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Optimum Design of Low-Pressure Micro-Resistojet Applied to Nano- and Pico-Satellites

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ABSTRACT: A Low-Pressure Micro-Resistojet (LPM) is under development at TU Delft with the intention to provide future nano- and pico-satellites with the necessary capability to execute formation flying maneuvers, orbit change maneuvers, and station keeping. In this particular type of electro-thermal thruster, water is a green propellant of excellent performance, which can be stored as a liquid or solid operating at very low pressure, under evaporation or sublimation conditions. The formed vapor flows to a series of hot microchannels in a heater chip. Then, the flow is heated and expanded at high Knudsen numbers to a high exhaust velocity. This concept is very promising when associated to the typical CubeSat or PocketQube requirements that demand low tank pressure, low system mass, intrinsic safety, "green" propellants – non-corrosive, non-flammable, non-toxic, with limited energetic content – and a sufficiently long operational life. This paper discusses the optimization of the LPM design applied to two different missions, one for a CubeSat mission which requires a formation flight and other for a PocketQube mission which will be used as a flight demonstration platform.

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

1. INTRODUCTION

CubeSat and PocketQube are the most common standards for nano- and pico-satellites respectively. CubeSats are characterized by a cube shape of 1000 cm^3, while a PocketQube is characterized by a volume eight times smaller than the CubeSat, i.e. a cube with a form factor of 5 cm. Even though many of these satellites are already in a high level of development, they are limited in performance due to a lack of adequate propulsion systems. The development of a propulsion system for these classes of satellite will allow, for instance, to increase the spacecraft lifetime by controlling the altitude, besides to enabling orbit change and formation flying. However, researchers and engineers are facing a challenge to meet the very strict requirements imposed by the satellite miniaturization [1], [2], [3].

Larger propulsion systems for space are usually at a high technology readiness level (TRL) level of development for decades, while microscale systems need a further development since they cannot simply rely on miniaturizing. Requirements such as a low mass, low internal pressure, low available power, low thrust, and low impulse besides the usage of "green" propellants are usual for small satellites [4]. These requirements represent a severe limitation for the use of traditional propulsion systems. For instance, cold gas propulsion usually needs a high tank pressure which also increases significantly the tank mass, while electrostatic propulsion needs a high level of power. Chemical propulsion uses non-green propellants (flammable, corrosive, unstable, or hazardous), and causes thermal stresses by very high temperatures in a miniaturized system.

The Space System Engineering (SSE) chair at Delft University of Technology (TU Delft) is currently developing two green micro-resistojet concepts with the intention to provide future nano- and pico-satellites with the necessary capability to execute formation flying maneuvers, orbit change maneuvers, and station keeping. They are known as Vaporizing Liquid Micro-Resistojet (VLM) and Low-Pressure Micro-Resistojet (LPM) [5]. This paper is focused on the LPM.

The LPM, also known as Free Molecule Micro-Resistojet (FMMR), is characterized by rarefied gas dynamics, i.e. its work principle relies on very low pressure. The LPM system is divided into three main parts: the tank, the feed system, and the thruster. In short, the propellant is evaporated or sublimated inside the tank, the vapor formed flows toward the feed system and then flows through a series of hot microchannels where it is expelled in a high exhaust velocity generating thrust [6].

A recent publication has selected nine interesting propellants, namely Acetone, Ammonia, Butane, Cyclopropane, Ethanol, Isobutane, Methanol, Propene, and Water, to be used in this concept [7]. These propellants have in common that they can be stored in liquid or solid phase at higher mass density allowing a compact tank and still work at a low internal pressure.

This paper is focused on LPM design optimized for two different mission concepts: one for a CubeSat mission which requires formation flight, and another for a PocketQube mission which will be used as a flight demonstration platform. Two main aspects are analyzed in this paper the scalability of the system and the performance.

2. PROPULSION CONCEPT

A simplified LPM propulsion concept is presented in Figure 1. The tank stores the propellant in a liquid or solid state. The gases from the evaporation or sublimation process flow through the valve. Then, the gases fill the plenum at a very low pressure and are expelled by the heat chip microchannels providing thrust.

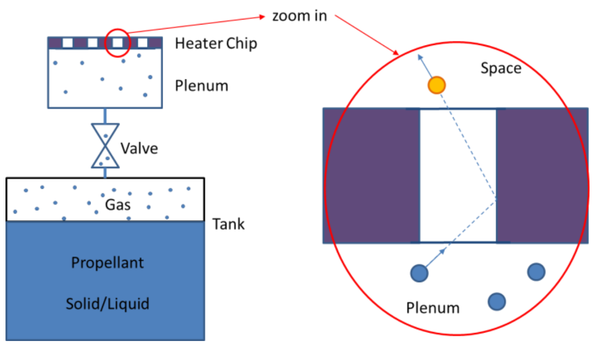

Figure 1. LPM Concept Scheme

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. Water presents the best velocity increment per volume of propellant, two times more than ammonia for instance. Additionally, its thermodynamic properties are suitable for the environment in which the propulsion system will work [7]. Based on that, the propulsion system is optimized using water as propellant.

3. THEORY AND OPTIMIZATION

The LPM thruster works at a Knudsen number between 0.1 and 10 that corresponds to a flow in the transitional regime. The Knudsen number Kn provides the degree of gas rarefaction and is defined as the ratio of average distance traveled by the molecules between collisions, the mean free path λ, to the flow characteristic dimension l_c [8]

$$Kn = \frac{\lambda}{l_c}. \tag{1}$$

Assuming the transitional regime and straight microchannels, we can estimate the mass flow rate $\dot{m}$ which flows through the thruster as

$$\dot{m} = \alpha P_0 \sqrt{\frac{m_a}{2\pi k T_0}} A_e \tag{2}$$

where P_0 is plenum pressure, α the transmission coefficient, A_e the exit cross-sectional area, T_0 plenum temperature, k the Boltzmann constant and m_a the molecule mass. The geometry of the microchannel plays an important role in the thrust performance. The transmission coefficient is the variable which represents the decrease of mass flow rate based on the microchannel aspect ratio. There are empirical equations that estimate the transmission coefficient based on the geometry. In this paper two different microchannel geometries are used the short cylindrical microchannel and the short cuboid microchannel [9].

Short cylindrical microchannel

$$\alpha = 1 + \delta^2 - \delta\sqrt{\delta^2+1} - \frac{\left[\left(2-\delta^2\right)\sqrt{\delta^2+1} + \delta^3 - 2\right]^2}{4.5\delta\sqrt{\delta^2+1} - 4.5\ln\left(\delta + \sqrt{\delta^2+1}\right)} \tag{3}$$

where δ is the microchannel length to diameter ratio l/d. This relation is valid for $\delta < 50$.

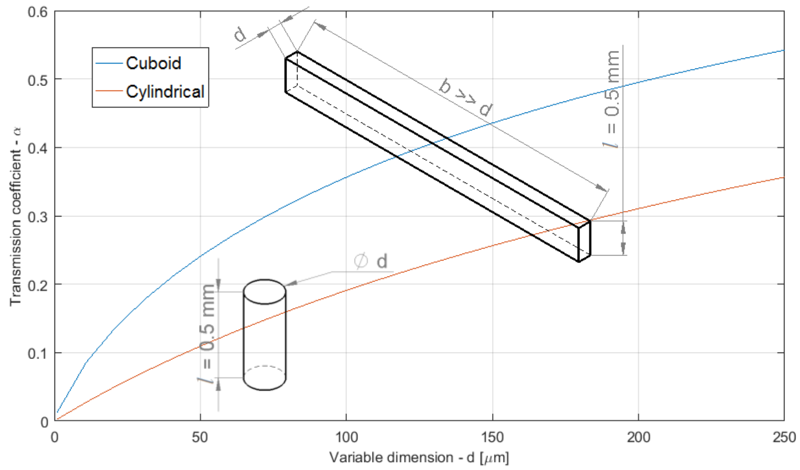

Figure 2. The relation between the transmission coefficient and the microchannel geometry, for microchannel length l=500 μm

Short cuboid microchannel

$$\alpha = 0.5\left(1+\sqrt{\phi^2+1}-\phi\right) - \frac{1.5\left[\phi-\ln\left(\phi+\sqrt{1+\phi^2}\right)\right]^2}{\phi^3+3\phi^2+4-\left(\phi^2+4\right)\sqrt{1+\phi^2}} \tag{4}$$

where ϕ is the microchannel length to small cross-sectional dimension ratio l/d. It is valid for $d << b$, where b is the large cross-sectional dimension, and $b >> l$. Figure 2 shows the relation between the transmission coefficient and the microchannel geometry according to above empirical equations, assuming a microchannel length as the standard value currently obtained in the micro-electro-mechanical systems (MEMS) silicon wafer developed at TU Delft, of 500 μm.

From a fabrication point of view presented in [6] and a numerical analysis presented in [10] and in [11], we decided to use a microchannel aspect ratio of 5 for straight microchannels. It leads to a transmission coefficient for the cylindrical microchannel of 0.19 and the cuboid microchannel of 0.36.

In order to estimate the thrust F_T, the following equations are used [12]

$$F_T = \alpha P_0 A_e \frac{(\pi+2)}{2\pi}\sqrt{\frac{T_w}{T_0}\left(\frac{6\gamma}{\pi+6\gamma}\right)} \tag{5}$$

where T_w is the heater chip temperature and γ the specific heat ratio. The specific impulse, I_{sp}, can be expressed as

$$I_{sp} = \frac{(\pi+2)}{g_0}\sqrt{\frac{kT_w}{2\pi m_a}\left(\frac{6\gamma}{\pi+6\gamma}\right)} \tag{6}$$

where g_o is the Earth's gravitational acceleration at sea level. The velocity increment Δv, from the linear approximation ($M_p/M << 1$) of the rocket equation is expressed as

$$\Delta v = g_0 I_{sp} \frac{M_p}{M} \tag{7}$$

where M the spacecraft mass and M_p the propellant mass. The power $\wp$, necessary to heat up the propellant inside the microchannel and to evaporate/sublimate the propellant inside the tank, can be estimated as

$$\wp = \left[C_p(T_w-T_0)+L\right]\dot{m} \tag{8}$$

where C_p is the specific heat of the propellant at constant pressure (assumed constant over the given range of temperatures), L the specific latent heat.

In order to define the optimized LPM design, we analyze two main aspects: *Scalability and Performance.*

<u>*Scalability*</u> – The size of the propulsion system is fundamental when designing it to very small satellites since the volume and mass is limited. The amount of propellant, the expected thrust, and the fixed parts (valve, feeding lines, structure,…) are the main responsible for the final size of the propulsion system.

<u>*Performance*</u> – It is always desired to have the highest performance when designing a propulsion system. The performance depends on different aspects as the propellant, the delivered thrust, the Delta-V, and the available power. The propellant is not discussed in this paper since it is already discussed in [7].

We focus the discussion on the effect of the heater chip size and the tank size. The heater chip size depends on the amount of required thrust and the available power. For simplicity, as presented in Figure 3, we calculate the heater chip area A_{hc} , is calculated as

$$A_{hc} = (a + 2c)^2 \tag{9}$$

where a is the width and height of the useful heater chip area where the microchammels are placed, and c is the dimension between the useful area and the heater chip edge, see Figure 3. It is assumed that the useful area, a^2, is twice the exit cross-sectional area A_e as $a^2 = A_e$ and $b = 1$ cm. This assumes sure that the heat chip is strong enough to support any mechanical strength, and there also is enough room to deposit the electrical resistance material between the microchannels.

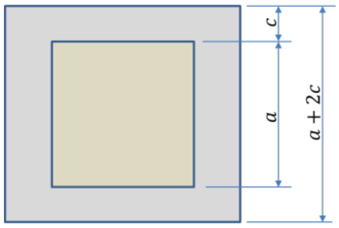

Figure 3. The heater chip scheme in order to simplify the total area.

The tank size is related to the amount of needed propellant and the needed mechanical strength against the internal pressure. The amount of propellant is defined based on the specific mission according to the requirements. Since we are assuming water as propellant the inner tank pressure can be as low as possible keeping the water as liquid and even as solid. As result, the tank thickness can be calculated just based on the expected launch loads, allowing for a reduced dry tank mass. Different tank designs are discussed in next section in order to define the best solution to store the propellant.

In order to exemplify the optimized design according to these requirements, we use two different cases: one based on a CubeSat mission which is supposed to perform a formation flight [9]; and another based on a PocketQube mission is demonstration a flight propulsion system [13] [14]. Table 1 presents the requirements to accomplish the formation flying mission as well as. the requirements to accomplish the flight demonstration.

Table 1. Case requirements for the CubeSat formation flying mission [15] and for the PocketQube propulsion demonstration mission [13] [14]

Parameter	CubeSat mission	PocketQube mission
Thrust [mN]	0.5 - 9.5	0.2 – 3.0
Delta-V [m/s]	15	N/A
Total mass [g]	< 459	< 75
Peak power consumption [W]	< 10	< 4
Plenum pressure [Pa]	< 300	< 300
Total size [mm]	< 90x90x80	< 42x42x30
Microchannel aspect ratio *AR*	5	5
Heater chip temperature [K]	< 700	< 700

4. RESULTS AND DISCUSSION

4.1. Optimization

The main limitations of a miniaturized system for nano- or pico-satellites are the volume, mass, and the available power. The requirements shown in Table 1 are good examples of typical classes of satellite requirements. Figure 4 and Figure 5 present the design space according to these requirements. Figure 4 is referred to the heater chip with a grid of circular microchannels and Figure 5 is referred to the heater chip with a grid of cuboid microchannels. The thrust is strictly limited by the available power. From Figure 4, we can conclude that for a maximum power of 10 W (CubeSat) the maximum thrust is 2.72 mN and for a maximum power of 4 W (PocketQube) is 1.09 mN. To achieve a minimum thrust level for the formation flying requirements, a minimum power of about 2 W is necessary.

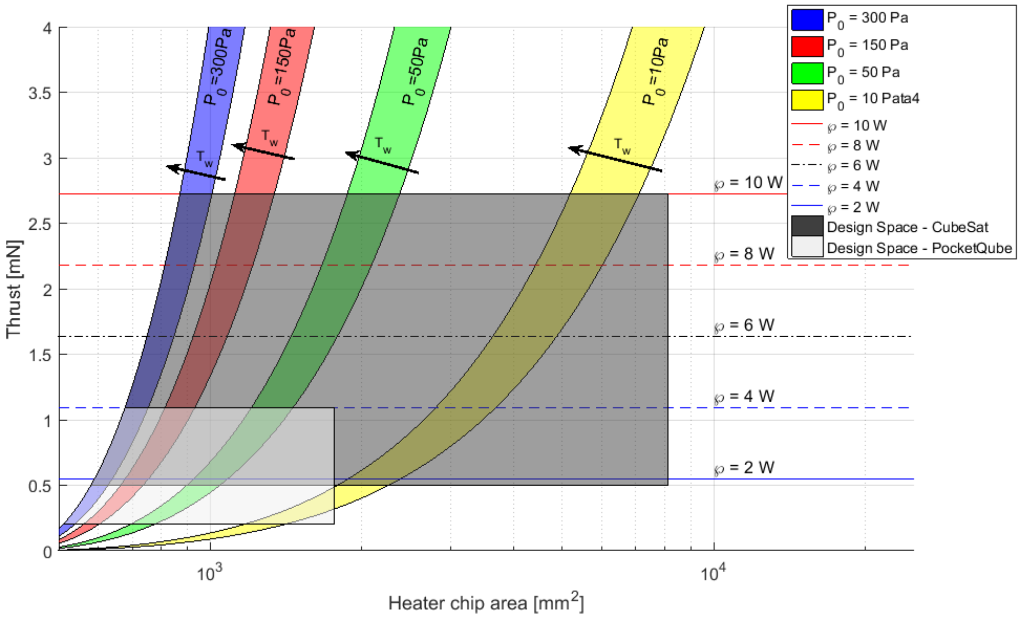

Figure 4. Design space for the CubeSat and PocketQube cases using the grid of holes.

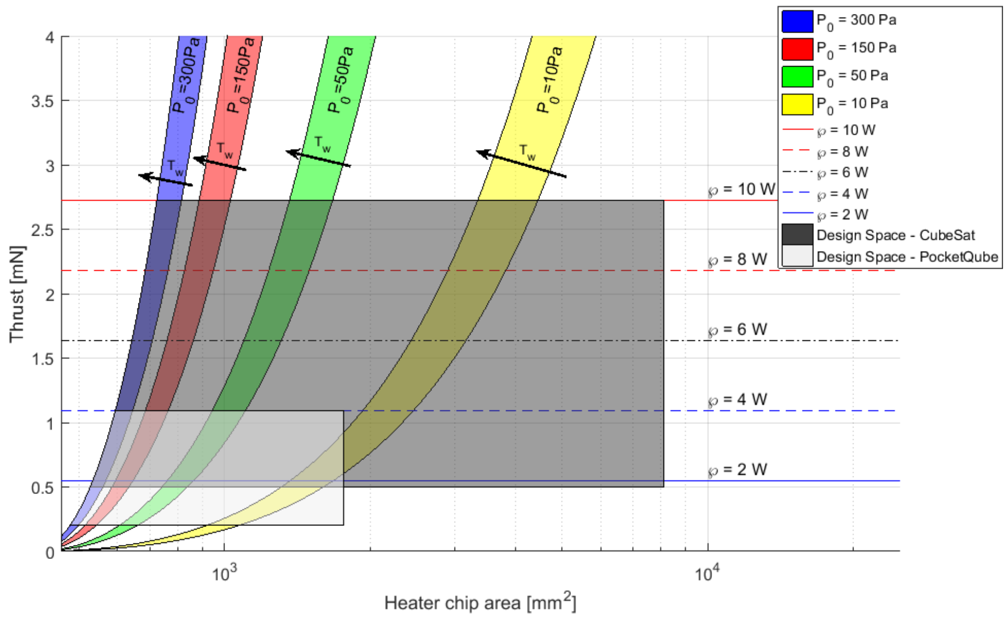

Figure 5. Design space for the CubeSat and PocketQube cases using the grid of slots.

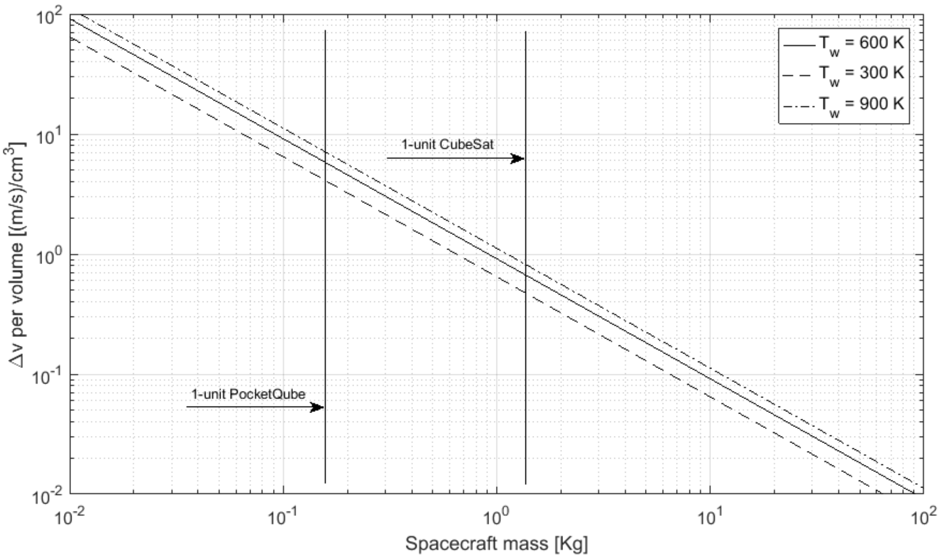

Figure 6. The relation between the Delta-V per volume of fluid and the spacecraft mass.

The natural decision is to choose the smallest heat chip that achieves the highest thrust level. Therefore, the smallest heater chip area for CubeSat case is 722 mm^2 for the grid of cuboid microchannels and 871 mm^2 for the grid of circular microchannels. The smallest heater chip area based on the PocketQube case is 594 mm^2 for the grid of cuboid microchannels and 677 mm^2 for the grid of circular microchannels.

On one hand, if the circular microchannel of a diameter of 100 μm is chosen, at least a grid of 68x68 microchannels are necessary to accomplish the CubeSat mission. While, it is necessary a grid of 43x43 microchannels to accomplish the PocketQube mission. On the other hand, if the cuboid microchannel with a cross-sectional dimension of 100 μm x 4.73 mm is chosen, at least a grid of 50x1 microchannels are needed to accomplish the CubeSat mission. While, with a slightly different cross-sectional dimension of 100 μm x 3.08 mm is chosen, it is necessary a grid of 31x1 microchannels to accomplish the PocketQube mission.

Figure 6 shows the relation between the velocity increment per volume of propellant and the spacecraft mass. Using the target mass of the spacecraft which is 3.6 kg for the CubeSat and 0.7 kg for the PocketQube, we can estimate the amount of propellant required. Based on that, the minimum propellant mass needed to accomplish the formation flying requirement is 59 g. Since the PocketQube is based on performing just a flight demonstration, it does not have a requirement on Delta-V. Assuming the same required Delta-V as in formation flying case, the minimum propellant mass in the PocketQube case would be 11.5 g.

4.2. Tank design solution

Another important aspect when designing the propulsion system is how to store the propellant in order to avoid the sloshing. Moreover, it is advised a tank solution that water can be stored in any phase state (Liquid, Solid and Vapor) avoiding to waste electrical power to keep the desired phase state. Figure 7 presents the breakdown of tank design solutions. The classic rigid tanks are the natural choices when design system to support high pressure level. Besides, the typical shapes such as spherical, cylindrical and cubic, it is possible to have a different shape in order to optimize the volume. However, they are not suitable for this type of propulsion systems due to the sloshing issue. The flexible tank can divide into bladder and pipe. The bladder tank is an interesting option considering an elastic material which shrinks as the propellant is used. However, it may not prevent the sloshing which may move the bladder in a random direction. On the contrary, the pipe tank is an interesting solution since the diameter of the pipe is small enough that capillary forces allow avoiding unacceptable mixing between the liquid and gaseous state of propellant. Another advantage of this suggested tank is that it can be placed in any available place within the spacecraft. It can be bent and inserted into places that are not been used, therefore optimizing the usage of space and the amount of propellant that can be carried on board. However, the disadvantage is that depending on the needed amount of propellant the length of the tubing might not be viable, causing an excessive friction force against the propellant movement within the pipe. As a consequence, this solution is quite interesting for pico-satellites, but it may not be viable for nano-satellites. It will be used for the first flight demonstration onboard of the Delfi-PQ satellite [13] [14].

Table 2 presents the estimation of Delta-V and the demonstration time depending on the pipe length considering a pipe diameter of 0.8 mm. Consuming the whole amount of propellant the propulsion system can be demonstrated accordingly to the minimum and maximum demonstration time which are related to the plenum pressure of 300 and 50 Pa, respectively. The minimum Delta-V is based on the heater chip temperature of 300 K, while the maximum Delta-V is based on the heater chip temperature of 700 K.

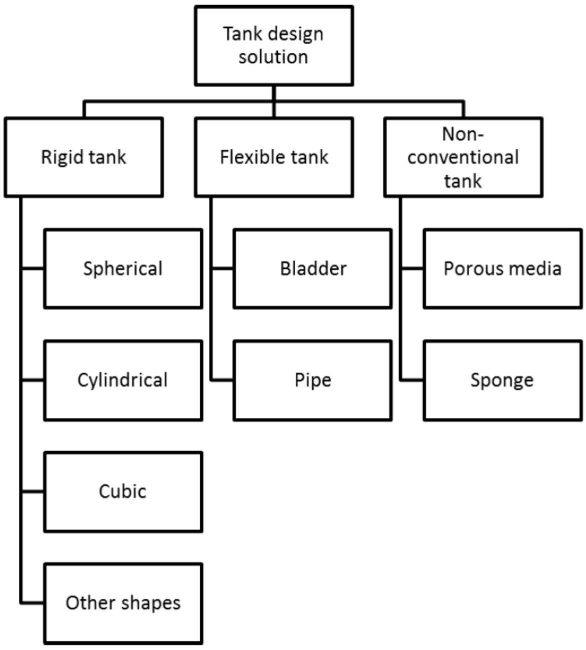

Figure 7. Tank design solution breakdown.

Table 2. Estimation of Delta-V and the demonstration time based on the pipe length for the PocketQube propulsion demonstration mission. [a] is assuming the plenum pressure as 300 Pa, and [b] is assuming the plenum pressure as 50 Pa.

Pipe length [m]	Propellant Mass [g]	Minimum Delta-V [m/s]	Maximum Delta-V [m/s]	Minimum demonstration time[a]	Maximum demonstration time[b]
1	0.503	0.49	0.84	7 min 48 s	46 min 46 s
2	1.005	0.99	1.69	15 min 35 s	1 h 33 min 32 s
3	1.508	1.48	2.54	23 min 23 s	2 h 20 min 17 s
4	2.011	1.97	3.38	31 min 11 s	3 h 7 min 3 s
5	2.513	2.47	4.23	38 min 58 s	3 h 53 min 49 s
6	3.016	2.96	5.07	46 min 46 s	4 h 40 min 35 s
7	3.519	3.45	5.92	54 min 33 s	5 h 27 min 21 s
8	4.021	3.94	6.76	1 h 2 min 21 s	6 h 14 min 7 s
9	4.524	4.44	7.61	1 h 10 min 9 s	7 h 0 min 52 s
10	5.027	4.93	8.45	1 h 17 min 56 s	7 h 47 min 38 s
11	5.529	5.42	9.30	1 h 25 min 44 s	8 h 34 min 24 s
12	6.032	5.92	10.14	1 h 33 min 32 s	9 h 21 min 10 s
13	6.535	6.41	10.99	1 h 41 min 19 s	10 h 7 min 56 s
14	7.037	6.90	11.83	1 h 49 min 7 s	10 h 54 min 42 s
15	7.540	7.40	12.68	1 h 56 min 55 s	11 h 41 min 27 s

Obviously, other non-conventional tanks could also be used such as the sponge and porous media. The sponge tank is a combination of a rigid tank with a sponge inside. The sponge minimizes the sloshing effect, but it does not avoid completely. Another interesting solution is to use a porous media with controlled cavities or microchannels as tank, again taking advantage of capillary force in the cavities. Another advantage of this suggested tank is that there is a large contact area between the porous media structure and the propellant. It improves the efficiency of the heat transfer during the phase change (evaporation or sublimation) in order to increase the mass flow rate to supply the thruster. This solution is interesting when a large amount of propellant is needed. For instance, it might be a viable solution to be applied for the two CubeSat formation flying scenario mission.

5. CONCLUSIONS:

Two different reference mission scenarios were used to optimize the LPM propulsion concept in terms of performance and scalability. One mission scenario was based on two CubeSats expected to perform formation flight. Another mission scenario was based on a PocketQube satellite expected to perform a technology demonstration. For each case an optimum heater chip size was determined and suitable tanks were discussed. This propulsion system is expected to be on board of one of the first launches of a Delfi-PQ satellite for an initial flight demonstration of its optimized design.

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NOMENCLATURE:

a	Width and height of the useful heater chip area
A_e	Exit cross-sectional area
A_{hc}	Heater chip area
b	Large cross-sectional dimension
c	Dimension between the useful area and the heater chip edge
C_p	Specific heat
d	Diameter ratio or small cross-sectional Dimension
F_T	Thrust
g_0	Earth's gravitational acceleration at sea level
I_{sp}	Specific impulse
k	Boltzmann constant
l	Microchannel lenght
l_c	Characteristic dimension
L	Specific latent heat
Kn	Knudsen number
m_a	Molecule mass
$\dot{m}$	Mass flow rate
M	Spacecraft mass
M_p	Propellant mass
P_0	Plenum pressure
T_0	Plenum temperature
T_w	Heater chip temperature
u_e	Exit velocity
α	Transmission coefficient
γ	Specific heat ratio
δ	Microchannel length to diameter ratio
ϕ	Microchannel length to small cross-sectional dimension ratio
λ	Mean free path
Δv	Velocity increment
$\wp$	Total power

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