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Vaporizing Liquid Microthrusters with integrated heaters and temperature measurement

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ABSTRACT

This paper presents the results of design, manufacturing and characterization of Vaporizing Liquid Microthrusters (VLM) with integrated molybdenum heaters and temperature sensing. The thrusters use water as the propellant and are designed for use in CubeSats and PocketQubes. The devices are manufactured using silicon based MEMS (Micro Electro Mechanical Systems) technology and include resistive heaters to vaporize the propellant. The measurements of the heaters' resistances are used to estimate the temperature in the vaporizing chamber. The manufacturing process is described as well as the characterization of the thrusters' structural and electrical elements. In total 12 devices with different combinations of heaters and nozzles have been assessed and four of them have been used to demonstrate the successful operation of the thrusters. Results are used to validate the thrusters and show a performance close to the design parameters and comparable to other devices found in the literature.

1. Introduction

Nano- and pico-satellites have grown in popularity in the last decades as these spacecraft have been applied in a wide range from industrial to educational applications. They have also been used to demonstrate novel technologies and as tools especially for Earth observation [1–3]. The maturity of this class of satellites is high but the research on micropropulsion for these spacecraft is still at an early stage and the systems are not yet at the required maturity.

Micropropulsion systems can be applied for a variety of functions, such as the execution of precise orbital and attitude maneuvers which are important for the execution of missions such as space debris removal, orbit transfer, and formation flying. Recently, many different micropropulsion systems have been developed particularly focused on the implementation on CubeSats [4].

Within micropropulsion systems, microresistojets are a very interesting choice, specifically for CubeSats, since it is one of the few types of such systems currently able to achieve a thrust level in the range 0.1–10 mN while still meeting all the constraints posed by extremely miniaturized spacecraft. The principle of microresistojets is based on heating a gaseous propellant with a resistance and then accelerating and expelling it to space. Some devices use propellants stored in liquid or solid phase, hence a phase-change process is required prior to the heating of the gas. The phase-change is done by heating a resistance in contact with the propellant that is kept in certain conditions of pressure and temperature to allow the phase change (sublimation or vaporization) to occur. Devices that use liquid propellants are called Vaporizing Liquid Microthrusters (VLM) and has been investigated by different research groups as will be discussed in the sequel.

Different designs can be found in the literature reporting the development of microresistojets. In [5] a micro-thruster is presented and tested; it consists of layers of ceramic. The micro-thruster is built by combining three layers of ceramic material: the combustion chamber, the inlet channel, and the nozzle are cut in the inner layer and a micro-heater is attached to the third layer. Tests were performed using water as propellant and it was found that the ceramic thruster is slightly more efficient than some silicon thrusters with respect to power consumption and delivered thrust. Authors in [6] present the details of fabrication and test of a low temperature co-fired ceramic (LTCC) micro-thruster. They analyze the results for pressure, temperature, power and thrust and also present some comments about the relation between the temperature of the chamber and the vaporization of the propellant.

In [7] the design, simulation, fabrication and test of a VLM are presented. The design of the chamber is based on basic calculations with temperature and residence time. The inlet channel is designed

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to reduce the pressure drop caused by the friction (which is high for diameters below 500 μm).

Authors in [8] describe the fabrication and test of a vaporizing liquid micro-thruster whose nozzle points in the direction normal to the chip plane. They built and tested two devices with different nozzle exit areas and tested them under different power conditions to characterize the thrust level per applied power.

The analytical modeling of a vaporizing liquid micro-thruster is shown in [9]. The thruster is the same presented in [8]. They focus on the formulation of the equations to calculate the power necessary to vaporize the liquid.

In [10] four micro resistojets were fabricated using MEMS technology and silicon wafers. The main differences among them are the type of nozzle (convergent or divergent) and the chamber volume (300 μm × 750 μm and 600 μm × 1500 μm).

Authors in [11] present the design and manufacturing techniques used to construct a micro resistojet consisting of an inlet portion, a heating section with one or more long channels, and a nozzle. Some tests were performed with three different devices: two with only one channel between the inlet and the nozzle with 10 μm and 5 μm wide, and other with 3 channels and 10 μm wide nozzle.

The devices found in literature often make use of complicated experimental setups including high performance data acquisition systems that might be incompatible with the limitations imposed by very small satellites such as CubeSats specially due to budgetary constrains since usually these satellites make extensive use of commercial-off-the-shelf components. Also, interfacing such a system to external components is always a challenge since these complex devices integrate fluidic, electrical, and mechanical characteristics into a very small device that also needs a reliable way of sensing the important parameters such as pressure and temperature.

In this paper, we present the design of VLMs with integrated heating and sensing capabilities that allow the easy operation of the microthrusters using standard commercial-off-the-shelf equipment. The devices are designed to meet the strict requirements of nano- and pico-satellites such as CubeSats and PocketQubes and operate using water as the propellant [12]. It has been shown that water is an interesting choice for micropropulsion applications as it can provide a very high Δv per volume of propellant when compared to other green propellants [13] making it very interesting for applications where orbital maneuvers are required. The heaters are made out of molybdenum which is a metal that can withstand very high temperatures (melting point 2693 °C) and can be patterned with standard dry or wet etching methods [14]. The resistivity of molybdenum is linearly proportional to the temperatures up to 700 °C allowing the design of heaters that also need precise temperature measurements as in the case of the VLMs. The structural design of the thrusters is based on previous work done in [15]. A special interface combining fluidic, electric, and mechanic connections has been developed to facilitate the operations of the thrusters right after dicing. The results of manufacturing and characterization of the VLMs are presented demonstrating the operations including feedback use of measurements of pressure and temperature. The devices have been manufactured with silicon wafers and tested under near-operational conditions in terms of pressure, mass flow, and power.

The remainder of this paper is organized as follows: Section 2 presents the background theory, Section 3 describes the designs of the thrusters, Section 5 shows the details of the experiments, the manufacturing process is described in Sections 4 and 6 presents the results of the tests, and finally Section 7 concludes the paper.

2. Background

2.1. Propulsion

The performance of micropropulsion systems can generally be analyzed using the same formulation as in normal sized systems. However, it is important to note that this formulation uses a set of assumptions that might not be applicable to micropropulsion systems as, for example, the assumption of negligible friction forces [16]. Thus, the following set of equations are used only to give insights into the ideal performance of such micropropulsion systems. In this case, two parameters are of major interest when analyzing the performance of the thruster: specific impulse and thrust. The thrust (F in Eq. (1)) is the force generated by the gas accelerated and expelled through the nozzle.

$$F = \dot{m} V_e + (p_e - p_a) A_e \tag{1}$$

where $\dot{m}$ is the mass flow rate, V_e is the exhaust velocity, p_e and p_a the exit and ambient pressures, and A_e is the exit area. The exhaust velocity can be calculated by (2) where M_e is the Mach number at the exit, k is the ratio of the specific heat at constant pressure and constant volume, T_1 is the chamber temperature, and R is the specific gas constant.

$$V_e = M_e \sqrt{kRT_1} \tag{2}$$

The mass flow rate can be written as a function of the chamber (stagnation) pressure and temperature (p_1 and T_1) and the area of the throat A_t:

$$\dot{m} = A_t p_1 k \frac{\sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}}{\sqrt{kRT_1}} \tag{3}$$

Eqs. (4)–(6) are used to calculate the Mach number, temperature, and pressure at the exit.

$$\frac{A_e}{A_t} = \left(\frac{k+1}{2}\right)^{-\frac{k+1}{2(k-1)}} M_e^{-1} \left(1 + \frac{k-1}{2} M_e^2\right)^{\frac{k+1}{2(k-1)}} \tag{4}$$

$$T_e = T_1 \left(1 + \frac{(k-1)}{2} {M_e}^2\right)^{-1} \tag{5}$$

$$p_e = p_1 \left(1 + \frac{(k-1)}{2} {M_e}^2\right)^{\frac{-k}{k-1}} \tag{6}$$

The specific impulse I_{sp} is a measure of efficiency regarding the consumption of propellant.

$$I_{sp} = \frac{F}{\dot{m} g} \tag{7}$$

where $g = 9.80665\ \mathrm{m\,s^{-2}}$ is the gravitational acceleration on Earth at sea level. Although the unit is given in seconds, it does not represent a measure of time but a measure of thrust per unit weight of propellant and it should be as high as possible for best propellant consumption efficiency.

Eqs. (1)–(7) are used to estimate the performance of the thrusters given the conditions of the experiments and the mechanical characterization of the devices.

2.2. Temperature dependent resistivity

The resistance of the heaters depends on the temperature and might be approximated by the following linear relation:

$$\alpha = \frac{R - R_0}{R_0 (T - T_0)} \tag{8}$$