FREE MOLECULE MICRO-RESISTOJET: NANOSATELLITE PROPULSION

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ABSTRACT

Constellations and platoons of small satellites can offer an assortment of benefits over larger, single function spacecraft. The strict mass, volume, and power limitations of small satellites will require unique micro-technologies to help develop efficient propulsion systems for maneuvering. The Free Molecule Micro-Resistojet (FMMR) has been analyzed and tested in this study to determine its applicability for an upcoming Texas A&M (TAM) nanosatellite mission. The nanosatellite mission will demonstrate the performance and survivability of a water propelled FMMR for attitude control maneuvers and could mark the first meaningful operation of a Microelectromechanical Systems (MEMS) fabricated thruster in space. The Mark 3.1 design of the FMMR heater chip uses a deposited serpentine heater pattern to resistively heat a gaseous propellant expanding through long (13 mm), narrow (100 µm) slots. Experimental data shows that the FMMR, with a heated wall temperature of 575 K, can attain a specific impulse of 65 seconds with a thrust level of 1.2 mN for a nitrogen gas propellant with a mass flow of 100 SCCM. The expected specific impulse when run on a water vapor propellant is expected to be 80 sec at similar thrust levels. Higher thrust levels can be achieved by increasing the temperature of the FMMR heater chip and / or the propellant mass flow through the expansion slots. The measured performance of the FMMR in this study has proven to be adequate to perform the attitude control maneuver for the TAM nanosatellite.

NOMENCLATURE

A_s	- slot area (m^2)
α	- transmission probability
β	- inverse of the most probable velocity (s/m)
g_0	- gravitational constant (9.81 m/s^2)
I_{sp}	- specific impulse (s)
k	- Boltzmann's constant (1.38E-23 J/K)
m	- molecular mass (kg)
$\dot{m}$	- mass flow (kg/s)
n	- number density (m^{-3})
Q	- variable parameter
T	- molecular temperature (K)
T_0	- stagnation temperature (K)
T_w	- expansion slot wall temperature (K)
u_e	- exit velocity (m/s)
v'	- thermal velocity (m/s)
$\overline{v'}$	- average thermal speed (m/s)

INTRODUCTION

There is a growing interest in the use of micro- and nanosatellites within the spacecraft community. Constellations and platoons of small satellites may eventually replace much larger, single function spacecraft as a cheaper, more flexible alternative. Micro-technologies will be required to enable small satellite missions including efficient, low cost propulsion systems for maneuvering[1]. Although the general design of the Free Molecule Micro-Resistojet (FMMR) has been around for several years, experimental validation of its performance was not available. For the first time, thrust and specific impulse measurements have been performed. This was accomplished through the use of the specially modified nano-Newton Thrust Stand (nNTS)[2] located at the Collaborative High Altitude Flow Facility Chamber IV (CHAFF-IV) at the University of Southern California.

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14. ABSTRACT
Constellations and platoons of small satellites can offer an assortment of benefits over larger, single function spacecraft. The strict mass, volume, and power limitations of small satellites will require unique micro-technologies to help develop efficient propulsion systems for maneuvering. The Free Molecule Micro-Resistojet (FMMR) has been analyzed and tested in this study to determine its applicability for an upcoming Texas A&M (TAM) nanosatellite mission. The nanosatellite mission will demonstrate the performance and survivability of a water propelled FMMR for attitude control maneuvers and could mark the first meaningful operation of a Microelectromechanical Systems (MEMS) fabricated thruster in space. The Mark 3.1 design of the FMMR heater chip uses a deposited serpentine heater pattern to resistively heat a gaseous propellant expanding through long (13 mm), narrow (100 µm) slots. Experimental data shows that the FMMR, with a heated wall temperature of 575 K can attain a specific impulse of 65 seconds with a thrust level of 1.2 mN for a nitrogen gas propellant with a mass flow of 100 SCCM. The expected specific impulse when run on a water vapor propellant is expected to be 80 sec at similar thrust levels. Higher thrust levels can be achieved by increasing the temperature of the FMMR heater chip and / or the propellant mass flow through the expansion slots. The measured performance of the FMMR in this study has proven to be adequate to perform the attitude control maneuver for the TAM nanosatellite.

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The FMMR is an electrothermal propulsion system designed for on-orbit maneuvers of nanospacecraft (mass ≤ 10 kg). As with any resistojet, the propellant flow through the FMMR is heated by passing it over an electrically heated solid surface[3].

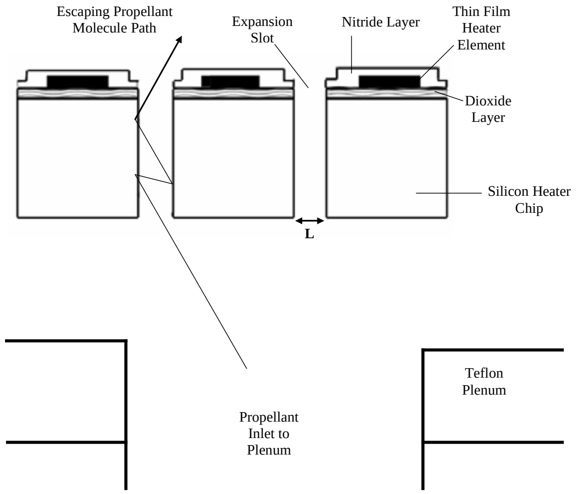


Figure 1: Conceptual diagram of the operation of the FMMR heater chip.

The operation of the FMMR is shown conceptually in Fig. 1. The propellant gas, originating from a propellant tank and passing through hydrophobic microporous membrane filters and a valve, enters the base of a Teflon plenum through an inlet as shown in Fig. 2. The hydrophobic microporous membrane uses the surface tension of the propellant to serve as a phase separator, allowing only the propellant vapor to pass through. The FMMR heater chip is secured to the top of the plenum through three #0-80 screws, as shown in Fig. 3. Propellant molecules gain kinetic energy as they collide with heated walls of the expansion slots. Here, energy is transferred from the vibrational energy of the expansion slot surface molecules to the kinetic energy of the propellant molecules through gas-surface collisions. The increase in kinetic energy of the propellant molecules is critical to the performance and operation of the FMMR. Due to the inherently low operating pressures of the FMMR, the propellant molecules are heated only through the direct interaction with the expansion slots, as intermolecular collisions are negligible[4].

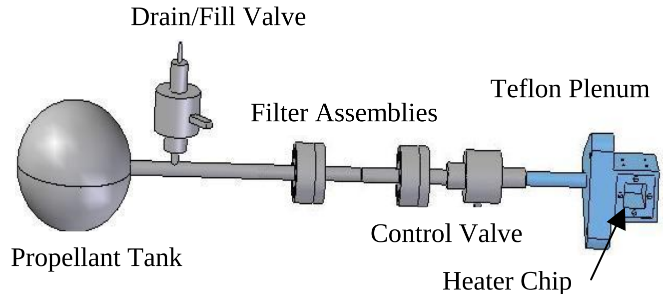


Figure 2: The flight schematic for the TAM flight.

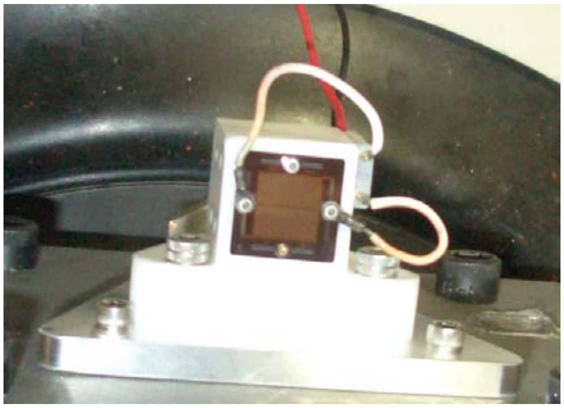


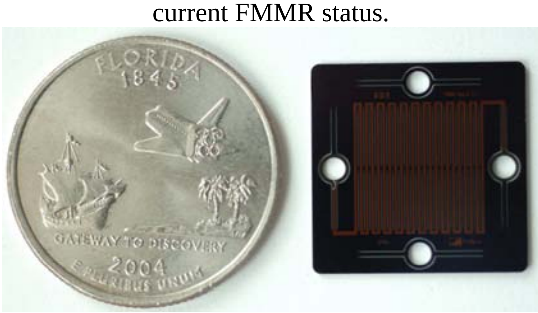
Figure 3: MEMS fabricated heater chip attached to Teflon flight plenum.

The FMMR exhibits many systems features that are beneficial to small satellite operations such as low cost, low power consumption, low mass, and low propellant storage volume. The FMMR operates at relatively low stagnation pressure to take advantage of the high storage density of liquid and solid propellants. By operating on the vapor pressure of the stored propellant, the FMMR reduces the amount of power required over thrusters that pre-vaporize the propellant to create high stagnation pressures. The simple design of the FMMR allows for low-cost manufacturing and testing. The FMMR is fabricated through simple MEMS fabrication techniques and uses common materials which results in low-cost batch fabrication. The expansion slot design leads to a reduction in the number of single point failures over a single nozzle expansion with a small throat diameter. The FMMR heater chip allows for large ranges of thrust levels without a significant loss in performance by varying the number and dimensions of the expansion slots.

The FMMR is being developed to fly on a Texas A&M (TAM) nanosatellite. The delivered thruster system will operate on the vapor pressure of water, stored in either a liquid or solid state (depending on the internal satellite temperature). The FMMR will provide a de-spin capability for the nanosatellite to allow proper positioning of the satellite. Various budgets for the FMMR, along with other mission requirements are presented in Table 1. This nanosatellite flight will investigate the survivability and capability of water propelled micro-thrusters for attitude control maneuvers on a small satellite and could also mark the first operation of a MEMS fabricated thruster in space.

System	Budget	Requirement	Status
Power (Heater Chip)			
-Steady State	5 W	-	3.2 W
-Transient	9 W	-	5 W
Mass (Propellant)	100 gm	-	87 gm
Volume (Propellant)	100 cm^3	-	87 cm^3
Thrust	-	0.8 mN	1.7 mN
Valve Actuation Time	-	0.2 s	0.1 s

Table 1: Various budgets and requirements of the FMMR for the TAM satellite mission, along with the current FMMR status.



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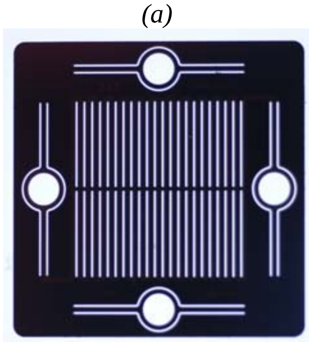

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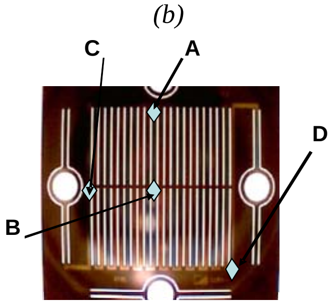

(c)

Figure 4: (a)MEMS fabricated heater chip. (b) Expansion slot configuration on the heater chip. (c) Locations of the attached thermocouples used in the experiment.

The current iteration of the FMMR heater chip, shown in Fig. 4, was designed specifically for the TAM nanosatellite mission. This Mark 3.1 iteration of the FMMR chip is an 18.6 mm by 18.6 mm square with a thickness of 500 µm. There are 44 interior expansion slots formed in two rows. Each slot is 100 µm wide by 6.5 mm long, and are etched completely through the FMMR. The expansion slots are outlined by a serpentine heater pattern consisting of a gold current carrying layer. This iteration contains four exterior thermal compensator flexures, reducing the stress caused by thermal expansion and contraction. The Mark 3.1 iteration was designed specifically to accommodate the required thrust of the TAM mission and to survive the expected G-loading of launch.

The aim of this research was to validate the Mark 3.1 iteration of the FMMR for flight on the TAM nanosatellite mission. This paper details propulsive and heat transfer characteristics of the FMMR heater chip design. A flight thruster system is currently being developed around the FMMR and will be delivered for final integration in the near future.

FMMR MARK 3.1 FABRICATION

The following section outlines the fabrication steps used in the creation of the Mark 3.1 FMMR heater chip. The heater chip is fabricated from silicon wafers using standard MEMS fabrication techniques[5]. A 5000 Å silicon dioxide layer is deposited on a 150 mm diameter silicon wafer through thermal deposition. The SiO_2 layer acts to electrically isolate the heater from the silicon substrate. The heater pattern is deposited on the electrical insulation by metallization through an e-beam evaporator. The heater consists of an initially deposited titanium layer, which acts as an adhesion promoting layer between the silicon dioxide and the remaining heater layers. A platinum layer is later deposited, which acts as a diffusion barrier between the silicon and silicon dioxide and the gold current carrying layer, deposited last. The Ti/Pt/Au stack is deposited in the proportions of 300 Å, 600 Å, and 8000 Å, respectively. The heater resistance was selected to allow the FMMR heater chip to reach operating temperatures while being supplied by the specific bus voltage of the TAM satellite. Upon completion of metallization patterning, the wafer is oxide coated with 1 µm of silicon oxide in order to encapsulate the heater, providing an isolation and scratch resistant layer. The oxide is deposited through the process of Plasma Enhanced Chemical Vapor Deposition (PECVD). A Scanning Electron Microscope (SEM) picture of the heater element and the oxide overlay, shown in Fig. 5, illustrates the three layers on the silicon substrate. The expansion slots and the thermal compensator flexures are formed through Deep Reactive Ion Etching (DRIE), where the final product is shown in Fig. 6.

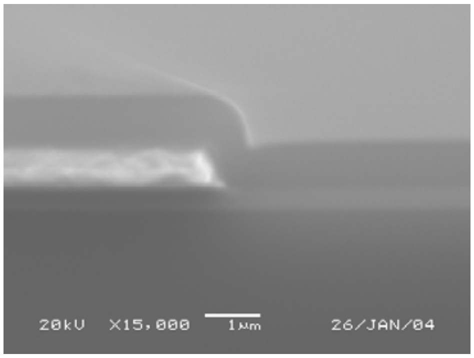

Figure 5: Scanning Electron Microscope image of the different layers of the FMMR.

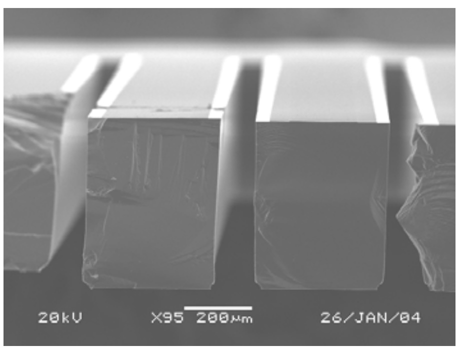

Figure 6: Scanning Electron Microscope image of the expansion slots in the FMMR. These slots were formed through Deep Reactive Ion Etching.

THEORY

The performance of the thruster is analyzed theoretically as the flux of mass, momentum or energy through a surface (expansion slot) per unit area.

$$\dot{Q} = n\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty} Qv'_x f\left(v'_x\right) dv'_z dv'_y dv'_x \qquad (1)$$

It is possible to find the flux of a molecular parameter Q (such as mass, momentum, and energy) through a surface with an orthogonal coordinate system x (surface normal), y and z (surface through which flow passes is in the y-z plane)[6]. Only molecules traveling in the positive x direction are analyzed. Using Eq. (1) the number flux through the surface can be found by setting $Q = 1$. Mass flow can be similarly found by multiplying the number flux by the mass of a molecule, m. The velocity distribution function is assumed to be a thermodynamic equilibrium distribution or Maxwellian[6]. Making these substitutions, the mass flow per unit time per unit area becomes

$$\dot{m} = mn\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty}\left(v'_x\right)\frac{\beta^3}{\pi^{3/2}} e^{-\beta^2 v'^2} dv'_z dv'_y dv'_x \qquad (2)$$

where β is

$$\beta = \sqrt{\frac{m}{2kT}} \qquad (3)$$

This analysis assumes an infinitely thin expansion slot; however the FMMR heater chip has a definite thickness (500 microns) requiring a transmission probability parameter, α, to determine the likelihood of a molecule exiting the slot after entering. Therefore, the actual mass flow can be found by multiplying Eq. (2) by the transmission probability and the area of the expansion slots. Solving the triple integrals of Eq. (2) yields a mass flow of

$$\dot{m} = \alpha mn\frac{\overline{v'}}{4}A_s \qquad (4)$$

where the temperature of the gas in the plenum is assumed to be the same temperature as the chip temperature, T_w and $\overline{v'}$ is given by

$$\overline{v'} = \sqrt{\frac{8kT_0}{\pi m}} \qquad (5)$$

Substituting for number density, the mass flow in terms of the plenum pressure can be written as

$$\dot{m} = \alpha\frac{Pm\overline{v'}}{4kT}A_s \qquad (6)$$

Thrust can then be defined as the mass flow multiplied by the exit velocity of the molecules,

$$\Im = \dot{m}u_e \qquad (7)$$

The average velocity of a molecule transported through an expansion slot (exit velocity) can be determined by setting $Q = \overline{v'_x}$ in Eq. (1) and dividing by total number flux through the surface as

$$u_e = \frac{n\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty} v'_x\left(v'_x\right)\frac{\beta^3}{\pi^{3/2}} e^{-\beta^2 v'^2} dv'_z dv'_y dv'_x}{n\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty}\left(v'_x\right)\frac{\beta^3}{\pi^{3/2}} e^{-\beta^2 v'^2} dv'_z dv'_y dv'_x} \qquad (8)$$

Solving for the integrals[6], substituting for β and simplifying Eq. (8) becomes

$$u_e = \sqrt{\frac{\pi kT_w}{2m}} \qquad (9)$$

Substituting Eq.(4), (5), and (9) into Eq. (7), the theoretical thrust of FMMR can be written as

$$\Im = \frac{\alpha m n A_s}{4} \sqrt{\frac{8kT_0}{\pi m}} \cdot \sqrt{\frac{\pi k T_w}{2m}} \qquad (10)$$

The thrust is seen to be proportional to the number density in the plenum and related to the expansion slot temperature.

The specific impulse (I_{sp}), a measure of propellant efficiency, of the FMMR is calculated by dividing the thrust by the mass flow times the gravitational constant or the exit velocity divided by the gravitational constant. For a theoretical I_{sp}, Eq. (9) is divided by g_0.

$$I_{sp} = \frac{\Im}{\dot{m} g_0} = \frac{u_e}{g_0} = \frac{\sqrt{\frac{\pi k T_w}{2m}}}{g_0} \propto \sqrt{T_w} \qquad (11)$$

The I_{sp} is proportional to the square root of the expansion slot temperature.

The efficiency of an electric propulsion system (such as the FMMR) is measured by the ratio of the thrust and specific impulse generated per unit power, and is given by

$$\eta = \frac{\Im^2}{2\dot{m}\wp} = \frac{I_{sp} \Im g_0}{2\wp} \qquad (12)$$

where $\wp$ is the input power of the thruster.

EXPERIMENTAL SETUP

The FMMR was tested to assess the heat transfer, total input power, thrust, and specific impulse. The purpose of characterizing the heat transfer across the FMMR heater chip was to gain knowledge of the thermal gradients present during operation. Due to the temperature (through the thrust and specific impulse) and power dependence on FMMR efficiency, a fully characterized thermal model of the FMMR chip for cases with and without gas flow was necessary. It was important to quantify the amount of power going into the propellant gas, the FMMR structure, and lost to the surrounding environment (conduction and radiation only in vacuum). The power being transferred to the propellant molecules is directly proportional to the increase of their kinetic energy.

Temperature measurements were obtained by attaching four Omega J-type thermocouples to the FMMR heater chip as marked in Fig. 4. The working gases used in the experiment were helium, argon, carbon dioxide, and nitrogen. A 100 SCCM mass flow meter was used to monitor the propellant mass flow rate. The pressure in the plenum was monitored by a 1.0 Torr differential pressure transducer. The FMMR heater chip was supplied with a DC voltage with the voltage and current draw (i.e. power) monitored on individual multimeters. The FMMR plenum and heater chip were placed in a vacuum chamber with background pressures ranging from 1E-6 Torr to 1E-4 Torr during thruster operation. The voltage, current, plenum pressure, mass flow, and temperature at each part of the FMMR heater chip were logged during a given test. The temperature gradient between the center and edge of the FMMR heater chip was determined.

The transient heat transfer of the FMMR was investigated by logging the current draw and the heater chip temperature as functions of time for varying input voltages. To assess the total input power into the propellant and FMMR structure, the FMMR was first set at an initial temperature. A propellant gas was introduced into the FMMR geometry resulting in a drop of the heater chip temperature. The power was increased until the heater chip regained its original temperature, and the required excess power was logged as a function of mass flow rate for each gas. This process was repeated for varying initial temperatures and all working gases. Finally, the FMMR was enclosed by a liquid nitrogen shield in the vacuum chamber to simulate radiation to the background temperature of space. The temperatures of the shield ranged from 133 K to 113 K. Input power and temperature measurements were again carried out.

To test the thrust, the FMMR was put on the nNTS. The nNTS is a torsional force balance utilizing viscous oil for damping, a Linear Variable Differential Transducer (LVDT) for deflection measurements, and a set of electrostatic combs[7] for calibration. The nNTS has been described in detail by Jamison, et al[2]; however, it was specially modified for the needs of the FMMR by attaching power and gas feeds as well as a thermocouple at position A as noted in Fig. 4. The mass flow was measured during thrust stand operation to give the thruster's specific impulse. Tests were conducted for a range of 0 SCCM to 100 SCCM at temperatures from 300 K to 600K with various propellants.

RESULTS

Due to the limited power available on the TAM satellite, a measurement of the FMMR temperature versus input power under vacuum condition was critical. The temperature of the FMMR with a mass flow of 50 SCCM of helium, argon, carbon dioxide, and nitrogen is shown in Fig. 7. The temperature gradient between position A and the center of the FMMR heater chip, position B, was at maximum 10 K.

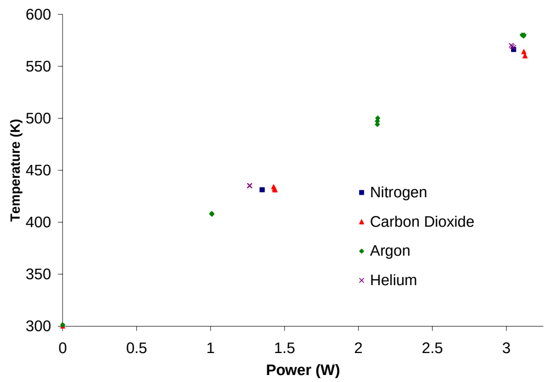

Figure 7: Temperature of the FMMR with respect to the power input at constant 50 SCCM.

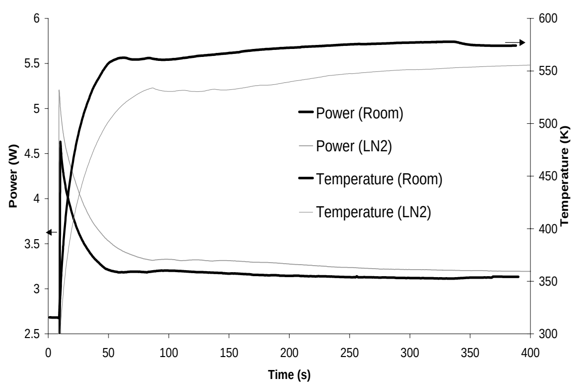

Figure 8: Transient data of the FMMR while radiating to room temperatures (300 K) and liquid nitrogen (77 K). The total power is shown on the primary axis, while the temperature at point A is on the secondary axis.

While operating in orbit, the FMMR will, at times, be radiating to the low temperatures of space. This was simulated by encapsulating the FMMR in a liquid nitrogen shield. Figure 8 shows the transient data of the FMMR while radiating to the vacuum chamber walls at 300 K and the liquid nitrogen shield at 117 K. The power as a function of time is shown on the primary axis, while temperature, as taken from position A on the FMMR, is shown on the secondary axis. The transient data shows that the FMMR exhibits a 0.5 W increase in power consumption during transient operation while radiating to the liquid nitrogen shield when compared to the 300K chamber walls. The increase in power consumption is important, as the FMMR is restricted to a limited power budget. During steady state operation an increase in power consumption of 0.1 W is shown; however, the steady state temperature of the FMMR heater chip is 25 K lower when radiating to the liquid nitrogen shield.

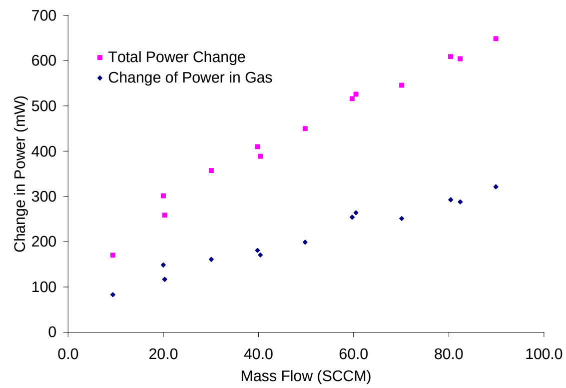

Figure 9: The required increase in power in order to maintain a constant temperature of 600 K at the center of the FMMR heater chip with nitrogen as the working gas.

The extra power required to regain a temperature of 600 K at position B on the FMMR heater chip as a function of nitrogen propellant mass flow rate is shown in Fig. 9. This test was run with the FMMR heater chip radiating to room temperatures of 300 K. The total increase in power is split between the power going into the gas and the power going into the FMMR structure. The area of interest, with respect to thrust, is the amount of power going into the gas, as the increase in power is directly proportional to the increase of kinetic energy of the propellant molecules.

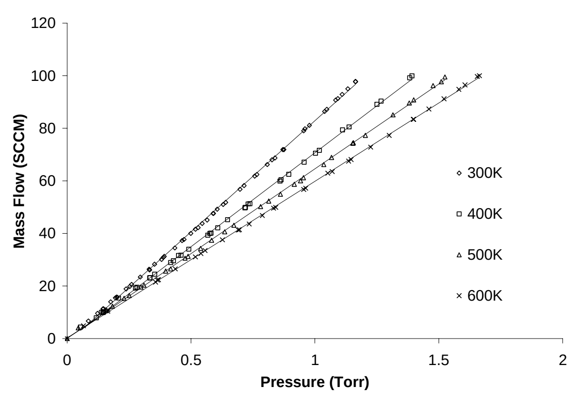

Figure 10: Mass Flow versus Pressure for argon at varying Temperatures

Figure 10 shows the relationship of plenum pressure and mass flow through the FMMR for argon at various temperatures. The slopes and R^2 values for these linear fits can be seen in Table 2. The mass flow is linear with the stagnation pressure as expected from Eq. (6); however the mass flow is still dependant on the stagnation temperature or in this case the temperature of the FMMR heater chip. As Eq. (6) suggests, the stagnation pressure divided by the square root of the heater chip temperature should produce a constant slope. This effect is shown in Fig. 11 for an argon gas at various heater chip temperatures.

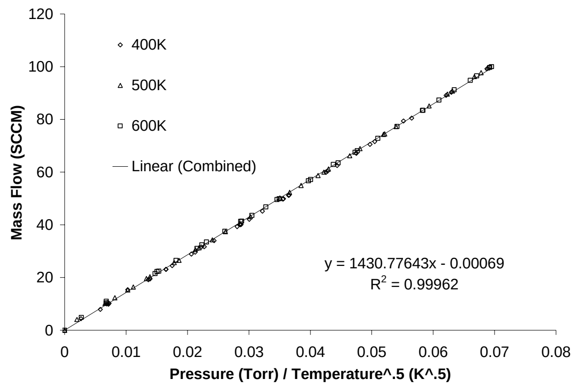

Figure 11: Mass Flow versus Pressure/SQRT Temp of argon

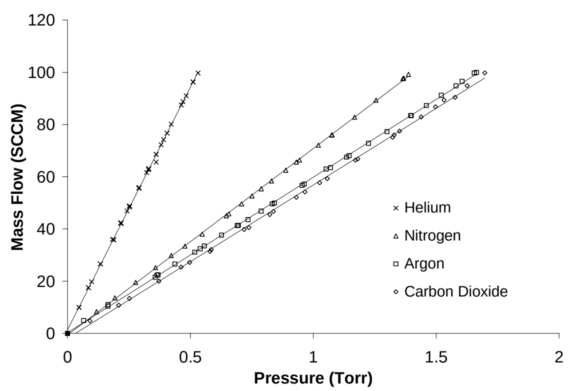

Figure 12: Mass Flow versus Pressure at constant Temperature for various gases

Figure 12 depicts mass flow as a function of plenum pressure for a constant chip temperature of 575 K for all four working gases. Data for the linear fits of these lines can also be found in Table 2. The relationship for each gas is linear, and the slopes of the lines are dependant on the square root of the molecular mass as defined in Eq. (6).

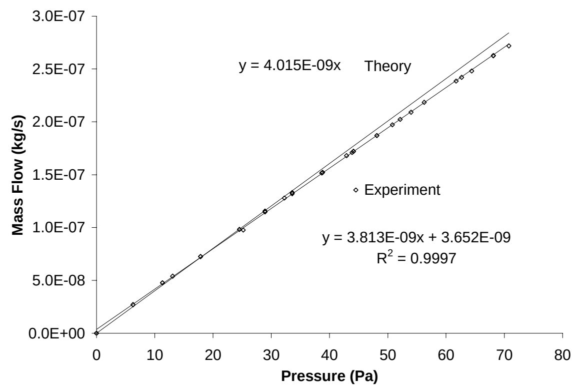

Figure 13: Mass Flow versus Pressure for helium compared to Theoretical Mass Flow

Figure 13 compares the experimental mass flow as a function of pressure for helium propellant flow at constant temperature to the theoretical mass flow obtained from Eq. (6). The transmission probability, α, has been estimated numerically through Direct Simulation Monte-Carlo (DSMC)[4]. For this analysis, α is assumed to equal 0.38. With Knudsen numbers ranging from 2 to 27, helium should match the analytical free molecule theory better than the heavier gases. A 5% difference is seen in Fig. 13 between experimental and theoretical results. Considering the unknown behavior of the flow in a transitional regime and the reliance on DSMC for α; this data follows theory within the uncertainty of the experiment.

As the pressure in the plenum increases, the flow moves closer to a continuum solution (i.e. the flow begins to depart from the free molecule theory presented earlier). The thrust from a continuum flow through the FMMR geometry would be higher than that of a free molecule flow. Figure 14 compares the obtained thrust from the nNTS versus helium pressure to the theoretical thrust given in Eq. (10) at a constant chip temperature of 575 K. There is approximately a 10% difference between the theory and experiment. This is the lowest difference of the four working gases. All four gases show theory under-predicting the thrust, with the gap widening as the flow Knudsen number decreases.

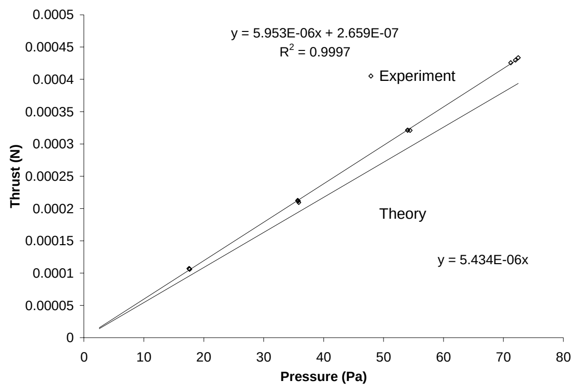

Figure 14: Thrust versus Pressure for helium compared to Theoretical Thrust

Even though these flows are in the transitional regime, in the short span of pressures and temperatures (Knudsen Numbers) the relationship between pressure (or mass flow) with thrust is still relatively linear for each gas, as seen in Fig. 15, and quantified in Table 2.

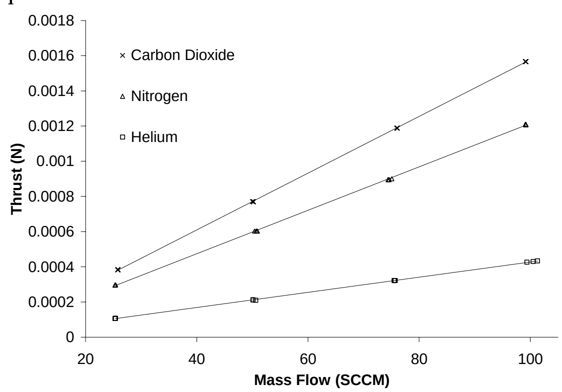

Figure 15: Thrust versus Mass Flow at 575K for varying gases

Figure	Temp	Equation	R^2
10	300K	y = 84.531x - 1.668	0.9996
10	400K	y = 71.360x - 0.721	0.9995
10	500K	y = 64.494x + 0.069	0.9997
10	600K	y = 59.546x + 0.273	0.9998
Figure	Gas	Equation	R^2
12	CO2	y = 58.73x - 1.8711	0.9991
12	Ar	y = 59.547x + 0.2735	0.9998
12	N2	y = 71.431x - 0.6047	0.9998
12	He	y = 186.13x + 1.3521	0.9994
15	CO2	y=1.613E-05x - 3.575E-05	1.0000
15	N2	y=1.234E-05x - 1.964E-05	0.9998
15	He	y=4.308E-06x - 3.779E-06	0.9998
16	CO2	$y = 4.862E\text{-}05x^{0.4335}$	0.9979
16	Ar	$y = 3.185E\text{-}05x^{0.4877}$	0.9998
16	N2	$y = 2.506E\text{-}05x^{0.5046}$	0.9995
16	He	$y = 1.505E\text{-}05x^{0.4143}$	0.9992
17	CO2	$y = 2.6154x^{0.4737}$	0.9994
17	Ar	$y = 2.4243x^{0.4836}$	0.9997
17	N2	$y = 3.0542x^{0.4788}$	0.999
17	He	$y = 9.3951x^{0.4431}$	0.9993

Table 2: List of Line Equations and R Squared Data

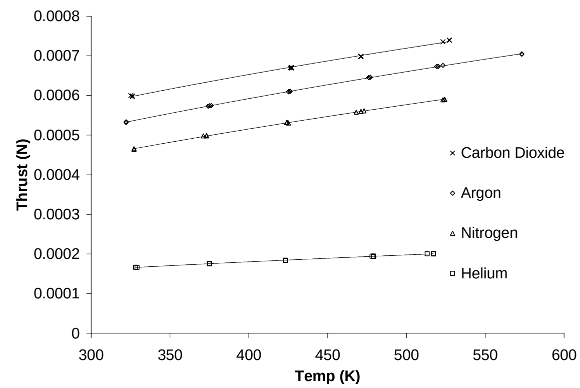

Figure 16: Thrust versus Temperature at 50 SCCM for varying gases

Figure 16 plots the experimental thrust of the four working gases against the heater chip temperature at a constant mass flow rate of 50 SCCM. A curve fit was applied to the data which is shown in Table 2. The relationship between temperature and thrust is shown to be close to the square root, as indicated by Eq. (10). Nitrogen and Argon fit very close to the $T^{1/2}$ dependence. Differences in carbon dioxide and helium may be attributed to inefficiencies caused by energy losses in molecular degrees of freedom, low momentum and energy accommodation coefficients, or transitional effects.

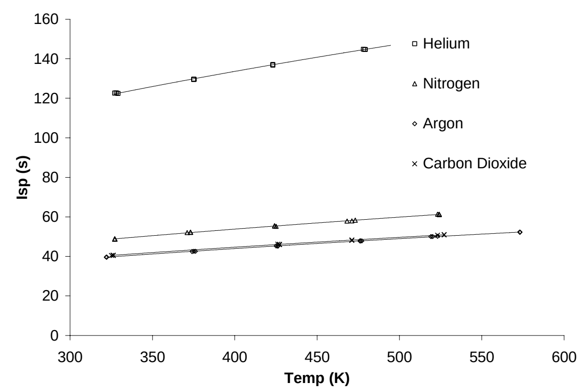

Figure 17: I_{sp} versus Temperature for varying gases

Figure 17 shows the specific impulse of the FMMR heater chip as a function of the wall temperature. Curve fit data for the lines can be seen in Table 2. According to Eq. (11), the I_{sp} should be proportional to the square root of the wall temperature, and the curve fit data supports this.

DISCUSSION

Although the FMMR was tested for a variety of working gases, the ultimate goal of the thruster is to use the vapor pressure of water as the working propellant. Using experimental trends and the theoretical relationship that mass flow, thrust, and I_{sp} have with the square root of the molecular mass of the propellant, the expected performance of the FMMR under operational conditions with the vapor pressure of ice are: pressure of 1.95 Torr (260 Pa), mass flow of 173 SCCM (2.118E-6 kg/s), thrust of 0.00169 N and an Isp of 79 sec.

With the option of using water as the propellant for the TAM mission, the mass and volume requirements for the FMMR propellant tank can be reduced dramatically. Water either in liquid or solid form has considerably more storage density then high pressure gases. Also the molecular weight is lower then nitrogen, argon, or other heavier propellant gases leading to a higher specific impulse. As such the FMMR and its storage tank will take up less space and weight then other alternatives such as a cold gas thruster.

The required thrust of the FMMR, in order to perform the reorientation maneuver of the TAM satellite, is listed in Table 1. The thrust of the FMMR, as demonstrated by the working gases and expected from water vapor, is 1.7 mN. This thrust level is adequate for the TAM satellite mission. The I_{sp} of FMMR is also adequate to allow the propellant mass to fit within the allotted mass budget of 100 gm. The expected I_{sp} of 79 sec for water vapor will allow the FMMR to perform the mission with only 87 gm of propellant. The ability of the FMMR to store the propellant in a high density phase, such as a solid or liquid, allows the required volume of propellant, 87 cm^3, to be within the budgeted volume of 100 cm^3. The required increase in transient and steady state power consumption, when radiating to a simulated space environment, results in a power consumption of 3.2 W, steady state, and 5 W, transient. Both amounts fall within the budgeted amount of 5 W and 9W respectively.

The uncertainty associated with this data is approximately 3% to 5%. For the graphs shown this is smaller then the size of the series icons. For each data point, 3 tests were performed, the standard deviation of these points never exceeded 2%. The thrust stand has been validated through numerical calculations for other thrusters to an error of 3% for a very thin walled orifice. Calibration of the various experimental steps has been verified to 4%[7].

CONCLUSIONS

The data obtained from the FMMR experiments adhere to theory. Mass flow for a given pressure using helium as a working gas, matched theory to within 5%. Thrust, also using helium, matched theory to within 10%. Extrapolating from the experimental data it is possible to predict the mass flow, thrust and I_{sp} of the thruster for a given pressure in the plenum, propellant molecular weight, and temperature of the heater chip. During operation on the TAM nanosatellite, FMMR will use water as its propellant with a plenum pressure of approximately 2 to 3 Torr. At this pressure, FMMR is expected to produce 1.7mN of thrust with an I_{sp} of 79 sec.

As shown by the requirements and budgets listed in Table 1, the FMMR meets or exceeds all of the mission requirements. The FMMR also produces more than the required thrust to perform the despin of the TAM satellite.

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