TUDelft

Delft University of Technology

Heater Chip with Different Microchannels Geometries for a Low Pressure Free Molecular Micro-Resistojet

Cordeiro Guerrieri, Daduí; de Athayde Costa e Silva, Marsil; Zandbergen, Barry; Cervone, Angelo

Heater Chip with Different Microchannels Geometries for a Low Pressure Free Molecular Micro-Resistojet

D. C. Guerrieri[(1)], M. de Athayde Costa e Silva, B. T. C. Zandbergen, A. Cervone

Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology; Delft, The Netherlands. [(1)]*Email: d.cordeiroguerrieri@tudelft.nl*

ABSTRACT: The Direct Simulation Monte Carlo method is used to describe the heat and fluid flow properties of a Low Pressure Free Molecular Micro-Resistojet working in the transitional regime (rarefied gas dynamics). The propellant considered in this propulsion concept is water. Different microchannels geometries were analysed presenting the impact of the divergent angle on the thruster performance. It is shown that the transmission coefficient plays an important role towards the optimization of the heater chip. Results show that when the transmission coefficient increases by changing the geometry the specific impulse decreases, while the thrust and power consumption increase. In addition, a heater chip with a grid containing 37x37 microchannels with modified geometry can achieve a thrust in the range from 0.286 to 2.923 mN, a specific impulse from 54.4 to 93.7 s, and a maximum power consumption of 0.32 W.

KEYWORDS: Micro-Resistojet, green propulsion, FMMR, Low pressure

1. INTRODUCTION

Nano- and pico-satellites are currently increasing their application range becoming attractive for different markets. For instance CubeSats in the last ten years have become more than just an educational tool to be a business for some companies. Earth observation is one of the potentially attractive applications for Cubesats as shown by [1] and [2].

The increasing demand of small satellites has required the development of new technology in all subsystems. Even though propulsion systems for space are at a high level of development, this is not true yet in relation to small (nano- and pico-) satellites size. The micro-propulsion systems require a low mass, low internal pressure, low thrust, and low impulse using a "green" propellant, meaning non-hazardous. These requirements allow the spacecraft to perform some maneuvers such as formation flight, station keeping or orbit change. Owing to this aspect some research groups are working constantly to develop a suitable propulsion system for this class of satellites. These propulsion systems have to be extremely miniaturized, highly integrated and be intrinsically safe [3].

The Space System Engineering (SSE) chair at Delft University of Technology (TU Delft) is currently developing two green micro-resistojet with the intention to provide future nano- and pico-satellites with the necessary capability to execute formation flying maneuvers, orbit change maneuvers and/or station keeping [4]. They are known as Vaporizing Liquid Micro-Resistojet (VLM) and Free Molecular Micro-Resistojet (FMMR). The focus in this paper is on the second one of these concepts.

An interesting alternative for micropropulsion is the FMMR that appeared in the late 90's [5]. The low pressure used during the operation is advantageous because it simplifies the components needed. Additionally, the propellant can be stored as liquid or solid at higher mass density, and the tank can be very compact and still work at a low internal pressure (when compared with the typical ones). Based on these considerations, the SSE group has been working on the development of a low-pressure micro-resistojet based on an evaporating/sublimating liquid/solid propellant [6].

The FMMR is characterized by transitional flow regime, meaning that only part of the molecules entering the microchannel or slot are actually expelled, and the remaining returns to the plenum after colliding with the walls or other particles, it is

measured by the transmission coefficient, α. The geometry of the channel is one of the main characteristics that directly influences the transmission coefficient. As an example, the transmission coefficient for a cylindrical tube with aspect ratio of 5 is about 0.19, and the transmission coefficient increases with decreasing aspect ratio [7]. Additionally, the propellant particles are accelerated mainly because of the high temperature of the wall as already shown by some researchers [3], [6], [8] and [9].

2. PROPULSION CONCEPT

This propulsion concept can be simplified as presented in Figure 1. The propellant is stored as liquid or solid and due to the phase change (evaporation or sublimation) the vapor passes through the valve that control the mass flow rate. Then, the vapor fills the plenum, at a very low pressure, and it is expelled by the heat chip channels providing thrust.
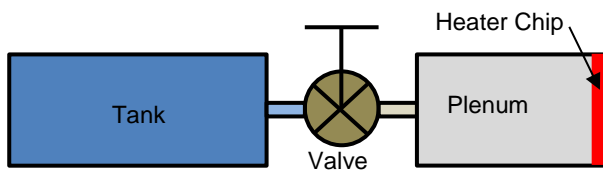

Figure 1. Micro-Resistojet Concept Scheme

One propellant which has the high potential to be used in this concept is water. Water meets all typical requirements for nano- and pico-satellites mainly because it is the most "green" substance. Additionally, its thermodynamic properties are suitable for the environment in which the propulsion system will work.

3. THEORETICAL AND NUMERICAL ANALYSIS

Typically, the fluid regime governing the dynamics of resistojets is continuum flow regime that can be characterized by a low Knudsen number (usually less than 0.1). However, FMMR usually works at a Knudsen number between 0.1 and 10 which means that the transitional regime has to be considered when modeling the dynamics. Knudsen number just provides the degree of gas

rarefaction, and is defined as the ratio of average distance travelled by the molecules between collisions (mean free path, λ) to the flow characteristic dimension, L [10]:

$$Kn = \frac{\lambda}{L} \qquad (1)$$

Because of the high Knudsen number (or low pressure) the Navier-Stokes equation cannot be applied, but the Boltzmann equation is the most suitable in this case. The Direct Simulation Monte Carlo (DSMC) method is the one of the famous algorithms to solve the time-dependent nonlinear Boltzmann equation. The DSMC method analyses the motion of the particles or molecules in a small volume by means of probabilistic physical simulation. The number of the particles/molecules is represented by a sample and not by the real number of particles/molecules. However, the probabilistic results give an adequate approximate solution [11].

The open source C++ toolbox OpenFOAM utilizing the DSMC method was used to analyse the thrust performance according to the fluid dynamic behaviour. The simulation setting was compared with the main literature related to this subject as presented in Table 1.

Table 1. Simulation setting according to [11], [12]

Element	Model/Value
Collision Particle-Particle	Larsen-Borgnakke
Collision Particle-Surface	Diffuse
Molecular Species	H_2O (water)
Mesh Size	$\leq 5\,\mu m$
Step Time	2×10^{-7} s
Number of Equivalent Molecules	10^4

It is known that the mass flow rate at the exit differs from that of the entrance of the channel which is a characteristic of the transitional regime and free molecule regime. In other words, the fluid is literally non-continuous. The transmission coefficient α is the ratio between the mass flow rate at the exit and at the entrance, for instance $\alpha = 0$ means no transmission (without mass flow rate at the exit) and $\alpha = 1$ means full transmission (continuous mass flow rate).
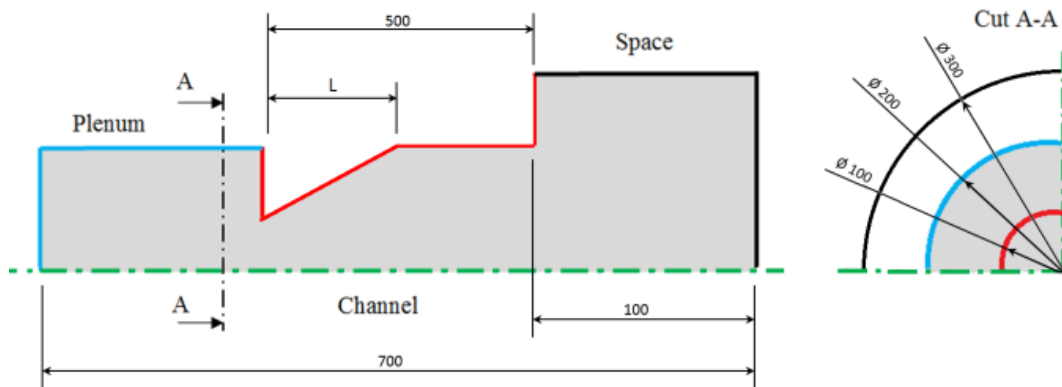
Figure 2. Scheme of the microchannel modelling, dimensions in μm. The plenum boundary condition is represented by a blue line, the channel by a red line, the space by a black line and the green dash dot line represents the symmetric plane boundary conditions

Intending to increase the transmission coefficient without affecting the heat transfer, that is important to accelerate the particles in the case of the FMMR [3], the design of a different configuration is analysed. A scheme of the micronozzle is presented in Figure 2. The section is axial symmetric. The entrance has a diameter of 100 μm and the exit of 200 μm. The first part of the microchannel presents a divergent configuration whose angle depends on the length *L*. In the simulations different values of *L*, from 50 μm to 250 μm, were compared. The plenum boundary condition was considered as a reservoir (stagnation conditions) with temperature of 300 K and a constant pressure of 50 Pa and 300 Pa. Two different values of the microchannel wall temperature were also considered in each case, 300 K and 900 K. The outer space was considered as vacuum at a temperature of 10 K. The 3-D simulation was carried out using those configurations.

4. RESULTS AND DISCUSSION

The transmission coefficient has a direct relation to the pressure in the entrance of the channel as already showed by [3] and [4]. The cross-sectional geometry of the channel plays an important role in helping the particles to get the right direction towards the outer space. In short, the entrance

pressure for straight channel is higher than the plenum pressure, consequently the transmission coefficient decreases dramatically [3]. Figure 3 and Figure 4 show the mean pressure along the microchannel. It is observed that decreasing the length *L* (or increasing the divergent angle) the entrance pressure decreases significantly.
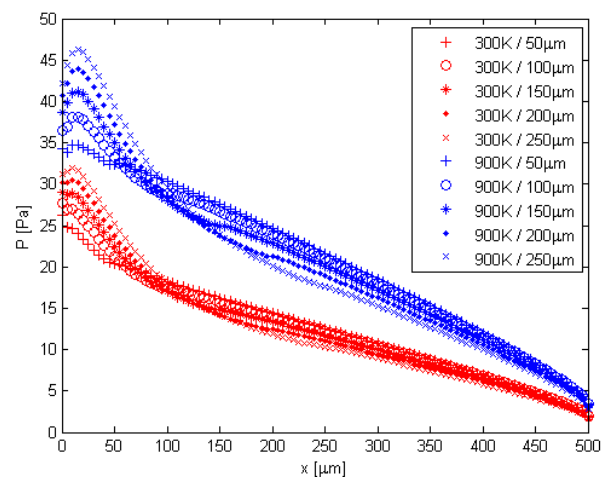

Figure 3. Mean Pressure along the microchannel for a plenum pressure of 50 Pa, for different wall temperatures and L values.

Even though the entrance pressure presents a significant change, the mean temperature along the channel does not show a significant change in relation to the *L* change, Figure 5 and Figure 6. The small difference is observed just because of

the density difference, due to the plenum pressure difference. In other words, the density increase affects the heat transfer by decreasing the mean temperature of the flow.
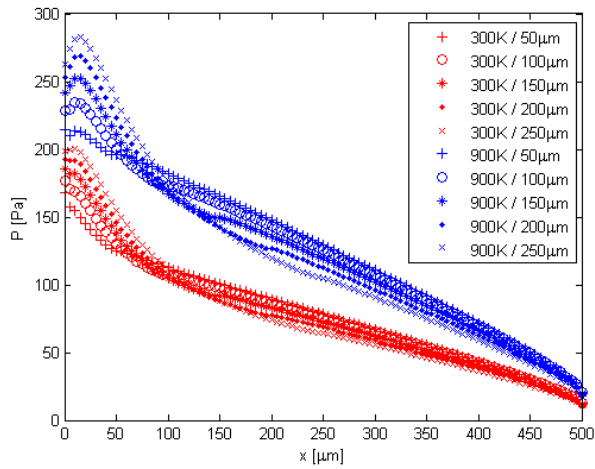

Figure 4. Mean Pressure along the microchannel for a plenum pressure of 300 Pa, for different wall temperatures and L values.
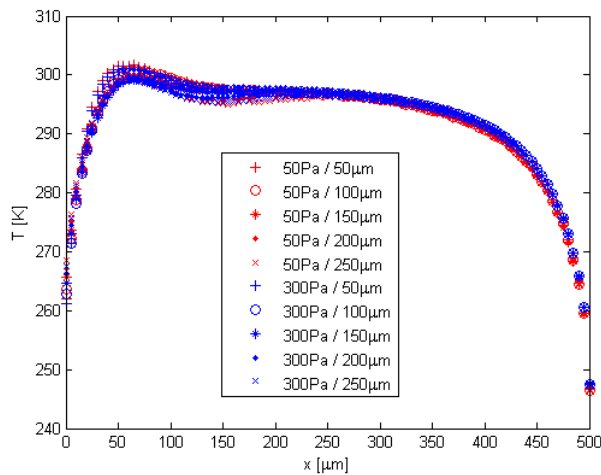

Figure 5. Mean Temperature along the microchannel for a wall temperature of 300 K, for different plenum pressure and L values.

In analogy to what happens in the classical ideal rocket theory, the temperature is responsible mainly for the exit velocity of the fluid which is important from the propulsion point of view. The exit velocity and the transmission coefficient for each case can be seen in Figure 7. As expected the exit velocity does not present any change due to the L change, although the transmission coefficient increases significantly by decreasing L. The transmission coefficient increases by about 20% when reducing L from 250 μm to 50 μm.
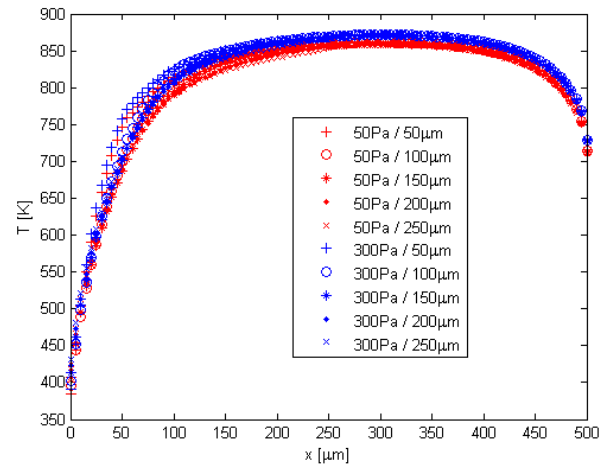

Figure 6. Mean Temperature along the microchannel for a wall temperature of 900 K, for different plenum pressure and L values.
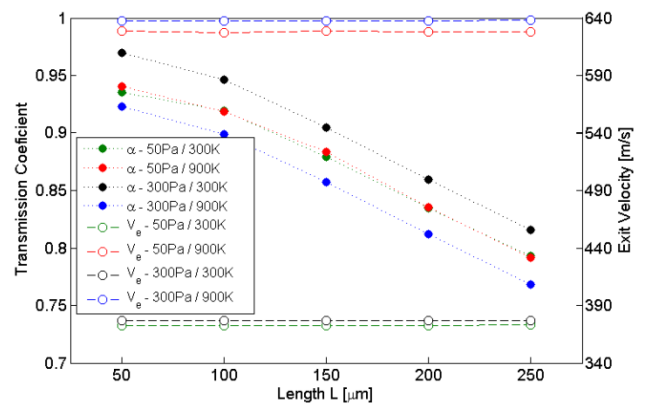

Figure 7. Transmission Coefficient and Exit Velocity for different plenum pressure and for different wall temperature.

The mass flow rate, the exit velocity, the exit pressure and the exit cross-sectional area are directly responsible for the thruster performance as seen in equations (2) and (3). The exit velocity (u_e) increases proportionally to the increase in the temperature of the walls. The exit pressure (P_e) does not present a significant difference for different cases.

$$F_T = m_f \cdot u_e + \left(P_e - P_a \right) \cdot A_e \qquad (2)$$

$$I_{sp} = \frac{F_T}{m_f g_0} \qquad (3)$$

where F_T is the thrust, m_f the mass flow rate, u_e the exit velocity, P_e the exit pressure, P_a the external pressure, A_e exit cross-sectional area, I_{sp}

4

the specific impulse, and g_o the Earth's gravitational acceleration at sea level.

The total mass flow rate can be increased by either increasing the transmission coefficient or increasing the number of channels in the heater chip. Therefore, two important observations are considered to justify the preference for the high transmission coefficients: first to avoid the return of particles to the plenum preventing the temperature increases in the plenum and therefore reducing the power consumption. Second, to reduce the number of channels in the heater chip for the same mass flow thus reducing the size of the chip.

Figure 8 shows that the specific impulse does not change by reducing L from 250 μm to 50 μm, although the thrust presents a significant increase. For pressure in the plenum of 50 Pa and wall temperature of 300 K, the thrust increases by 15.25 % when changing L from 250 μm to 50 μm. For pressure in the plenum of 300 Pa and wall temperature of 900 K, the thrust increases by 16.98 % when changing L from 250 μm to 50 μm.
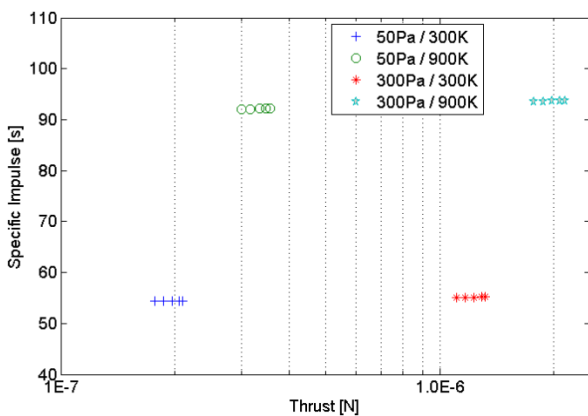

Figure 8. Thrust Versus Specific Impulse for different plenum pressure and for different wall temperature.

Comparing the results with the ones presented in a previous paper [3], which analyzed a grid of 67x67 microchannels with 10x10 mm area on the heater chip, a reduction in the size of the chip and the number of channels is possible. As Table 2 shows, for the same setting, a reduction of 72% in the power consumption is possible for plenum pressure of 300 Pa and wall temperature of 900 K, while the specific impulse decreases only by

about 15%. In the case analyzed in that paper, a straight channel with a cross-sectional area of 10,000 μm^2 and length of 500 μm was used. In the case analyzed here, considering the cross-sectional exit area almost unchanged, a grid of 37x37 microchannels must be considered using the presented configuration with L equal to 50 μm. The channels can be placed in a 9.2x9.2 mm area on the heater chip using the same pitch (distance between the channels) that as used in the previous work.

Table 2. Comparison of the current work results with previous ones [3]

		50	300	50	300
	P_o [Pa]	50	300	50	300
	T_w [K]	300	300	900	900
from [3]	α	0.24	0.24	0.23	0.22
	I_{sp} [s]	63.7	64.6	108.9	110.7
	F_T [mN]	0.284	1.736	0.479	2.723
	Q_{th} [W]	0	0	0.21	1.15
Current work	α	0.93	0.97	0.94	0.92
	I_{sp} [s]	54.4	55.2	92.3	93.7
	F_T [mN]	0.286	1.808	0.488	2.923
	Q_{th} [W]	0	0	0.06	0.32

5.   CONCLUSION:

The heat and flow properties in a rarefied gas were analysed with the intention to optimize the heater chip geometry. Simulations of different microchannel geometries were performed showing that the geometry influences the mass flow rate which directly affects the thruster performance. The specific impulse does not change much for the proposed geometries, but the thrust presents a significant increase of about 15%.

When the proposed heater chip is compared to a baseline heater chip geometry keeping the same exit cross-sectional area, the specific impulse decreases slightly and the power consumption decreases significantly. This configuration can therefore be attractive for different mission requirements. If the mission requires a higher specific impulse the baseline heater chip is suitable, but if it requires a lower power consumption and smaller heater chip dimensions

the new proposed heater chip geometry is preferable.

Future work will be focused on testing this device in an adequate environment, possibly up to flight demonstration. This is a promising green propulsion system for very small satellites as nano- and pico-satellites, and further investigations will be carried out by the SSE group intending to prove the concept.

ACKNOWLEDGEMENTS:

NOMENCLATURE:

A_e	exit cross-sectional area [m^2]
F_T	thrust [N]
g_0	Earth's gravitational acceleration at sea level [m/s^2]
I_{sp}	specific impulse [s]
k	Boltzmann constant [J/K]
L	characteristic dimension [m]
Kn	Knudsen number
m_f	mass flow rate [kg/s]
P	pressure [Pa]
P_0	plenum fluid pressure [Pa]
P_a	external pressure [Pa]
P_e	exit pressure [Pa]
Q_{th}	thermal power from heater chip [W]
T_w	heater walls temperature [K]
u_e	exit velocity [m/s]
λ	mean free path [m]

REFERENCES:

[1] D. Selva and D. Krejci, "A survey and assessment of the capabilities of Cubesats for Earth observation," *Acta Astronautica,* vol. 74, pp. 50-68, 2011.

[2] C. R. Boshuizen, J. Mason, P. Klupar and S. Spanhake, "Results from the Planet Labs Flock Constellation," in *28th Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, 2014.

[3] D. C. Guerrieri, M. d. A. Costa e Silva, B. T. C. Zandbergen and A. Cervone, "Development of a Low Pressure Free Molecular Micro-Resistojet for CubSat Applications," in *66th IAC*, Jerusalem, Israel, 2015.

[4] A. Cervone, B. Zandbergen, D. C. Guerrieri, M. De Athayde Costa e Silva and H. van Zeijl, "Green Micro-Resistojet Research at Delft University of Technology: the New Frontiers of Cubesat Propulsion," in *5TH CEAS AIR & SPACE CONFERENCE*, Delft, 2015.

[5] A. Ketsdever, D. Wadsworth, S. Vargo and E. Muntz, "A free Molecule Micro-Resistojet: An Interesting Alternative to Nozzle Expansion," in *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 1998.

[6] A. Cervone, A. Mancas and B. Zandbergen, "Conceptual design of a low-pressure micro-resistojet based on a sublimating solid propellant," *Acta Astronautica,* vol. 108, pp. 30-39, 2015.

[7] J. M. Lafferty, Foundations of Vaccum Science and Technology, John Wiley and Sons., 1998.

[8] A. Ketsdever, R. Lee and T. Lilly, "Performance Testing of a Microfabricated Propulsion System for Nanosatellite Applications," *Journal of Micromechanics and Microengineering,* vol. 15(2), pp. 2254-2263, 2005.

[9] C. Wang, B. Zandbergen, A. Cervone and J. Chu, "Numerical Studies on Performance of Free Molecule Micro-Resistojet with Ice Propellant," in *6th European Conference for Aeronautics and Sciences (EUCASS)*, Krakow, Poland, 2015.

[10] G. Karniadakis, A. Beskok and N. Aluru, Microflows and Nanoflows Fundamentals and Simulation, Springer Science, 2005.

[11] G. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flow, Oxford: Claredon, 1994.

[12] T. J. Scanlon, E. Roohi, C. White, M. Darbandi and J. M. Reese, "An open source, parallel dsmc code for rarefied gas flows in arbitrary geometries," *Computers and Fluids,* vol. 39, pp. 2078-2089, 2010.