Master of Science Thesis Report

A critical review of
Adsorption Desalination

The road to sustainable desalination or wishful thinking

J.A. Schakel

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by

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in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology

March 28, 2019

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Foreword

Water, water everywhere,
Nor any drop to drink

These are the famous lines from the poem 'The Rime of the Ancient Mariner' of Samuel Taylor Coleridge. It is a poem that tells the story of a few mariners who are stranded at sea without any fresh water. It is a cruel irony that an ocean of water surrounds them, but they cannot drink. It sounds like a Tantalus torment. These lines always come to my mind if I think about the water problems of our world. When astronauts of the Apollo program talked about our earth, they always called that blue dot in the sky. Our planet is not a green planet but a blue planet. Our planet is covered for more than 70 per cent with water. Unfortunately, most of this water cannot be drunk by us. Only less than 2.5 per cent is fresh, and most of that is locked in ice. The water that is available to use, is quickly diminishing. So every time some water problems are mentioned, my thoughts are always: '*Water, water everywhere, nor any drop to drink*'.

It has been two years since I first came into contact with Adsorption Desalination. I was immediately drawn to it. It is a fascinating topic with many problems and promises. It can be the road to sustainable desalination. Desalination is a growing market and will keep growing due to the fact of the increasing water shortages worldwide. It is a logical causality since most water in the world is saline. It is one of the solutions to solve our water problems, and that worries me. It is currently not an environmentally friendly solution. The result can be that two of the sustainabilities goals, 'Affordable and Clean Energy' and 'Clean Water and Sanitation' are in conflict which is awkward. Adsorption Desalination could prevent this conflict and therefore deserves our attention.

I started maybe with too much optimism on this project. Building a set-up based on this technology was exciting but also challenging. The whole process was sometimes disappointing but in the end knowledge-rich. Sometimes I believed that this technology was not 'a road to sustainability' and thought it was a perfect example of wishful thinking. In the end, it was more complex. It has its problems, like any other new technology, but it deserves your attention. I invite you to read this report and make up your own conclusion about Adsorption Desalination. Is it the road to sustainable desalination or wishful thinking?

Acknowledgements

There are many people I like to express my graduate to for their support. First of all, I like to thank my family for all the support they have given me since they were always a voice of reason and love. Furthermore, I like to express my thanks to my thesis committee, to my supervisor dr. ir. H.L.F.M. Spanjers who always had my back. Furthermore to the other committee members, Prof. dr. ir. B.J.Boersma en dr. ir. S.G.J. Heijman for their commentary, insight and knowledge I could use. Also, special thanks goes to dr. M. Jafar, the lab technician of the Waterlab of the TU Delft. His help and cheerful remarks during my time in this lab were always of great support.

I also like to thank my fellow students who accompanied me during the summer in the lab. Special thanks go to G.L. Bandinu, T.M. Motchan, D. Diamantidou, A. Deiana, H.C. Yu, F.M. Rahman, H. Schijfsma and J.H. Kim. Also, my appreciations go to my fellow students of graduation room 4.84. It was a great experience spending time with them together. Special thanks go to A.L. Goense, I.Abbas, H.P. Hagedooren, M.G.J. Mulder, R.E.A. Burger, M.C. van Delden, I.A.J. Nederlof, T.J.T. van der Heijden, E.C. Buist, S. Klop, W. Neisingh, N. Hunink and of course my roommate N.A. Jooste.

Other special thanks go to other great friends for their support. First of all, I need to thank my graphic designer G.H. Gerritsen. Also, my appreciation goes to I.N. Streefkerk, C. Merola, J. Schoester, J.D. Verhagen, G. van der Zalm, A.J.J. Geertsen, S.D.G. van Haaren, D.V. Koenders, N.V. van Jaarsveld, S. Broere and N. van der Vliet. I experienced it as pleasant moments, those moments at the coffee corner or during lunch. Furthermore, I like to thank my fitness crew: R.W. van Dijk and M. Huber. Special thanks goes to the bastard who always cheered me up with the name D.J. de Villiers. I also like to thank V.P.J. Bost for all the love and support she gave me during my studies. Furthermore, I like to thank my old friends from the bachelor. Special thanks go to F.D.M. van Dam, N.J. Brouwer and V.J. Olijslager.

Executive Summary

Water is the most dominant substance on the planet and has always been a synonym for life. On this planet, fresh water has always been plentiful. Therefore, the conclusion of the United Nations in 2015 was even more shocking. The United Nations estimated that in 2030 a freshwater gap would exist of 40%. The withdrawal of fresh water would be 40% larger than the amount that is replenished every year. We are living on borrowed time, and we need to close this gap. Since most water on the earth is saline, desalination could be a possible solution. Unfortunately, desalination is an energy-intensive process, despite the different methods that can be implied. The energy consumption would always be rather large. Fossil fuels still create much of our energy in most areas in the world. Our increasing demand for fresh water can lead to a larger fossil footprint and therefore augmenting climate change. Climate change negatively impacts our water supplies. A negative spiral could be the result.

The world is consuming a large amount of energy. Unfortunately, this is not done efficiently. It is estimated that 72% of worldwide energy consumption is lost after conversion. Waste heat is an unwanted product as a result of this inefficient conversion. It is estimated that 63% of this waste heat has a temperature of 100 degrees Celcius or lower. If this energy could be harvested, the water gap could be closed by desalination without increasing the carbon footprint. That would be a remarkable feat. However, how to do this? A solution can be found in Japan and at your dry cleaner: Evaporation by vapour pressure lowering by using silica gel.

In the seventies, when the oil crisis was at its peak, Japan had a problem. It had a high need for air conditioning which is energy intensive. A device was created that could use waste heat to create cooling by using silica gel. The general public knows silica gel as moist eaters that are included in your dry cleaning. By placing silica gel in a closed environment, liquid water could be evaporated. Evaporation needs energy, and this could create cooling. In early 2000, some folks in Singapore realised that this technology could also be used to desalinate. Adsorption Desalination was born.

Adsorption Desalination (also known as AD) is a desalination technique that uses boiling point elevation and vapour pressure lowering. Silica gel has a high affinity to adsorb water vapour. Since this is done in a closed environment, the pressure is lowered till boiling. When an energy source is placed inside the liquid, an equilibrium can be found without lowering the pressure further. Once the silica gel is saturated, it is heated t0 a certain temperature at which it starts to desorb the vapour again. This vapour is collected and condensed into a clean product. The mass transport takes place by a pressure difference. Since the evaporation takes place in vacuum conditions, it is around room temperature. Therefore it can have a low sensitivity for erosion and since it is an evaporation technique, also for fouling. On paper, it can be a feasible desalination technology with low operational costs compared to others. In reality, a couple of barriers have to be conquered. The aim of this research to give a

critical review of this new emerging technology and to study to feasibility due to technical, biological and practical concerns.

One of the barriers is the characteristics of the core element of this technology, the silica gel. The reason that silica gel can adsorb water vapour so well is due to two main elements. First, it is an incompletely dehydrated polymeric structure of colloidal silica acids. Therefore it can create hydrogen bonds, polar bonds and weak electron bonds with other molecules. Water is a bipolar molecule, and therefore silica gel can adsorb water exceptionally well. It can create hydron bonds efficiently, and due to the bipolar nature of water, multiplayer on top of each other can be formed. The second element is the high specific surface of silica gel. It has many pores, and therefore a specific surface equal to human lungs can be formed. In the end, a high-quality silica gel can adsorb until 40% of their body weight.

The ability to make connections and the high specific surface determine the maximum amount of vapour silica gel can adsorb. However, two parameters determine whether the silica gel can adsorb; the temperature and vapour pressure. If the temperature is high, the vapour pressure has also to be high to ensure adsorption and the other way around. The same account for the opposite effect. Therefore energy transfer is vital for smooth operation. Unfortunately, the thermal conductivity of silica gel is extremely low. Besides energy transfer to change the temperature of silica gel to go from adsorping to desorbing and reverse, much energy has to be transported during the adsorption and desorption phase. During adsorption, water vapour transforms from a gas phase to a semi-solid phase. In this phase, the energy level is lower. Since energy cannot be destroyed, this energy has to be removed. The same applies to the opposite. If the heat exchanger is not well designed, the adsorption and desorption phase are prolonged, and the daily water production is diminished.

Even if the whole set-up is well designed, there is still one element of silica gel that can also diminish the water production of the set-up: the degradation of silica gel. Multiple mechanisms can degrade silica gel, but the two most important are fragmentation and pore pollutions by metal ions. Fragmentation (the breaking up into smaller parts) occurs by the high thermal stress the silica gel endures and the pollutions by the feed. A part of the sorption ability is destroyed or temporarily inhibited. The use of acid water can remove the pollution, so maintenance on the silica gel is necessary. Replacing the silica gel by other sorbents like zeolite is possible. Unfortunately, it has a lower adsorption capacity which leads to a less compact device and is, therefore, more expensive. Another unfortunate fact is that zeolite desorbs at a higher temperature. When using zeolite, Adsorption Desalination can no longer use waste heat of low quality to desalinate.

The last problem with using silica gel, but also other sorbents, are the instabilities with the sorption characteristics in vacuum conditions. The sorption characters depend as mentioned before on the temperature and the vapour pressure. Inside vacuum conditions, a disturbance of the vapour pressure can negatively influence the sorption characteristics and can lead to desorption at the wrong moment. Since it is done in a closed environment, it can lead to condensation which lowers the vapour pressure further. A complete breakdown of performance can be the result. Disturbances can happen through air leakage, which is are a common problem in industries. There are some solutions, but in the end, the permanent one is a high-quality vacuum system and intensive maintenance.

Even with these barriers, Adsorption Desalination is still an attractive technology due to its relationship with its energy consumption pattern. The energy consumption is high but stable and barely sensitive to change in conditions like feed salinity and recovery. Its energy consumption stays around the 40 kWh/m^3 in most cases. Only a small part, around 1.38 kWh/m^3 or even less has to be mechanical energy. All others can come from waste heat. If the other operating costs are kept low, it is a promising technology to use, especially for brine treatment since waste heat is an inexpensive energy source.

Some researchers claim that waste heat is a free energy source, but that statement cannot be valid. To use waste heat, infrastructure is necessary to collect it and transport it. There is probably enough waste heat in the world to close the water gap. As an example, the Netherlands is the second biggest producers of waste heat in Europe and creates enough to produce probably more 850 km^3 potable water. Unfortunately, there are some uncertainties. Waste heat is only classified in three rough categories, low, medium or high. Low is everything below 100 degrees Celcius. It could be that most energy is trapped in waste heat with a temperature of 30 degrees. More validation is necessary since the future of Adsorption Desalination is intertwined with waste heat. Without waste heat, it cannot be an inexpensive desalination technique.

Since it is still an experimental technology, not a lot of data is available to create a solid picture of the costs involved with Adsorption Desalination. Only two studies exist today [56, 72], and both estimate that the cost for seawater desalination using Adsorption Desalination is between 50% and 70% of the cost while using reverse osmosis. Only one study gives insight into the different sectors of cost [72]. What is notable is that the other costs, replacement cost for parts and chemical cost for Adsorption Desalination are kept at zero. A strange conclusion since silica gel can degrade and replacement can be necessary, chemicals are necessary for the heating and cooling water that is used bAD uses. No conclusion can be drawn about the final costs of AD, but it seems that the statements of these studies are unlikely. For seawater desalination, the costs are probably in the same range as reverse osmosis.

Furthermore, there is a strong case that AD can remove biological pollutants since it is an evaporation technique. The original aim of this research was to research these claims. Unfortunately, the set-up was not functioning properly due to practical problems like air leakages. Even with this result, much knowledge was gained, and a few remarks and conclusions can be made. Remarks like where further research is necessary to understand the vulnerabilities of AD better.

To conclude, Adsorption Desalination is a newly emerging technology with many interesting aspects. It can provide an alternative for standard desalination techniques while being sustainable. There are a few barriers to overcome, but it deserves attention. Further developments should be stimulated since the water gap should be close in an environmentally friendly matter. Adsorption Desalination is a sustainable solution that should always be considered.

Contents

List of Figures

List of Tables

Nomenclature

Electrical Engineering

I	Electrical current/ampere (A)
R	Electrical resistance (Ω)
V	Voltage (V)

Standard Symbols

ρ	Density (kg/m^3
d	Diameter (m)
d	gravitation accelaration (m/s^2)
L	Length (m)
r	Radius (m)
t	Time (s)
u	Specific volume (m^3/kg
v	Velocity (m/s)
z	Height (m)

Sorption Characteristics

K_0^I	Vapour correlations coefficient (Pa^{-1})
P_v	Partial vapour pressure (Pa)
q	Adsorption capacity (kg_{water}/kg_{silica})
Qst	Sorption energy correlation coefficient (J/kg)
R_v	Ideal gas constant for water vapour ($\frac{J}{K\,kg}$)
T_{si}	Temperature silica gel (K)

Superscripts

*	Restricted state

Thermodynamica

$\dot{m}$	Mass flow rate (kg/s)

$\dot{Q}$	Heat transfer rate (W)
$\dot{Q}_{least}$	Least heat of seperation (W)
$\dot{Q}_{least}^{min}$	Minimum least heat of seperation (W)
$\dot{Q}_{sep}$	Heat of seperation (W)
$\dot{S}_{gen}$	Entropy generation rate (W/K)
$\dot{W}$	Work transfer rate (W)
$\dot{W}_{least}$	Least work of seperation (W)
$\dot{W}_{least}^{min}$	Minimal east work of seperation (W)
$\dot{W}_{sep}$	Work of seperation (W)
$\dot{W}_{sep}^{rev}$	Minimal reversible work needed for seperation (W)
μ_i	The chemical potential (J/mol)
θ	Saturation rate (-)
C_p	Specific isobaric heat ($\frac{J}{kg\,K}$)
C_v	Specific isochoric heat ($\frac{J}{kg\,K}$)
e_d	Specific exergy destroyed (J/kg)
e_f	Exergy flow (J/kg)
G	Gibbs free energy (J)
g	Specific Gibbs free energy (J/kg)
H	Enthalpy (J)
h	Specific enthapy of the system (J/kg)
k	Thermal conductivity (W/K)
M	Moleculair mass (kg/mol)
m	Mass (kg)
N	Mol (mol)
P	Total pressure (Pa)
P_{air}	Partial pressure air (Pa)
P_{vapour}	Partial pressure water vapour (Pa)
R_{he}	Thermal resistance for heat transfer (K/W)
R_{vp}	Resistance against leakage ($\frac{s}{Pa\,kg}$)
s	Specific entropy of the system ($\frac{J}{K\,kg}$)
T_0	Ambient (dead sate) temperature (K)

T_H	Temperature of hot-side reservoir (K)
w	The salt concentration (g/kg)

Subscripts

0	Environment, or global dead state
atm	Atmospheric
b	Brine
f	Feed
he	Heat exchanger
i	ith species, inlet state
n,N	Neutral species
o	Outlet state
p	Product
r	rth location in radius definied at finite elements
sat	Saturated state
sb	Silica bed
si	Silica gel
sorption	Behaviour/value related to the adsorption/desorption of silica gel
sys	State of the system
t	tth moment in time in a discontinue scale
v	Water vapour
w	Liquid water

Glossary

Adsorption Adsorption is a surface phenomenon where adhesion of atoms, ions or molecules from a liquid, gas or dissolved solid with the surface occurs. 21, 28, 30, 34, 35

Adsorption Cooling See Adsorption Refiguration. 44

Adsorption Desalination A desalination technique in which desalination occurs by evaporation. The main driver of the evaporation is the lowering of the condensation pressure by water vapour adsorption. 6, 20–25, 27–29, 32, 37, 38, 40, 43, 46, 50, 51, 59, 74, 75, 78, 88, 89, 91, 93, 121, 123–126, 128–135, 137–140

Adsorption Refrigeration A refrigeration technique in which cooling occurs by evaporation. The main driver of the evaporation is the lowering of the condensation pressure by water vapour adsorption. 29, 32, 43

Brine The concentrate of a saline solution. 9, 28, 30, 31, 48, 49, 74, 88, 89, 125, 126, 130, 133, 137–141

Concentrate It is the form of a substance where the majorite of its base component is removed. As example see brine.. 24, 43, 50, 71, 74, 76, 89, 121

Condenser An condenser is a device in a process used to turn a vapour of a substance into its liquid form. 28–31, 40, 44, 63–65, 81, 123, 126

Desalination Desalination is a process that removes mineral from a medium. Most usually used when salts and minerals are removed from saline water.. 5, 9, 20, 24, 27, 29, 46–51, 56, 121, 123, 125–127, 130–132, 137, 138

Eustatic Freezing Desalination A desalination technique that uses as colligative property depression of freezing point.. 121

Evaporator An evaporator is a device in a process used to turn the liquid form of a substance into its vapour form. 5, 28–31, 40, 42–44, 61, 62, 64, 65, 81, 88, 89, 121, 122, 126, 137

Feed The supply, raw stream that enters a process. Also known as the starting product. As an example: The seawater that enters a desalination process is called the feed.. 5, 9, 20, 24, 28, 30, 31, 43, 44, 47–49, 61, 71, 81, 88, 89, 121, 122, 125, 126, 130–133, 137, 139, 140, 158

Flash Evaporation Evaporation that occurs when a saturated liquid undergoes a sudden reduction in pressure and the pressure becomes lower than the vapour pressure. 44

Mechanical Vapour Compression It is a desalination technique that involves an energy recovery process where energy is added to low-pressure vapour by recompression it.. 50

Membrane Distillation Membrane Distillation is a thermally driven membrane desalination technique that uses as collegative propertie vapour pressure lowering. 20, 121

Multi-Effect Distillation It is a distillation processes used for desalination. It consists of multiple effects. The hot condens is used to an energy source to evaporate a saline batch. 50

Partial Pressure It is the pressure exerted by an individual gas/vapour. 34, 35, 78, 79, 83, 84, 124

Product The sorptive is the material that can be adsorpt/absorpt by a sorbent.. 24, 28, 30, 31, 43, 48–50, 59, 71, 74, 76, 81, 88, 89, 133, 134

Recovery The efficiency of a desalination process. The percentage of desalinatated water that is produced.. 24, 29, 31, 40, 41, 47–49, 125, 126, 130

Reverse Omosis It is desalination technique where ions, molecules and large particles are removed by using a partially permeable membrane. The colligative property it uses to desalinate is osmotic pressure.. 20, 46, 50, 51, 121, 127, 130–132

Silica Bed In singular form, the device in which the silica-covered heat exchangers are placed, is the definition of a silica bed. In plural form, the silica-covered heat exchangers itself are the definition.. 5, 28–31, 40, 42, 44, 62, 63, 65, 78, 80, 81, 86, 88, 89, 122–124, 126, 127, 135, 137, 139

Silica Gel An incompletely dehydrated polymeric structure of colloidal silica acids. It can form hydrogen, polar and weak bonds with other molecules. Due to its high specific surface, it can adsorb water to a great extent. 21, 24, 27, 28, 30, 31, 35–39, 41–44, 52, 62, 74, 78, 80, 81, 83, 85–88, 121–127, 131–135, 137–140

Sorbate The sorbate is the material that is adsorpt/absorpt by the sorbent.. 86

Sorbent The sorbent is the material used to adsorb or absorb liquid or gases. 34, 38, 39, 43–45, 139

Sorptive The sorptive is the material that can be adsorpt/absorpt by a sorbent.. 33

Technique Technique refers to a method of a unit or activity.. 20–23, 27–30, 38, 44, 47, 52, 121, 123, 133, 137

Technology Technology refers a summation of complex processes and principles used in applications and gadgets of science and engineering.. 20–24, 27, 29, 37, 38, 46, 51, 56, 127, 130–133, 137, 138

Vapour Pressure The pressure exerted by a vapour in thermodynamic equilibrium with between the gases and liquid phase. 27, 50

Work In thermodynamics work is energy transfer to a system or produced by a system in the form of mechanical work. As an example, a pump in a system needs mechanical energy and therefore work in thermodynamical jargon. 5, 43, 48–50

Zeolite It is a microporous aluminosilicate mineral. It is used as an adsorbent or catalyst. It has a crystal structure, and there are over 200 different kinds. 38, 39, 123, 124

Acronyms

AC Air conditioning. 29

ACS Air conditioning systems. 29

AD Adsorption Desalination. 24, 29, 34, 40, 44, 51, 52, 65, 75, 76, 124, 126–133, 139, 140

COP Coefficient of performance. 43, 44

ED Electrical Dialysis. 51

GOR Gained Output Ratio. 50

MED Multi Effect Distillation. 51

MSF Multi Stage Flash. 51

RO Reverse Osmosis. 51, 52, 132

SCP Specific cooling power. 43

SEC Specific Electricity Consumption. 50

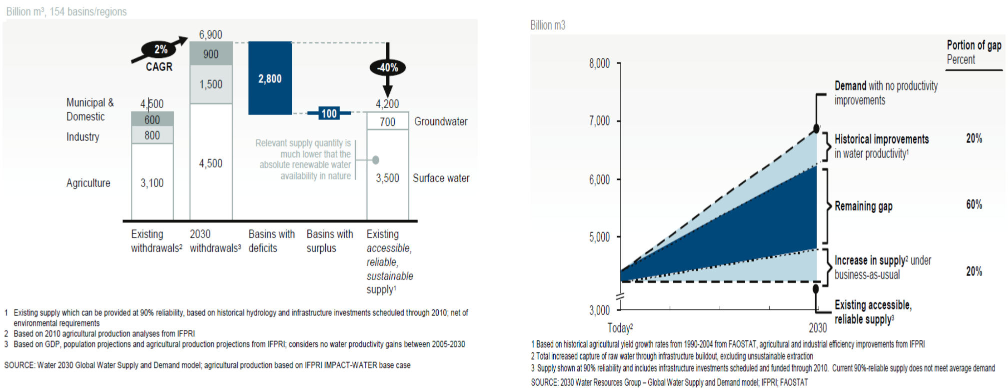
VC Vapour Compression. 51

1 | Introduction

1.1 Background

In 2015 the United Nations presented a report with shocking conclusions. In this report, the statement was made that in 2030, now only 11 years away, a shortage of sustainable fresh water would exist that would be as high as 40% [11]. The concept of sustainable water is as follow: it is water than can every year be extracted from a source without depleting it. The percentage 40% originates from a report of the Water Research Group 2030 (WRG2030). The WRG2030 is a group consisted out of different companies whom all have a benefit from the world with a sustainable water supply. The group did an extensive study and had the following to tell about their results:

’*By 2030, under an average economic growth scenario and if no efficiency gains are assumed, global water requirements will grow from 4,500 billion* m^3 *to 6,900 billion* m^3*. As Figure 1.1a shows, this is a full 40 per cent about current accessible reliable supply (including return flows and taking into account that a portion of supply should be reserved environmental requirement). This global figure is really the aggregation of a very large number of local gaps, some of which show an even worse situation: one-third of the population, concentrated in developing countries, will live in basins where this deficit is larger than 50 per cent.*’ [1]



1 Existing supply which can be provided at 90% reliability, based on historical hydrology and infrastructure investments scheduled through 2010; net of environmental requirements
2 Based on 2010 agricultural production analyses from IFPRI
3 Based on GDP, population projections and agricultural production projections from IFPRI; considers no water productivity gains between 2005-2030

SOURCE: Water 2030 Global Water Supply and Demand model; agricultural production based on IFPRI IMPACT-WATER base case

1 Based on historical agricultural yield growth rates from 1990-2004 from FAOSTAT, agricultural and industrial efficiency improvements from IFPRI
2 Total increased capture of raw water through infrastructure buildout, excluding unsustainable extraction
3 Supply shown at 90% reliability and includes infrastructure investments scheduled and funded through 2010. Current 90%-reliable supply does not meet average demand

SOURCE: 2030 Water Resources Group – Global Water Supply and Demand model; IFPRI; FAOSTAT

(a) Expected global gap between accessible, reliable supplies and the expected 2030 water withdrawls

(b) Bussiness-as-usual approaches will not meet demand for raw water

Figure 1.1: Predictions for the situation in 2030 involving water [1]

This expectation is hugely worrisome. A shortage of water can underpin economic growth, sustainable development, environmental sustainability. As said by the UN: *’From food and energy security to human and environmental health, water contributes to improvements in social well-being and inclusive growth, affecting the livelihoods of billions’*.

The report further mentions that they expect an increase in global water demand by 55% in 2050. The main reason for this increase is industrialisation and urbanisation. The demand for water by the manufacturing industries is expected to grow by 400% compared with 2000. Growing needs for manufacturing, electricity generation and domestic use are the most critical factors. Competition between different users for water is expected. The increasing water gap increases the probability of localised conflicts, and it can continue inequalities between access to services [11].

Using fresh water more efficiently or reusing wastewater could be a solution, but since the water consumption will keep growing, it is doubtful that these measures alone will be enough. Therefore, desalination could be a possible outcome to close the water gap. Water shortages are a local problem. Most industries and urban centres are in coastal areas; therefore, access to the large saline water source is not the problem. At the moment desalinationis a fast-growing market. It is expected by some research reports that the market has a value of US$52.4bn by 2020. Compared with the US$12.5bn market in 2010, this is an increase of 320.3% [59]. In 2015, 18,426 desalination plants were operational worldwide, producing 86.8 million cubic meters of fresh water per day. 300 million people were provided with fresh water by desalination [50]. The problem, however, is that desalination techniques consume much energy. Around 50-60% of the total costs are energy costs. Even with new developments, desalination shall always consume more energy than traditional freshwater treatment techniques [81]. Since the desalination market will grow, so shall energy consumption by this market. The energy that the market consumes is probably partly produced out of fossil fuels. It is estimated that in 76 million tonnes of carbon dioxide were released into the atmosphere in 2018 by the desalination market and that shall increase till 218 million tones of carbon dioxide a year in 2040 if nothing changed [62]

Closing the water gap while increasing the carbon footprint is not a promising sustainable future. Fortunately, there are many different desalination techniques. Some of which are more sustainable than others. Reverse Omosis is the most dominant player in the market currently and has an energy consumption of higher than 2.5 kWh/m^3, and in practice between 4 and 6 kWh/m^3 [3]. Energy consumption can differ depending on the salinity of the feed, quality of the membranes and configuration. It is expected that the energy consumption of this technology shall decrease in the future due to further technical developments. Research is currently done on other membrane techniques which can maybe push the electrical consumption down to 1.5 kWh/m^3 in combination with smart configurations [4]. Besides emerging membrane-based technologies also thermal-based desalination technologies can provide a solution. Technologies like Membrane Distillation, Humidification-dehumidification or Adsorption Desalination. These technologies who can use sustainable sources like solar as an energy source for their desalination [69]. Using solar as an energy source is an exciting idea since more than half of the desalination market is located in the middle-east and Africa [50]. Areas with many solar potentials.

Adsorption Desalination is maybe one of the most interesting new developing desalination techniques because it can use a low-grade energy source as the primary energy source. It can run on waste heat. Waste heat is the thermal energy that is a byproduct after energy conversion. A byproduct that is not desirable and is mostly discharge into the environment. It is estimated that 72% of the global energy consumption is lost as waste heat after conversion [22]. 63% of this waste heat has a temperature lower than 100 degrees Celcius [22]. Especially the energy market and the industry are a large producer of this waste heat [22]. These sectors are also mostly located in coastal areas and consume an enormous amount of water. In Europe, the energy sector accounts for 28% of the water usage annually while industry and mining account for 18%. Together they are responsible for 46% of the water consumption of this continent. Adsorption Desalination could be therefore a sustainable solution for these sectors to fight their water shortages.

Adsorption Desalination is evaporation technique that takes place inside a vacuum environment. The general idea is evaporation created by adsorption of water vapour by silica gel. Silica gel is a material that can adsorb water vapour at room temperature, but when heated it starts to desorb the vapour again. Since the silica gel only needs to be heated till around 80 degrees Celcius, many applications involving waste heat are possible. It is a technology first developed on the National University of Singapore, and it is inspired by Adsorption Cooling. The technology is still in the experimental phase, but the researchers are extremely excited about the applications and future possibilities. Out of their research, they have claimed that electrical energy consumption is only 1.38 kWh/m^3 [47]. Three pumps and the pneumatic valves are responsible for this consumption. It does need around 38.8 kWh/m^3 thermal energy, but since this is waste heat, they claim it has no negative influence on economics or sustainability. Furthermore, it is claimed that the technology is more economic friendly than the competing technologies since it is less vulnerable to fouling or erosion. Another claim is made is that it can remove biological contaminants besides salinity [47]. Many believe that a great future can be expected for this technology. The question that now arises is: can these claims be validated?

1.2 Problem Description

All could agree that on paper Adsorption Desalination is a promising new technology. It is a handy new tool in the toolbox to battle the water gap while at the same time keeping the promise of a more sustainable future. A technique, when implanted on a large commercial scale could help different sectors of industries become even water independent while downscaling their carbon footprint on their water consumption and usage. Only at a few locations in the world there are operational AD-device. One is in Singapore [46] and there is also currently one under construction in Saudia-Arabia [77]. There are however many different questions which are in need to be answered.

One question that wonders the mind: is it feasible? It is one thing if it is technically possible on paper to desalinate a saline source using this method, but is it still technically possible in the long term? The whole process seems to be based on silica gel. What is precisely this material and how does it work? Does silica gel also work after a long period or has it a limited technical lifespan? Other technical questions that arise are about fundamental physical questions. How does it come that this material can desalinate? What is the process that makes this magic happen? What is most important to make the process succeed and if a breakdown in performance occurs, what is the most likely cause for it? Moreover, if a breakdown of performance occurs, what solution could be implemented to repair it? Also, which other design criteria should one keep in mind when designing an Adsorption Desalination device?

It is stated that it can remove salinity, but it is also claimed that it can remove biological contaminants. That last statement is currently not validated, which is regrettable since it could add value to this technology. A possible explanation of why it has not been validated is that much research done on this subject has been done with computer simulation. To validate this claim, an experimental set-up has to be built. A process that comes along with certain complications.

Besides question about the technical potential of this technology, there are also question about the energy consumption. A question which is extremely important in the current times. An Adsorption Desalination device needs to get most of its energy consumption from waste heat to be compatible with other technologies. However, what is waste heat exactly? How useful is it and how much it there in the world? Also, you probably need to collect it and transport it? Which challenges are involved with this task?

Moreover, at last, there is a significant difference between commercial and practical use and what can be promised on paper. Even with the fact that it has been tested out in laboratories [76], still, it cannot be said that this technique could be chiefly implanted on a full commercial scale in industries. The technology is still in its experimental phase. Laboratories are protected environments. In laboratories, initial conditions are known, and the environment can be controlled. The reality is different. When a technique is used in practice not all elements can be influenced and controlled. Therefore it is necessary to know the vulnerabilities of this new technique when upscaling, and commercial implantation occurs. How feasible Adsorption Desalination is in practice is probably to most urgent question to answer.

2 | Research Question

2.1 Scope of the Thesis Research

The scope of this thesis research is broad. It started it out as a general interest in a new emerging technology. With this interest, many different questions did arise. Questions involving fundamental scientific issues, but also practical and economical ones. The original idea was to research the ability by Adsorption Desalination to remove biological contaminants. The advantage was that this a was a good narrow scope for thesis research and an unanswered question. The only problem was that an experimental set-up had to be built to answer this question. To build this set-up, other questions had to be answered. Not only design questions but also questions about the fundamental physical working of Adsorption Desalination. Unfortunately, at the end of the thesis period, the author of this report was unable to construct a proper working experimental set-up. Therefore additional research was done to explain why the experimental set-up did not function. As a result, extensive research was done. Therefore, the main research question is formulated broader than in most thesis researches. In the end, it is the purpose of this research to provide a deeper understanding of this new technology and provide insight into what can be expected in the future.

2.2 Main Research Question

As said before, it is the purpose of this research to acquire a better understanding of Adsorption Desalination. To understand how well it can desalinate a saline source and which other applications are possible. However, for every new emerging technology, it is also important to understand its vulnerabilities and its strength. All of this is necessary to be able to predict the future of this technology. Therefore, the main research question is:

What is the feasibility of Adsorption Desalination concerning the physical, biological and practical factors?

2.3 Subquestions

To answer the main research question, different questions have to be answered. Questions about the inner workings of this technique, about the removal of pollutants, design problems, but also questions about how to counteract these vulnerabilities. The literature review answers will answer some subquestions, while empirical and practical research mainly answers the other subquestions. The subquestions are as follow:

How does the desalination process of Adsorption Desalination work?
The purpose of this subquestion is to get a deep understanding of the whole desalination process. How can silica gel desalinate a saline source and which elements are important to acquire success?

What are the characteristics of Silica Gel?
What is silica gel and how does can it adsorb water vapour? Which sorption and thermodynamic characteristics does it has and on which factors do these characteristic depend?

What is the theoretical minimum energy consumption of Adsorption Desalination?
It is probably a complicated question to answer what the average energy consumption of an AD-device since it is a technology with much design freedom and the answer would also depend on the quality of the feed, recovery and other circumstances where a desalination plant operates. To answer this question, a method would be created to calculate the theoretical minimum energy consumption of AD by the circumstances.

What are the design criteria when designing an Adsorption Desalination vessel?
The purpose of this question is to understand the vulnerabilities of the design of an AD-device.

What is the potential of using waste heat for Adsorption Desalination?
It is known that waste heat exists, but is it possible to use it for AD. How much waste heat is technically available and how much economical feasible? What is also the future of this potentially sustainable energy source? These are the questions this subquestion tries to answer.

What are the costs involved Adsorption Desalination?
The researcher claim that it is a more economically friendly desalination method compared with other methods. This statement is a bold statement for an experimental technology. It is therefore interesting to understand how much truth in this statement can be found.

How well does Adsorption Desalination remove biological contaminants?

- What is are the water qualities in the concentrate and product by a feed salinity of 20 till 80 g/L from recoveries 20% till 80% with a half cycle time from 100 till 400 seconds?

- What is are the water qualities in the concentrate and product by a feed that contains acetic acids from recoveries 20% till 80% with a half cycle time from 100 till 400 seconds?

- What is are the water qualities in the concentrate and product by a feed that contains E.Coli from recoveries 20% till 80% with a half cycle time from 100 till 400 seconds?

The answer to this sub-subquestion can clarify how well Adsorption Desalination can remove biological contaminants.

How vulnerable is Adsorption Desalination to practical disturbances? This subquestion has the purpose the answer the question if a breakdown of performance can occur and why it can occur. Also, it answers the question of how easily it can be solved. Also, concerns about other practical issues are addressed with this subquestion. At the end, this question is also based on the reflection of building an experimental set-up.

With these subquestions, all the physical, biological and practical vulnerabilities of Adsorption Desalination are studied. The following chapter an in-depth literature review is given which can answer a part of these questions. The other questions are answered with the help of different numeric models and a laboratory set-up.

3 | Literature Review

3.1 General Description of the Technology

Adsorption Desalination, also known as AD, is a newly developed evaporation/desalination technique based on adsorption cooling. The design of an adsorption cooling device is almost similar to the design of an Adsorption Desalination device. The concept has been developed at the National University of Singapore. The general idea is to desalinate a saline source by the use of evaporation, but instead of using mechanical or electrical energy as the primary energy source, a low-grade thermal energy source is used. Of course, this technology can also separate water from other particles than salts. The main principle behind this technique is artificially created evaporation by the use of silica gel. Silica gel has at low temperatures (around room temperature or lower) a high affinity for water vapour. Some very high-quality silica gels can adsorb till 40% of its body weight of water. By adsorbing water vapour in a closed environment, the silica gel lowers the water vapour pressure of the saline solution and therefore initialling evaporation also known as boiling [73]. The reason for this effect is that the complete device is an isolated system. Since it is a closed environment, it wants to find an equilibrium. To counteract the fact that the water holds too much energy at this lower pressure, liquid water evaporates. At higher temperature like 80 degrees Celsius, silica gel starts to desorb water vapour. With this principle, desalination is possible while only using a low-grade thermal energy source as the primary energy source.

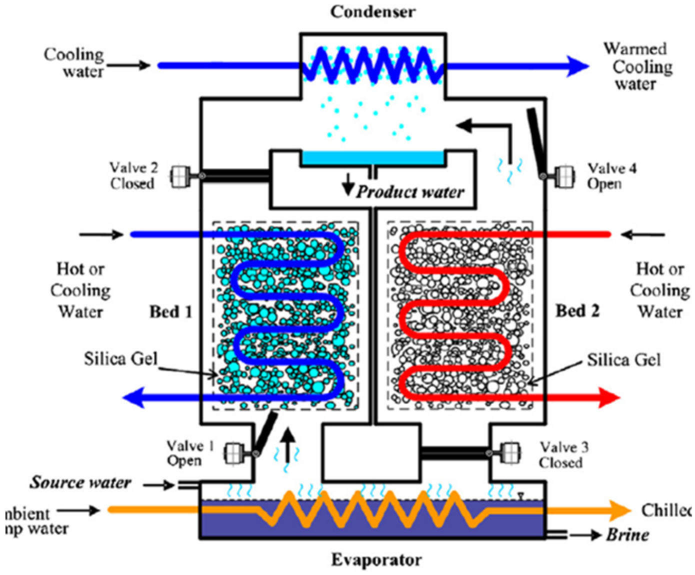


Figure 3.1: Standard design of an AD-device [79]

An Adsorption Desalination device exists out of three main elements. The first is the element is the evaporator. In the evaporator, the feed is evaporated. By the use of phase difference, salts and other particles are separated from the water; thus clean water vapour and a brine (a residue of water containing all particles) are created. The evaporator can be operated in a continuous modus or batch modus. Since most AD-devices work with a constant pressure in the evaporator, thermal energy is added by the use of a heat exchanger to the liquid solution in the evaporator. It is necessary since evaporation costs energy because the energy content of water vapour is higher compared to liquid water. In most AD-devices the saline source is evaporated around room temperature or ten degrees above that. There could be two reasons for this choice of operation. A first reason could be the fact that less energy is necessary to heat the feed to the desired temperature. Increasing the temperature of water is an energy consuming process. Secondly, at a low temperature, the corrosion rate is lower. A lower corrosion rate means less corrosion in the evaporator. Therefore a lower corrosion rate translates into lower maintenance compared to evaporators where a similar saline source is evaporated at higher temperatures. To evaporate a saline source like sea water (average salinity of 35 g/kg), the pressure inside the evaporators needs to be in a range of 2kPa to 5kPa, depending on the salt content of the solution. Pressures at these values are 20 till 50 times lower than the standard atmospheric pressure. Therefore, the evaporator of an AD-device also needs to be a vacuum system.

The second element is the silica bed. The silica bed is the device in which silica gel is placed. Note, the word silica bed is also changeable for the definition 'silica gel covered heat exchanger'. As long one is talking about silica bed in singular form, the unit in which the silica gel beds are placed is discussed. Also in the silica bed vacuum conditions are maintained. A heat exchanger can control the temperature of the silica gel. The silica gel is located around the heat exchanger. In section 3.5 further information is given about the optimal design of such a heat exchanger. An AD-device can have one or multiple silica beds. The working principle is as follow: when the silica gel is unsaturated, a connection exists between the evaporator and a silica bed (the device in which the silica gel is located). Due to diffusion, a pressure difference or forced convection the water vapour is transported from the evaporator to the silica bed. Inside the silica bed, the vapour is adsorbed by the silica gel. Since the evaporator and the silica bed are both vacuum vessels, the pressure tends to lower itself. However, as said before, to achieve an equilibrium more water evaporates due to the fact the saturation temperature is lowered because the pressure is lowered. The adsorption of water vapour by the silica gel releases energy. To keep the silica gel at a constant temperature, the silica gel is cooled. When the desired level of saturation is achieved, the silica gel is heated until the necessary temperature. The water vapour adsorbed by the silica gel starts to desorb. The released water vapour by desorption travels from the silica beds to the third essential element of an AD-device, the condenser.

The third element is the condenser. The primary function of the condenser is clear. The condenser condenses the water vapour that originates of a silica bed into the product. You could call the whole Adsorption Desalination process a two-trap or double evaporation technique. Therefore, you could expect a water quality equal to demi-water or higher. The water vapour arrives in the condenser from the silica bed by the use of diffusion, convection or forced convection. The natural convection is created since the pressure lowers itself in the condenser (it is also a vacuum vessel), due to the fact that water vapour is transformed into liquid water. Liquid water has a lower density, and since it is a closed environment, the pressure drops, therefore. In the literature, it is unclear which mechanism is dominant for mass transport. From these three main elements, an AD-device can be constructed.

3.2 History of AD - Adsorption Cooling

Adsorption cooling, also known as Adsorption Refrigeration is an environmentally friendly refrigeration technology that traces back its origin to Japan in the '80s. It was probably developed as a response to the energy crisis from the '70s. Japan has always been a country that relies heavily on ACS. ACS play an important element in Japanese society due to the sweltering summers and the dressing codes of the offices. Therefore it is vital for Japenese businesses to have a proper working-temperature in their offices. Due to the energy crisis in the '70s, a greater urge to developed more energy friendly refrigeration techniques was born.

The reason why human sweat is to lose heat, to loss thermal energy. The thermophysical principle behind sweating is that evaporation of water costs energy since the energy content of water vapour is higher than the energy content of liquid water. The result is the creation of cooling. The working principle of Adsorption Refrigeration is the same as the working principle of Adsorption Desalination as discussed in section 3.1. The main difference is that the main objective of AD is to create desalination while the main objective of Adsorption Refrigeration is to create cooling. While it is not the main objective of Adsorption Refrigeration to desalinate, it has the ability. The same applies to AD. It also creates cooling. The exact location and moment of time that the idea that Adsorption Refrigeration could also be applied to create desalination was born is not exactly known. However, based on the location and time (read when the first papers about AD started to appear), it could be said AD was first developed in the early 2000s at the National University of Singapore.

Since it's creation, a lot of research and development has been done on this subject. Just like AD, Adsorption Refrigeration uses a low-grade thermal energy source as the primary energy source. Sources like heat-waste, geothermal or solar energy. Research has been done how Adsorption Refrigeration could be used as an AC system for a building in combination with solar collectors on its roof. Since its introduction, it has been halted as a promising technique that could create cooling in a more sustainable matter. However, it has not been able to ensure a dominant position in the Air Conditioning Market.

3.3 Operational Strategy

One of the advances of Adsorption Desalination is that the operation scheme can be very flexible. You can play around with different configurations of elements (evaporators, silica beds and condenser), different connections between these elements, different pressure, different temperatures and different recovery rates. The operational strategy depends on the different phases of

AD-device. The different phases are as follow:

Phase 0 - Preparation

In this phase, the complete process is prepared. The saline feed is fed into the evaporator. Before it was fed in, the feed was pre-treated. Since it not a membrane technique but an evaporation technique, only degassing is necessary. One of the important reasons why the feed needs to degassed is discussed in subsection 3.4.4. Some filtration could be necessary, but the intensity is significantly less compared with membrane technolgies. In most cases, a couple of sieves would be sufficient. Another preparation step could be heating the feed to the required temperature depending on the salinity of the feed and the desired saturation pressure.

Phase 1 - Evaporation and Adsorption

In the first phase, the evaporation of the feed and the adsorption of the created water vapour takes place. During this phase, a valve that connects the evaporator and a silica bed is opened. The silica gel adsorbs the water vapour. As said before, during the adsorption thermal energy is created, around 2800 kJ/kg [51]. To discharge this energy, the silica gel is cooled down.

Phase 2 - Heating the Silica Bed

When the desired saturation of the silica gel is reached, the connecting valve between the evaporator and the silica bed is closed. After this valve is closed, the cooling water that flows through the heat exchanger of the silica bed is replaced by a medium of a higher temperature. This medium could be steam, hot condens or chilled water or any other suitable medium. The purpose of this phase is to heat the silica gel to the required temperature. This temperature could be 80 degrees Celcius, but there are also operational strategies known where the silica gel is heated till only 60 degrees. If the silica gel is placed into a perfect air-tight vacuum vessel, the pressure might rise in the vessel during this phase. The pressure might rise due to the fact the temperature of the air increases. Other reason could be the silica gel starts to release water vapour.

Phase 3 - Desorption and Condensation

When the desired temperature is reached in the silica gel, the valve that connects the silica bed with a condenser is opened. The water vapour travels from the silica bed to the condenser. During this process, the silica gel is heated till a higher temperature or kept at a constant process while cooling water is pumped through the condenser to ensure the water vapour does condens.

Phase 4 - Cooling down the Silica Bed

When all water vapour or just an acceptable amount has travelled from the silica bed to the condenser, the valve between these two elements is closed again. Cold water is pumped through the heat exchangers of the silica bed to cool down the silica gel. During this process, it is possible depending on the settings and the state of the device, that the pressure drops inside of the silica bed. When the silica gel has reached the desired temperature, the valve between the evaporator and the silica bed is opened again to redo the whole process again. The operation starts at phase one once again.

Phase 5 - Harvesting the product and the brine If an AD-device works in a batch mode (the feed, brine and product are not constantly pumped in and out of the device), a phase 5 is also present. When the desired recovery is reached, the operation is put on hold, and the brine and clean product are pumped out of the system. When phase 5 is at its end, the whole system starts at phase 0 again.

The six different phases described above are the main elements of an operational strategy of an AD-device. With these different phases, an operator can play around with duration, temperature, pressure or recovery rates. Different configuration can have a different advantage. As an example how you could play around with temperature: you could achieve a higher SWDP (Specific Daily Water Production $[kg_{water}/kg_{silicagel}]$) when you desorb the water vapour at a higher temperature. However, your performance ratio (efficient use of your thermal energy) is lower. The opposite is also true, desorbing at a lower temperature does increase the performance of your device, but your SWDP decreases [71]. The temperature difference between the feed and the condens also has a significant influence on the efficiency and water production of an AD-device. Research has shown that when the temperature on which the water vapour condens in the condenser is lower than the saturation temperature of the feed, the AD-device achieves its maximum water production with minimum energy consumption [79]. Another parameter that can be used to influence the performance of an AD-device is the cycle/half-cycle time. The time that is necessary for the vessel to go through phase one till four. Depending on the desired temperature to desorb the water vapour, an optimum exists on which the SWDP is on its maximum. The same is true for PR. For the maximum PR-value, a longer cycle time is necessary than for the maximum SWDP [71]. All of this has been proven by different experiments, but also by numerical simulations [73].

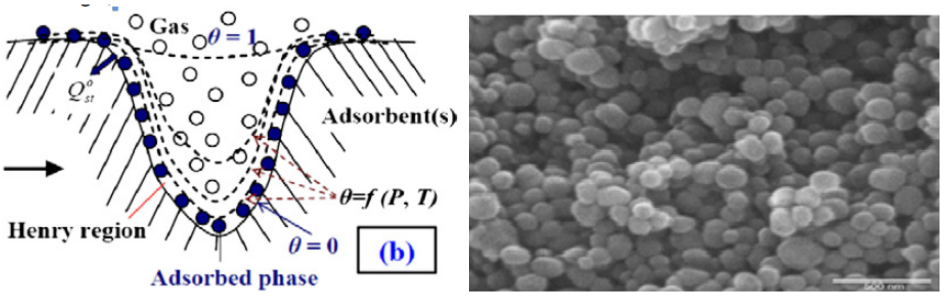
Besides controlling parameters that can be influenced during the operation, also different configurations of the building blocks of an AD-device can significantly influence the performance of a set-up. The use of multiple silica beds that operate independently from each other can, for example, improve the performance. When a vessel exists out of two silica beds, it can warm half the silica gel while cooling down the other half. This second silica bed can create a more continuous performance. The performance of a vessel with four silica beds is even better than the performance of one with only two [71]. Each bed can be in a different phase, and therefore constant evaporation in the evaporator is possible. The same is also true for the condensation in the condenser. It also enables the possibility for two beds two work in a Master-Slave configuration. In this configuration, the used cooling water or hot water in the master bed is reused again in the slave bed. Therefore, the complete device has a better performance ratio. Another experiment that has been done is connecting two silica beds directly to each other sideways. In this set-up, a valve is opened between two beds when one of these beds is cooled down while the other is heated up. Due to the pressure difference, convection occurs, and water vapour transport is possible. This addition can improve the SWDP of an AD-device. Besides using multiple silica beds, there are also designs which use multiple evaporators or condensers. In another design, the silica bed, evaporator and condenser are placed in one vacuum vessel. No vacuum-valves are necessary for this set-up. Another option is the placement of pumps between the different elements and making, therefore, forced convection possible between the evaporators, silica beds and condensers. Forced convection has been used in the design of an Adsorption Refrigeration device which improves the performance. Since both technologies are similar, it could also be used in Adsorption Desalination.

3.4 Silica Gel

3.4.1 General Description

Silica dioxide in an amorphous form, also known as Silica Gel, is an incompletely dehydrated polymeric structure of colloidal silica acid [45]. The material can be found in powder form or granular/beads. It is constructed as a silicon dioxide hydrosol after condensation polymerisation, ageing and partially dehydration. Over the surface of a silica gel beam, various functional groups can be found which can make a different kind of connections with other molecules. Connections like hydrogen bonds, polar and weak electron bonds. These functional groups can be classified. The first group are free or isolated silanol group, the second interparticle hydrogen-bonded silanol groups. The third and fourth groups are hydrogen-bonded surface silanol groups and inner silanol group [57].

This list is a very detailed chemical description of the surface of a silica gel particle, but in most of the papers is described as a structure with a high specific surface (depending on the quality of the Silica Gel but on average about 800 m^2/kg). The reason it has a high specific surface is that the complete surface is covered with micropores [47]. Since it has such a high specific surface and the ability to make connections like hydrogen bonds, polar or weak electron bonds, it can adsorb a sorptive extremely well. For an example of how exactly this would look like on a micro scale, a photo and a detailed figure can be found in Figure 3.2.



(a) A cross-section of a micropore located
in a silica gel structure [47]

(b) A transmission electron micrograph
of silica gel [47]

Figure 3.2: Displays of silica gel on a micro scale level

3.4.2 Adsorption Characteristics

Silica gel has especially a high affinity to adsorb the sorptive water [73]. It can adsorb till around 40% of its body weight in water depending on its quality. The reason it can adsorb such amount of water is due to the fact water is bipolar. Therefore multilayers of water molecules can be formed on the surface of silica gel structure [80]. The water can exist in the silica gel in three different states. As free water exists as water that is physically adhered on the surface. The second state is as capillary condensation water in the micropores of the silica gel. The third state is as chemical water. Chemical water exists as a silanol group in silica gel. The molecular structure is irregular since the silicon atoms are not distributed homogenous [76].

Often the Langmuir Model, Henry's law, Freundlich or Dubinin-Astakhov equation are used to explain the adsorption-desorption characteristics of silica gel. All these different models have in common is that they are isothermal explanations of adsorption. In total 15 different adsorption models exist today [21]. One of the most famous ones is Henry's law (technically it is a chemistry law, but can be used to calculate adsorption). Henry's law states that the quantity of dissolved gas is proportional to its partial pressure. His variant is the simplest adsorption isotherm model to explain adsorption. It is a linear model in which the surface coverage of the adsorbent is calculated by multiplying the partial pressure with "Henry's adsorption constant" [18]. The value of this constant depends on the temperature and the sorbent. The simples nonlinear model without empirical constants is the Langmuir model. It assumes a monolayer vapour uptake at a homogeneous surface. This monolayer contains a uniform charged energy. At every vacant pore site, one single sorption event takes place. It is filled with one single molecule [35]. In reality, a homogeneous surface doesn't exist, and it also is known that during the adsorption of water vapour a multilayer of water molecules is created instead of a monolayer. The Freundlich adsorption isotherm is developed for multisite adsorption on rough surfaces [30], and therefore a more usable isotherm equation to predict the adsorption capacity of silica gel. However, at low pressure, from zero till 7000 Pascal, Henry's adsorption constant is sufficiënt according to one study [45]. In Figure 3.4 this linear relationship can be observed.

However, what are the parameters that influence the adsorption capabilities of silica gel? Those parameters are the relative pressure, the total pressure, the temperature, the specific area of the silica gel and the pore width. The higher the relative pressure of the water vapour, the higher the capacity of the adsorbent. When the silica gel has a higher temperature, this relationship shifts, and a higher relative pressure is necessary for the adsorbent to keep the uptake of water vapour constant. Since with AD the silica gel is in a closed environment and therefore the relative pressure inside the vacuum tank

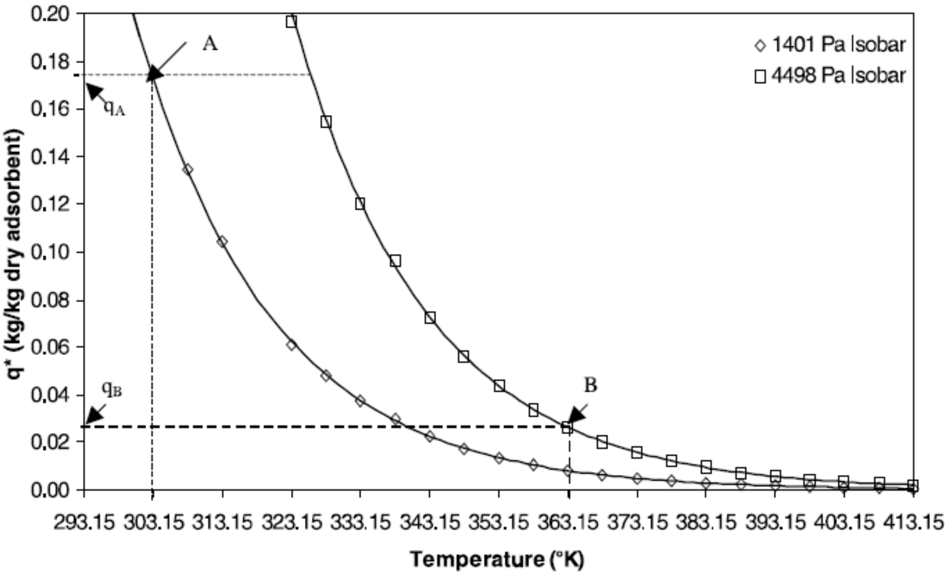


Figure 3.3: Display of desorption of water vapour by silica gel at different temperatures and pressures [45]

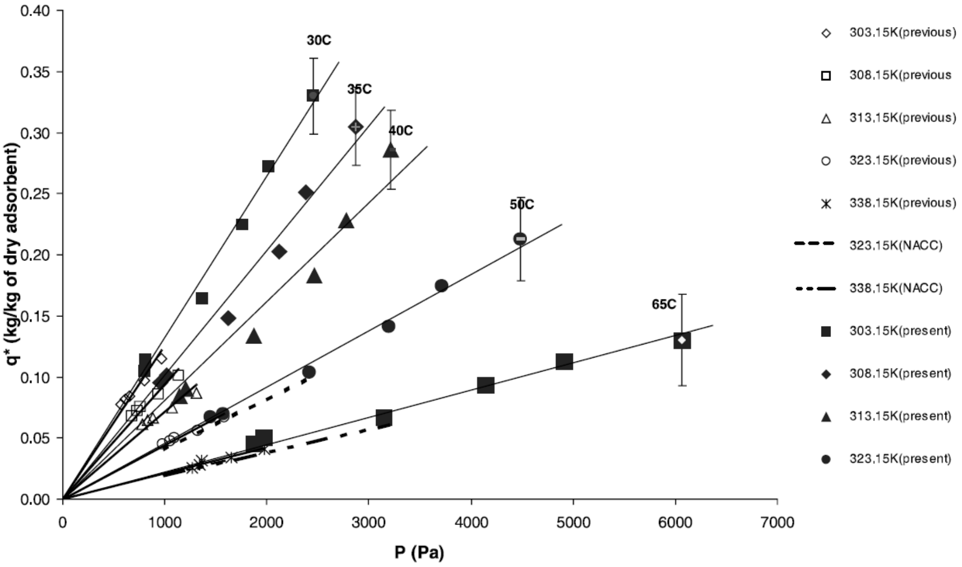


Figure 3.4: Display of water vapour uptake at different total pressures and temperatures [45]

doesn't change significantly when all valves are closed, the silica gel starts to desorb the water vapour. If the total pressure inside the vacuum tank is lower, the desorption process goes faster [45]. An example of this can be found in Figure 3.4. The dependency of the adsorption capacity on the temperature of the silica gel and the partial pressure of the vapour can be calculated with Equation 3.1. This formula is the result of Langmuir's model in combination with the ideal gas law and Henry's law. The corresponding correlations coefficient, the adsorption energy (Qst) and pressure constant (K_0^I) depend on the type silica and as can be seen in Table 3.1. Even the batch it was produced in can influence the quality. The quality is probably never constant. Even the same producer cannot guarantee a perfect constant quality. What does become clear is that the influence of the partial pressure is linear while the influence of the temperature is exponential.

$$q = P_v\ K_0^I\ exp[Q_{st}/(R_v\ T_{si})] \qquad \text{if} \quad q \leq 0.4 \tag{3.1}$$

Table 3.1: Correlation coefficients [45]

Silica Type	K_0^I (Pa^{-1})	Qst (kJ/kg)
Type 3A	5.2E-12	2.38E3
Type RD (batch 1992)	2E-12	2.51E3
Type RD (batch 2001)	5.5E12	2.37E3

Other parameters that influence the adsorption capacity are the pore radius and pore volume. These parameters are however mostly constant during the operation and do not depend on the temperature or partial pressure. The reasons why the values of these parameters can change are discussed in subsection 3.4.4 . The pore radius influences the pore volume. The pore volume influence again the micropore area which is an addition to the surface area, therefore creating a higher specific surface area. In one study [73], three different silica gels have been examined and compared to each other, see Table 3.2. In Figure 3.5 you can observe that the type of silica gel with the highest water uptake is indeed also the silica gel with the highest specific surface. These studies [45, 73] shows other different kinds of behaviours. One is the hysteresis relationship between adsorption and desorption, which can be observed in Figure 3.5. Further, the desorption can take place for 95% within 250 s with certain types of silica gel [45]. Because the water vapour goes from a phase state to a sort of semi-solid phase, energy is released. Adsorption energy also called. No much information is available about this energy. It is unclear if this adsorption energy is constant or even if the desorption energy is equal to it. Desorption energy is the energy necessary for the water to become a vapour again and leave the semi-solid phase it is in.

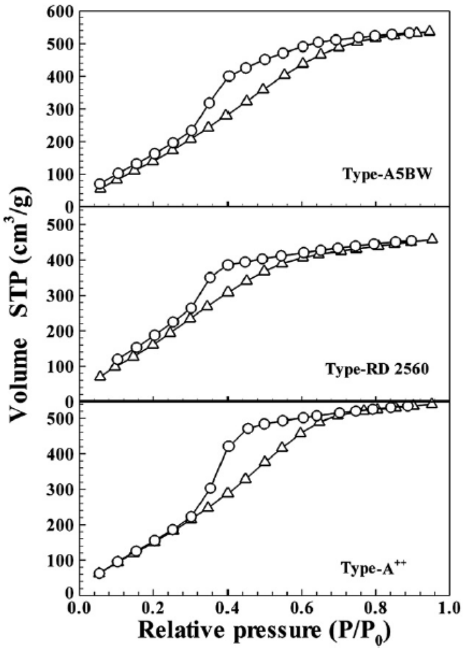


Figure 3.5: Illustration of hysteris of silica gel water vapour uptake and desorption. [triangle adsorption, circle desorption] [73]

Table 3.2: Comparison porevolume and surface area of three different types of silica gels [73]

Parameter	**Type-A5BW**	**Type-RD 2560**	**Type-A++**
Micropore volume (cm^3/g)	0.030	0.047	0.038
Micropore area (m^2/g)	75.6	108.1	93.4
External surface area (m^2/g)	693.5	528.3	770.1
Specific surface area (m^2/g)	769.1	636.4	863.6

3.4.3 Thermodynamic Characteristics

As said in subsection 3.4.2, the temperature has a great influence on the adsorption characteristics. It is therefore important for an AD-device to be able to keep the silica gel at the desired temperature. To keep it at the desired temperature, two parameters of the silica gel are dominant: the specific heat and the thermal conductivity. Other parameters are the water content and porous volume. The exact values of these parameters depend on the quality of the silica gel, but the value of these parameters are in the same order as can be seen in Table 3.3. One thing that should be noticed is that silica gel is a bad thermal conductor compared to metals. This behaviour is not a great quality when altering its temperature is important. As an example, copper is a widely used thermal conductor in heat exchangers as commercial bronze. It has a thermal conductivity constant value of 52 W/mk around room temperature [42]. That is about 260 times higher than silica gel. Therefore different studies have been carried out to improve thermal conductivity. Two other parameters that can already greatly influence and improve the thermal conductivity are the water content at the silica gel and the pressure around it. A higher water content improves the thermal conductivity [9]. Higher pressure improves the apparent conductivity since air can act as a medium for thermal energy transfer[31]. The higher the amount of air (read pressure), the higher the probability of thermal energy transfer is. Therefore is porosity also a parameter that can influence the apparent thermal conductivity. The lower the porosity, the lower the conductivity. Different studies have been done to look for a method to improve the conductity. One method is combining the silica gel with graphite. Graphite has a very high thermal conductivity. By combining these two materials and constructed them in blocks, a conductivity of 88.1 W/mK was reached. Of course has this method a negative influence on the apperent specific surface and therefore the adsorption capacity [31]. Another method was mixing the silica gel beds with an iron, copper or aluminum fillings. With this method the average conductivity could also be improved. They found out that when using aluminnum filling with a concentration of 30% the cycle time can be decreased by 50% [8]. A doubling of thermal conductivity was measured.

Table 3.3: Thermophysical properties of silica gel [45]

Parameter	**Type A**	**Type 3A**	**Type RD**
Specific surface area (m^2/g)	650	606	650
Porous volume (ml/g)	0.36	0.45	0.35
Average pore diameter (A)	22	30	21
Apperent density (kg/m^3)	730	770	800
pH	5.0	3.9	4.0
Water content ($wt.\%$)	<2.0	0.87	-
Specific heat capacity (J/kgK)	921	921	921
Thermal conductivity (W/mK)	0.174	0.174	0.198
Mesh size	10-40	60-200	10-20

3.4.4 Degradation

When trying to answer the question of what the lifespan of silica gel is, many sources can be found that say that silica gel has an infinite lifespan since it can adsorb water vapour and desorb it again. It is a physical process and not a chemical one[26, 78]. One would, therefore, expect that no operational problems exist for Adsorption Desalination that is caused by the silica gel. Since it is still a new technology, there is is not a lot of data available about the practicality of this technology. There is however information available about adsorption cooling, the twin brother of this technology.

Silica gel degradation is a subject that is rarely discussed by most papers who research Adsorption Desalination. Only a few do discuss it. It is true that on paper, silica gel can have an infinite lifespan since it is a physical process. The reality is unfortunately different. There are publications available that report on adsorption chillers whose capacity sharply decline after one year of usage. These devices were later shut down because it was no longer economically feasible to keep them operating [76]. The degradation of the silica gel is a challenging problem for this technology, and it influences the question largely whether Adsorption Desalination is an appropriate technique for desalination. There are five different known reasons for the degradation of the silica gel.

The first possible reason could be the thermal stress that the silica gel endures. During its technical lifespan in an AD-device, it endures a lot of thermal energy changes since it has to switch many times between adsorption and desorption. The energy exchange on the microporous surfaces can be intense, and this can change the surface. A change in the surface can negatively impact the performance of the water production[76]. This phenomenon is not only sighted with silica gel. It can also be observed with other possible sorbents like Zeolite. In one study it was concluded that after 15,000 cycles with Zeolite, a loss in initial adsorption capacity of 21% was found, while for silica gel only a loss of capacity of 5% was found [27].

A second possible reason could be that the number of silanol groups declines. As told before, different kind of mechanisms are responsible for the adsorption qualities of silica gel. Silica gel is stable in surroundings that are non-alkalescence. A change in pH could change the number of silanol groups and therefore negatively influence the adsorption performances [76]. A third possible reason could be capillary condensation of water. Condensation can occur inside of the pores. When this phenomenon occurs, the liquid water blocks these pores[23]. This blockage decreases the available specific surface, and therefore the sorption capacity is negatively influenced. This process is not only limited to silica gel, but it does also occur with Zeolite [2].

A fourth possible reason can be fragmentation. Fragmentation occurs due to high thermal stress. Silica gel receives a large amount of thermal energy due to adsorption. This energy cannot easily be relocated since silica gel is a bad thermal conductor. Therefore the temperature of the silica gel can reach high levels. A possible outcome is that the silica gel can break into smaller particles. There are even studies conducted were explosions were observed due to the high thermal stress that the silica gel endures [70]. That is, of course, an extreme case. Most times a popping sound can be heard when the thermal stress for silica gel becomes too high. By the manufacturers, this phenomenon is known. When buying silica gel, in the technical sheet information can be given about mass loss when regenerating the silica gel. The last possible reason for silica gel degradation can be pore pollutions by metal ions. These impurities can also accelerate the silanol denaturation, shrink the micropore radius or block the pores. Only one possible solution has been found till now to restore the adsorption capacity. It is possible to restore adsorption capacity by soaking the silica gel in acidic solution and washing it with distilled water [76].

3.4.5 Other Sorbent Possibilities

Instead of using silica gel as an sorbent, there are also possibilities for other sorbent materials who have as sorptive water. Another often used material is Zeolite. This material is a type of aluminium silicate crystal composed of alkali substance [7]. Zeolite can have multiple different functions. Depending on the situation what is most useful, Zeolites can be adsorbers, ion exchangers, molecular sieves or catalysts. Zeolites can adsorb several different molecules, molecules including water, nitrogen, ammonia, lead and chromium. There are about 48 types of natural Zeolites and over 150 synthesised Zeolites. The main advantage of Zeolites compared to silica gel is due to their structure. The atoms in Zeolite are perfectly well regulated[38]. Unlike with silica gel where the pore size varies within one type, with Zeolite the pore size is constant. There is only a difference in pore size between different types of Zeolite. These differences enable researchers or manufacturers to produce a Zeolite with the optimised structure for the desired function. Unlike silica gel, Zeolite does have a higher desorption temperature. The desorption temperature of Zeolite is between 250 and 300 degrees Celcius. The heat of adsorption is between 3300 and 4200 kJ/kg [51]. It also has a lower adsorption capacity compared to silica gel. The maximum adsorption found is 0.12 kg_{water}/kg_{ad} when the Zeolite was at a temperature range of 40 till 150 degrees Celcius and the pressure inside the system was between 0.87 and 7.38 kPa [82].
The thermal conductivity of Zeolite gel can between 0.75 and 3.62 $W/(mK)$ depending on the structure and direction [61].

Another possibility is using a chemical adsorption pair instead of physical ones. In this option, the water vapour undergoes a reversible chemical reaction instead of becoming physically attached to the adsorbent in a semi-solid state. A known example involving metal oxides and water is the reaction between magnesium oxide and water. Water vapour reacts with the solid magnesium oxide and becomes solid magnesium hydroxide. When the magnesium hydroxide is heated till 100 - 200 degrees Celcius, dehydration occurs and water vapour is created. The working pressure is between 30 and 203 kPa [33].

3.5 Design of an Adsorption Desalination Device

3.5.1 Problem Description

As described in section 3.1, an AD-device exist out of three main elements: The evaporator, the silica beds and the condenser. A designer can play around with these elements. A design can use one of multiple evaporator units. The same also applies to the silica bed and condenser. Over the years different designs have been proposed or patented. One of the reasons that many different design options exist today for Adsorption Desalination or adsorption refrigeration is the great variety of different configurations that exist. The second fundamental reason is the need to find a perfect optimise design with maximum water production, minimal operational and investment costs and maximum efficiency. During the design of an AD-device the following design challenges occur:

- Combating the poor heat transfer of silica gel.
- The need for a high-quality vacuum system/reactors.
- Minimalising the water vapour transport resistance.
- Maximising water evaporation.
- Thermal energy recovery
- Minimalising the total volume of the device

A high-quality vacuum device is a matter of investment and craftsmanship. Minimalising the water vapour transport resistance can be solved by creating a hydraulic system with solutions that are usually used to minimalise the pressure drop in a conventional water transport system. Increasing parameters like the diameter or decreasing the length or velocity of the medium can do the trick according to the Darcy-Weisbach equation [24]. Another option could be enforced convection since in the original designs the water vapour transport inside an AD system between the different units depends on pressure difference and to some degree also to natural convection and diffusion. Other design problems that are summed up above are discussed in the section here below.

3.5.2 Design of a Heat Exchanger - Thermal Energy Transfer

For the design of a heat exchanger, many different possibilities exist. The basic building blocks of a heat exchanger are the medium that is receiving the thermal energy and the medium that is providing it. These two mediums are separated by another medium which is in most cases a static solid medium. The two other mediums act as a fluid (gasses or liquid or both). With the dimensions and geometry, much freedom exists. Also the flow direction, discharge and velocity are parameters that have to be kept in mind while designing a heat exchanger.

In general, you can divide all heat exchanger into two categories. Co-current

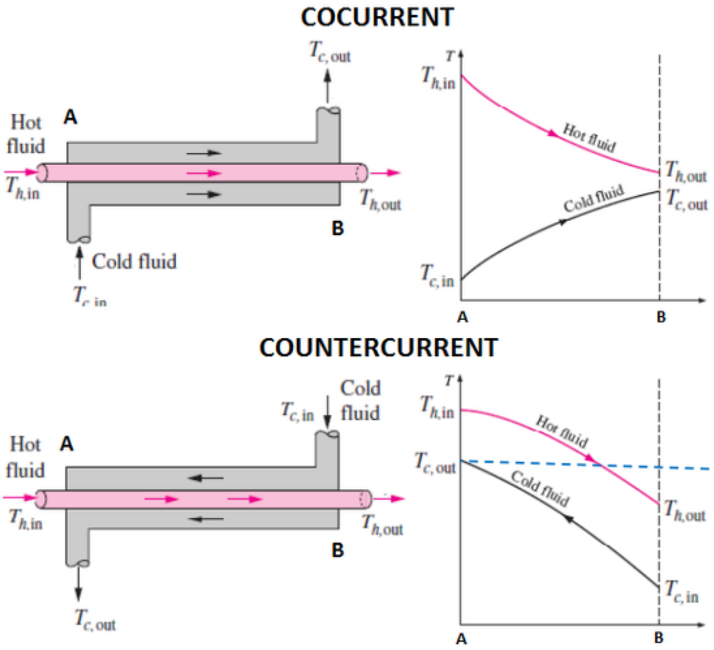


Figure 3.6: Schematic diagram of the behaviour of a co-current and counter-current heat exchanger [44]

heat exchanger and counter-current heat exchanger. Both have their advantage and disadvantages. In a countercurrent heat exchanger the two mediums that exchange thermal energy with each other flow in opposite directions as can be seen in Figure 3.6. An objective of the flow control can be to keep the temperature difference between the two mediums constant. By doing this and keeping the temperature difference as low as possible, the complete design can be extremely energy efficient. However, a greater heat transfer area is necessary to obtain an equal energy transfer assuming the residence time stays equal. In a co-current heat exchanger, it is physically impossible to keep the temperature difference equal over the length of the heat exchanger. The characteristic behaviour of this design choice is that the most energy transfer occurs mostly at the beginning of the energy exchange and exponential declines further over its length. A batch pan heat exchanger (see Figure B.1a in Appendix B), can also be distinguished as an co-current heat exchanger. The significant difference is that it is not a steady state system and that the energy transfer declines significantly over time instead of over length.

3.5.3 Design of the Silica bed - Mass Transfer

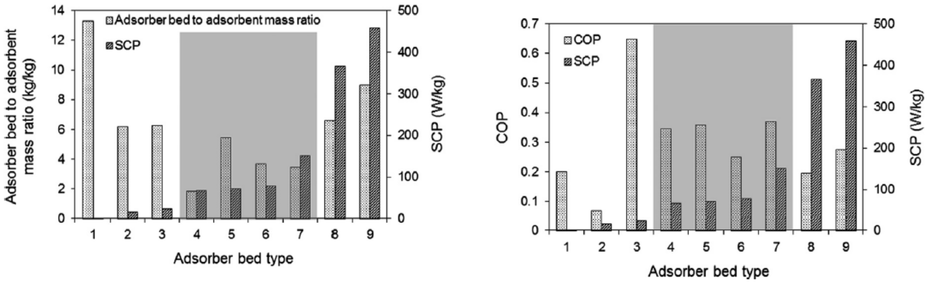
The design objectives while designing a heat exchanger for the silica gel are challenging. You have to design an excellent heat exchanger because it is critical to keep the silica gel at the desired temperature. Another critical aspect is the ability to transport thermal energy as fast as possible. This ability is vital since the faster the thermal energy transport occurs, the smaller the cycle time of a device is and therefore the higher the water production of the design is. This objective is challenging because, as told before, the thermal conductivity of the silica gel is extremely poor. Other requirements to keep in mind while designing the heat exchanger are the optional possibility of energy recovery and minimalising the water transport resistance. Since you are not heating or cooling down a solid block of silica gel, but a granular bed, other design problems occurs. What is the desired porosity to operate on is one of these questions that needs to be answered. A higher porosity ensures less water vapour transport resistance, but it does decrease the apparent thermal conductivity of the silica bed. What is the length and therefore the maximum distance of one part of silica gel to the evaporator? What is the maximum distance a water molecule has to travel? These are all questions an engineer needs to answer when designing the silica bed.

One study from 2011 [65], goes with a numerical model in great depth to examine the relationship between many of these different parameters. The researchers made a model in which the temperature of the silica gel is controlled by placing the silica gel inside a tube. In the centre of the silica gel, a mass transfer tube is placed. The thermal energy transfer takes place from the outside to the inside in the case of heating up, see Figure A.1. It is an Annulus tube heat exchanger. As expected, the greater the thickness, the longer it takes to heat it or cool down the bed. However, it is striking that a thickness of 52 mm would already be problematic. Even after 30000 seconds, there still would be a temperature difference of 20 kelvin between the inside and the outside of the bed. A bed with a thickness of 13.5 mm would be a more probably realistic thickness since after 2000 seconds only a temperature difference of 10 kelvin exists, see Figure A.2. Since the desorption of the water vapour can take place in 2.5 min, see subsection 3.4.2, the duration of heating the silica gel or cooling it down with 60 kelvin would be preferable. The faster the cycle time of an AD-reactor, the higher the water production. Furthermore according to Figure A.3, the porosity (between 0.826 and 0.478) doesn't seem to have a great influence on the duration of temperature change. The particle size, however, does as can be seen in Figure A.4. Also, the amount of water the bed can adsorb on average has significant influence as can be seen Figure A.5. According to the simulation, the greater the particle size of the silica gel, the faster the energy transfer occurs, and the higher the water vapour uptake is.

As said before, besides changing parameters like porosity, length or radius, the geometric can also have a significant influence on the performance. Many different shapes of heat exchanger exist. In one study [63], many of these different types have been put to the test. The following heat exchangers have been tested:

- Spiral plate
- Shell and tube
- Hairpin
- Annulus tube
- Plate fin
- Finned tube
- Plate-tube
- Simple tube
- Plate

See Figure A.6 in Appendix A for an overview of these different designs. In this study, they tested the different design on three different elements: the COP, the SCP and the mass ratio between the mass of the adsorber bed and the adsorbent. The lower this ratio between the masses, the higher the vapour uptake by the adsorber bed. A higher uptake means a compacter and more efficient design. The COP, the coefficient of performance is the ratio between the thermal energy removed divided by the work. In other words, the amount of water that evaporates divided by the mechanical/electrical energy that is added to the system. The higher this value, the better the design is. The last parameter, the SCP, stands for the amount of energy that is used divided by the mass of the adsorber bed. The lower this value is, the more efficient the thermal energy transfer in the adsorber bed. So to sum up: a lower value for our SCP and mass ratio and a higher value for the COP is desirable. The best design of a heat exchanger for the silica gel for an Adsorption Refrigeration is probably also the best design for Adsorption Desalination. If we look at the results of this study, see Figure 3.7, we can see that design 4 to 7 are the best candidates according to our requirements. According to the study, number six, the finned tube adsorber bed is the best selection for practical reasons. It is effortless to increase the thermal conductivity of the design and heat and mass transfer inside the adsorber bed by optimisation of the fin spacing and fin height in the finned tube heat exchanger [63]. Other studies have concluded the same. According to one study, the finned tube heat exchanger offers the most substantial reduction in weight, cost, volume and it substantially improves the best thermal conductivity [74].



(a) Adsorber bed to adsorbent mass ratio and SCP

(b) Adsorber bed to COP and SCP

Figure 3.7: The results of the difference in performance by one study. (1) Spiral plate, (2) Shell and tube, (3) Hairpin, (4) Annulus tube, (5) Plate fin, (6) Finned tube, (7) Plate-tube, (8) Simple tube, (9) Plate. [63]

3.5.4 Design of the Evaporator

A second significant important element of an AD-reactor, as indicated before, is the evaporator. The evaporator is the location where the separation of the product and the concentrate out of the feed takes place. Therefore a couple of elements are vital for the design of an evaporator. Elements like the heat transfer area or the minimum temperature difference, as discussed in subsection 3.5.2. Another important element is the minimum residence time. Depending on the content of the feed, this can be an important factor. An important benefit of minimalising the residence time is that pollutants in your feed are less able to create fouling, scaling or erosion in your system. In

Appendix B a summary of the different design possibilities for an evaporator are discussed. The following design choices are present in this summary:

- Co-current versus counter-current heat exchanger
- Phase separator combined with the heat exchanger versus both elements separate from each other
- Forced circulation versus natural circulation
- Thermal energy transfer area: tubular or plate.

There is no standard design choice for the evaporator of an AD-reactor or an Adsorption Cooling device. Based on schematic diagrams of an AD set-up from different papers [46, 73, 76]), most designs use the Batch Pan design, sometimes in combination with installed sprayers. Sprayers can be installed to increase the surface area of the feed and therefore increase the evaporation capacity of the evaporator. This enlargement of the surface area is due to the fact that the droplets are in contact with the air. A spray system can also enable the possibility of using flash evaporation. Flash-evaporation is an evaporation technique whereby pressurised heated water undergoes a sudden reduction in pressure until such a point that the saturation temperature is lower or equal to the temperature of the heated water. When this situation occurs, the water starts to evaporate [75].

3.5.5 Design of the Condenser

Just as an evaporator, a condenser is nothing more than a heat exchanger. Only the primary function is not to transform a liquid into a gas, but to transform a vapour into a liquid. The objective is reversed. Conventional designs for condensers can be a typical shell and tube cooled condenser. This design is a design in which tubes are placed inside the vessel. The vapour enters the vessel and comes in contact with the tubes. The tubes have a lower temperature than the saturation temperature; therefore condensation takes place [20]. Another possible design choices can be tube sheet or baffles [5]. A standard choice of type is unclear. In many patents, it is not clear what kind is used, and the same can be said for the schematic diagrams of the papers.

3.5.6 Alternative Design for Heat Transfer

Besides the more traditional design for an AD-vessel, there are also more unusual designs to improve the mass recovery and heat transfer. One method suggests using the water vapour that enters or leave the sorbent bed as the cooling or heating medium. This method implies that no heat exchangers have to be placed inside the silica bed to heat or cool the silica gel. Instead, during an adsorption phase, cold air with the water vapour from the evaporator is pumped into the bed.

This action has two functionalities: first to deliver the water vapour quicker to the sorbent and therefore to decrease the adsorption time that is necessary to achieve the desired bed saturation. The second functionality is cooling the bed down. This action removes the heat that is created during the adsorption of water on silica gel. The different design improves the COP slightly, but it does cut the power density necessary to heat or cool the bed in half. [12]. Another study from the same author concludes that lengthening the adsorbent bed even improves the performance [13]. One would not expect this since with the standard design a longer bed meant more resistance and therefore a decrease in mass recovery.

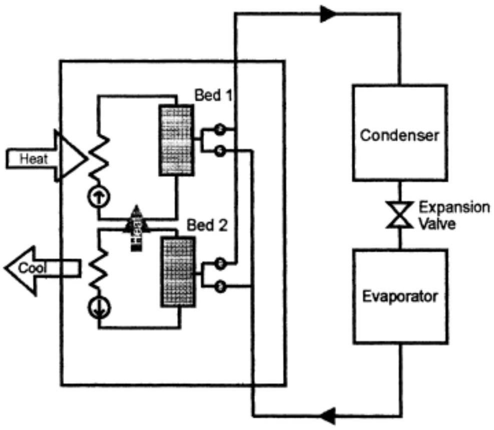


Figure 3.8: A schematic diagram of an AD set-up using forced convection to improve mass recovery and heat transfer [13]

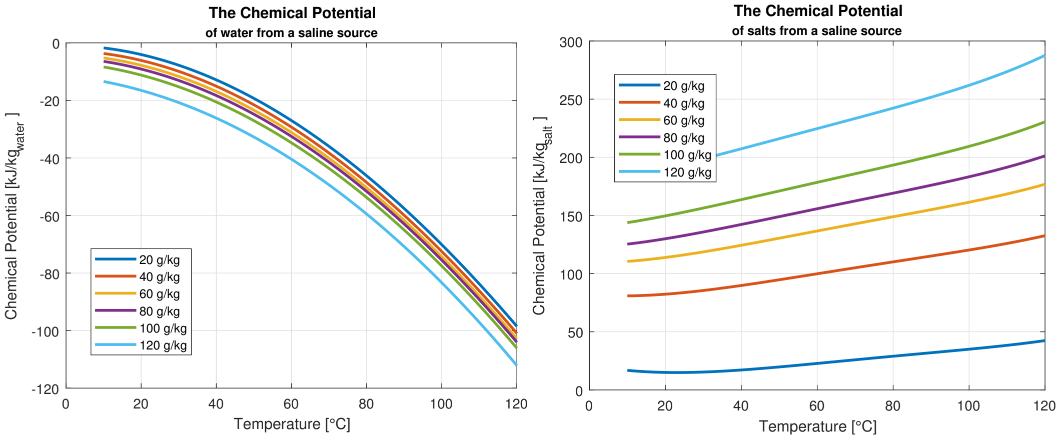
3.6 The Thermodynamics of Desalination

An astounding low energy consumption for desalination is reported for Adsorption Desalination. A value of 1.38 kWh/m^3 is calculated to be the specific energy consumption of this technology. The value of this estimate is based on the three pumps and the pneumatically-operated valves it is using [47]. They deem the thermal energy as free and therefore it is not included in this number. Reverse Omosis has currently an energy consumption between 2.5-3.5 kWh/m^3 [3] and is expected to have an even lower consumption in the future [10]. However, to which extent is it possible to further mimilise the energy consumption for desalination? What is the glass ceiling for desalination?

When discussing the possible limitation of further reduction of energy consumption of desalination, the thermodynamic limit is named. However, there seems not to be a consensus on what the thermodynamic limit is since different values for seawater (35 g/kg) desalination exist. Some papers estimated it to be $0.70 kWh/m^3$ [66], while others estimated the value at $0.72 kWh/m^3$ (2.59 kJ/kg) [36] and the researcher of Adsorption Desalination from NUS estimated it at $0.78 kWh/m^3$ [47]. According to them, the definition of the thermodynamic limit of desalination is as follow:

The thermodynamic limit is the minimum unit cost at a given solution concentration that is needed to produce potable water irrespective of the physical methods employed [71].

In this case, the definition of the thermodynamic limit is based on an optimum between costs and energy consumption. In other cases, only the energy necessary to remove the salts is used as the definition. The chemical potential is used to establish the thermodynamic limit. The chemical potential is a thermodynamic function expression of thermodynamic concentration. It related to the change in energy of a component when it is added to a mixture [36]. It explains how much energy is necessary to remove water from a saline concentration, as can be seen in Figure 3.9a. The Chemical Potential of water in a saline source depends on the concentration and the temperature. The higher the salt concentration and the temperature, the large the value of the potential is. As can be seen in Figure 3.9, this behaviour does not only applies for water, but also for salts. The chemical potential can be calculated by differentiating Gibbs free energy while keeping the temperature and pressure constant, see Equation 3.2.



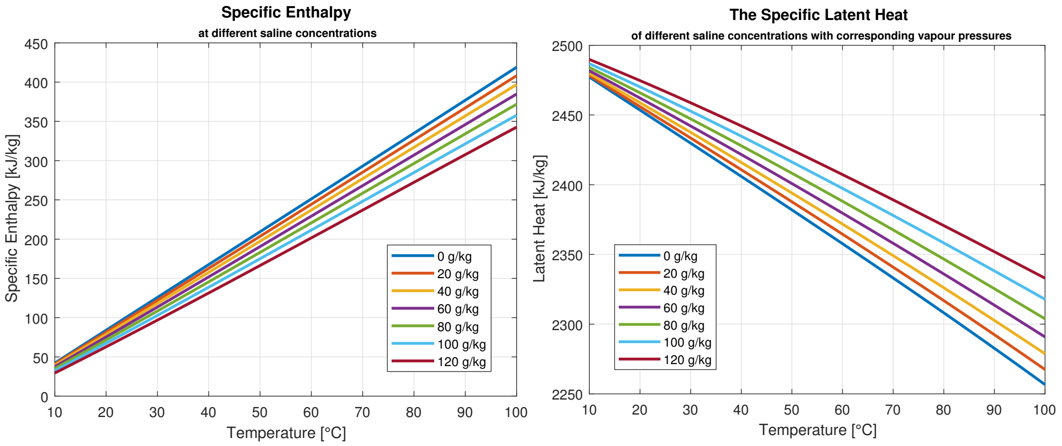
(a) The chemical potential of water in a saline source

(b) The chemical potential of salt in a saline source

Figure 3.9: The chemical potentials

$$\mu_i = (\frac{\partial G}{\partial N_i})_{T,p} \tag{3.2}$$

Unfortunately, it is problematic to use the chemical potential to establish the minimal possible energy consumption of desalination. The reason is that this technique doesn't make a separation between different methods of desalination. The chemical energy necessary to separate salts from water is for every technique the same. Furthermore, the chemical potential only depends on the temperature and concentration, while other parameters also influence the minimal energy consumption, parameters like recovery, feed concentration or when using thermal desalination parameters like latent heat. It is true that at higher temperatures the chemical energy for separation is higher. However, less energy is necessary to vaporise saline water at high temperatures, see Figure 3.10b. Therefore, an exergy and entropy analysis can be a better tool to estimate the minimal energy consumption of a desalination method. An entropy creation analysis can also estimate the efficiency of a process and highlight which processes inside a method are most inefficient.



(a) The enthalpy of different salt concentrations

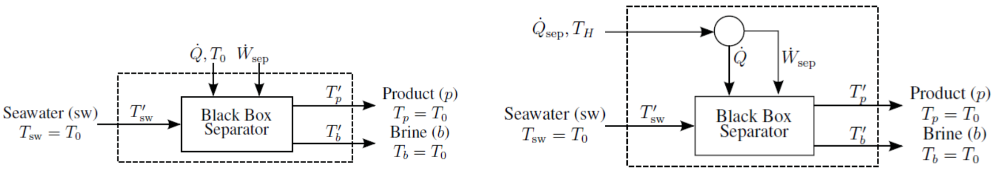
(b) The latent heat of different salt concentrations

Figure 3.10: The enthalpy and latent heat

Exergy analysis is especially a powerful diagnostic tool for performance evaluation when using thermal desalination methods [64]. To quote 'Exergy is the maximum amount of work obtainable when a system is brought into equilibrium from its initial state to the environmental (dead) state' [64]. The dead state is the conditions of the surrounding environment. These equilibria can be achieved when the concentration, temperature and pressure of the system are equal to the surrounding environment. Exergy consists therefore out of a chemical part (the concentration) and a thermomechanical part (the pressure and temperature) [36]. For an open system, the exergy can be calculated according to Equation 3.3 where properties with superscript * are determined at the temperature and pressure of the environment (T_0, p_0). Harvesting the exergy could decrease the total energy consumption of a desalination method while destroying exergy leads to entropy creation and results in a less efficient process.

$$e_f = (h - h^*) - T_0(s - s^*) + \sum_{i=1}^{n} w_i(\mu_i^* - \mu_{i,0})/M_i \tag{3.3}$$

Desalination methods could be simulated by using a simple black-box separator model where the volume is controlled [43], see Figure 3.11a. work necessary for the separation of the salts and water enters the system while also heat transfer into the system is denoted. Since the purpose of a desalination plant is to desalinate and provide a clean product and not cold or hot water, it is desired that the brine and product have the same pressure and temperature as the feed. If hot brine and product water are produced and the exergy of these streams is not harvested, entropy is created. Therefore, the method is less efficient [36]. The work necessary for separation can be calculated by using the First and Second Laws of Thermodynamics. With the specific Gibbs free energy, it can be calculated, and the result can be seen in Equation 3.4. In a perfect system, no entropy creation (S_gen) exist, and the process is reversible. In such a case, using Equation 3.5, the least work necessary can be calculated, see *Thermodynamics, Exergy, and Energy Efficiency in Desalination Systems* [36] for the complete calculations. The result can be seen in Figure 3.12.



(a) Simple blackbox seperator model

(b) Blackbox seperator model with a thermal source

Figure 3.11: Blackbox desalination seperator models [43]

$$\dot{W}_{sep} = \dot{m}_p g_p + \dot{m}_b g_b - \dot{m}_f g_f + T_0 \dot{S}_{gen} \tag{3.4}$$

$$\dot{W}_{least} = \dot{G}_p + \dot{G}_b - \dot{G}_f \tag{3.5}$$

As can be seen in Figure 3.12, the minimal work that is necessary for separation depends on the recovery (and temperature). The lower the recovery, the less energy that is necessary. The reason for this is that during the separation process, the feed becomes more and more concentrated and as can be seen in Figure 3.9a, the higher the concentration, the higher the chemical potential.

Therefore, the most efficient desalination is desalination where the recovery approaches zero. For seawater with an approximate salinity of 35 g/kg, the least minimal work is 2.67 kJ/kg or 0.74 kWh/m^3. The least minimal work can be a great method to calculate the thermodynamic limit. It does still disregard the method used to desalinate. Most desalination plants use to consume 5 to 26 times more work as the theoretical minimum [3]. When the energy for separation is provided by a heat source, like with thermal desalination methods, the heat of separation ($\dot{Q}_{sep}$) becomes a more relevant parameter, see Figure 3.11b.

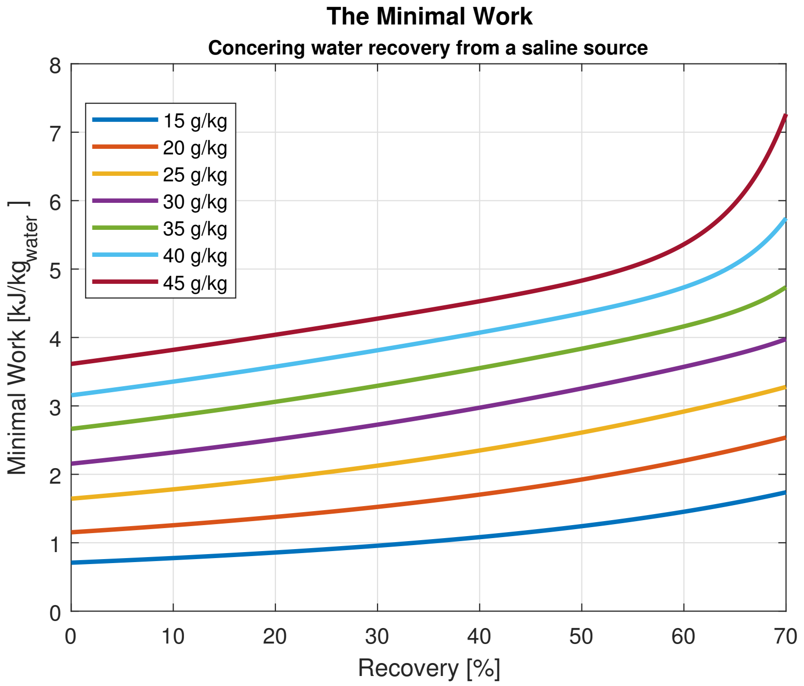


Figure 3.12: The minimal work at differnet feed concentrations at T=25 degrees Celcius

$$\frac{\dot{Q}_{sep}}{\dot{m}_p} = \frac{\dot{W}_{sep}}{(1 - \frac{T_0}{T_H}\dot{m}_p)} = \frac{\dot{W}^{rev}_{sep} + T_0\dot{S}_{gen}}{(1 - \frac{T_0}{T_H}\dot{m}_p)} \tag{3.6}$$

The energy of separation can be calculated by using Equation 3.6, again see *Thermodynamics, Exergy, and Energy Efficiency in Desalination Systems* [36] for the complete calculations. In an ideal system, the entropy generation would be zero, but in practice, it dominates over the least work or least heat [43]. Entropy generation and exergy destruction do not have to be equal to each other, but since it assumed that the product and brine leave the system at the same temperature and pressure as the feed enters the system, they are equal to each other. It can be calculated using Equation 3.7.

$$e_d = \frac{T_0\dot{S}_{gen}}{\dot{m}_p} \tag{3.7}$$

'The Second Law (or exergetic) efficiency is employed as a measure of the thermodynamic reversibility of a desalination system' [36]. This law measures in a system the irreversible losses. It should be written as the least exergy of separation divided by the exergy input. There are two different methods to calculate this efficiency. By the first method, the product and the brine are bought into a chemical equilibrium (a total dead state, TDS). The reversible work corresponds to the least work at zero recoveries. By the second method, only the product is brought in to a chemical equilibrium (restricted dead state, RDS). Equation 3.8 can be used for desalination methods using only mechanical work like Reverse Omosis and Equation 3.9 can be used for thermal desalination methods.

$$\eta_{II} = \frac{\dot{W}^{min}_{least}}{\dot{W}_{sep}} = \frac{\dot{W}^{min}_{least}}{\dot{W}^{min}_{least} + T_0 \dot{S}^{TDS}_{gen}} = \frac{\dot{W}^{min}_{least}}{\dot{W}_{least} + T_0 \dot{S}^{RDS}_{gen}} \tag{3.8}$$

$$\eta_{II} = \frac{\dot{W}^{min}_{least}}{\dot{W}_{sep}} = \frac{\dot{Q}^{min}_{least}}{\dot{Q}^{min}_{least} + (1 - \frac{T_0}{T_H}^{-1}) T_0 \dot{S}^{TDS}_{gen}} = \frac{\dot{Q}^{min}_{least}}{\dot{Q}_{least} + (1 - \frac{T_0}{T_H}^{-1}) T_0 \dot{S}^{RDS}_{gen}} \tag{3.9}$$

Besides calculating the Second Law of efficiency, there are also other Energetic Performance Parameters that can be used to express the performance of a desalination system. The ratio of the enthalpy required to evaporate or the energy released in condensation can be calculated by the Gained Output Ratio (GOR), see Equation 3.10. The GOR tells how well a system recovers its energy. The second parameter is the Performance Ratio which is defined as the ratio of product divided by the discharge of heating steam (see Equation 3.11), and the third is the Specific Electricity Consumption (SEC), see Equation 3.12

$$GOR = \frac{\dot{m}_p \, h_{fg} \, T_0}{\dot{Q}_{sep}} \tag{3.10}$$

$$PR = \frac{\dot{m}_p}{\dot{m}_s} \tag{3.11}$$

$$SEC = \frac{\dot{W}_{sep}}{\dot{m}_p} \tag{3.12}$$

All this work is however pointless if the entropy creation cannot be calculated. There are different mechanisms at work in different desalination methods that create entropy. The different mechanisms for entropy creation are as follow:

- Flashing (evaporation by vapour pressure lowering)
- Flow through an expansion device without phase change
- Pumping and compression
- Isobaric heat transfer (heat exchanger)
- Boiling or Condensing
- Thermal disequilibrium of discharge streams
- Chemical disequilibrium of the concentrate stream

For the formula's to calculate the entropy creation by these mechanisms see the same study [36] as said before or see the methodology (see section 4.4). A complete exergy analysis has not been done for Adsorption Desalination, but it has been done for Reverse Omosis, Multi-Effect Distillation, Direct Contact Membrane Distillation and Mechanical Vapour Compression.

3.7 Life Cycle Analysis

Since Adsorption Desalination is a new experimental technology and it is currently only used at one location on industrial scale [77], little information is available about the life expectancy, operational costs, investment costs and maintenance costs that are involved by a desalination plant that uses AD. A Life Cycle Analysis or Assessment (LCA), can give a great insight into possible vulnerabilities of a technology beside the obvious vulnerability any LCA displays (the economic feasibility). The author of this thesis was only able to find two papers written about a LCA. Other papers about adsorption cooling/refrigeration with a LCA can be found, but mostly in combinations with solar power as the provider of the thermal energy. Since these devices have another objective and a completely different operational scheme during the day, an LCA of these papers are therefore not extremely valuable.

The first study [72] was conducted in 2012. During this period, the only available and operational AD-device was inside the lab of the National University of Singapore (NUS) and had a specific daily water production of 12-25 m^3/d. In this study are AD-plant is modelled with a water production of 1000 m^3/d. Values about operational costs, investment cost and other costs which were collected during their experience building this laboratory set-up at NUS, were modelled to this fictional desalination plant. One of the first element this study talks about is the energy cost comparison. A table is presented, see Table 3.4, were the different energy costs are compared. The data about AD is from their research; the other data comes from the California Coastal Commission who have done a study about it [41]. The electrical rate is 0.13 [$\$/kWh$]. They argue that the thermal energy used for AD is not part of the equation since this energy is free. If this statement true is open to different interpretations. Should the costs that involved the transport and treatment of this thermal energy consumption be part of the equation probably depends on personal opinion.

Table 3.4: Energy costs of different desalination methods [25, 29, 47]

Method	Thermal Energy [kWh/m^3]	Electrical Energy [kWh/m^3]	Energy Cost [$US\$/m^3$]
MSF	12	35	1.11
MED	16.4	3.8	0.86
VC	-	11.1	1.44
RO	-	0.4-7	0.05-0.91
ED	-	1	0.13
AD	40	1.38	0.18

Later in this study, a comparison was made between the costs of this fictional 1000 $m3/d$ AD-plant and the published costs of two Reverse Omosis plants with equal production capacity. The results can be seen in Table 3.5 and 3.6. There is also a literature review that compares 42 different RO plants that desalinate seawater from 1991 to 2008 [29]. In this comparison, the average total water production costs (included capital costs) is 0.86 $\$/m^3$. A number which is in the same range as the values of the second Reverse Omosis plant that is presented by Table 3.5. However, these values are based on relatively small seawater desalination plants. It is known that for SWRO plants with a larger capacity, the costs are reduced [37]. Another cost reduction with RO can be expected in the future due to developments in the technique [10].

Three remarks can be made about Table 3.5. Remarks about the value of AD about maintenance, chemical and the other costs. As told in section 3.4, the silica gel will degrade and should be maintained or replaced. This issue is not discussed in this study. Maintenance is assumed as 4.63% of the investment costs. Where this value is based on is unknown. Also, the value of the chemical treatment costs is up for debate since the cooling and heating water that flows through the device is probably treated with anti-scaling chemicals. The last remark is about the fact that AD has no other costs is never explained in this study. The other study which has also done a LCA about AD does also not explain in details what the source is of their values. However, their final calculation is higher than that of the other study. They estimate a total water production cost of 0.57 $\$/m^3$ [56].

Table 3.5: Cost comparison: Part 1 [72]

	AD			RO 1			RO 2		
Element	Costs after 30 Year [$]	Costs [$/m3]	Ratio	Costs after 30 Year [$]	Costs [$/m3]	Ratio	Costs after 30 Year [$]	Costs [$/m3]	Ratio
Capital	2,836,050	0.26	56.67%	78,475	0.22	22.78%	1,390,650	0.13	15.89%
Electrical	1,795,800	0.16	35.89%	94,900	0.26	27.54%	2,847,000	0.26	32.54%
Labor	229,950	0.02	4.60%	547,500	0.05	5.30%	229,950	0.02	2.63%
Pre-treatment	10,950	0.00	0.22%	383,250	0.04	3.71%	38,325	0.00	0.44%
Chemical	0	0.00	0.00%	383,250	0.04	3.71%	1,095,000	0.10	12.52%
Maintenance	131,400	0.01	2.63%	667,950	0.06	6.46%	427,050	0.04	4.88%
Membrane replacement	0	0.00	0.00%	657,000	0.06	6.36%	219,000	0.02	2.50%
Other	0	0.00	0.00%	2,496,600	0.23	24.15%	2,496,600	0.23	28.54%
Total	5,004,150	0.46	100.00%	10,336,800	0.94	100.00%	8,749,050	0.80	100.00%

Table 3.6: Cost comparison: Part 2 [72]

	AD	RO 1	RO 2
Total [$\$/m^3$]	0.46	0.94	0.80
Capital [$\$/m^3$]	0.26	0.22	0.13
Operational [$\$/m^3$]	0.20	0.73	0.67

3.8 Potential of Waste Heat

3.8.1 The Global Picture of Waste Heat

Waste heat is thermal energy that is produced as a byproduct of a process due to inefficiencies. It is estimated that 72% of the global primary energy consumption is lost after conversion [22]. Of this waste heat, abound 63% has a temperature below 100 degrees Celcius [22]. As can be seen in the Figure 3.13 and 3.14, there is a difference by sector in the percentage of low, medium and high-grade waste heat (lower than 100, between 100 and 300 and higher than 300 degrees Celcius). Besides a difference worldwide in the distribution of quality (high, medium or low), there is also a big difference in the amount of waste heat each sector produces. Especially the industrial and transportation sector are large producers. However, the largest producer is the energy sector [22].

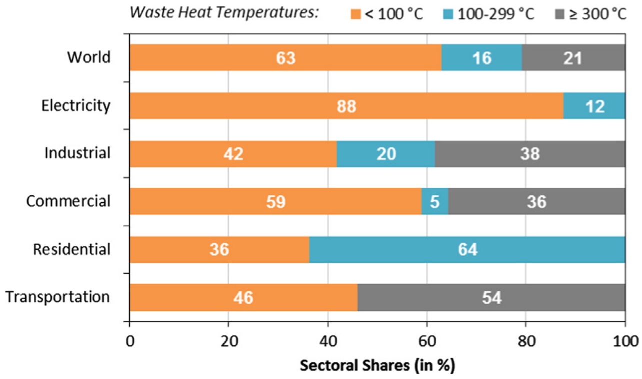


Figure 3.13: Sectoral shares of waste heat distribution [22]

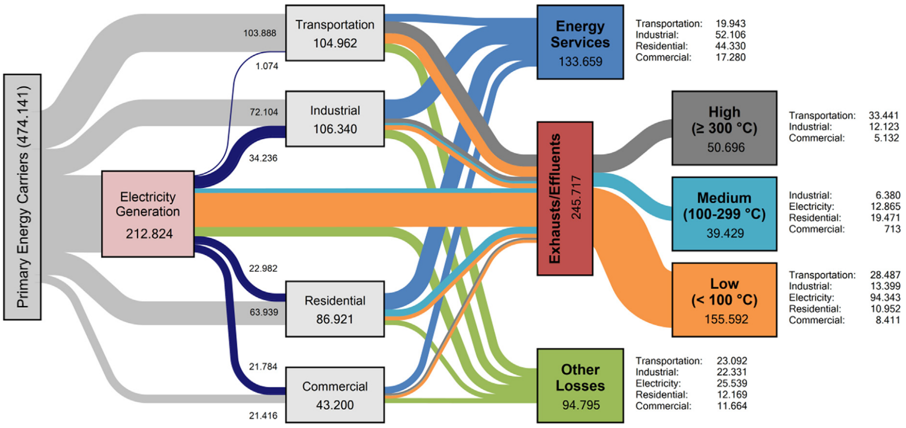
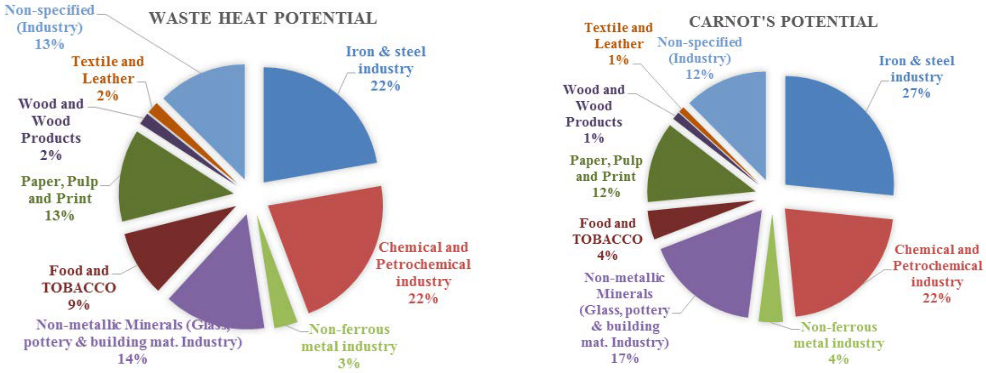


Figure 3.14: Estimated global waste heat distribution of 2012 in PJ [22]

In Europe, a similar story can be found. Europe consumes 11.6% of global energy consumption (109.6E12 kWh/y) in which European industries consume 25.9% of this amount [49]. Just like in the rest of the world, European industries do also produce waste heat. This waste heat is an untapped potential new energy source. However, the existence of waste heat does not have to mean directly that this energy can be used. It first needs to be extracted and transported. There are different barriers to overcome. One could argue that there is a theoretical/physical potential, the technical potential and the economic/feasible potential. One could even argue that there is a difference between technical theoretical potential and technical applicable potential [49].

To clarify to prevent further confusion, in this research when discussing potential waste heat, the quantity that can be extracted from a heat source is discussed. It is named residual heat from this moment. The definition of waste heat is applied to the total quantity of thermal energy that is discharged to the environment. As said before, many barriers exist. However, even with these barriers, it estimated that waste heat recovery market is projected to reach \$53.12 billion in 2018 and \$65.87 billion in 2021 [52]. In Europe, this market is at its largest share. Europe accounts for 38% of the global heat recovery market.



(a) Waste Heat Potential distribution in European Industries

(b) Carnot's Potential distribution in European Industries

Figure 3.15: A pie charts overview of the distribution of potentials [49]

There is, of course, a difference between different sectors of industries in the amount of waste heat they produce and definitely in the residual heat. In Figure 3.15a the distribution by European industries can be found in the potential reusable waste heat they produce. Some sectors even produce waste heat of such quality that it can be used to be transformed into work Carnot Theorem (Carnot Theorem explains the maximum amount of work that can be extracted from a heat source). The distribution of the Carnot potential can be observed in Figure 3.15b. Just like there is a difference in the industrial sector, there is also a difference by country in the production of residual heat. The biggest producer is Germany, followed by the Netherlands. The third place goes to France. According to the study, the Netherlands produces 43.7 TWh of residual heat each year, see Figure 3.16. To see the data in greater detail, see Appendix C.

3.8.2 The Situation in the Netherlands

The Dutch government gives on its site a similar value. The government states that in the Netherlands there are 34.7 TWh of waste heat available with a temperature of 100 degrees Celcius or higher [54]. Relative to its size, the Netherlands does use much energy compared to the rest of Europe. The Netherlands uses 3200 PJ (888.9 TWh) of energy annually. About 40% of this energy goes to applications involving thermal energy [60]. The consumption of this energy and production of waste heat does vary by province as can be seen in Figure 3.17. In the provinces Drenthe, Flevoland, Friesland, Overijssel and Utrecht almost no production of residual heat takes place. In other provinces like Groningen and Zeeland, a lot of residual heat is produced, but there is no potential demand for it, according to one study ([60]. In provinces like Gelderland, Noord-Brabant, Limburg and North and South-Holland, much residual

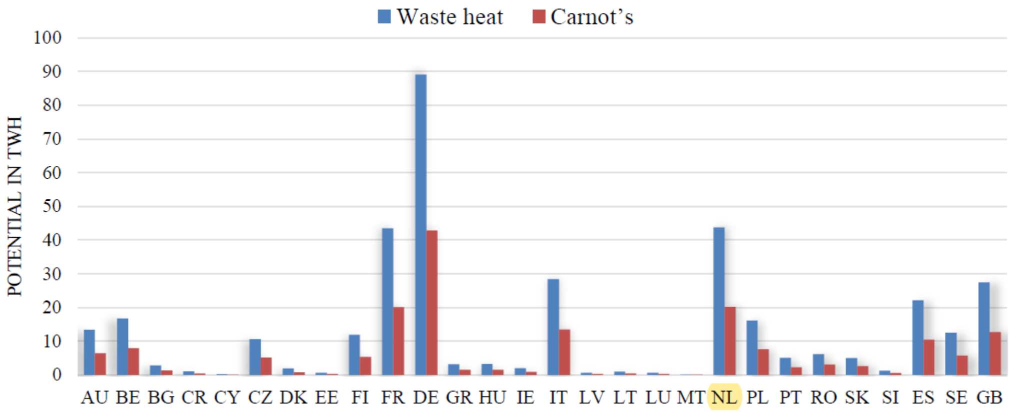
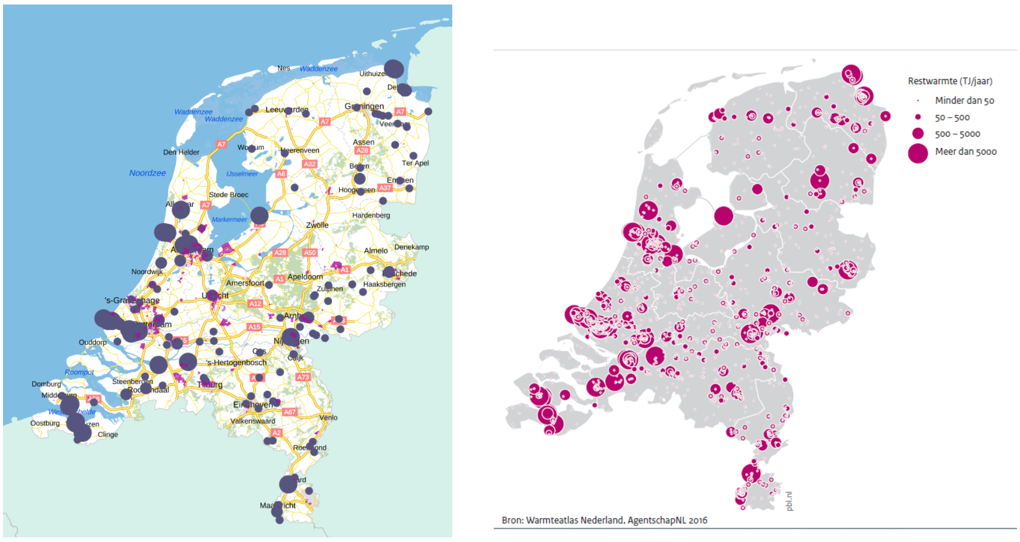


Figure 3.16: Overview of production of residual heat and Carnot's Potential in Europe [49]

heat is produced which can easily be used for other applications. As an example, the port of Rotterdam discharges each year 150 PJ of thermal energy into the harbour [48]. To clarify this number, this number is based on the total amount of thermal energy that is discharged, not the amount of energy that can be reused according to the technical and economical possibility. A practice that is wasteful and can also do harm the environment. See Figure 3.17b for an overview of all thermal energy discharges on waterbodies in the Netherlands. Dutch industries and energy plants discharge heat in the water and air about 250 PJ each year[15]. A great example of production of waste heat and potential usage can again be found in the port of Rotterdam. While the port of Rotterdam is discharging 150 PJ of thermal energy each year, 1.6 million households in the area require 73 PJ annually to warm their houses.



(a) WarmteAtlas Netherlands. Blue: Industries with waste heat. Purple: Existing Thermal Energy Networks [55]

(b) Location of thermal energy discharge to rivers or water bodies

Figure 3.17: Overview of locations of waste heat in the Netherlands [15]

However, as said before, one should make a distinction between thermal energy that is physically available and potential thermal energy that is technical and economically feasible to be reused. There is a multitude of questions that should be answered. First, how to collect the energy at the source? Various technologies can be used to recover waste heat. Technologies like recuperators, regenerators (rotating or furnace), heat wheels, passive air preheaters, regenerative and recuperative burners, heat exchangers or economisers [32]. There also new technologies that specialise on low-grade waste heat recovery like Exergyn. As said before, 63% of all waste heat is low grade (below 100 degrees Celcius), and this energy is the most difficult to recover [34]. There is now also a new technology that claims that it can transform waste heat into electricity. A technology called Thermagy [16].

The second problem to solve is how to transport it and possible store it. It can be transported by the use of liquid mediums or gases. If storages are necessary, it could be stored possibly in thermal aquifers. It is even possible to store energy till temperatures of 90 degrees Celcius, but unfortunately with the current Dutch legislation, only till 25 is allowed. Another solution is to ensure that thermal energy is constantly exchanged between different parties. A great example of this is the 'Warmterotonde' in South-Holland [60].

The third problem is the quality of the thermal energy and the uncertainty about the quantity. In the WarmteAtlas the waste heat is classified into three categories: Low, medium and high. Low, as said before, is everything below 100 degrees Celcius. It could easily mean that the multitude of waste heat in this category is hot cooling water at a temperature of 30 degrees. That is not very valuable for AD. One main reason for this uncertainty has to do with privacy. Many producers of waste heat do not like to give much information about their production processes. There is, therefore, much uncertainty about the amount of residual heat in the Netherlands. Many different parties like the government, Rijkswaterstaat, Deltares, the waterboards, CBS and PBL try to map the available amount of waste heat in the Netherlands, but none of these parties has a complete overview [60]. There are also other barriers to the use of waste heat as an energy source, barriers like high investment costs. Since thermal energy is still relatively cheap, the return period for creating such an infrastructure is substantial. Furthermore, many different shareholders need to be involved. It will be a complex social structure, the organisation that operates such a heat network. There are however already many of such networks in operation, as can be seen in Figure 3.17a. Some are used to heat greenhouses, other households. In 2016 2% of all households were connected to such a network, and the expectations are that the networks are going to be developed further [15]. In Figure 3.18 a map of the Netherlands in 2050 and the estimated development of waste heat and corresponding networks can be seen. What is interesting to see it that most development probably takes place in the coastal areas. Areas where many troubles are expected with salt intrusion and where maybe desalination can play a more significant role, see Figure 3.19.

It will, however, be difficult to say what can be expected about waste heat in the future. In one study where a couple of interviews were taken, the following was said: "Wasting waste heat is wasteful, but is there a future for waste heat? The Netherlands can assume a unique position in promoting the sustainability of energy supply in Europe. It is unknown what the future of waste heat will be; we assume it is approximately the same as today" [48].

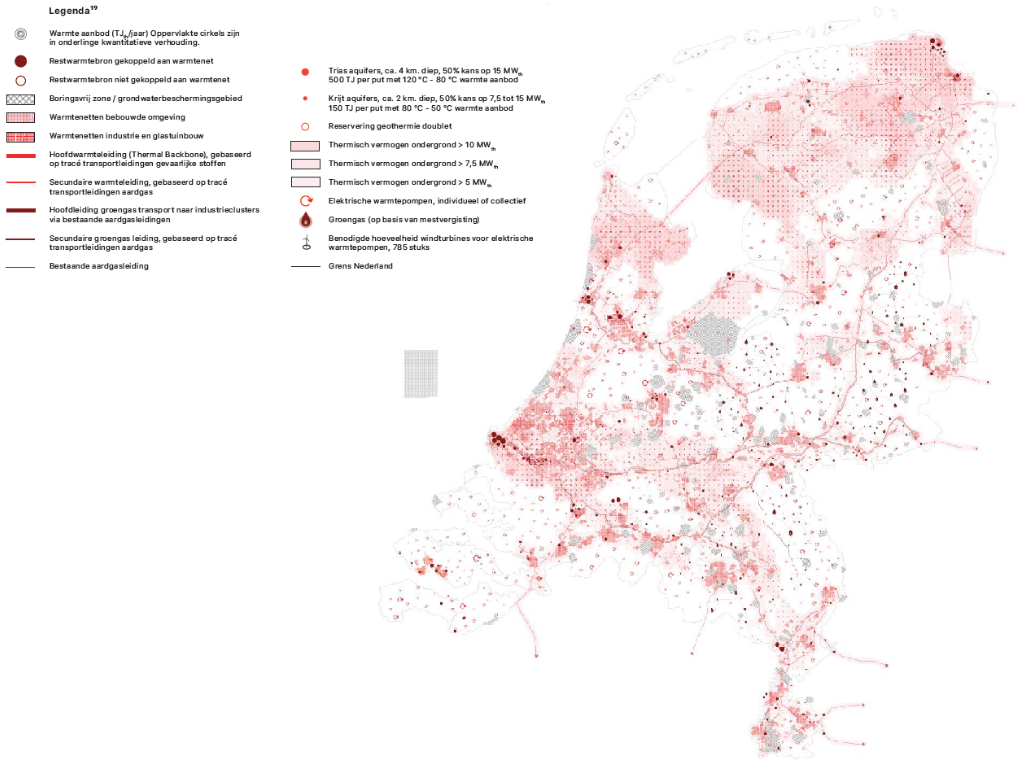


Figure 3.18: Expectations for 2050 of development of waste heat in the Netherlanderlands [15]

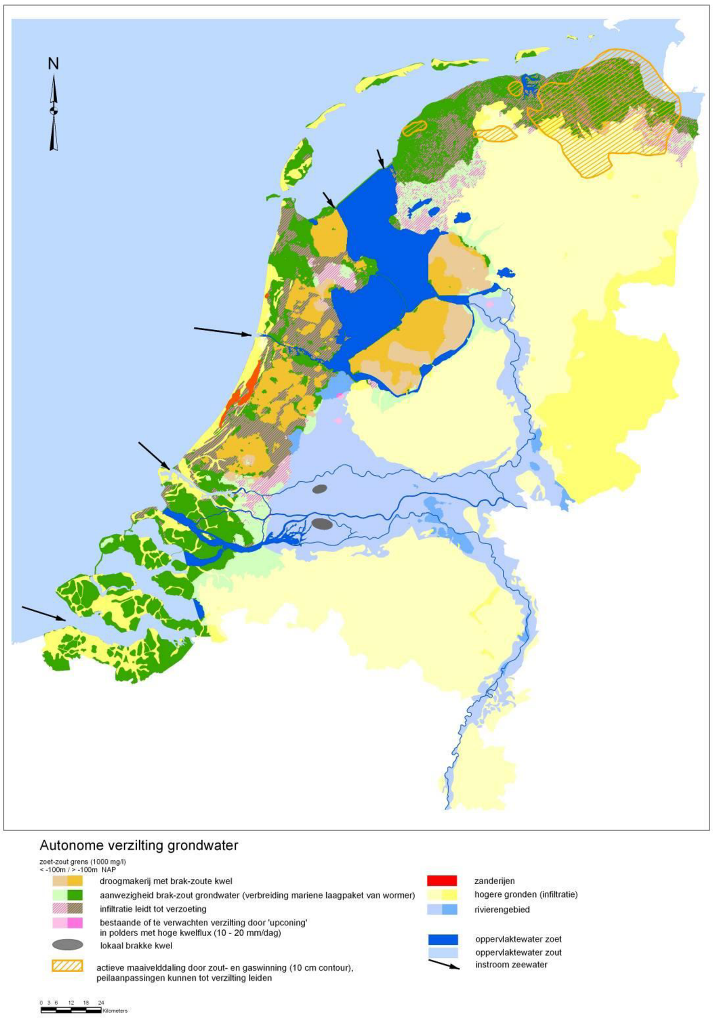


Figure 3.19: Salt intrusion in the Netherlands [68]

4 | Methodology

4.1 Desig of the Experimental Set-Up

4.1.1 Overview of Requirements

The purpose of the set-up that was built in the Waterlab of the TU Delft was to examine how well Adsorption Desalination can remove biological contaminants like acetic acids (a fatty acid) and E.coli. Acetic Acid is a simple biological molecule with a saturation pressure close to water. As is discussed in section 4.2, the idea is to do experiments at different configurations: different recoveries, concentrations and cycle times. As said, this is done to ensure an orthogonal approach and to be able to determine the risk of biological contaminants in the product when using Adsorption Desalination. To be able to create a successful laboratory set-up, the device has the fulfil different design requirements. These requirements are as follow:

Robust
Due to the fact it is built in a laboratory, and different experiments are conducted with the set-up, it is desirable that the risk of failure is minimised.

Economical Attractive
Since it is the first attempt to create a set-up based on Adsorption Desalination at the TU Delft, an economic friendly design is necessary because of a limited budget.

Ergonomical
It should be possible for a user with limited experience and no practical knowledge about the hardware, software code, mechanical or electrical parts to use the set-up.

Simplicity
Because the objective of this set-up is to create the possibility to do experiments about the water qualities with Adsorption Desalination, other functionalities are not necessary. That would make the device more complex. The more complex a device is, the higher the change on failure. Therefore it is the desire to make the set-up as simple as possible.

Accuracy
The device should be able to measure the parameters such as flow, temperature and pressure inside of the system with such accuracy that the results of the experiments are reliable.

Endurable
Because multiple experiments are done that require a certain amount of time, it is necessary that the set-up can be operational for a longer period. Sensors and other equipment should have a minimal technical life expectancy of one year for the sake of the experiments.

Modulair
A modular design is desirable since it ensures that the design in total is more robust and ergonomic. When a part breaks down, it can easily be replaced. Also, alterations can be made easier. The design can be changed on location after overall production, and it enables to option the optimise the performance. Furthermore, it can also ensure that the design is more economically attractive.

High Quality Vacuum Tighness
Since the device works at extremely low pressure, at vacuum conditions (3-6 kPa), it is necessary that the set-up can maintain these pressure for a long period. Too many fluctuations could influence the results

Safety
The set-up works with extreme pressure difference, large temperature variations, probably a variety of acid levels, biological molecules, different voltages and currents. Therefore safety should have a high priority.

Reproducible
As any good academic research should be reproducible, so should also any person have the ability to reproduce the set-up after reading this report.

This list is the summation of the different requirements that are kept in mind when designing this laboratory set-up.

4.1.2 General Overview of Elements

Description

The set-up exist out of 10 different elements/subsystems as can be seen in Figure 4.1. The device is made up of simple elements such as the frame and more complex systems such as the Electronic Control System. A scheme is given here below:

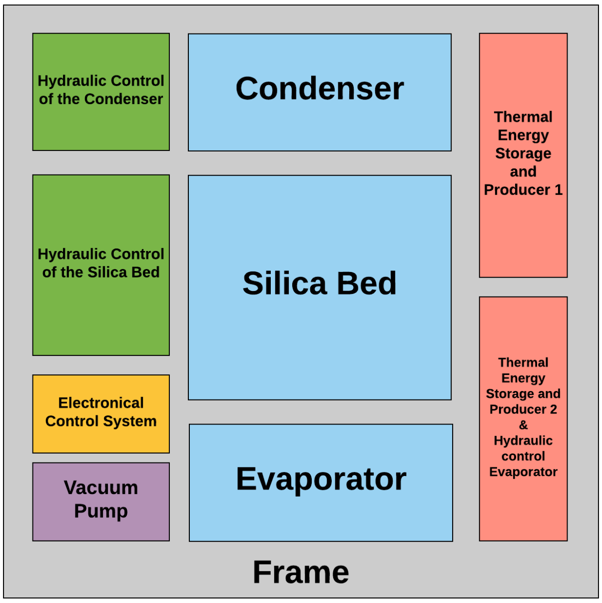


Figure 4.1: Overview of the different elements of the set-up

Evaporator

The functionality of the evaporator is to evaporate the feed around room temperature. As told before, this evaporation is done by lowering the pressure inside the vessel and adding thermal energy to the feed by utilising a heat exchanger. The shape of the evaporator is a cylinder with the following dimensions Ø160x200 mm. A detailed description of all the dimensions can be found in Appendix E. This subsystem consists of the following components

- Inlet/Outlet vacuum valves connector 4x
- Vacuum valves 3x
- Inlet/Outlet Heat exchanger connectors 2x
- Silicone Heat exchanger tube 1x
- Sensor Wire connectors 1x
- Air Temperature sensor 1x
- Water Temperature Sensor 1x
- Flowing Water Temperature sensor 2x
- Humidity sensor 1x
- Pressure sensor 1x
- Low-Pressure vessel

As can be seen in Figure 4.2b, 4 Vacuum valves connectors are placed in the top lid of the vessel (brown coloured), besides two heat exchange connectors (red coloured). The functionality of the sensor wire connector (black coloured) is to be the location where wires of the sensors can leave the vessel without the possibility that leakage can take place. Only three of the four vacuum valves are seen as a part of the evaporator. The vacuum valves that regulate the transport of vapour to the silica bed are seen as a part of the silica bed. The low-pressure vessel is a PVC tube with two fittings lids which are altered for their function. See Appendix E to examine these alterations in great detail.

(a) 3D representations of the condenser (b) 3D representations of the evaporator

Figure 4.2: 3D representation of the condenser and evaporator

Silica Bed

The functionality of the silica bed is to act as a vessel where the silica gel can adsorb and desorb water vapour consecutively. Four heat exchangers covered with silica gel are heated up or cooled down consecutively in this vessel. In Figure E.3 in Appendix E an overview of the different processes/systems that occur in the silica bed can be found. The shape of the silica bed is a cylinder with the following dimensions Ø160x600 mm. In Appendix E the dimensions of the device can be studied in greater detail. The same applies to the circuit diagrams. This element consists of the following components:

- Inlet/Outlet vacuum valves connector 2x
- Vacuum valves 2x
- Heat exchanger covered with Silica Gel 4x
- 19 mm hose connectors 8x
- Sensor Wire connectors 1x
- Air Temperature sensor 3x
- Humidity sensor 1x
- Pressure sensor 1x
- Low-pressure vessel

Two of the temperature sensors are located in one of the columns filled with silica gel. These sensors are placed to measure the temperature of the silica at the top and bottom of the column. It is assumed that all four heat exchangers act in the same manner compared to each other. Therefore no additional sensors are placed in the silica gel of the other heat exchanger. Doing that would make the device more expensive and complicated, which would contradict the requirements that were set up. The low-pressure vessel is a tube made out of PVC-C. This PVC-C is a material with a higher resistance against a high-pressure difference at high temperatures. The material of the lids is PVC again.

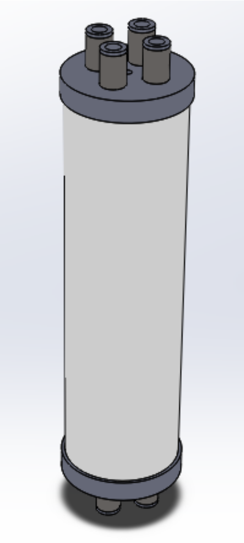


Figure 4.3: 3D view of the silica bed

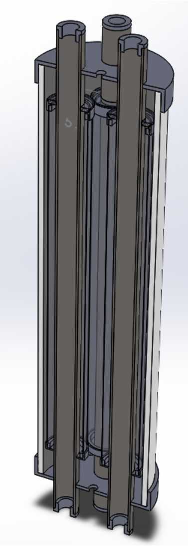


Figure 4.4: Vertical cross-section of view of the silica bed

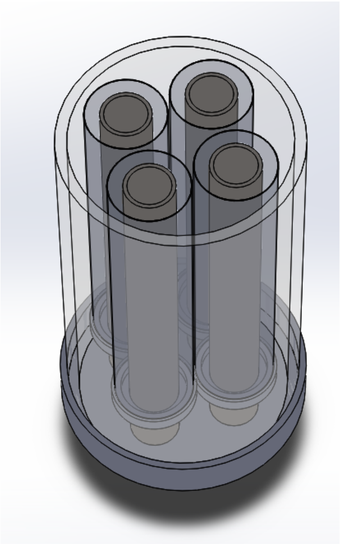


Figure 4.5: Horizontal cross-section view of the silica bed

Condenser

The functionality of the condenser is to condense the water vapour that originates from the silica bed. When cooling water is pumped through a heat exchanger, the temperature of the chamber is lowered. Energy is removed. The result is the condensation of water vapour. The shape of the condenser is a cylinder with the following dimensions Ø160x200 mm. A more detailed description of the dimensions can be found in section Appendix E. The condenser consists of the following components:

- Inlet/Outlet vacuum valves connector 3x
- Vacuum valves 2x
- Inlet/Outlet Heat exchanger connectors 2x
- Heat exchanger 1x
- Sensor Wire connectors 1x
- Temperature sensor 2x
- Humidity sensor 1x
- Pressure sensor 1x
- Low-Pressure Vessel 1x

Hydraulic Control Silica Bed

This component controls the hydraulics of the silica bed. As can be seen in Figure E.4 in Appendix E, the Hydraulic Control of the silica bed exist out of the hydraulic switches that determine if hot or cold water is flowing through the heat exchangers. The Hydraulic Control of the silica bed consists of the following components:

- Solenoid Water Valve 8x

- Flowing Water Temperature Sensor 4x
- T-tube connector "G1/2" 10x
- 19 mm hose connectors 12x

As said before, in Appendix E the dimensions of the device can be studied in greater detail. The same applies to the circuit diagrams.

Hydraulic Control Condenser

This component is in charge of controlling the hydraulics of the condenser. It opens or closes the valve that ensures if cooling water flows through the heat exchanger of the condensers. The Hydraulic Control of the Condenser consist out of the following components:

- Solenoid Water Valve 1x
- Flowing Water Temperature Sensor 2x
- T-tube connector "G1/2" 2x
- 19 mm hose connectors 4x

Thermal Energy Storage and Producer 1 and 2

Thermal Energy Storage and Producer 1 and 2 are identical. The only difference is that the hydraulics of number is a closed system. Therefore no single valve is needed. The pump of this component is the only actuator that decides if hot water is flowing through the heat exchanger of the evaporator. The functionality of these vessels is to produce and store thermal energy (hot water to be exact). The shape of these vessels are cylinders with the following dimensions Ø160x600 mm. These devices consist of the following components per device:

- Electrical heater 1x
- Water Temperature sensor 1x
- Hot water pump 1x
- Waterflowsensor 1x

Frame

The functionality of the frame is to act as a skeleton where all other components can be placed. It is constructed out of steel pipes and certain connectors. It consists of the followings parts (pipes and pipe couplings:

- Ø33.1x1400mm 4x
- Ø33.1x40mm 4x
- Ø33.1x30mm 20x
- Ø33.1mm Pedestal 6x
- Ø33.1mm T-connector with side outlet 4x
- Ø33.1mm Three way elbow 6x
- Ø33.1mm Angle piece continuous 6x

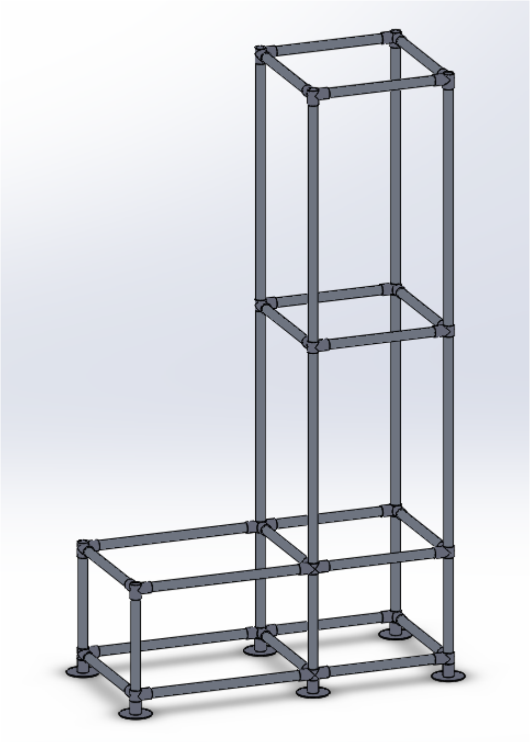


Figure 4.6: 3D model of the frame of the set-up

Vacuum Pumps

Two small industrial pumps provide the possibility to create a vacuum inside the three vessels (evaporator, silica bed and condenser). The electronic control system controls it. The pumps have separate the capacity of 1.5 m^3/h and can together lower the pressure to a vacuum of 5 kPa.

Electronical Control System

The electronic control system is the collections of the electrical circuit in combinations with some transistors, resistors and converters. Two Arduino's microcontrollers in combination with a laptop control all actuators and sensor of the device. The arduinos (one Arduino Uno and one Arduino Mega) read the voltage signals from the sensors, processed them and based on the instructions they activate different actuators to ensure a smooth operation of the AD set-up.

4.1.3 Sensors, Actuators and Electrical Circuit

Air or Water Temperature Sensor

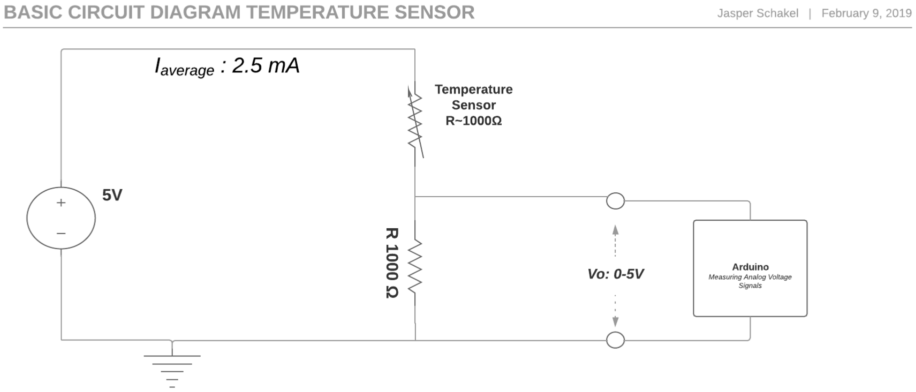


Figure 4.7: Basic circuit diagrams of a temperature sensor

The sensor to measure the temperature is a thermistor in combinations with a fixed resistor. Together they form a voltage divider. Since the resistance of the thermistor change, the Arduino can measure the temperature change, a change of voltage.

$$V_o = \frac{R_{sensor}}{R_{constant} + R_{constant}} V_{source} \tag{4.1}$$

When combining Ohm's law with an equation for a voltage divider, Equation 4.1 is obtained. A constant voltage of 5 Volt is put on the whole circuit of the temperature sensors, and with the technical table provided by the manufacturer of these thermistors, the correct temperature can be read. The thermistors are placed inside an epoxy of silicone. They are placed inside the epoxy to protect them against the environment and prevent short circuit. Silicone is chosen since it is less vulnerable for salinities than metals. It is also easier to use in construction.

Flowing Water Temperature

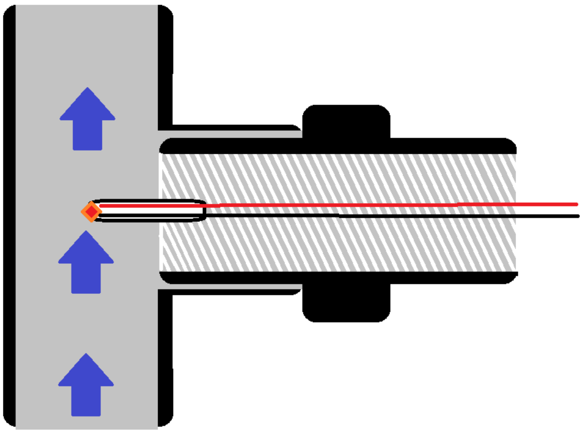


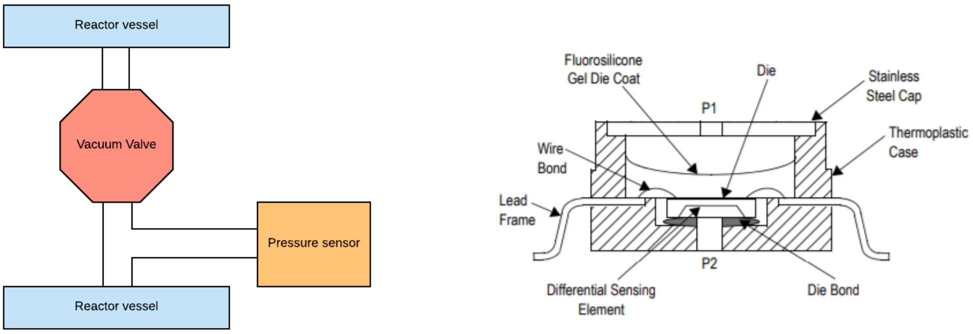
Figure 4.8: Schematic cross-section image of a Flowing Water Temperature

A flowing water temperature sensor has the same working principle as the other temperature sensors, the only difference is how it is placed inside the system. It is made with the following components:

- PP T-Piece 3/4"
- PP Nipple 3/4"
- Thermo Resistor
- Silicone epoxy
- Metal epoxy

The sensor is submerged in the metal epoxy to create a stiff and strong little stick. That stick is placed on the outside of the nipple. The remaining gap in the nipple is filled up with the silicone epoxy. This nipple can be placed in the T-piece. With this method, an easy and cheap flowing water temperature sensor is created which can easily be replaced. See Figure 4.8 to see an overview of how it exactly would look like.

Pressure Sensor



(a) A schematic overview of the location of a pressure sensor in the system

(b) A cross-section of a pressure sensor

Figure 4.9: The location and a cross-section of a pressure sensor

The pressure sensor is an analogue sensor that can measure the difference in pressure by comparing the pressure inside of the system with the atmospheric pressure. It is only able to measure the relative pressure difference, whereas it is necessary to measure the absolute pressure inside of the system. This problem is solved by measuring at the beginning of the operation the atmospheric pressure as a reference value. By doing this, the software can calculate the absolute pressure inside of the system. The sensor is located outside of a vessel, just such as the vacuum valve. It is placed between the valve and a vacuum vessel. In this configuration, it can measure the pressure inside the vessel, see Figure 4.9a. As said before the sensor is analogue and produces a voltage signal from 0 till 5 voltage which can be converted into a pressure value. The voltage signal changes due to the fact the resistance of a membrane located inside of the sensor changes, see Figure 4.9b.

Humidity Sensor

The humidity sensor is also an analogue sensor that produces a zero till 5 voltage depending on the relative humidity inside of the system. It is placed inside the vessel in the same manner as the air and water temperature sensors.

Water Flow Sensor

The water flow sensor is a hall effect sensor that can measure the water flow that flows through it. The water flows through a copper body in which a magnetised water rotor is located. When this rotor rotates, a frequency signal is produced with an amplitude of 5 volts. The Arduino measured the frequency which is translated into a discharge value. In this manner, the flow through a hydraulic system is measured.

Vacuum Pump Control

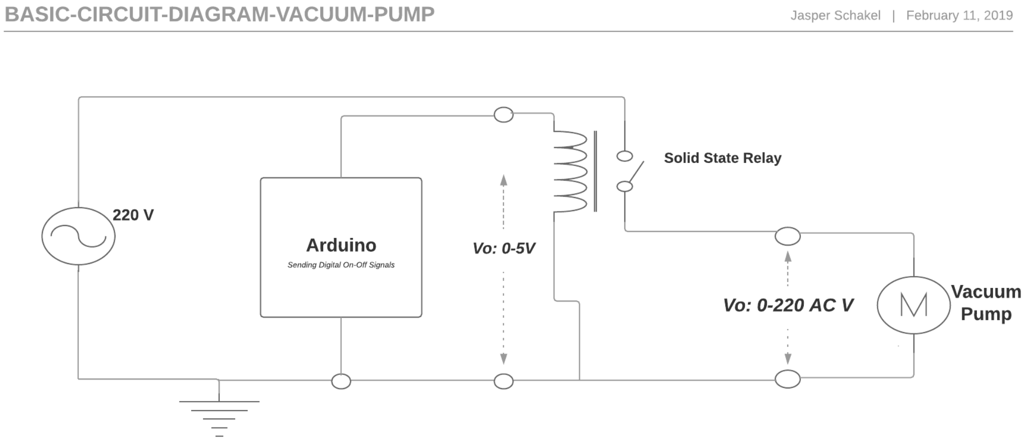


Figure 4.10: The basic electrical circuit featuring Vacuum Pump Control

Since no perfect vacuum tight device exists, a control system is necessary. This control system can influence the pressure inside a device vessel by turning the vacuum pumps on when it is necessary to lower the pressure inside a device vessel. In Figure 4.10 an overview can be observed which explains how the system can turn the pump on or off, how the pump is turned into a controlled actuator. The pumps work in 220 AC voltage. Therefore a transistor is not suitable to be placed inside the circuit. A solid state relay is a mechanical device, but an electrically controlled switch that can handle the high power that flows through the system. It can disconnect and connect the pumps with the power source.

Vacuum Valve Control, Water Valve Control and Heater Control

The vacuum valves are controlled similarly as the vacuum pump. Only a transistor instead of a solid state relay is used, and the working voltage is 24 DC instead over 220 AC. See Appendix E for the circuit diagrams. The Water Valves are controlled in the same manner as the vacuum valves; only the working voltage is 12 DC. The heater control is more similar to the vacuum pump control since they also work on 220 AC and a solid state relay is used to control them. See Appendix E for more information.

Water Pump Control

The water pumps were originally controlled in a similar matter as the water valves. The working voltage is 12 DC, and the transistors originally controlled them. A Pulse Width Modulation was used to control the voltage that was provided to the pumps. Since the pumps worked on a DC-motor, by changing the voltage, a change in discharge can be achieved. Only due to practical problems (the transistors overheating), it was changed to solid state relays, and the pump speed was fixed.

4.1.4 Software Design

The software designed for the Arduino's in the language C++. Because it is a complex digital system, the whole system has been designed using Standard Combinational Modules Approach [19]. The general idea is to break down the complete complex system into small modules with each their own self defined simple task who communicate with each other. To quote:

- "Decompose the overall functionality of the system into subfunctions that can be mapped onto standard; and"
- "Interconnect the chosen standard components as a modular network."

In Figure 4.12 an overview is given of the different modules and their interconnections and in Figure 4.13 the same can be found. The Arduino UNO and Arduino MEGA are working together in a master-slave configuration where the Arduino UNO is the master, and the Arduino MEGA is the slave. Communications between the Arduinos and the Graphical User Interface (GUI) takes place in the form of serial data. In the GUI, the user can define values such as the number of runs, desired working pressure or temperatures or the cycle time. The GUI also collects the data from all the sensors.

The software of the Arduino UNO has the following modules:

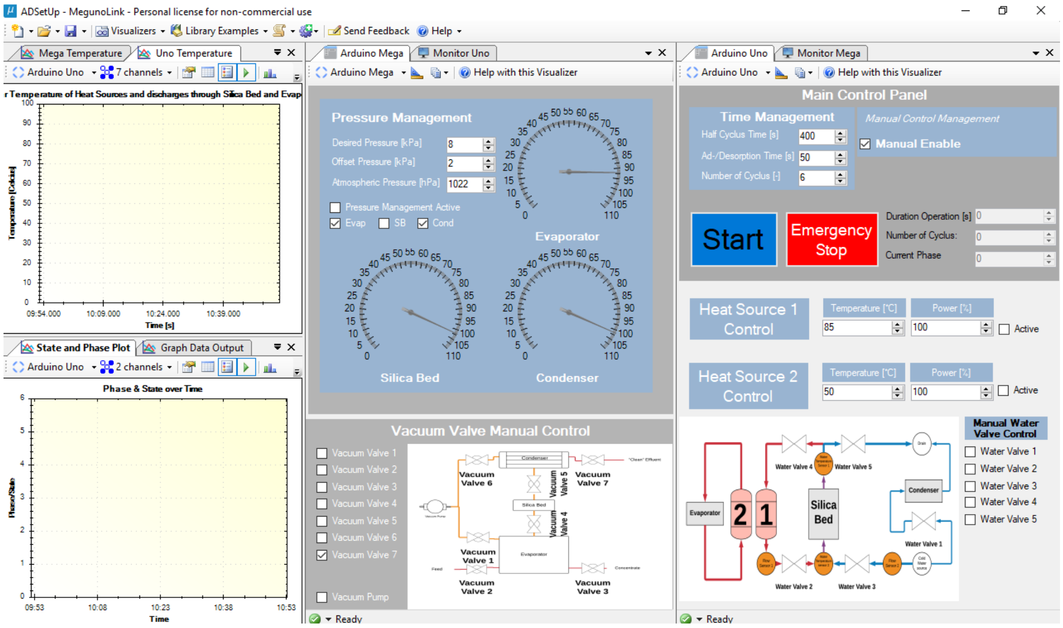
- General Control
- Processing Sensor Unit
- Hydraulic Control Condenser
- Hydraulic Control Silica Bed
- Hydraulic Control Evaporator
- Thermal Energy Control
- Clock

The General Control receives from the GUI the instructions such as cycle time, the maximum number of cycles and if the device should be active, inactive or on manual control mode. It translates these instructions into commands to the other modules on the Arduino Uno and the General Control of the Arduino Mega. The communications between Arduino UNO and MEGA is in the format of serial data, but also as a digital signal. These digital signals are called Communication Data in Figure 4.12 and 4.13. The basic functionality is that when Master Arduino tells the Slave that it wants to send a command by serial data that it should listen. The Slave Arduino sends a signal back that it is listening and that the master can proceed with sending the data. Because it also communicates with a clock, it can tell in which phase the operation is and how the other modules should behave. The hydraulic control modules decide which valves to open or which pumps to activate. The processing sensor unit is a completely independent module whose only task is to process the data from a number of sensors and send the data to the GUI or the Thermal Energy Control. The Thermal Energy Control is a semi-independent module. It only relies on the GUI for instructions. Instructions such as if the heaters should be turned on and which temperature the water in the storage tanks should have.

The structure software of the Arduino MEGA is comprehensible to the structure of the UNO. The big difference is that the General Control of the MEGA doesn't communicate with a clock, but receive the data which time related from the UNO. Another big difference is that the UNO was completely in charge of the hydraulics of the device, while the Mega is in charge of the vacuum systems. The summation of the different modules is as follow:

- General Control
- Processing Sensor Unit
- Vacuum Valve Control
- Pressure Controller Valve Control
- Pressure Control
- Vacuum Pump Control

Another big difference is that the functionality of software on the MEGA is divided into two parallel systems, except for the Processing Sensor Unit. The systems function independently from each other but do need to work together. The General Control and Vacuum Valve Control is in one of two systems. These modules operate the valves between the device vessels and the valves which are responsible for the entrance and exit of the feed, concentrate and product. The other system exists out of the modules Pressure Control, Pressure Controller Valve Control and Vacuum Pump Control. This function controls the pressure inside of the vessels. A major important aspect of this function is to assure that it does not disrupt the function of the other system so that it does not disrupt the general operation of the AD-reactor. In Figure 4.11



Desired Pressure [kPa] 8
Offset Pressure [kPa] 2
Atmospheric Pressure [hPa] 1022
☐ Pressure Management Active
☑ Evap ☐ SB ☑ Cond

☐ Vacuum Valve 1
☐ Vacuum Valve 2
☐ Vacuum Valve 3
☐ Vacuum Valve 4
☐ Vacuum Valve 5
☐ Vacuum Valve 6
☑ Vacuum Valve 7
☐ Vacuum Pump

Half Cyclus Time [s] 400
Ad-/Desorption Time [s] 50
Number of Cyclus [-] 6
☑ Manual Enable

Duration Operation [s] 0
Number of Cyclus: 0
Current Phase 0

Heat Source 1 Control: Temperature [°C] 85, Power [%] 100, ☐ Active
Heat Source 2 Control: Temperature [°C] 50, Power [%] 100, ☐ Active

☐ Water Valve 1
☐ Water Valve 2
☐ Water Valve 3
☐ Water Valve 4
☐ Water Valve 5

Figure 4.11: Display of the Graphic User Interface

a display of the Graphic User Interface can be seen. On the right the control panels of the Arduino UNO and MEGA can be found and on the left a part of the data is display in the form of graphs. The software used to make this is called MegunoLink.

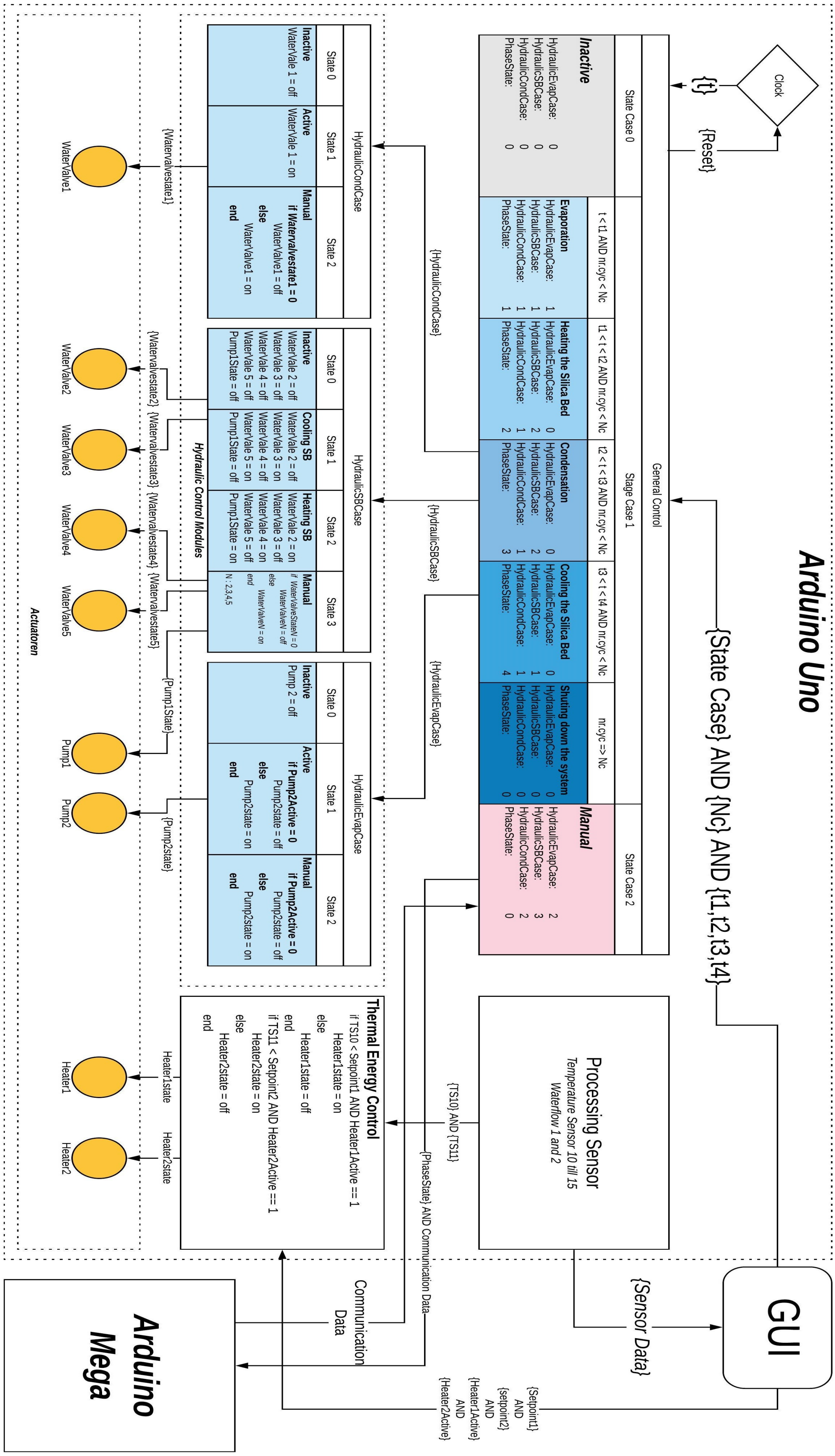


Figure 4.12: Overview of the Standard Combinational Modules of the software on the Arduino Uno

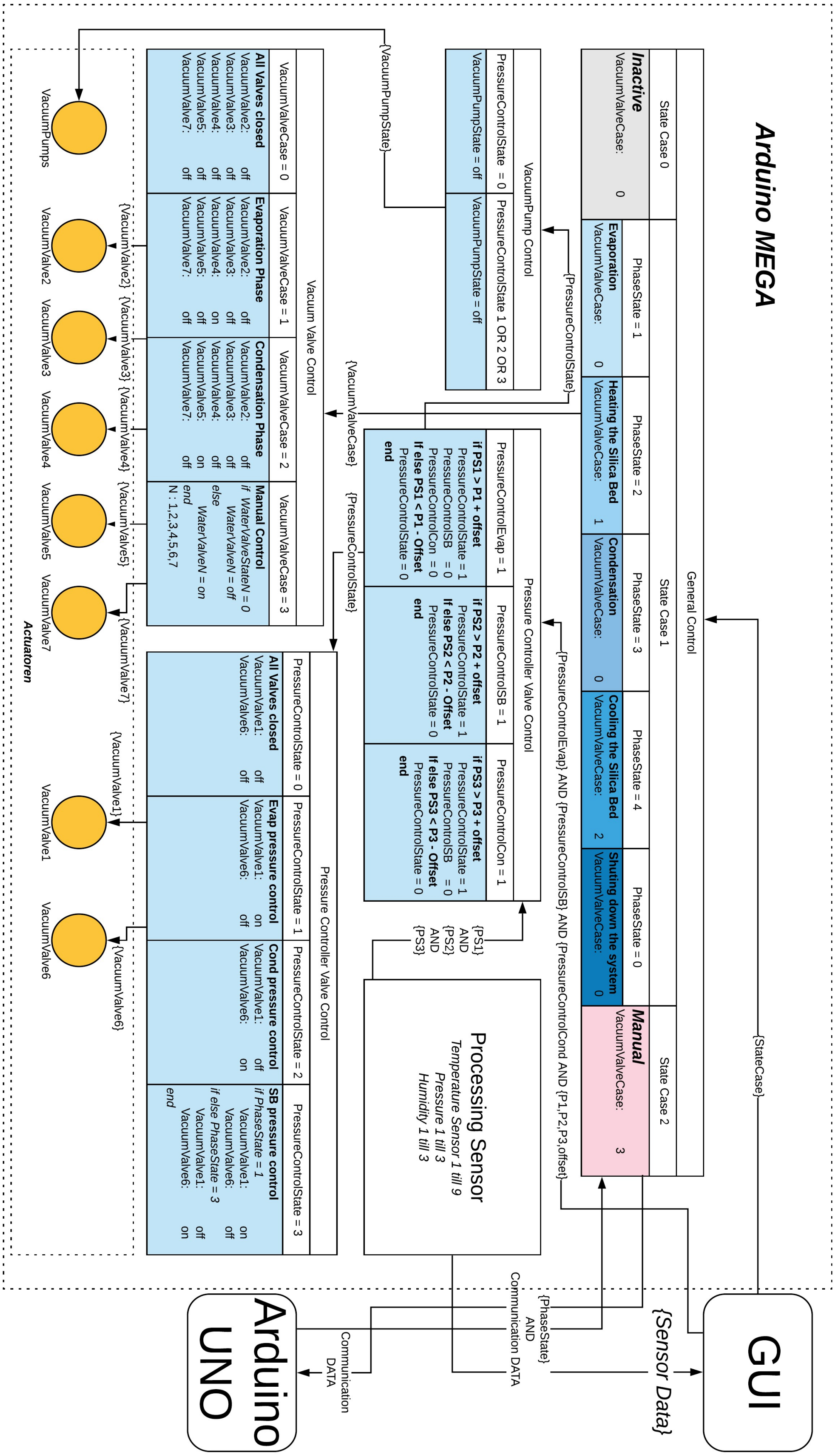


Figure 4.13: Overview of the Standard Combinational Modules of the software on the Arduino Mega

4.2 Experiments

4.2.1 Salinity - Reference Experiments

Background

Salinity refers to the presence of dissolved inorganic solutes in an aqueous solution like Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^- or SO_4^{2-}. The total soluble salt concentration can be measured with multiple different methods. One method is with electrical conductivity. Another method is by measuring the mass difference. It is done by weighing the residue before and after evaporation the evaporation event of the aqueous solution [53]. Salinity significantly influences the evaporation rate since the dissolved salts lower the free energy of the water molecules. This lowering of free energy translates into a lower saturation vapour pressure. When the salinity is increased further, the lower evaporation rate becomes compared with fresh water [58].

Objective

The objective of these experiments is that they can be used as a reference point. The primary function of Adsorption Desalination is of course desalination. An optimal configuration for the set-up can be determined by the hand of the results of these experiments and the results can be compared with literature.

Preparations of Water with Salinity

With the help of a weighing scale and measuring cup, kitchen salt (also known as NaCl) is dissolved in the water at different concentrations ranging from 20 till 80 g/L. Approximal 1.0 till 2.5 litres of an aqueous saline solution is prepared per experiment since the evaporation chamber has approximately a volume of 3.6 litres.

Testing Schedule

In total 64 experiments shall be conducted. The time it takes to experiment mainly depends on the half-cycle time of the device. The half-cyle time translates into the operational speed of the device. Half-cycle time stand for half the time that the device needs to do one run: adsorption, heating up, desorption and cooling down. The duration of the experiment depends on the water production of the device. The number of litres of product it can produce each hour. This value depends mainly on the adsorption characteristics of the silica gel and the thermal energy transfer efficiency of the heat exchangers. Of course, the initial salinity content does also influence the duration of an experiment since it influences the evaporation rate. At the end of the experiment, a three-dimensional result matrix can be constructed where the values can tell the final salinity of the concentrate and product, the duration of the experiment and the energy consumption. The number of different configuration per parameter (salt concentration, recovery rates, cycles time) is kept at four to keep the total number of experiment below the 100. The range of salt concentration is chosen based on the different concentration that can be found in different seas or brine solutions [39].

Table 4.1: Testing schedule for salinities experiments

Different salt concentrations	Different recoveries rates	Different half cycle times
20 g/L	20%	400 s (4.50 runs/hour)
40 g/L	40%	600 s (3.00 runs/hour)
60 g/L	60%	800 s (2.25 runs/hour)
80 g/L	80%	1000 s (1.80 runs/hour)

Method of Measurements

At the beginning, a linear formula of salt concentration and electrical conductivity will be established. The electrical conductivity will be measured with an EC-meter.

4.2.2 Acetic Acid - Biological Containment Experiments: Part 1

Background

Acetic acid is one of the fatty acids that can be found in wastewater or industrial water. It is an organic molecule containing a carboxylic group [40]. The vapour pressure is below, but very close to the vapour pressure of water, which means that compared with other fatty acids, Adsorption Desalination has the most trouble of removing acetic acid with the exception of Formic acid. The vapour pressure of these fatty acids can be calculated with the Antoine Equation in combination with the right Antoine Equation parameters. These can be found inside the Dortmund Data Bank [14] . Therefore, the removal of acetic acid is a beneficial indicator for the removal of other fatty acids. In the end, acetic acid can function as an indicator parameter or other biological molecules.

Objective

The objective of these experiments is that acetic acid is a great indicator for a biological molecule. Therefore it is a suitable candidate to answer the question about how well AD can remove biological contaminants.

Preparations of Water with Acetic Acid

With the help of a measuring cup and or a bucket with volume scale, pure acetic acid is dissolved at different concentrations.

Testing Schedule

In total 64 experiments will be done. The evaporation rate is influenced by the initial acid concentrations [6]. However, since the quality and not the speed of the process is the main objective, this is not a problem. No problems are expected. As one can observe, the methodology of the testing schedule of these experiments is the same as the salinity experiments.

Table 4.2: Testing schedule for acetic acid experiments

Different concentrations	Different recoveries rates	Different half cycle times
20 g/L	20%	400 s (4.50 runs/hour)
30 g/L	40%	600 s (3.00 runs/hour)
40 g/L	60%	800 s (2.25 runs/hour)
50 g/L	80%	1000 s (1.80 runs/hour)

Method of Measurements

The concentration of acetic acid in the concentrate and product will be measured using gas chromatography. With this device the number of atoms can be counted inside a fluid and therefore the final concentration can be estimated.

4.2.3 E.coli - Biological Containment Experiments: Part 2

Background

Escherichia is a coliform that can be found in all mammal faeces and does not multiply in the environment. Therefore it is a very suitable biological indicator for public health protection. It can surrogate for bacteria and virus contamination [17].

Objective

The reason why E. Coli is used for these experiments is that E. Coli is a great indicator of biological pollutants that can harm people. In contrast to an ordinary biological molecule, E.Coli is a living organism. It always has been a great candidate for indicators that can indicate the presence of bacteria or other living biological components. Therefore, it is a now also suitable candidate to answer the question about how good AD can remove biological contaminants.

Preparations of Water with E.coli

The following steps are necessary to create E.coli ATCC 25922. First 150 mL of nutrient broth with 3 mL of the previous stock of E.Coli is inoculated. This mixture is incubated overnight at 37 degrees Celcius on a shaking platform at 150rpm. The stock concentration, based on experience, is approximately 108 CFU/ml. This stock can then be diluted to the desired concentration.

Testing Schedule

In total 64 experiments are done. In Table 4.3 the testing schedule can be found. The concentrations that are used are between 20 and 80 CFU/ml. An upper limit is chosen due to practical reasons and safety. The method used to make the stock can produce a concentration of around 108 CFU/ml. The method can always guarantee that experiments can be done on a concentration of 80 CFU/ml. All other concentrations below are chosen arbitrarily and with a focus on orthogonal research.

Table 4.3: Testing schedule for acetic acid experiments

Different concentrations	**Different recoveries rates**	**Different half cycle times**
20 CFU/mL	20%	400 s (4.50 runs/hour)
40 CFU/mL	40%	600 s (3.00 runs/hour)
60 CFU/mL	60%	800 s (2.25 runs/hour)
80 CFU/mL	80%	1000 s (1.80 runs/hour)

Measurements

With the 3M Petri film E. coli/Coliform Count plates, which are designed to identify both E.Coli and another coliform. First 1 mL of the sample is spread over the plate. Secondly, the petrifilm count plate is incubated at the correct temperature. The final step is to count the colonies. Red or blue colonies are coliforms. Blue colonies with gas bubbles are E.coli.

4.3 Numeric Models

4.3.1 Dynamic Energy Based Evaporation Sorption Condensation model

As is told in section 3.4, the sorption characteristics of silica gel are not constant. These characteristics can change depending on two parameters. The temperature of the silica gel itself is one of these parameters. The partial pressure of the water vapour that surrounds the silica gel is the second. The first parameter, the temperature of the silica gel depends on two elements. The first element is the amount of water vapour that is adsorbed during a period. The adsorption of water vapour produces, as is said in section 3.4, energy. When this energy cannot be transported from the silica gel to another location, an increase in temperature can be expected. The adsorption energy increases the internal energy which translates to temperature. Since the ability to transport energy influence directly the temperature, the second element that influences the sorption characteristics of the silica gel is the total thermal conductivity of the silica bed.

The second parameter that influences the sorption characteristics is the partial pressure of the water vapour. Different elements determine the partial pressure of the water vapour. The initial conditions like temperature, total pressure and the initial partial pressure of the water vapour. A second important element is the relationship between the saturation pressure and the saturation temperature. When the pressure is lowered inside a closed system due to the intake of water vapour by the act of sorption, it also lowers the temperatures on which evaporation and condensation occur. Evaporation increases the partial pressure inside a closed system while condensation lowers it again. The other element is the energy balance of the system. Since evaporation requires energy and condensation releases energy, an energy balance is a vital part of this model. The last element is the mass balance of the system. Mass that is removed by adsorption could be replaced by means like a leakage. The mass balance has a direct influence on the total pressure inside the system.

An orthogonal approach is desirable when studying the influence of the different elements on the performance of Adsorption Desalination. In this model, the temperature of the silica gel is kept constant to ensure the influence of the partial pressure of water vapour can be studied in depth without any disturbances. The model is named the Dynamic Energy Based Evaporation Sorption Condensation model, also called DEBESC-model. As said before, there are four elements in this model. The first element is the initial conditions; the second element is the saturation relationship between pressure and temperature, the third element is the energy balance, and the last element is the mass balance. The model is a numeric model with a backward Euler solver. Since many parameters in the model influence each other, the following assumptions are made to make these parameters independent from each other at the moment they are used inside the calculations. This method is necessary to ensure a numeric model is possible:

The water vapour and air act as an ideal gas.
It is indeed true that water vapour and air are not ideal gases. However, they do act as ideal gasses at low pressures and temperatures. Since the model

works at extremely low pressures and relatively low temperatures, it is assumed that both gases behave as ideal gases.

The density of the liquid water is constant
The density of saturated water does change due to changes in pressure and temperature. However, since the changes are minimal on the scale the model operates, the changes in density are negligible. Therefore it is assumed that the density of water is constant. The water is incompressible

During the mass transfer calculations, the system is isochoric, isobaric and isothermal.
These assumptions are made to ensure that the enthalpies of these elements are constant during the mass transfer. They do change in reality, but since the model is modelling with such a small time step, the changes in the enthalpies are infinitesimal.

During the pressure, temperature and mass distributions calculations, the system is isochoric, and the mass stays constant.
These assumptions are made to simplify the model and to ensure it is possible the calculated the new equilibrium. Changes do of course occur, but it is assumed that during the time step these are negletiable

During volume calculations, the system is isobaric, isothermal and the mass stays constant.
Since the water is incompressible, the only changes in the volume are the changes in the mass of liquid water. The total volume of the system stays constant. Therefore it can as well be concluded that the changes in volume for the liquid water are equal to the changes in the volume of the gases.

The total pressure homogeneous over the whole system
The set-up is divided into three different chambers. Chambers in which the gases are located and transport of these gases takes place between these chambers. Even when the mass transport is at its maximum, the pressure drop is negligible even in the narrowest passage. For evidence see Appendix D.

The temperature is equal over the whole system.
The temperature is nothing more than an indicator of internal energy. Furthermore, the gases behave as ideal gases, and the system is saturated. Therefore the temperature depends on the pressure of the system and reversed. Since the pressure is equally divided over the whole system, it is assumed that the temperature is equally divided over the system.

The partial pressures of the vapour and the air are equal over the whole system
Since both gases behave as ideal gases and the temperature and total pressure are equally divided over the whole system, it is assumed that the partial pressure of both gasses is also the same over the whole system since both occupy the same volume. Due to the same assumption, it is also assumpted that the concentration of both gases is as well equal over the whole system. It should be stressed that this assumption does not mean that both have the same value.

There is no energy exchange with the surroundings of the system through conduction or radiation.
This assumption is made to simplify the model and to ensure that conclusions can be made without the interference of the surroundings.

The temperature of the heat exchanger and silica gel stays constant.
This assumption is made to simplify the model and to safeguard the orthogonal approach. The only exception is when this model is used to simulate the conditions inside the silica bed vessel during phase 2 and 4 of the operational strategy

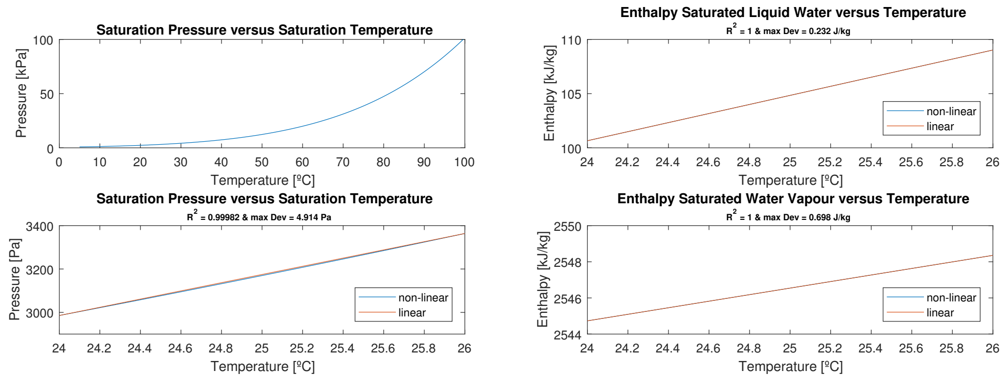
The relationship between temperature and pressure, enthalpy saturated vapour or enthalpy saturated liquid water is linear.
The relationship between pressure and temperature for saturated water has an exponential behaviour, but at low pressures and temperatures with small changes the relationship is linear as can be seen in Figure 4.14a. The same can be said for the enthalpy of liquid water and water vapour, see Figure 4.14b.

The rate of saturation for silica gel is independent of the adsorption capacity
In section 3.4 it is explained that the differential of saturation by time is constant as can be seen in Figure 3.3. In this study, it is assumed that the differential does not dependent on the adsorption capacity of the silica gel [45].

The desorption rate is equal to the change of adsorption capacity
The desorption velocity is not determined unfortunately in that same study [45]. Therefore it is assumed that the desorption rate is equal to the loss of adsorption capacity in a timestep.

The resistance against leakage in a vacuum system is constant
It is observed that when the air leaks into a vacuum system, the relationship between time and pressure is one of a logarithmic nature. The differential of the pressure over time decreases in a logarithmic behaviour. The mass flow of the air seems to depend on the pressure difference between the pressure inside the system and the pressure outside the system. For means as simplification, it is assumed that the resistance is independent of this pressure difference. The mass flow is calculated by dividing the pressure difference by a constant.

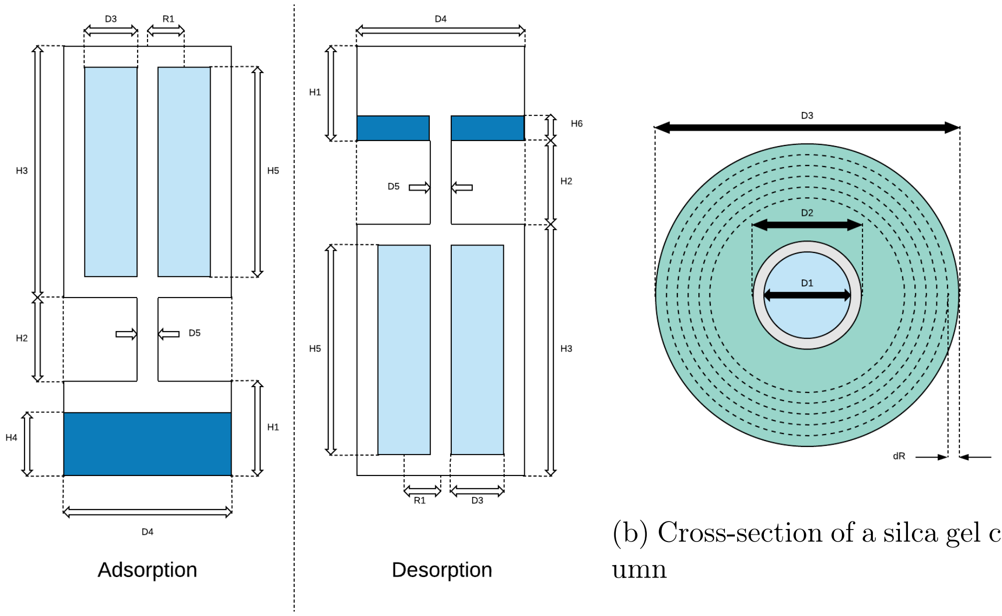
In Figure 4.15 the layout on which the DEBESC model is based can be found. It should be emphasised that the model is not using every dimensional parameter that is displayed in Figure 4.15a. Different factors are the reason for abanding some dimensional parameters. As an example, the DEBESC model neglects the values of H2 and D5. The reason is that these parameters would only influence the results if diffusion or pressure drop by convection had a significant influence on the outcome of these results. As can be seen in Appendix D, this is not the case.



(a) Relationship between pressure and temperature

(b) Relationship between enthalpy and temperature

Figure 4.14: Linear behaviour at small differences in temperature and pressure



(b) Cross-section of a silca gel column

(a) A schematic 2D overview of the set-up

Figure 4.15: Schematic overview of the set-up on which the numeric models are based

$H1$: Heigh evaporator and condenser [mm]
$H2$: Distance between silica bed and evaporator or condenser [mm]
$H3$: Height silica bed [mm]
$H4$: Height feed/concentrate inside the evaporator [mm]
$H5$: Height silica gel column [mm]
$H6$: Heigh product inside the condenser [mm]
$R1$: Distance between vertical axis silica bed and axis silica gel column [mm]
$D1$: Inner diameter of heat exchanger tube [mm]
$D2$: Outer diameter of heat exchanger tube [mm]
$D3$: Diameter silica gel column [mm]
$D4$: Diameter evaporator, silica bed and condenser [mm]
$D5$: Diameter transport tube connection silica bed with the evaporator or condenser [mm]

Parameter	**Value [mm]**
H1	250
H2	200
H3	600
H4	0.7 H1
H5	500
R1	40
D1	28.5
D2	33.8
D3	54
D4	160
D5	20

Table 4.4: Overview value of dimensional parameters

Since this model is energy based, let's first discuss the energy balance. The energy balance is based on the first law of thermodynamics. The change of the energy of the system can be calculated with this law when all the proper parameters are estimated. As can be seen in Equation 4.2, the change in energy depends on four elements. The change in mass of the liquid water, the change in mass of the water vapour, the change in mass of the air inside the system and the energy added or removed by the heat exchanger.

$$\begin{aligned}\frac{dE_{system}}{dt} &= m_2 * (h_2 + \frac{1}{2}v_2^2 + g\ z_2) - m_1 * (h_1 + \frac{1}{2}v_1^2 + g\ z_1) + Q - W \\ &= m_2\ h_2 - m_1\ h1 + Q_{he} \\ &= \frac{dE_{water}}{dt} + \frac{dE_{air}}{dt} + Q_{he} \\ &= \frac{dE_w}{dt} + \frac{dE_v}{dt} + \frac{dE_{air}}{dt} + Q_{he} \\ &= \frac{dm_w}{dt}\ (h_v - h_w) + \frac{dm_v}{dt}\ h_v + \frac{dm_{air}}{dt}\ h_{air} + Q_{he}\end{aligned} \tag{4.2}$$

where:

$$\begin{aligned}\frac{dm_w}{dt} &= -\frac{dm_{evaporation}}{dt} \\ \frac{dm_v}{dt} &= \frac{dm_{evaporation}}{dt} - \frac{dm_{sorbate}}{dt} \\ \frac{dm_{water}}{dt} &= \frac{dm_w}{dt} + \frac{dm_v}{dt} \qquad = -\frac{dm_{sorbate}}{dt}\end{aligned} \tag{4.3}$$

Combining Equation 4.2 and Equation 4.3 results into Equation 4.4. Equation 4.5 can be used to calculated the energy transfer by the heat exchanger inside the system.

$$\frac{dE_{system}}{dt} = -\frac{dm_{sorbate}}{dt}\ h_v + \frac{dm_{air}}{dt}\ h_{air} + Q_{he} \tag{4.4}$$

$$\begin{aligned}Q_{he} &= \frac{T_{he} - T_{sys}}{R_{he}} \\ R_{he} &= \frac{log(r_0/r_i)}{2\pi k_{he}\ L_{he}}\end{aligned} \tag{4.5}$$

To solve Equation 4.4, the differentials of the mass transfer by sorption and air has to be calculated. The differential of the mass transfer by sorption is calculated by combining Equation 3.1 with the constant saturation differential. The result can be seen in Equation 4.6. Of course, this formula can only be used when the mass the silica has adsorbed is lower than the maximum the silica gel can adsorb. The alternative formula for that occasion can also be found in Equation 4.6. The maximum mass the silica gel can adsorb is calculated by multiplying Equation 3.1 times the total mass of the silica gel inside the system.

$$\begin{aligned} \frac{dm_{sorbate}}{dt} &= m_{si}\ P_v\ K_0^I exp[Q_{st}/(RT)]\ \frac{d\theta}{dt} && \text{if} \quad m_{sorbate} < m_{max.sorbate} \\ &= (m_{sorbate} - m_{max.sorbate})/\delta t && \text{if} \quad m_{sorbate} \geq m_{max.sorbate} \end{aligned} \tag{4.6}$$

$$\frac{dm_{air}}{dt} = \frac{P_{atm} - P(t)}{R_{air}} \tag{4.7}$$

To calculate the differential by the mass of air a simplified formula is used. Since it is assumed that the gases behave as an ideal gas, it can be assumed that the differential of mass over time is the same as the differential of pressure over time. The differential of mass by time depends therefore as well on the pressure difference. A simplified formula has been made to calculate this differential. This formula can be seen in Equation 4.7. The resistance factor (R_{air}) is empirically calculated. In Appendix D the model and formulas used can be found to calculate this resistance factor.

At last, it is possible to calculate the change in energy and with a backward Euler numeric model the new level of energy inside the system. The knowledge of the new energy level of the system doesn't provide information about the new pressure and temperature of the system, unfortunately. Parameters that should be known when calculating the new sorption characteristics of the silica gel. Elements on which the change in energy depends. However, since the energy of the system is known, it is possible the calculate the pressure and the temperature by reversing the formula or by the use of iterations in combinations with a proportional feedback loop. In Equation 4.8 it is described how the energy of the system can be calculated with these parameters. This formula is rewritten to enable that with the temperature of the system the energy can be calculated. It is possible to do so since the pressure depends on the temperature since it is a saturated system. The new total mass of the air and the water are already calculated earlier thanks to the mass balances calculations in Equation 4.3.

$$E_{system} = m_w\ h_w + m_v\ h_v + m_{air}\ h_{air} \tag{4.8}$$

$$\begin{aligned} P_{sat}(T) &= P_{0,sat} + \frac{dP}{dT}\ T \\ h_w(T) &= h_{0,liquid} + \frac{dh_w}{dT}\ T \\ h_v(T) &= h_{0,vapour} + \frac{dh_v}{dT}\ T \\ h_{air}(T) &= c_v\ \frac{m_{air}}{M_{air}}\ T + P_{sat}(T)\ V_{gas} \end{aligned} \tag{4.9}$$

Since the new mass of the air is known, the partial pressure of the air can be calculated. When total pressure is subtracted with the partial pressure of the air, the partial pressure of the water vapour can be detemined. When the partial pressure of the water vapour is known, the mass of the water vapour can be calculated. Since the total mass of the water is earlier calculated with the mass balance, the mass of the liquid water is determined. These equations can be seen in Equation 4.10. Combining all these equations results in Equation 4.11. As said before, in combination with a negative properational feedback the temperature of the system can be determined which translated. When the correct new temperature is calculated, all other parameters are also correctly estimated.

$$\begin{aligned} P_{air}(T) &= \frac{m_{air}\ R\ T}{M_{air} V_{gas}} \\ m_v(T) &= \frac{(P_{sys} - P_{air}(T))\ V_{gas}}{R\ T}\ M_{water} \\ m_w(T) &= m_{water} - m_v(T) \end{aligned} \tag{4.10}$$

$$E_{system}(T) = (m_{water} - m_v(T))\ h_w(T) + m_v(T)\ h_v(T) + m_{air}\ h_{air}(T) \tag{4.11}$$

$$V_{gas} = V_{sys} - m_w / \rho_{water_w} \tag{4.12}$$

The last task is calculating the new volume that the gasses occupy. Equation 4.12 can do so. Combine all these equations in the right sequence, and a numeric model as DEBESC-model can be made. These equations only overlook one element: they ignore the vacuum pump. The vacuum pump can influence the process when it is turned on. It changes the differentials of the mass transfer of the air and water. The new differentials when the pump is active can be observed in Equation 4.13. Just like the case with the air leaks, the pressure curve also behaves as a logarithmic function during the moment the vacuum pumps are active. The same method to estimate the mass removal by the vacuum pump is used as with Equation 4.7. The resistance coefficient R_{vp} is also empirical established with the help of an algorithm. This algorithm can also be found in Appendix D.

$$\begin{aligned} \frac{dm_{air}}{dt} &= \frac{P_{atm} - P(t)}{R_{air}} - \frac{P_{air}(t)}{R_{vp}} \\ \frac{dm_v}{dt} &= \frac{dm_{evaporation}}{dt} - \frac{dm_{sorbate}}{dt} - \frac{P_v(t)}{R_{vp}} \\ \frac{dm_{water}}{dt} &= -\frac{dm_{sorbate}}{dt} - \frac{P_v(t)}{R_{vp}} \end{aligned} \tag{4.13}$$

4.3.2 Dynamic Energy Based Silica Adsorption Desorption - Model

As said in subsection 4.3.1, besides simulating the changing adsorption characteristics of silica gel by the vapour pressure, it is also the objective to simulate the adsorption characteristics by changing the temperature of the silica gel. The temperature of the silica gel can change due to adsorption energy as told in section 3.4. The adsorption of water vapour by silica gel releases energy on the silica gel. If it is the case that the silica gel is unable to relocate this energy, the temperature of the silica gel increases. Depending on the temperature and the vapour pressure around the silica gel, the adsorption characteristics can be negatively influenced when the energy cannot sufficiently be relocated. As an example, if the silica gel is not able to relocate the adsorption energy, and in the hypothetical case the temperature does not influence the adsorption characteristics, the temperature of the silica gel could rise more than 100 degrees. See Appendix D for this example. The relocation of energy can happen by three different mechanisms: Conduction, Convection and Radiation. Since the silica gel is located around a heat exchanger and tightly packed together at very low pressure, convection is probably negligible. Radiation is also negligible. Most energy of the silica gel would also be radiating into a neighbouring silica gel bead. The only mechanism that can have the most significant influence on the energy transport is conduction. The problem that arises is that silica gel is a terrible conductor compared to other materials like copper and steel. In this model, the Dynamic Energy Based Silica Adsorption Desorption model, also known as DEBSAD Model, the relationship between these different elements to be able to predict the adsorption behaviour of silica gel by the adsorption energy and conduction characteristics of the same material. To create this model, the following assumptions are made:

The vapour pressure is constant
To ensure an orthogonal research approach, the vapour pressure is constant and does not depend on the evaporation and condensation.

Energy transport by radiation or convection are neglible
The influences of these two mechanisms are negligible because the silica gel is tightly packed together in an extremely low-pressure environment.

The temperature of the heat exchanger is constant
Due to the fact it is desirable to have an orthogonal approach, the influences of other parameters have to be cancelled out. Therefore it is desired to keep the temperature of the heat exchanger constant over time.

The adsorption energy and desorption energy is equal to the enthalpy of the water vapour
When the silica gel adsorbs water, the water becomes a semi-solid, see section 3.4. In this status, the water has a lower energy level than when it was a vapour. The adsorption energy is the energy difference between these two statuses. When water is adsorbed, it needs to get rid of this difference; hence this surplus energy is released on the silica gel. When the silica gel desorbs the water vapour, the energy level of the water is increased. It is assumpted the enthalpy of the water vapour that exit the bed is equal to the enthalpy of water vapour with the same pressure of the system and temperature of the

silica gel.

The temperature of the adsorbed water vapour is equal to the temperature of the silica gel
When the energy level of the silica gel increased, the energy level of adsorbed water vapour does also increase. It is assumed that there is no barrier for energy exchange between the sorbent and the sorbate. Therefore it is assumed that the temperature of the sorbent and the temperature of the sorbate is equal to each other.

The specific heat constant of the sorbate is constant and equal to a saturated liquid.
As said in section 3.4, the sorbate, the water vapour, is a semi-solid. Since it is a semi-solid, the thermodynamical behaviour can differ from a liquid at the same pressure and temperature. Unfortunately, exact data of the specific heat constant of water in a semi-solid phase is unknown. Therefore, it is assumed that it is equal to the specific heat constant of liquid water

The adsorption rate is constant and homogeneous through the whole silica bed
There is a chance that there is a difference between the adsorption capacity of the silica gel located further into the silica bed then the silica gel located on the boundaries of the silica bed. This situation could be the case due to the possibility that the vapour pressure is lower inside the silica bed than on the outside. The silica bed is porous, but it would be naive to assume that there is no resistance to the gases that travel through this porous bed. However, since there is no data available on how much the vapour pressure can differentiate, it is assumed that this difference is negligible. Therefore the adsorption rate is constant

The desorption rate depends on the differential of the temperature of the silica gel
Since the temperature of the silica gel increases, the adsorption capacity of the same material decreases. The silica gel starts to desorb the water vapour, which does decrease the temperature of the silica gel. This action starts to increase the adsorption capacity. The real desorption rate, therefore, is the equilibrium between the differential of the temperature over time and the desorption rate.

There is no temperature difference over the length of the silica gel column
The assumption is made that energy exchange only happens over the radial axis of the model and the length of the silica gel. Since it is assumpted that the temperature of the heat exchanger is constant over time and length of the column and the adsorption rate is homogeneous, no temperature difference over the length of the column is expected, only over the radius of the column.

The conduction resistance and contact resistance of the heat exchanger tube is negletible
Since the contact resistance and the conduction resistance of the heat exchanger are very small compared to the thermal resistance of the whole silica bed, they are neglected. This decision is made to make it possible to run the

model on a larger time step and therefore make it more ergonomic to run. It is assumed that it has no significant influence on the final results of the model.

In Figure 4.15b, the schematic overview of the DEBSAD model can be seen. It is a model constructed on a radius coordinate system in which the silica gel is divided into small rings. Just like the other numerical model, this model is also energy based. The change of energy inside a ring is calculated with Equation 4.14, 4.15 and 4.16. With the change of energy, the change of the temperature can be calculated using Equation 4.17. As can be seen, the temperature depends on the current mass of the adsorbed water mass and the mass of the silica gel and the accompanying specific heat constant. The adsorption rate is similarly defined as with the DEBESC model, the desorption rate is not, as can be seen in Equation 4.18. As told in the assumptions about the desorption rate, the desorption rate depends on the equilibrium between the change in temperature and the change in water uptake capabilities of the silica gel. As can be seen in Appendix D, by combining Equation 4.14, 4.17 and 4.19 into an algorithm, the desorption rate (dm/dt) can be estimated.

$$\frac{dE_{sb,r}}{dt} = \frac{dE_{sorbate,r}}{dt} + \frac{dE_{he,r}}{dt} \tag{4.14}$$

$$\frac{dE_{he,r}}{dt} = \frac{T_{r-1} - T_r}{R_{sb,r}} + \frac{T_r - T_{r+1}}{R_{sb,r+1}} \tag{4.15}$$

$$\frac{dE_{sorbate,r}}{dt} = h_v \, \frac{dm_{sorbate,r}}{dt} \tag{4.16}$$

$$\frac{dT_r}{dt} = \frac{1}{Cp_{water}\ m_{water,r} + Cp_{si}\ m_{silica,r}} \frac{dE_{sb,r}}{dt} \tag{4.17}$$

$$\begin{aligned} \frac{dm_{soprtion}}{dt} &= m_{si}\ P_v\ K_0^I exp[Q_{st}/(RT)]\ \frac{d\theta}{dt} && \text{if} \quad m_{sorbate} < m_{max.sorbate} \\ &= \theta_{max}\ m_{si}\ \frac{dq}{dt} && \text{if} \quad m_{sorbate} \geq m_{max.sorbate} \end{aligned} \tag{4.18}$$

$$\frac{dq}{dt} = q(T_{t-dt}) - q(T_t)/dt \quad \text{where} \quad T_t = T_{t-dt} + \frac{dT}{dt}\, dt \tag{4.19}$$

4.4 Exergy and Entropy Creation Analysis

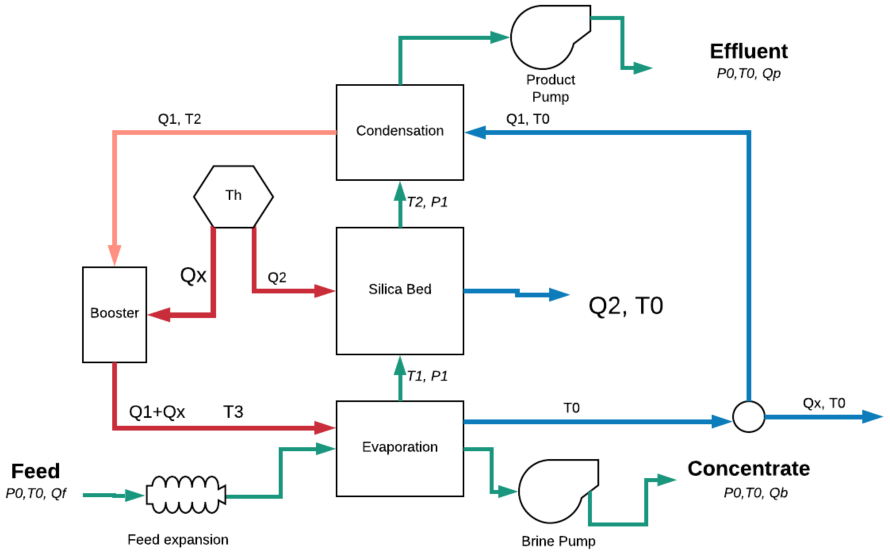


Figure 4.16: Entropy Creation Model of AD

An Adsorption Desalination plant exist in this model out of the following components:

- Evaporator
- Condenser
- (an ideal) Silica Bed vessel
- Booster
- Expansion Unit for the feed
- Pump for the brine
- Pump for the product

As known, in the evaporator, the feed is evaporated while in the condenser the product is condens. In the ideal silica bed, the vapour from the evaporator is adsorbed, while later being desorbed. As said in the last assumption made, here below, the whole system is in a continuous operation. This modus is possible due to an unknown number of silica beds. Therefore the silica bed unit is continuously adsorbing and desorbing vapour and heating and cooling silica gel. The thermal energy of the condenser is reused, but it needs a little bit of a boost. The booster adds extra energy and mass to the hot cooling water from the condenser. This additional mass is after the evaporator removed again, see Figure 4.16 for the whole overview of the model.

For this model, a couple of assumptions are made. The largest is the ideal designed silica bed vessel. In the silica bed, a lot of energy exchange occurs. During the adsorption phase, the thermal exchange has to be removed while during the desorption phase almost equal amount of energy has to be relocated back. The silica itself has to be heated till 80 degrees and be cooled down again. Depending on the configuration, a number of silica columns that are placed inside, the ability to reuse energy and heat exchanger design, the silica bed unit creates entropy. It is assumed the silica bed is ideal because the objective is to find the minimal energy consumption of Adsorption Desalination. An ideal silica bed unit creates a minimal amount of entropy. All energy that enters the system is used, and all elements are heated or cooled down till the right temperature. In reality, this would mean many silica beds operate independently and work in master and slave configuration. If it is ever possible to create such a unit is open for discussion.

The second assumption is that all heat exchangers are ideal. Typically, a small temperature difference has to exist. Otherwise, no energy transfer would take place. This temperature difference creates entropy. Depending on the quality of the design, this difference can be large or small. However, compared to the entropy creation by boiling or condensation, the entropy creation is negligible, therefore for simplicity, it is neglected.

The third and fourth assumptions are about the evaporator and the silica bed. Since the salinity increase in the evaporator, boiling point elevation exists inside the evaporator. Therefore not all vapour has the same temperature and energy content. For simplicity, it is assumed that all evaporated on the average temperature of the average salinity inside the evaporator. For the silica bed as similar problem exit. Not all vapour is desorbed at the same temperature, and therefore, just like with the evaporator, an average value is taken.

The fifth assumption is that all pumps have an isotropic efficiency of 80%. The sixth assumption involves the reality that the concentrate has a little higher temperature and higher salinity than the feed due to boiling point elevation and concentration. Not reclaiming this energy is entropy creation, also known as Thermal disequilibrium and chemical disequilibrium. This destruction is neglected since they are unusually small, as long the recovery is not higher than a certain threshold. The maximum recovery in this model is 80%. The seventh assumption involves pressure. It is assumed that no leakage exists and that the volume balance between the feed, product and brine is equal to zero. Therefore, no pressure regulation is necessary. The last assumption is that the whole system works in a continues modus. Therefore counter heat exchanger are possible in the evaporator and the condenser.

To calculate the entropy created by the expansion Equation 4.20 is used. For the entropy creation by the pumps another formula is used, see Equation 4.21. All other processes (Booster, Evaporator, Condenser and Silica Bed Unit) have masses flow in and out of their system without a change in pressure of each of these flows individually. Therefore, Equation 4.22 can be used. With these three equations, a simple entropy creation model based on the model of Figure 4.16 is created.

$$s_{gen}^{\Delta p} = c\, ln\Big[1 + \frac{v}{cT_i}(p_i - p_o)\Big] \tag{4.20}$$

$$s_{gen}^{pumping} = c\, ln\Big[1 + \frac{v}{cT_i}(p_o - p_i)\Big(\frac{1}{\mu_p}\Big)\Big] \tag{4.21}$$

$$\dot{S}_{gen}^{HX} = \sum_{i=1}^{n} \left[\dot{m}_i (s_o - s_i) \right] \tag{4.22}$$

5 Results

5.1 Experiments including Salinity, Acetic Acid and E.Coli

Unfortunately, no results are available due to the failure of the set-up to evaporate water from the evaporator. All components were functional. The reactors were not perfectly vacuum-tight as no reactor would ever be. However, the leakage was substantial and could be the reason for the breakdown in the functionality of the whole set-up. It was calculated that the leakage was on average 1463 $\mu gram/(s*L)$. Meaning that the reactor would be full of air around 10 minutes. The vacuum control system could control the vacuum and keep it on the desired pressure by pumping around 40% of the operational time. The results of the numeric models could provide insight into the question of why precisely a complete breakdown of performance instead of a loss of efficiency or water production capabilities. After multiple attempts, the vacuum pumps short-circuit due in no small amount of water vapour travelled into their systems. Because multiple months had passed without any results, equipment broke down, and no performance was measured in the meantime, it was decided to abandon the experiments completely. Hopefully, further analysis can provide insight and provide guidance for the next research that tries to attempt the same goal.

5.2 DEBESC: Introduction

The results of the DEBESC model are displayed in multiple different plots. The following elements are plotted: Energy of the system, the pressure of the system, partial vapour pressure, partial air pressure, temperature of the system, mass adsorbed by the water vapour and many others. In section 5.3 the two colligative properties of Adsorption Desalination are explored. It shows, the difference between a saline source and non-saline source. Also, the importance of a heat exchanger inside the evaporator is demonstrated. In section 5.4 the results of phase 1, the adsorption phase is displayed. subsection 5.4.1 displays the results when a small leakage is introduced. Leakages from 16 till 63 $\mu g/(s\ L)$.

The unit used to display these leakages is microgram per litre and second. It means the average mass that leaks inside a system between zero pascal and 95 per cent of the atmospheric pressure. When a leakage exists of 10 $\mu g/(s\ L)$ inside a system of 1 litre, it means that 10 micrograms per second on average leaks inside this system. This approach is chosen since in reality the mass that leaks inside the system is not constant or linear. It depends on the pressure difference between the environment and the pressure inside the system. In reality, it follows a logarithmic behaviour.

In subsection 5.4.2 the same is displayed as in subsection 5.4.1, only now it also does include the leakage of the set-up that was constructed in the Waterlab. The leakage was 1463 $\mu g/(s\ L)$. The size of the leakage or multiple leakages is around the thickness of a hair as can be observed in section D.7. Furthermore, also the situation when the vacuum controller is activated is displayed. In subsection 5.4.3, 5.4.4 and 5.4.5 are the results with different saturation temperatures. They show how much changing the saturation temperature can influence the process. Also, as last, in subsection 5.4.6, the results at different initial vapour concentration conditions are shown.

5.3 DEBESC: Analysis of Collegative Properties

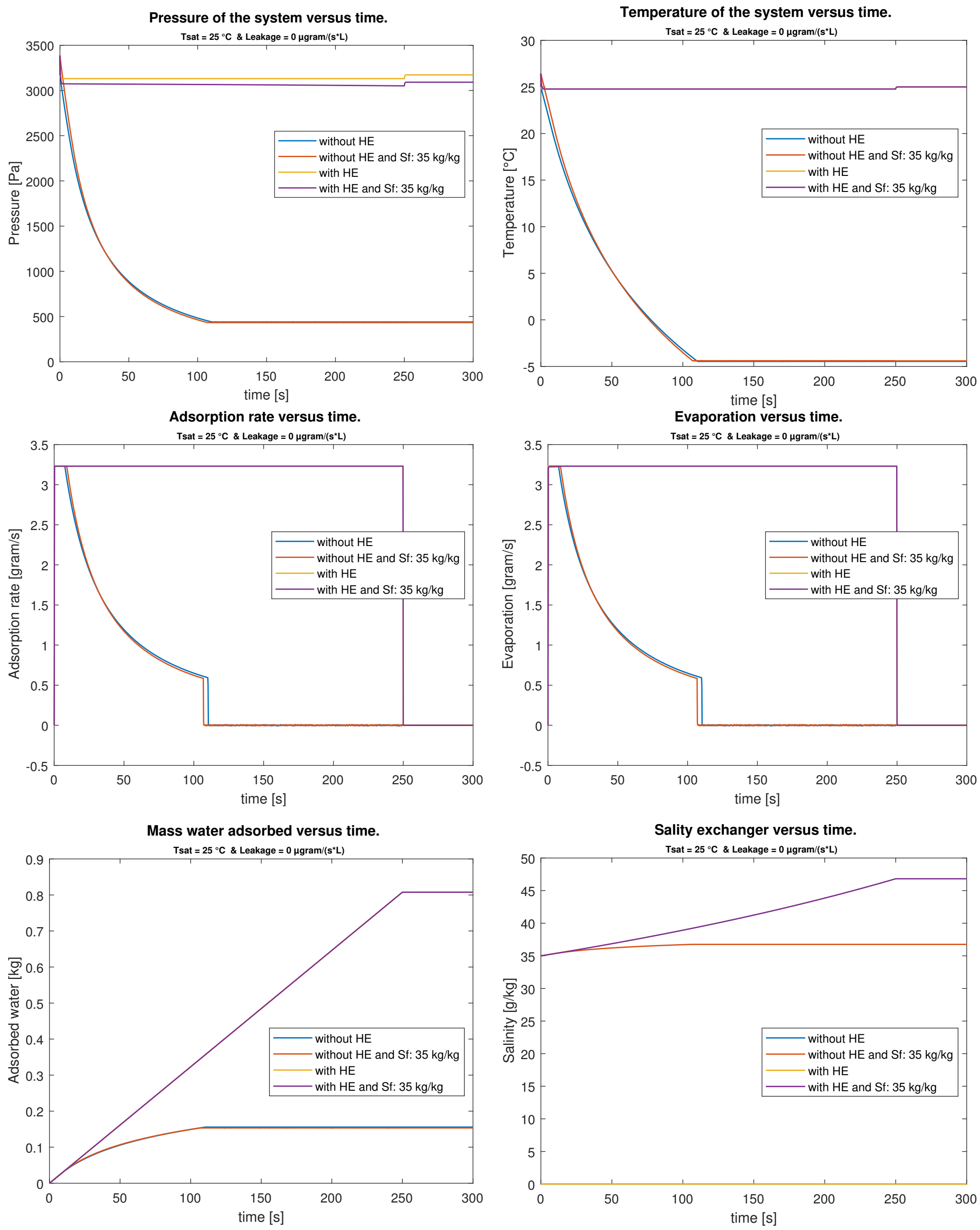


Figure 5.1: Difference between Adsorption Desalination based on only vapour presusre lowering and combined vapour pressure lowering and boiling point elavation.

5.4 DEBESC: Phase 1 - Evaporation and Adsorption Phase

5.4.1 System performance with a leakage from 0 till 63 µg/(s L)

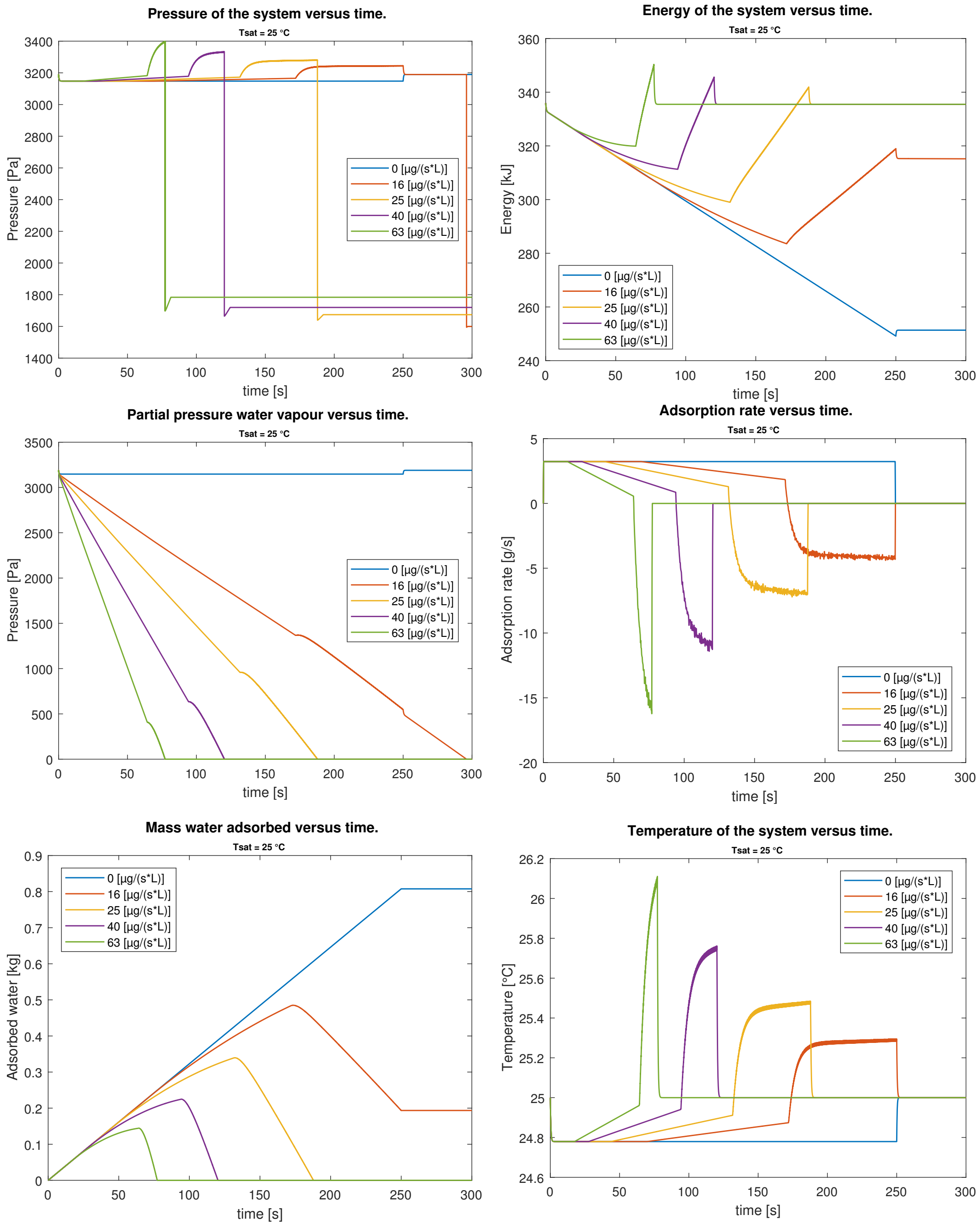
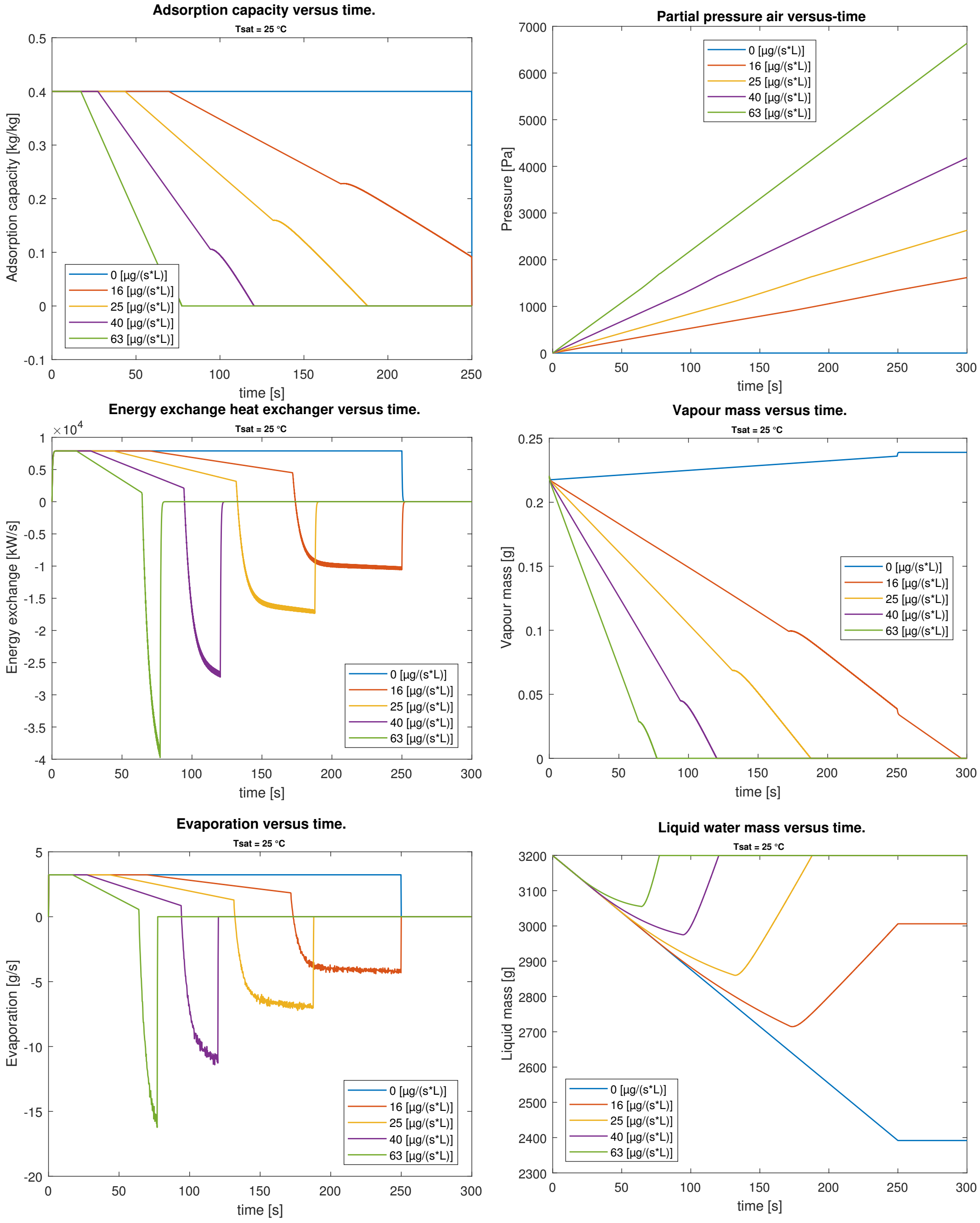


Figure 5.2: Part 1: Overview different parameters during a leakage from 0 till 63 µg/(s L)


Adsorption capacity versus time.

Partial pressure air versus-time

Energy exchange heat exchanger versus time.

Vapour mass versus time.

Evaporation versus time.

Liquid water mass versus time.

Figure 5.3: Part 2: Overview different parameters during a leakage from 0 till 63 µg/(s L)

5.4.2 System Performance with a Leakage from 0 till 1463 µg/(s L)

No Vacuum-Controller Active

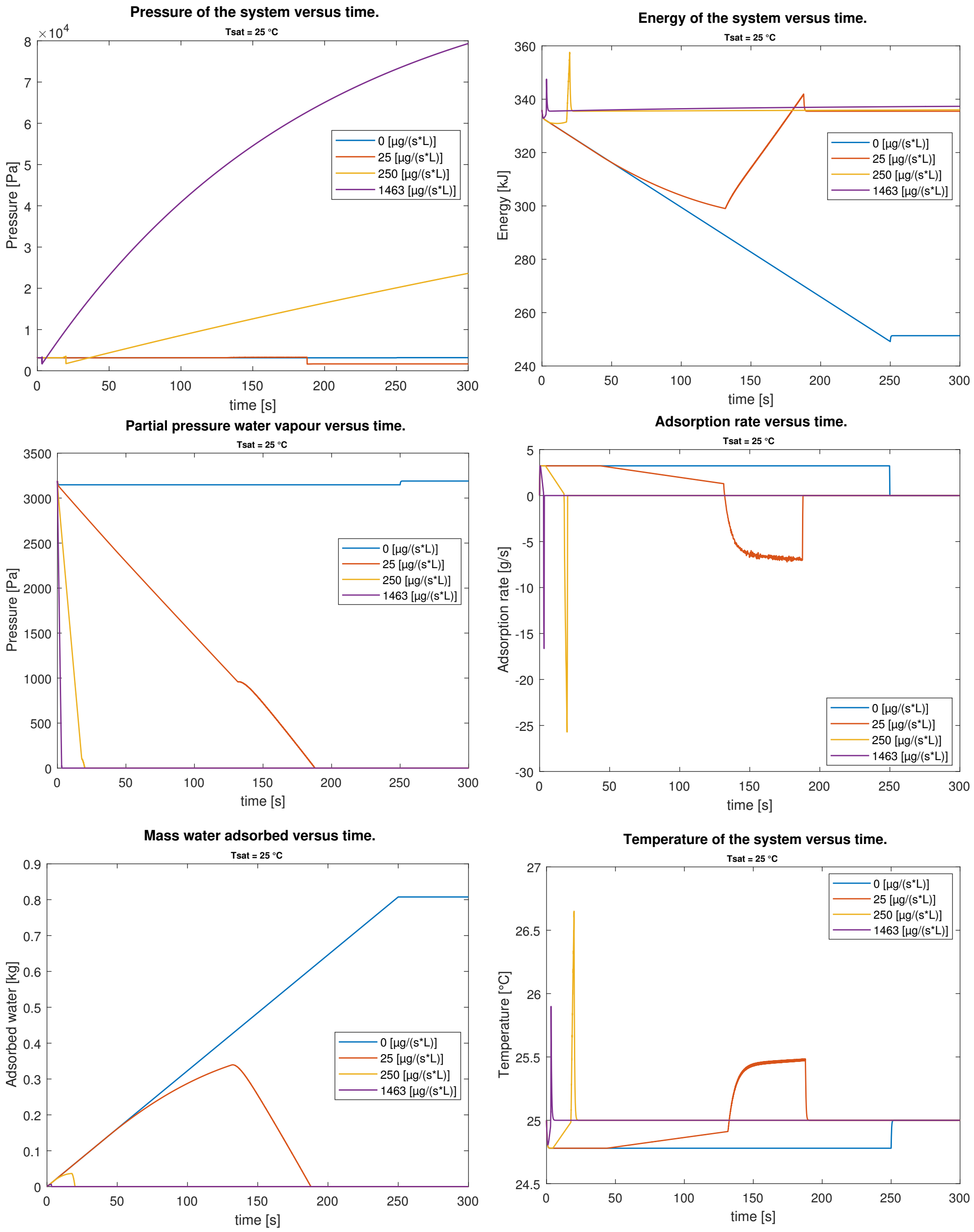


Figure 5.4: Part 1: Overview different parameters during a leakage from 0 till 1463 µg/(s L)

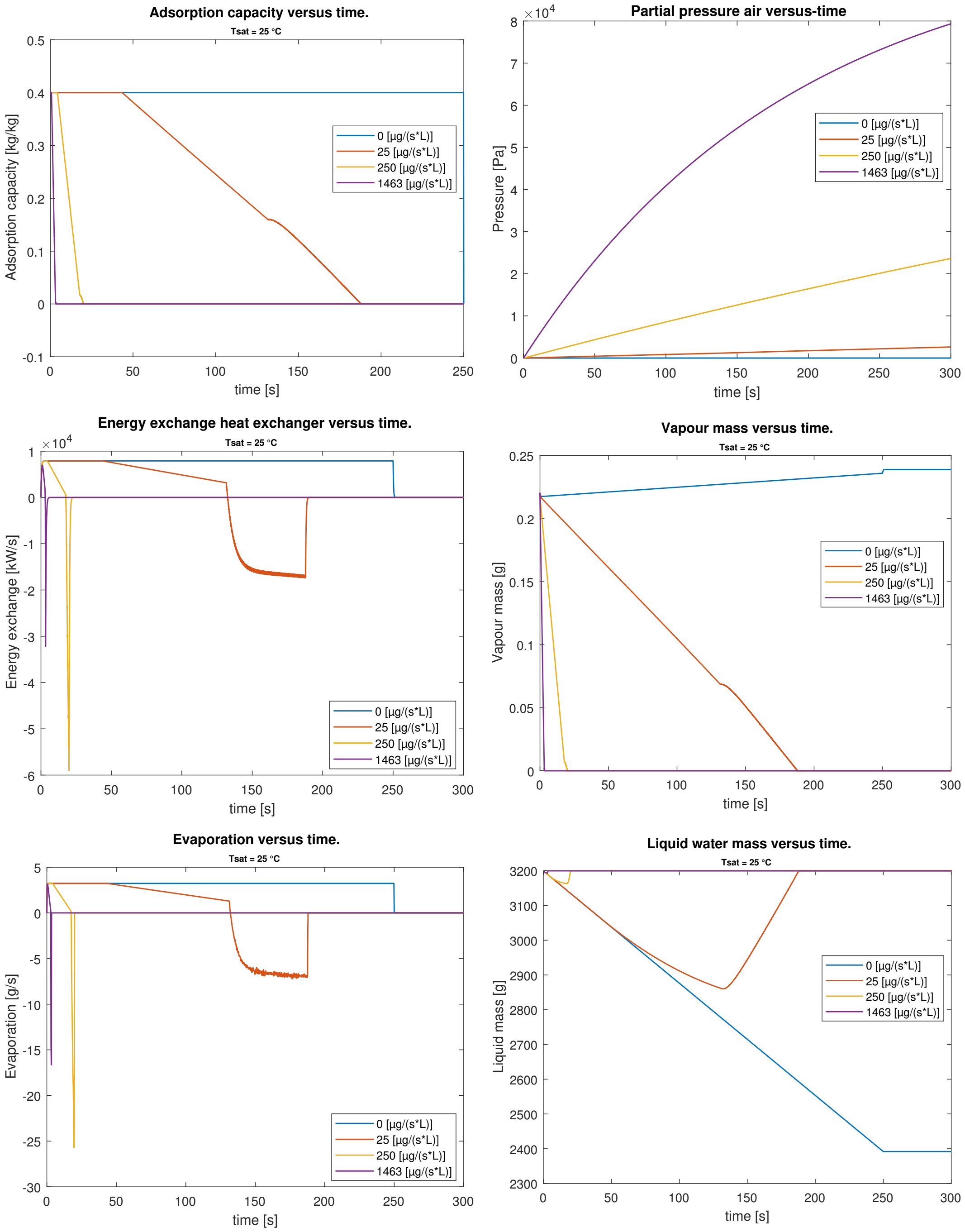


Figure 5.5: Part 2: Overview different parameters during a leakage from 0 till 1463 µg/(s L)

Vacuum-Controller Active

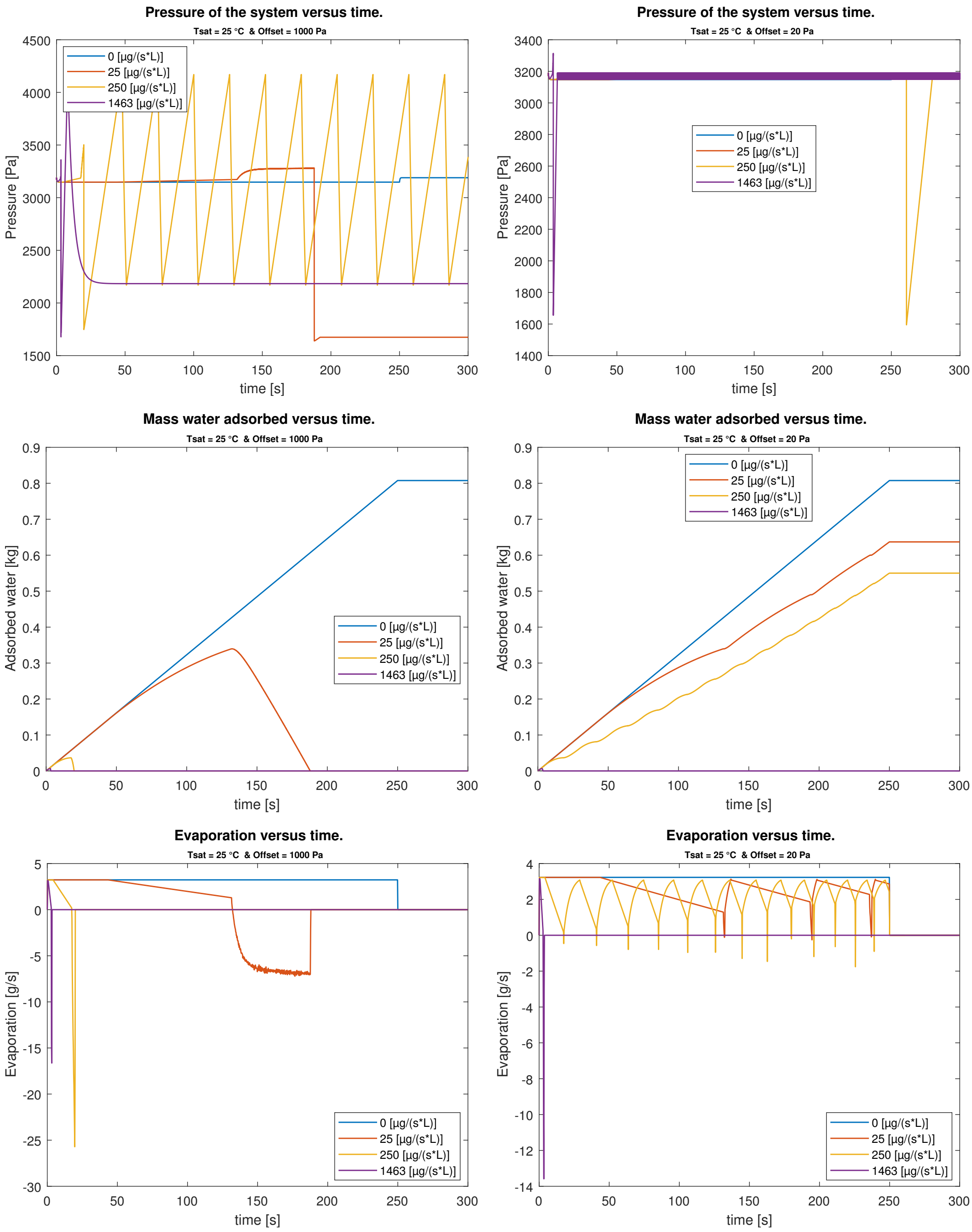


Figure 5.6: Part 3: Overview different parameters during leakage from 0 till 1463 µg/(s L) while the vacuum-controller is active.

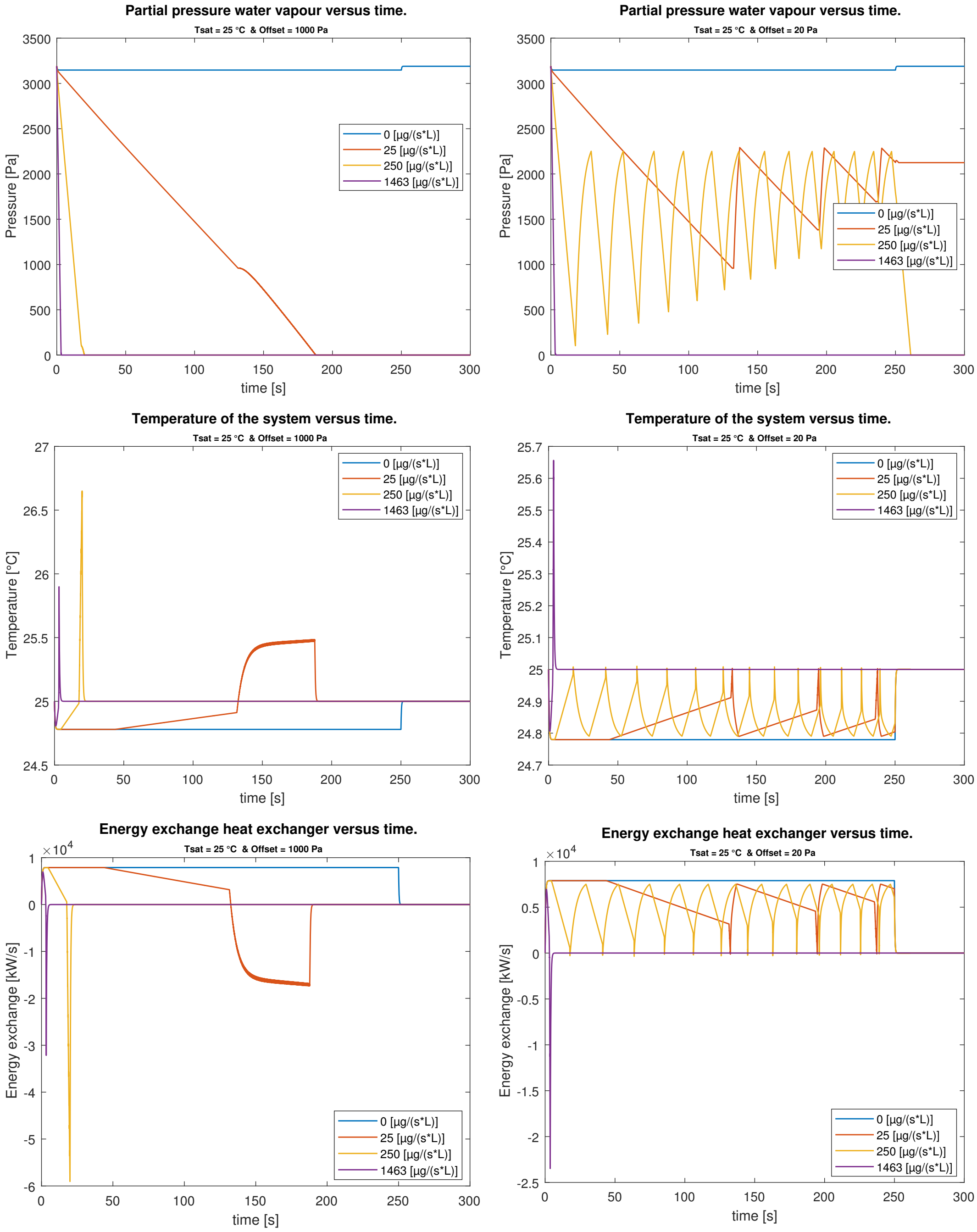


Figure 5.7: Part 4: Overview different parameters during leakage from 0 till 1463 µg/(s L) while the vacuum-controller is active.

5.4.3 System Performance at different Saturation Temperatures with no Leakages

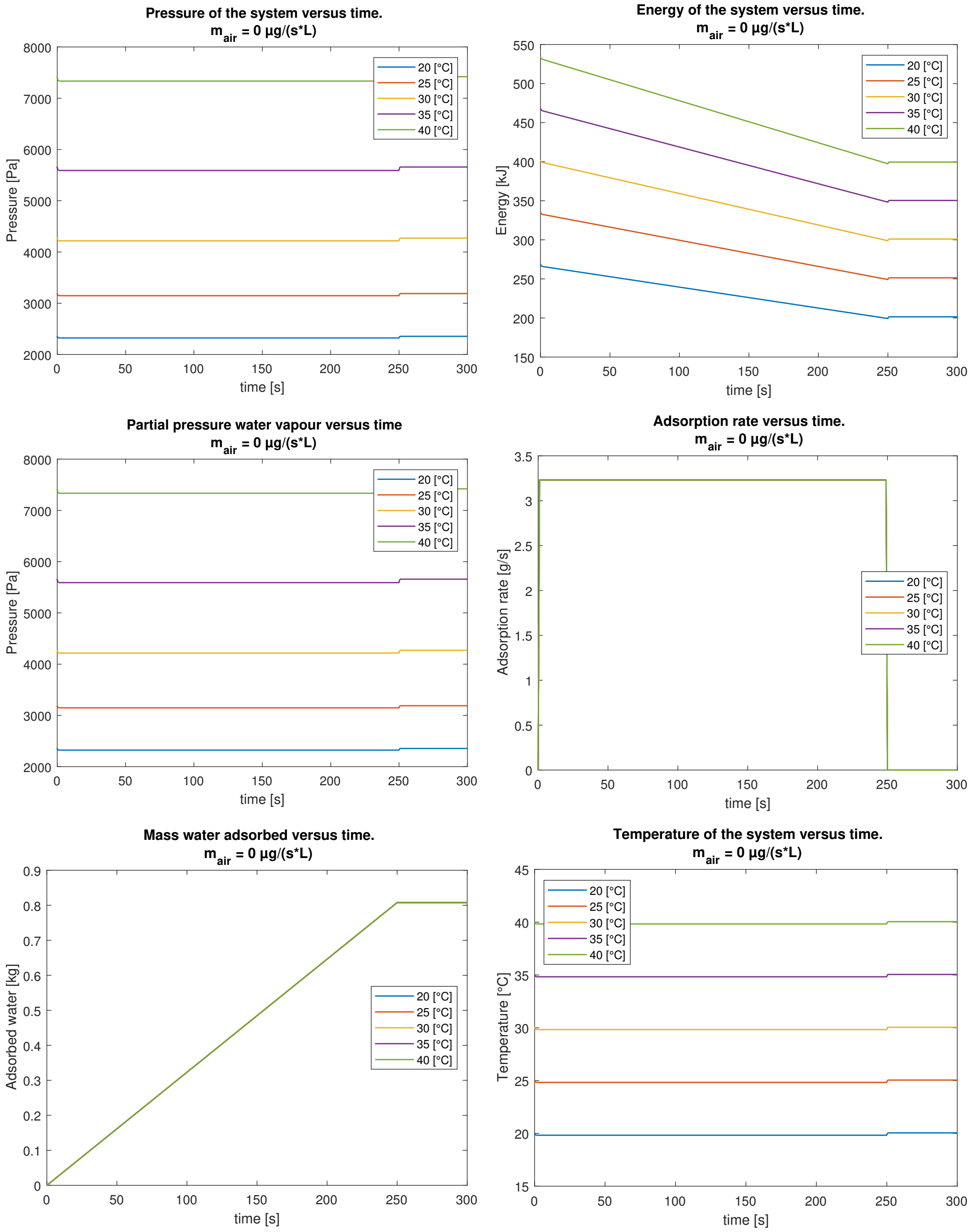


Figure 5.8: Part 1: Overview different parameters at different saturation temperatures and 0 µg/(s L)

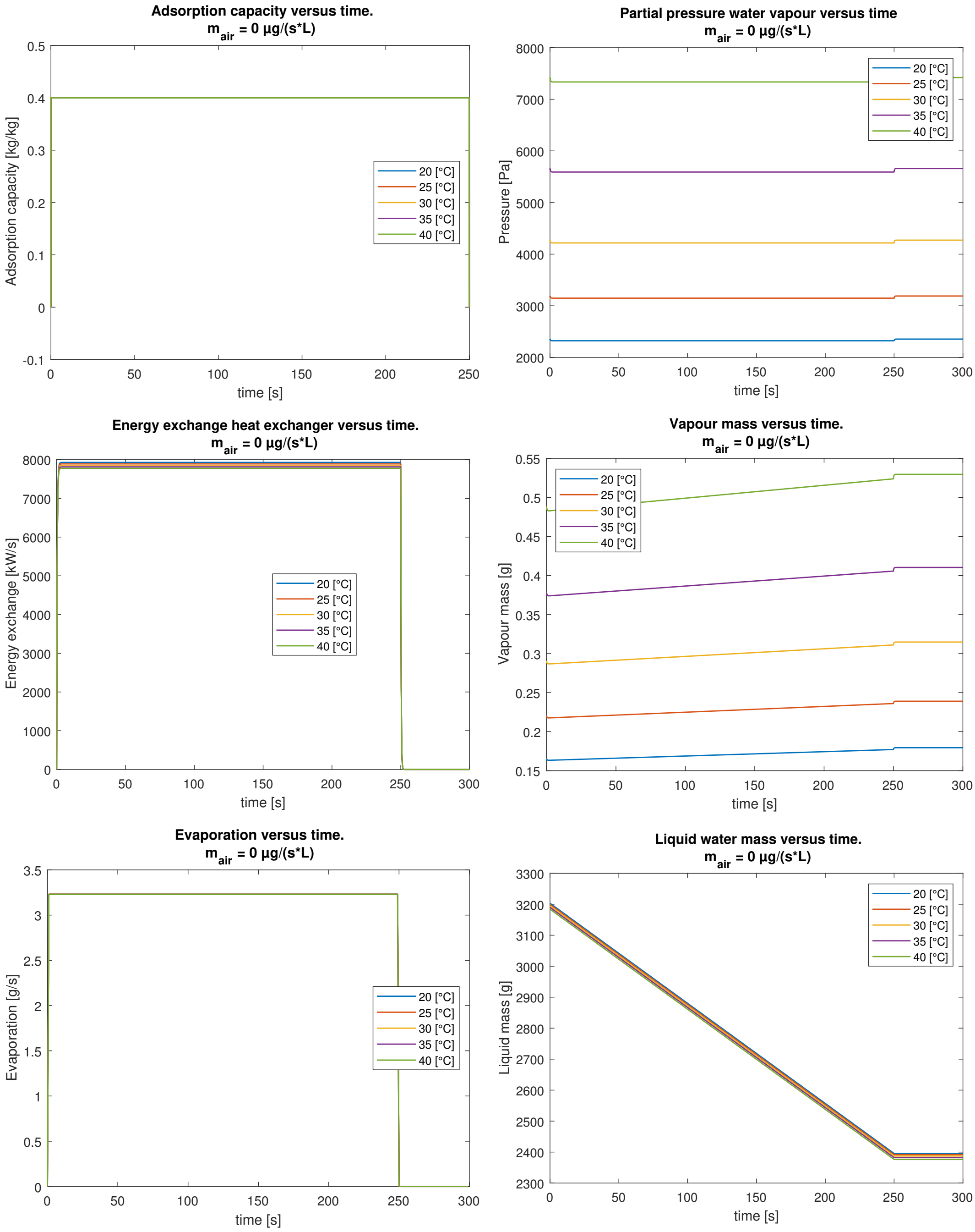


Figure 5.9: Part 2: Overview different parameters at different saturation temperatures and 0 µg/(s L)

5.4.4 System Performance at different Saturation Temperatures with a Leakage of 25 µg/(s L)

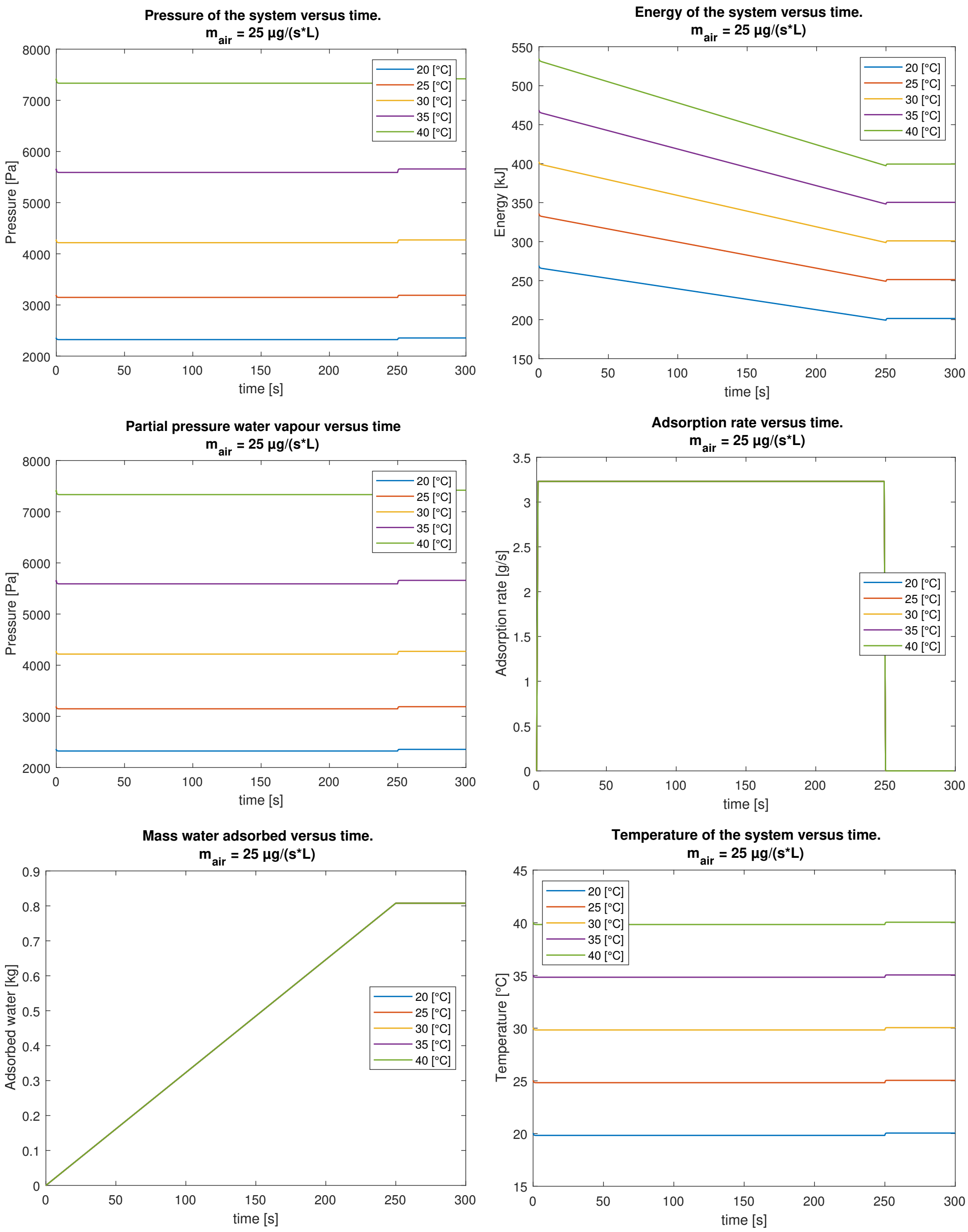


Figure 5.10: Part 1: Overview different parameters at different saturation temperatures and 25 µg/(s L)

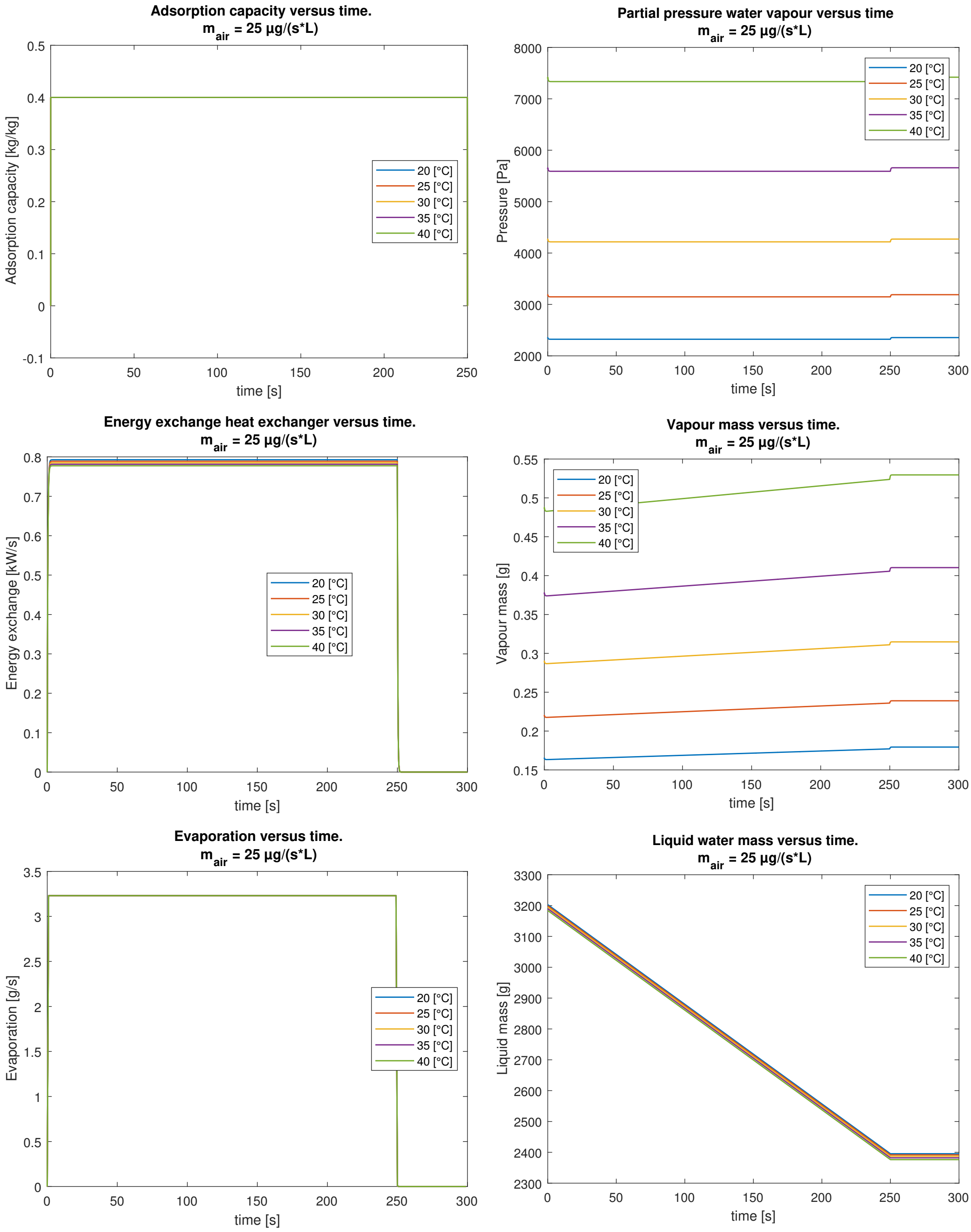


Figure 5.11: Part 2: Overview different parameters at different saturation temperatures and 25 µg/(s L)

5.4.5 System Performance at different Saturation Temperatures with a Leakage of 1463 µg/(s L)

No Vacuum-Controller Active

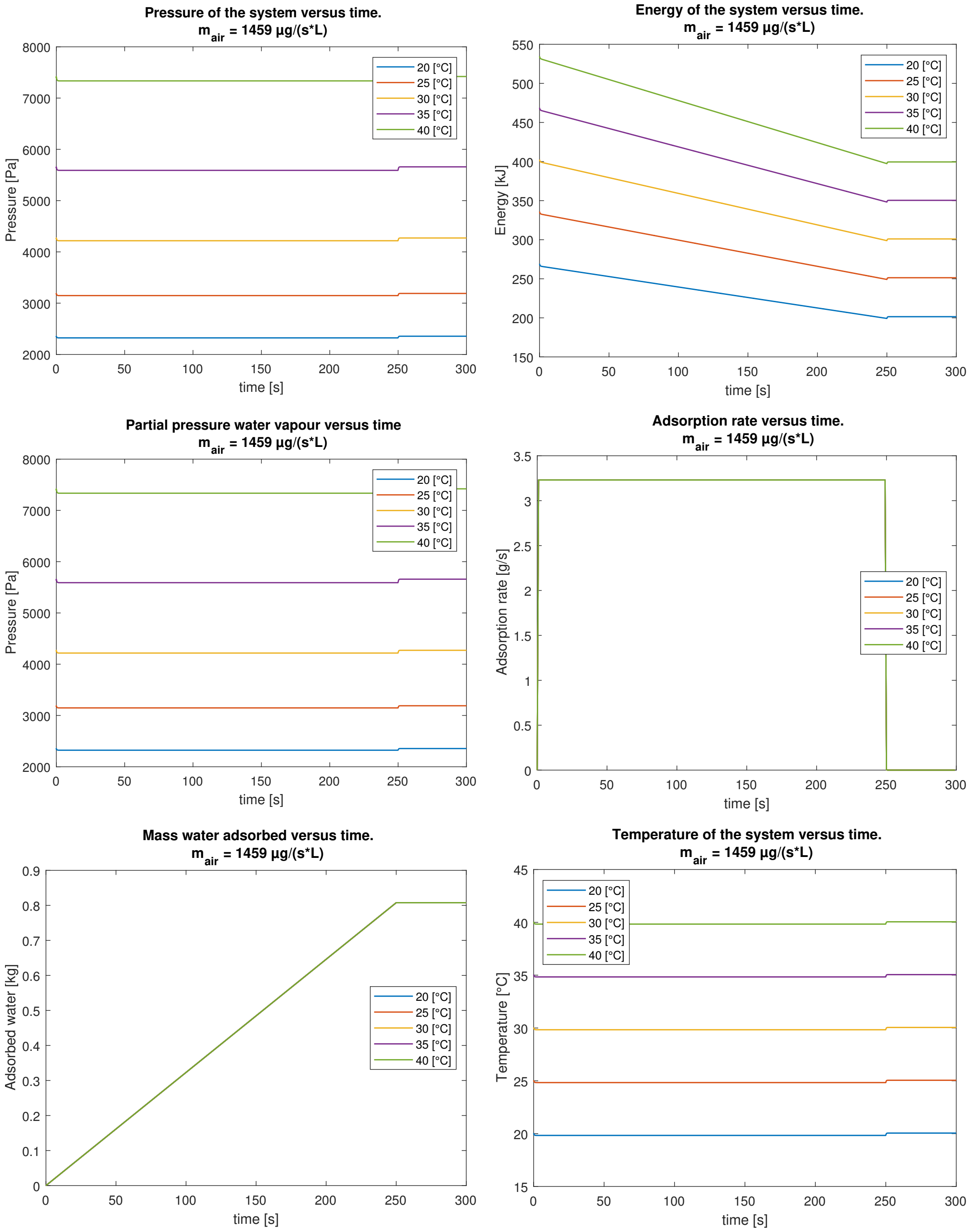


Figure 5.12: Part 1: Overview different parameters at different saturation temperatures and 25 µg/(s L)

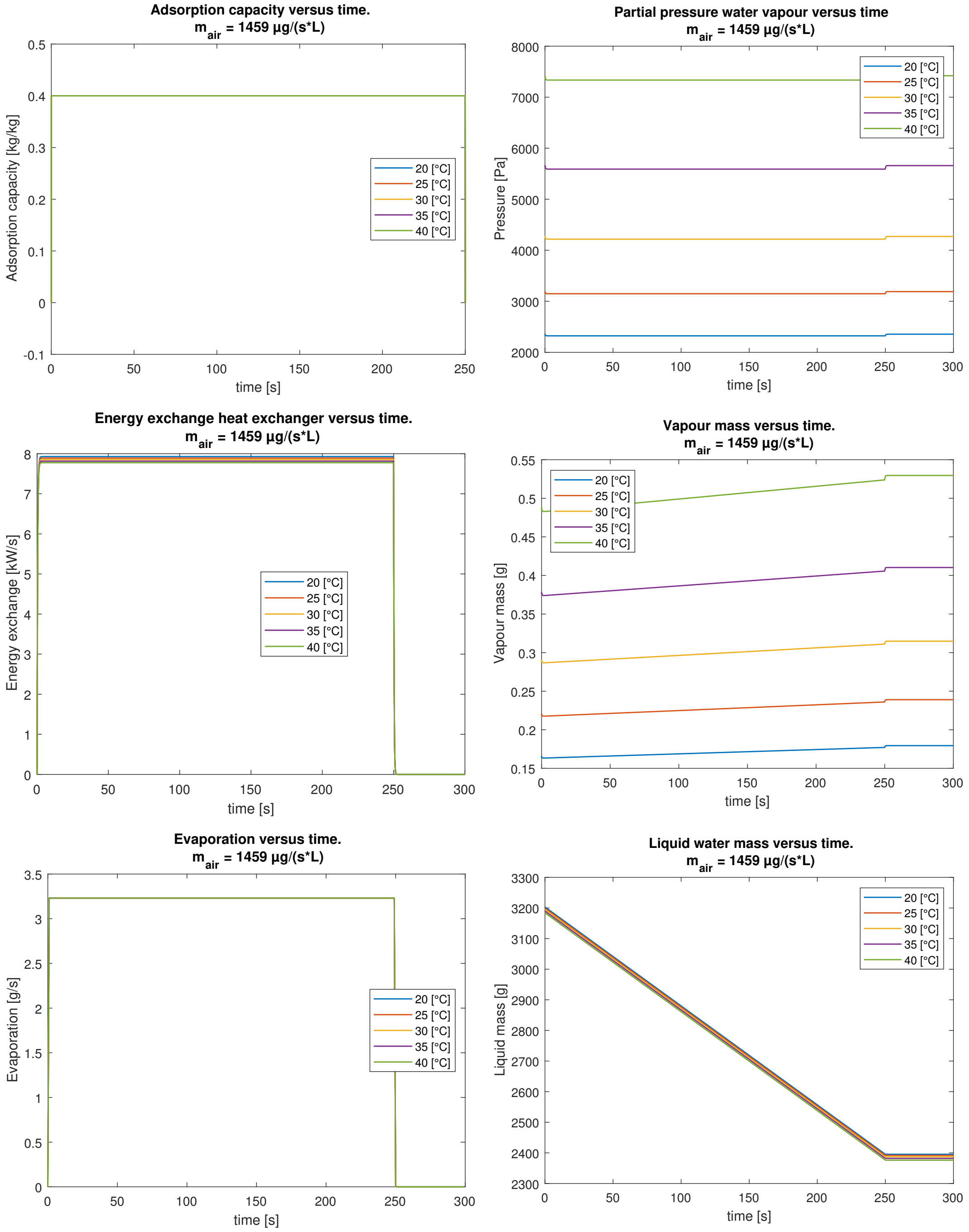


Figure 5.13: Part 2:Overview different parameters at different saturation temperatures and 25 µg/(s L)

Vacuum-Controller Active

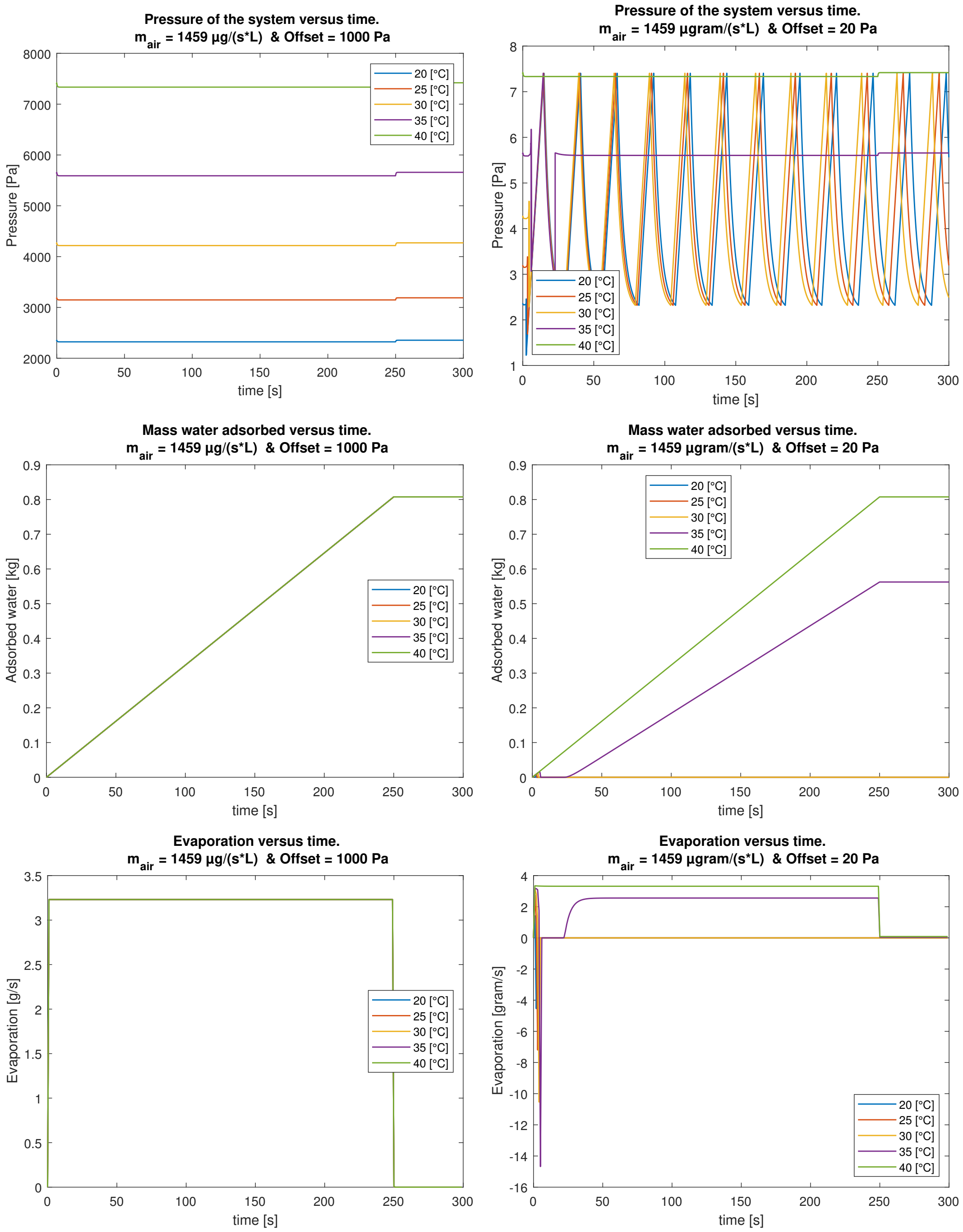


Figure 5.14: Part 3: Overview different parameters at different saturation temperatures and 25 µg/(s L)

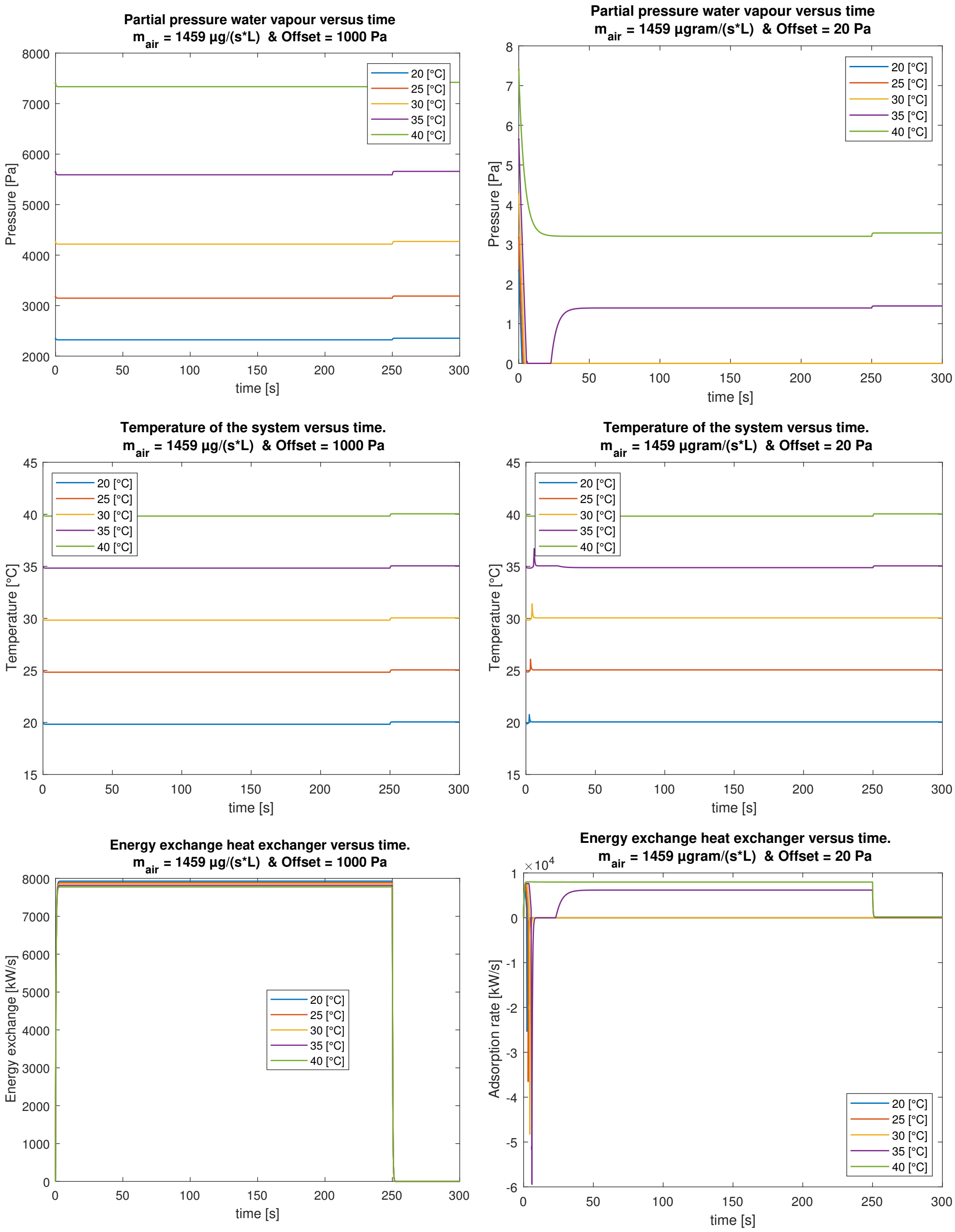


Figure 5.15: Part 4: Overview different parameters at different saturation temperatures and 25 µg/(s L)

5.4.6 System Performance at different Initial Vapour Pressures and no Leakage

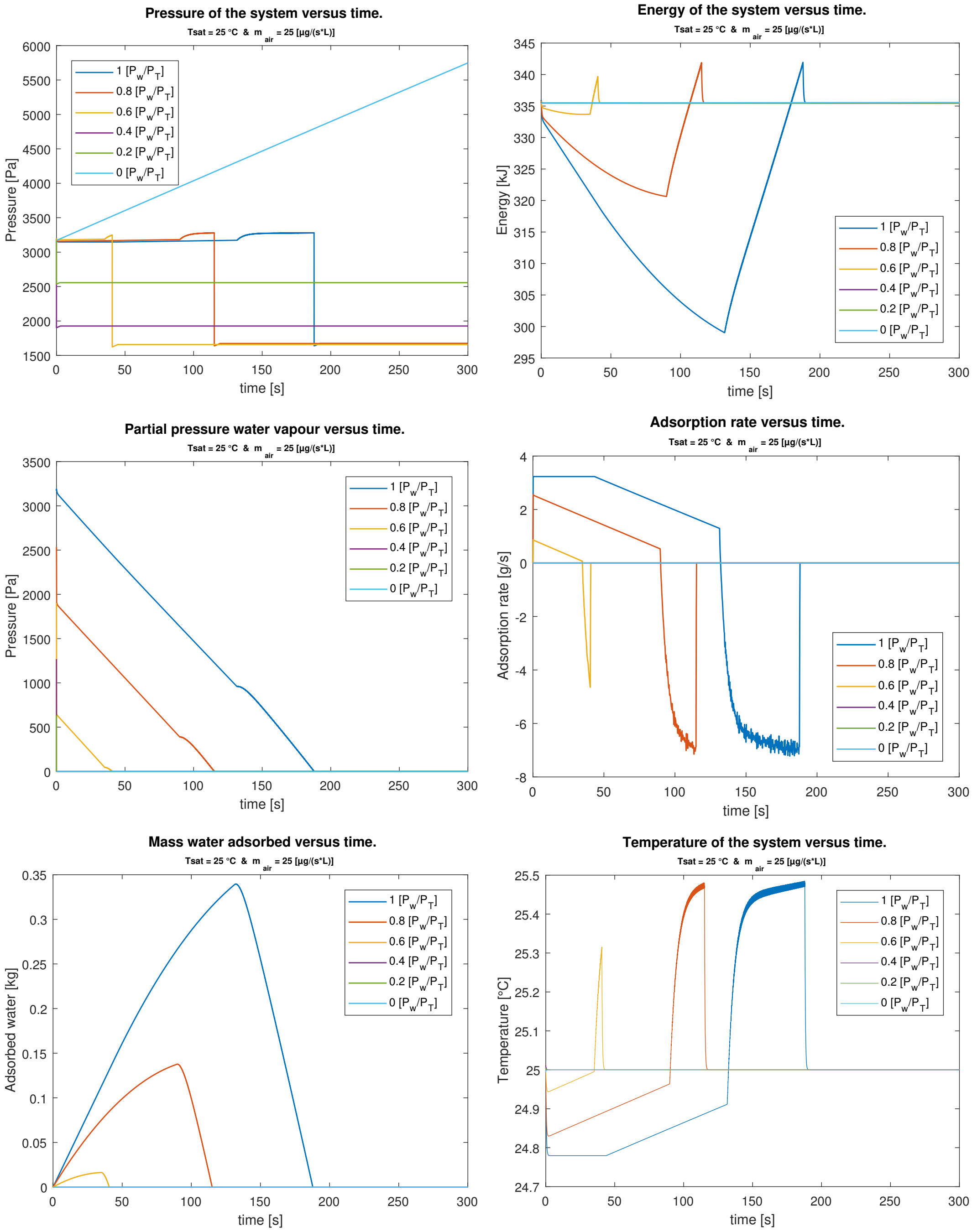


Figure 5.16: Part 1: Overview different parameters at different inital vapour pressures and no leakage

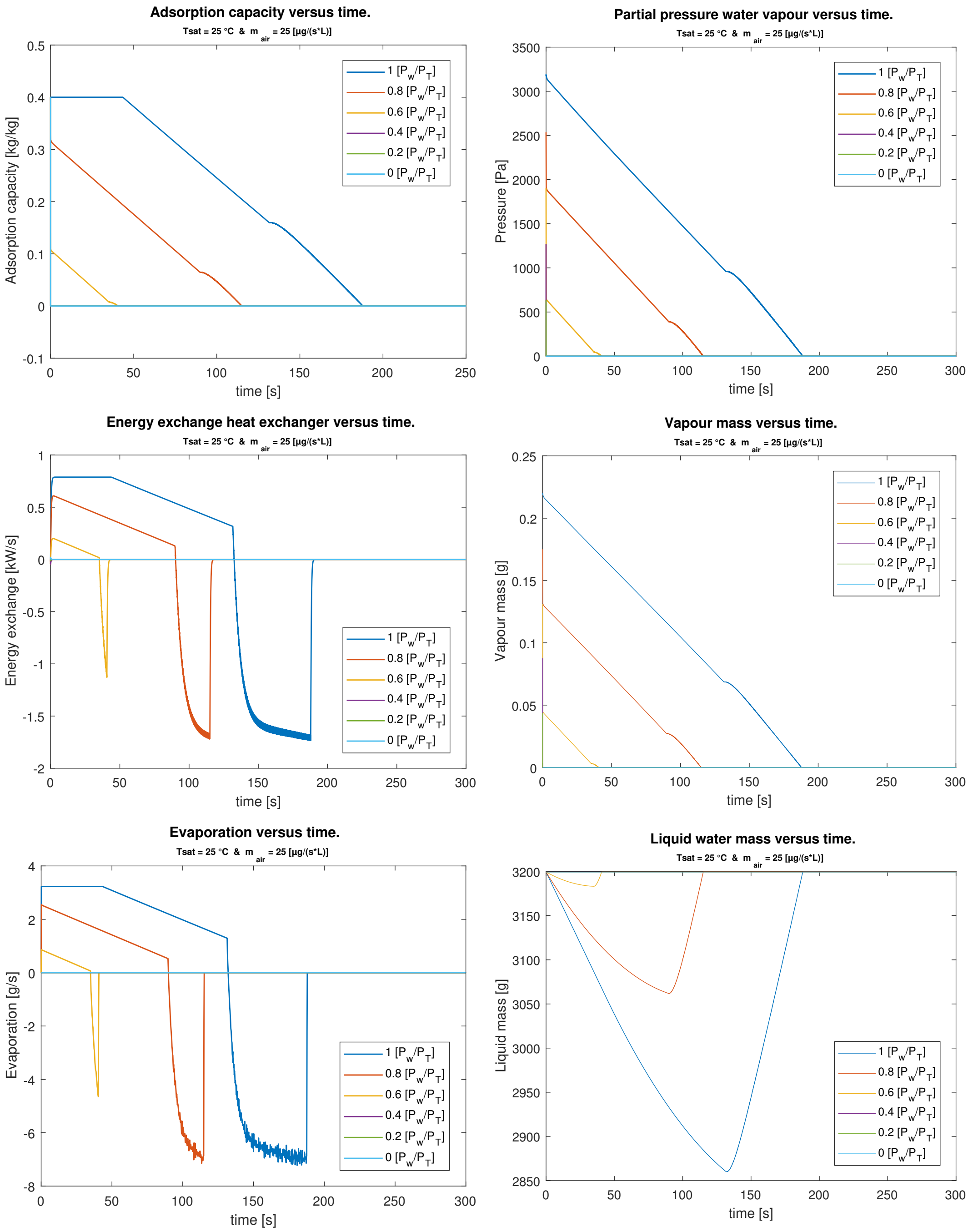


Figure 5.17: Part 2: Overview different parameters at different inital vapour pressures and no leakage

5.5 DEBSA Results while Simulating Phase 1

5.5.1 Radius vs. Temperature and Saturation - Phase 1

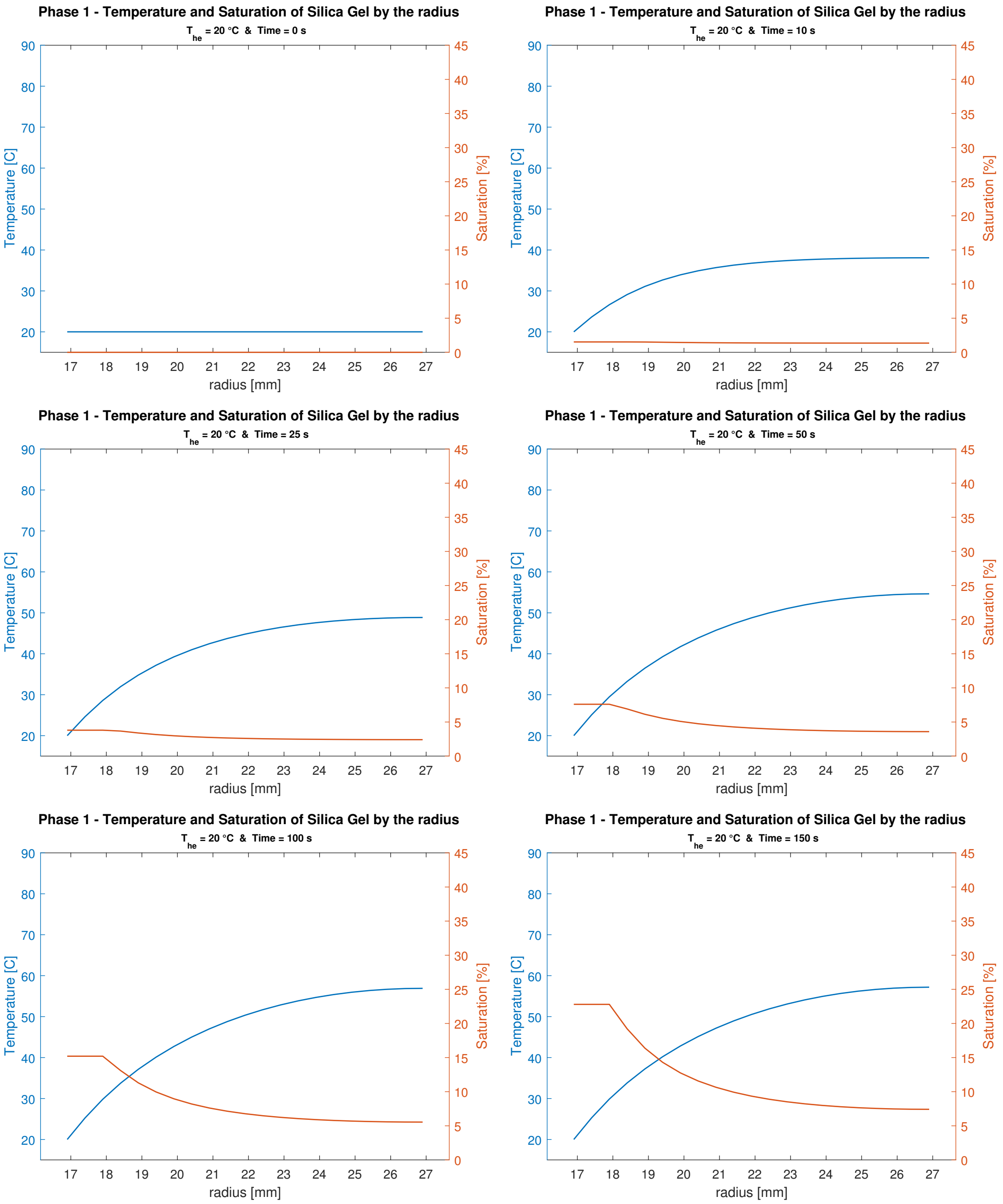


Figure 5.18: Part 1: The temperature cross-section of a silica bed during phase 1. Daily production estimated at 11.32 kg_w/kg_{si}

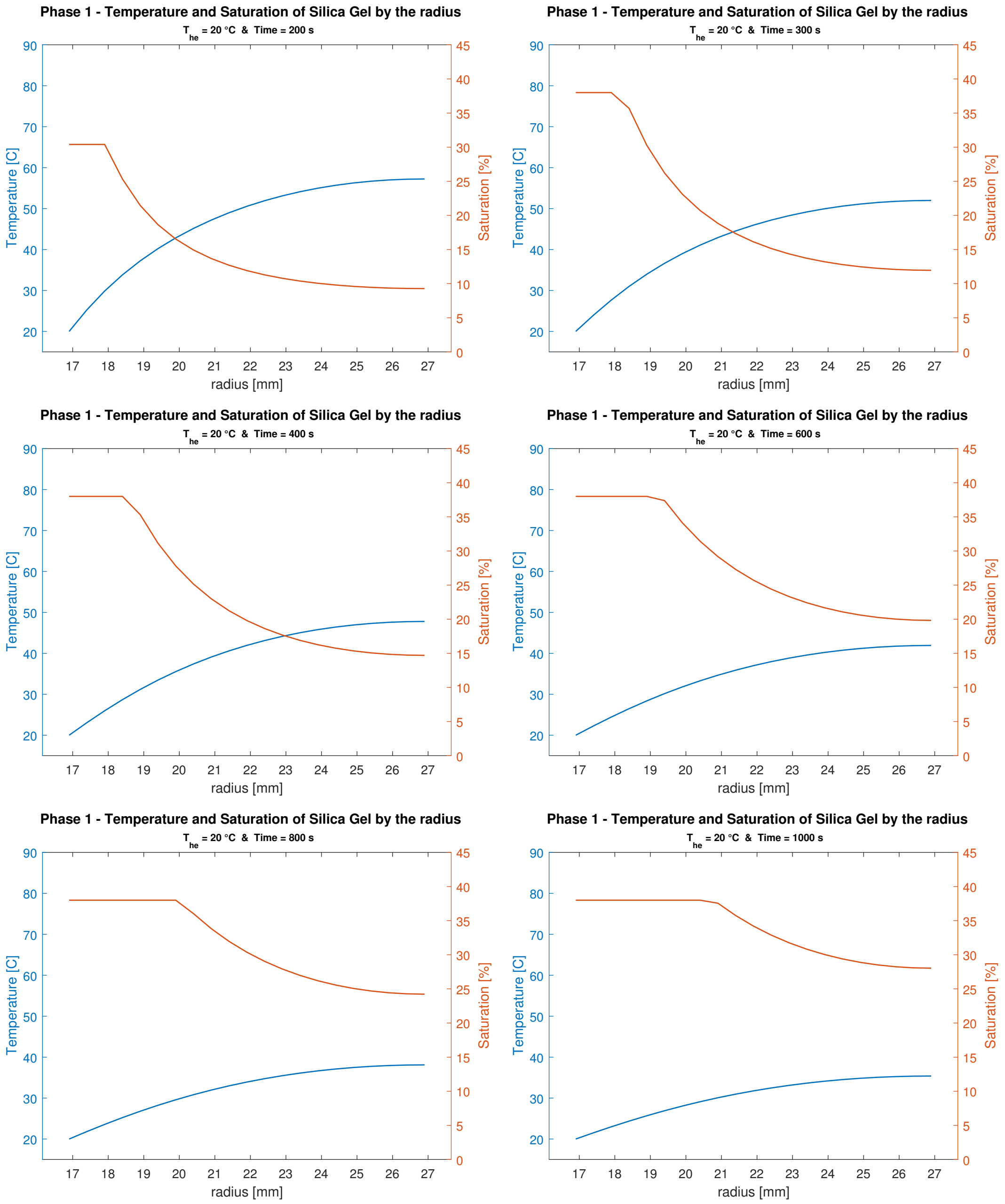


Figure 5.19: Part 2: The temperature cross-section of a silica bed during phase 1. Daily production estimated at 11.32 kg_w/kg_{si}

5.5.2 Time vs. Temperature and Saturation - Phase 1

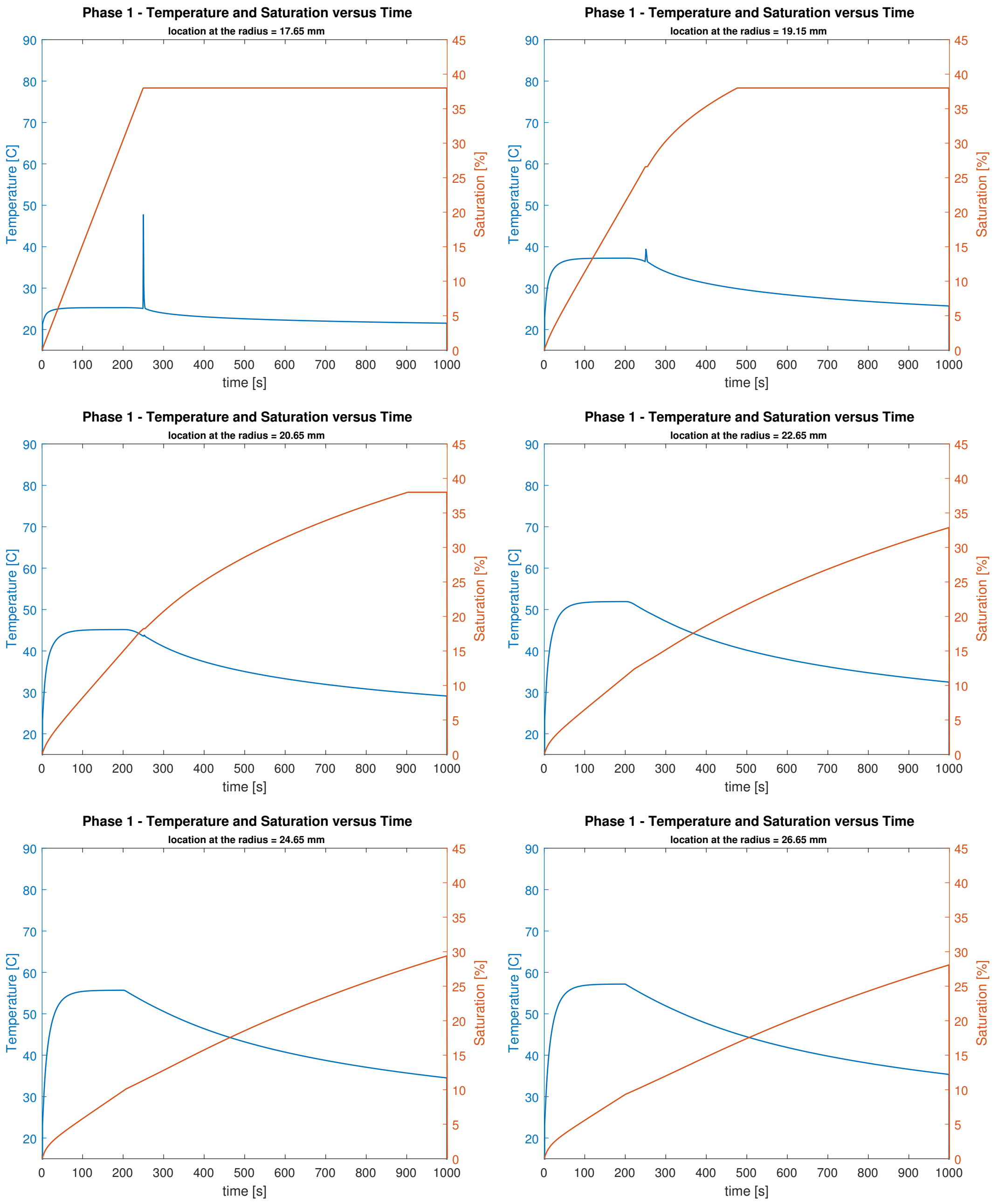


Figure 5.20: Time vs. the temperature and saturation of the silica gel at different locations during phase 1. Daily production estimated at 11.32 kg_w/kg_{si}

5.6 DEBSA Results while Simulating Phase 2

5.6.1 Radius vs. Temperature and Saturation - Phase 2

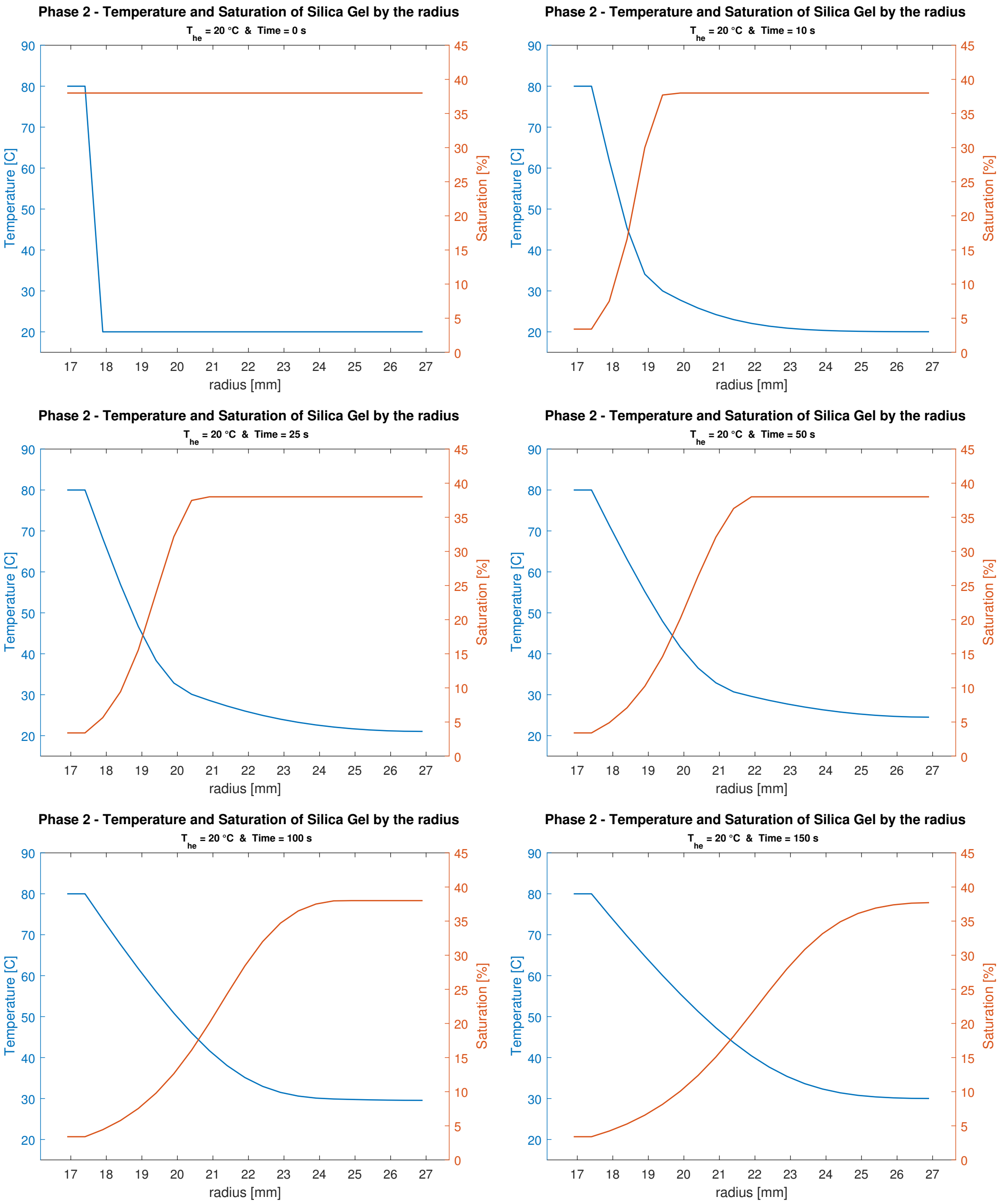
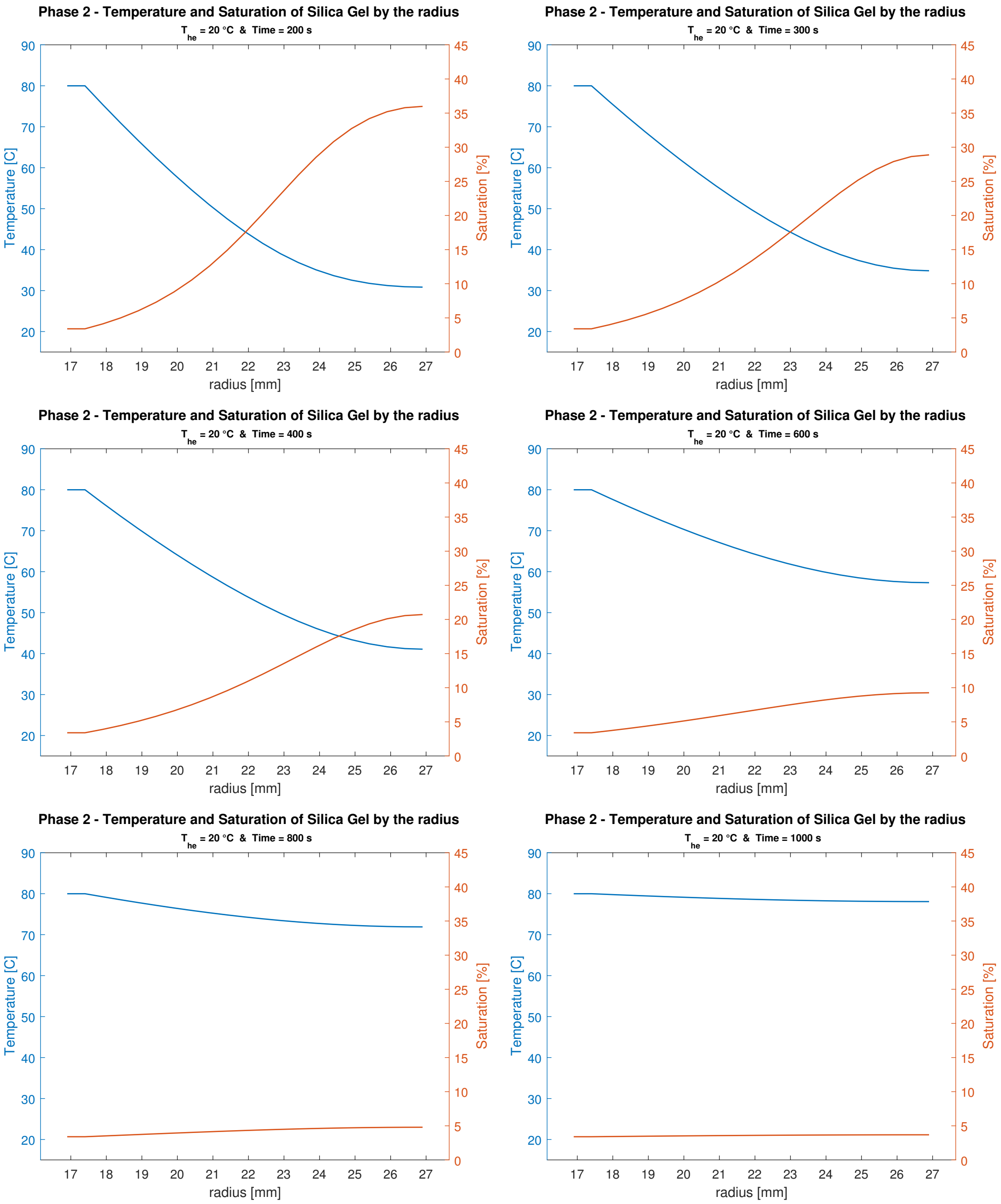


Figure 5.21: Part 1: The temperature cross-section of a silica bed during phase 2. Daily production estimated at 11.32 kg_w/kg_{si}



Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 200 s

Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 300 s

Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 400 s

Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 600 s

Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 800 s

Phase 2 - Temperature and Saturation of Silica Gel by the radius

T_{he} = 20 °C & Time = 1000 s

Figure 5.22: Part 2: The temperature cross-section of a silica bed during phase 2. Daily production estimated at 11.32 kg_w/kg_{si}

5.6.2 Time vs. Temperature and Saturation - Phase 2

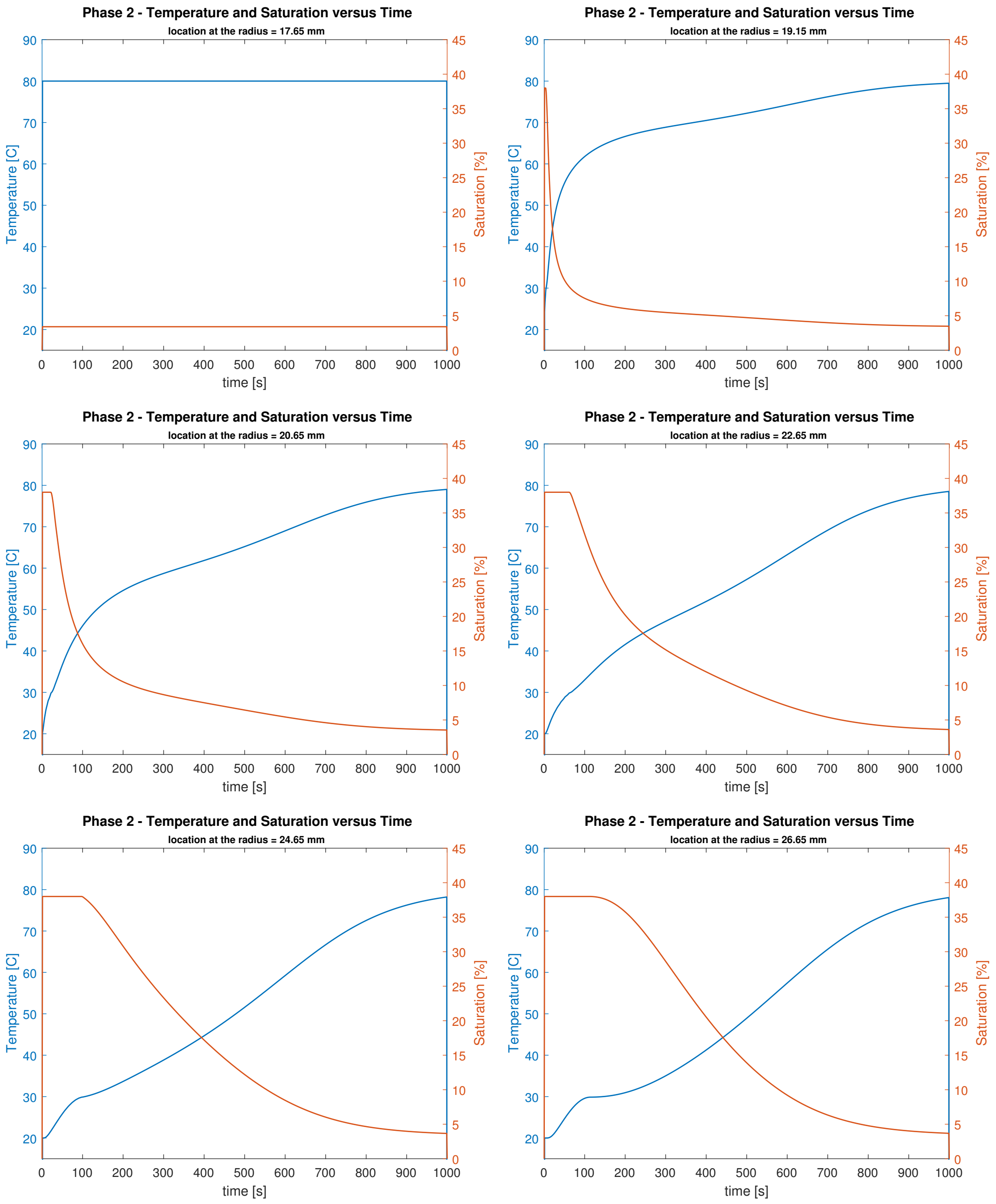


Figure 5.23: Time vs. the temperature and saturation of the silica gel at different locations during phase 2. Daily production estimated at 11.32 kg_w/kg_{si}

5.7 Entropy Creation and Efficiency Analysis of Adsorption-Desalination at T_0s 25 Celcius.

5.7.1 Efficiency Analysis at T_hs 80 Celcius

Entropy Generation [$J/(kg\ K)$]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	519.72	519.35	523.25	529.62	537.40	546.11	555.84
40%	519.42	519.71	524.79	532.50	541.64	551.89	563.79
60%	519.24	520.43	527.22	536.82	547.94	560.82	577.18
80%	519.04	522.02	531.90	544.74	559.89	579.95	610.76

Table 5.1: Entropy generation at differenct configurations

Minimal Work [kWh/m^3]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	0.03	0.38	0.85	1.24	1.52	1.84	2.52
40%	0.04	0.47	0.99	1.37	1.75	2.56	4.58
60%	0.06	0.61	1.16	1.71	3.18	7.33	16.80
80%	0.11	0.83	2.22	9.07	31.74	86.16	193.86

Table 5.2: Minimal work at different configurations

The Exergy Input [kWh/m^3]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	43.08	43.39	44.19	45.10	46.03	47.07	48.55
40%	43.06	43.52	44.45	45.47	46.61	48.27	51.27
60%	43.06	43.71	44.82	46.17	48.56	53.77	64.61
80%	43.10	44.06	46.27	54.19	78.10	134.19	244.44

Table 5.3: The exergy input at different configurations

The Second Law Effiency [%]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	0.06	0.74	1.68	2.48	3.05	3.48	4.08
40%	0.06	0.74	1.67	2.46	3.01	3.39	3.86
60%	0.06	0.73	1.65	2.43	2.89	3.04	3.07
80%	0.06	0.73	1.60	2.07	1.80	1.22	0.81

Table 5.4: The Second Law efficiency at different configurations

Gained Output Ratio (GOR) [-]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	51.09	48.55	46.03	43.54	41.09	38.71	36.43
40%	51.02	48.25	45.50	42.79	40.12	37.56	35.15
60%	50.91	47.82	44.75	41.71	38.76	35.97	33.41
80%	50.72	47.08	43.45	39.87	36.48	33.40	30.74

Table 5.5: The GOR at different configurations

Performance Ratio (PR [-]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	4.81	4.57	4.33	4.09	3.85	3.62	3.41
40%	4.80	4.54	4.28	4.02	3.76	3.51	3.28
60%	4.79	4.50	4.20	3.91	3.63	3.36	3.12
80%	4.78	4.43	4.08	3.74	3.41	3.11	2.86

Table 5.6: The PR at different configurations

5.7.2 Additional Efficiency Analysis at T_hs 60 Celcius

The Exergy Input [kWh/m^3]

Recovery\Feed salinity	5 g/kg	20 g/kg	35 g/kg	50 g/kg	65 g/kg	80 g/kg	95 g/kg
20%	38.98	39.23	39.95	40.78	41.62	42.57	43.95
40%	38.97	39.34	40.19	41.12	42.15	43.70	46.59
60%	38.97	39.52	40.53	41.77	44.03	49.11	59.80
80%	38.99	39.84	41.93	49.69	73.44	129.34	239.42

Table 5.7: The exergy input at different configurations at T_h: 60 Celcius

5.7.3 Entropy Creation Distribution at T_hs 80 Celcius

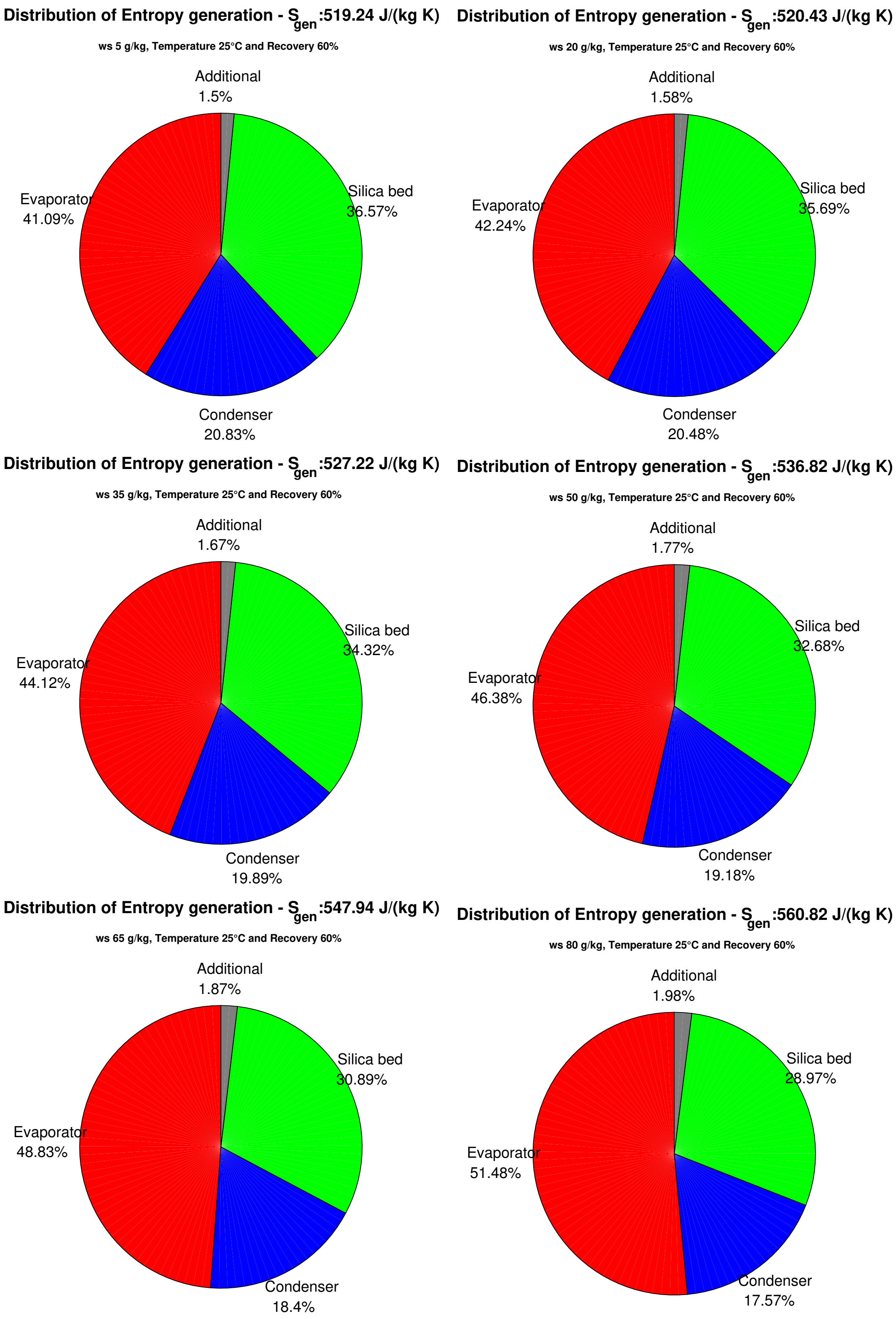
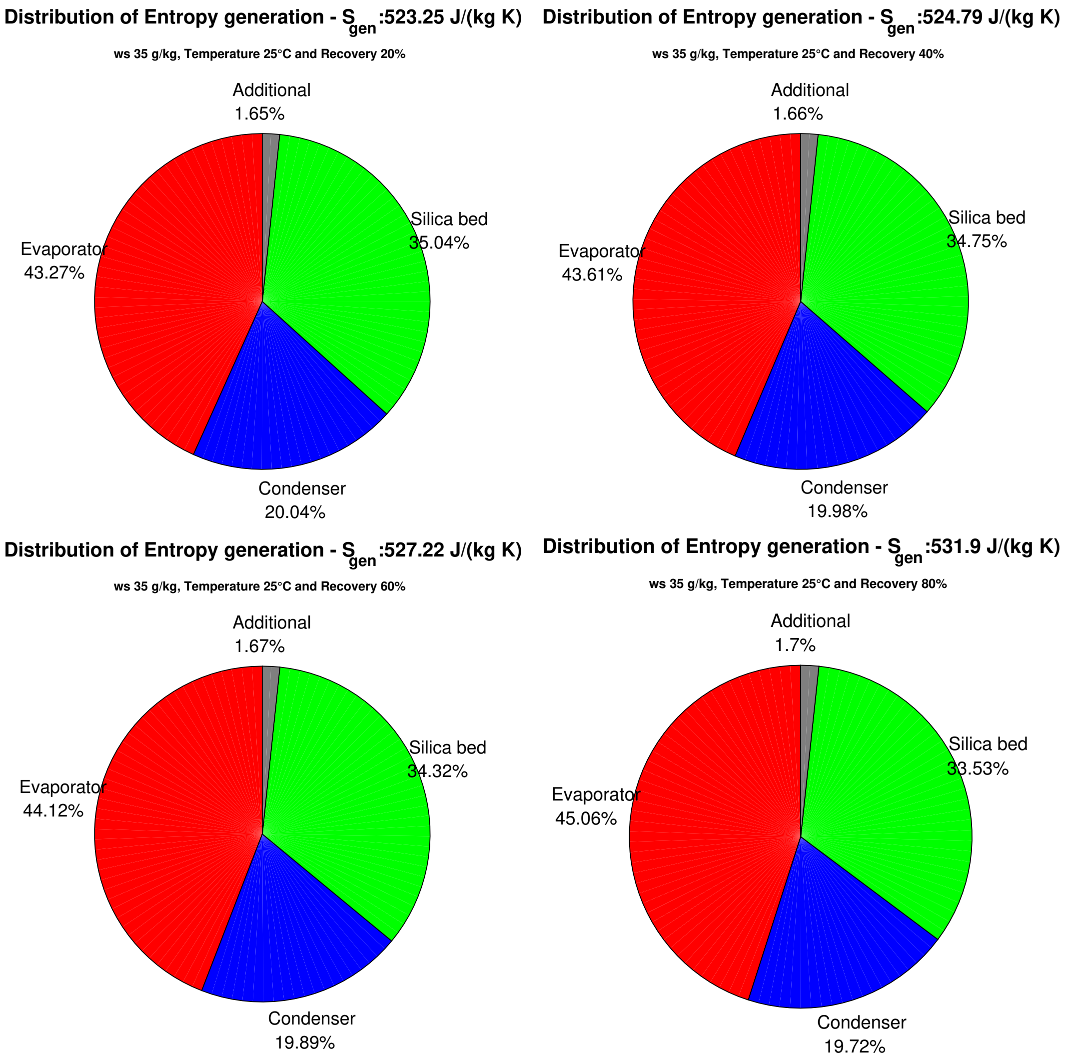


Figure 5.24: The distribution of entropy generation by element at different feed salinities



Distribution of Entropy generation - S_{gen}:523.25 J/(kg K)

ws 35 g/kg, Temperature 25°C and Recovery 20%

Distribution of Entropy generation - S_{gen}:524.79 J/(kg K)

ws 35 g/kg, Temperature 25°C and Recovery 40%

Distribution of Entropy generation - S_{gen}:527.22 J/(kg K)

ws 35 g/kg, Temperature 25°C and Recovery 60%

Distribution of Entropy generation - S_{gen}:531.9 J/(kg K)

ws 35 g/kg, Temperature 25°C and Recovery 80%

Figure 5.25: The distribution of entropy generation by element at different recoveries

6 | Discussion

6.1 How does the Desalination Process of Adsorption Desalination Work?

Most papers that discuss Adsorption Desalination do not go into the exact details about the desalination process. Most papers tell that silica gel is located inside the device and that it creates desalination. In fortunately cases it is possible to find a line like this about the process: *'Owing to the high affinity for water vapour, unsaturated silica gel contained with the designed beds rapidly draw water vapour from the evaporator, lowering its vapour pressure of seawater to initiate boiling'*. While these line gives some information about the desalination process, it does not tell the complete story. It does not tell how the mass transfer takes place, what the exact composition of gas inside the device should be or what the minimum speed is of the process. desalination is the process of removing salt from a saline source. Like any process, to keep the process operational an equilibrium should be found. There are four different colligative properties that distinction different desalination process by the chemical equilibrium. The first is boiling point elevation, the second the freezing point depression, the third the osmotic pressure and the fourth is vapour pressure lowering [36]. Membrane desalination techniques like Reverse Omosis are osmotically driven Multistage Flash, Multi-effect distillation and mechanical vapour compression are thermal systems who desalinate by boiling point elevation. Eustatic Freezing Desalination is of course by freezing point depression, and Membrane Distillation is desalination process that functions of vapour pressure lowering. So which colligative property is the driving force for Adsorption Desalination?

While, according to the results in section 5.4, it appears that Adsorption Desalination depends on two properties. Adsorption Desalination is a boiling point elevation and vapour pressure lowering desalination process. It depends on the configuration/construction of an AD-device which colligative property is dominant. When no heat exchanger is present in the evaporator or non-functional, the whole desalination process depends solely on vapour pressure lowering. At a certain point, the desalination process stops since equilibrium is found between the sorption characteristics and the vapour pressure. When a heat exchanger is introduced, an equilibrium is found before the sorption characteristics of the silica gel are negatively influenced, depending on the circumstances. At the beginning of the evaporation, before the equilibrium is found, the main driver of evaporation is vapour pressure lowering; after that, it is boiling. When the AD-device works with the feed and the concentrate in a batch operation, the average salinity in the evaporator increases. This increase influences the vapour pressure, and as a result, no equilibrium is found.

The pressure is lowering inside the evaporator, but slower than with the case where the heat exchanger is absent. As can be seen in section 5.4, the influence is almost negligible. The ratio between the volume of the evaporator and the adsorption capacity of a silica bed determine how much the decreasing vapour pressure influence the desalination. When the system doesn't operate in a batch mode, but continuously and with multiple beds, the pressure stays constant continuous inside the evaporator. Boiling point elevation is the dominant mechanism in such a case.

The mass transfer can take place by diffusion, but the dominant mechanism is by a pressure difference. The pressure is lowered due to the intake of vapour by the silica gel around the silica bed. The result is mass transport to these areas. Diffusion can only be the dominant mass transport mechanism when no adsorption or desorption takes place. However the same can be said for advection or convection. In reality, the only driving force of mass transport of vapour inside the system is by the pressure gradient. As a result, the evaporation is always equal to the adsorption rate as can be seen in the results of section 5.4.

Things seem to change when leakage is introduced. No vacuum system is perfect and therefore is valid to simulate the process during a situation involving leakage. As can be seen in the result of section 5.4, an introduction of leakage slows down the evaporation rate. The evaporation rate is slowed down because the silica gel can now less effectively lower the pressure inside the system since a leakage exists. Depending on the size of the leakage, this lower evaporation rate can influence the performance of the system. Since the evaporation rate depends on the adsorption, but the adsorption rate is independent of the evaporation rate, the decrease does not influence it until a certain moment. When the vapour pressure inside the system has dropped till such an extent, the low vapour pressure starts to influence the adsorption rate negatively. Firstly, the adsorption rate slows down till at a moment equilibrium is found. At that moment the evaporation and the adsorption rate are both equal to zero. The situation is equal to the situation in an AD-device where no heat exchanger is present inside the evaporator. Unfortunately, in this case, it is not a stable equilibrium. Since the temperature of the feed is still lower than the temperature of the heat exchanger, energy transfer takes places. This energy however no longer feeds the evaporation, but only increase the temperature and the pressure. The result is that condensation takes places. The condensation is the death stroke to the performance of the system, and a complete break down of performance is the result.

Due to the condensation, the vapour pressure is lowered further. The further lowering of the vapour pressure decreases the sorption characteristic of the silica gel further. The result is that the silica gel starts to desorb the water vapour. The further introduction of water vapour increases the pressure and temperature further since water vapour has a higher energy level compared to liquid water. More condensation is the result which decreases the sorption characterised further. The whole system comes crashing down. The silica gel is sucking itself dry at the end and is also the main driver at the process. At that moment the heat exchanger is pumping energy out of the system again, trying to save it, but it has no result. There is only one important remark to make about this analysis. In practice, it can be less dramatic. One of the key assumptions of this model is that the temperature of the gas and the liquid are equal since the whole system is saturated and there a no temperature difference across the system (liquid and gas). In reality, a difference in temperature can be the case and can influence the final result. The heterogeneous difference of temperature, how infinitesimal it may be, can act as a damper and maybe prevent in some cases a breakdown of performance. A 3-dimensional model based on a finite element analysis could do the trick.

The results of subsection 5.5.1 that the sorption characteristics are not constant during the adsorption phase and that the sorption energy can create significant problems during the adsorption phase. The amount of sorption energy is larger than the energy necessary to heat the silica until 80 degrees and can slow down phase 1 (the adsorption phase) or decrease the performance. Further, subsection 5.6.1 showed that the desorption already starts at the beginning of the phase. It could be more practical to combine phase 2 and 3. These combinations could decrease the cycle time. There are two main reasons. The first is desorption and condensation in the condenser simultaneously would keep the pressure low and therefore keep the sorption capacity low of the silica. A characteristic necessary for the desorption phase. Secondly, the vapour transport from the silica bed till the condenser can start earlier, therefore decreasing the time necessary in phase 3 to have a complete mass transfer. The mass transfer is also pressure difference driven since the contraction of gases by a lower temperature creates a pressure difference, just like with a Stirling cycle. Further, the density of water is higher than that of vapour. Therefore condensation creates a further pressure difference.

In the end, Adsorption Desalination is a desalination technique driven by boiling point elevation and vapour pressure lowering where mass transport is driven by pressure difference due to adsorption/desorption and density differences.

6.2 The Characteristics of Silica Gel

In section 3.4 an analysis of silica was done based on different literature studies. Silica gel appears to be an incompletely dehydrated polymeric structure of colloidal silica acids. It means that it can adsorb other elements due to the fact it can make connections in the form of hydrogen bonds, polar bonds or weak electron bonds. Since water is a bipolar molecule, it can especially adsorb water vapour extremely well since this molecule can create hydron bond efficiently and multiple layers can be adsorbed due to the fact it is has a bipolar structure. When silica gel is constructed as a material with many pores, it can achieve an extremely high specific surface. A specific surface equal to the specific surface of human lungs. Since the adsorption capacity depends heavily on the available surface, see Henry's law, an high specific surface increase the adsorption. Therefore, certain silica gels qualities can adsorb water until 40% of their own bodyweight.

Silica gels can adsorb water vapour better than its greatest competitor, Zeolite. Zeolite can at is maximum only adsorb 12% of its weight as water (the density is in the same range), and the desorption temperature is around 250-300 degrees Celcius. Therefore one could argue that silica gel is always the better choice when choosing a sorbent for Adsorption Desalination. However, there is a negative element in the sorption characteristics: the uncertainty. Due to the crystal structure of Zeolite, the pore width and therefore specific surface can be determined and manufactured specifically. The same cannot be said for silica gel. By silica gel, there is only a probability. The only way to know the specific surface of a silica gel is by actively measuring it. A manufacturer cannot even guarantee that the silica gel always has the exact specific surface. An example could be seen in section 3.4, where silica gel from the same type but a different batch, had different sorption characteristics.

Besides uncertainties about the sorption characteristics of silica gel, there are also problems involving the bad conductivity of silica gel. Since the adsorption and desorption processes are thermal processes, silica gel endures high thermal energy changes. Therefore a great thermal conductivity is essential, something silica gel lacks. As can be seen in the results of subsection 5.5.1 and 5.6.1, the transport of energy is not only essential for heating the silica gel till 80 degrees Celcius or cooling it down to the desired temperature. Energy transport is also essential for the adsorption and desorption of water vapour. During adsorption, since the water in the semi-solid state at the surface has less energy than as vapour, a large amount of energy is released at the silica gel. Silica gel is heated up till during the adsorption, while it is essential to keep the silica gel cool to prevent the loss of sorption capabilities. At desorption, the problems are reversed. The desorption of vapour cools the silica gel, which increases the sorption abilities while it is necessary to keep those down to ensure a successful desorption phase. Different solutions have been tried like mixing the silica bed with metals or creating silica gel Zeolite blocks. It did result in a better conductivity, but sorption abilities were sacrificed. Switching to a solvent like a Zeolite could be a solution for the problems involving thermal conductivity. It does depend of course on the type of Zeolite that is chosen.

As said earlier, the sorption characteristics depend heavily on the temperature of the silica. Beside the temperature also the partial pressure of the vapour influences the characteristics. This dependency on vapour pressure can be a weakness in a vacuum system. The idea of AD is to evaporate a saline source around room temperature to prevent scaling and erosion problems. Therefore the pressure inside the vacuum vessel operates between 1000 and 4000 kPa. As can be seen in Figure 3.4, but can also be calculated using Equation 3.1, depending on the temperatures, a change in pressure influence greatly the sorption capabilities. Especially, the lower the temperature of the silica, the greater the influence of a change in vapour pressure. As the results of section 5.4 shows, a disturbance in the vapour pressure can have a negative consequence. Consequences like desorption of vapour a the wrong moment which can cause critical breakdown of performance. The lower the pressure conditions in a vessel, the more unstable the sorption characteristics of silica gel become.

The last point that should be discussed is the degradations of the silica gel. As told in section 3.4, sometimes the claim is made that silica gel has an infinite lifespan due to the fact no chemical reactions occurs during the adsorption and desorption phase. This process is a physical process and therefore does not degrade the quality of the silica gel. The reality is different. Silica-gel does degrade and due to a different process. Fragmentation occurs due to high thermal stress. Since the silica gel is constantly heated up and cooled, it endures much thermal stress. Therefore during the lifespan of silica gel, the sorption characteristic degrades. A second important element in the degradations of silica gel is the pollutions by metal ions. These ions cause blockage in the pores which decrease the specific surface of the silica gel. Other processes could also block the pores like capillary condensation. As told before, an example exists where adsorption cooling devices had to be shut down after one year of operation due to a loss in sorption characteristic. These devices operate in a clean and controlled environment. The only pollutions could have come from the refrigerant (which is demi water with a possible chemical) or by air leakage. It is reasonable to believe that the silica gel located in Adsorption Desalination has a higher change on degradations because in the feed and brine of a saline source more pollutants are present that in the air or demi water. However, is the loss of sorption characteristic a single event and does it stabilise or does the silica gel keep losing its sorption capacity?

Silica gel has been praised in Adsorption Desalination since it has a high affinity and it enables the use of a low-grade waste heat source as the primary energy source. However, there also negative sides for using silica gel like the thermal conductivity, sorption instabilities at vacuum conditions and the degradations. Therefore, when designing an AD-device, one should also examine other possible sorbents.

6.3 The Theorectical Energy Consumption of Adsorptoin Desalination

As discussed in the literature, there is no absolute energy limit. There is a limit depending on the method that is used, the temperature of the feed, salinity and recovery. As was shown section 3.6, the thermodynamic limit that is discussed in most probably based on the least work method. With this method, the least amount of energy that is necessary to desalinate a saline source at a set temperature and salinity when the recovery goes to zero, can be calculated. However, this method does not distinguish between methods. The least amount of work method can give the wrong impression. According to this method, the lowest recovery is always the best solution when desalinating a saline source. As one can observe in section 5.7, this is indeed the case. However, the difference between the exergy input between recoveries at 20% and on at 80% is minimal for specific salinities. Every desalination method has its weaknesses. Some methods are more suitable for brackish desalination at a low recovery while others are more suitable for brine treatment at high recoveries.

As can be observed in section 5.7, the energy consumption of Adsorption Desalination is around 44 kWh/m^3 in most cases. The average of the matrix display in Table 5.3 is 58.18 kWh/m^3. This higher value is due to the higher energy demand at the 80% recoveries at the higher salinities (65 g/kg or higher). The energy demand of the model is equal to the value that was reported by the researcher of NUS [47]. A primary energy input of 39.80 kWh/m^3 was reported for the most efficient configuration. This configuration was probably one where the recovery went to the lowest point possible and a heat source of 60 degrees Celcius as can be seen in Table 5.7. The model seems to simulate energy consumption accurately. However, it would be interesting to research to the location of entropy creation into more detail since at this moment it is only divided into three main elements (the others are almost negligible).

The three elements are the evaporator, condenser and silica bed. The evaporator and condenser together are the largest producer of entropy. The reason for this is that the mass to recover the thermal energy from the condenser is relatively large compared to the mass necessary to transport the energy necessary for the silica bed. However, the silica bed is also a significant producer of entropy. A critical remark about the silica bed. It seems that entropy creation seems to keep constant. It even becomes lower at higher salinities and recovery levels. The silica bed is semi-independent of the recovery and the salinity of the feed. The additional entropy creation existing out of the pumps, expansion valve and booster stays almost constant. The mechanical work required for Adsorption Desalination is probably also semi-independent of the recovery and the feed salinity.

In the end, Adsorption Desalination seems to best suitable for brine treatment at high recoveries. The efficiency is indeed smaller, but this comes probably since the chemical energy of the brine is not recovered. The entropy creation stays in the same range of magnitude. The most is to gain for brine treatment. At other configuration, it can still be used, however the entropy creation relatively high compared to the minimal work that is necessary. Of course, if there are almost no costs involves when using waste heat and the investment cost are no problem, it shouldn't cause any problems. It only seems a little bit too much. Using AD for brackish water desalination at a low recovery would be the same as putting a rocket engine on a motorbike. It gets the job done, but it is not an efficient process.

6.4 Designing an AD-Device

When designing an AD-device, there are three main important objectives. First, make it vacuum-tight. Minimise the chance on a leak. Secondly, ensure a maximum average thermal conductivity for the silica bed and thirdly, maximise the heat recovery to minimise the total thermal energy consumption.

The reason that the chance on leakages should be minimised is due to the great influences a leakage can have on the total performance of AD. As is proven in section 5.4, the evaporation rate is directly connected to the adsorption rate of water vapour by silica gel. A leak would decrease the evaporation rate and therefore decrease the water production of the device. A vacuum controller could keep the damage minimised, but there are limitations. Depending on its quality, its influence can be minimal and also depends on the accuracy of the sensors. Furthermore, the activity of the pump increases power consumption and makes it, therefore, less compatible with other desalination technologies.

Ensuring maximum average thermal conductivity in the silica bed is crucial for two main reasons. First, it increases the performance of the whole design. If it is possible to relocate the adsorption energy release efficiently during adsorption, the adsorption characteristics are less negatively influenced. The same applies during the desorption phase. Desorption requires energy and can only occur when the silica gel is heated, a process also in need of energy. The better the conductively of the bed, the faster the adsorption an desorption process can occur. The short the cycle time, the higher the water production of a device is. The second reason is to minimise the thermal stress the silica gel endures and therefore minimalise the probability on degradations. Increasing the average thermal conductivity can be done by two different methods. Increasing the conductivity of the silica gel composition by mixing it with other materials with a higher conductivity as discussed before, other optimising the dimensions of the heat exchanger. These solutions can include finding an ideal thickness for the silica bed or by using tools like fins attached to the heat exchanger and placed inside the bed. In the end, the optimisation would depend on the maximising the cycle time that can be acquired while minimising the material costs involved.

The third main concern is to maximise heat recovery. The requirement to maximise heat recovery is influenced by the desire to increase energy efficiency. One could argue that heat recovery is not the main concern since the thermal energy used by AD is waste heat and is free. If this statement is valid is discussed later in this discussion, but minimising the thermal energy consumption has another benefit than beside a lower thermal energy consumption. It also lowers the electrical energy consumption of a device. Most electrical energy goes to the pumps which are necessary to displace the heating and cooling water inside the device. As one can tell when looking at a simple formula for the consumption of energy by a pump, lowering the discharge by 50% translates into a lower energy consumption of 87.5% (assuming the static head is negligible and dynamic head linear).

$$\begin{aligned} E &= \frac{Q\ H\ g\ \rho}{\eta pump} \\ H &= C_d\, Q^2 \qquad\qquad C_s = 0 \\ E &= \frac{C_d\ H\ g\ \rho}{\eta pump}\, Q^3 \end{aligned} \tag{6.1}$$

Besides these three main concerns, other design requirements are necessary to keep in mind when designing an AD set-up or plant. Because the silica seems to degrade or gets clogged due to pollutants, it should be made simple to clean or replace them. Every time replacing the device completely or just only the silica bed doesn't seem to be a sustainable solution. A possible solution could be that the silica gel is placed as stacks inside the vessel. However, the solution for this problem shouldn't degrade the quality concerning the vacuum conditions. It shouldn't increase the probability of leakages. Another concern is the compactness of the whole device. A lot of different elements are necessary, and therefore great quantities of materials besides the silica gel are also necessary. The daily production of silica gel compared to its weight would always probably be lesser than with technologies as Reverse Omosis. An AD-plant shall therefore always be bigger than a desalination plant using another technology while having the same daily water production. Since the volume a technology requires at a location would always be of some concern (depending on the location, this is a large or small concern), compactness is element a designer should always strive at.

As told in section 3.7 and is discussed later in this discussion. High investment costs are involved with Adsorption Desalination. To minimise these costs should be a goal. A possible solution could be creating a modular design. The benefit of the modular design is that it enables the possibility for mass construction and therefore decreasing investment cost. It also enables the possibility to decrease maintenance costs since parts worldwide can easily be replaced.

As for last a reflection should be made at the failure of creating a working experimental set-up in the laboratory. This reflection is made in another part of the discussion. In section 6.8 this element is discussed.

6.5 Potential of Waste Heat for Adsorption Desalination

It is a valid statement that the future of Adsorption Desalination is intertwined with the future of waste heat. Indeed, AD can also receive its thermal energy from solar or geothermal, but there are some conditions involving locations with those other sources. Solar would only function at one part of the day and at locations of the world where many sun hours are present annually. Geothermal is a costly adventure since an expensive underground infrastructure is necessary to collect the energy. The location also strongly influence the use of potential. Areas, where more volcanic activity is present, are areas where the potential to use thermal energy are more significant. Areas like Iceland or Japan. Waste heat, in contrast, is available worldwide in populated areas with industries. These are areas mostly located around the coasts and have large water needs. One could argue that therefore Adsorption Desalination is a perfect fit for those locations. Significant production of waste heat in combination with extensive water extraction. A perfect fit is necessary since Adsorption Desalination can only compete with other technologies if it has easy access to cheap thermal energy. So one can conclude that the future of waste heat heavily influence the future of AD. Therefore a discussion about the future of waste heat is necessary.

Looking at the numbers it is easy to assume that investing in waste heat is a reasonable action. A lot of waste heat is available worldwide because 72% of the global energy consumption is transformed into waste heat. However, a distinction should always be made between the thermal energy that is physically present and the thermal energy that economically and technically can be reused. A distinction that can sometimes be difficult to make because waste heat is categorised roughly. 63% of all waste heat is categorised as low. A category that includes everything below 100 degrees. It could very well be that almost all of the waste heat in this category has a temperature around 30 degrees. A temperature that is suitable for warming households in the winter, but not suitable for Adsorption Desalination.

One could argue: 'well at least 37% of the waste heat is above a 100 degrees Celcius. That energy is perfectly suitable to be used for AD'. A waste heat source of 1 kg steam at 150 degrees can create 3 kg of hot water with a temperature of 80 degrees. However, this waste heat has a higher value than the low-grade waste heat of below 100 degrees. There are more suitable applications for this waste heat than if it was the case with a waste heat source providing less than 100 degrees. More competitions exist for this source. The usability of waste heat has not gone unnoticed worldwide. In the Netherlands alone, many different applications for waste heat are used today. As an example, in Oosterhorn in Delfzijl the waste incinerator is providing companies steam at 290 and 210 degrees Celcius. It is used to create electricity, heating or the steam itself is used as process-steam [15]. Applications that are also valuable and which AD has to compete against to gain this thermal energy. The author of this report had once a conversation with a person who is involved with the chemical industry in the Netherlands. This person told that even waste heat of 80 degrees is seen as valuable nowadays and is always reused in the chemical industry. If it is the goal to create sustainable and economical friendly desalination, it is, therefore, important that AD tries to collect its waste heat from source with few competitors. At preference sources who cannot use the waste heat itself.

Moreover, collecting waste heat could be something with difficulties. Since it can be a costly endeavour to collect and transport the waste heat. Going back of the example of Delfzijl, the investment costs were €10 million and the return period is estimated at the 20 years. Also, one should notice that this energy didn't even leave the premise of the industrial park of the source. Transportation is limited. For companies who do not benefit from the reuse of their waste heat, there should be some incentive to collect their waste heat. Different barriers would have to be overcome. Fears about economic penalties or disrupting their production processes are one. Different parties need to work together to ensure a success [15, 60]. Costs will be involved by collecting and transporting energy. Therefore, it is challenging to believe that waste heat is free in contrast to other claims.

Other concern is the stability of the waste heat sources. It is now unclear if a source can provide thermal energy the whole year through or if it is season bound. In the winter at the Northern Hemisphere, less waste heat is probably available since more heat is lost to the environment due to lower air temperatures. Less energy is available to desalinate while the consumption stays the same. Creating a solution for this temporary shortage of energy could be a costly endeavour. This problem could be solved with ATES systems where it is possible to store till 90 degrees Celcius of thermal energy with approximately 50% efficiency. Only current Dutch legislation doesn't allow due to valid safety concerns. Furthermore, it unclear how much waste heat is available in the future. In the Netherlands, the chemical industry and oil refineries are the largest producers of waste heat. As seen with the example of Delfzijl, the return period could 20 years. Are these companies still producing the same amount of waste heat in 20 years? The market demand for gasoline goes probably down in the future, and a change in different chemicals could also happen. Different products mean different processes and therefore different productions of waste heat. However, the chemical industry is growing and is expected to at least double in 2050, so the amount of waste heat in the future is probably the same or more [48].

To conclude, the potential for waste heat for Adsorption Desalination is looking good since a lot of waste heat is available. However, more information is necessary about the quality and the stability to create an accurate picture. Waste heat is indeed an inexpensive energy source, but infrastructure is necessary to collect it and transport it. Therefore, the statement that 'the thermal energy for AD is free' is not valid. It will always be more complicated to run a process on waste heat than compared with electrical energy.

6.6 The Costs of Adsorption-Desalination

Due to the fact that Adsorption Desalination is still a new technology in its experimental phase, there is not much information to answer this question. In contrast with Reverse Omosis, there is no database with the expenses of desalination plants who use as primary desalination technology Adsorption Desalination. Furthermore, as mentioned insection 6.3, the energy consumption of a desalination process depends heavily on the boundary conditions. What is the original salt content of the feed? Which recovery is desired? What is the temperature of the feed? These three parameters heavily influence the energy consumption. Since almost 50% of the costs of desalination by most technologies are energy costs, it is a critical aspect to take into consideration.

As said in section 3.6, the value that is often used as the thermodynamic limit is 0.78 kWh/m^3. This value is however based on the situation when the costs are minimal to desalinate seawater using Reverse Omosis. The energy costs are not the only operational costs. There is also maintenance. Maintenance like replacing components due to corrosion or fouling. Both factors that depend on the original quality of the feed and the circumstances desalination occurred. Also, finally, besides operational costs, also investment costs and the technical lifespan influence the final total costs of a desalination technology.

As told in section 3.7, only two life cycle analyses were done. Both can provide some insight to make a realistic estimation when using Adsorption Desalination to desalinate seawater. The first study [72] was done by the researcher of NUS who also developed the technology. The benefit of this study is that they can provide empirical data about the costs that were involved when constructing their experimental set-up. They used this data and interpolated to a desalination plant with the capacity of 1000 m^3/d. It is a fascinating and useful study, but there are a few things that a worrisome about how they got to their results. Different numbers are used to make their calculations; no sources or methodology is provided. These values are the result of their cost data based on a set-up that can produce 25 m^3/d. It could be that these costs were only multiplied by a factor 40. A second element that is troubling is their assumption to keep the costs for chemical treatment, part replacement (called membrane replacement) and other costs at zero when they compare it with the costs of Reverse Omosis.

First, let's discuss the chemical treatment. It is indeed true that for Adsorption Desalination no chemicals are necessary to remove the brine out of the membranes simply because this technology doesn't use any membranes. However, that doesn't have to mean that any chemicals are absent in Adsorption Desalination. One thing that AD does use in contrast to Reverse Omosis is cooling water and heating water. One of the significant reasons a breakdown in heat exchanger occurs is due to erosion in their piping. This breakdown is combatted with the use of chemicals. Chemicals that are quite costly. A whole industry is based on selling these anti-corrosion chemicals. Any technology that uses heat and cooling water should account for these chemicals in their cost analysis. The second element of concern is the fact that the replacement cost for parts is kept at zero. To be fair, officially the part is called 'membrane replacement' in Table 3.5 and indeed, no membranes are present in this technology. It does not function on membranes, but it does function on silica gel. Silica gel degrades as was told in section 3.4. It is a not valid statement that silica gel has an infinite lifetime. Maybe on paper, but the reality is different. Silica gel needs to be replaced regularly in practice due to especially two elements. First, due to thermal stress it received, something it receives a lot with AD. Second, the clogging by pollutions of metal ions. As told before, with adsorption cooling (the twin brother of the Adsorption Desalination) examples exist of a situation where the technology was implied but had to be shut down after one year of service because the silica gel dramatically lost it sorption capacity. It lost so much sorption capacity that it was no longer economically feasible to keep it operational. This degradation happened in a situation where the only pollution was by metal ions which originated from the demi water or air that leaked into the vacuum system. Saline water contains far more metal ions than those sources. It is reasonable to expect that the sorption characteristics of silica gel involving AD will decrease much faster. Therefore it is not unreasonable to think that the silica gel needs to be replaced multiple times during the 30-year life span of an AD-plant. To conclude, it is questionable why the costs were not mentioned in this study. At last, the third element that is troubling in Table 3.5 are the other costs. The other costs are zero for AD while for Reverse Omosis, they are around 25% of the total cost of RO. How does it come that there are no additional costs involved with AD?

Often the statement is made that the costs of waste heat are not included since it is free. It is hard to believe this statement. Indeed, waste heat is the energy that is lost after conversion of an energy source. A source that is acquired for another function, therefore if the waste can be used, a person could argue that the funds to acquire this energy source are not necessary. However, in the modern days, the statement that waste is free is no longer true. Waste can be quite useful and have an economic value. Furthermore, many municipalities will tell that acquiring waste and transporting it does need certain funds. Funds to finance the infrastructure around it. For waste heat, the same principle does apply. Infrastructure is necessary to collect the waste heat and to transport it as said before in section 3.8. The final cost of this infrastructure depends on the quality of the waste heat, how efficient it can be acquired, which difficulties are connected to this problem and the distance it has to be transported. One thing is for sure is that some costs shall exist when using waste heat as potential thermal energy. The same can be said when geothermal energy or solar energy is used as the primary energy source for Adsorption Desalination. Even if it was the case the thermal energy and its accompanying infrastructure were free from any economic penalty, the amount of thermal energy an AD-reactor consumes does influence the costs. As an example, the thermodynamic limit of desalination is less influential on the cost of desalination due to the fact that waste heat is used. Waste heat is less valuable than electricity or an other energy sources since it is still waste. However, since a medium of water has transports this waste heat, a doubling of the thermal energy consumption means eight times more energy is necessary to feed this energy consumption of AD. This additional consumption does influence the cost more directly. Also, this additional waste heat needs to be collected. Doubling the thermal energy consumption translates in a doubling of the infrastructure that is needed to collect it. Therefore it is highly unlikely that no additional costs are present with Adsorption Desalination as Table 3.5 would want us to believe.

In the end, this study concludes that the total costs that involve AD for a plant of 1000 m^3/d for the next 30 years shall be 0.46 $\$/m^3$. RO, based on historical data, has a total cost of 0.87 $\$/m^3$ for a plant with the same production capacity on average. This average is based on two data point. Historical data of 42 RO plants, however, gives a similar number, 0.86 $\$/m^3$. They conclude that AD can be twice as economically friendly as RO, which is until now the most economical choice for desalination in most cases. A second study [56], which also advocated a new approach to thermo-economic modelling for AD, concludes a number that is higher than the first study. They conclude a total price of 0.57 $\$/m^3$. Unfortunately, they are even less informative about their source and methodology about these numbers. One thing that should be stressed is that these researchers are not directly connected to the earlier researcher. The earlier researchers were also involved with the development of this technology. Therefore, one could argue that the researchers of this second study are probably more independent.

In conclusion, what can be said about the total cost is that they are twice as low as Reverse Omosis is probably not true. It is very reasonable to believe that the operational costs are lower of AD compared to RO and other technologies because AD is less likely to be vulnerable to fouling and corrosion and that it has probably a lower electricity consumption. However, the costs are probably higher due to the fact the infrastructure that is necessary to deliver the thermal energy that AD consumes and the chemicals that are necessary to maintain this infrastructure. Furthermore, also costs are involved with the necessary replacement of the silica gel to upkeep the production capacity of an AD-reactor. The final cost will always depend on the quality of the design and the boundaries that are placed on the whole process. However, it is very likely that with seawater desalination, the cost of AD is in the best case scenario in the same range as RO.

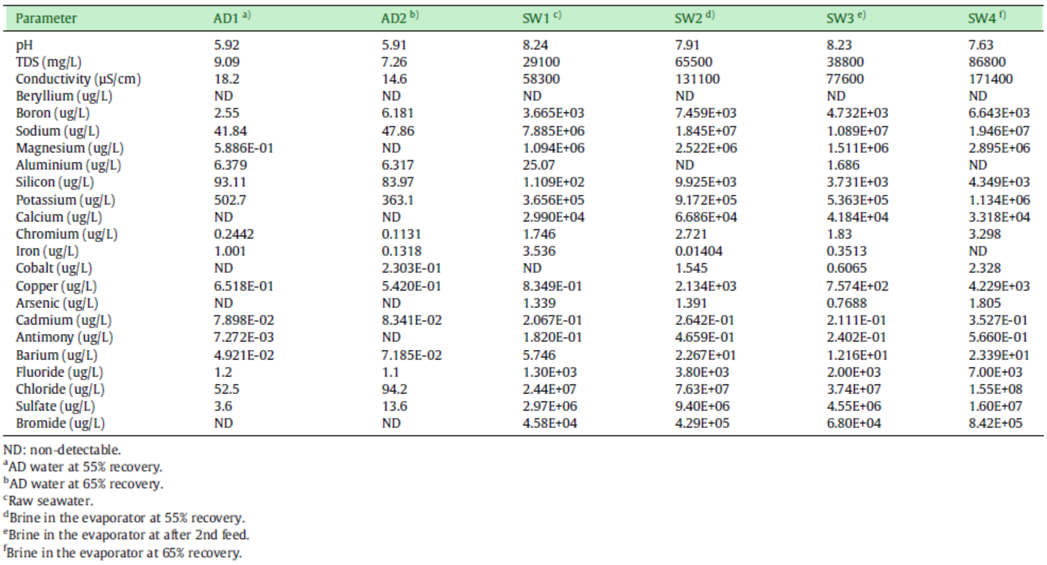
6.7 The Removal of Biological Contaminants by Adsorption Desalination

Since no results of the experiments with biological contaminants are available, no conclusion can be made based on empirical evidence. Researchers of different papers claimed that this technology could remove biological contaminants. None, however, provided any empirical data on which this claim is based. Only one study [47], provided a table that gave some insight into the water qualities that are achieved, see Table 6.1.

However, this table only includes metals, elements, conductivity and pH. No biological parameters are present. The only claim based on empirical evidence that can be made is that AD can remove the chemical elements sufficient enough that it can be used as drinking water or demi water. For boiler feed, the conductivity is too high. However certain chemical elements are to low for

Dutch drinking water standards. To use it as drinking water, the product has to be mineralised before it is safe for consumption.

Table 6.1: Overview of the different water qualities of the feed, brines and products [47]



Parameter	AD1 a)	AD2 b)	SW1 c)	SW2 d)	SW3 e)	SW4 f)
pH	5.92	5.91	8.24	7.91	8.23	7.63
TDS (mg/L)	9.09	7.26	29100	65500	38800	86800
Conductivity (µS/cm)	18.2	14.6	58300	131100	77600	171400
Beryllium (ug/L)	ND	ND	ND	ND	ND	ND
Boron (ug/L)	2.55	6.181	3.665E+03	7.459E+03	4.732E+03	6.643E+03
Sodium (ug/L)	41.84	47.86	7.885E+06	1.845E+07	1.089E+07	1.946E+07
Magnesium (ug/L)	5.886E-01	ND	1.094E+06	2.522E+06	1.511E+06	2.895E+06
Aluminium (ug/L)	6.379	6.317	25.07	ND	1.686	ND
Silicon (ug/L)	93.11	83.97	1.109E+02	9.925E+03	3.731E+03	4.349E+03
Potassium (ug/L)	502.7	363.1	3.656E+05	9.172E+05	5.363E+05	1.134E+06
Calcium (ug/L)	ND	ND	2.990E+04	6.686E+04	4.184E+04	3.318E+04
Chromium (ug/L)	0.2442	0.1131	1.746	2.721	1.83	3.298
Iron (ug/L)	1.001	0.1318	3.536	0.01404	0.3513	ND
Cobalt (ug/L)	ND	2.303E-01	ND	1.545	0.6065	2.328
Copper (ug/L)	6.518E-01	5.420E-01	8.349E-01	2.134E+03	7.574E+02	4.229E+03
Arsenic (ug/L)	ND	ND	1.339	1.391	0.7688	1.805
Cadmium (ug/L)	7.898E-02	8.341E-02	2.067E-01	2.642E-01	2.111E-01	3.527E-01
Antimony (ug/L)	7.272E-03	ND	1.820E-01	4.659E-01	2.402E-01	5.660E-01
Barium (ug/L)	4.921E-02	7.185E-02	5.746	2.267E+01	1.216E+01	2.339E+01
Fluoride (ug/L)	1.2	1.1	1.30E+03	3.80E+03	2.00E+03	7.00E+03
Chloride (ug/L)	52.5	94.2	2.44E+07	7.63E+07	3.74E+07	1.55E+08
Sulfate (ug/L)	3.6	13.6	2.97E+06	9.40E+06	4.55E+06	1.60E+07
Bromide (ug/L)	ND	ND	4.58E+04	4.29E+05	6.80E+04	8.42E+05

ND: non-detectable.
[a] AD water at 55% recovery.
[b] AD water at 65% recovery.
[c] Raw seawater.
[d] Brine in the evaporator at 55% recovery.
[e] Brine in the evaporator at after 2nd feed.
[f] Brine in the evaporator at 65% recovery.

Since the technology can so well remove chemical elements, one could argue that the same could apply for biological parameters. Adsorption Desalination is an evaporation technique. In theory, the only physical solution for these parameters to end up into the product is that they also underwent a phase difference and evaporated. However, of all chemical elements, their boiling point is not even near that of water. In practice, there are two reasons why these chemical elements are measured inside the product of AD. It could be an error in measurement, or it is the result of a carry-over effect. The carry-over effect is the result that elements are carried upwards by the water vapour. The force created by the velocity and drag of the vapour is in such a case substantial to overcome the weight of elements, and therefore these elements are being transported.

One thing that AD has working in its favour is that it operates in vacuum conditions. Since the atmosphere is thinner inside these vessels, the drag that can be created by the uplifting vapour is less, and therefore the probability that elements are carried through the air is less. The chance of the pollutions of the product by the carry-effect is therefore probably less. Fortunately, the boiling point of most chemical elements is not near water, but some are, and this is definitely the case for specific biological molecules. As told in the Methodology, the boiling point of acetic acid is extremely close to that of water, and the boiling point formic acid is even below that of water. These biological pollutants could end up in the product due to evaporation. Furthermore, if the feed has not been probably degassed, certain gasses could also end into the product.

The claim that Adsorption Desalination can easily remove biological pollutant is partly based on pasteurisation. Since the silica gel is heated till temperatures of 80 degrees Celcius, bacteria are removed due to pasteurisation. However, since not all vapour is released at 80 degrees, but also at lower temperatures, pathogens could spread by vapour transport (carry-over effect) to the product.

Furthermore, the effect of pasteurisation also depends on the duration that the pathogens are exposed to high temperatures. Therefore it is unclear how much effect pasteurisation has on the removal of pathogens.

In the end, there are claims that Adsorption Desalination can remove biological contaminants. Based on logical reasoning, these arguments can be substantiated. However, as long there is no experimental data available, these claims are not empirically proven.

6.8 Practical Vulnerabilities - Reflections on Building the Experimental Set-Up

The experimental set-up was unable to produce an product because no evaporation took place. As discussed before and showed in section 5.4, the evaporation in Adsorption Desalination is equal to adsorption of vapour by silica gel in a perfect system. Unfortunately, the system was not perfect. A leakage was present. The vacuum controller could keep the vacuum around the desired pressure, but it was not precise and fast enough to keep the vapour pressure at a certain threshold. It failed to prevent the loss of sorption characteristics. The required vapour pressure to keep the process was not sustained. It can be compared with an old car where a slingshot is necessary to start the engine. The slingshot of the set-up was broken. The leakage was further so high compared to the adsorption rate that within a second even at ideal starting conditions the evaporation stopped completely.

Does it mean that every leakage in an AD-device has to lethal? No, that doesn't have to be the case as can be seen in section 5.4. If the leak is relatively small and the control system relatively accurate, the evaporation process keeps being operational. No breakdown of performance has to occur. Another possible short-term solution, besides a highly accurate control system, is increasing saturation pressure: change the working pressure inside the vessel. Due to the logarithmic behaviour of leakage, by decreasing the pressure difference with the atmospheric pressure, the pressure inside the system is rising less fast. As a result, the evaporation decreases less due to the leakage. The downside of this practice is that the evaporation takes places at a higher temperature and therefore the system becomes more vulnerable to scaling or erosion. These are two possible short-term solutions that can help. Unfortunately, both couldn't be applied to the experimental set-up.

Another practical problem that the set-up endured was due to the heat exchangers. As subsection 5.6.1 already showed was that the heat exchangers of the silica gel beds were not properly designed. When designing the heat exchanger, the thermal energy transport necessary to the adsorption and desorption transport was neglected. This neglection is a large error since the thermal energy necessary for the adsorption and desorption is more significant than that of heating the silica gel until the desired temperature. This problem, however, is easily overcome by extending the cycle time of the device. It does decrease the daily water production, but it still would be capable of producing water. However, this was not the problem with the heat exchangers. The problem that occurred with the heat exchangers was that they expanded and contracted constantly. Heat and cold water (alternating) were flowing through the metal pipes. This behaviour created stress and fatigue in the materials. The result was leakage in the hydraulic system and probably also leakage in the vacuum system. A better-designed system can handle this fatigue probably better, but the principle where this problem is based on is always present. An AD-device is a device that endures large temperature differences. Due to this difference, materials are constantly expanding and contracting. Material fatigue occurs at the same moment. This fatigue can result in leakage in the hydraulic system or vacuum system. In the end, pollutions of the silica gel or even a completely breakdowns of performance due to leakage can occur.

At last, there are also some practical problems involving the silica gel. Since it can degrade and has to be replaced after some time, practical uses can occur. silica gel can only be replaced by dismantling of the silica bed or by using a smartly designed system where the silica gel can be removed out of the vessel without dismantling. New or cleaned silica gel has to be placed back. However, there is a possibility that the silica gel is already polluted again before it is placed inside the vessel due to the environment. It could be a real possibility that maintenance on the silica gel can only be done in a clean room. In the end, highly trained mechanics are necessary for maintenance. Maintenance could be a costly endavour.

In conclusion, Adsorption Desalination is a complex solution for sustainable desalination. Complex systems are more vulnerable for malfunctions, can be more costly and can create more practical issues.

7 | Conclusion

Adsorption Desalination is a newly emerging technology with many interest aspects. It can create cooling besides desalination, and it can run primarily on waste heat. Since the evaporation takes place around room temperatures, maintenance can be low considering fouling and erosion. On paper, it can provide a sustainable alternative for conventional desalination. Indeed, large investment costs are necessary, but the operational costs could be low compared to other techniques. To emphasise on "could be low", there are few barriers to overcome for Adsorption Desalination.

Adsorption Desalination, when operated in a continues modus, is a low-pressure boiling-point-elevation desalination technique. The sorbent, in all cases until now silica gel, adsorbs water vapour. Normally, this would lower the pressure inside a closed system. However, when a heat exchanger is placed inside an evaporator, evaporation counteracts the lowering of the pressure. Inside a perfect system, the evaporation rate is equal to the adsorption rate. The mass transfer inside the system is due to a small pressure difference between components. Unfortunately, the moment a leakage is introduced, vulnerabilities of the system are exposed. A leakage decreases the evaporation rate and therefore the water production capabilities of the technology. In practice, vacuum systems are always vulnerable to leakages, and it is a known problem in industries. The sorption characteristics are unstable in low-pressure conditions, and a leakage can exploit these instabilities. In a case where the leakage is relatively large enough, a complete break-down of performance occur. There are some short-term solutions, but at the end, a costly high quality vacuum system is always necessary.

Another barrier to overcome is the problems involving the design of the silica bed. Silica gel is a bad conductor of thermal energy while it endures big temporal difference and needs to transport much energy. Since the sorption characteristics do also depend on the temperature, bad design for the silica bed can have serious influences in the performance of the whole system. It is also necessary to construct a well-designed silica bed unit to minimise its energy consumption and entropy creation. As the energy analysis shows, the silica bed consumes a great portion of the thermal energy. This consumption seems to be semi-independent of the salinity of the feed. Adsorption Desalination seems therefore to be very suitable for brine treatment. The higher the salinity of the feed, the more efficient the process becomes.

There is only one big concern when using Adsorption Desalination for brine treatment. Brine contains many metals. The metal ions could pollute the silica gel and decrease sorption characteristics. Besides the pollution by metals, there are also other possible ways silica gel can degrade. Fragmentation by thermal stress can also degrade the silica gel and therefore decrease the performance of the system. To more thermal cycles silica gel endures, the higher the fragmentation. Adsorption Desalination is a technology where the silica gel is exposed to much temperature differences and thermal cycles. Fragmentation, therefore, is always a problem. It could be beneficial to study also other sorbent materials since the silica gel seems to be one of the major vulnerabilities of Adsorption Desalination.

However, it is an interesting technology since the work necessary for the desalination is significantly small compared to thermal energy. The work necessary only depends on the pumps and the valves. The researcher at NUS only needed 1.38 kWh/m^3 for the mechanical work. By using more efficient pumps, enlarging the scale or other solutions, mechanical work consumption could be lower further. It could even be possible to be lower than the thermodynamical limit. As long there are no significant other costs involved with the thermal energy consumption, Adsorption Desalination can be cheaper than other technologies based on energy consumption. However, this is a technology that heavily depends on the usability of a thermal energy source like waste heat to be compatible. To use these thermal energy sources, infrastructure is necessary to collect it and transport it. Therefore, the statement that waste heat, solar or geothermal energy is a free energy source is not valid.

To conclude, if all these barriers for Adsorption Desalination are overcome, this technology can be a powerful tool for sustainable desalination. It can especially be a powerful tool for sustainable brine treatment. Adsorption Desalination is a sustainable solution that should always be considered when applying desalination.

8 | Recommendations

The following recommendations are made considering the knowledge and insight that was gain during this research. The first recommendation involves the construction of an experimental set-up. The reason for failure was that the quality of construction was not high enough. There are specific technologies that can have a high threshold of malfunctions and error inside their systems before a breakdown of performance occurs. Adsorption Desalination is not such a system. It is a delicate, sensitive process that depends on significant small pressure and temperature differences. Therefore disturbances due to leakages and isolation problems can be fatal. To ensure a functional process, a high technical valuable machine has to be constructed. To construct such a device, high experience with constructing vacuum systems is necessary. When creating such a device, one who lacks such experience should work together with other parties who have this experience. Without, the probability of a functional device is low. A second recommendation is that a designer of a heat exchanger for a silica bed should take into considerations the energy transport by adsorption and desorption. The energy involves with the sorption is considered more significant than the energy transport necessary for alternating the temperature of the silica gel. If a designer constructs a silica bed without considering these elements, poor performance is the result.

The third recommendation is considered for water quality research. Unfortunately, this research was not possible since the device was not functioning correctly. Besides the recommendation to redo this research, it would also be interesting to research if any pathogens are present on the silica gel after usage. Since the carry-over effect is probably the dominant mechanism for the transfer of contaminants, it can be interesting to understand how much the pressure inside a vacuum system can influence this effect. Furthermore, it should be proven that most pathogens transfer is indeed by the carry-over effect.

The fourth recommendation goes back to the silica gel. The degradation of silica gel should be further studied. Which mechanisms are most dominant in Adsorption Desalination and how much does the quality of the feed influence degradation. From the discussion, it seems that the most applicant future of AD lies in brine treatment. However, if brine treatment results in faster degradation and higher cost, this application could be less practical. Besides degradation, also the regeneration of the quality of silica gel should be further examined. That is the fifth recommendation. The sixth is further research an alternative sorbent for Adsorption Desalination. Silica-gel could be the most significant vulnerability inside the AD-process. It is reasonable to further research alternatives. Considerating the vulnerabilities of silica. From the DEBESC model, it seems that the sorption characteristics of silica gel are unstable in those vacuum conditions. Considering what was said about this instability in the discussion, it would be interesting to model these conditions again, but then in a finite model analysis. The gain is that small temperature differences in the gas and liquid can now also be simulated. This ability can give insight into how problematic the instability of the sorption characteristics is in practice. Besides that, it would also be interesting to combine the DEBESC and DEBSAD model, to see the simulate how the thermal conduction of the silica gel influence the adsorption rate in combination with a changing vapour pressure inside the system.

The eight and ninth recommendations involve the cost and energy consumption of AD. A more detailed study about entropy creation by Adsorption Desalination is appropriate since in this research only a simplified model constructed on average values and assumptions was used. Since energy consumption correlates with cost, a comprehensive life cycle analysis should also be done. It could be very well that the solution that consumes that less energy is not always the most economical attractive. The tenth recommendation concerns the last two. Since Adsorption Desalination seems to be most applicable for brine treatment, the necessity of brine treatment should be examined. Brine treatment cost an enormous amount of energy compared to other water treatments. Therefore, brine treatment is not sustainable considering energy consumption, but considering protecting aquatic life it is sustainable since discharging brine back into the environment could cause harm. Could an equilibrium be found?

To sum all the recommendations:

- Reconstruct experimental set-up using an expert with a background in vacuum systems.
- Take the transport of energy considering adsorption and desorption also into account when designing a silica gel covered heat exchanger.
- When researching the reduction factor of AD concerning biological containing, research also the effects on contaminations by pathogens on the silica gel and the dependency of the carry-over effect concerning the working pressure.
- Research the mechanisms of degradation of silica gel concerning Adsorption Desalination at different feed qualities and working conditions.
- Research the regeneration of the quality of silica gel concerning removing pathogens and restoring sorption characteristics.
- Research the instability of the sorption characteristics of silica gel in vacuum conditions using the finite model analysis.
- Combine the DEBESC and DEBSAD model.
- Construct a more detailed entropy creation model for Adsorption Desalination.
- An extensive Life cycle analysis for AD also concerning maintenance for silica gell degradation, but also investment and operational costs for waste heat collection and transportation.

- Research the sustainability of brine treatment concerning energy consumption, transportation of the salt and harmfulness to aquatic life.

Bibliography

[1] L. Addams, G. Boccaletti, M. Kerlin, and M. Stuchtey. Charting our water future. Technical report, 2030 Water Resourche Group, 2009.

[2] H. Ahn and C.-H. Lee. Effects of capillary condensation on adsorption and thermal desorption dynamics of water in zeolite 13x and layered beds. *Chemical Engineering Science*, 59(13):2727–2743, 2004.

[3] A. Al-Karaghouli and L. L. kamerski. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, 24:343–356, 2013.

[4] G. Amy, N. Ghaffour, Z. Li, L. Francis, R. V. Linares, T. Missimer, and S. Lattemann. Membrane-based seawater desalination: Present and future prospects. *Desalination*, 401:16–21, 2017.

[5] Anonymous. *Chemical Engineering Design.* National Programme on Technology Enhanced Larning, Bombay, India, 2019. URL `https://nptel.ac.in/courses/103103027/pdf/mod3.pdf`.

[6] R. J. Archer and V. K. La-Mer. The rate of evaporation of water through fatty acid monolayers. *The Journal of Physical Chemistry*, 59(3):200–208, 1954.

[7] A. A. Askalany, M. Salem, I. M. Ismeal, A. H. H. Ali, M. G. Morsy, and B. B. Saha. An overview on adsorption pair for cooling. *Renewable and Sustainable Energy Reviews*, 19:565–572, 2013.

[8] A. A. Askalany, S. K. Henniger, M. Ghazy, and B. B. Saha. Effect of improving thermal conductivity of the adsorbent on performance of adsorption cooling system. *Applied Thermal Engineering*, 110:695–702, 2017.

[9] H. Bjurstrom, E. Karawacki, and B. Carlsson. Thermal conductivity of a microporous particulate medium: moist silica gel. *Heat mass Transfer*, 27(11):2025–2036, 1984.

[10] U. Caldera and C. Breyer. Learning curve for seawater reverse osmosis desalination plants: Capital cost trend of the past, present, and future. *Water Resources Research*, 53(12):10,523–10,538, 2017.

[11] R. Connar. The united nations world water development report 2015 - water for a sustainable world. Technical report, United Nations, 2015.

[12] R. E. Critoph. Forced convection enhancement of adsorption cycles. *Heat Recovery systems and CHP*, 14(4):343–350, 1994.

[13] R. E. Critoph. Forced convection adsorption cycle with packed bed heat regeneration: Cycle à adsorption à convection forcée avec régénération thermique du lit fixe. *International Journal of Refrigeration*, 22(1):38–46, 1999.

[14] DDBST. Dortmund data bank, 2019. URL `http://www.ddbst.com`.

[15] Deltares. Verkenning warmtelozingen en duurzaam hergebruik restwarmte. Technical report, Deltares, 2018.

[16] R. Development. Thermagy, 2019. URL `http://www.rgsdevelopment.nl/solutions/`.

[17] S. C. Edberg, E. W. Rice, R. J. Karlin, and M. J. Allen. Escherichia coli: The best biological drinking water indicator for public health protection. *Journal of Applied Microbiology*, 88:106–116, 2000.

[18] H. Y. Erbil. *Surface Chemistry of Solid and Liquid Interface*. John Wiley & Sons, Inc, Oxford, United Kingdom, 2009.

[19] M. D. Ercegovac, T. Lang, and J. H. Moreno. *Introduction to Digital Systems*. John Wiley & Sons, Inc., Oxford, United Kingdom, 1999.

[20] *Piping Evaporative Condensers*. Evapco Incorporation, Westminster, Maryland, United States, 2018. URL `https://www.evapco.com/sites/evapco.com/files/2018-02/EvapcoPiping%20EvapCond131A.pdf`.

[21] K. Y. Foo and B. H. Hameed. Insights into the modeling of adsoprtion isotherm systems. *Chemical Engineering Journal*, 156(1):2–10, 2010.

[22] C. Forman, I. K. Muritala, R. Pardemann, and B. Meyer. Estimating the global waste heat potential. *Renewable and Sustainable Energy Reviews*, 57:1568–1579, 2016.

[23] A. G. Foster. The sorption of cendensible vapours by porous solids. part i. the applicability of the capillary theory. *Transaction of the Faraday Society*, 28:645–657, 1932.

[24] R. T. Francis S Manning and R. E. Thompson. *Oilfield Processing of Petroleum: Natural Gas*. PennWell Books, Houston, Texas, 1991.

[25] C. Fritzmann, J. Löwenberg, T. Wintgents, and T. Melin. State-of-the-art of reverse osmosis desalination. *Desalination*, 216:1–76, 2007.

[26] S. gel desiccants bags. Silica gel for absorption of moisture and water drying, 2017. URL `https://silicageldesiccantbags.wordpress.com/2017/10/02/silica-gel-for-absorption-of-moisture-and-water-drying/`.

[27] S. K. Henniger, G. Munz, K. F. Ratzsch, and P. Schossig. Cycle stability of sorption maertials and composites for the use in heat pumps and cooling machines. *Renewable Energy*, 36(11):3043–3049, 2011.

[28] M. Holmgren. Xsteam, 2019. URL `www.x-eng.com`. Matlab function.

[29] R. Huehmer. Detailed estimation of desalination system cost using computerized cost projection tools. *ResearchGate*, 2019.

[30] M. Jaroniec. Adsorption on heterogeneous surfaces: The exponential equation for the overall adsorption isotherm. *Surface Science*, 50(2):553–564, 1975.

[31] L. Jiang, L. W. Wang, and R. Z. Wang. Investigation on thermal conductive consolidated comosite $cacl_2$ for adsorption refrigeration. *International Journal of Thermal Sciences*, 81:68–75, 2014.

[32] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou. Waste heat recovery technologies and applications. *Thermal Science and Engineering progess*, 6:268–289, 2018.

[33] Y. Kato, Y. Sasaki, and Y. Yoshizawa. Magnesium oxide/water chemcial heat pump to enhance energy utilization of a cogeneration system. *Energy*, 30(11-12):2144–2155, 2005.

[34] M. Langan and K. O'Toole. A new technology for cost effective low grade waste heat recovery. *Energy Procedia*, 123:188–195, 2017.

[35] I. Langmuir. The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of American Chemical society*, 40(9):1361–1403, 1918.

[36] J. H. Lienhard, K. H. Mistry, M. H. Sharqawy, and G. P. Thiel. Thermodynamics, exergy, and energy efficiency in desalination systems. In *Desalination Sustainability: A technical Socieconomic, and Envronmental Approach*. Elsevier Publishing Co, 2017.

[37] S. Loutatidou, B. Chalermthai, P. R. Marpu, and H. A. Arafat. Capital cost estimation of ro plants: Gcc countries versus southern europe. *Desalination*, 347:103–111, 2014.

[38] M. Mangnus. Development of a sorption cooling test device, using a thermochemical material. Master's thesis, Technical University Eindhoven, 2007.

[39] T. J. McDougal, R. Feistel, D. G. Wright, R. Pawlowicz, F. J. Millero, D. R. Jacket, B. A. King, G. A. King, S. Seitz, P. Spitzer, and A. Chen. *The international thermodynamic equatio of seawater*. Intergovernmental Oceanographic Commision, 2010.

[40] J. E. McMurry. *Organic Chemistry*. Brooks Cole Publishing Co., Salt lake City, Utah, 2010.

[41] J. E. Miller. Review of water resources and desalination technologies. Technical report, Sandia National Laboratories, Livermore, California, 2003.

[42] A. F. Milss. *Heat Transfer*. Prentice Hall, Upper Saddle River, New Jersey, 1999.

[43] K. H. Mistry, R. K. McGovern, G. P. Thiel, E. K. Summers, S. M. Zubair, and J. H. Lienhard. Entropy gneeration analysis of desalination technologies. *Entropy*, 13:1829–1864, 2011.

[44] M. J. Moran and H. N. Shapiro. *fundamentals of Engineering Thermodynamics*. John Wiley & Sons, Inc, Oxford, United Kingdom, 2010.

[45] K. C. Ng, H. T. Chua, C. Y. Chung, C. H. Loke, T. Kashiwagi, A. Akisawa, and B. B. Saha. Experimental investigation of the silica gel-water adsorption isotherm characteristics. *Applied Thermal Engineering*, 21: 1631–1642, 2001.

[46] K. C. Ng, K. Thu, B. B. Saha, and A. Chakraborty. Study on waste heat-driven adsorption cooling cum desalination cycle. *International Journal of Refrigeration*, 35(3):685–693, 2011.

[47] K. C. Ng, K. Thu, Y. Kim, A. Chakraborty, and G. Amy. Adsorption desalination: An emerging low-cost thermal desalination method. *Desalination*, 308:161–179, 2013.

[48] B. A. Owoyele. Scenario analysis of methanol path for waste heat potential in 2050 deeply decarbonized port of rotterdam (in support of dutch goals). Master's thesis, Technische Universtät Berlin, 2018.

[49] G. P. Panayiotou, G. Bianchi, G. Georgiou, L. Aresti, M. Argyrou, R. Agathokleous, K. M. Tsamos, S. A. Tassou, G. Florides, S. Kalogirou, and P. Christodoulides. Preliminary assessment of waste heat potential in major european industries. *Energy Procedia*, 123, 2017.

[50] D. I. M. Research. Global desalination market - size, share and forecast (2018-2025). Technical report, Data Intelligence, 2017.

[51] A. review of adsorbents and adsorbates in solid–vapour adsorption heat pump systems. N c scrivastava and i w eames. *Applied Thermal Engineering*, 18(9-10):707–714, 1998.

[52] RM. Waste heat recovery system market by applications - global trends and forecast. Technical report, Research and Markets, 2016.

[53] J. D. Rohades. *Salinity: Electrical Conductivity and Total Dissolved Solids*, chapter 14, page 417. Soil Science Society of America, 1996.

[54] RVO. Restwarmte, 2019. URL `https://www.rvo.nl`.

[55] RVO. Warmte atlas, 2019. URL `http://rvo.b3p.nl/viewer/app/Warmteatlas/v2`.

[56] S. Sadri, M. Ameri, and R. H. Khoshkhoo. A new approach to thermo-economic modeling of adsorption desalination system. *Desalination*, 428: 69–75, 2018.

[57] B. B. Saha, S. Koyama, J. B. Lee, K. Kumahara, K. C. A. Alam, Y. Hamamoto, A. Akisawa, and T. Kashiwagi. Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller. *International Journal of Multiphase Flow*, 29(8):1249–1263, 2003.

[58] A. M. Salhotra, E. E. Adams, and D. R. F. Harleman. Effect of salinity and ionic composition on evaporation: Analysis of dead sea evaporation pans. *Water Resources Research*, 21(9):1336–1344, 1985.

[59] SBI. World desalination components and technologies. Technical report, SBI Energy, 2011.

[60] B. L. Schepers and M. van Lieshout. Ipo nationale routekaart restwarmte. Technical report, IPO, 2017.

[61] S. K. Schnell. *Molecular Simulations of Zeolites*. PhD thesis, Technical University Delft, 2013.

[62] M. W. Shahzad, M. Burhan, L. Ang, and K. C. Ng. Energy-water-enviroment nexus underpinning future desalination sustainability. *Desalination*, 413:52–64, 2017.

[63] A. Sharafian and M. Bahrami. Assessment of adsorber bed designs in waste-heat driven adsorption cooling systems for vehicle air conditioning and refrigeration. *Renewable and Sustainable Energy Reviews*, 30:440–451, 2014.

[64] M. H. Sharqawy, J. H. Liendhard, and S. M. Zubair. On exergy calculations of seawater with applications in desalination methods. *International Journal of Thermal Sciences*, 50:187–196, 2011.

[65] I. Solmuş, D. A. Rees, C. Yaali, D. Baker, and B. Kaftanoğlu. Numerical investigation of coupled heat and mass transfer inside the adsorbent bed of an adsorption cooling unit. *International Journal of Refrigeration*, 35 (3), 2012.

[66] K. S. Spiegler and Y. M. El-Sayed. The energetics of desalination processes. *Desalination*, 134:109–128, 2001.

[67] *Evaporation Handbook*. SPX Coporation, Getzville New York, 2008.

[68] R. Stuurman and G. O. Essink. Tno bouw en ondergrond. Technical report, TNO, 2007.

[69] A. Subramani and J. G. Jacungelo. Emerging desalination technologies for water treatment: A critical review. *Water Reserach*, 75:164–187, 2015.

[70] S. C. E. P. Technology. Food desiccant in the confined space will explode with water is true?, 2017. URL `http://www.absorbwell.com/news/food-desiccant-in-the-confined-space-will-expl-9637233.html`.

[71] K. Thu, K. C. Ng, B. B. Saha, A. Chakraborty, and S. Koyama. Operational strategy of adsorption desalination systems. *International Journal of Heat and Mass Transfer*, 52(7-8):1811–1816, 2009.

[72] K. Thu, A. Chakraborty, B. B. Saha, W. G. Chun, and K. C. Ng. Life-cycle cost analysis of adsoprtion cycles for desalination. *Desalination and Water Treatment*, 20(1-3):1–10, 2012.

[73] K. Thu, A. Chakraborty, Y.-D. Kim, A. Myat, B. B. Saha, and K. C. Ng. Numerial simulation and performance investigation of an advanced adsorption desalination cycle. *Desalination*, 308:209–218, 2013.

[74] M. Verde, K. Harby, and J. M. Corberán. Optimisation of thermal design and geometrical parameters of a flat tube-fin adsorbent bed for automobile air conditioning. *Applied Thermal Energineering*, 111:489–502, 2017.

[75] S. M. Walas. *Chemical Process Equipment - Selection and Design*. Butterworth-Heinemann, Oxford, United Kingdom, 1998.

[76] D. Wang, J. Zhang, Y. Xia, Y. Han, and S. Wang. Investigation of adsorption performance deterioration in silica gel-water adsorption refrigeration. *Energy Conversion and Management*, 58:157–162, 2012.

[77] WaterWorld. Low energy adsorption desalination and cooling plant opened in saudi arabia, 2016. URL `https://www.waterworld.com/articles/wwi/2016/09/low-energy-adsorption-desalination-and-cooling-plan`.

[78] S. Weintraub. Demystifying silica gel. *Object Specialyt Group Postprints*, 9:169–194, 2002.

[79] J. W. Wu, E. J. HU, and M. J. Biggs. Thermodynamic cycles of adsorption desalination system. *Applied Energy*, 90(1):316–322, 2012.

[80] Y. Yuan, H. Zhang, F. Yang, N. Zhang, and X. Cao. Inorganic composite sorbents for water vapor sorption: A research progress. *Renewable and Sustainable Energy Reviews*, 54:761–776, 2016.

[81] D. Zarzo and D. Prts. Desalination and energy consumption. what can we expect in the near future? *Desalination*, 427:1–9, 2018.

[82] İsmail Solmuş, C. Yamali, B. Kaftanoğlu, D. Baker, and A. Çağlar. Adsorption properties of a natural zeolite-water pair for use in adsorption cooling cycles. *Applied Energy*, 87(6):2062–2067, 2009.

Appendices

A | Design of a Sorbent Bed

A.1 Schematic Overview of the Set-Up

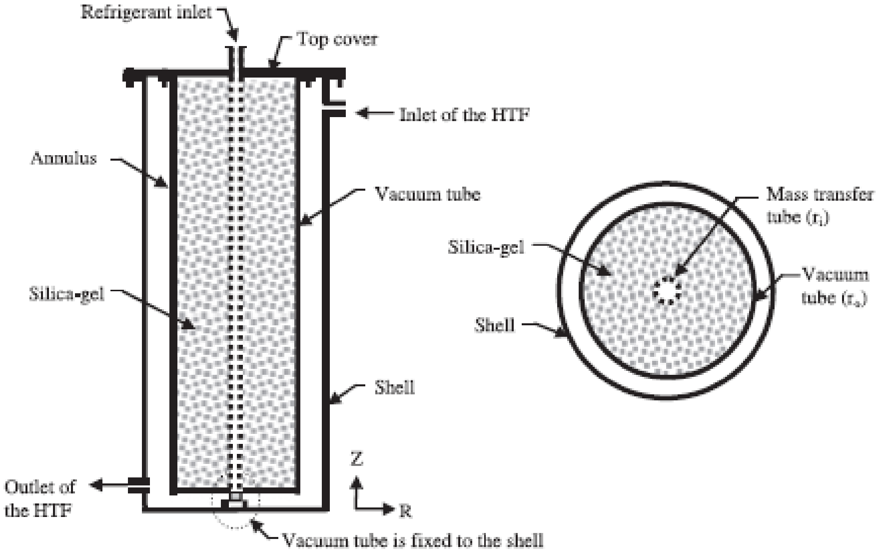


Figure A.1: A schematic view of the cylindrical adsorbent bed [65].

A.2 Data Results

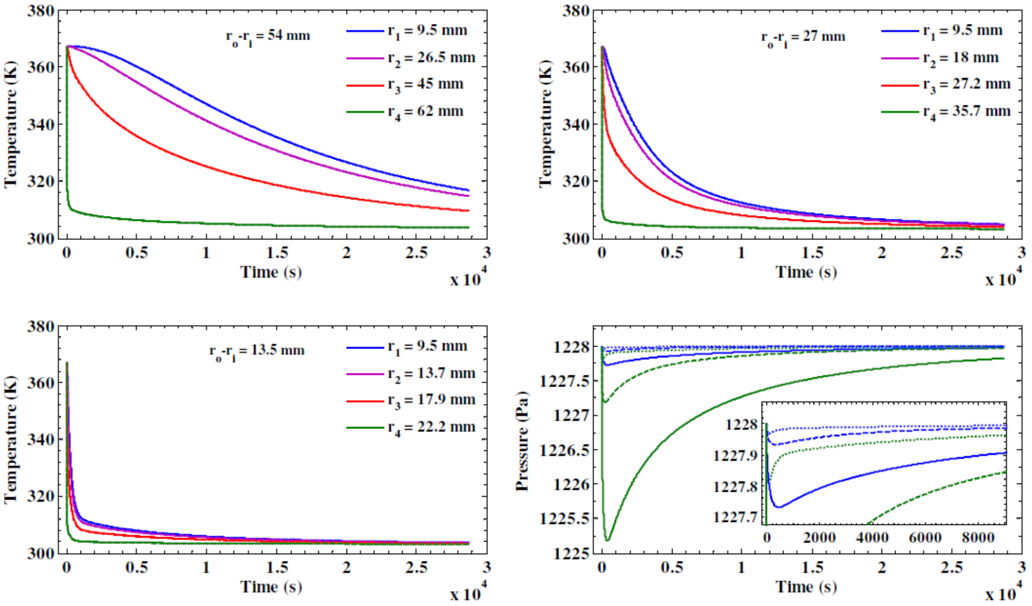


Figure A.2: Transient temperature of solid and gas phase and pressure distributions for various adsorbent bed thicknesses (Temperature: solid lines = T_s. dashed lines = T_g. Pressure with same locations as the temperatures: solid lines for $r_0 - r_i = 54mm$; dashed lines for $r_0 - r_i = 27mm$; and, square dots for $r_0 - r_i = 13.5mm$) [65].

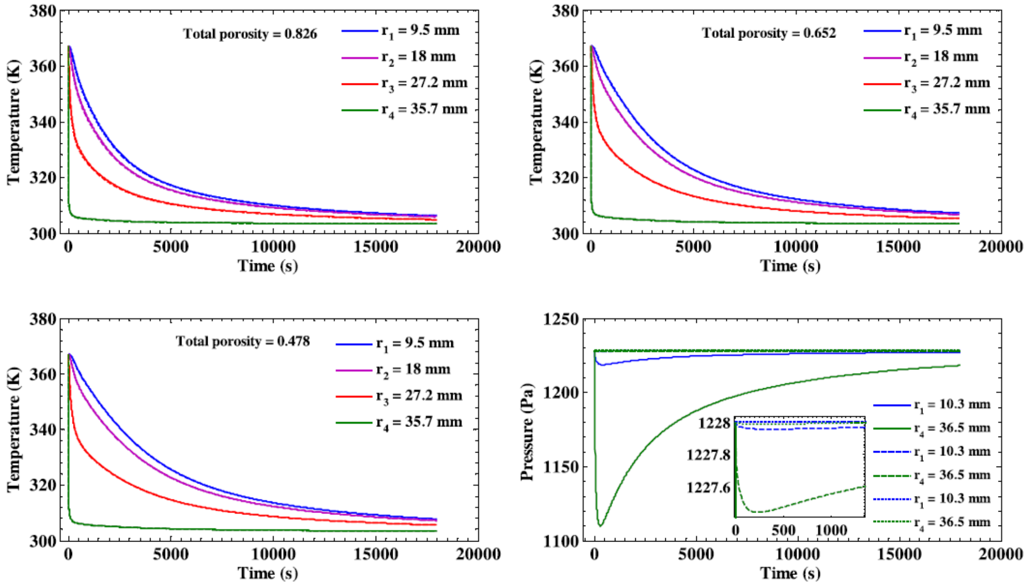


Figure A.3: Transient temperature of solid and gas phase and pressure distributions for various total porosities of the adsorbent bed (Temperature: solid lines = T_s. dashed lines = T_g. Pressure: solid lines for $\epsilon_t = 0.478$; dashed lines for $\epsilon_t = 0.652$; and square dots for $\epsilon_t = 0.826$) [65].

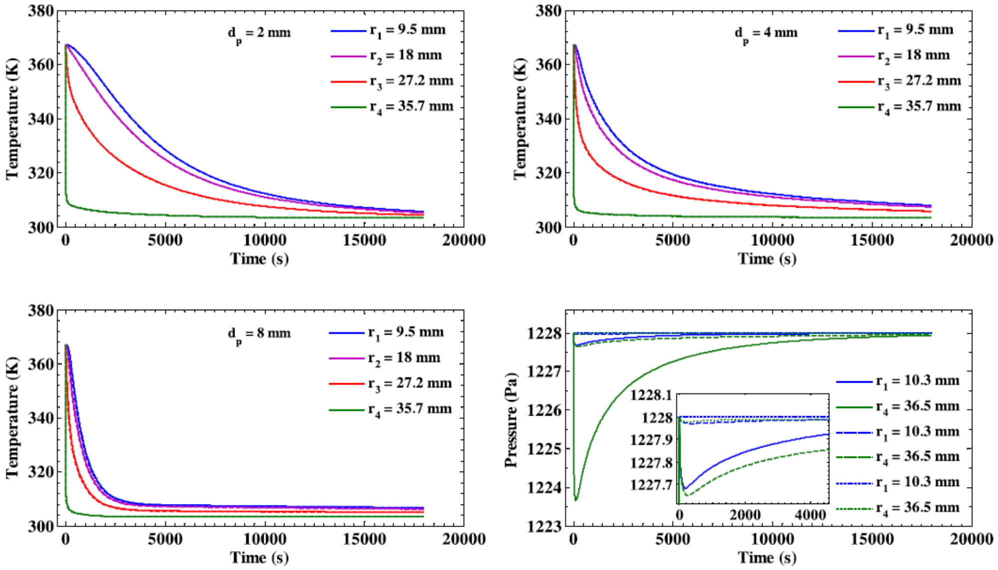


Figure A.4: Transient temperature of solid and gas phase and pressure distributions for various adsorbent bed thicknesses (Temperature: solid lines $= T_s$; dashed lines $= T_g$. Pressure with same locations as the temperatures: solid lines for $r_o - r_i = 54mm$; dashed lines for $r_o - r_i = 27mm$; and, square dots for $r_o - r_i = 13.5mm$ [65].

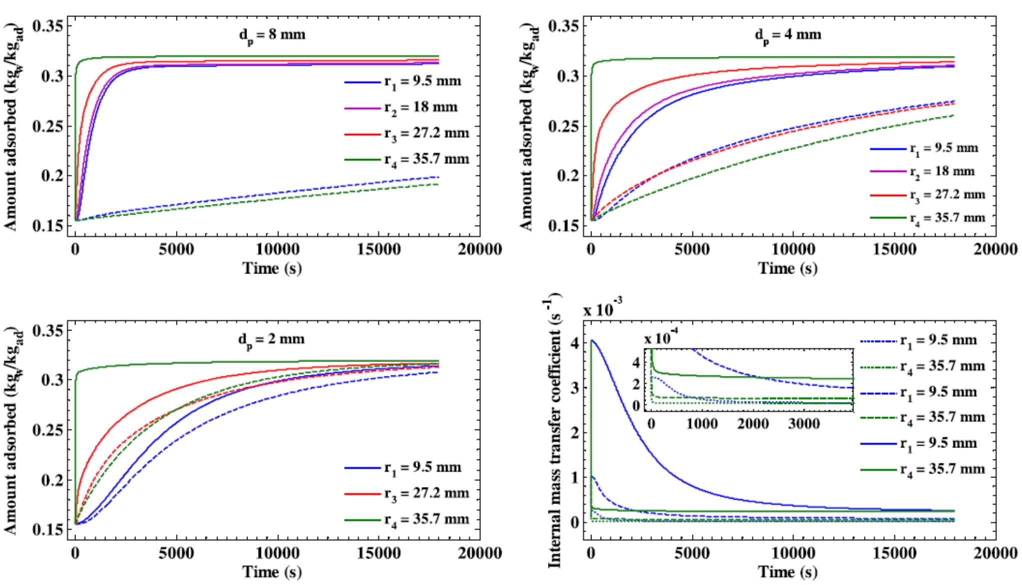


Figure A.5: Transient amount adsorbed and internal mass transfer coefficient distributions for various adsorbent particle diameters (Amound adsorbed: solid lines $= X_\infty$; dashed lines $= X$. Internal mass transfer coefficient: solid lines for $d_p = 2mm$; dashed lines for $d_p = 4mm$: and, square dots for $d_p = 8mm$) [65].

A.3 Parameters used in Model

Parameter	**Value**	**Unit**
r_o	36.5	mm
r_i	9.5	mm
P_{ev}	1.228	kPa
T_b	30	°C
T_h	120	°C
P_c	4.246	kPa

Table A.1: Main simualation parameters [65]

A.4 Overview of Appearances of different Heat Exchangers Designs

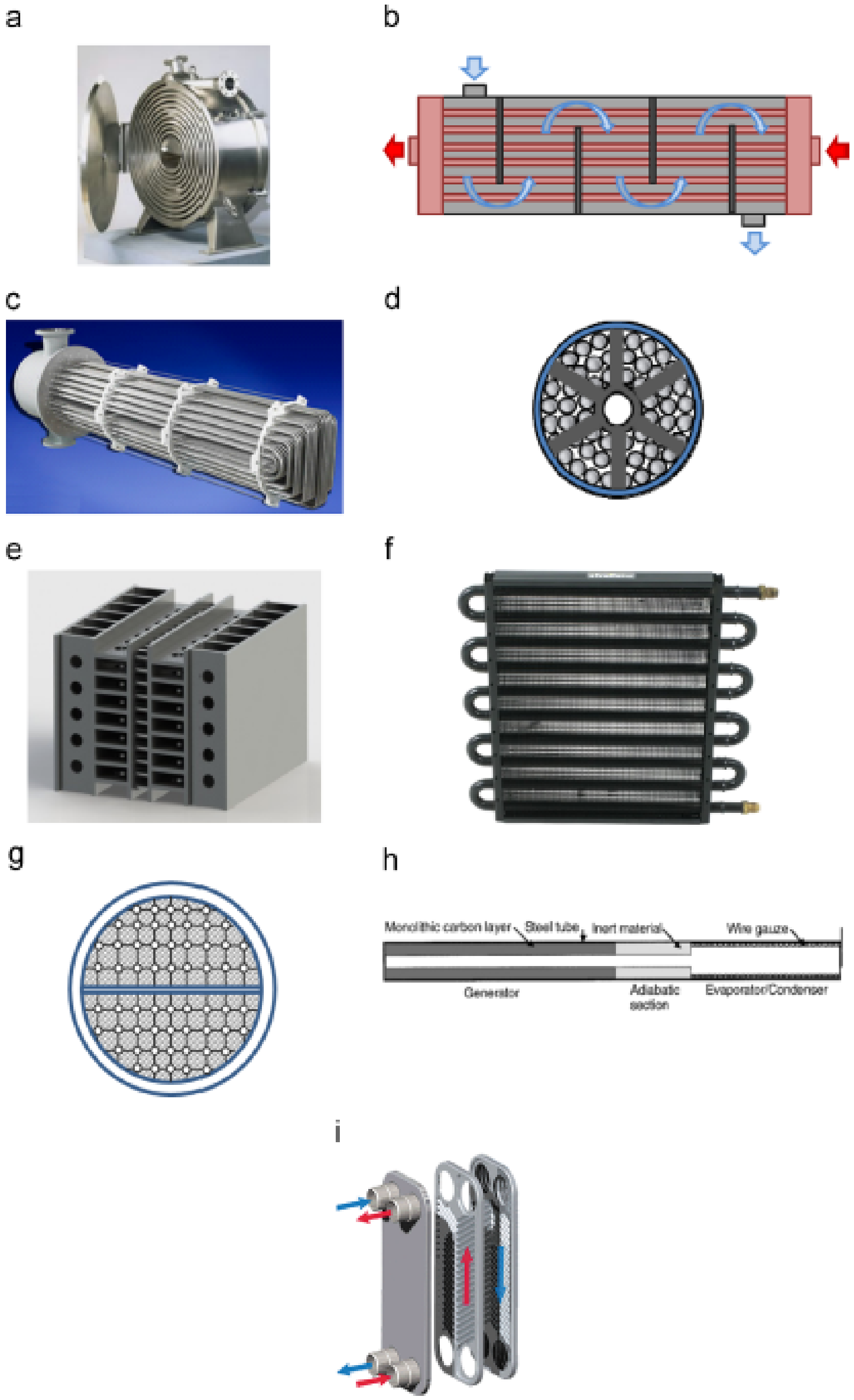


Figure A.6: Various heat exchanger types used as adsorber bed of waste-heat driven ACS. (a) Spiral Plate, (b) Shell and tube, (c) Hairpin, (d) Annulus tube, (e) Plate fin, (f) Finned tube, (g) Plate-tube, (h) Simple tube, (i) Plate [63].

B | Summary of Evaporator Handbook

B.1 Types and design

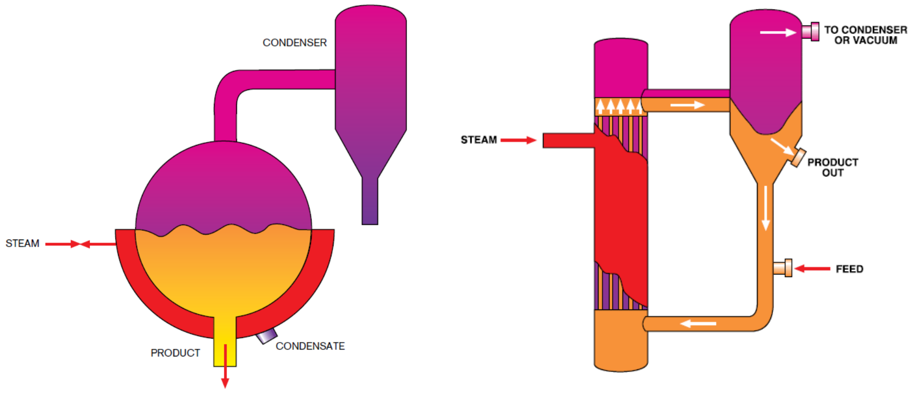
B.1.1 Overview

Every kind of model of evaporator has one main function: concentration of a product by boiling out a solvent. In most cases this solvent is water. The functionality is the separation of the solvent and the product inside the solvent. The design criteria can be the same regardless of the industry. Two of these design criteria are always in question. Firstly, is this equipment best suited for the task and secondly, what is best efficient and economical use. Therefore, as a result, many different types of evaporators have been designed. A summation of these different types are summoned up here below:

- Batch pan
- Forced circulation
- Natural circulation
- Wiped Film
- Rising film tubular
- Plate equivalents of tubular evaporators
- Falling film tubular
- Rising/falling film tubular

B.1.2 Batch Pan

The batch pan is one of the oldest and simplest methods of evaporation. Today its use in industries is minimal. The process is a batch process. Therefore the product residues for a long time inside the system compared with other evaporators. Thermal energy is transferred by conduction through the wall of the system, or the system has internal coil/heaters. Due to the design, the heat transfer area is relatively small. Therefore the Heat Transfer Coefficient (HTC) tends to be low under natural convection conditions. Due to the low HTC and low surface area, the evaporation capacity is limited. Heat transfer can be improved by mixing. See Figure B.1a for a schematic overview of this system.



(a) Schematic overview of a Batch Pan Evaporator

(b) Schematic overview of a Natural Circulation Evaporator

Figure B.1: Schematic overview of a batch pan and a natural circulation evaporator [67]

B.1.3 Natural Circulation

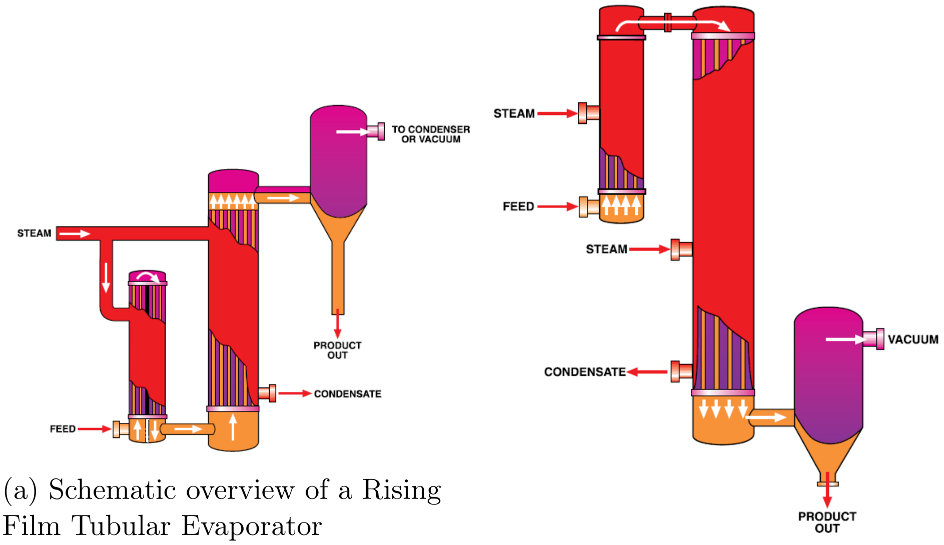
Due to natural circulation, evaporation is achieved. The design exists out of two tanks which are connected by two tubes. One tank has a main function to separate the product and the vapour. This separation is achieved by the density difference between the two phases and gravity. In the other tank has the function as an external heater. The advantage is that the size of the separation tank does not influence the evaporation capacity of the whole design. High evaporation capacities can be achieved. See Figure B.1b for a schematic overview of this system. This type of heat exchanger is the most simple version of a tubular evaporator.

B.1.4 Rising Film Tubular

As can be seen in Figure B.2a, this design exist out of three elements: A separator, a pre-heater and finally an evaporator. As the name suggests, in the evaporator, the product and produced steam flow upwards. The general idea is that the product/steam flows upwards in tubes and that thermal energy is added from the outside of the tubes. Steam is formed and forms a centre, pushing the water/product to the outside against the wall of the tubes and forming a film around it. Hence the name Rising Film Tubular Evaporator. This design provides higher HTC's and shorter product residence time. The innovating design results in higher evaporation capacities while having a low need in higher transfer area requirements.

B.1.5 Failing Film Tubular

The falling film tubular evaporator works with the same principle as the rising one. The layout of the design is also the same, as can be seen in Figure B.2b. The big difference is of course that the product and vapour are transported downwards instead of upwards. The advantage is that the film is moving down with gravity resulting in a thinner and faster-moving film. The result is a shorter product contact time and further improvement of the HTC. Another big advantage is that the temperature difference across the medium is smaller.



(a) Schematic overview of a Rising Film Tubular Evaporator

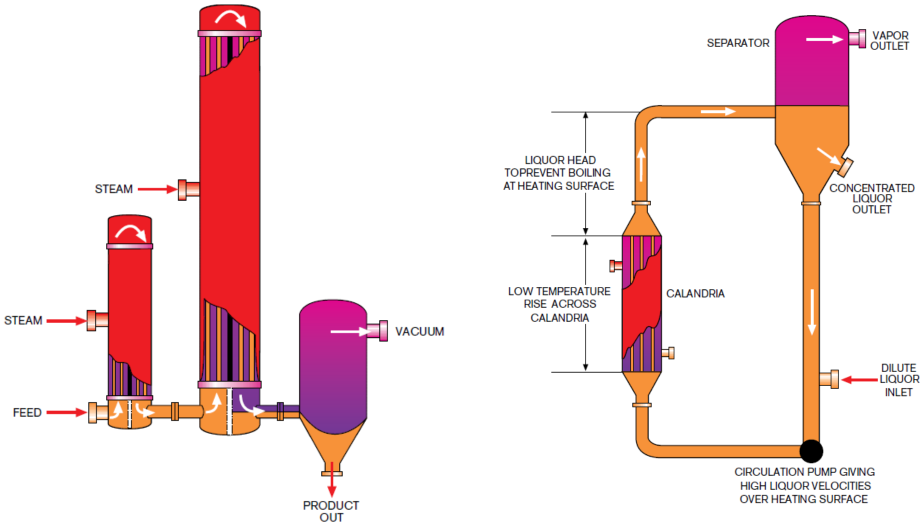
(b) Schematic overview of a Falling Film Tubular Evaporator

Figure B.2: Schematic overview of a batch pan and a natural circulation evaporator [67]

The medium that carries the thermal energy and does also carries a mixture of vapour and product. It can be smaller than with a rising film tubular evaporator.

B.1.6 Rising/Falling Film Tubular

The rising/falling film tubular evaporator is a rising and falling film tubular evaporator combined. Both processes are combined to maximise evaporation capacity while minimising the length of the film evaporator. See Figure B.3a for a schematic overview.



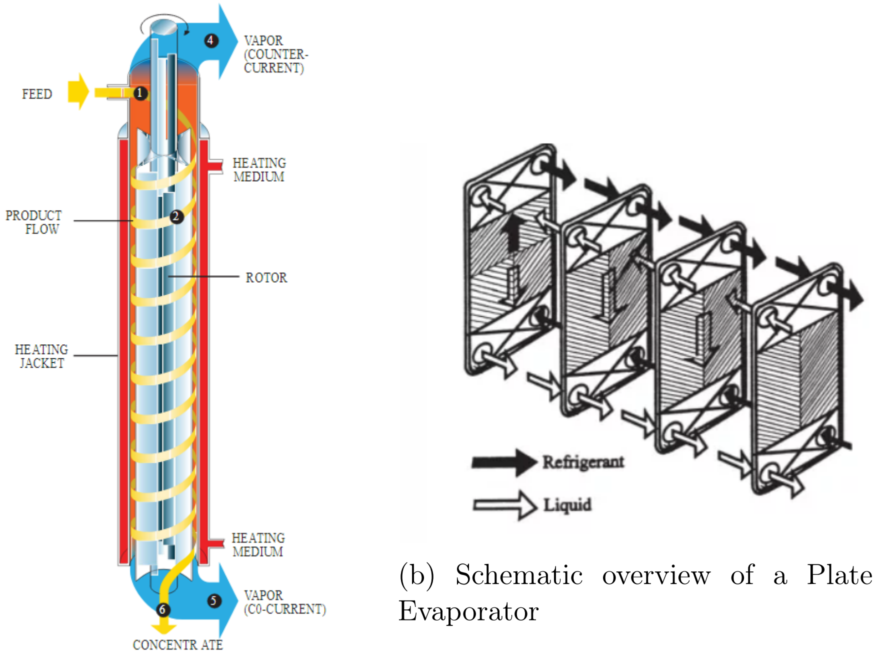
(a) Schematic overview of a Rising and Falling Film Tubular Evaporator

(b) Schematic overview of a Forced Circulation Evaporator

Figure B.3: Schematic overview of a batch pan and a forced circulation evaporator [67]

B.1.7 Forced Circulation

As the name suggests, forced circulation is an evaporator technique in which the feed is circulated through the system. It has almost the same design as natural convection evaporation. Only no natural convection occurs since the convection is artificial due to the placement of a circulation pump. The technique was developed for products/feeds which tend scale or crystalised. Boiling is prevented due to a hydrostatic head that is created. See Figure B.3b for a schematic overview. After the product enters the separator, it flashed and vapourised due to the lower pressure that exists in the separator. The temperature rise that occurs in the bundle heat exchanger is kept very low (in the range of 2 to 3 degrees). Therefore the recirculation is kept very high to limit the temperature decrease that occurs due to the entering of the new colder feed. Another reason to keep the recirculation high is to keep the velocities high. The high velocities prevent the deposits of materials inside the system. The negative side of this design choice is the high investment cost and operating cost compared to the film evaporators. Many pipes and large pumps are needed.



(a) Schematic overview of a Wiped Film Evaporator

(b) Schematic overview of a Plate Evaporator

Figure B.4: Schematic overview of a Wiped Film and a Plate evaporator

B.1.8 Wiped Film

A Wiped Film Evaporator is an evaporator with an active mechanical part inside of it, see Figure B.4a. This type of evaporator is used for highly viscous feeds. Another application is stripping the solvents to deficient levels. The feed enters the tube at the top, and the vapour can leave it again at the top or the bottom as can be seen in Figure B.4a. The product settles at the walls of the tube due to the phase difference. A rotor with blades strips the concentrate of the walls and pushes it down to the exit of the device. It is a costly operation, and therefore the use in industries is limited.

B.1.9 Plate

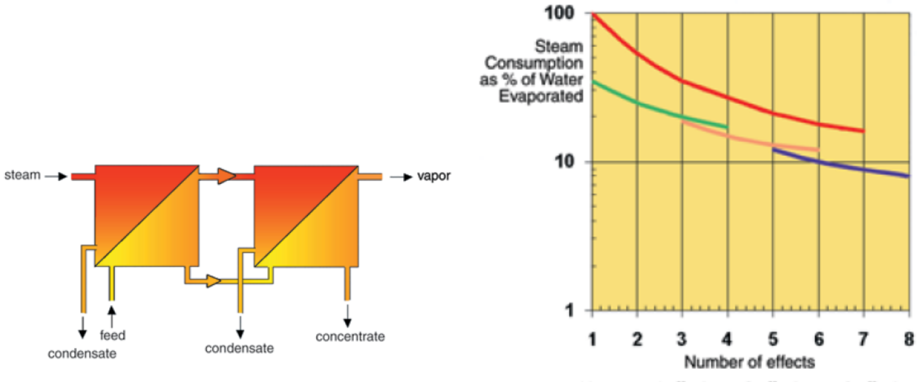
Plate Evaporators are evaporators with a high HTC but low residence time. Therefore it is highly used in the food industry. They are an alternative to tubular evaporators. Their main advantage is the full accessibility to the heat transfer surfaces and flexibility. By adding or removing plates, the characteristics of the complete device can easily be changed. It leads to a compact design. See Figure B.4b for a schematic overview.

B.2 Energy Conversation Methods

B.2.1 Overview of Methods

Since evaporation is a high energy intensive process, energy conversation is a desirable trait. Due to this fact, different kind of configurations or designs have been developed to achieve this goal. In the handbook the three following methods are presented:

- Multi-Effect Evaporation
- Thermo Vapor Recompression (TVR)
- Mechanical Vapor Recompression (MVR)



(a) Schematic overview of a Multi-Effect configuration

(b) Overview of the benefit of Multi-Effect in combination with TVR. Red is multi-effect evaporation without TVR, green is TVR at the first effect, etc.

Figure B.5: Overview of a a Multi-Effect configuration and supporting data

B.3 Multi-Effect Evaporation

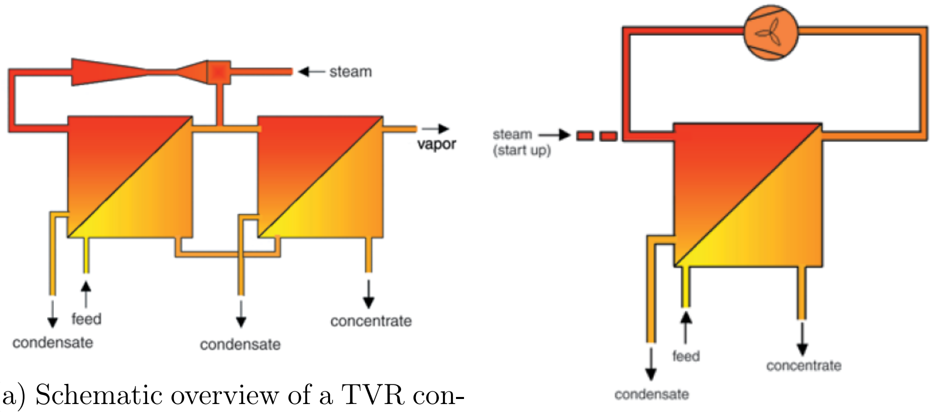
This technique is an energy conversation technique in which the thermal energy of the produced water vapour of one evaporator is used to evaporate the product in another evaporator. It is standard to keep the pressure in the second evaporator at a lower level. Therefore, the saturation pressure of the product is lower in the second evaporator. A schematic overview of this kind of configuration can be seen in Figure B.5a. In a two-effect evaporator, it is possible to create 2 kg of vapour of 1 kg of steam. Cutting the energy need in half compared with an evaporator that doesn't use an energy conversation technique. In the graph in Figure B.5b an impression of the possibilities of energy conversation can be found.

B.4 Thermo Vapour Recompression

Thermo Vapour Recompression, also known as TVR, is a relatively cost-effective technique for energy conversation. Steam entering the heat exchanger is compressed by a steam jet to a higher pressure. The steam that is compressed can partly exist out of water vapour from the evaporator. Be using a part of the water vapour, thermal energy recovery is possible depending on the ratio of water vapour that is injected into the steam jet. See Figure B.6a for a schematic overview.

B.5 Mechanical Vapour Recompression

Mechanical Vapour Recompression, also known as MVR, is the same method as TVR. The big difference is that it doesn't use a steam jet to recompressed the steam, but it uses mechanical thermo-recompression. A principal advantage is that this method can use all of the water vapour from the evaporator instead of only using a part of the vapour. Complete thermal energy recovery is theoretically possible. See Figure B.6b for a schematic overview.



(a) Schematic overview of a TVR configuration

(b) Schematic overview of a MVR configuation

Figure B.6: Schematic overview of a TVR and MVR configuration

C | Waste Heat Data

Energy consumption by sector

Country\Sector	**I&S**	**C&P**	**NFM**	**NMM**	**TE**	**MAC**	**M&Q**	**F&T**	**PPP**	**WWP**	**CON**	**T&L**	**Total**
AU	40.6	16.6	3.2	14.3	2.1	10.4	2.5	9.2	27.7	11.1	8.0	1.4	147.1
BE	38.7	45.2	4.9	21.2	6.1	2.1	0.6	21.7	12.0	4.0	3.2	3.2	163.0
BG	1.2	9.1	1.7	5.8	0.2	1.4	1.1	2.8	2.9	0.7	0.8	0.8	28.3
CR	0.3	1.6	0.2	3.9	0.2	0.7	0.3	2.5	0.7	0.4	1.3	0.3	12.3
CY	0.0	0.0	0.0	1.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.0	2.1
CZ	34.0	16.5	1.0	15.7	7.4	11.9	1.3	9.0	9.5	3.6	3.2	2.2	115.3
DK	0.5	2.8	0.0	4.4	0.4	3.2	0.7	7.3	2.0	1.0	1.8	0.3	24.0
EE	0.0	0.9	0.0	2.0	0.1	0.5	0.2	0.8	0.7	1.4	0.6	0.2	7.2
FI	13.1	12.2	3.5	3.1	0.7	3.3	1.8	4.0	68.5	7.2	4.6	0.4	122.4
FR	90.3	84.4	18.6	67.9	18.1	32.1	4.4	80.4	44.7	9.6	18.2	5.0	473.8
DE	218.7	231.7	31.9	105.3	50.7	95.8	6.1	80.5	94.9	24.0	0.0	8.1	948.0
GR	1.6	1.3	10.3	8.5	0.1	0.3	0.9	5.5	1.1	0.3	1.0	0.5	31.0
HU	4.5	8.7	1.8	4.4	2.4	4.4	0.3	5.9	2.1	0.7	2.3	0.4	38.0
IE	0.0	2.7	5.6	3.5	0.3	2.8	1.3	5.0	0.3	1.6	0.1	0.2	23.4
IT	60.6	47.9	7.4	58.1	4.2	39.0	1.3	30.9	23.5	4.7	4.2	13.6	295.0
LV	0.3	0.3	0.0	1.7	0.1	0.2	0.2	1.1	0.1	4.2	0.5	0.1	8.8
LT	0.0	3.5	0.0	2.2	0.0	0.3	0.1	2.2	0.4	1.1	0.5	0.4	10.7
LU	2.8	0.6	0.0	1.2	0.1	0.3	0.0	0.3	0.1	0.2	0.3	0.2	6.1
MT	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.3
NL	38.1	98.1	5.0	8.9	1.5	8.4	1.8	31.0	11.2	0.9	7.8	1.7	214.6
PL	28.1	34.6	4.7	29.6	4.7	8.5	4.4	21.4	18.3	10.0	2.1	1.3	167.8
PT	2.1	5.8	0.3	12.6	0.6	1.9	1.3	4.9	16.3	1.2	1.6	3.4	51.9
RO	19.5	19.1	0.0	9.2	2.4	4.2	0.5	6.2	0.9	3.0	4.6	0.0	69.5
SK	25.6	3.4	2.8	4.5	1.9	2.2	0.1	1.6	5.0	0.5	0.3	0.3	48.3
SI	1.7	1.7	1.8	2.1	0.4	1.6	0.2	0.7	1.9	0.5	0.3	0.3	13.1
ES	37.2	46.7	12.8	39.3	4.5	10.0	4.9	25.3	23.9	5.9	14.6	4.0	229.0
SE	18.3	6.5	3.8	3.7	2.3	4.0	5.2	4.4	68.0	6.3	1.1	0.2	124.0
GB	45.0	37.8	6.3	30.5	11.3	20.9	0.2	31.1	19.0	0.0	7.2	8.4	217.7
EU	722.9	739.9	127.6	465.2	123.0	270.3	41.6	396.2	455.8	103.9	90.3	57.0	3592.7

Legend: I&S: Iron & Steel industry, C&P: Chemical and Petrochemical industry, NFM: Non-ferrous metal industry, NMM: Non-metallic Minerals, TE: Transport Equipment, MAC: Machinery, M&Q: Mining and Quarrying, F&T: Food and Tobacco, PPP: Paper, Pulp and Print, WWP: Wood and Wood Products, CON: Construction, T&L: Textile and Leather

Table C.1: Energy consumptie by European sectors [TWh] [49]

Potential Waste Heat Production

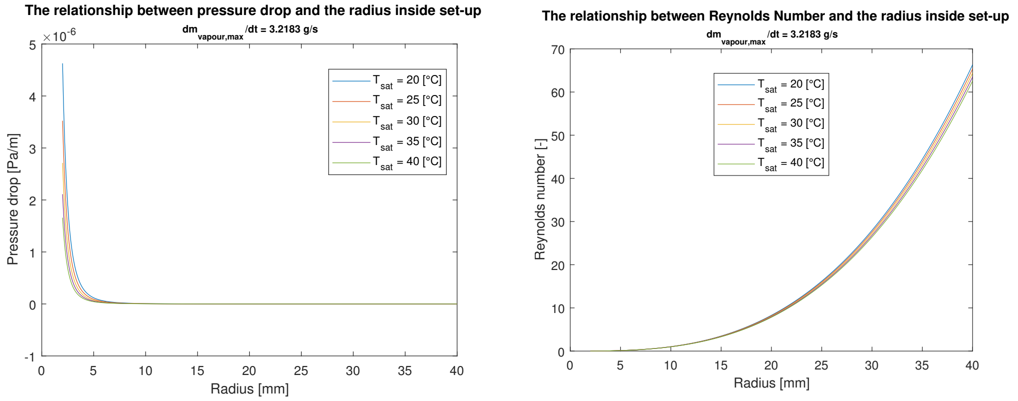
Country/Industry	**I&S**	**C&P**	**NFM**	**NMM**	**F&T**	**PPP**	**WWP**	**T&L**	**Total**
AU	4.6	4.5	3.9	4.6	3.5	4.3	2.4	4.5	36.6
BE	4.4	5.0	0.5	2.4	1.9	1.3	0.2	0.4	16.8
BG	0.1	1.0	0.2	0.7	0.2	0.3	0.0	0.1	2.8
CR	0.0	0.2	0.0	0.4	0.2	0.1	0.0	0.0	1.0
CY	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2
CZ	3.9	1.8	0.1	1.8	0.8	1.0	0.2	0.2	10.6
DK	0.1	0.3	0.0	0.5	0.6	0.2	0.1	0.0	2.0
EE	0.0	0.1	0.0	0.2	0.1	0.1	0.1	0.0	0.6
FI	1.5	1.3	0.3	0.4	0.3	7.2	0.4	0.0	11.9
FR	10.3	9.3	1.8	7.7	6.9	4.7	0.6	0.6	43.5
DE	24.9	25.5	3.1	12.0	7.0	10.0	1.4	0.9	89.2
GR	0.2	0.1	1.0	1.0	0.5	0.1	0.0	0.1	3.1
HU	0.5	1.0	0.2	0.5	0.5	0.2	0.0	0.0	3.3
IE	0.0	0.3	0.5	0.4	0.4	0.0	0.1	0.0	2.0
IT	6.9	5.3	0.7	6.6	2.7	2.5	0.3	1.5	28.4
LV	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.6
LT	0.0	0.4	0.0	0.3	0.2	0.0	0.1	0.0	1.0
LU	0.3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.6
MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NL	4.3	10.8	0.5	1.0	2.7	1.2	0.1	0.2	43.7
PL	3.2	3.8	0.5	3.4	1.8	1.9	0.6	0.1	16.2
PT	0.2	0.6	0.0	1.4	0.4	1.7	0.1	0.4	5.1
RO	2.2	2.1	0.0	1.0	0.5	0.1	0.2	0.0	6.2
SK	2.9	0.4	0.3	0.5	0.1	0.5	0.0	0.0	5.0
SI	0.2	0.2	0.2	0.2	0.1	0.2	0.0	0.0	1.2
ES	4.2	5.1	1.2	4.5	2.2	2.5	0.4	0.4	22.1
SE	2.1	0.7	0.4	0.4	0.4	7.2	0.4	0.0	12.5
GB	5.1	4.2	0.6	3.5	2.7	2.0	0.0	0.9	27.4
EU	722.9	739.9	127.6	465.2	123.0	270.3	41.6	396.2	455.8

Legend: I&S: Iron & Steel industry, C&P: Chemical and Petrochemical industry,
NFM: Non-ferrous metal industry, NMM: Non-metallic Minerals,
F&T: Food and Tobacco, PPP: Paper, Pulp and Print,
WWP: Wood and Wood Products, T&L: Textile and Leather

Table C.2: Potential waste heat by European industries [TWh] [49]

D | Substantiate calculations

D.1 Evidence for negligible pressure drop by mass flow inside the set-up



(a) Relationship between the pressuredrop by distance and the radius

(b) Relationship between the Reynolds Number and the radius

Figure D.1: Evidence for the statement that pressure drop by mass displacement is negltible

As can be seen in Figure D.1a, the pressure drop over the length inside the system is smaller than 5E-6 at different radiuses. As can be observed, that even at the smallest radiuses inside the system, see Table 4.4, the pressure drop is negligible. For example, the distance it has to travel before even one-pascal pressure drop occurs is the distance to the moon. Different working conditions at different saturation pressure and temperatures don't seem to have a significant difference between each other. All stay in the same range.

Most of the parameters used can be seen in Table D.1. Other values like the saturation pressure, the density of the water vapour and dynamic viscosity are calculated using the Xsteam function of Matlab [28]. With the values from the table and Equation D.1, the maximum vapour transported inside of the system can be determined. The pressure drop is established by using the Darcy-Weisbach equation, see Equation D.2. Since the flow is laminar, see Figure D.1b, the friction factor is established by dividing 64 by the Reynolds Number. It is assumed in with these calculations that no air is present and therefore only vapour is transported in one dimension. Since the dynamic viscosity of air is in the same range as water vapour, similar results can be expected when the air is present inside the system. If there is, in reality, a pressure difference inside the system, it is more likely that this is presence due temporal and therefore density difference.

Parameter	Value	Unit	Description	Source
ρ_{silica}	760	kg/m^3	Density of the silica gel	[45]
q_{max}	0.4	kg_{water}/kg_{silica}	Maximum uptake of water	[45]
θ_{max}	0.95	-	Maximum saturation within t_{sat}	[45]
t_{sat}	250	s	Duration till S_{max}	[45]
d_i	33.8	mm	Inner diameter of silica column	See Appendix E
d_o	54	mm	Outer diameter of silica column	See Appendix E
L_{column}	0.5	m	Length of a silica gel bed column	See Appendix E
$nr_{columns}$	4	-	Number of silica gel bed columns	See Appendix E

Table D.1: Parameters used during calculation: Part 1

$$\frac{dm_{vapour,max}}{dt} = \frac{\frac{1}{4}\pi * (d_o^2 - d_i^2) * L_{column} * nr_{columns} * \rho_{silica} * q_{max} * \theta_{max}}{t_{sat}} \tag{D.1}$$

$$\frac{dP}{dL} = f_D \frac{\rho}{2} \frac{v^2}{D_h} \tag{D.2}$$

D.2 Algoritme to establish Air Leak Resistance Coefficient

```
while abs(error) > error_min

        m_air_leak              = 0;
        t_air_leak              = 0;
        i                       = 1;
        P_air_leak(i)           = 0;

        while P_air_leak(i) < P_max
            i                               = i + 1;
            dmdt                            = (Patm-P_air_leak(i
               -1))/R_air;
            m_air_leak                      = m_air_leak +dmdt*
               dt;
            t_air_leak                      = t_air_leak+dt;
            P_air_leak(i)                   = m_air_leak*R*T_atm
               /(V_sys*M_air);
        end

        error = P_min-P_air_leak(i-t_diff/dt);

        R_air = R_air+error*Kp;
end
```

D.3 Algoritme to establish Mass Removal Resistance by Vacuum Control Coefficient

```
while abs(error) > error_min

        m_air_leak              = m_air;
        t_air_leak              = 0;
        i                       = 1;
        P_air_leak(i)           = Patm;

        while P_air_leak(i) > P_min
            i                               = i + 1;
            dmdt                            = (P_air_leak(i-1)/
               R_vc) -(Patm-P_air_leak(i-1))/R_air;
            m_air_leak                      = m_air_leak - dmdt*
               dt;
            t_air_leak                      = t_air_leak+dt;
            P_air_leak(i)                   = m_air_leak*R*T_atm
               /(V_sys*M_air);
        end

        error = P_max-P_air_leak(i-t_diff/dt);
        R_vc = R_vc+error*Kp;
end
```

D.4 DEBESC Model

```
for i = [2:1:nt]

    %Sorption
    if t(i) <= t_sat

        Theta(i)            = P_vapour(i-1)*K0*exp((Qst*18)/(R*T_silica));

        if Theta(i)> 0.4
            Theta(i) = 0.4;
        elseif Theta(i)<0
            Theta(i)=0;
        end

        m_water_silica_max  = Theta(i)*m_silica;

        if m_water_silica(i-1)  < m_water_silica_max
            dm_water_silicadt   = m_silica*Theta(i)*dsatcapcdt;
        else
            dm_water_silicadt   = (m_water_silica_max-m_water_silica(i-1))/dt;
        end
    else
        dm_water_silicadt = 0;
    end

    m_water_silica(i)   = m_water_silica(i-1)+dm_water_silicadt*dt;

    if m_water_silica(i) < 0
        m_water_silica(i) = 0;
    end

    %vacuum control
    if P_sys(i-1) > Psat_max + offsetPc
        vc = 1;
    end
    if P_sys(i-1) < Psat_max - offsetPc
        vc = 0;
    end
    if vc == 1
        dm_vc_airdt     = (P_air(i-1)/Rpc);
        dm_vc_waterdt   = (P_vapour(i-1)/Rpc);
    else
        dm_vc_airdt     = 0;
        dm_vc_waterdt   = 0;
    end

    %air balance
```

```
    dm_leak_air_dt      = (Patm-P_sys(i-1))/Rp;
    dm_airdt            = dm_leak_air_dt-dm_vc_airdt;
    h_air               = Cv_air*T_sys(i-1)+R*T_sys(i-1)*m_air(i
       )/M_air;

    %water balance
    dm_water_dt         = dm_water_silicadt+dm_vc_waterdt;

    %Energy heat exchanger
    dEhedt              = (T_he-T_sys(i-1))/R_k;

    %Energy
    dEaddt              = (hV0+dhVdT*T_sys(i-1))*dm_water_dt;
    dEairdt             = h_air*dm_airdt;
    dEsysdt             = dEhedt+dEairdt-dEaddt;

    E_sys(i)             = E_sys(i-1)+dEsysdt*dt;

    %Mass balance
    m_water(i)          = m_water(i-1)-dm_water_dt*dt;
    m_air(i)            = m_air(i-1)+dm_airdt*dt;
    if  m_water(i) < 0
        m_water(i) = 0;
        m_water_silica(i) = m_water_silica(i-1);
    end
    if  m_air(i) < 0
        m_air(i) = 0;
    end

    %Volume
    V_gas(i)            = V_sys-m_liquid(i-1)/rho_water;

    %Pressure
    error               = dEsysdt*dt;
    T_sys(i)            = T_sys(i-1);
    P_sys(i)            = P_sys(i-1);
    m_vapour(i)         = m_vapour(i-1);
    m_liquid(i)         = m_liquid(i-1);
        while abs(error) > error_min
            %System is saturatated
            T_sys(i)    = T_sys(i)+error*Kp;
            P_sys(i)    = P0 + dPdT*T_sys(i);
            hL_new      = hL0 + dhLdT*T_sys(i);
            hV_new      = hV0 + dhVdT*T_sys(i);
            m_vapour(i) = ((P_sys(i)-P_air(i))*V_gas(i))/(R*
               T_sys(i))-m_air(i)
                            /M_air)*M_water;
            m_liquid(i) = m_water(i)-m_vapour(i);
            Enew        = m_liquid(i)*hL_new + m_vapour(i)*
               hV_new
                            + h_air*m_air(i);
            error       = (E_sys(i)-Enew);
```

```
        end

    P_vapour(i)         = m_vapour(i)*R*T_sys(i)/(M_water*V_gas(i));
    P_air(i)            = m_air(i)*R*T_sys(i)/(M_air*V_gas(i));
end
```

D.5 DEBSAD Model

```
for t = [2:1:n_t]
        for r = [1:1:length(msb)]
            % Adsorption capacity
            q(t,r) = Pvapour*K0*exp((Qst*M_water)/(R*Tsys(t-1,r)));
            if q(t,r)> 0.4
                q(t,r) = 0.4;
            elseif q(t,r)<0
                q(t,r)=0;
            end

            m_water_silica_max  = q(t,r)*msb(r)*theta;

            % Energy transfer by conduction
            if r == 1
                dEhedt(t,r)              = (2*pi*k_he*dL)*(T_he-Tsys(t-1,r))/log(rv(r+1)/rv(r)) - (2*pi*k_silica*dL)*(Tsys(t-1,r)-Tsys(t-1,r+1))/log(rv(r+2)/rv(r+1));
            elseif r == length(msb)
                dEhedt(t,r)              = (2*pi*k_silica*dL)*(Tsys(t-1,r-1)-Tsys(t-1,r))/log(rv(r+1)/rv(r));
            else
                dEhedt(t,r)              = (2*pi*k_silica*dL)*(Tsys(t-1,r-1)-Tsys(t-1,r))/log(rv(r+1)/rv(r)) - (2*pi*k_silica*dL)*(Tsys(t-1,r)-Tsys(t-1,r+1))/log(rv(r+2)/rv(r+1));
            end

            % Vapour Mass transfer calc
            if m_water_silica(t-1,r)  < m_water_silica_max
                dm_water_silicadt(t,r) = msb(r)*q(t,r)*dsatcapcdt;
            else
                error = m_water_silica(t-1,r)-m_water_silica_max;
                while abs(error) > error_min
                    dm_water_silicadt(t,r) = dm_water_silicadt(t,r)+error*Kp;

                    m_water_silica(t,r)   = m_water_silica(t-1,r) + dm_water_silicadt(t,r)*dt;
                    dEdt(r)                = h_vapour*dm_water_silicadt(t,r) + dEhedt(t,r);
                    Esys(t,r)              = Esys(t-1,r)+dEdt(r)*dt;
                    Tsys(t,r)              = Esys(t,r)/(m_water_silica(t,r)*Cp_w
```

```
                                                + msb(r)*cp_silica);
                    q(t,r)              = Pvapour*P_sys*K0*exp((
                        Qst*M_water)/
                                                (R*Tsys(t-1,r)));
                    m_water_silica_max      = q(t,r)*msb(r)*theta
                        ;
                    error                   = m_water_silica(t,r)
                        - m_water_silica_max;
                end
            end
        end

    % Mass Balance
    m_water_silica(t,:) = m_water_silica(t-1,:) +
        dm_water_silicadt(t,:)*dt;
    saturation(t,:)     = m_water_silica(t,:)'./msb';

    % Energy balance
    dEdt                = h_vapour*dm_water_silicadt(t,:) +
        dEhedt(t,:);
    Esys(t,:)           = Esys(t-1,:)+dEdt*dt;

    % New temperature
    Tsys(t,:)           = Esys(t,:)'./(m_water_silica(t,:)'*Cp_w
                            + msb'*cp_silica);
    Tsys(:,1)          = T_he;
end
```

D.6 Theoretical possible maximum temperature incease

$$\delta T_{max} = \frac{q_{max} * Qst}{Cp_{silica} + q_{max} * Cp_{water}} \tag{D.3}$$

Parameter	Value	Unit	Description	Source
q_{max}	0.4	kg_{water}/kg_{silica}	Maximum water uptake	[45]
Qst	2300	kJ/kg	Adsorption energy	[45]
Cp_{silica}	0.921	$kJ/(kg * k)$	Specific heat constant silica gel	[45]
Cp_{water}	4.182	$kJ/(kg * k)$	Specific heat constant saturated water	[28]

Table D.2: Parameters used during calculation: Part 2

When using the values from Table D.2 into Equation D.3, it is calculated that a temperature increase can be expected of 354.68 Kelvin. However, this would never happen in reality since the adsorption characteristic of silica gel depends partly on the temperature of the silica gel itself, and a part of the thermal energy is discharged to the surroundings, but give an impression about the large quantity the silica gel receive when adsorbing water vapour. It can only lead to the conclusion that good thermal conduction during the adsorption phase is an essential aspect of the design of a silica bed.

D.7 Diameter of leakages

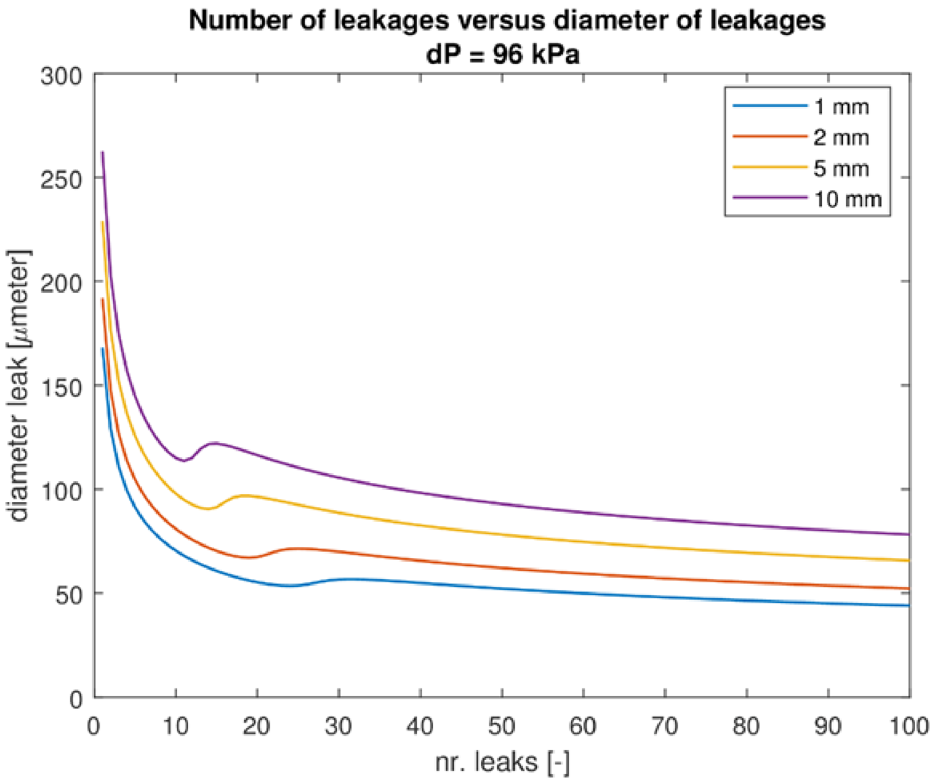


Figure D.2: Display of the size of the leakage at a pressure difference of 96 kPa

E | Design Set-up

E.1 Process Diagrams

E.1.1 General Overview of the complete set-up

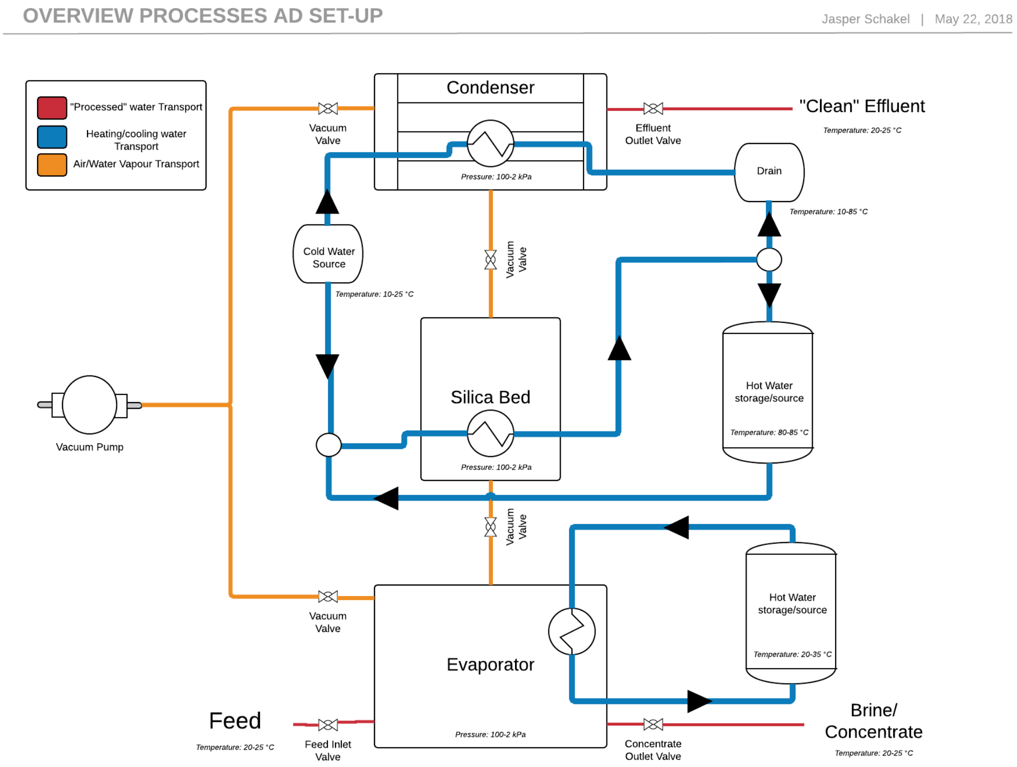


Figure E.1: General overview of the processes of the AD Set-up

E.1.2 Evaporator reactor

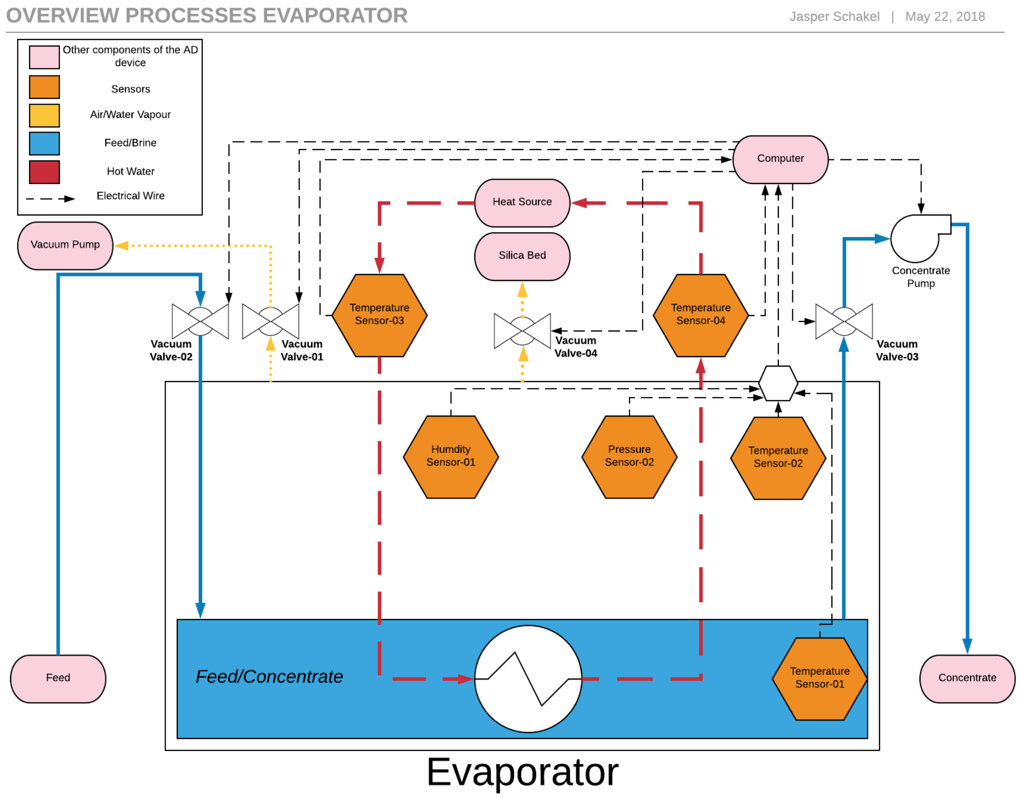


Figure E.2: Overview of the processes inside the evaporator reactor and the hydraulic system

E.1.3 Silica bed reactor

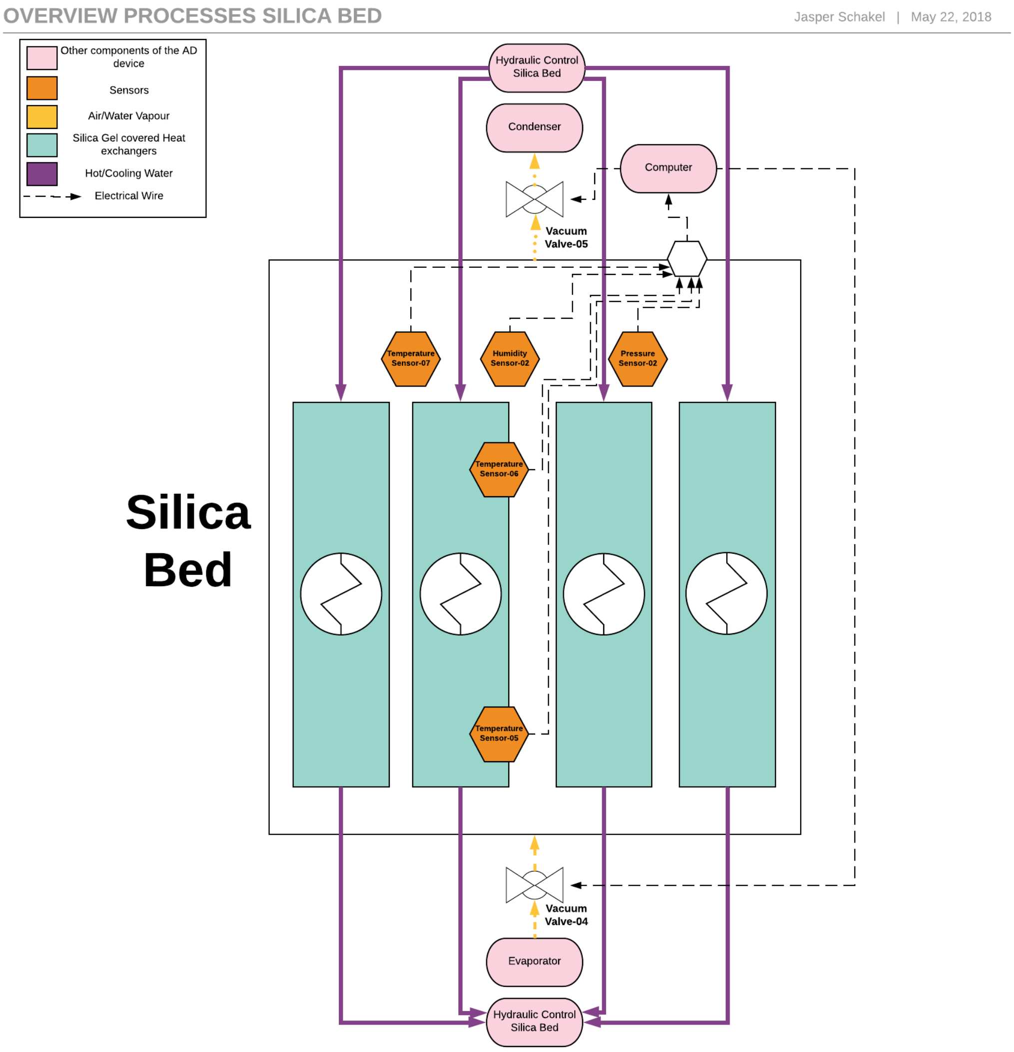


Figure E.3: Overview of the processes inside the silica bed reactor

E.1.4 Hydraulic system of the silica bed reactor

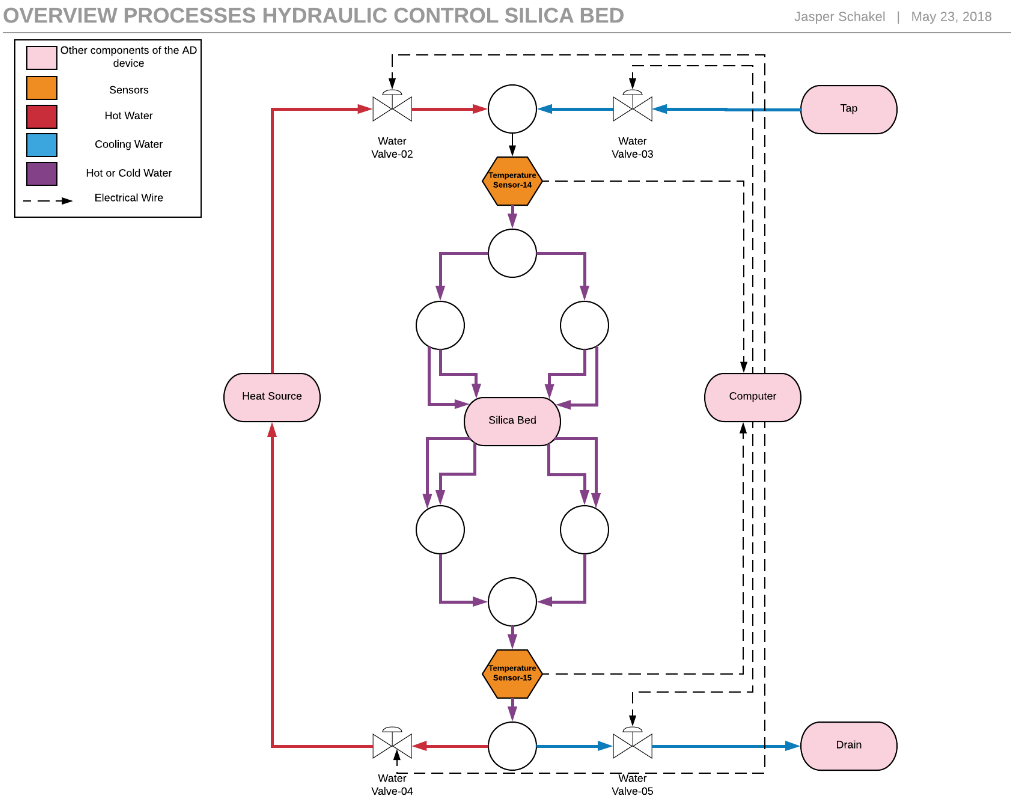


Figure E.4: Overview of the processes of the hydraulic system of the silica bed reactor

E.1.5 Condenser reactor

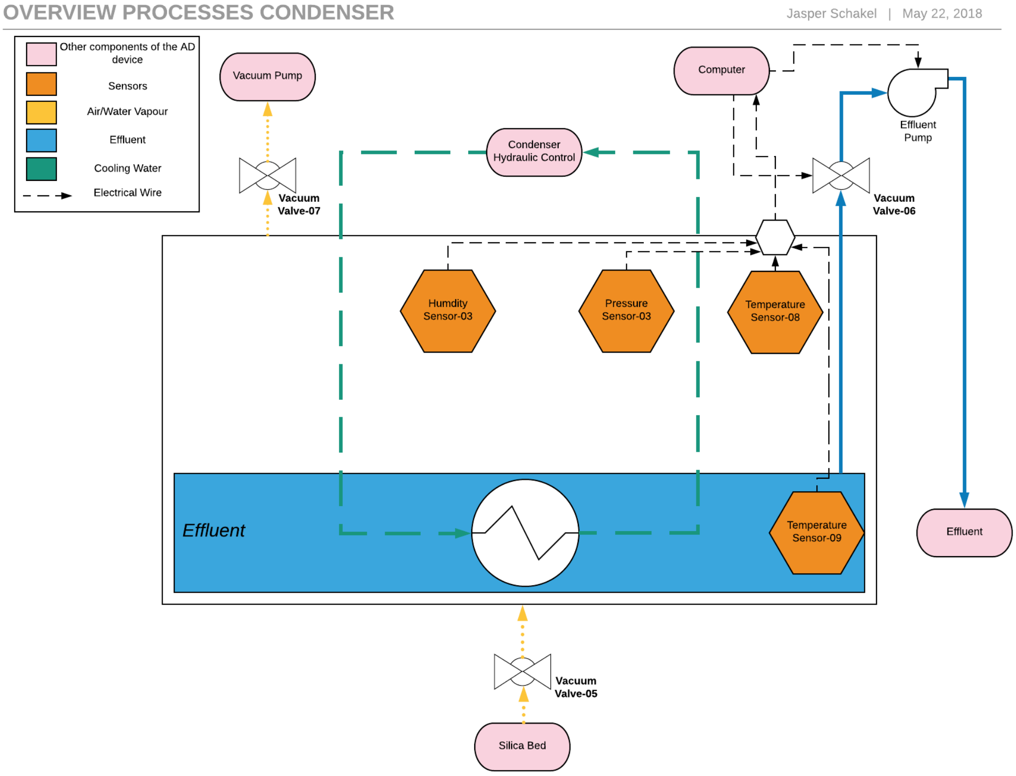


Figure E.5: Overview of the processes of the condenser reactor

E.1.6 Hydraulic system of the condenser reactor

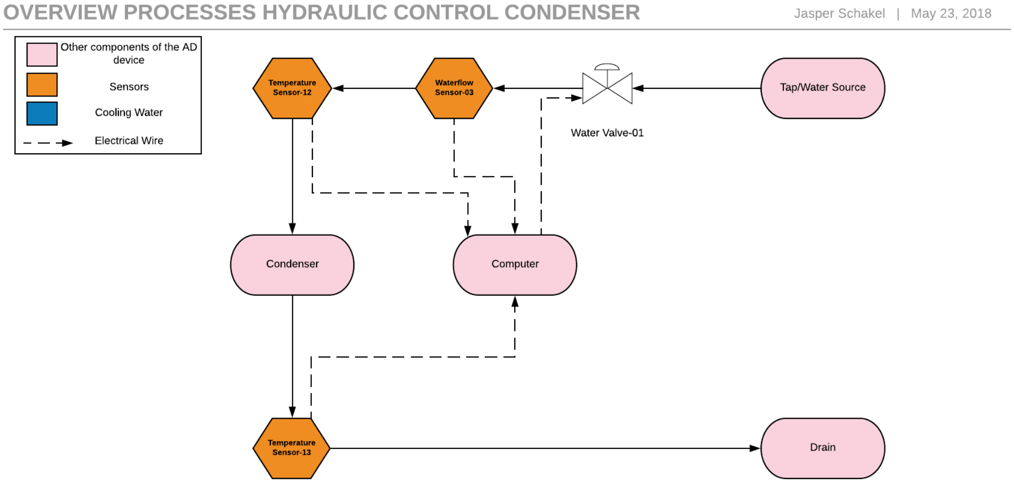


Figure E.6: Overview of the process of the hydraulic system of the condenser reactor

E.1.7 Thermal energy sources 1 and 2

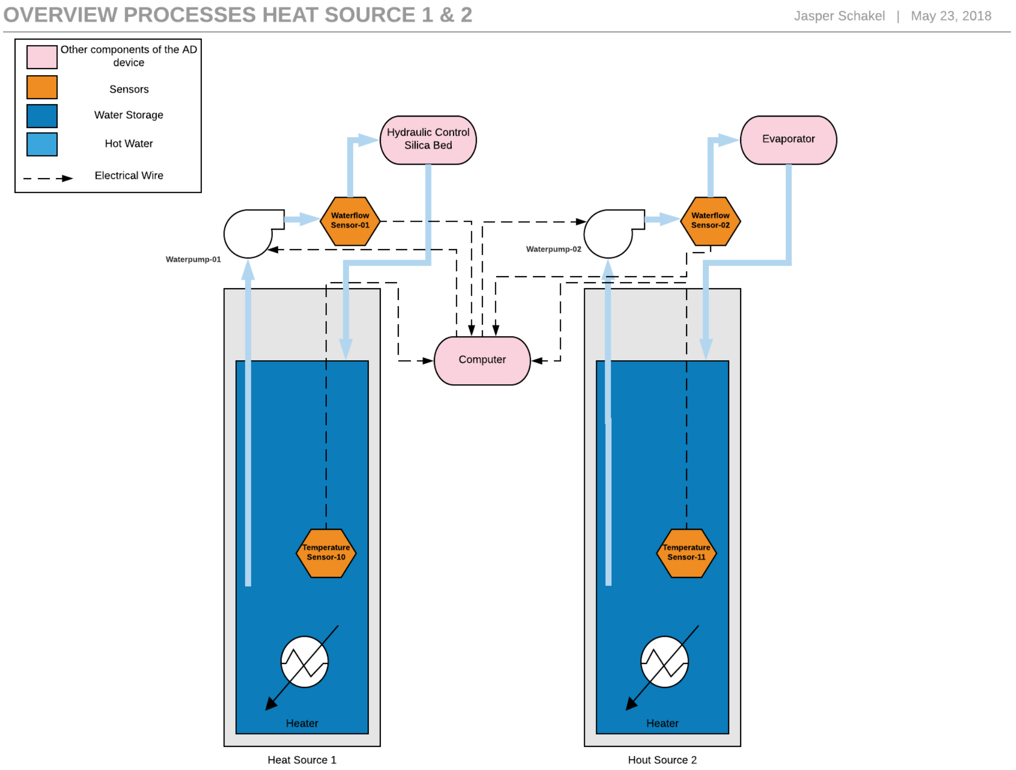


Figure E.7: Overview of the process of the thermal energy sources 1 and 2

E.2 Hydraulic Diagrams

E.2.1 Evaporator

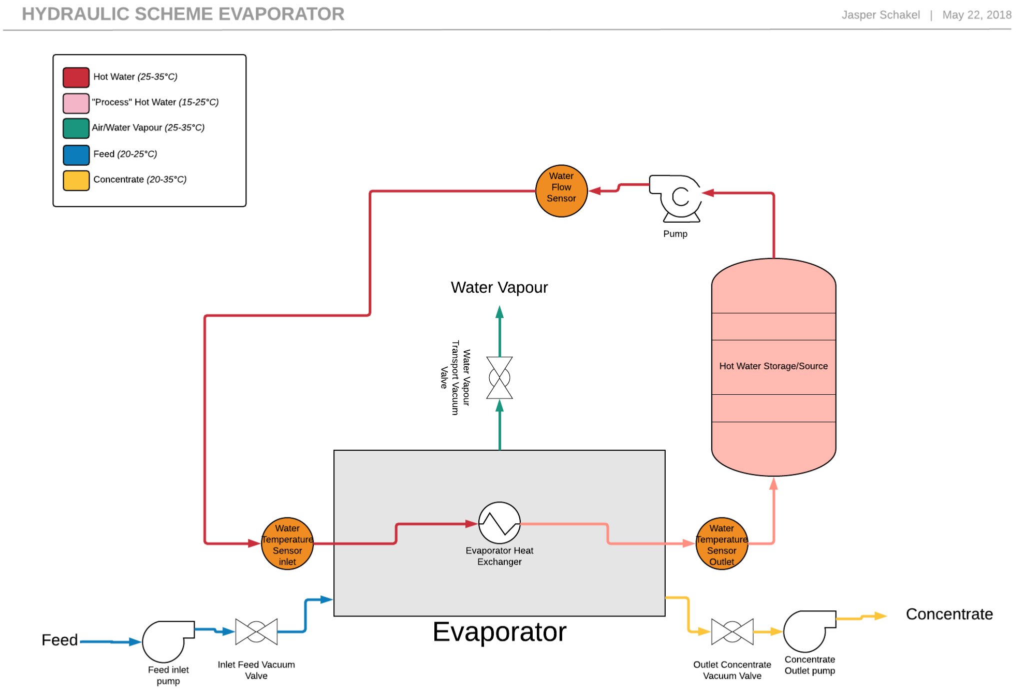


Figure E.8: Hydraulic diagram evaporator reactor

E.2.2 Silica Bed

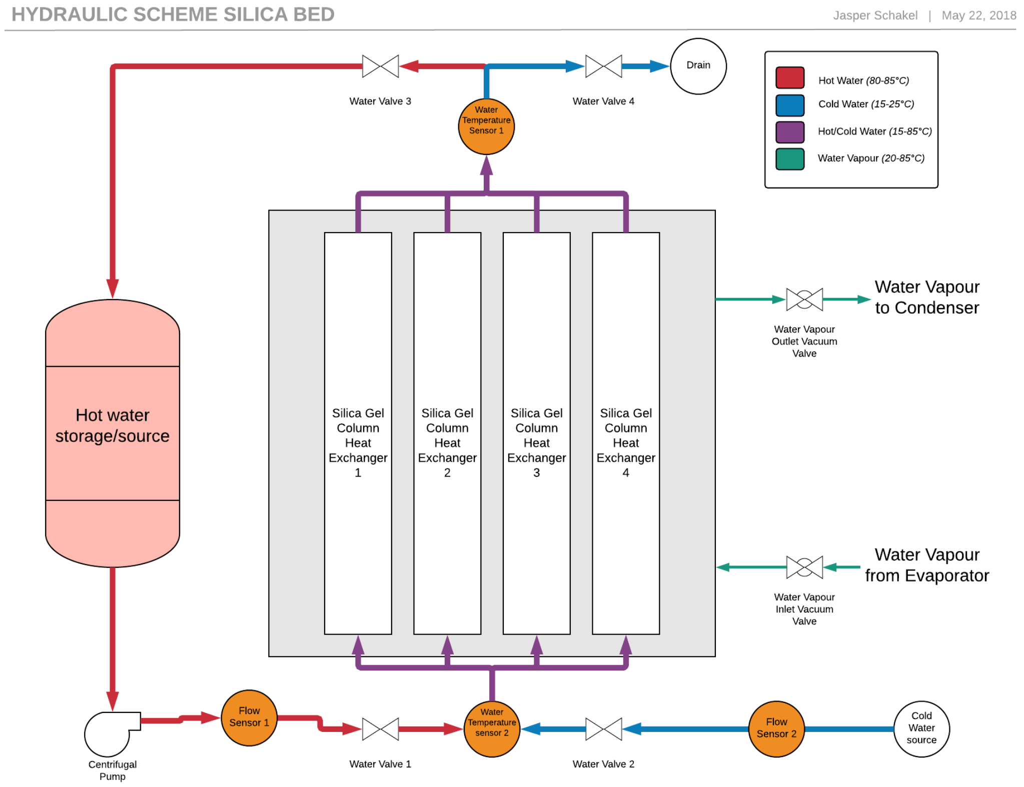


Figure E.9: Hydraulic diagram silica bed reactor

E.2.3 Condenser

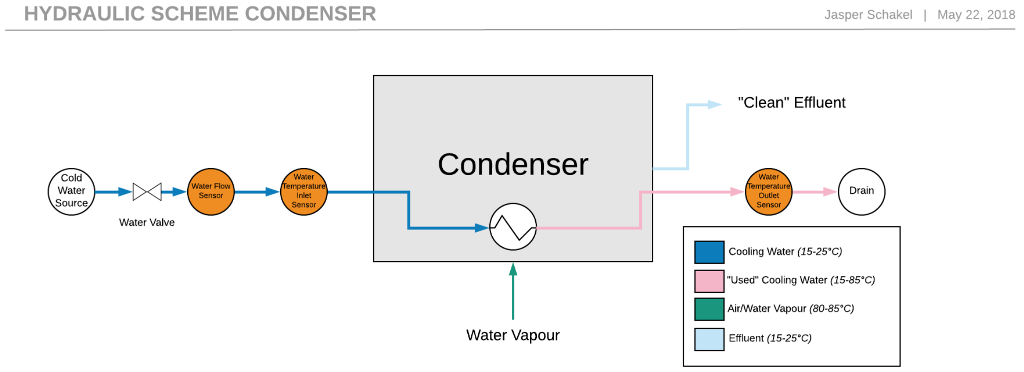


Figure E.10: Hydraulic diagram condenser reactor

E.3 Circuit Diagrams

E.3.1 Evaporator Reactor

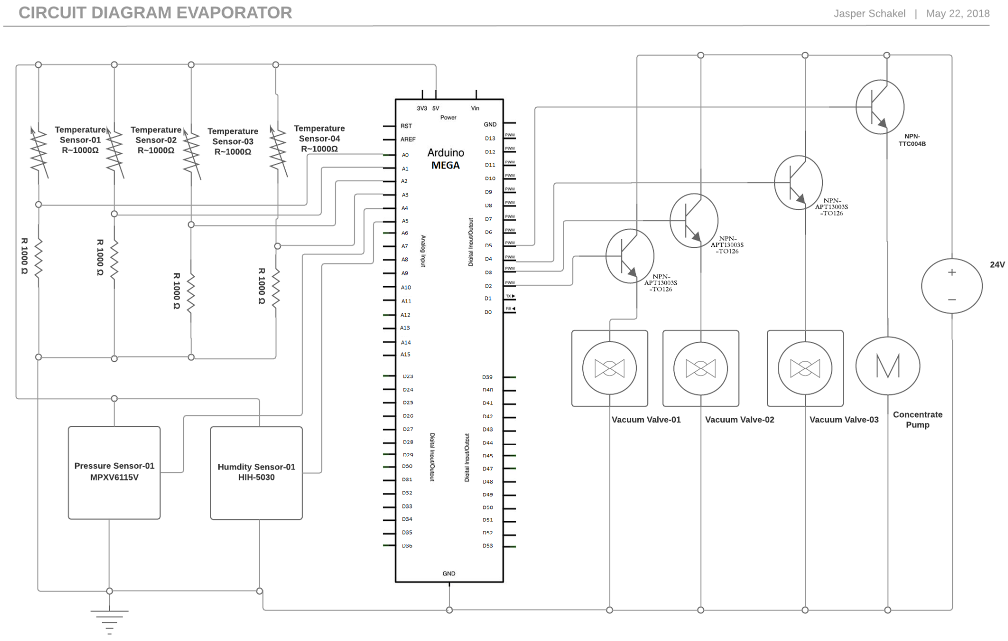


Figure E.11: Circuit diagram of the evaporator reactor and the hydraulic system

E.3.2 Silica bed reactor

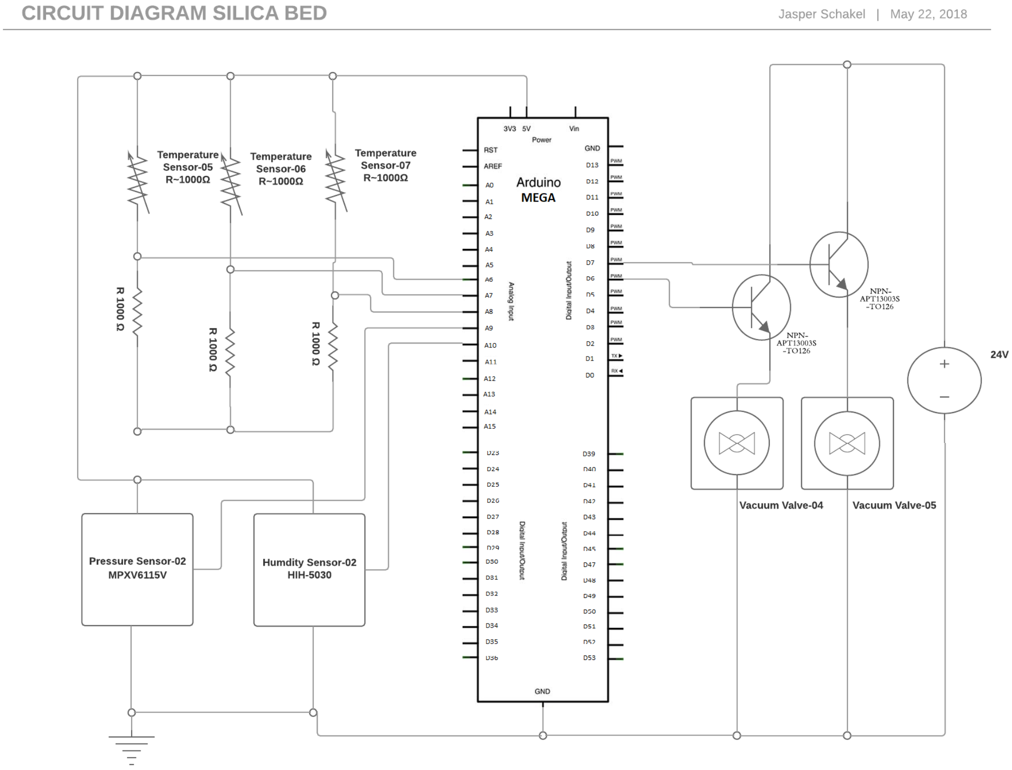


Figure E.12: Circuit diagram of the silica bed reactor

E.3.3 Hydraulic system of the silica bed

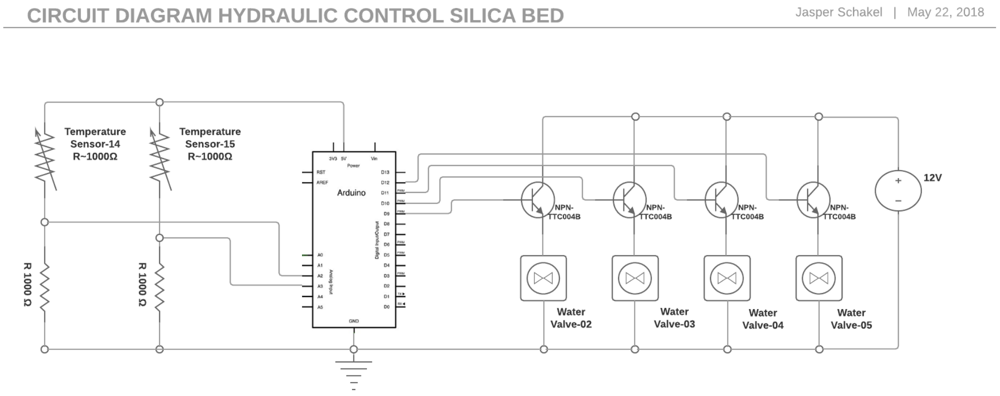


Figure E.13: Circuit diagram of the hydraulic system of the silica bed

E.3.4 Condenser reactor

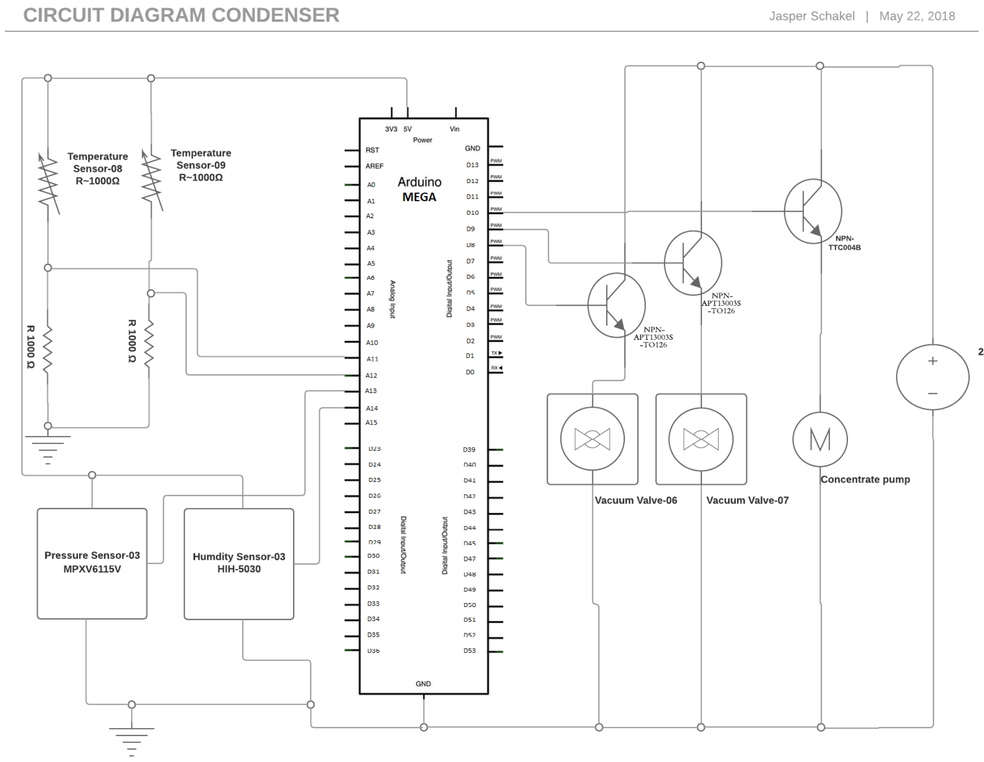


Figure E.14: Circuit diagram of the condenser reactor

E.3.5 Hydraulic system condenser

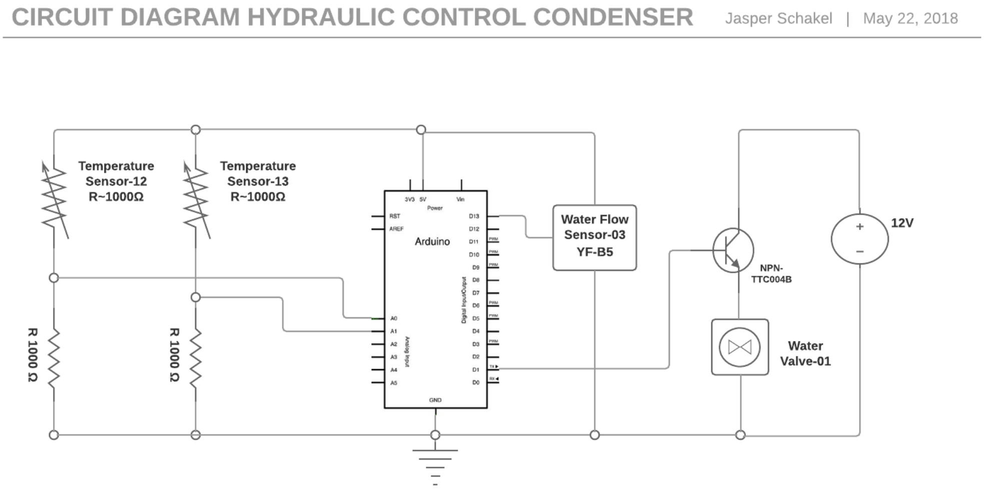


Figure E.15: Circuit diagram of the hydraulic system of the condenser

E.3.6 Thermal Energy Source 1

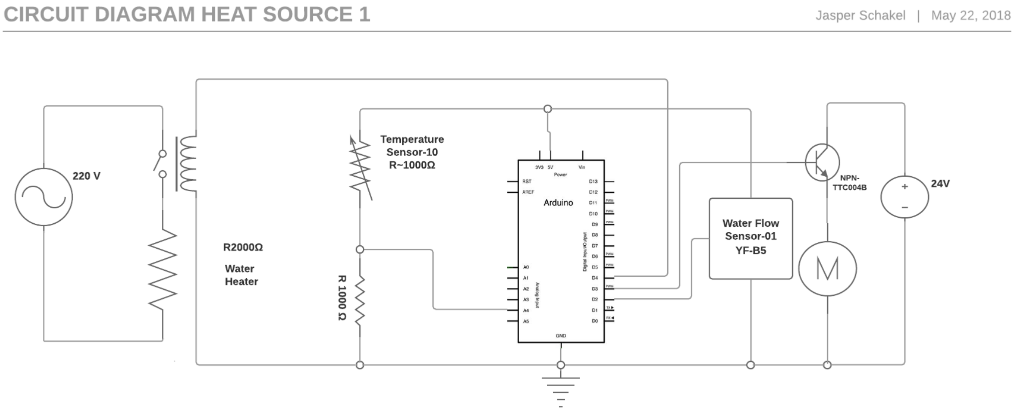


Figure E.16: Circuit Diagram of the Thermal Energy Source 1

E.3.7 Thermal Energy Source 2

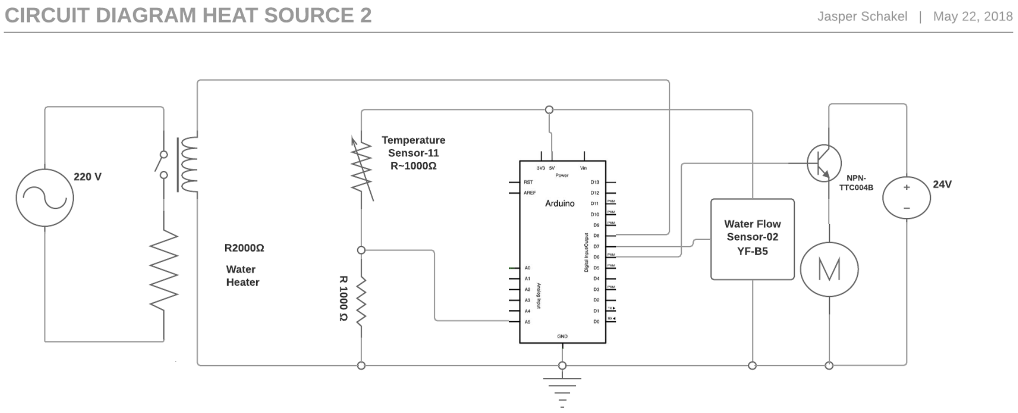


Figure E.17: Circuit Diagram of the Thermal Energy Source 2

E.4 Blueprints

E.4.1 Silica Bed

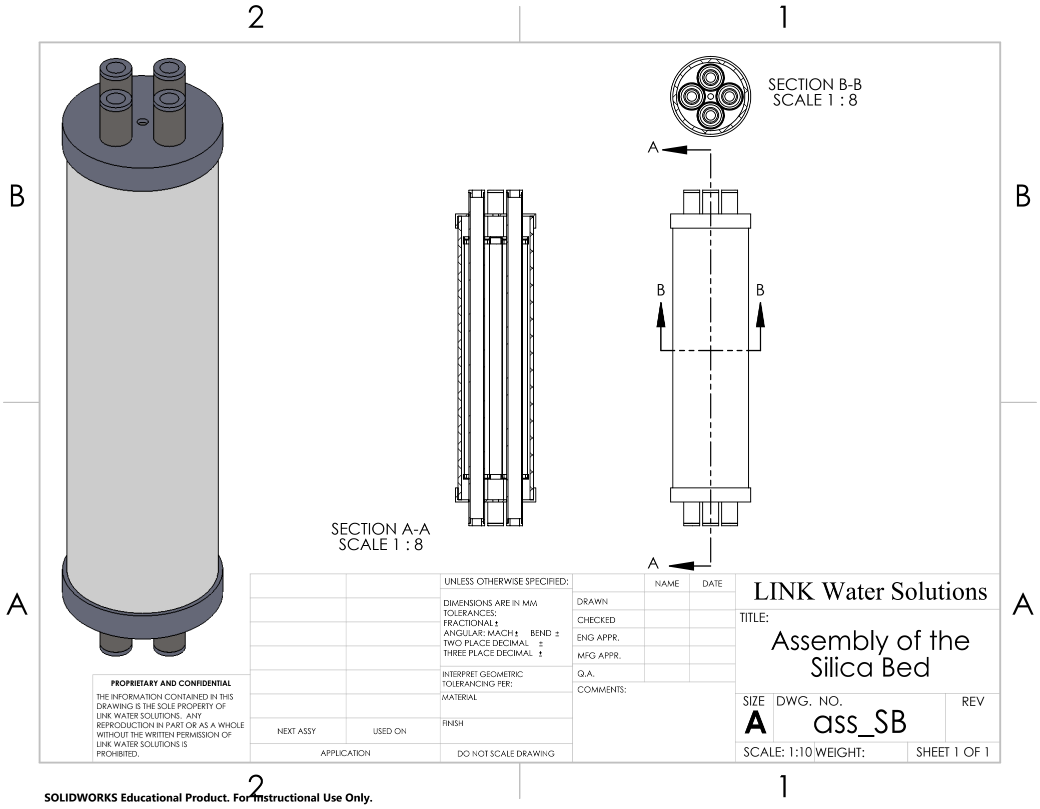


Figure E.18: Technical drawing of the Silica Bed Vessel

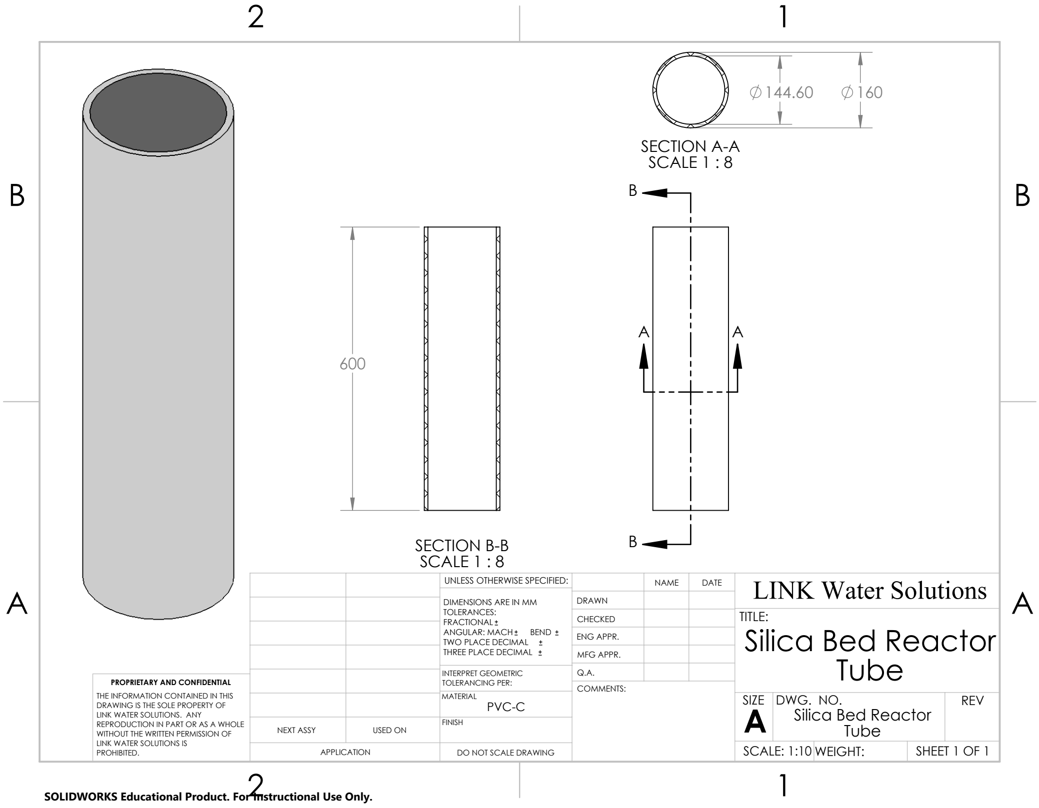


Figure E.19: Technical drawing of the Silica Bed Tube

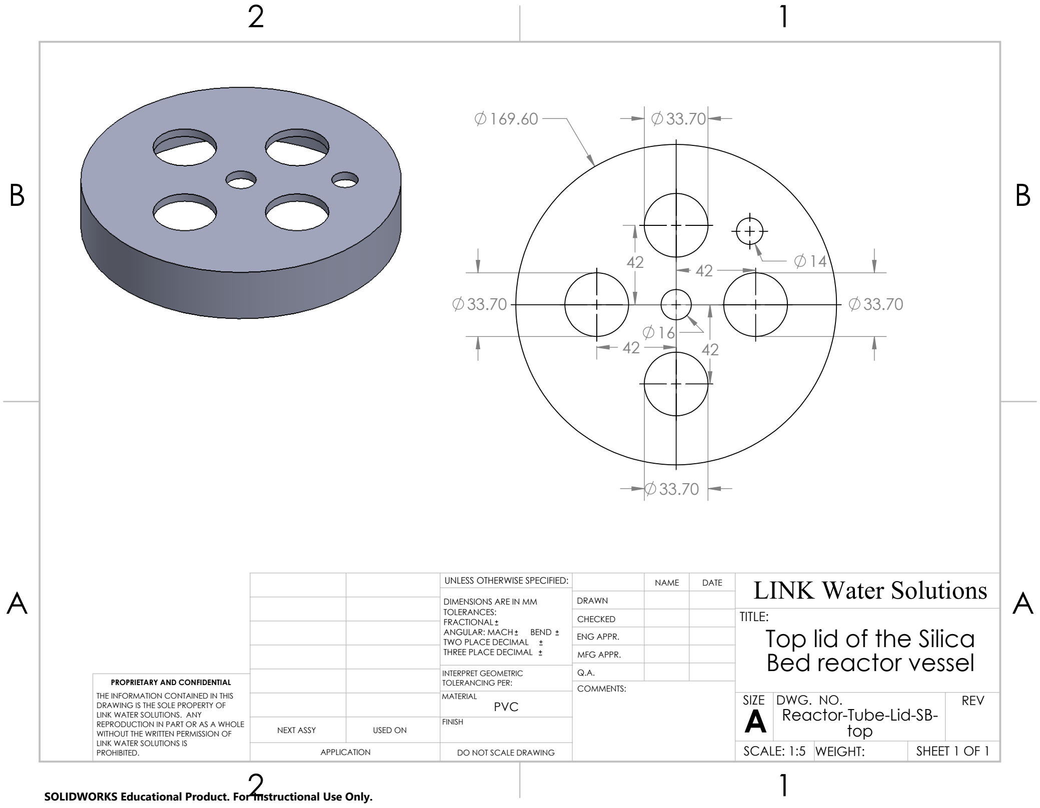


Figure E.20: Technical drawing of the Silica Bed Tube top lid

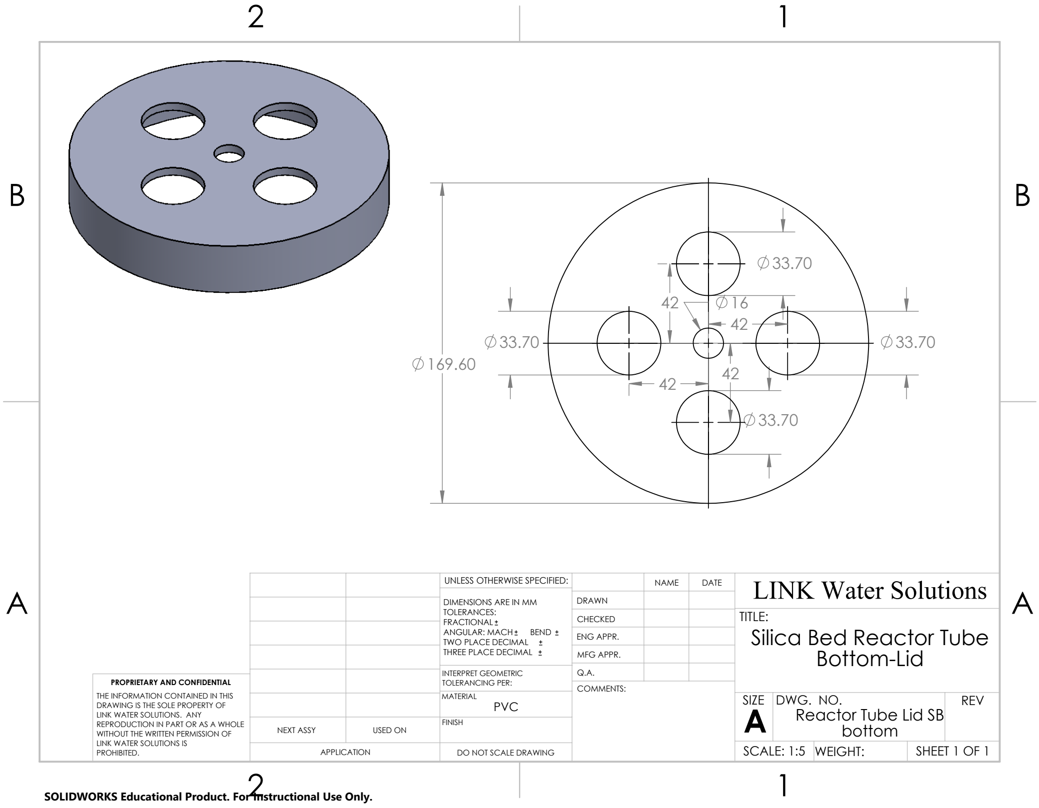


Figure E.21: Technical drawing of the Silica Bed Tube bottom lid

E.4.2 Silica gel covered Heat Exchangers

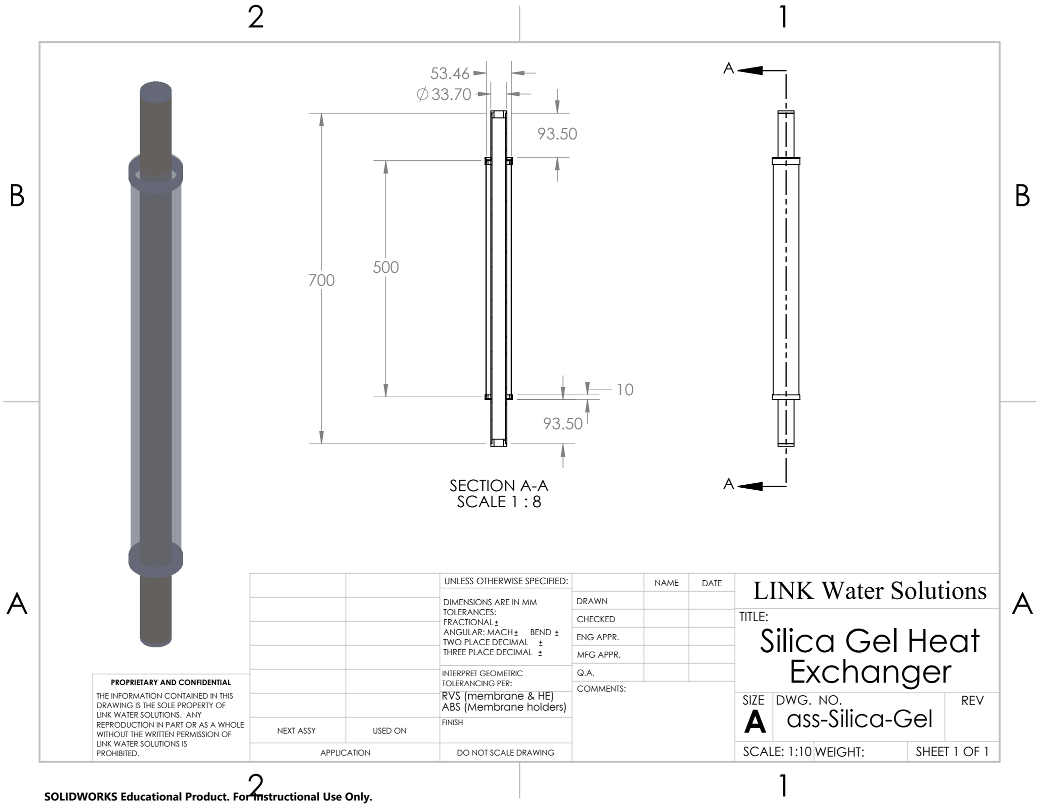


Figure E.22: Technical drawing of the silica gel covered heat exchangers

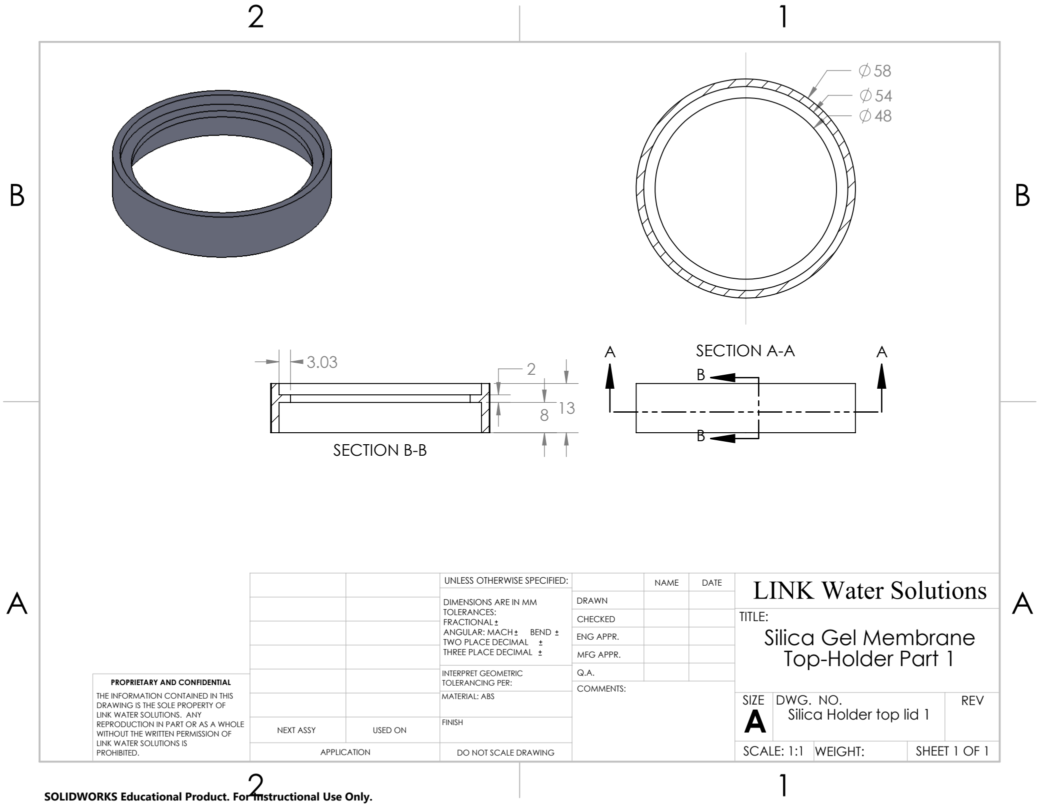


Figure E.23: Technical drawing of the top lid of membrane holder of the silica gel holder: Part 1

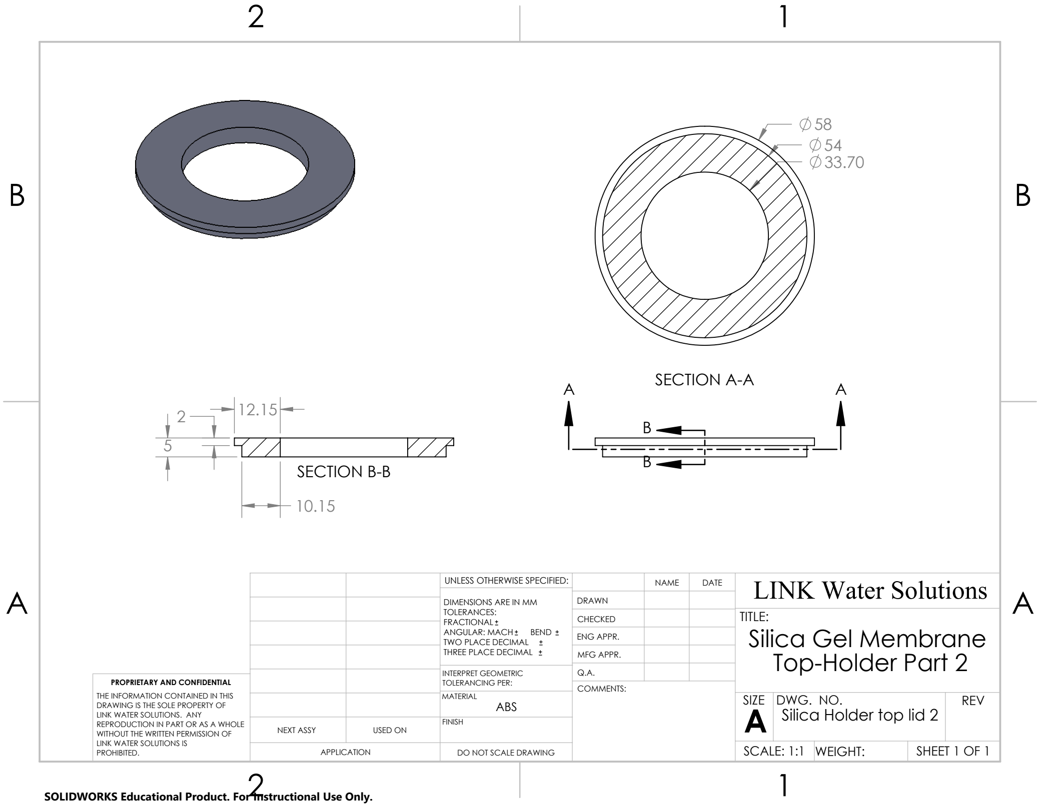


Figure E.24: Technical drawing of the top lid of membrane holder of the silica gel holder: Part 2

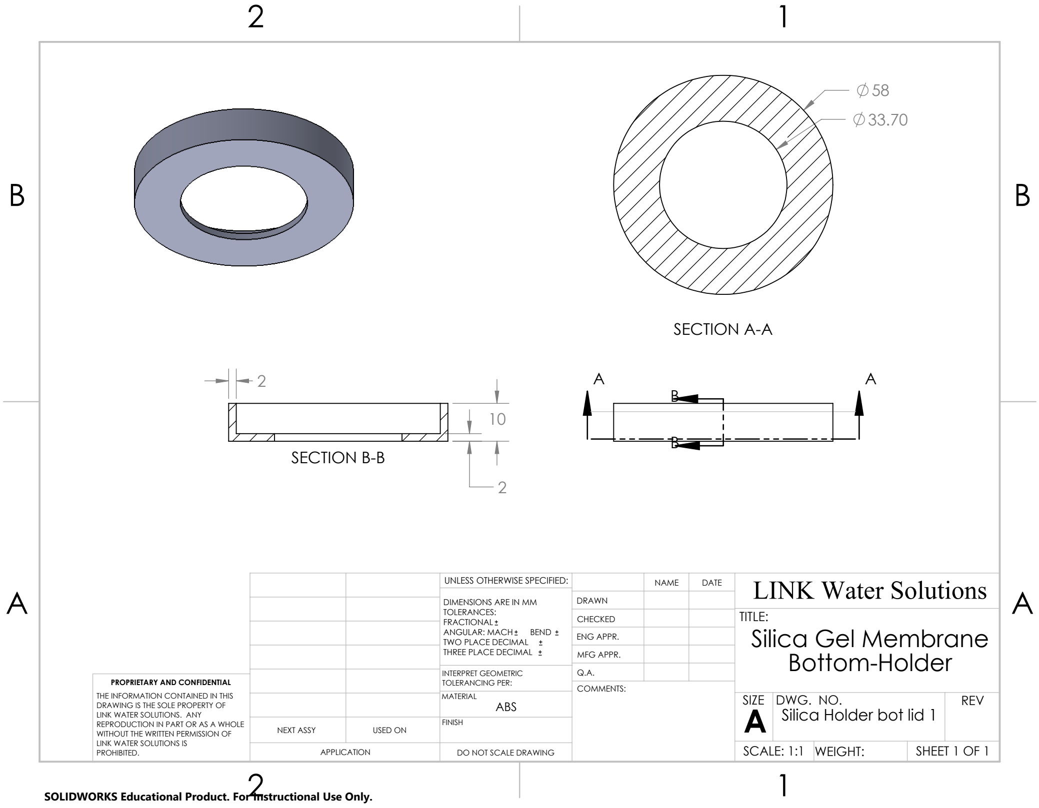


Figure E.25: Technical drawing of the bottom lid of membrane holder of the silica gel holder

E.4.3 Evaporator and Condenser Units

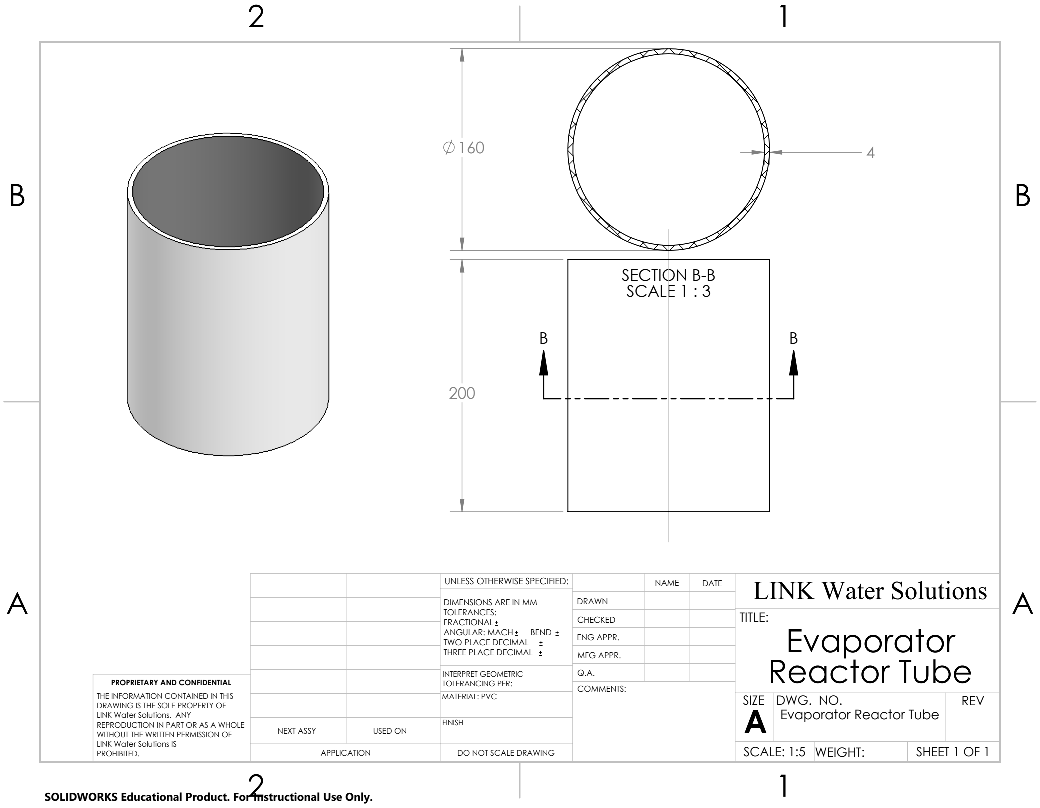


Figure E.26: Technical drawing of tube vessel of the evaporator or condenser

Unfortunately, the blueprint about the lids of the condenser and evaporator are lost. However, with the dimensions of the other lids, it should be possible the constructed them.