liquid part
\[
\text{v}_{l\_vec\_20\_Nozz}(j,:) = m_{Nozz(j)}/(\text{A}_{20} \times \text{rho}_{l\_vec\_Nozz})^(-1); \quad \% [m/s]
\]
\[
\text{f}_{l\_vec\_20\_Nozz}(j,:) = \text{computeF}(\text{species, } D_{20}, \text{Dcoil}_{20}, T_{l\_vec}, m_{Nozz(j)}, \text{correlation}_l);
\]
\[
\text{v}_{l\_mean\_20\_Nozz}(j) = \text{mean}(\text{v}_{l\_vec\_20\_Nozz}(j,:));
\]
\[
\text{f}_{l\_mean\_20\_Nozz}(j) = \text{mean}(\text{f}_{l\_vec\_20\_Nozz}(j,:));
\]
\[
\text{deltaP}_{l\_mean\_20\_Nozz}(j) = 1/2*\text{f}_{l\_mean\_20\_Nozz}(j)^2 - \text{L}_{l\_20\_Nozz}(j)/\text{D}_{20}\times \text{rho}_{l\_mean\_Nozz}\times \text{v}_{l\_mean\_20\_Nozz}(j)^2;\]
\% Vapour part
\[
\text{v}_{g\_vec\_20\_Nozz} = m_{Nozz(j)}/(\text{A}_{20} \times \text{rho}_{g\_vec\_Nozz})^(-1); \quad \% [m/s]
\]
\[
\text{f}_{g\_vec\_20\_Nozz} = \text{computeF}(\text{species, } D_{20}, \text{Dcoil}_{20}, T_{g\_vec\_Nozz}, m_{Nozz(j)}, \text{correlation}_g);
\]
\[
\text{v}_{g\_mean\_20\_Nozz}(j) = \text{mean}(\text{v}_{g\_vec\_20\_Nozz}(j,:));
\]
\[
\text{f}_{g\_mean\_20\_Nozz}(j) = \text{mean}(\text{f}_{g\_vec\_20\_Nozz}(j,:));
\]
\[
\text{deltaP}_{g\_mean\_20\_Nozz}(j) = 1/2*\text{f}_{g\_mean\_20\_Nozz}(j)^2 - \text{L}_{g\_20\_Nozz}(j)/\text{D}_{20}\times \text{rho}_{g\_mean\_Nozz}\times \text{v}_{g\_mean\_20\_Nozz}(j)^2;\]
\% Two-phase flow
\[
\text{v}_{lo\_20\_Nozz}(j) = m_{Nozz(j)}/(\text{rho}_{lo} \times A_{20});
\]
\[
\text{f}_{lo\_20\_Nozz}(j) = \text{computeF}(\text{species, } D_{20}, \text{Dcoil}_{20}, T_{boil\_l}, m_{Nozz(j)}, \text{correlation}_l);
\]
\[
\text{deltaP}_{l\_20\_Nozz}(j) = 1/2*\text{f}_{lo\_20\_Nozz}(j)^2 - \text{L}_{2ph\_20\_Nozz}(j)/\text{D}_{20}\times \text{rho}_{lo}\times \text{v}_{lo\_20\_Nozz}(j)^2;\]
\%
\%
\]
\[
\text{psi}_{20\_Nozz}(j) = 1 + (x*(1-x)*(1000/G_{20\_Nozz}(j) - 1)*(\text{rho}_{lo}/\text{rho}_{gi})/(1+(1-x)\times (\text{rho}_{lo}/\text{rho}_{gi})));\]
\[
\text{psi}_{20\_Nozz}(j) = 1 + (x*(1-x)*(1000/G_{20\_Nozz}(j) - 1)*\text{psi}_{20\_Nozz}(j) * \text{psi}_{20\_Nozz} * (1 + x*(\text{rho}_{lo}/\text{rho}_{gi})));\]
\[
\text{deltaP}_{2ph\_20\_Nozz}(j) = \text{deltaP}_{l\_20\_Nozz}(j) * \text{psi}_{20\_Nozz}(j) * \text{psi}_{20\_Nozz} * (1 + x*(\text{rho}_{lo}/\text{rho}_{gi})));\]
deltaPf_total_20_Nozz = deltaP_l_mean_20_Nozz.*10^-5 + deltaP_2ph_20_Nozz.*10^-5 +
                       deltaP_g_mean_20_Nozz.*10^-5;
deltaP_total_20_Nozz = deltaPf_total_20_Nozz + deltaPm_20_Nozz.*10^-5;
end
% Te_vect = 500 : 500/25: 1000;

% Plotting

p_tank = 5 + m_vec*0;
p_valve = 4 + m_vec*0;
p_max_Nozz = 2 + m_Nozz*0;
p_heater1 = p_valve-deltaP_l_mean.*10^-5;
p_heater2 = p_valve-deltaP_l_mean.*10^-5-deltaP_2ph_c1.*10^-5;
p_heater3 = p_valve-deltaP_l_mean.*10^-5-deltaP_2ph_c1.*10^-5-deltaPm.*10^-5;
p_heater4 = p_valve-deltaP_l_mean.*10^-5-deltaP_2ph_c1.*10^-5-deltaPm.*10^-5-deltaP_g_mean.*10^-5;
m_vec = m_vec*10^6;

function f = computeF(species, d, D, T, m, correlation)
    % f = computeF(species, d, D, T, m, correlation)
    % Computes the friction factor for an internal flow through a tube of
    % circular cross section. The Darcy-Weissbach friction factor is used.
    %
    % f: friction factor [-]
    % species: 'Air', 'NH3', 'CO2', 'CO', 'H2', 'N2', 'O2', 'H2O'
    % d: inner diameter of tube [m]
    % D: mean diameter of coil [m]
    % (D=0, if straight)
    % T: temperature of fluid [K]
    % m: mass flow through tube [kg / s]
    % correlation: what correlation to use
    % 'schmidt', 'ito', 'white' for coiled tubes and
    % laminar flow
    % 'white', 'srinivasan', 'ito', 'ruffel', 'guo' for coiled
    % tubes and turbulent flow
    % 'straight' for a straight tube and laminar flow
    % The values for H2O are for 2bars
    % Correlations for friction factor obtained from:
    % MSc Thesis Rycek (2005)
    % Guo (2001)

    A = pi*d^2/4;
    mu = computeMu(species, T);
    Re = m*d/A.*mu.^(-1);
    if m == 0
        f = 0;
    else
        % Straight tube
        if(strcmp(correlation, 'straight') == true)
            f=zeros(1,length(Re));
            for j=1:length(Re)
                if(Re(j) < 2320)
                    f(j) = 64*Re(j)^(-1);
                elseif(Re(j) < 1E5) && (Re(j) > 2320)
                    f(j) = 0.316 * Re(j)^ -0.25;
                else
                    f(j) = 0.0032 + 0.221* Re(j)^ -0.237;
                end
            end
        % Coiled tube
        else
            Re_cr = 284 * (d / D) ^ 0.32;
            f_S = 64 ./ Re.^(-1); % Friction factor for straight tube, laminar flow
            De = Re .* (d / D) .^ 0.5; % Dean number
            % Laminar flow and turbulent flow
            f=zeros(1,length(Re));
            I=zeros(1,length(Re));
            for j=1:length(Re)
                if(Re(j) < Re_cr)% Laminar flow
                    if(strcmp(correlation, 'white') == true)
                        f(j) = real(f_S(j) / (1 - (1 - (11.6 / De(j)) ^ 0.45) ^ (1/0.45)));
                    elseif(strcmp(correlation, 'schmidt') == true)
                        f(j) = 1 - 0.644 * (d / D) ^ 0.312;
                    end
                    if(strcmp(correlation, 'ito') == true)
                        f(j) = 0.25 * f_S(j) * (1 + 0.14 * (d / D) ^ 0.97 * Re(j)) ^ I(j);
                    elseif(strcmp(correlation, 'ruffel') == true)
                        f(j) = 21.5 * f_S(j) * De(j) / (1.56 + log10(De(j))) ^ 5.7;
                    end
                else % Turbulent flow
                    if(strcmp(correlation, 'white') == true)
                        % confirmed
                        % confirmed
                    end
                end
            end
        end
    end
end
3 Files of model predictor

function F_ext = View_factor_coil()
% view factor
% For a coil with 7 loops as DUR 1.0
% Rodrigo A. Ferreira

clear all

s       = 0.0035;   %mean value of the distance between loops [m]
r       = 0.003/2;  %radius of the tube [m]
Dcoil   = 0.04;     %Mean diameter of the coil [m]
s1      = (Dcoil^2+(s/2+r)^2)^(1/2)-2*r;
s2      = (Dcoil^2+(s/2+r+s+2*r)^2)^(1/2)-2*r;
s3      = (Dcoil^2+(s/2+r+2*s+4*r)^2)^(1/2)-2*r;
s4      = (Dcoil^2+(s/2+r+3*s+6*r)^2)^(1/2)-2*r;
s5      = (Dcoil^2+(s/2+r+4*s+8*r)^2)^(1/2)-2*r;
s6      = (Dcoil^2+(s/2+r+5*s+10*r)^2)^(1/2)-2*r;
s7      = (Dcoil^2+(s/2+r+6*s+12*r)^2)^(1/2)-2*r;
X       = 1+s/(2*r);
X1      = 1+s1/(2*r);
X2      = 1+s2/(2*r);
X3      = 1+s3/(2*r);
X4      = 1+s4/(2*r);
X5      = 1+s5/(2*r);
X6      = 1+s6/(2*r);
X7      = 1+s7/(2*r);
F       = 1/pi*((X^2-1)^(1/2)+asin(1/X)-X); %View factor to the side
F1      = 1/pi*((X1^2-1)^(1/2)+asin(1/X1)-X1);
F2      = 1/pi*((X2^2-1)^(1/2)+asin(1/X2)-X2);
F3      = 1/pi*((X3^2-1)^(1/2)+asin(1/X3)-X3);
F4      = 1/pi*((X4^2-1)^(1/2)+asin(1/X4)-X4);
F5      = 1/pi*((X5^2-1)^(1/2)+asin(1/X5)-X5);
F6      = 1/pi*((X6^2-1)^(1/2)+asin(1/X6)-X6);
F7      = 1/pi*((X7^2-1)^(1/2)+asin(1/X7)-X7);
%View factors of different loops
F_best  = 2*F+2*F1+2*F2+2*F3+4*F4; %Middle loops
F_good  = 2*F+2*F1+2*F2+2*F3+2*F4+2*F5; %Second and penultimate half loop
F_mid   = 2*F+2*F1+2*F2+2*F3+2*F4+2*F5+2*F6; %First and last half loop
F_bad   = F+2*F1+2*F2+2*F3+2*F4+2*F5+2*F6; %Second and penultimate half loop
F_worst = F+F1+F2+F3+F4+F5+F6; %First and last half loop
%View factor from coil to itself
F_mean  = (4*F_best+4*F_good+2*F_mid+2*F_bad+2*F_worst)/14;
%View factor from de coil to the exterior
F_ext   = 1-F_mean;

function [T_final_flow_coil, T_final_wall_coil] = Twall_Tflow(T_mean_coil, m_flow, species)
% Twall_Tflow(T_mean_coil, m_flow, species)
% Compute the final temperature of the wall and flow
% T_mean_coil:         Mean temperature of the heater [K]
% m_flow:              Mass flow [Kg/s]
% species:        'H2O'
% Rodrigo A. Ferreira
% 2008
%
% Input!!
T_mean_coil = 540;
m_flow = 31.9*10^-6; %[kg/s]
species = 'H2O';
M = computeM(species); [%kg/mol]
RA = 8.314472; % [J/(molK)]
for jj=1:length(To_flow_j2)
mu_flow_j = computeMu(species, To_flow_j2(jj));
% Specific heat [J/kg/K]
Cp_flow_j = computeCp(species, To_flow_j2(jj)); %[J/mol/K]
% Thermal conductivity [W/m/K]
k_flow_j = computeK(species, To_flow_j2(jj));
Pr_flow_j = mu_flow_j*Cp_flow_j/M; %[J/mol/K]
cp_flow_j = Cp_flow_j/M;
% Thermal conductivity [W/m/K]
Re_flow_j = 4*m_flow/(pi*dtube_in*mu_flow_j);
if Re_flow_j < Re_crit
  if (Pr_flow_j > 5) && (Pr_flow_j < 175)
    Nu_flow = 0.76+0.65*Re_flow_j^0.5*(dtube_in/Dcoil)^0.25*Pr_flow_j^0.175;
  else
    Nu_flow = 0.913*(Re_flow_j*dtube_in/Dcoil)^0.5*0.476*Pr_flow_j^0.2;
  end
else
  if (Re_flow_j>6000) && (Re_flow_j<100000)
    Nu_flow = 0.023*Re_flow_j^0.85*Pr_flow_j^0.4*(dtube_in/Dcoil)^0.1;
  else
    Nu_flow = Re_flow_j^0.8*Pr_flow_j^0.4*(dtube_in/Dcoil)^0.1/(26.2*(Pr_flow_j^0.3-0.074))+(1+0.098/(Re_flow_j*dtube_in/Dcoil)^0.5)));
  end
  h_flow_j = Nu_flow*k_flow_j/dtube_in;
  Two_j2(jj) = m_flow*(Entalp_o-Entalp_i)/(L*dtube_in*pi*h_flow_j)+To_flow_j2(jj);
diff2(jj) = Two_j2(jj)-To_flow_j2(jj);
end
end
if Tfinal(i) > Tboil_g %Gas in the output
  Tboil_1stwall_vec = Two_j1(length(To_flow_j1))+10^-8:(2*10^-8)/50:Two_j1(length(To_flow_j1))+10^-8;
  Tboil_2ndwall_vec = Two_j2(1)-10^-8:(2*10^-8)/50:Two_j2(1)+10^-8;
  T_wall_mean_liq = mean(Two_j1);
  T_wall_1stmean_boil = mean(Tboil_1stwall_vec);
  T_wall_2ndmean_boil = mean(Tboil_2ndwall_vec);
  T_wall_mean_gas = mean(Two_j2);
  T_wall_mean2 = T_wall_mean_liq*Lliq/L+T_wall_1stmean_boil*L2ph_1st/L+T_wall_2ndmean_boil*L2ph_2nd/L+T_wall_mean_gas*Lgas/L;
  T_wall_i_mean(i) = T_wall_mean2;
  T_final_flow(i) = To_flow_j2(length(To_flow_j2));
  T_final_wall(i) = Two_j2(length(To_flow_j2));
else
  if Tfinal(i) > Tboil_i && Tfinal(i) < Tboil_g
    Tboil_1stwall_vec = Two_j1(length(To_flow_j1))+10^-8:(2*10^-8)/50:Two_j1(length(To_flow_j1))+10^-8;
    Tboil_2ndwall_vec = Two_j2(1)-10^-8:(2*10^-8)/50:Two_j2(1)+10^-8;
    T_wall_mean_liq = mean(Two_j1);
    T_wall_1stmean_boil = mean(Tboil_1stwall_vec);
    T_wall_2ndmean_boil = mean(Tboil_2ndwall_vec);
    T_wall_mean2 = T_wall_mean_liq*Lliq/L+T_wall_1stmean_boil*L2ph_1st/L+T_wall_2ndmean_boil*L2ph_2nd/L;
    T_wall_i_mean(i) = T_wall_mean2;
    T_final_flow(i) = To_flow_j2(length(To_flow_j2));
    T_final_wall(i) = Two_j2(length(To_flow_j2));
  else
    if no boiling
      T_wall_mean_liq = mean(Two_j1);
      T_wall_mean2 = T_wall_mean_liq*Lliq/L;
      T_wall_i_mean(i) = T_wall_mean2;
      T_final_flow(i) = To_flow_j2(length(To_flow_j2));
      T_final_wall(i) = Two_j2(length(To_flow_j2));
    end
  end
else %No boiling
  T_wall_mean_liq = mean(Two_j1);
  T_wall_mean2 = T_wall_mean_liq*Lliq/L;
  T_wall_i_mean(i) = T_wall_mean2;
  T_final_flow(i) = To_flow_j1(length(To_flow_j1));
  T_final_wall(i) = Two_j1(length(To_flow_j1));
end
end
if T_mean_coil > max(T_wall_i_mean)
  T_mean_coil = max(T_wall_i_mean);
end
T_final_flow = interp1(T_wall_i_mean,T_final_flow,T_mean_coil);
T_final_wall = interp1(T_wall_i_mean,T_final_wall,T_mean_coil);

% function [T_final_flow_coil,T_final_wall_coil] = Twall_Tflow(T_mean_coil, m_flow, species)
% T_wall_Tflow(T_mean_coil, m_flow, species)
% Compute the final temperature of the wall and flow
% T_mean_coil: Mean temperature of the heater [K]
% m_flow: Mass flow [Kg/s]
% species: 'H2O'
% Rodrigo A. Ferreira
% 2008
% Input!!
T_mean_coil = 590;
m_flow = 31.9*10^-6; [%kg/s]
species = 'H2O';

M = computeM(species); \text{[kg/mol]}
\% RA = 8.314472; \% [J/(molK)]

T\_room = 295; \%[K]
T\_boil = 393.36; \%[K]
T\_boil\_l = 393.36-1e-6; \%[K]
T\_boil\_g = 393.36+1e-6; \%[K]

\% N = 7; \%number of loops
D\_out = 0.043; \%coil outer diameter [m]
d\_tube = 0.003; \%tube diameter [m]
\% D\_coil = D\_out-d\_tube; \%mean coil diameter [m]
d\_tube\_in = 0.0025; \%tube inner diameter [m]
L = 0.95; \% [m]
T\_final = 300:10:1000;

\text{for } i=1:length(T\_final)
\quad \text{Entalp\_i = computeEnthalpy(species, T\_room, p)/M; \[J/kg\]}
\quad \text{Entalp\_liq = computeEnthalpy(species, T\_boil\_l, p)/M; \[J/kg\]}
\quad \text{Entalp\_vap = computeEnthalpy(species, T\_boil\_g, p)/M; \[J/kg\]}
\quad \text{Entalp\_o = computeEnthalpy(species, T\_final(i), p)/M; \[J/kg\]}
\text{if } T\_final(i) < T\_boil\_l \%No boiling
\quad \text{L\_liq = L;} \quad \text{L\_2ph}\_1st = 0;
\quad \text{L\_2ph}\_2nd = 0;
\quad \text{L\_gas = 0;}
\quad \text{T\_final\_liq = T\_final(i);} \text{else}
\quad \text{T\_final(i) < T\_boil\_g && T\_final(i) > T\_boil\_l}
\quad \text{L\_liq = L^* (Entalp\_liq-Entalp\_i)/(Entalp\_o-Entalp\_i);} \quad \text{L\_2ph}\_1st = L^* (Entalp\_vap-Entalp\_liq)/(Entalp\_o-Entalp\_i)*0.9;
\quad \text{L\_2ph}\_2nd = L^* (Entalp\_o-Entalp\_liq)/(Entalp\_o-Entalp\_i)*0.1;
\quad \text{L\_gas = 0;}
\quad \text{T\_final\_liq = T\_boil\_l;} \text{else}
\quad \text{\%Gas in the output}
\quad \text{L\_liq = L^* (Entalp\_liq-Entalp\_i)/(Entalp\_o-Entalp\_i);} \quad \text{L\_2ph} = L^* (Entalp\_vap-Entalp\_liq)/(Entalp\_o-Entalp\_i)*0.9;
\quad \text{L\_2ph}\_1st = L^* (Entalp\_vap-Entalp\_liq)/(Entalp\_o-Entalp\_i)*0.1;
\quad \text{L\_gas = L^* (Entalp\_o-Entalp\_vap)/(Entalp\_o-Entalp\_i);} \quad \text{T\_final\_liq = T\_boil\_l;} \text{end}
\text{end}

T\_to\_flow\_j1 = T\_room:(T\_final\_liq-T\_room)/50:T\_final\_liq;
\text{for } jj=1:length(T\_to\_flow\_j1)
\quad \text{mu\_flow\_j = computeMu(species, T\_to\_flow\_j1(jj));}
\quad \% Specific heat \[J/kg/K\]
\quad \text{Cp\_flow\_j = computeCp(species, T\_to\_flow\_j1(jj));}
\quad \% Thermal conductivity \[W/m/K\]
\quad \text{k\_flow\_j = computeK(species, T\_to\_flow\_j1(jj));}
\quad \text{Pr\_flow\_j = mu\_flow\_j*Cp\_flow\_j/k\_flow\_j;}
\quad \text{Re\_flow\_j = 4*m\_flow/(pi*d\_tube_in*pi*h\_flow\_j);} \quad \text{if } Re\_flow\_j < 2300
\quad \quad \text{Nu\_flow = 4.364;} \text{else}
\quad \quad \text{Nu\_flow = 0.023*Re\_flow\_j^4*(4/5)*Pr\_flow\_j^0.4; \%Dittu-Boelter correlation}
\quad \text{end}
\quad \text{h\_flow\_j = Nu\_flow*k\_flow\_j/d\_tube_in;}
\quad \text{Two\_j1(jj) = m\_flow*(Entalp\_o-Entalp\_i)/(L*4*d\_tube_in*pi*h\_flow\_j)+To\_flow\_j1(jj);} \quad \text{diff(jj) = Two\_j1(jj)-To\_flow\_j1(jj);} \text{end}
\text{for } jj=1:length(T\_to\_flow\_j1)
\quad \text{mu\_wo\_j = computeMu(species, Two\_j1(jj));}
\quad \% Specific heat \[J/kg/K\]
\quad \text{Cp\_wo\_j = computeCp(species, Two\_j1(jj));}
\quad \% Thermal conductivity \[W/m/K\]
\quad \text{k\_wo\_j = computeK(species, Two\_j1(jj));}
\quad \text{Pr\_wo\_j = mu\_wo\_j*Cp\_wo\_j/k\_wo\_j;}
\quad \text{Re\_wo\_j = 4*m\_flow/(pi*d\_tube_in*pi*h\_flow\_j);} \quad \text{if } Re\_wo\_j < 2300
\quad \quad \text{Nu\_wo\_j = 4.364;} \text{else}
\quad \quad \text{if (abs(T\_to\_flow\_j1(jj)-Two\_j1(jj)))>56}
\quad \quad \quad \text{if (Re\_wo\_j>10^4) && (Pr\_wo\_j >= 0.5) && (Pr\_wo\_j < 16700)}
\quad \quad \quad \quad \text{Nu\_wo\_j = 0.027*Re\_wo\_j^4*(4/5)*Pr\_wo\_j^1*(1/3)*mu\_flow\_j/mu\_wo\_j)^0.14; \%Dittu-Boelter correlation}
\quad \text{end}
\quad \text{end}
else
    Nu_flow = 0.023*Re_flow_j^4/5*Pr_flow_j^0.4*(To_flow_j1(jj)/Two_j1(jj))^0.47;
  Pethukov correction
end
else
    Nu_flow = 0.023*Re_flow_j^4/5*Pr_flow_j^0.4; % Dittus-Boelter correlation
end
end
h_flow_j = Nu_flow*k_flow_j/dtube_in;
Two_j1(jj) = m_flow*(Entalp_o-Entalp_i)/(L*dtube_in*pi*h_flow_j)+To_flow_j1(jj);
diff(jj) = Two_j1(jj)-To_flow_j1(jj);
end
if Tfinal(i) < Tboil_g
    To_flow_j2 = 0;
elser
    To_flow_j2 = Tboil_g:(Tfinal(i)-Tboil_g)/50:Tfinal(i);
for jj=1:length(To_flow_j2)
    mu_flow_j = computeMu(species, To_flow_j2(jj));
    Cp_flow_j = computeCp(species, To_flow_j2(jj)); % [J/mol/K]
    cp_flow_j = Cp_flow_j/M;
    k_flow_j = computeK(species, To_flow_j2(jj));
    Pr_flow_j = mu_flow_j*cp_flow_j/k_flow_j;
    Re_flow_j = 4*m_flow/(pi*dtube_in*mu_flow_j);
    if Re_flow_j < 2300
        Nu_flow = 4.364;
    else
        Nu_flow = 0.023*Re_flow_j^4/5*Pr_flow_j^0.4; % Dittus-Boelter correlation
    end
    h_flow_j = Nu_flow*k_flow_j/dtube_in;
    Two_j2(jj) = m_flow*(Entalp_o-Entalp_i)/(L*dtube_in*pi*h_flow_j)+To_flow_j2(jj);
diff2(jj) = Two_j2(jj)-To_flow_j2(jj);
    end
end
if Tfinal(i) > Tboil_g
    Tboil_1stwall_vec = Two_j1(length(To_flow_j1))-10^-8:(2*10^-8)/50:Two_j1(length(To_flow_j1))+10^-8;
    Tboil_2ndwall_vec = Two_j2(1)-10^-8:(2*10^-8)/50:Two_j2(1)+10^-8;
    T_wall_mean_liq = mean(Two_j1);
    T_wall_1stmean_boil = mean(Tboil_1stwall_vec);
    T_wall_2ndmean_boil = mean(Tboil_2ndwall_vec);
    T_wall_mean_gas = mean(Two_j2);
    T_wall_mean2 = T_wall_mean_liq*Lliq/L+T_wall_1stmean_boil*L2ph_1st/L+T_wall_2ndmean_boil*L2ph_2nd/L+T_wall_mean_gas*Lgas/L;
    T_wall_i_mean(i) = T_wall_mean2;
    T_final_flow(i) = To_flow_j2(length(To_flow_j2));
elseif Tfinal(i) < Tboil_g && Tfinal(i) > Tboil_l
    Tboil_1stwall_vec = Two_j1(length(To_flow_j1))-10^-8:(2*10^-8)/50:Two_j1(length(To_flow_j1))+10^-8;
    Tboil_2ndwall_vec = Two_j2(1)-10^-8:(2*10^-8)/50:Two_j2(1)+10^-8;
\[ T_{\text{wall, mean liq}} = \text{mean}(T_{\text{wall, liq}}); \]
\[ T_{\text{wall, 1stmean boil}} = \text{mean}(T_{\text{boil, 1stwall vec}}); \]
\[ T_{\text{wall, 2ndmean boil}} = \text{mean}(T_{\text{boil, 2ndwall vec}}); \]
\[ T_{\text{wall, mean2}} = T_{\text{wall, mean liq}} \times L_{\text{liq}} / L + T_{\text{wall, 1stmean boil}} \times L_{2ph, 1st} / L + T_{\text{wall, 2ndmean boil}} \times L_{2ph, 2nd} / L; \]
\[ T_{\text{wall, i mean}}(i) = T_{\text{wall, mean2}}; \]
\[ T_{\text{final, flow}}(i) = T_{\text{flow, j2}}(\text{length}(T_{\text{flow, j2}})); \]
\[ T_{\text{final, wall}}(i) = T_{\text{flow, j2}}(\text{length}(T_{\text{flow, j2}})); \]
\[ \text{else} \% \text{No boiling} \]
\[ T_{\text{wall, mean liq}} = \text{mean}(T_{\text{flow, j1}}); \]
\[ T_{\text{wall, mean2}} = T_{\text{wall, mean liq}} \times L_{\text{liq}} / L; \]
\[ T_{\text{wall, i mean}}(i) = T_{\text{wall, mean2}}; \]
\[ T_{\text{final, flow}}(i) = T_{\text{flow, j1}}(\text{length}(T_{\text{flow, j1}})); \]
\[ T_{\text{final, wall}}(i) = T_{\text{flow, j1}}(\text{length}(T_{\text{flow, j1}})); \]
\[ \text{end} \]
\[ T_{\text{final, flow coil}} = \text{interp1}(T_{\text{wall, i mean}}, T_{\text{final, flow}}, T_{\text{mean}}); \]
\[ T_{\text{final, wall coil}} = \text{interp1}(T_{\text{wall, i mean}}, T_{\text{final, wall}}, T_{\text{mean}}); \]

% %
% Harrie Leenders and Rodrigo A. Ferreira
%
clc
clear all
close all

species = 'H2O';
M = computeM(species); \% [kg/mol]
T_room = 298; \% [K] Actual room temperature
N = 7; \% number of loops
Dout = 0.043; \% coil outer diameter [m]
dtube = 0.003; \% tube outer diameter [m]
Dcoil = Dout - dtube; \% mean coil diameter [m]
L = N*pi*Dcoil; \% coil length [m]
L_cyl = 45*10^-3; \% [m] distance from one part of the coil to the other
dtube_in = 0.0025; \% tube inner diameter [m]
Ac = pi*(dtube/2)^2-(dtube_in/2)^2; \% [m^2]
R0 = 740E-9/L/\% [ohm]
R0 = 0.315; \% [A]
II = 10;
I2 = 0;
V = II*R0
dens_coil = 7817; \% [kg/m^3] [Bejan]
mass_coil = dens_coil*Ac*L \% [kg]
mass_coil = 0.018 \% measured value (coil - fitting) [Kg]
min = 16; \% [min] Number of minutes
t = 60*min; \% [s] Seconds
time_on = 8*60

cp = 500; \% [J/kgK] Specific heat of ss 316
T_air = T_room; \% [K] Temperature of the air
eps_coil = 0.8; \% [-] Emissivity of oxidized steel [table of emissivities from Harrie]
sigma = 5.669e-8; \% [W/m^2K] Stefan-Boltzmann constant
A = L*pi*dtube; \% [m^2] Outer area of the coil
A_cyl = pi*Dcoil*L_cyl;

T_test = 434; \% [K]
R = -1.478*10^{-7}.*(T_test-T_room).^2+3.394*10^{-4}.*(T_test-T_room)+R0;
P_in = II^2*R0;
F_coil = View_factor_coil()
h_form = (P_in/A - F_coil*sigma*(T_test^4-T_room^4)*(eps_coil)/(F_coil*(1-eps_coil)+eps_coil))/(T_test-T_room)
h_vect = [5;h_form;25] \% depending on the reference, the minimum convection coefficient can be 2
g0 = 9.80665;
dt = 0.1; \% [s] Time increment
j = 1;
for h_vect = [h_vect(1) h_vect(2) h_vect(3)]
    T = T_room;
    To_flow = T;
dT=zeros(1,t/dt);
Temp=zeros(1,t/dt);
ii = 1;
for i = 0.1:dt:t;

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% DRY OPERATION
if t < 8*60
  if t < Time_on
    I = I1;
  else
    I = I2;
  end
DT = T-T_room; % [K] Temperature difference
R = -1.478*10^(-7).*DT.^2+3.394*10^-4.*DT+R0; % [W] Inlet power
P_in = I^2*R; % [W] Inlet power
Q_i_in(ii) = P_in;
Q_i_in(ii) = P_in;
Q_rad = F_coil*sigma*(T^4-T_room^4)/(F_coil*(1-eps_coil)+eps_coil); % [W] Power
lost due to radiation
P_in = I^2*R; % [W] Inlet power
Q_i_in1(ii) = P_in_1;
Q_i_in2(ii) = P_in_2;
Q_rad_1 = F_coil*sigma*(T1_1^4-T_room^4)/(F_coil*(1-eps_coil)+eps_coil); % [W] Power
lost due to radiation
P_in_1 = I^2*R_1; % [W] Inlet power
P_in_2 = I^2*R_2; % [W] Inlet power
Q_i_out1_1(ii) = Q_out1_1;
Q_i_out1_2(ii) = Q_out1_2;
Q_i_out1_1(ii) = Q_out1_1;
Q_i_out1_2(ii) = Q_out1_2;
\[ Q_{1,1} = Q_{in,1} - Q_{out,1}; \quad \text{[W] Nett power} \]
\[ Q_{1,2} = Q_{in,2} - Q_{out,2}; \]
\[ T_{o1,1} = T_{1,1}; \]
\[ T_{o1,2} = T_{1,2}; \]
\[ T_{i1,ii} = T_{o1,1}; \]
\[ T_{i2,ii} = T_{o1,2}; \]
\[ E_{1,1} = Q_{1,1} \times dt; \quad \text{[J] Nett energy} \]
\[ E_{1,2} = Q_{1,2} \times dt; \]
\[ dT_{1,ii} = E_{1,1} / (cp \times \text{mass coil}); \quad \text{[K] Temperature increase} \]
\[ dT_{1,ii} = E_{1,2} / (cp \times \text{mass coil}); \]
\[ \text{Temp}_{1,ii} = T_{room} + \sum dT_{1,ii}; \quad \text{[K] Temperature of the system} \]
\[ \text{Temp}_{1,ii} = T_{room} + \sum dT_{1,ii}; \]
\[ ii = ii + 1; \]
\[ dT_{total,1}(:,1,:) = dT_{1,1}; \]
\[ dT_{total,2}(:,1,:) = dT_{1,2}; \]
\[ \text{Temp}_{total,1}(:,1,:) = \text{Temp}_{1,1}; \]
\[ \text{Temp}_{total,2}(:,1,:) = \text{Temp}_{1,2}; \]
\[ \text{P}_{in,1}(:,1,:) = P_{i,1}; \quad \text{[W] Inlet power} \]
\[ \text{P}_{in,2}(:,1,:) = P_{i,2}; \]
\[ \text{Q}_{in,1}(:,1,:) = \text{P}_{in,1}; \quad \text{[W] Inlet power} \]
\[ \text{Q}_{in,2}(:,1,:) = \text{P}_{in,2}; \]
\[ \text{Q}_{rad,1}(:,1,:) = F_{coil} \times \sigma \times (T_{2,1}^4 - T_{room}^4) \times (\epsilon_{coil} A) / (F_{coil} \times (1 - \epsilon_{coil}) + \epsilon_{coil}) ; \quad \text{[W] Power lost due to radiation} \]
\[ T_{air,1} = (T_{2,1} + T_{room}) / 2; \]
\[ T_{air,2} = (T_{2,2} + T_{room}) / 2; \]
\[ k_{air,1} = \text{computeK('Air', T_{air,1});} \]
\[ k_{air,2} = \text{computeK('Air', T_{air,2});} \]
\[ rho_{air,1} = \text{computeRho('Air', T_{air,1}, 1E5);} \]
\[ rho_{air,2} = \text{computeRho('Air', T_{air,2}, 1E5);} \]
\[ mu_{air,1} = \text{computeMu('Air', T_{air,1});} \]
\[ mu_{air,2} = \text{computeMu('Air', T_{air,2});} \]
\[ Cp_{air,1} = \text{computeCp('Air', T_{air,1});} \]
\[ Cp_{air,2} = \text{computeCp('Air', T_{air,2});} \]
\[ M_{air} = \text{computeM('Air');} \]
\[ cp_{air,1} = Cp_{air,1} / M_{air}; \]
\[ cp_{air,2} = Cp_{air,2} / M_{air}; \]
\[ Pr_{air,1} = \text{computePr('Air', k_{air,1});} \]
\[ Pr_{air,2} = \text{computePr('Air', k_{air,2});} \]
\[ X = \text{Dcoil}; \]
\[ beta_{1} = 1 / T_{air,1}; \]
\[ beta_{2} = 1 / T_{air,2}; \]
\[ Gr_{1} = 0 \times \text{beta} \times \text{rho}_{air,1} \times X \times 2 \times (T_{2,1} - T_{room}); \]
\[ Gr_{2} = 0 \times \text{beta} \times \text{rho}_{air,2} \times X \times 2 \times (T_{2,2} - T_{room}); \]
\[ Ra_{1} = Gr_{1} \times Pr_{air,1}; \quad \% [-] Rayleigh number \]
\[ Ra_{2} = Gr_{2} \times Pr_{air,2}; \]
\[ Nu_{2,1} = (0.64 \times 0.28 \times 0.64 \times 0.28 \times 0.64) / (1 + 0.559 \times Pr_{air,1} \times 9.16 \times 8.27)^{2}; \]
\[ Cl_{2} = 0.671 / (1 + 0.492 \times Pr_{air,2} \times 9.16^{4} / 49); \]
\[ Nucond_{2} = 1.549; \]
n_2 = 1.11;
m_2 = 8;
G_2 = 0.881;
Ct_2 = 0.110;
Nu2_2 = ((Nucond_2^n_2+G_2*Cl_2^2*Ra_2^(1/4))^(n_2))^(m_2/n_2)+(Ct_2*Ra_2^(1/3))^m_2; 
Q_conv2_1 = A_cyl*Nu1_1*k_air_1/Dcoil;
Q_conv2_2 = A_cyl*Nu2_2*k_air_2/Dcoil;
Q_out2_1 = Q_rad1 + Q_conv2_1;
Q_out2_2 = Q_rad2 + Q_conv2_2;
Q_i_out2_1(ii) = Q_out2_1;
Q_i_out2_2(ii) = Q_out2_2;
Q2_1 = Q_in_1-Q_out2_1;                                       % [W] Nett power
Q2_2 = Q_in_2-Q_out2_2;

E2_1 = Q2_1*dt;                                             % [J] Nett energy
E2_2 = Q2_2*dt;

dT2_1(ii) = Temp2_1 - Temp2_2;

dT_total2(1,:) = dT2_1;
dT_total2(2,:) = dT2_2;
Temp_total2(1,:) = Temp2_1;
Temp_total2(2,:) = Temp2_2;
P_in_total2(1,:) = P_i_in2_1;
P_in_total2(2,:) = P_i_in2_2;
Q_out_total2(1,:) = Q_i_out2_1;
Q_out_total2(2,:) = Q_i_out2_2;
h_conv_total2(1,:) = h_i_conv2_1;
h_conv_total2(2,:) = h_i_conv2_2;

% Harrie Leenders and Rodrigo A. Ferreira
% 
% clc
% clear all
% close all

species = 'H2O';
M = computeM(species); %[kg/mol]
T_room  = 295;   % [K] Room temperature
Tboil = 393.36;%[K]
Tboil_l = 393.36-1e-6;%[K]
Tboil_g = 393.36+1e-6;%[K]
Tm_liq = (T_room+Tboil)/2;
p=2;%[bar]
Entalp_i = computeEnthalpy(species, T_room,p)/M; % [J/kg]
Entalp_liq = computeEnthalpy(species, Tboil_l,p)/M; % [J/kg]
Entalp_vap = computeEnthalpy(species, Tboil_g,p)/M; % [J/kg]

N = 7;                  %number of loops
Dout = 0.043;           %coil outer diameter [m]
dtube = 0.003;          %tube outer diameter [m]
Dcoil = Dout-dtube;     %mean coil diameter [m]
L = N*pi*Dcoil;         %coil length [m]
L_cyl = 45*10^-3;       %[m] distance from one part of the coil to the other
dTube_in = 0.0025;      %tube inner diameter [m]
Ac = pi*((dTube/2)^2-(dTube_in/2)^2); % [m^2]
R0 = 7409*9/L/Ac          %[ohm]
%R0 = 0.316
%I = 9.9776;   %[A]
I1 = 5;
I2= 16;
Time1 = 10;
Time2 = 18;
V = I1*R0
\text{dens} = 7817 \text{ [kg/m}^3\text{]} \text{ [Bejan]}\\
\text{mass} = \text{dens} \times \text{Ac} \times \text{L} \\text{ [kg]}\\
\text{mass} = 0.018 \\text{ [measured value (coil - fitting)] [Kg]}\\
\text{min} = 25; \\% \text{ [min] Number of minutes}\\
t = 60 \times \text{min}; \\% \text{ [s] Seconds}\\
cp = 500; \\% \text{ [J/kgK] Specific heat of ss 316}\\
T_{\text{air}} = T_{\text{room}}; \\% \text{ [K] Temperature of the air}\\
\text{eps} = 0.8; \\% \text{ [-] Emissivity of oxidized steel [table of emissivities from Harrie]}\\
sigma = 5.696 \times 10^{-8}; \\% \text{ [W/m}^2\text{K] Stefan-Boltzmann constant}\\
A = \pi \times \text{dtube}; \\% \text{ [m}^2\text{] Outer area of the coil}\\
A_{\text{cyll}} = \pi \times \text{Dcoil} \times \text{L_cyl};\\
\text{T_test} = 434; \\% \text{ [K]}\\
\% R = R_0 \times 1 + 0.820 \times 10^{-3} \times 25; \\% \text{ [K]}\\
P_f = \text{P}_f \times \pi \times \text{tub e}; \\% \text{ [m}^2\text{]}\\
\text{h} = \text{View} \times \text{factor coil}()\\
h_{\text{conv}} = \text{h}_i \times \text{fract} \times \frac{T_{\text{test}}^4 - T_{\text{room}}^4 \times \text{eps} \times \text{A}}{\text{Q}_i \times \text{fract} \times \text{eps} \times \text{A}}; \\% \text{ [W] Power lost due to radiation}\\
\% \text{T_axis} = \frac{T + T_{\text{room}}}{2}; \\% \text{ [K] Temperature of the axis}\\
h_{\text{for conv}} = \text{h}_i \times \text{fract} \times \frac{T_{\text{test}} - T_{\text{room}}}{\text{Q}_i \times \text{fract} \times \text{eps} \times \text{A}}; \\% \text{ [W] Power lost due to convection}\\
\% \text{T_axis} = \text{T}_{\text{room}} + \text{sum}(\text{dT}(\text{i};\text{j}))}; \\% \text{ [K] Temperature of the axis}\\
\% \text{if I < Time1*60}\\
m_flow = 0; \\% \text{[kg/s]}\\
\% \text{Q} = \text{Q}_i - \text{Q}_o; \\% \text{[W]} \text{Nett power}\\
\% \text{dT} = \text{E} / (\text{cp} \times \text{mass} \times \text{coi}); \\% \text{[K]} \text{Temperature increase}\\
\% \text{T_axis} = \text{T}_{\text{room}} + \text{sum}(\text{dT}(\text{i};\text{j}));


\begin{verbatim}
Temp(ii) = T_room+sum(dT(1:ii)); % [K] Temperature of the system
\end{verbatim}
Two1_2i (ii) = Two1_2;
else
    % With mass flow
    m_flow = 30*10^-6; % [kg/s]
    [To1_1flow,Two1_1] = Twall_Tflow(T1_1, m_flow, species); % for coiled
    % [To1_1flow,Two1_1] = Twall_Tflow_straight(T1_1, m_flow, species); % for straight
    Two1_1i (ii) = Two1_1;
    if i < Time2*60
        if To1_1flow > Two1_1
            To1_1flow = Two1_1;
            Two1_1i (ii) = Two1_1;
        end
    end
end
Entalp_o_1 = computeEnthalpy(species, To1_1flow,p)/M; % [J/kg]
Qflow_1 = m_flow*(Entalp_o_1-Entalp_i);
Q1_1 = Q_flow_1/(cp*mass_coil); % [J] Nett energy
dT1_1(ii) = El_1/(cp*mass_coil);
Temp1_1(ii) = T_room+sum(dT1_1(1:ii)); % [K] Temperature of the system
T1_1 = Temp1_1(ii);
To1_i1_flow (ii) = To1_1flow;
if i < Time2*60
    if To1_1flow > Two1_2
        To1_1flow = Two1_2;
        Two1_1i (ii) = Two1_2;
    end
end
Entalp_o_2 = computeEnthalpy(species, To1_2flow,p)/M; % [J/kg]
Qflow_2 = m_flow*(Entalp_o_2-Entalp_i);
Q1_2 = Q_flow_2/(cp*mass_coil); % [J] Nett energy
dT1_2(ii) = El_2/(cp*mass_coil);
Temp1_2(ii) = T_room+sum(dT1_2(1:ii)); % [K] Temperature of the system
T1_2 = Temp1_2(ii);
To1_i2_flow (ii) = To1_2flow;
end
ii = ii+1;
end
dT_total1(1,:) = dT1_1;
dT_total1(2,:) = dT1_2;
Temp_total1(1,:) = Temp1_1;
Temp_total1(2,:) = Temp1_2;
P_in_total1(1,:) = P_i_in1_1;
P_in_total1(2,:) = P_i_in1_2;
Q_out_total1(1,:) = Q_out1_1;
Q_out_total1(2,:) = Q_out1_2;
h_conv_total1(1,:) = h_i_conv1_1;
h_conv_total1(2,:) = h_i_conv1_2;
To_ij1_flow(1,:) = To1_i1_flow;
To_ij1_flow(2,:) = To1_i2_flow;
T_excel1_1 = Temp_total1(1,:);
T_excel1_2 = Temp_total1(2,:);
P_excel1_1 = P_in_total1(1,:);
P_excel1_2 = P_in_total1(2,:);
P2_1 = T2_1-T_room; % [K] Temperature difference
P2_2 = T2_2-T_room;
R_1 = -1.478*10^-7.*DT2_1.^2+3.394*10^-4.*DT2_1+R0;
R_2 = -1.478*10^-7.*DT2_2.^2+3.394*10^-4.*DT2_2+R0;
P_in_1 = 1*2*R_1; % [W] Inlet power
P_in_2 = 1*2*R_2;
P_i_in2_1(ii) = P_in_1;
P_i_in2_2(ii) = P_in_2;
Q_in_1 = P_in_1;
Q_in_2 = P_in_2;
\[ Q_{\text{rad}} = F_{\text{coil}} \sigma (T_2^4 - T_{\text{room}}^4) \frac{\varepsilon_{\text{coil}} A}{(F_{\text{coil}}(1-\varepsilon_{\text{coil}})+\varepsilon_{\text{coil}})} \text{[W]} \]

Power lost due to radiation

\[ Q_{\text{rad}} = F_{\text{coil}} \sigma (T_2^4 - T_{\text{room}}^4) \frac{\varepsilon_{\text{coil}} A}{(F_{\text{coil}}(1-\varepsilon_{\text{coil}})+\varepsilon_{\text{coil}})} \]

\[ T_{\text{air}} = \frac{T_2 + T_{\text{room}}}{2} \]

\[ k_{\text{air}} = \text{computeK('Air', T_{\text{air}})} \]

\[ \rho_{\text{air}} = \text{computeRho('Air', T_{\text{air}}, 1E5)} \]

\[ \mu_{\text{air}} = \text{computeMu('Air', T_{\text{air}})} \]

\[ C_{p_{\text{air}}} = \text{computeCp('Air', T_{\text{air}})} \]

\[ \frac{\text{M}_{\text{air}}}{C_{p_{\text{air}}}} \]

\[ \text{Pr}_{\text{air}} = \frac{\mu_{\text{air}}}{k_{\text{air}}} \]

\[ \beta_1 = \frac{1}{T_{\text{air}}} \]

\[ \beta_2 = \frac{1}{T_{\text{air}}} \]

\[ Gr_1 = g_0 \beta_1 \rho_{\text{air}}^2 (T_2 - T_{\text{room}}) X^3 \mu_{\text{air}}^2 \]

\[ Gr_2 = g_0 \beta_2 \rho_{\text{air}}^2 (T_2 - T_{\text{room}}) X^3 \mu_{\text{air}}^2 \]

\[ Ra = Gr \text{Pr} \]

\[ Nu_{\text{out}} = \left( 0.61\left( 0.492/Pr_{\text{air}} \right) \right)^{m_2} \]

\[ Q_{\text{conv}} = (A_{\text{cyl}} \frac{Nu_{\text{out}}}{D_{\text{coil}}}) (T_2 - T_{\text{room}}) \]

\[ Q_{\text{out}} = Q_{\text{rad}} + Q_{\text{conv}} \]

if \( i < \text{Time}*60 \)

\[ m_{\text{flow}} = 0 \text{[kg/s]} \]

\[ Q_1 = Q_{\text{in}} - Q_{\text{out}} \]

\[ E_1 = Q_1 \times dt \]

\[ \text{Temp} = T_{\text{room}} + \sum \text{Temp}_1 \]

else

\[ m_{\text{flow}} = 30 \times 10^{-6} \text{[kg/s]} \]

\[ Q_{\text{flow}} = \frac{\text{M}{\text{flow}} \times \text{Entalp}_o - \text{M}{\text{flow}} \times \text{Entalp}_i}{\text{M}} \]

\[ Q_{\text{out}} = Q_{\text{in}} - Q_{\text{out}} - Q_{\text{flow}} \]

\[ E_1 = Q_{\text{flow}} \times dt \]
% Temperature increase
dT2_1(ii) = E2_1/(cp*mass_coil); % [K]
Temp2_1(ii) = T_room+sum(dT2_1(1:ii)); % [K]

% Temperature of the system
T2_1 = Temp2_1(ii);

% m_flow = 30*10^-6; %[kg/s]
[To2_2flow,Two2_2] = Twall_Tflow(T2_2, m_flow, species); %for coiled
[To2_2flow,Two2_2] = Twall_Tflow_straight(T2_2, m_flow, species); %for straight
Two2_2i = Two2_2;
if i < Time2*60
  if To2_2flow > Two2_2
    To2_2flow = Two2_2;
    Two2_2i = Two2_2;
  end
end

% Nett energy
E2_2 = Q2_2/(cp*mass_coil); % [J]
Temp2_2(ii) = T_room+sum(dT2_2(1:ii)); % [K]

% Temperature of the system
T2_2 = Temp2_2(ii);

ii = ii+1;

% Coil with insulation around
% Harrie Leenders and Rodrigo A. Ferreira
% clc
clear all
close all

T_room = 295; % [K] Actual room temperature
N = 7; % number of loops
Dout = 0.043; % coil outer diameter [m]
dtube = 0.003; % tube diameter [m]
Dcoil = Dout-dtube; % mean coil diameter [m]
L = 0.95; % [m]
dtube_in = 0.0025; % tube inner diameter [m]
Ac = pi*(dtube^2/2-(dtube_in/2)^2); % [m^2]
Th_ins = 0.025;
Dtot = 0.088; % mean value of measured values
Lcoil = 0.045; % coil length [m]
Ltot = 0.093; % mean value of measured values
r1 = Dcoil/2; %
r2 = 0.088/2; %
As1 = 2*pi*Dcoil/2*Dcoil*pi/4*(Dcoil)^2;
As2 = 2*pi*Dtot/2*Ltot*pi/4*(Dtot)^2;
Ltot_c = Ltot*Dtot/2; %corrected length that takes into account the sides, as a fin

R0 = 0.315 %[ohm] measured value in test without flow
I1 = 9.9776; %[A]
I2 = 0;
Time_on = 20*60;

V = I1*R0
dens_coil = 7817; % [kg/m^3] [Bejan]
\[ \text{mass}_{\text{coil}} = \text{dens}_{\text{coil}} \times \text{Ac} \times \text{L} \quad \text{[kg]} \]
\[ \text{mass}_{\text{coil}} = 0.018 \quad \text{[measured value (coil - fitting) [Kg]]} \]
\[ \text{min} = 40; \quad \% \text{[min]} \text{ Number of minutes} \]
\[ \text{t} = 60/\text{min}; \quad \% \text{[s]} \text{ Seconds} \]
\[ \text{cp} = 500; \quad \% \text{[J/kgK]} \text{ Specific heat capacity of ss 316} \]
\[ \text{T}_{\text{air}} = \text{T}_{\text{room}}; \quad \% \text{[K]} \text{ Temperature of the air} \]
\[ \text{eps}_{\text{coil}} = 0.8; \quad \% \text{[-]} \text{ Emissivity of oxidized steel [table of emissivities from Harrie]} \]
\[ \text{eps}_{\text{ins}} = 0.2; \quad \% \text{[-]} \text{ Emissivity of aluminium foil around the insulation, worst value found in literature} \]
\[ \text{sigma} = 5.669\times10^{-8}; \quad \% \text{[W/m^2K]} \text{ Stefan-Boltzmann constant} \]
\[ \% \text{A} = \text{L} \times \pi \times \text{dtube}; \quad \% \text{[m^2]} \text{ Outer area} \]

% For 3 different convection coefficients
\[ \text{T}_{\text{test}} = 900; \quad \% \text{[K]} \]
\[ \text{T}_{\text{ins}} = 350; \quad \% \text{[K]} \]
\[ \% \text{R} = \text{R}_0 \times (1+0.820\times10^{-3} \times (\text{T}_{\text{test}}-\text{T}_{\text{room}})); \]
\[ \% \text{R} = \text{R}_0 \times (1+0.9914\times10^{-3} \times (\text{T}_{\text{test}}-\text{T}_{\text{room}})); \]
\[ \% \text{R} = \text{R}_0 \times (1+0.820\times10^{-3} \times (\text{T}_{\text{test}}-\text{T}_{\text{room}})); \]
\[ \% \text{F}_{\text{coil}} = \text{View factor coil}() \]
\[ \% \text{F}_{\text{tot}} = 1; \]
\[ \% \text{h}_{\text{form}} = (\text{P}_{\text{in}}/\text{As}_2 - \text{F}_{\text{tot}} \times \text{sigma} \times (\text{T}_{\text{ins}}^4 - \text{T}_{\text{room}}^4) \times \text{eps}_{\text{ins}})/(\text{T}_{\text{ins}} - \text{T}_{\text{room}}); \]
\[ \% \text{h}_{\text{vect}} = \left[ \frac{5}{8} \times \text{h}_{\text{form}}; 25 \right] \quad \% \text{depending on the reference, the minimum convection coefficient can be 2} \]

% DRY OPERATION
\[ \text{if } \text{t} < \text{Time_on} \]
\[ \% \text{I} = \text{I}_1; \]
\[ \% \text{else} \]
\[ \% \text{I} = 0; \]
\[ \% \text{end} \]
\[ \% \text{T}_{\text{mean}} = (\text{T}_{\text{r1}}+\text{T}_{\text{r2}})/2; \]
\[ \% \text{k}_{\text{ins}} = \text{computeK('Fiberfrax', } \text{T}_{\text{mean}}); \]
\[ \% \text{T}_{\text{air}} = (\text{T}_{\text{r2}} + \text{T}_{\text{room}})/2; \]
\[ \% \text{h}_{\text{i,conv}}(\text{i}) = \text{h}_{\text{vect}}; \]
\[ \% \text{Q}_{\text{conv}} = (\text{As}_2 \times \text{h}_{\text{vect}} \times (\text{T}_{\text{r2}}-\text{T}_{\text{room}}); \]
\[ \% \text{DTr1} = \text{T}_{\text{r1}} - \text{T}_{\text{r2}}; \]
\[ \% \text{DTr2} = \text{T}_{\text{r2}} - \text{T}_{\text{room}}; \]
\[ \% \text{Q}_{\text{rad}} = \text{F}_{\text{tot}} \times \text{sigma} \times (\text{T}_{\text{r2}}^4 - \text{T}_{\text{r1}}^4) \times (\text{eps}_{\text{ins}} \times \text{As}_2)/(\text{F}_{\text{tot}} \times (1 - \text{eps}_{\text{ins}}) + \text{eps}_{\text{ins}}); \]
\[ \% \text{Power lost due to radiation} \]
\[ \% \text{Q}_{\text{out}} = \text{Q}_{\text{rad}} + \text{Q}_{\text{conv}}; \]
\[ \% \text{Outgoing power, lost power} \]
\[ \% \text{Air inside the Coil at constant pressure} \]
\[ \% \text{T}_{\text{m, int}} = \text{T}_{\text{r1}}; \]
\[ \% \text{rho}_{\text{air}} = \text{computeRho('Air', } \text{T}_{\text{m, int}}, 1E5); \]
\[ \% \text{Vol}_{\text{air}} = \pi \times \text{r}_1^2 \times \text{L}_{\text{coil}}; \]
\[ \% \text{m}_{\text{air}} = \text{rho}_{\text{air}} \times \text{Vol}_{\text{air}}; \]
\[ \% \text{Cp}_{\text{int, air}} = \text{computeCp('Air', } \text{T}_{\text{m, int}}); \]
\[ \% \text{M}_{\text{int, air}} = \text{computeM('Air');} \]
\[ \% \text{cp}_{\text{int, air}} = \text{Cp}_{\text{int, air}}/\text{M}_{\text{int, air}}; \]
\[ \% \text{R} = -1.478 \times 10^{-7} \times (\text{T}_{\text{r1}}^2 - \text{T}_{\text{r2}}^2); \]
\[ \% \text{P}_{\text{in}} = \text{I}^2 \times \text{R}; \]
\[ \% \text{Inlet power} \]
\[ \% \text{Q}_{\text{i, in}}(\text{i}) = \text{P}_{\text{i, in}}; \]
\[ \% \text{Q}_{\text{i, out}}(\text{i}) = \text{Q}_{\text{i, in}}(\text{i}) - \text{Q}_{\text{in}}; \]
\[ \% \text{Inlet power} \]
\[ \% \text{Q} = \text{Q}_{\text{i, out}}; \]
\[ \% \text{Nett power} \]
\[ \% \text{To}_{\text{flow}} = \text{T}_{\text{r1}}; \]
\[ \% \text{To}_{\text{i, flow}}(\text{i}) = \text{To}_{\text{flow}}; \]
\[ \% \text{Two} = \text{T}_{\text{r1}}; \]
\[ \% \text{E} = \text{Q} \times \text{dt}; \]
\[ \% \text{Nett energy} \]
\[ \% \text{dTr1}(\text{i}) = \text{E} / (\text{cp} \times \text{mass}_{\text{coil}} + \text{cp}_{\text{int, air}} \times \text{m}_{\text{air}}); \]
\[ \% \text{Temperature increase} \]
\[ \% \text{Temp}(\text{i}) = \text{T}_{\text{r1}} + \text{sum} \times (\text{dTr1}(\text{i}) + \text{Temp}(\text{i})) / \text{dt}; \]
\[ \% \text{Temperature of the system} \]
\[ \% \text{Ts2 = T}_{\text{room}} / (\text{T}_{\text{r1}}+\text{T}_{\text{room}}); \]
\[ \% \text{for j=1:length(Ts2)} \]
\[ \% \text{i} = (\text{As}_2 \times \text{h}_{\text{vect}}) \times (\text{Ts2}(\text{j}) + \text{T}_{\text{room}}) + \text{F}_{\text{tot}} \times \text{sigma} \times (\text{Ts2}(\text{j})^4 - \text{T}_{\text{room}}^4) \times (\text{eps}_{\text{ins}} \times \text{As}_2) / (\text{F}_{\text{tot}} \times (1 - \text{eps}_{\text{ins}}) + \text{eps}_{\text{ins}}) \times \log(\text{r}_2/\text{r}_1) / (2 \times \text{pi} \times \text{L}_{\text{tot}} \times \text{r}_1^2) \times \text{Ts2}(\text{j}); \]
\[ \% \text{end} \]
\[ \% \text{Tempr2}(\text{i}) = \text{interp1}(\text{Ts1}, \text{Ts2}, \text{T}_{\text{r1}}); \]
Tr2 = Temp2(i);
end
dT_total(j,:)=dTr1;
Temp_total(j,:)=Temp;
Temp_total2(j,:)=Temp2;
P_in_total(j,:)=P_i_in;
P_in_total2(j,:)=P_i_in;
h_conv_total(j,:)=h_i_conv;
Temp_final()=Temp2(i);
time(j)=(cp*mass_coil*(Temp2(i)-T_room)/P_in)/60; %[min]
time2(j)=(-cp*mass_coil/((h_vect*As2)*log(1-(Temp2(i)-T_room)*h_vect*As2/P_in)))/60; %[min]
j=j+1;
end
T_excel1 = Temp_total(1,:);'
P_excel1 = P_in_total(1,:);'
T_excel2 = Temp_total(3,:);'
P_excel2 = P_in_total(3,:);'
Tr1_1 = T_room;
Tr2_1 = T_room;
for i = 1:dt:t;
   t = i;
   % [s] Time
   % DRY OPERATION
   if t<Time_on
      I = I1;
   else
      I = 0;
   end
   T_mean = (Tr1_1+Tr2_1)/2;
   k_ins = computeK('Fiberfrax', T_mean);
   T_air = (Tr2_1 + T_room)/2;
   k_air = computeK('Air', T_air);
   h_conv1 = computeH(Dtot, Ltot_c, Tr2_1, T_room, T_air, 1E5, 0, 0, 'Air', 'free', 'outside', 0, 'cyl');
   h_i_conv1(i) = h_conv1;
   Q_conv = (As2*h_conv1)*(Tr2_1-T_room);
   DTr1_1 = Tr1_1-T_room; %[K] Temperature difference on the coil
   DTr2_1 = Tr2_1-T_room; %[K] Temperature difference on the insulation
   Q_rad = F_tot*sigma*(Tr2_1^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins); %[W] Power lost due to radiation
   Q_out1 = Q_rad + Q_conv; %[W] Outgoing power; lost power
   % Air inside the Coil at constant pressure
   T_m_int = Tr1_1;
   rho_air = computeRho('Air',T_m_int,1E5);
   Vol_air = pi*r1^2/2*Lcoil;
   m_air = rho_air*Vol_air;
   Cp_int_air = computeCp('Air', T_m_int);
   M_int_air = computeM('Air');
   cp_int_air = Cp_int_air/M_int_air;
   %R = R0*(1+0.9914E-3*DTr1_1);
   R = -1.478*10^(-7).*DTr1_1.^2+3.394*10^-4.*DTr1_1+R0;
   P_in1 = I^2*R;
   P_i_in1(i) = P_in1;
   Q1 = Q_i1 - Q_out1;
   E1 = Q1*dt;
   dTr1_1(i) = E1/(cp*mass_coil+cp_int_air*m_air);
   Temp_l(i) = T_room+sum(dTr1_1(1:i));
   %[K] Temperature of the system
   Tr1_1 = Temp_l(i);
   Ts2_1 = T_room:(Tr1_1-T_room)/100:Tr1_1;
   for jj=1:1:length(Ts2_1)
      Ts1_1(jj) = ((As2*h_conv1)*(Ts2_1(jj)-T_room)+F_tot*sigma*(Ts2_1(jj)^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins))*log(r2/r1)/(2*pi*Ltot_c*k_ins)+Ts2_1(jj);
   end
   Tempr2_1(i) = interp1(Ts1_1, Ts2_1, Tr1_1);
   Tr2_1 = Tempr2_1(i);
end
h_conv1
dT_total1(1,:) = dTr1_1;
Temp_total1(1,:) = Temp_1;
Temp_total2_1(1,:) = Temp2_1;
P_in_total1(1,:) = P_i_in1;
h_conv_total1(1,:) = h_i_conv1;
T_excel1_1 = Temp_total1(1,:);'
T_excelr2_1 = Temp_totalr2(1,:);'
Tr1_2 = T_room;
Tr2_2 = T_room;
for i = 1:dt:t;
% DRY OPERATION

if t < Time_on
    I = I1;
else
    I = 0;
end

T_mean = (Tr1_2+Tr2_2)/2;
k_ins = computeK('Fiberfrax', T_mean);
T_air = (Tr2_2 + T_room)/2;
k_air = computeK('Air', T_air);
rho_air = computeRho('Air', T_air, 1E5);
mu_air = computeMu('Air', T_air);
Cp_air = computeCp('Air', T_air);
M = computeM('Air');
cp_air = rho_air*cP_air/k_air;
X = dtot;

% Air inside the CoIl at constant pressure

R = g_0 + beta * rho_air ^ 2 * (Tr2_2 - T_room) * X ^ 3 / mu_air ^ 2;

Nu2 = (0.6*(0.387*Ra^1/6)/(1 + 0.559/Pr_air ^9/16))^2;

h_conv2 = Nu2*k_air/Dtot;

h_i_conv2(i) = h_conv2;

Q_conv = (As2*h_conv2)*(Tr2_2-T_room);

DTr1_2 = Tr1_2-T_room;

DTr2_2 = Tr2_2-T_room;

Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);

Q_out2 = Q_rad + Q_conv;

% Air inside the CoIl at constant pressure

% [W] Power lost due to radiation

Q_out2 = Q_rad + Q_conv;

% [W] Power lost due to radiation

% [W] Power lost due to convection

Q_conv = (As2*h_conv2)*(Tr2_2-T_room);

DTr1_2 = Tr1_2-T_room;

DTr2_2 = Tr2_2-T_room;

Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);

Q_out2 = Q_rad + Q_conv;

% [W] Power lost due to convection

Q_conv = (As2*h_conv2)*(Tr2_2-T_room);

DTr1_2 = Tr1_2-T_room;

DTr2_2 = Tr2_2-T_room;

Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);

Q_out2 = Q_rad + Q_conv;

% [W] Power lost due to convection

Q_conv = (As2*h_conv2)*(Tr2_2-T_room);

DTr1_2 = Tr1_2-T_room;

DTr2_2 = Tr2_2-T_room;

Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);

Q_out2 = Q_rad + Q_conv;

% [W] Power lost due to convection

Q_conv = (As2*h_conv2)*(Tr2_2-T_room);

DTr1_2 = Tr1_2-T_room;

DTr2_2 = Tr2_2-T_room;

Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);

Q_out2 = Q_rad + Q_conv;
\[ M = \text{computeM('Air')} \]
\[ \text{cp\_air} = \text{Cp\_air}/M; \]
\[ \text{Pr\_air} = \text{mu\_air}\times\text{cp\_air}/k\_air; \]
\[ X = D\_tot; \]
\[ \beta = 1/T\_air; \]
\[ G = \text{g0} \times \beta \times \text{rho\_air}^2 \times (T\_2 - T\_room) \times X \times 3 / \text{mu\_air}^2 \]
\[ \text{Ra} = \text{Gr}\times\text{Pr\_air}; \quad \% \text{[-]} \text{Rayleigh number} \]
\[ \text{Cl\_3} = 0.671/((1+0.492/\text{Pr\_air}) \times (9/16))^{(4/9)}; \]
\[ \text{Nucond\_3} = 1.549; \]
\[ n\_3 = 3.11; \]
\[ m\_3 = 8; \]
\[ C\_3 = 0.881; \]
\[ G\_3 = 0.110; \]
\[ \text{Nu\_3} = (\text{Nucond\_3}\times n\_3 + (G\_3 \times C\_3 \times \text{Ra}^{(1/4)}) \times (n\_3) \times (m\_3/n\_3) + (C\_3 \times \text{Ra}^{(1/3)}) \times m\_3)/(1/m\_3); \]
\[ \text{h\_conv\_3} = \text{Nu\_3} \times \text{rho\_air} / D\_tot; \]
\[ \text{h\_1\_conv\_3} = \text{h\_conv\_3}; \]
\[ \text{Q\_conv\_3} = (A\_2 \times \text{h\_conv\_3})^{(T\_2 - T\_room)}; \quad \% \text{[W]} \text{Power lost due to convection} \]
\[ \text{DTr\_3} = T\_1 - T\_room; \quad \% \text{[K]} \text{Temperature difference on the coil} \]
\[ \text{DTr\_2} = T\_2 - T\_room; \quad \% \text{[K]} \text{Temperature difference on the insulation} \]
\[ \text{Q\_rad} = F\_tot \times \sigma \times (T\_2^4 - T\_room^4) \times (\text{eps\_ins} \times A\_2)/(F\_tot \times (1 - \text{eps\_ins}) + \text{eps\_ins}); \quad \% \text{[W]} \text{Power lost due to radiation} \]
\[ \text{Q\_out\_3} = \text{Q\_rad} + \text{Q\_conv\_3}; \quad \% \text{[W]} \text{Outgoing power; lost power} \]
\[ \% \text{Air inside the coil at constant pressure} \]
\[ \text{T\_m\_int} = T\_1; \]
\[ \text{rho\_air} = \text{computeRho('Air', T\_m\_int, 1E5)}; \]
\[ \text{Vol\_air} = \pi \times r\_1^2 \times 2 \times L\_coil; \]
\[ \text{m\_air} = \text{rho\_air} \times \text{Vol\_air}; \]
\[ \text{cp\_int\_air} = \text{computeCp('Air', T\_m\_int)}; \]
\[ \text{M\_int\_air} = \text{computeM('Air')}; \]
\[ \text{cp\_int\_air} = \text{Cp\_int\_air}/\text{M\_int\_air}; \]
\[ \text{R} = -1.478 \times 10^{-7} \times D\_Tr\_1^2 + 3.394 \times 10^{-4} \times D\_Tr\_1 + R\_0; \]
\[ \text{I} \times \text{I} \times \text{R} = \text{P\_in\_3}; \quad \% \text{[W]} \text{Inlet power} \]
\[ \text{P\_i\_in\_3} = \text{P\_in\_3}; \quad \% \text{[W]} \text{Inlet power} \]
\[ \text{Q\_3} = \text{Q\_in\_3} - \text{Q\_out\_3}; \quad \% \text{[W]} \text{Nett power} \]
\[ \text{E\_3} = \text{Q\_3}/dt; \quad \% \text{[J]} \text{Nett energy} \]
\[ \text{dT\_Tr\_1\_3}\_{(i)} = \text{E\_3}/(\text{cp\_mass\_coil} \times \text{cp\_int\_air} \times \text{m\_air}); \quad \% \text{[K]} \text{Temperature increase} \]
\[ \text{Temp\_3}\_{(i)} = \text{T\_room} + \text{sum}(\text{dT\_Tr\_1\_3}\_{(1:i)}); \quad \% \text{[K]} \text{Temperature of the system} \]
\[ \text{Tr\_1} = \text{Temp\_3}\_{(i)}; \]
\[ \text{Ts\_2}\_{(i)} = (\text{As\_2} \times \text{h\_conv\_3})^{(T\_2 - T\_room)}; \quad \% \text{[T]} \text{Temperature difference on the coil} \]
\[ \text{Ts\_1}\_{(i)} = \text{((As\_2 \times \text{h\_conv\_3})^{(T\_2 - T\_room)} + \text{P\_tot} \times \sigma \times (T\_2^4 - T\_room^4) \times (\text{eps\_ins} \times A\_2)/(\text{F\_tot} \times (1 - \text{eps\_ins}) + \text{eps\_ins}) + \text{Ts\_2}\_{(i)})); \]
\[ \% \text{Coil with insulation around} \]
\[ \% \text{Rodrigo A. Ferreira} \]
\[ \% \text{clc} \]
\[ \text{clear all} \]
\[ \text{close all} \]
\[ \text{species} = '\text{H2O}'; \]
\[ \text{M} = \text{computeM(species)}; \quad \% \text{[kg/mol]} \]
\[ \text{M\_int\_air} = \text{computeM('Air')}; \quad \% \text{Air inside the coil and insulation [kg/mol]} \]
\[ \text{T\_room} = 295; \quad \% \text{[K]} \]
\[ \text{T\_boil} = 393.36; \quad \% \text{[K]} \]
\[ \text{p\_2} = (\text{T\_room} + \text{T\_boil})/2; \]
\[ \text{p\_2} = \text{computeP\_2(species, T\_room, p\_2)/M}; \quad \% \text{[J/kg]} \]
\[ \text{Q\_out\_3} = \text{computeQ\_out(species, T\_boil, p\_2)/M}; \quad \% \text{[J/kg]} \]
\[ \text{Q\_in\_3} = \text{computeQ\_in(species, T\_boil, p\_2)/M}; \quad \% \text{[J/kg]} \]
\[ \text{Q\_vap\_3} = \text{computeQ\_vap(species, T\_boil, p\_2)/M}; \quad \% \text{[J/kg]} \]
\( N = 7; \) %number of loops
\( \text{Dout} = 0.043; \) %coil outer diameter [m]
\( \text{dtube} = 0.003; \) %tube diameter [m]
\( \text{Dcoil} = \text{Dout} - \text{dtube}; \) %mean coil diameter [m]
\( L = 0.95; \) % [m]
\( \text{dtube}_{\text{in}} = 0.0025; \) %tube inner diameter [m]
\( A_c = \pi * ((\text{dtube}/2)^2 - (\text{dtube}_{\text{in}}/2)^2); \) % [m^2]
\( \text{Th}_{\text{ins}} = 0.025; \) %mean value of measured values
\( L_{\text{coil}} = 0.088; \) %mean value of measured values
\( L_{\text{tot}} = 0.093; \) %mean value of measured values
\( r_1 = \text{Dcoil}/2; \)
\( r_2 = 0.088/2; \) %mean value of measured values
\( A_{s1} = 2\pi \text{Dcoil}/2 \cdot L_{\text{coil}} + \pi/4 \cdot (\text{Dcoil})^2; \)
\( A_{s2} = 2\pi \cdot \text{Dtot}/2 \cdot L_{\text{tot}} + \pi/4 \cdot (\text{Dtot})^2; \)
\( L_{\text{tot}} = L_{\text{tot}} + \text{Dtot}/2; \) %corrected length that takes into account the sides, as a fin

\( R_0 = 0.315 \) %[ohm] measured value in test without flow
\( I_1 = 5; \) %[A]
\( I_2 = 16; \)
\( \text{Time}_1 = 20; \)
\( \text{Time}_2 = 25; \)

\( \text{V} = I_1 \cdot R_0 \)
\( \text{dens}_{\text{coil}} = 7817; \) % [kg/m^3] [Bejan]
\( \text{mass}_{\text{coil}} = \text{dens}_{\text{coil}} \cdot A_c \cdot L \) %[kg]
\( \text{mass}_{\text{coil}} = 0.018 \) %measured value (coil - fitting) [Kg]

\( \text{min} = 35; \) % [min] Number of minutes
\( t = 60 \cdot \text{min}; \) % [s] Seconds
\( \text{cp} = 500; \) % [J/kgK] Specific heat capacity of ss 316

\( \text{T}_{\text{air}} = \text{T}_{\text{room}}; \) % [K] Temperature of the air
\( \text{eps}_{\text{coil}} = 0.8; \) % [-] Emissivity of oxidized steel [table of emissivities from Harrie]
\( \text{eps}_{\text{ins}} = 0.2; \) % [-] Emissivity of aluminium foil around the insulation, worst value found in literature
\( \text{sigma} = 5.669 \times 10^{-8}; \) % [W/m^2K] Stefan-Boltzmann constant

% For 3 different convection coefficients
\( \text{T}_{\text{test}} = 900; \) %[K]
\( \text{T}_{\text{ins}} = 350; \) %[K]
\( R = R_0 \cdot (1 + 0.820 \times 10^{-3} \cdot (T_{\text{test}} - T_{\text{room}})); \)
\( P_{\text{in}} = I_1^2 \cdot R; \)
\( \text{Q}_{\text{conv}} = A_{s2} \cdot h_i \cdot (T_{\text{coil}} - T_{\text{air}}); \) % [W] Power lost due to convection

\( \text{h}_i = \text{h}_i + (T_{\text{test}} - T_{\text{room}}) \)
\( \text{for h}_i = 5; 25; \) % depending on the reference, the minimum convection coefficient can be 2

\( \text{g}_0 = 9.80665; \)
\( \text{dt} = 1; \) % [s] Time increment
\( \text{dt} = 1; \)
\( j = 1; \)
\( \text{tic} \)
\( \text{for h}_i = [h_i(1) h_i(2)]; \) %depending on the reference, the minimum convection coefficient can be 2

\( \text{T}_{\text{room}}; \)
\( \text{T}_{\text{coil}} = \text{T}_{\text{room}}; \)
\( \text{Q}_{\text{i}_{\text{out}}} = \text{zeros}(1,t); \)
\( \text{P}_{\text{i}_{\text{in}}} = \text{zeros}(1,t); \)
\( \text{dTr}_{\text{i}} = \text{zeros}(1,t); \)
\( \text{Temp}_{\text{r}_1} = \text{zeros}(1,t); \)
\( \text{Temp}_{\text{r}_2} = \text{zeros}(1,t); \)
\( \text{T}_{\text{coil}} = \text{zeros}(1,t); \)
\( \text{Temp}_{\text{r}_1} = \text{zeros}(1,t); \)
\( \text{Temp}_{\text{r}_2} = \text{zeros}(1,t); \)
\( \text{for i = dt1:dt1:t; \% [s] Time} \)
\( \text{t} = t; \)
\( \text{if i > Time}_2 \times 60 \)
\( \text{I} = 12; \)
\( \text{else} \)
\( \text{I} = 11; \)
\( \text{end} \)

\( \text{T}_{\text{mean}} = (\text{T}_{\text{r}_1} + \text{T}_{\text{r}_2})/2; \)
\( \text{k}_{\text{ins}} = \text{computeK('Fiberfrax', T_{\text{mean}});} \)
\( \text{T}_{\text{air}} = (\text{T}_{\text{r}_2} + \text{T}_{\text{room}})/2; \)
\( \text{h}_{\text{i_conv}} = \text{h}_{\text{i_conv}}(i) = \text{h}_{\text{conv}} \)
\( \text{Q}_{\text{conv}} = (A_{s2} \cdot \text{h}_{\text{conv}}) \cdot (\text{T}_{\text{r}_2} - \text{T}_{\text{room}}); \) % [W] Power lost due to convection
\( \text{DTr}_{\text{i}} = \text{T}_{\text{r}_1} - \text{T}_{\text{room}}; \) % [K] Temperature difference on the coil
\[ D_{Tr2} = Tr2 - T_{room} \] % [K] Temperature difference on the insulation

\[ Q_{rad} = F_{tot} \cdot \sigma \cdot (T_{r2}^4 - T_{room}^4) \cdot (\varepsilon_{ins} \cdot A_{s2}) / (F_{tot} \cdot (1 - \varepsilon_{ins}) \cdot \varepsilon_{ins}); \] % [W] Power lost due to radiation

\[ Q_{out} = Q_{rad} + Q_{conv}; \] % [W] Outgoing power, lost power

\[ Q_{i\_out(i)} = Q_{out}; \] % Air inside the Coil at constant pressure

\[ T_{m\_int} = Tr1; \]
\[ rho_{air} = \text{computeRho('Air', } T_{m\_int}, 1E5); \]
\[ Vol_{air} = \pi \cdot r1^2 \cdot L_{coil}; \]
\[ m_{air} = \text{rho_{air} \cdot Vol_{air};} \]
\[ CP_{int\_air} = \text{computeCp('Air', } T_{m\_int}); \]
\[ cp_{int\_air} = CP_{int\_air} / M_{int\_air}; \]
\[ R = -1.478 \times 10^{-7} \cdot D_{Tr1}^2 \cdot 3.394 \times 10^{-4} \cdot D_{Tr1} + R0; \]
\[ P_{in} = I^2 \cdot R; \] % [W] Inlet power

\[ P_{i\_in(i)} = P_{in}; \]
\[ Q_{in} = P_{in}; \]
\[ dTr1(i) = \frac{E}{cp \cdot mass_{coil} + cp_{int\_air} \cdot m_{air}}; \] % [K] Temperature increase

\[ Temp(i) = T_{room} + \sum(dTr1(1:i)); \] % Temperature of the system

\[ Tr1 = Temp(i); \]
\[ To\_flow = T_{room}; \]
\[ To\_i\_flow(i) = T_{room}; \]
\[ Two = Tr1; \]
\[ Two\_i(i) = Two; \]
\[ ii = ii + 1; \]
\[ m_{flow} = 30 \times 10^{-6}; \] % [kg/s]

\[ E = \frac{Q_{in} - Q_{out} \cdot Q_{i\_in}}{dt}; \] % [J] Nett energy

\[ dTr1(i) = \frac{E}{cp \cdot mass_{coil} + cp_{int\_air} \cdot m_{air}}; \] % [K] Temperature increase

\[ Temp(i) = T_{room} + \sum(dTr1(1:i)); \] % Temperature of the system

\[ Tr1 = Temp(i); \]
\[ To\_flow = T_{room}; \]
\[ To\_i\_flow(i) = To\_flow; \]
\[ Two = Tr1; \]
\[ Two\_i = Two; \]
\[ jj = jj + 1; \]

\[ Ts1(jj) = ((A_{s2} \cdot h_{vect}) \cdot (Ts1(jj) - T_{room}) + F_{tot} \cdot \sigma \cdot (T_{s1}^4 - T_{room}^4) \cdot (\varepsilon_{ins} \cdot A_{s2}) / (F_{tot} \cdot (1 - \varepsilon_{ins}) \cdot \varepsilon_{ins}) \cdot \log(r2 / r1)) / (2 \cdot pi \cdot L_{tot} \cdot c \cdot k_{ins}) \cdot Ts2(jj); \]

\[ Temp2(jj) = \text{interpl(Ts1, Ts2, Tr1);} \]
\[ Tr2 = Temp2(jj); \]
\[ dT_{total}(j,:,:) = dTr1; \]
\[ Temp_{total}(j,:) = Temp; \]
\[ Temp_{total\_trans}(j,:) = Temp_{total}(j,:); \]
\[ Temp_{total2}(j,:) = Temp2; \]
\[ P_{in\_total}(j,:) = P_{i\_in}; \]
\[ P_{in\_total\_trans}(j,:) = P_{in\_total}(j,:); \]
\[ h_{conv\_total}(j,:) = h_{i\_conv}; \]
\[ h_{i\_flow}(j,:) = h_{i\_flow}; \]
\[ Q_{out\_total}(j,:) = Q_{i\_out}; \]
\[ Q_{i\_out}(j,:) = Q_{i\_out}; \]
\[ Two\_i\_all(j,:) = Two\_i; \]
\[ Temp_{final}(j,:) = Temp2; \]
\[ time(j) = \text{cp \cdot mass_{coil} \cdot (Temp2(j) - T_{room}) / P_{in} / 60; \} \]

\[ time2(j) = (cp \cdot mass_{coil} / (h_{vect} \cdot A_{s2}) \cdot \log[1 - (Temp2(j) - T_{room}) \cdot h_{vect} \cdot A_{s2} / P_{in}) / 60; \]

\[ j = j + 1; \]

\[ T_{excel1} = Temp_{total}(1,:); \]
\[ P_{excel1} = P_{in\_total}(1,:); \]
\[ T_{excel2} = Temp_{total}(2,:); \]
\[ P_{excel2} = P_{in\_total}(2,:); \]

% End.
for i = dt1:dt:t;
    % t = i;                           % [s] Time
    if i > Time2*60
        I = I2;
    else
        I = I1;
    end
    T_mean  = (Tr1_1+Tr2_1)/2;
    k_ins   = computeK('Fiberfrax', T_mean);
    T_air   = (Tr2_1 + T_room)/2;
    k_air   = computeK('Air', T_air);
    h_conv1 = computeH(Dtot, Ltot_c, Tr2_1, T_room, T_air, 1E5, 0, 0, 'Air', 'free', 'outside', 0, 'cyl');
    h_i_conv1(i) = h_conv1;
    Q_conv  = (As2*h_conv1)*(Tr2_1-T_room);                        % [W] Power lost due to convection
    DTr1_1    = Tr1_1-T_room;                                 % [K] Temperature difference on the coil
    DTr2_1    = Tr2_1-T_room;                                 % [K] Temperature difference on the
    insulation
    Q_rad   = F_tot*sigma*(Tr2_1^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);% [W] Power
    lost due to radiation
    Q_out1   = Q_rad + Q_conv;                      % [W] Outgoing power; lost power
    Q_i_out1(i)= Q_out1;
    % Air inside the Coil at constant pressure
    T_m_int = Tr1_1;
    rho_air = computeRho('Air',T_m_int,1E5);
    Vol_air = pi*r1^2/2*Lcoil;
    m_air = rho_air*Vol_air;
    cp_int_air = computeCp('Air', T_m_int);
    cp_int_air = Cp_int_air/M_int_air;
    R = -1.478*10^(-7).*DTr1_1.^2+3.394*10^-4.*DTr1_1+R0;
    P_in1    =   I^2*R;                                  % [W] Inlet power
    P_i_in1(i)  = P_in1;
    Q_in1    = P_in1;                                            % [W] Inlet power
    if i < Time1*60
        m_flow = 0; %[kg/s]
        Q1 = Q_in1 - Q_out1; % [W] Nett power
        E1 = Q1*dt;     % [J] Nett energy
        dTr1_1(i) = EI/(cp*mass_coil+cp_int_air*m_air); % [K] Temperature increase
        Temp_1(i) = T_room+sum(dTr1_1(1:i));              % [K] Temperature of the
        system
    else  % With mass flow
        m_flow = 30*10^-6; %[kg/s]
        [To_flow1,Two1] = Twall_Tflow(Tr1_1, m_flow, species);%for coiled
        [To_flow1,Two1] = Twall_Tflow_straight(Tr1_1, m_flow, species); %for straight
        Two1 (i) = Two1;
        if i < Time2*60
            if To_flow1 > Two1
                To_flow1 = Two1;
            end
            if i < Time2*60
                if To_flow1 > Two1
                    To_flow1 = Two1;
                end
                Qflow1 = m_flow*(Entalp_o-Entalp_i);
                Q1      = Q_in1 - Q_out1 - Qflow1;
                E1       = Q1*dt;                                             % [J] Nett energy
                dTr1_1(i) = E1/(cp*mass_coil+cp_int_air*m_air);                  % [K] Temperature increase
                Temp_1(i) = T_room+sum(dTr1_1(1:i));              % [K] Temperature of the
                system
        end
        end
    end
end
Ts2_1 = T_room:(Tr1_1-T_room)/100:Tr1_1;
for jj=1:length(Ts2_1)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ts1_1(jj) = ((As2*h_conv1)*(Ts2_1(jj)-T_room)+F_tot*sigma*(Ts2_1(jj)^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins))*log(r2/r1)/(2*pi*Ltot_c*k_ins)+Ts2_1(jj);
end
Temp2_1(i) = interp1(Ts1_1, Ts2_1, Tr1_1);
Tr2_1 = Temp2_1(i);
end
dT_total1(1,:) = dTr1_1;
Temp_total1_1(1,:) = Temp1_1;
Temp_totalr2_1(1,:) = Temp2_1;
P_in_total_1(1,:) = P_i_in1;
h_conv_total1(1,:) = h_i_conv1;

% h_ij_flow1 (1,:) = h_i_flow1;
Q_out_total1(1,:) = Q_i_out1;
toci = toc
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tr1_2 = T_room;
Tr2_2 = T_room;

h_i_conv2 = zeros(1,t);
Q_i_out2 = zeros(1,t);
P_i_in2 = zeros(1,t);
dTr1_2 = zeros(1,t);
Temp_2 = zeros(1,t);
Two_i2 = zeros(1,t);
To_i_flow2 = zeros(1,t);

% Air inside the Coil at constant pressure
T_m_int = Tr1_2;
rho_air = computeRho('Air', T_m_int, 1E5);
Vol_air = pi*r1^2/2*Lcoil;
m_air = rho_air*Vol_air;
Cp_int_air = computeCp('Air', T_m_int);
cp_int_air = Cp_int_air/M_int_air;
R = -1.478*10^-7.*DTr1_2.^2+3.394*10^-4.*DTr1_2+R0;
P_in2 = I^2*R;

% [W] Power due to radiation
Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);% [W] Power lost due to radiation
Q_out2 = Q_rad + Q_conv; % [W] Outgoing power; lost power
Q_i_out2(i) = Q_out2;
Q_conv = (As2*h_conv2)*(Tr2_2-T_room);  % [W] Power lost due to convection
% % [K] Temperature difference on the coil
DTr1_2 = Tr1_2-T_room;
DTr2_2 = Tr2_2-T_room;

% % [K] Temperature difference on the insulation
Q_rad = F_tot*sigma*(Tr2_2^4-T_room^4)*(eps_ins*As2)/(F_tot*(1-eps_ins)+eps_ins);% [W] Power

for i = dt1:dt:t;
  if i > Time2*60
    I = I2;
  else
    I = I1;
  end
  T_mean = (Tr1_2+Tr2_2)/2;
  k_ins = computeK('Fiberfrax', T_mean);
  T_air = (Tr2_2 + T_room)/2;
  k_air = computeK('Air', T_air);
  rho_air = computeRho('Air', T_air, 1E5);
  Vol_air = pi*r1^2/2*Lcoil;
  m_air = rho_air*Vol_air;
  Cp_int_air = computeCp('Air', T_m_int);
  cp_int_air = Cp_int_air/M_int_air;
  R = -1.478*10^-7.*DTr1_2.^2+3.394*10^-4.*DTr1_2+R0;
  P_in2 = I^2*R;
  if i < Time1*60
    m_flow = 0; % [kg/s]
    Q2 = Q_i_out2(i) - Q_out2(i); % [W] Nett power
    E2 = Q2*dt; % [J] Nett energy
    dTr1_2(i) = E2/(cp_mass Coil+cp_int_air*m_air);
    Temp_2(i) = T_room+sum(dTr1_2(1:i)); % [K] Temperature increase
  else % With mass flow
    m_flow = 0; % [kg/s]
    Q2 = Q_i_out2(i) - Q_out2(i); % [W] Nett power
    E2 = Q2*dt; % [J] Nett energy
    dTr1_2(i) = E2/(cp_mass Coil+cp_int_air*m_air);
    Temp_2(i) = T_room+sum(dTr1_2(1:i)); % [K] Temperature increase
  end
end

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\( m_{\text{flow}} = 30 \times 10^{-6} \text{ kg/s} \)

\([\text{To}_{\text{flow}2}, \text{Two}2] = \text{Twall_Tflow(Tr1_2, m_{\text{flow}}, \text{species});} \) %for coiled
\([\text{To}_{\text{flow}2}, \text{Two}2] = \text{Twall_Tflow_straight(Tr1_2, m_{\text{flow}}, \text{species});} \) %for straight

\( \text{Two}_{12} (i) = \text{Two}2; \)
if \( i < \text{Time2} \times 60 \)
if \( \text{To}_{\text{flow}2} > \text{Two}2 \)
\( \text{To}_{\text{flow}2} = \text{Two}2; \)
\( \text{Two}_{12} (i) = \text{Two}2; \)
end
end

\( \text{Enthalp}_o = \text{computeEnthalpy(species, To}_{\text{flow}2},p)/M; \) % [J/kg]
\( Q_{\text{flow}2} = m_{\text{flow}} \ast (\text{Enthalp}_o - \text{Enthalp}_i); \)
\( \text{QZ} = Q_{\text{in}2} - Q_{\text{out}2} - Q_{\text{flow}2}; \) % [J] Netty energy
\( d\text{Tr1}_2(i) = \text{QZ}/(cp \ast \text{mass}_\text{coil} + cp \ast \text{int}_\text{air} \ast \text{m}_\text{air}); \) % [K] Temperature increase
\( \text{Temp}_2(i) = \text{Temp}_\text{room} + \text{sum}(d\text{Tr1}_2(1:i)); \) % [K] Temperature of the system

\( \text{Tr1}_2 = \text{Temp}_2(i); \)
\( \text{To}_{1,\text{flow}2} (i) = \text{To}_{\text{flow}2}; \)
end
\( \text{Ts}_{12} = \text{Temp}_2(1:10:100):\text{Tr1}_2; \)
for \( jj=1:1:length(\text{Ts}_{12}) \)
\( \text{T}_{12}(jj) = (((\text{As}_2 \ast \text{h}_{\text{conv}2}) \ast (\text{Ts}_{2,12}(jj) - \text{Tr}_{1,\text{room}}) + \text{F}_\text{tot} \ast \text{sigma} \ast (\text{Ts}_{2,12}(jj)^4 - \text{Tr}_{1,\text{room}}^4) \ast (\text{eps}_\text{ins} \ast \text{As}_2)/(\text{F}_\text{tot} \ast (1 - \text{eps}_\text{ins}))) \ast \log(\text{r}_2/\text{r}_1)/(2 \ast \text{pi} \ast \text{L}_\text{tot}_\text{c} \ast \text{k}_\text{ins}) + \text{Ts}_{2,12}(jj)); \)
end
\( \text{Tempr2}_2(i) = \text{interp1(T}_{12}, \text{Ts}_{2,12}, \text{Tr1}_2); \)
\( \text{Tr2}_2 = \text{Tempr2}_2(i); \)
\( \text{dT}_\text{total2}(1,:) = d\text{Tr1}_2; \)
\( \text{Temp}_{\text{total}1,2}(1,:) = \text{Temp}_2; \)
\( \text{P}_{\text{in}_{\text{total}2}}(1,:) = \text{P}_{\text{in}_2}; \)
\( \text{h}_{\text{conv}_{\text{total}2}}(1,:) = \text{h}_{\text{conv}_2}; \)
\( \% h_{\text{i}j_{\text{flow}2}} (1,:) = h_{\text{i}_{\text{flow}2}}; \)
\( \text{To}_{\text{i}_{\text{flow}2}} (1,:) = \text{To}_{\text{i}_{\text{flow}2}}; \)
\( \text{Q}_{\text{out}_{\text{total}2}}(1,:) = \text{Q}_{\text{out}_2}; \)
toki = toc

\( \% \text{T}_{1,3} = \text{Temp}_3; \)
\( \text{Tr}_{2,3} = \text{Temp}_3; \)
\( \text{h}_{\text{i}_{\text{conv}3}} = \text{zeros}(1,t); \)
\( \text{Q}_{\text{i}_{\text{out}3}} = \text{zeros}(1,t); \)
\( \text{F}_{\text{i}_{\text{in}3}} = \text{zeros}(1,t); \)
\( \text{dTr}_{1,3} = \text{zeros}(1,t); \)
\( \text{Temp}_{3} = \text{zeros}(1,t); \)
\( \text{Two}_{1,3} = \text{zeros}(1,t); \)
\( \text{To}_{1,\text{flow}3} = \text{zeros}(1,t); \)
\( \text{Tempr2}_3 = \text{zeros}(1,t); \)
tic
\( \% \text{Combined operation} \)
\( \% \text{I = 12;} \)
end
\( \text{T}_{\text{mean}} = (\text{Tr}_{1,3} + \text{Tr}_{2,3})/2; \)
\( \text{k}_{\text{ins}} = \text{computeK('Fiberfrax', T}_{\text{mean}}); \)
\( \text{T}_{\text{air}} = (\text{Tr}_{2,3} + \text{T}_{\text{room}})/2; \)
\( \text{k}_{\text{air}} = \text{computeK('Air', T}_{\text{air}}); \)
\( \text{rho}_{\text{air}} = \text{computeRho('Air', T}_{\text{air}}, 1E5); \)
\( \text{mu}_{\text{air}} = \text{computeMu('Air', T}_{\text{air}}); \)
\( \text{Cp}_{\text{air}} = \text{computeCp('Air', T}_{\text{air}}); \)
\( \text{cp}_{\text{air}} = \text{Cp}_{\text{air}}/\text{int}_\text{air}; \)
\( \text{Fr}_{\text{air}} = \text{mu}_{\text{air}} \ast \text{cp}_{\text{air}}/\text{k}_{\text{air}}; \)
\( \text{X} = \text{D}_{\text{tot}}; \)
\( \beta = 1/\text{T}_{\text{air}}; \)
\( \text{Gr} = g_0 \ast \beta \ast \text{rho}_{\text{air}} \ast 2 \ast (\text{Tr}_{2,3} - \text{T}_{\text{room}}) \ast X^3 / \text{mu}_{\text{air}} \ast 2; \)
\( \text{Ra} = \text{Gr}_{\text{Fr}_{\text{air}}}; \)
\( \text{C1}_{3,3} = 0.671/(1+(0.492/\text{Fr}_{\text{air}})^{9/16})^{(4/9)}; \)
\( \text{Nucond}_{3} = 1.549; \)
\( \text{n}_{3} = 1.11; \)
\( \text{m}_{3} = 8; \)
\( \text{G}_{3} = 0.881; \)
\( \text{C}_{3,3} = 0.110; \)
\( \text{Nu3} = (\text{Nucond}_{3} \ast \text{n}_{3} \ast (\text{G}_{3} \ast \text{C1}_{3,3} \ast \text{Ra}^{1/4}) \ast (\text{n}_{3}))^{(\text{m}_{3} / \text{n}_{3})} + (\text{Ct}_{3} \ast \text{Ra}^{1/3}) \ast (1 / \text{m}_{3}); \)
\( \text{h}_{\text{conv}3} = \text{Nu3} \ast \text{mu}_{\text{air}} / \text{D}_{\text{tot}}; \)
\( \text{h}_{\text{i}_{\text{conv}3}}(i) = \text{h}_{\text{conv}3}; \)
\( \text{Q}_{\text{conv}3} = (\text{As}_2 \ast \text{h}_{\text{conv}3}) \ast (\text{Tr}_{2,3} - \text{T}_{\text{room}}); \)
\( \% \text{Q}_{\text{conv}} = \text{As}_2^{2} \text{h}_{\text{conv}} \text{*(Tr}_{2,3} - \text{T}_{\text{room}}); \)
\( \% \text{DTr}_{1,3} = \text{Tr}_{1,3} - \text{T}_{\text{room}}; \) % [K] Temperature difference on the coil
\[
\text{DTr}_2 = \text{Tr}_2 - T_{\text{room}}; \quad \% \text{[K]} \text{ Temperature difference on the insulation}
\]

\[
\text{Q}_\text{rad} = P_{\text{tot}} \cdot \text{sigma} \cdot (\text{DTr}_2^4 - T_{\text{room}}^4) \cdot (\text{eps}_{\text{ins}} \cdot A_{\text{S2}}) / (P_{\text{tot}} \cdot (1 - \text{eps}_{\text{ins}}) + \text{eps}_{\text{ins}}); \quad \% \text{[W]} \text{ Power lost due to radiation}
\]

\[
\text{Q}_\text{out3} = \text{Q}_\text{rad} + \text{Q}_\text{conv}; \quad \% \text{[W]} \text{ Outgoing power; lost power}
\]

\[
\text{Q}_\text{i_out3}(i) = \text{Q}_\text{out3}; \quad \% \text{[W]} \text{ Outgoing power; lost power}
\]

\[
\text{T}_m_{\text{int}} = \text{Tr}_1 - \text{Tr}_3; \quad \text{rho}_{\text{air}} = \text{computeRho}('\text{Air}', \text{T}_m_{\text{int}}, 1E5);
\]

\[
\text{Vol}_{\text{air}} = \pi \cdot r_1^2 / 2 \cdot L_{\text{coil}};
\]

\[
\text{m}_{\text{air}} = \text{rho}_{\text{air}} \cdot \text{Vol}_{\text{air}};
\]

\[
\text{Cp}_{\text{int_air}} = \text{computeCp}('\text{Air}', \text{T}_m_{\text{int}});
\]

\[
\text{cp}_{\text{int_air}} = \text{Cp}_{\text{int_air}} / \text{M}_{\text{int_air}};
\]

\[
\text{R} = -1.478 \cdot 10^{-7} \cdot \text{DTr}_1^2 + 3.394 \cdot 10^{-4} \cdot \text{DTr}_1 + \text{R}_0;
\]

\[
\text{P}_{\text{in3}} = I^2 \cdot \text{R}; \quad \% \text{[W]} \text{ Inlet power}
\]

\[
\text{P}_{\text{i_in3}}(i) = \text{P}_{\text{in3}}; \quad \% \text{[W]} \text{ Inlet power}
\]

\[
\text{Q}_{\text{in3}} = \text{P}_{\text{in3}}; \quad \% \text{[W]} \text{ Inlet power}
\]

\[
\text{if} \ i < \text{Time1} \cdot 60
\]

\[
\text{m_flow} = 0; \quad \% \text{[kg/s]}
\]

\[
\text{Q}_3 = \text{Q}_{\text{in3}} - \text{Q}_{\text{out3}}; \quad \% \text{[W]} \text{ Nett power}
\]

\[
\text{E}_3 = \text{Q}_3 \cdot \text{dt}; \quad \% \text{[J]} \text{ Nett energy}
\]

\[
\text{dTr}_1(i) = \text{E}_3 / (\text{cp} \cdot \text{mass}_{\text{coil}} + \text{cp}_{\text{int_air}} \cdot \text{m}_{\text{air}}); \quad \% \text{[K]} \text{ Temperature increase}
\]

\[
\text{Temp}_3(i) = \text{T}_{\text{room}} + \text{sum} (\text{dTr}_1(1:i)); \quad \% \text{[K]} \text{ Temperature of the system}
\]

\[
\text{Tr}_1 = \text{Temp}_3(i);
\]

\[
\text{To}_{\text{flow3}} = \text{T}_{\text{room}};
\]

\[
\text{To}_{\text{i_flow3}}(i) = \text{T}_{\text{room}};
\]

\[
\text{Two}_3 = \text{Tr}_1 - \text{Tr}_3;
\]

\[
\text{Two_13}(i) = \text{Two}_3;
\]

\[
\text{if} \ i < \text{Time2} \cdot 60
\]

\[
\text{if} \ \text{To}_{\text{flow3}} > \text{Two}_3
\]

\[
\text{To}_{\text{flow3}} = \text{Two}_3;
\]

\[
\text{To}_{\text{i_flow3}}(i) = \text{Two}_3;
\]

\[
\text{Two_13}(i) = \text{Two}_3;
\]

\[
\text{end}
\]

\[
\text{Entalp}_o = \text{computeEnthalpy}('\text{species}', \text{To}_{\text{flow3}}, p) / \text{M}; \quad \% \text{[J/kg]}
\]

\[
\text{Q}_{\text{flow3}} = \text{m}_{\text{flow}} \cdot \text{Entalp}_o / \text{M}; \quad \% \text{[J/kg]}
\]

\[
\text{E}_3 = \text{Q}_{\text{flow3}} \cdot \text{dt}; \quad \% \text{[J]} \text{ Nett energy}
\]

\[
\text{dTr}_1(i) = \text{E}_3 / (\text{cp} \cdot \text{mass}_{\text{coil}} + \text{cp}_{\text{int_air}} \cdot \text{m}_{\text{air}}); \quad \% \text{[K]} \text{ Temperature increase}
\]

\[
\text{Temp}_3(i) = \text{T}_{\text{room}} + \text{sum} (\text{dTr}_1(1:i)); \quad \% \text{[K]} \text{ Temperature of the system}
\]

\[
\text{Tr}_1 = \text{Temp}_3(i);
\]

\[
\text{To}_{\text{flow3}}(i) = \text{To}_{\text{flow3}};
\]

\[
\text{end}
\]

\[
\text{Ts}_{2,3} = \text{T}_{\text{room}}:(\text{Tr}_1 - \text{Ts}_{2,3}) / 100:100; \text{T}_{\text{room}};
\]

\[
\text{Ts}_{1,3}(jj) = ((\text{As}_2 \cdot h_{\text{conv}}) \cdot (\text{Ts}_{2,3}(jj) - \text{T}_{\text{room}}) + \text{P}_{\text{tot}} \cdot \text{sigma} \cdot (\text{Ts}_{2,3}(jj) - \text{Ts}_{2,3}(jj) - \text{T}_{\text{room}}) \cdot 4) / (\text{eps}_{\text{ins}} \cdot \text{A}_2) / (\text{P}_{\text{tot}} \cdot (1 - \text{eps}_{\text{ins}} + \text{eps}_{\text{ins}}) / \text{log}(\text{r}_2 / \text{r}_1) / (2 \cdot \pi \cdot \text{L}_{\text{tot}} \cdot \text{c} \cdot \text{ins}) + \text{Ts}_{2,3}(jj));
\]

\[
\text{Temp2r}_3(i) = \text{interp1}('\text{Ts}_{1,3}', '\text{Ts}_{2,3}', \text{Tr}_1 - \text{Tr}_3);
\]

\[
\text{Dr}_{\text{total3}}(1,:) = \text{Dr}_{\text{total3}};
\]

\[
\text{Temp}_{\text{total13}}(1,:) = \text{Temp}_{\text{total13}};
\]

\[
\text{Temp}_{\text{total23}}(1,:) = \text{Temp}_{\text{total23}};
\]

\[
\text{P}_{\text{in_total3}}(1,:) = \text{P}_{\text{in_total3}};
\]

\[
\text{h}_{\text{conv_total13}}(1,:) = \text{h}_{\text{conv_total13}};
\]

\[
\text{h}_{\text{conv_total23}}(1,:) = \text{h}_{\text{conv_total23}};
\]

\[
\text{To}_{\text{i_flow3}}(1,:) = \text{To}_{\text{i_flow3}};
\]

\[
\text{Q}_{\text{out_total3}}(1,:) = \text{Q}_{\text{out_total3}};
\]

\[
\text{toki} = \text{toc}
\]

\[
\text{m}_{\text{flow}} = \text{m}_{\text{flow}} \cdot 10^6; \quad \% \text{[mg/s]}
\]

\[
\text{clear}
\]

\[
\text{close all}
\]

\[
\% \text{Input!!}
\]

\[
\text{T}_{\text{mean_coil}} = 438; \quad \% \text{[K]}
\]

\[
\text{m}_{\text{flow}} = 30 \cdot 10^{-6}; \quad \% \text{[kg/s]}
\]

\[
\text{species} = '\text{H}_2\text{O}';
\]

\[
\text{p} = 2; \quad \% \text{only for 2 bar!!}
\]

\[
\text{T}_{\text{room}} = 296; \quad \% \text{[K]}
\]

\[
\text{M} = \text{computeM('species')} \quad \% \text{[kg/mol]}
\]

\[
\text{RA} = 8.314472; \quad \% \text{[J/(molK)]}
\]
\[ p_{vec} = [1 1.5 2]; \]
\[ T_{boil\_l\_vec} = [372.76+1e-6 384.5+1e-6 393.36+1e-6]; \]
\[ T_{boil\_g\_vec} = [372.76-1e-6 384.5-1e-6 393.36-1e-6]; \]
\[ T_{boil} = [372.76 384.5 393.36]; \]
\[ T_{boil\_l} = \text{interp1}(p_{vec}, T_{boil\_l\_vec}, p); \]
\[ T_{boil\_g} = \text{interp1}(p_{vec}, T_{boil\_g\_vec}, p); \]
\[ T_{boil} = \text{interp1}(p_{vec}, T_{boil}, p); \]
\% N = 7; \% number of loops
\] 
\[ D_{out} = 0.043; \] \% coil outer diameter [m]
\[ d_{tube} = 0.003; \] \% tube diameter [m]
\[ D_{coil} = D_{out} - d_{tube}; \] \% mean coil diameter [m]
\[ d_{tube\_in} = 0.0025; \] \% tube inner diameter [m]
\[ L = 0.95; \] \% [m]
\[ T_{final\_vec} = 300:20:1000; \]
\[ R_{e\_crit} = 2100*(1+12*(d_{tube\_in}/D_{coil})^0.5); \]
\for i=1:length(T_{final\_vec})
\[ \text{Entalp\_i} = \text{computeEnthalpy(species, T\_room, p)}/M; \] \% [J/kg]
\[ \text{Entalp\_liq} = \text{computeEnthalpy(species, T_{boil\_l}, p)}/M; \] \% [J/kg]
\[ \text{Entalp\_vap} = \text{computeEnthalpy(species, T_{boil\_g}, p)}/M; \] \% [J/kg]
\[ \text{Entalp\_o} = \text{computeEnthalpy(species, T_{final\_vec(i)}, p)}/M; \] \% [J/kg]
\if T_{final\_vec(i)} < T_{boil\_l} \% No boiling
\[ L_{liq} = L; \]
\[ L_{2\_ph\_1st} = 0; \]
\[ L_{2\_ph\_2nd} = 0; \]
\[ L_{gas} = 0; \]
\[ T_{final\_vec\_liq} = T_{final\_vec(i)}; \]
\[ \text{end} \]
\[ \text{elseif T_{final\_vec(i)} < T_{boil\_g} && T_{final\_vec(i)} > T_{boil\_l}} \]
\[ L_{liq} = L*(\text{Entalp\_liq-Entalp\_i})/(\text{Entalp\_o-Entalp\_i}); \]
\[ L_{2\_ph\_1st} = L*(\text{Entalp\_vap-Entalp\_liq})/(\text{Entalp\_o-Entalp\_liq}); \]
\[ L_{2\_ph\_2nd} = L*(\text{Entalp\_o-Entalp\_liq})/(\text{Entalp\_o-Entalp\_i}); \]
\[ L_{gas} = 0; \]
\[ T_{final\_vec\_liq} = T_{boil\_l}; \]
\[ \text{elseif T_{final\_vec(i)} > T_{boil\_g}} \% Gas in the output
\[ L_{liq} = L*(\text{Entalp\_liq-Entalp\_i})/(\text{Entalp\_o-Entalp\_i}); \]
\[ L_{2\_ph} = L*(\text{Entalp\_vap-Entalp\_liq})/(\text{Entalp\_o-Entalp\_liq}); \]
\[ L_{gas} = L*(\text{Entalp\_o-Entalp\_vap})/(\text{Entalp\_o-Entalp\_liq}); \]
\[ T_{final\_vec\_liq} = T_{boil\_l}; \]
\[ \text{end} \]
\end{for}
\[ T_{flow\_j1} = T_{\\text{room}};(T_{final\_vec\_liq-T_{\\text{room}}})/50:T_{final\_vec\_liq}; \]
\[ \text{for jj=1:length(T_{flow\_j1})} \]
\[ \mu_{flow\_j} = \text{computeMu(species, T_{flow\_j1(jj)})}; \]
\[ \% \mu_{wo\_j} = \text{computeMu(species, T_{\text{wo}\_j1(jj)})}; \]
\[ \% Specific heat [J/kg/K] \]
\[ C_{p\_flow\_j} = \text{computeCp(species, T_{flow\_j1(jj)})}; \]
\[ \% Thermal conductivity [W/m/K] \]
\[ k_{flow\_j} = \text{computeK(species, T_{flow\_j1(jj)})}; \]
\[ \% Pr_{flow\_j} = \text{mu_{flow\_j}/C_{p\_flow\_j}/k_{flow\_j}}; \]
\[ \% Re_{flow\_j} = 4*m_{flow}/(pi*d_{tube\_in}*\mu_{flow\_j}); \]
\[ \% Nu_{flow} = \text{computeNu(species, T_{flow\_j1(jj)})} \]
\[ \% Specific heat [J/kg/K] \]
\[ C_{p\_flow\_j} = \text{computeCp(species, T_{flow\_j1(jj)})}; \]
\[ \% Thermal conductivity [W/m/K] \]
\[ k_{flow\_j} = \text{computeK(species, T_{flow\_j1(jj)})}; \]
\[ \% Re_{flow\_j} = 4*m_{flow}/(pi*d_{tube\_in}*C_{p\_flow\_j}/k_{flow\_j}); \]
\[ \% Nu_{flow} = \text{computeNu(species, T_{flow\_j1(jj)})} \]
\[ \% Specific heat [J/kg/K] \]
\[ C_{p\_flow\_j} = \text{computeCp(species, T_{flow\_j2(jj)})}; \]
\( cp_{\text{flow}_j} = \frac{cp_{\text{flow}_j}}{M}; \)

% Thermal conductivity [W/m/K]
\( k_{\text{flow}_j} = \text{computeK(species, } T_{\text{flow}_j2(jj)}); \)

\( Pr_{\text{flow}_j} = \mu_{\text{flow}_j}/(cp_{\text{flow}_j}/k_{\text{flow}_j}); \)

if \( Re_{\text{flow}_j} < Re_{\text{crit}} \)
  if \( (Pr_{\text{flow}_j} > 5) \&\& (Pr_{\text{flow}_j} < 175) \)
    \( Nu_{\text{flow}} = (0.76 + 0.65*Re_{\text{flow}_j}^{0.5}*(dtube_in/Dcoil)^{0.25})^{0.5}*Pr_{\text{flow}_j}^{0.476} \)
  else
    \( Nu_{\text{flow}} = 0.513*(Re_{\text{flow}_j}*(dtube_in/Dcoil)^{0.5})^{0.5}*Pr_{\text{flow}_j}^{0.32} \)
  end
else
  if \( (Re_{\text{flow}_j} > 6000) \&\& (Re_{\text{flow}_j} < 100000) \)
    \( Nu_{\text{flow}} = 0.023*Re_{\text{flow}_j}^{0.85}*(dtube_in/Dcoil)^{0.5} \)
  else
    \( Nu_{\text{flow}} = Re_{\text{flow}_j}^{0.8}*(dtube_in/Dcoil)^{0.5}*(1+0.098/(Re_{\text{flow}_j}*(dtube_in/Dcoil)^{0.5}))^{1.5} \)
  end
end

\( h_{\text{flow}_j} = Nu_{\text{flow}}*k_{\text{flow}_j}/\text{dtube}_in; \)

\( Two_j2(jj) = m_{\text{flow}}*(\text{Entalp}_o-\text{Entalp}_i)/(\pi*\text{dtube}_in^2*h_{\text{flow}_j}+T_{\text{flow}_j2(jj)}); \)

\( \text{diff2(jj)} = Two_j2(jj)-T_{\text{flow}_j2(jj)}; \)

end

if \( T_{\text{final}_vec}(i) > T_{\text{boil}_g} \) %Gas in the output
  \( T_{\text{boil}_1stwall_vec} = \text{Two}_1(length(\text{To}_\text{flow}_1))-10^{-8}:(2*10^{-8})/50:2*10^{-8}; \)
  \( T_{\text{boil}_2ndwall_vec} = \text{Two}_2(1)-10^{-8}:(2*10^{-8})/50:2*10^{-8}; \)
  \( T_{\text{wall}_1stmean} = \text{mean}(\text{Two}_1); \)
  \( T_{\text{wall}_1stmean}_\text{boil} = \text{mean}(\text{Toil}_1stwall_vec); \)
  \( T_{\text{wall}_2ndmean}_\text{boil} = \text{mean}(\text{Two}_2ndwall_vec); \)
  \( T_{\text{wall}_1stmean}_\text{gas} = \text{mean}(\text{Two}_2); \)
  \( T_{\text{wall}_2ndmean}_\text{gas} = \text{mean}(\text{Toil}_2ndwall_vec); \)
  \( T_{\text{wall}_1stmean} = \text{mean}(\text{L}_\text{liq}/L+T_{\text{wall}_1stmean}_\text{boil}*L_{\text{2ph}_1st}/L+T_{\text{wall}_2ndmean}_\text{boil}*L_{\text{2ph}_2nd}/L+T_{\text{wall}_1stmean}_\text{gas}*_L_{\text{gas}}/L; \)
  \( T_{\text{wall}_1stmean} = \text{mean}(\text{L}_\text{liq}/L+T_{\text{wall}_1stmean}_\text{boil}*L_{\text{2ph}_1st}/L+T_{\text{wall}_2ndmean}_\text{boil}*L_{\text{2ph}_2nd}/L+T_{\text{wall}_1stmean}_\text{gas}*_L_{\text{gas}}/L; \)
else \%No boiling
  \( T_{\text{wall}_1stmean} = \text{mean}(\text{Two}_1); \)
  \( T_{\text{wall}_1stmean} = \text{mean}(\text{Two}_1); \)
  \( T_{\text{final}_flow}(i) = \text{Toil}_1(length(\text{To}_\text{flow}_1)); \)
  \( T_{\text{final}_wall}(i) = \text{Two}_2(1); \)
end

\( T_{\text{mean}_\text{coil}} = \text{max}(T_{\text{wall}_1stmean}); \)

\( T_{\text{final}_\text{flow}_\text{coil}} = \text{interp1}(T_{\text{wall}_1stmean},T_{\text{final}_\text{flow}},T_{\text{mean}_\text{coil}}); \)

\( T_{\text{final}_\text{wall}_\text{coil}} = \text{interp1}(T_{\text{wall}_1stmean},T_{\text{final}_\text{wall}},T_{\text{mean}_\text{coil}}); \)

\( T_{\text{final}_\text{flow}_\text{coil}} = \text{Entalp}_i = \text{computeEnthalpy(species, } T_{\text{_room}},p)/M; \) % [J/kg]

\( T_{\text{final}_\text{flow}_\text{coil}} = \text{Entalp}_\text{liq} = \text{computeEnthalpy(species, } T_{\text{boil}_1,},p)/M; \) % [J/kg]

\( T_{\text{final}_\text{flow}_\text{coil}} = \text{Entalp}_\text{vap} = \text{computeEnthalpy(species, } T_{\text{boil}_g,},p)/M; \) % [J/kg]
Using the enthalpy method, the following equations are used:

\[
T_{\text{final liq}} = T_{\text{final}}; \\
\text{elseif } T_{\text{final}} < T_{\text{boil g}} \text{ and } T_{\text{final}} > T_{\text{boil l}} \text{, then:} \\
L_{\text{liq}} = L \times \frac{(E_{\text{enthalpy liq}} - E_{\text{enthalpy i}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})}; \\
L_{\text{2ph}} = L \times \frac{(E_{\text{enthalpy vap}} - E_{\text{enthalpy liq}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})} \times 0.7; \\
L_{\text{2ph 2nd}} = L \times \frac{(E_{\text{enthalpy vap}} - E_{\text{enthalpy liq}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})} \times 0.3; \\
L_{\text{gas}} = 0; \\
L_{\text{liq vec}} = 0:L_{\text{liq}}/50:L_{\text{liq}}; \\
L_{\text{2ph vec}} = L_{\text{liq}}:(L_{\text{2ph}})/50:(L_{\text{2ph}}+L_{\text{liq}}); \\
L_{\text{2ph 1st vec}} = L_{\text{liq}}:(L_{\text{2ph 1st}})/50:(L_{\text{2ph 1st}}+L_{\text{liq}}); \\
L_{\text{2ph 2nd vec}} = (L_{\text{2ph 1st}}+L_{\text{liq}}):(L_{\text{2ph 2nd}})/50:(L_{\text{2ph}}+L_{\text{liq}}); \\
L_{\text{gas vec}} = 0; \\
T_{\text{final liq}} = T_{\text{boil l}}; \\
\text{else} \\
L_{\text{liq}} = L \times \frac{(E_{\text{enthalpy liq}} - E_{\text{enthalpy i}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})}; \\
L_{\text{2ph}} = L \times \frac{(E_{\text{enthalpy vap}} - E_{\text{enthalpy liq}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})}; \\
L_{\text{2ph 1st}} = L \times \frac{(E_{\text{enthalpy vap}} - E_{\text{enthalpy liq}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})} \times 0.7; \\
L_{\text{gas}} = L \times \frac{(E_{\text{enthalpy o}} - E_{\text{enthalpy vap}})}{(E_{\text{enthalpy o}} - E_{\text{enthalpy i}})}; \\
L_{\text{liq vec}} = 0:L_{\text{liq}}/50:L_{\text{liq}}; \\
L_{\text{2ph vec}} = L_{\text{liq}}:(L_{\text{2ph}})/50:(L_{\text{2ph}}+L_{\text{liq}}); \\
L_{\text{2ph 1st vec}} = L_{\text{liq}}:(L_{\text{2ph 1st}})/50:(L_{\text{2ph 1st}}+L_{\text{liq}}); \\
L_{\text{2ph 2nd vec}} = (L_{\text{2ph 1st}}+L_{\text{liq}}):(L_{\text{2ph 2nd}})/50:(L_{\text{2ph}}+L_{\text{liq}}); \\
L_{\text{gas vec}} = (L_{\text{2ph}}+L_{\text{liq}}):(L_{\text{gas}})/50:(L_{\text{gas}}+L_{\text{2ph}}+L_{\text{liq}}); \\
T_{\text{final liq}} = T_{\text{boil l}}; \\
\text{end}
\]

\[
\text{To}_j = T_{\text{room}}: (T_{\text{final liq}} - T_{\text{room}})/50:T_{\text{final liq}}; \\
\text{for } jj = 1:length(\text{To}_j) \\
\text{Entalp}_o_j = \text{computeEnthalpy(species, To}_j, p)/M; \quad \text{[J/kg]} \\
\text{mu}_j = \text{computeMu(species, To}_j, p)/M; \quad \text{[kg/m/s]} \\
\text{cp}_j = \text{computeCp(species, To}_j, p)/M; \quad \text{[J/kg/K]} \\
\text{k}_j = \text{computeK(species, To}_j, p)/M; \quad \text{[W/m/K]} \\
\text{Re}_j = 4*\text{m}_j/(\pi*\text{dtube}_in*\text{mu}_j); \\
\text{if } \text{Re}_j < \text{Re}_{\text{crit}} \\
\text{if } (\text{Pr}_j > 5) \text{ and } (\text{Pr}_j < 175) \\
\text{Nu}_j = (0.76 + 0.65\times\text{Re}_j^{0.5}\times(\text{dtube}_in/\text{Dcoil})^{0.25})\times\text{Pr}_j^{0.175}; \\
\text{else} \\
\text{Nu}_j = 0.913\times(\text{Re}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.5})\times\text{Pr}_j^{0.2}; \\
\text{end} \\
\text{else} \\
\text{if } (\text{Re}_j > 6000) \text{ and } (\text{Re}_j < 10000) \\
\text{Nu}_j = 0.023\times(\text{Re}_j^{0.85}\times\text{Pr}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.1}); \\
\text{else} \\
\text{if } \text{Pr} > 0.9 \text{ or } \text{Pr < 1.1} \\
\text{Nu}_j = (0.098/(\text{Re}_j^{2/3}\times(\text{dtube}_in/\text{Dcoil})^{2/3}))\times(\text{Re}_j^{0.8}\times(\text{Pr}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.1})/2); \\
\text{end} \\
\text{end} \\
\text{h}_j = \text{Nu}_j\times\text{k}_j/\text{dtube}_in; \\
\text{Two}_j = \text{m}_j\times(\text{Entalp}_o - \text{Entalp}_i)/(\text{dtube}_in\times\pi\times\text{h}_j) + \text{To}_j; \\
\text{diff}(jj) = \text{two}_j - \text{To}_j; \\
\text{end} \\
\text{if } T_{\text{final}} < T_{\text{boil g}} \\
\text{To}_j = 0; \\
\text{else} \\
\text{To}_j = \text{To}_j: (\text{To}_j - \text{To}_j)/50: \text{To}_j; \\
\text{for } jj = 1:length(\text{To}_j) \\
\text{mu}_j = \text{computeMu(species, To}_j, p)/M; \quad \text{[kg/m/s]} \\
\text{cp}_j = \text{computeCp(species, To}_j, p)/M; \quad \text{[J/kg/K]} \\
\text{Re}_j = 4*\text{m}_j/(\pi*\text{dtube}_in*\text{mu}_j); \\
\text{if } \text{Re}_j < \text{Re}_{\text{crit}} \\
\text{if } (\text{Pr}_j > 5) \text{ and } (\text{Pr}_j < 175) \\
\text{Nu}_j = (0.76 + 0.65\times\text{Re}_j^{0.5}\times(\text{dtube}_in/\text{Dcoil})^{0.25})\times\text{Pr}_j^{0.175}; \\
\text{else} \\
\text{Nu}_j = 0.913\times(\text{Re}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.5})\times\text{Pr}_j^{0.2}; \\
\text{end} \\
\text{else} \\
\text{if } (\text{Re}_j > 6000) \text{ and } (\text{Re}_j < 10000) \\
\text{Nu}_j = 0.023\times(\text{Re}_j^{0.85}\times\text{Pr}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.1}); \\
\text{else} \\
\text{if } \text{Pr} > 0.9 \text{ or } \text{Pr < 1.1} \\
\text{Nu}_j = (0.098/(\text{Re}_j^{2/3}\times(\text{dtube}_in/\text{Dcoil})^{2/3}))\times(\text{Re}_j^{0.8}\times(\text{Pr}_j^{0.4}\times(\text{dtube}_in/\text{Dcoil})^{0.1})/2); \\
\text{end} \\
\text{end} \\
\text{h}_j = \text{Nu}_j\times\text{k}_j/\text{dtube}_in; \\
\text{Two}_j = \text{m}_j\times(\text{Entalp}_o - \text{Entalp}_i)/(\text{dtube}_in\times\pi\times\text{h}_j) + \text{To}_j; \\
\text{diff}(jj) = \text{two}_j - \text{To}_j; \\
\text{end} 
\]
\[ \text{Nu}_{\text{flow}} = 0.023 \cdot (\text{Re}_{\text{flow}})^{0.85} \cdot (\text{Pr}_{\text{flow}})^{0.4} \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)^{0.1}; \]

\text{else} \quad \text{if} \quad \text{Re} \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)^{2} > 0.1 \quad \text{||} \quad \text{Pr} > 0.9 \quad \text{||} \quad \text{Pr} < 1.1

\[ \text{Nu}_{\text{flow}} = \left(\frac{\text{Re}_{\text{flow}}}{100}\right)^{0.8} \cdot \left(\frac{\text{Pr}_{\text{flow}}}{50}\right) \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)^{0.1} \cdot \frac{1}{26.2 \cdot \left(\frac{\text{Pr}_{\text{flow}}}{50}\right)^{2/3} - 0.074} \cdot (1 + 0.098 \cdot (\text{Re}_{\text{flow}})^{(2/3)} - (2/3) \cdot \text{Pr}_{\text{flow}})^{(1/5)}; \]

\text{end}

\[ \text{h}_{\text{flow}} = \frac{\text{Nu}_{\text{flow}} \cdot k_{\text{flow}}}{d_{\text{tube}}}; \]

\[ \text{Two}_{\text{j}2(jj)} = \text{m}_{\text{flow}} \cdot (\text{Entalp}_{\text{o}} - \text{Entalp}_{\text{i}}) \cdot (L \cdot d_{\text{tube}} \cdot \pi \cdot h_{\text{flow}}) + \text{To}_{\text{flow}}_{\text{j}2(jj)}; \]

\[ \text{diff2(jj)} = \text{Two}_{\text{j}2(jj)} - \text{To}_{\text{flow}}_{\text{j}2(jj)}; \]

\text{end}

\text{end}

\text{if} \quad \text{T}_{\text{final}} > \text{T}_{\text{boil_g}}

\text{plot}(\text{To}_{\text{flow}}_{\text{j}2}, \text{Two}_{\text{j}2})

\text{grid \ on}

\text{figure(4)}

\text{plot}(\text{To}_{\text{flow}}_{\text{j}2}, \text{diff2})

\text{grid \ on}

\text{T}_{\text{boil_flow_vec}} = \text{To}_{\text{boil}} - 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{To}_{\text{boil}} + 10^{-8}; \quad 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{Two}_{\text{j}1(1)} \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)^{10^{-8}}; \quad 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{Two}_{\text{j}2(1)}(1) + 10^{-8}; \quad 

\text{T}_{\text{wall}_{\text{mean_liq}}} = \text{mean}(\text{Two}_{\text{j}1}); \quad 

\text{T}_{\text{wall}_{\text{1stmean_boil}}} = \text{mean}(\text{To}_{\text{boil}_{\text{l}}}); \quad 

\text{T}_{\text{wall}_{\text{2ndmean_boil}}} = \text{mean}(\text{To}_{\text{boil}_{\text{2nd}}}); \quad 

\text{T}_{\text{wall}_{\text{mean2}}} = \text{T}_{\text{wall}_{\text{mean_liq}}} \cdot L_{\text{liq}}/L + \text{T}_{\text{wall}_{\text{1stmean_boil}}} \cdot L_{\text{2ph}_{1st}}/L + \text{T}_{\text{wall}_{\text{2ndmean_boil}}} \cdot L_{\text{2ph}_{2nd}}/L + \text{T}_{\text{wall}_{\text{mean_gas}}} \cdot L_{\text{gas}}/L

\text{else if} \quad \text{T}_{\text{final}} < \text{T}_{\text{boil_g}} \quad \text{&&} \quad \text{T}_{\text{final}} > \text{T}_{\text{boil_l}}

\text{T}_{\text{boil_flow_vec}} = \text{To}_{\text{boil}} - 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{To}_{\text{boil}} + 10^{-8}; \quad 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{Two}_{\text{j}1(1)} \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)^{10^{-8}}; \quad 10^{-8}; \quad (2 \cdot 10^{-8})/50: \text{Two}_{\text{j}2(1)}(1) + 10^{-8}; \quad 

\text{T}_{\text{wall}_{\text{mean_liq}}} = \text{mean}(\text{Two}_{\text{j}1}); \quad 

\text{T}_{\text{wall}_{\text{1stmean_boil}}} = \text{mean}(\text{To}_{\text{boil}_{\text{l}}}); \quad 

\text{T}_{\text{wall}_{\text{2ndmean_boil}}} = \text{mean}(\text{To}_{\text{boil}_{\text{2nd}}}); \quad 

\text{T}_{\text{wall}_{\text{mean2}}} = \text{T}_{\text{wall}_{\text{mean_liq}}} \cdot L_{\text{liq}}/L + \text{T}_{\text{wall}_{\text{1stmean_boil}}} \cdot L_{\text{2ph}_{1st}}/L + \text{T}_{\text{wall}_{\text{2ndmean_boil}}} \cdot L_{\text{2ph}_{2nd}}/L

\text{else} \quad \text{no boiling}

\text{T}_{\text{boil_flow_vec}} = 0;

\text{T}_{\text{wall}_{\text{1stmean_liq}}} = 0;

\text{T}_{\text{wall}_{\text{2ndmean_liq}}} = 0;

\text{T}_{\text{wall}_{\text{mean_liq}}} = \text{mean}(\text{Two}_{\text{j}1});

\text{T}_{\text{wall}_{\text{mean2}}} = \text{T}_{\text{wall}_{\text{mean_liq}}} \cdot L_{\text{liq}}/L

\text{end}

\% \text{:(Two}_{\text{j}2(1)}(1) - \text{Two}_{\text{j}1(1)} \cdot \left(\frac{d_{\text{tube}}}{D_{\text{coil}}}\right)))/50: \text{Two}_{\text{j}2(1)};

\% \text{T}_{\text{test}} = [0.035, 363];

\% \text{T}_{\text{test}} = [0.035, 366];

\% \text{T}_{\text{2test}} = [L/2, 455];

\% \text{T}_{\text{3test}} = [L-0.025, 791];

\% \text{T}_{\text{nosezzle test}} = [L, 653];

\% \text{x}_{\text{test}} = \text{T}_{\text{test}(1)} \cdot \text{T}_{\text{test}(1)} \cdot \text{T}_{\text{test}(1)} \cdot \text{T}_{\text{nosezzle test}(1)};

\% \text{y}_{\text{test}} = \text{T}_{\text{test}(2)} \cdot \text{T}_{\text{test}(2)} \cdot \text{T}_{\text{nosezzle test}(2)};

\% \text{Error}_{\text{L}} = [L-3.45 18 24];

\% \text{T}_{\text{3testMax}} = [L-0.025, 809];

\text{m}_{\text{flow}} = \text{m}_{\text{flow}} \cdot 10^{6};