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Design, simulation and optimisation of a low-pressure micro-resistojet for small satellite missions

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Abstract

Incorporating propulsion in small satellites is becoming a growing trend, due to its potential for enabling new and ambitious mission objectives. One of these objectives is formation flying, that will be pursued by TU Delft for the DelFFi mission as part of the larger QB50 project. For DelFFi, two identical spacecraft will use propulsion to allow for relative positioning. Due to the intrinsic limitations in mass, volume, power and propellant choice, pico-/nanosatellite propulsion poses different challenges when compared to larger spacecraft. The design of a MEMS (Micro Electro-Mechanical Systems) resistojet using water (ice) as propellant, operating at low pressures in the range of 50 to 200 Pa (below the vapour pressure of ice at temperatures below 270 K) will be described. The main results of a set of DSMC (Direct Simulation Monte Carlo) simulations performed with the open source *dsmcFoam* solver, showing the influence of geometry on thruster performance, in particular thrust and specific impulse, at a given input power will be presented. The low operating pressure allows for using the vapour pressure of ice as the only method of propellant feeding. The design presented in the paper will use few moving parts — one in the thruster and two or three in the propellant storage subsystem — and two heat inputs: one in the thruster and one to maintain the propellant temperature in the tank. The simulations, performed with various geometries and propellant storage conditions, show that the proposed design represents an alternative, low risk, micro-propulsion system suitable for small satellite missions, with the pressure inside the system never exceeding 600 Pa.

Keywords: micro-propulsion, low-pressure thrusters, resistojet, small satellites

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Nomenclature

A_{s}	expansion slot cross-sectional area as seen by the flow ($L \times b$)
b	expansion slot width
c_p	specific heat at constant pressure
g_0	Earth sea-level gravitational acceleration
I_{sp}	specific impulse
k	Boltzmann constant
L	expansion slot length
l	expansion slot depth
$\dot{m}$	mass flow rate
m_a	molecular mass of the propellant
Ma	Mach number
N_{s}	number of expansion slots
P	pressure
T	absolute temperature
α	transmission coefficient
η	efficiency
$\triangle_{\mathrm{sub}}h_{\mathrm{H_2O}}$	sublimation enthalpy of water
$\wp$	power
$\Im$	thrust
$_0$	plenum properties
$_{\mathrm{w}}$	heater chip properties

1. Introduction

In the past ten years there has been an increase in the number and importance of small satellite (below 10 kg) missions [1]. Adding more functionality to them is challenging due to their limited size and mass; one possible way

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to do it is to design a formation flying mission, where hardware is spread across multiple satellites. Maintaining the formation requires some kind of propulsion system, which is still a challenge on anything as small — or smaller — than a microsatellite (less than 100 kg).

Recently, TU Delft has worked on implementing a propulsion system in a CubeSat. This was achieved in 2013, with the launch of Delfi-n3Xt, which implemented a propulsion system called T^{3}µPS designed in cooperation with TNO [2]. T^{3}µPS is a cold gas thruster, utilising nitrogen as the propellant. The nitrogen is stored in the solid phase, in cold gas generators (CGGs) designed by TNO. The performance figures include a 68 s specific impulse and 6 mN of thrust. One disadvantage of the system is the low mass and volume efficiency of the propulsion system and the CGGs (one of the test models has 1 g of propellant and a 140 g system mass; only a fraction — less than one half — of the CGGs is propellant and they have quite low density), which limits the total delta-v achievable in the volume and mass constraints of a nanosatellite.

For the next step in the development, TU Delft is planning a formation flying mission called DelFFi. DelFFi will include two satellites (both 3U^2 in size) and is part of the wider QB50 mission. Both satellites will contain the QB50 scientific payload (intended to make measurements in the lower thermosphere) and a propulsion system to counteract the differences in drag between the two satellites. The propulsion system for DelFFi has to provide a delta-v of at least 10 m/s, with 20 m/s being the extended mission target, and a thrust between 0.5 and 9.5 mN. The entire propulsion system will have to fit inside a 1U unit of the satellite and use less than 10 W of peak power and less than 100 kJ/day of total energy [2].

One of the propulsion system concepts investigated for DelFFi was to use water, stored as ice, as the propellant and operate the propulsion system at its vapour pressure. This is an extension of a somewhat similar design (solid phase stored propellants were never implemented), developed by Andrew Ketsdever and others between about 2000 and 2005 in the United States [3, 4, 5, 6].

This paper will present the basic concept of the propulsion system and an overview of performance figures obtained through computer simulations. It presents the key points of the lead author's master thesis [7]^3. All tables and figures are adapted from it.

2. Propulsion system concept

As stated in the introduction, the propulsion system design is an extension of the work of Ketsdever et al., with the addition of propellant storage in the solid phase, and the optimisation of the thruster geometry.

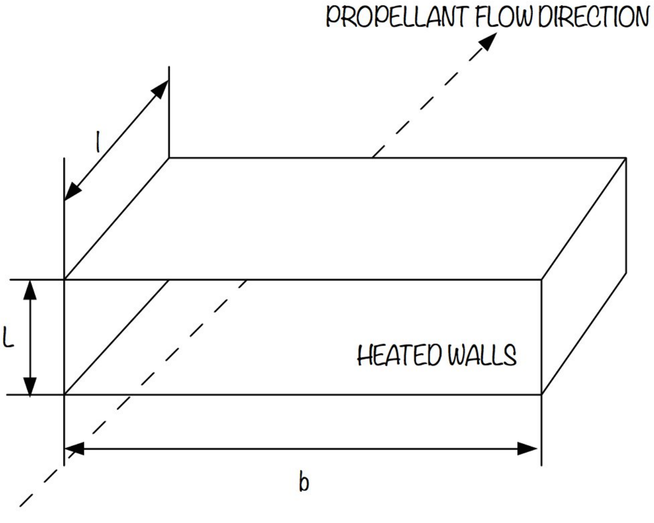

Figure 1: Expansion slot dimensions

The propulsion system operates in the following way:

Some ice molecules will sublimate to make the pressure inside the tank equal to the vapour pressure (below 600 Pa for ice). The sublimation absorbs some heat from the ice and lowers its temperature — the amount of heat is determined by $\triangle_{\mathrm{sub}} h_{\mathrm{H_2O}}$, which is about 2.8 MJ/kg [8]. A heating element will pump this heat back into the ice to maintain the temperature and vapour pressure in the tank constant. The motion of the ice vapour molecules will take some of the molecules in the tank through the feed system and into the plenum (this will lower the pressure in the tank below the vapour pressure so more ice will sublimate and maintain the cycle). Some of the molecules in the plenum will then flow through an expansion slot in the heater chip, absorb some heat from its walls and some of these will exit into outer space and generate thrust. The heater chip will be able to be heated to a high temperature (in resistojet-mode operation) and will function as both heating element and nozzle.

3. Theoretical background

The geometry of one expansion slot is presented in figure 1, together with the flow direction. The expansion slot has a basic cuboid shape due to: (1) at the low density in the plenum, the throat of a con-di nozzle would have to be on the order of centimetres in diameter and (2) ease of manufacturing. Since the slot is cut into the hot heater chip, all the internal walls of the slot are heated.

The performance of the thruster, in terms of mass flow rate, specific impulse and thrust, can be estimated (assuming collision-less, high Ma flow) with the following formulae [5]:

$$\dot{m} = \alpha P_0 \sqrt{\frac{m_a}{2\pi k T_0}} A_{\mathrm{s}} N_{\mathrm{s}} \tag{1}$$

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[2] $10 \times 10 \times 30$ cm

[3] It will be available on `repository.tudelft.nl`.

$$I_{sp} = \sqrt{\frac{\pi k T_{\mathrm{w}}}{2 m_a g_0^2}} \tag{2}$$

$$\Im = \frac{\alpha P_0 A_{\mathrm{s}} N_{\mathrm{s}}}{2} \sqrt{\frac{T_{\mathrm{w}}}{T_0}} \tag{3}$$

The geometry of the expansion slot directly influences the performance of the thruster through a parameter called the transmission coefficient (α). The simplest way to explain it would be: a number of molecules in the plenum (N_{i}) will enter the expansion slots due to their velocities; once inside one of the expansion slots they can collide with walls[4] or other molecules, but one of two things will eventually happen: some molecules will exit the expansion slots out into space and generate thrust (N_{o}), while some will return to the plenum (N_{i} - N_{o}). The transmission coefficient is the ratio of molecules exiting into space and molecules entering the expansion slot, $\alpha = N_{\mathrm{o}}/N_{\mathrm{i}}$. For a molecule to return to the plenum after entering the expansion slot it must first hit something, most likely the expansion slot walls. This collision will absorb heat from the walls, increase the power usage and lower the (thrust) efficiency of the thruster. Collisions between the propellant molecules and the walls are not bad per se, since they are the only way to heat up the propellant, but they must be managed somehow. A transmission coefficient of 1 would mean no molecules hit the expansion slots walls so the thruster only works in cold gas mode. Bearing in mind these considerations, the power used by the heater chip can be estimated from the equation:

$$\wp_{\mathrm{chip}} = \frac{\dot{m}}{\alpha} c_p \left(T_{\mathrm{w}} - T_0\right) \tag{4}$$

To the power calculated with equation 4, the power needed to offset the sublimation enthalpy in the tank, given in equation 5 has to be added.

$$\wp_{\mathrm{tank}} = \dot{m} \triangle_{\mathrm{sub}} h_{\mathrm{H_2O}} \tag{5}$$

For the entire system, thrust efficiency can be calculated as:

$$\eta_{thrust} = \frac{\frac{\dot{m} g_0^2}{2} I_{sp}^2}{\wp_{\mathrm{chip}} + \wp_{\mathrm{tank}}} \times 100\,\% \tag{6}$$

Equations 1 - 3 were confirmed to be within 10 % of experimental values[5], but the transmission coefficient can be calculated only for simple rectangular and circular expansion slot cross-sections [10]. For more complex geometries computer simulations are required. Investigating more complex geometries was very important for the DelFFi propulsion system, since using the same geometry as Ketsdever et al. would not meet the requirements (power usage would be much too high at the required thrust levels). Furthermore, whether or not the molecules heat up to T_{w} for higher transmission coefficients cannot be determined without computer simulations.

4. Computer simulations

The aforementioned computer simulations were run using the Direct Simulation Monte Carlo (DSMC) solver — *dsmcFoam* — provided in the *OpenFOAM* CFD package. *OpenFOAM* is open source, so it will always be available and the source code can be modified, which was done for the validation simulations. All simulations were 2D, since the expansion slot width (≈ 5 mm) is much larger that the length (≈ 100 µm) or depth (≈ 500 µm). The parameters used in all the simulations, regardless of propellant choice or geometry, were determined with a sensitivity analysis[6] and were:

1. a cell size of around 6.25 µm (16 cells in a 100 µm long expansion slot);
2. a time step of $2 \cdot 10^{-7}$ s;
3. a number of equivalent molecules in the range of 10^3 to 10^4, depending on the size of the simulation space;
4. only one expansion slot and some exhaust area, but no plenum area were simulated.

Validating the results against the experimental results of Ketsdever et al. [5] and computer simulations results of Ahmed et al. [6] proved to be difficult, due to unknown exhaust boundary conditions in the reference cases. The best that was achieved was ±10 % in the quantitative results and very good qualitative matching, with similar axial velocity and pressure fields to Ahmed et al. [6].

The computer simulations were run with water as the propellant. Two geometries for the expansion slot were tested, a 100 µm × 500 µm slot (geometry used by Ketsdever et al.; the baseline geometry) and a 200 µm × 500 µm slot with 15° of divergence for the last half of the expansion slot depth (the optimised geometry). The optimised geometry improves the transmission coefficient from 0.36 to 0.63. Both geometries are shown in figure 2. The latter geometry was determined by examining the impact of various geometrical parameters on performance and finding that increasing length an adding exit divergence improves thrust efficiency. Other parameters tested were:

- making the expansion slot entry convergent, which increased mass flow rate, but greatly increased the power usage;

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[4] The direction in which a molecule is reflected after colliding with a wall is random in all the applicable collision models [9].

[5] The collision-less flow assumption did not hold for the experiments run by Ketsdever et al. in [5], so this is a coincidence.

[6] Formulae for determining most of these parameters are available in literature [9, 11] and were used as the starting values. The values used in the simulations were vastly different and allowed for much faster simulations with a difference in results of less than 4.4 %.

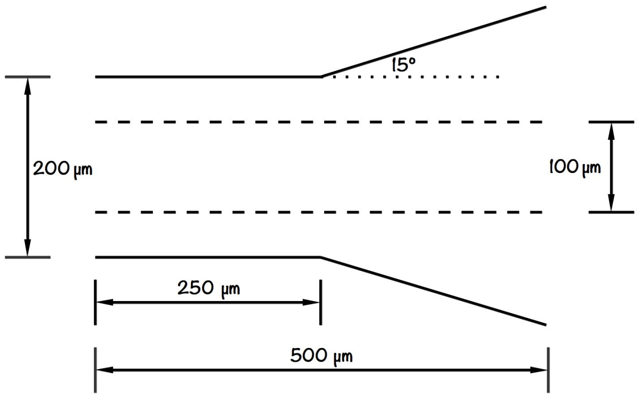

Figure 2: Comparison of baseline (dashed) and optimised (continuous lines) expansion slots (flow direction is left to right)

- other variations in length/depth combinations, which did not offer the desired performance;
- making the entire expansion slot divergent, which did not offer the desired performance; it increases the expansion slot exit cross-sectional area and reduces the number of expansion slots that can be put on a chip.

The results from the DSMC simulations are mass flow rate, specific impulse, thrust and power input to the heater chip. These four performance indicators are computed from the more basic data output by *dsmcFoam*, like mass and momentum flow through the expansion slot exit plane and heat transfer across the expansion slot walls.

For both geometries two other parameters were varied: the expansion slot wall temperature (T_w) and the plenum pressure (P_0), the latter influencing the mass flow rate. Figure 3 shows thrust against mass flow rate, from one expansion slot with a width of 5 mm at four plenum pressures and three heater chip temperatures, for the baseline and optimised geometries respectively. The slopes of the six lines are proportional to the specific impulse values, which are higher for the baseline than optimised geometry. The specific values are given in table 1. The thrust from one slot is on the order of 10^{-5} N, so tens of slots are needed to obtain a thrust on the order of millinewtons. Figure 4 shows thrust against heater chip input power. The data is plotted for both baseline (circles) and optimised (squares) geometries and for 600 (continuous) and 900 K (dashed) temperatures. It shows that the optimised geometry and lower temperatures provide more thrust at the same power input.

Since the plots in figure 4 do not take into account the power input to the propellant tank, a thrust efficiency plot, calculated with equation 6 (tank power input calculated with equation 5 and heater chip power input from DSMC simulations) is provided in figure 5. The thrust

Table 1: Specific impulse for the baseline and optimised geometries

T_w [K]	I_{sp} [s]	
	BASELINE	OPTIMISED
300 K	69.6	70.2
600 K	96.5	92.7
900 K	116.9	110.0

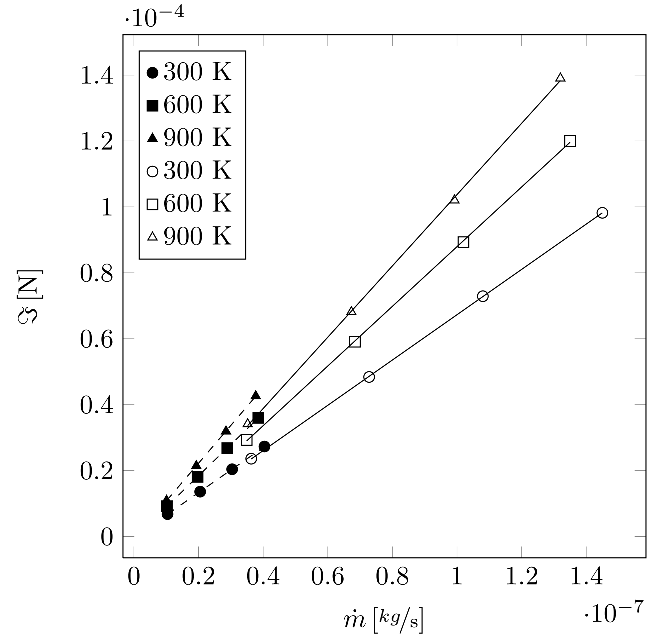

Figure 3: Thrust against mass flow rate for the baseline (black circles, squares and triangles and dashed lines — mostly bottom left) and optimised (empty circles, squares and triangles— mostly top right) geometries and different heater chip temperatures

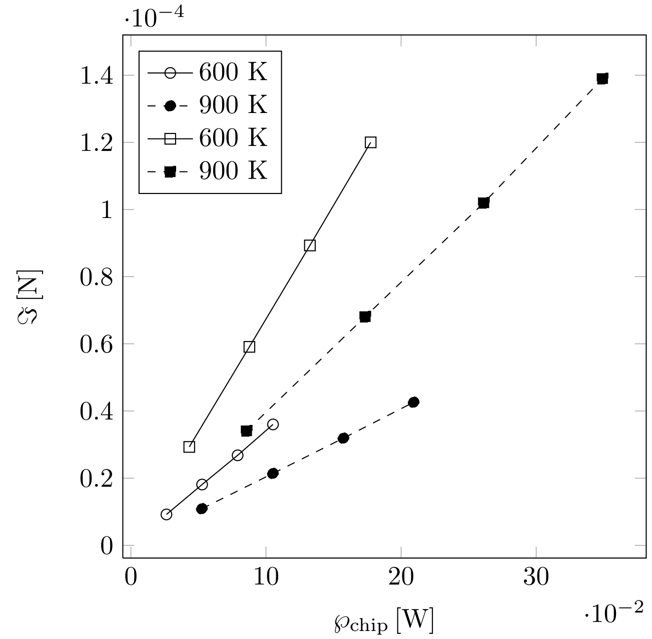

Figure 4: Thrust against input power at $T_\mathrm{w} = 600\,\mathrm{K}$ and $T_\mathrm{w} = 900\,\mathrm{K}$ for the baseline (circles) and optimised (squares) geometry

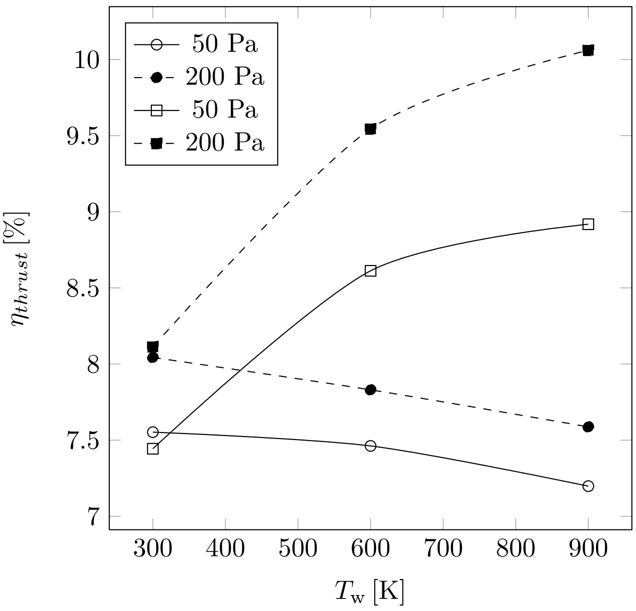

Figure 5: Thrust efficiency against heater chip temperature for the baseline (circles) and optimised (squares) geometries

efficiency is not very high, with the highest values being around 10 %[7]. The optimised geometry shows an increase with T_w while the baseline shows a decrease — the better transmission coefficient makes the heating loses smaller for the optimised geometry. For all cases, higher plenum pressures — higher mass flow rate through one slot — correspond to slightly higher thrust efficiency. In cold gas mode ($T_w = 300$ K) the efficiency is the same for both the optimised and baseline geometries since the slot geometry itself has no direct influence on specific impulse or power input to the propellant tank.

Computer simulations also revealed information about the suitability of the equations presented in section 3 for performance estimation. Equation 1 can be used to calculate the mass flow rate, with the appropriate value of the transmission coefficient, but equations 2 and 3 underestimate the actual values. Equation 4 can be used, but c_p has to be substituted with a value determined with DSMC simulations, which was found to be 2.8 kJ/(kg K) for water[8]. For the sizing of the propulsion system and the performance figures in section 5, equation 1 was used for mass flow rate (allowing to change plenum/temperature and pressure without doing a new batch of simulations), the specific impulse were taken from table 1 and equations 4 (with the c_p value given earlier in this paragraph) and 5 were used to compute power input. Radiative loses were taken into account, but it was assumed equation 4 provided an adequate estimation of conductive loses.

5. System design

Figure 6 shows the concept, and contains labels for all the parts. The two main components are the thruster (top part in the figure; from the gate valve up) and propellant storage system (bottom part; from the gate valve down). The design fits within the volume constraints of DelFFi, which are roughly a 9 cm cube. Almost any shape is possible, within reason, as long as there is enough volume available.

The THRUSTER consists of: (1) the square heater chip, with 10 5 mm wide expansion slots (with the optimised geometry in figure 2); the heater chip will be made out of silicon, coated with gold (to reduce radiative loses), have 10 mm sides and a thickness of 0.5 mm; (2) the plenum/feed system has the same section as the heater chip (10 × 10 mm) and is made of 1 mm thick aluminium; and (3) a (custom) butterfly valve to control the water vapour flow and an electric motor to actuate it.

The PROPELLANT TANK consists of: (1) a (custom) gate valve to keep the liquid water inside the tank during LEOP; freezing the water in orbit is the only choice available, since keeping the water solid from integration to launch is very difficult[9]; (2) a 2-layer propellant tank casing; a 1 mm thick aluminium outer layer and a flexible inner membrane to keep contact with the heating and cooling system; the propellant tank holds 100 g of water to provide 20 m/s of delta-v; (3) the heating and cooling system, which freezes the water in orbit and keeps its temperature constant during thrusting; made up of a Peltier device (a Tellurex C2-23-0905 was selected which can pump the required 4 W with a 0.5 W power input[13]) for heat pumping, aluminium heating fins and a thermal connection to the spacecraft, actuated by a linear electric motor, which allows thermal conduction during thrusting and maintains insulation when not; (4) a fill valve and fill tubing; (5) mechanical connectors to the spacecraft and (6) a control board[10] (not pictured). Custom valves are required due to the combination of large physical size and very small pressures.

The system was sized to provide 20 m/s (the extended target for DelFFi) of delta-v at $T_w = 300$ K, which is close to cold gas mode and requires 103 g of propellant. No extra propellant allowance was made. For the system mass, all the structural elements were counted as being made of 1 mm thick aluminium, which is an over-design. System mass can be reduced further, but this is not really necessary right now as the system is below the 459 g mass limit for DelFFi. An overview of the performance, including a total mass estimate, is given in table 2. All the performance requirements of DelFFi are met. A comparison with a theoretical extension of T^3-µPS is presented in table 3.

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[7] The large value of sublimation enthalpy for water, 2.84 MJ/kg[8], makes power input to the tank larger than power input to the heater chip.

[8] The average value of c_p for water vapour in the heater chip temperature range is 1.923 kJ/(kg K)[12]

[9] For details on why it is difficult see the end of the section.

[10] For mass estimations, 40 g were added for the board, which is the weight of an Arduino Mega control board [14].

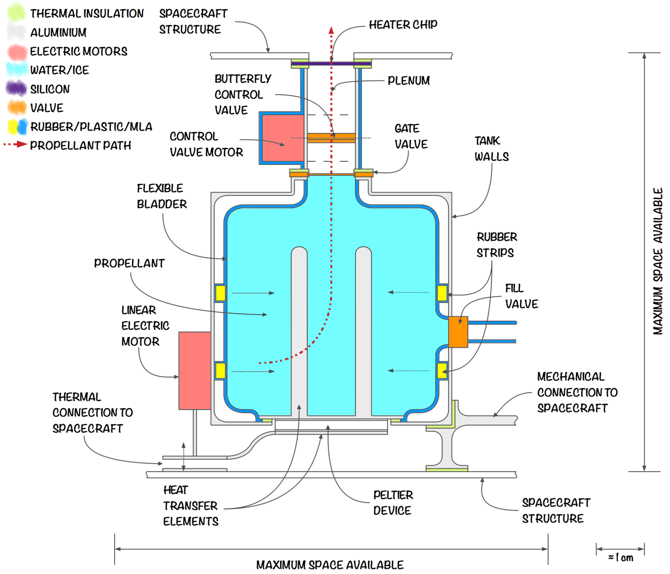

Figure 6: Final propulsion system design concept

Table 2: Performance of the design and DeFFi propulsion system requirements

	PERFORMANCE	REQUIREMENT
thrust	1 — 1.6 mN	0.5 — 9.5 mN
specific impulse	70 — 110 s	—
delta-v	$>$ 20 m/s	10 m/s baseline 20 m/s extended
propellant	water, 100 g	
mass	$<$ 380 g	$<$ 459 g
power	0.8 — 5.6 W	$<$ 10 W

The ice-propelled micro-resistojet offers higher specific impulse and lower total mass, but also lower thrust. In order to provide 20 m/s of delta-v, the T^3-µPS extension would exceed the volume budget, due to CGG inefficiency [2], but this can be addressed by a redesign and/or further development.

Operating the ice-propelled micro-resistojet is a somewhat complicated issue. Unless the satellite using the system is integrated and launched from a place with temperatures below 0° C (say Kiruna or Baikonur during local winter), freezing the ice before launch is out of the question. The amount of thermal insulation required depends on the time between integration and launch and weather conditions at the integration/launch site. The water has to be inserted in the liquid phase and frozen after launch (this also requires the presence of the gate valve to keep the water in place during LEOP). The Peltier device can be used for this, but it will take several days, depending on the power available. The heater chip cannot allow enough mass flow through to make use of the sublimation enthalpy for freezing (thrust without heating the propellant in the tank), and unless the satellite is already de-tumbled, liquid water will be lost. Solving these issues requires either a particular mission profile (having enough time in LEOP to freeze the propellant) and being allowed to launch with liquid water on-board, or, as it will be discussed in the next section, using a different propellant.

Table 3: Performance comparison between the ice-propelled micro-resistojet and T^3-µPS extension (data for the latter from [2])

INDICATOR	ICE-PROPELLED	T^3-µPS
$\triangle v$ [$^m/_s$]	$>$ 20 m/s	20 m/s
m_{prop} [g]	100 (at 70 s)	100 (no allowance)
I_{sp} [s]	70 — 110	68
$\Im$ [mN]	1 — 1.6	6
m_{tot} [g]	$<$ 380	$>$ 400
$\wp$ [W]	0.8 — 5.6 for thrusting	0.4 for thrusting 10 for ignition

6. Future work

The ice-propelled micro-resistojet concept can be split into two research areas: the thruster itself and the propellant tank. The low pressure thruster designed has been researched into great depth, and the only issues remaining are manufacturing related, like applying the gold coating. The propellant tank is in fact the most challenging part of the design and the main obstacle to implementing it into a spacecraft. The simplest way to simplify the propellant tank design is to use a different propellant. Water is attractive since it has low molar mass (18 kg/kmol) and is cheap, but its melting point is causing design challenges. It would be better to look into a different propellant, which should meet two basic criteria: a melting point higher than, say, 50° C[11] and a vapour pressure of more than 400 Pa[12] (possible alternatives are naphthalene and paradichlorobenzene — p-DCB; both will lead to much lower I_{sp} values, due to a high molar mass). If such a propellant is selected, the system can be simplified to using only the butterfly valve for flow control and no in-orbit freezing would be needed. It would also be desirable for the propellant to have low molecular mass (for better specific impulse) and low sublimation enthalpy (to reduce power input to the propellant tank).

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[11] The value can change a bit depending on launch conditions. It should be high enough to remain in the solid phase during launch

[12] A factor of 2 higher than the highest plenum pressure used in the simulations

7. Summary and conclusions

A design for an ice-propelled MEMS resistojet, suitable for a nanosatellite, has been developed and its performance investigated using DSMC simulations. Its size and performance show great future potential. While the thruster design itself is quite mature (a similar design has been experimentally tested by [5]), a lot of work has to be done on the propellant storage components. While water looks attractive as a propellant choice, due to low molecular mass and availability, its melting point makes storing it in the solid phase very difficult for pico-/nanosatellite missions. Exploring an alternative propellant with a higher melting point will make the propulsion system design much more attractive.

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