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Plume diagnostics of BUSTLab microwave electrothermal thruster using Langmuir and Faraday probes

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Abstract

This study presents the Langmuir and Faraday probe measurements conducted to determine the plume characteristics of the BUSTLab microwave electrothermal thruster (MET). The thruster, designed to operate at 2.45 GHz frequency, is run with helium, argon and nitrogen gases as the propellant. For the measurements, the propellant volume flow rate and the delivered microwave power levels are varied. Experiments with nitrogen gas revealed certain operation regimes where a very luminous plume is observed. With the use of in-house-built Langmuir probes and a Faraday probe with guard ring, thruster plume electron temperature, plasma density and ion current density values are measured, and the results are presented. The measurements show that MET thruster plume effects on spacecraft will likely be similar to those of the arcjet plume. It is observed that the measured plume ion flux levels are very low for the high volume flow rates used for the operation of this thruster.

Keywords: microwave electrothermal thruster, plasma diagnostics, plume plasma, faraday probe

(Some figures may appear in colour only in the online journal)

1. Introduction

Electric propulsion systems are used for in-space propulsive needs of satellites or spacecraft such as orbit maintenance, orbit raising or inclination change required based on specific mission objectives. Electric propulsion systems have advantages over traditionally used chemical systems in terms of their higher specific impulse levels and resulting reduction in fuel consumption. On the other hand, low thrust levels and complexity of required power systems are the main drawbacks of these systems compared to their chemical counterparts [1, 2].

In addition to these drawbacks, effects of the energetic charged particles expelled from these thrusters must be taken into consideration as a satellite-thruster integration issue. Sputtering of the spacecraft surface materials bombarded by the energetic plume ions is one of the main issues for such thrusters. Another issue is the re-deposition of sputtered material on sensitive surfaces, resulting in the malfunction certain subsystems after a long period of operation. Besides these two effects, electromagnetic waves used for communication purposes could interact with the plume plasma, causing attenuation and phase shifts of the intended signal [3].

Mentioned adverse effects of the plume depend on the plume plasma parameters that vary based on the type of the thruster being used. In the plume of common plasma thrusters such as ion engines and Hall thrusters, the plasma temperature exceeds 1 eV and the plasma densities typically reaches to the order of 10^{18} $\#/m^3$ [3–6]. On the other hand, the exhaust gases of electrothermal thruster systems, that use conventional nozzle to convert the thermal energy of the hot gas into kinetic energy, are mostly neutral. A neutralizer cathode for the neutralization of the plume ions is not used with the electrothermal thrusters [7]. Although the plume of arcjet thruster, a type of electrothermal thruster, is slightly charged, several studies had been conducted to determine its effects on the degradation of solar panel surface coating, electrostatic discharge and the communication systems of spacecraft in long term operations, as these are the key issues of spacecraft-thruster integration. In these studies electron densities in the arcjet plume are reported to be on the order of 10^{15} $\#/m^3$ and electron temperatures to be between 0.1 and 0.9 eV [8–12].

Microwave electrothermal thruster (MET) which employs a free floating plasma to heat the propellant is a type of an electrothermal thruster. In METs, the goal is to convert a microwave resonant cavity to a heating chamber of a propulsion system. In these systems the propellant is heated with a free floating plasma that is generated by microwave power, before being expelled from a conventional nozzle. Main parts of a MET are resonant cavity, microwave generator and nozzle plate. A separation plate made of dielectric material is placed between the antenna zone and the plasma zone to prevent antenna from erosion due to contact with the plasma discharge [13–15]. In MET systems, electromagnetic energy is transmitted into the cavity and a standing wave is formed. The free electrons in the propellant gas are coupled to the electric field of the wave and they are energized [16, 17]. New electrons are produced after successive collisions between electrons and the neutral atoms. The plasma is generated in the plasma zone of the cavity. The discharge is maintained as long as the production rate of electrons compensates the loss of electrons due to attachment and recombination processes, or losses to the walls. Once started it acts as a resistive load and absorbs microwave energy. The microwave energy is transferred to the gas by elastic collisions and the propellant temperature increases to about 2000 K [18–23].

The location of the plasma is important for minimizing the heat transfer before expelling the gas out of the cavity. To decrease the losses to a minimum, gas must be exhausted as soon as heated. In order to achieve this, plasma must be formed near the nozzle inlet by adjusting the electric field distribution. For cylindrical cavities the best field distribution can be provided by using TM_{011} mode for which the maximum electric field intensity occurs at the very end of the cavity where the nozzle inlet is located [24, 25].

MET thrusters are still in the levels of early development. METs operating at power levels from a few Watts to 50 kW, and at frequencies from 0.915 to 17.8 GHz have been designed and tested. Performance of propellants such as He, N_2, N_2O and simulated hydrazine have been measured in these studies [22]. Moreover, the plasma density inside the cavity is evaluated using different spectral emission measurements for different gases [26]. Inside the cavity, the electron temperatures are computed to be about 1 eV and the plasma density is evaluated to be about 10^{19}–10^{20} $\#/m^3$ at atmospheric chamber pressures [27]. To date, there have also been several studies conducted to determine the performance parameters such as thrust, specific impulse and power deposition from microwave supply to the plasma [27–29]. On the other hand, there have been almost no efforts to understand the plume characteristics of the MET thrusters. Studies conducted only present the measurements of the velocity of exhaust gas using nonintrusive methods [30, 31].

Describing the exhaust characteristics of MET thrusters is important for a fundamental understanding of potential effects that the plume may have on the spacecraft surfaces and operations. In this study, in order to determine the MET plume characteristics, two sets of experiments are conducted. In the first, plume plasma density and electron temperature measurements are conducted using a single Langmuir probe. The Langmuir probe data is taken at 10 mm from the nozzle exit plane. The analyses of the measured probe data are performed according the thin sheet theory [32]. In the second set of experiments, the angular distribution of the plume ion flux density is measured using a Faraday probe. Plasma ion current density is measured at 100 mm from the nozzle exit plane as the probe is swept from $-60°$ to $+60°$.

2. BUSTLab MET

The BUSTLab MET thruster, seen in figure 1, was designed to operate at 2.45 GHz microwave frequency. For this prototype thruster, the resonant cavity, made of stainless steel, has an inner diameter of 100 mm and a length of 175 mm corresponding to TM_{011} mode of operation at 2.45 GHz frequency. The thruster uses a 31 mm long ($\lambda/4$) copper antenna as the coupling probe. The antenna zone and the plasma zone of the thruster are separated by a 10 mm thick quartz plate. On the exhaust side of the resonant cavity, a converging-diverging nozzle with a throat diameter of 2.32 mm and an expansion ratio of 88 is placed.

3. Langmuir probe measurements

In METs, plasma, which is created with an antenna creating electrical and magnetic fields inside the chamber, heats the propellant gas. The propellant is then expelled through a nozzle to atmosphere or vacuum [22]. Since the thruster expels mostly neutral propellant gas, it is expected that the plasma density at the exit of the thruster nozzle would be low.

3.1. Bell jar experimental setup

For the operation of the MET, the microwave power is delivered to the thruster using a microwave transmission system that has an isolator, a coupler with two stub tuner system, a waveguide to coaxial cable adapter and a coaxial cable with 7/16 connectors on both ends. As the microwave generator, a Richardson power supply, SM745, and a 1.2 kW Richardson magnetron head, MH1.2W-S, are used, and for measuring the delivered and reflected power levels two Booton 52 012 power sensors are utilized. For the Langmuir probe measurements of the MET, the tests are conducted using a specially designed cylindrical Pyrex vacuum chamber that is 40 cm in diameter and 60 cm in length, as shown in figure 2. The MET thruster is attached to the ISO 320 K flange at the bottom side of the cylindrical vacuum chamber. This Pyrex chamber is pumped with a rotary vane pump with roots blower. The pressure inside the Pyrex vacuum chamber, hence the back-pressure of the thruster, is measured by a convection gauge attached to a QF25 port of the Pyrex vacuum chamber.

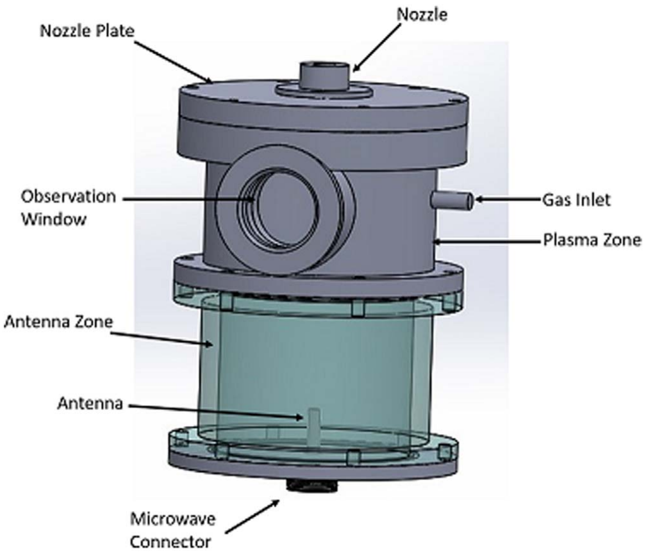

Figure 1. Schematic of BUSTLab MET thruster.

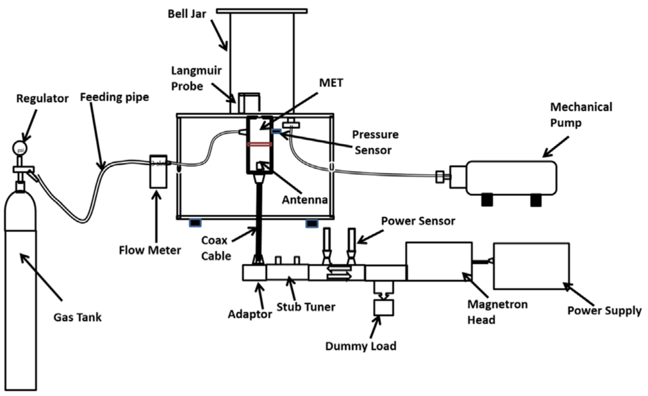

Figure 2. Schematic of Bell jar experimental setup.

The propellant gas was fed to the MET thruster from a 1/4 inch port on the side wall of the plasma zone side of the resonant cavity. In order to measure the pressure of the plasma zone side of the cavity, a Keller 33X pressure sensor is used.

3.2. Experimental measurements

For the current study, the BUSTLab MET was operated with delivered microwave power levels of up to 550 W. For the measurements two different single Langmuir probes were used. The first probe is a flat probe that has a 1 mm diameter molybdenum rod inside a single hole alumina tube of 3.2 mm outer diameter. The second Langmuir probe is a cylindrical probe with a molybdenum wire of 0.55 mm in thickness and 2 mm in length. A Keithley 2410 sourcemeter is used for biasing the probe electrode and collecting current. For the measurements, the probe tip is placed in the plume of the thruster at 10 mm away from the nozzle exit plane as shown in figure 3.

The effect of the microwave on the measurements is not taken into account because it is assumed that no microwave leakage from the resonant cavity would happen. Also, the

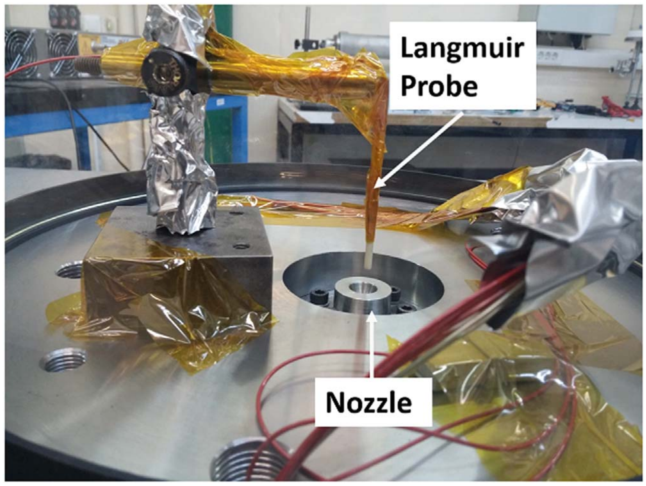

Figure 3. View of the at Langmuir probe in front of the nozzle before experiments.

diameter of the nozzle orifice is small enough to prevent microwave leakage. The tests of the BUSTLab MET thrusters were carried out with helium, argon and nitrogen gases as the propellant for different volume flow rates and at different power levels for each gas.

3.3. Results and discussions

For helium and argon gases, the plume was relatively faint and had a very short, on the order of 5–10 cm visible part as shown in figure 4(a). However, for similar microwave power levels, when the thruster was operated with nitrogen gas, the plume was very luminous and filled the entire length of the 60 cm long Pyrex vacuum chamber. The reason for this significant difference is not yet understood. But, nitrogen is a molecular gas, and helium and argon are monatomic gases. Molecular nitrogen typically has a reddish purple plasma. Looking at the National Institute of Standards and Technology Atomic Spectra Database, one can see that atomic nitrogen has strong lines in the 575–583 nm range, hence possible explanation for the bright yellow color observed in the experiments with nitrogen gas. Therefore dissociation of nitrogen and the presence of atomic nitrogen in the plume plasma might be the cause of the very luminous, bright yellow plume as seen in figure 4(b).

In the measurements with helium gas, the flat Langmuir probe is used. For 500 W of microwave power delivered, helium flow rates varied from 15 to 30 standard liters per minute (SLM), where the minimum reflections are measured by microwave power sensors. At these flow rates more than 95% of microwave power is deposited into the working gas via plasma. Three sets of measurements are done for each flow rates. The measured electron temperature and plasma density values are shown in figure 5. The measured electron temperatures vary from 0.19 to 0.7 eV and densities are on the order of 10^{18} $\#/m^3$.

Second set of measurements are conducted with argon gas; the cylindrical Langmuir probe is used (as seen in figure 4(a)). For 200 W of microwave power delivered, MET

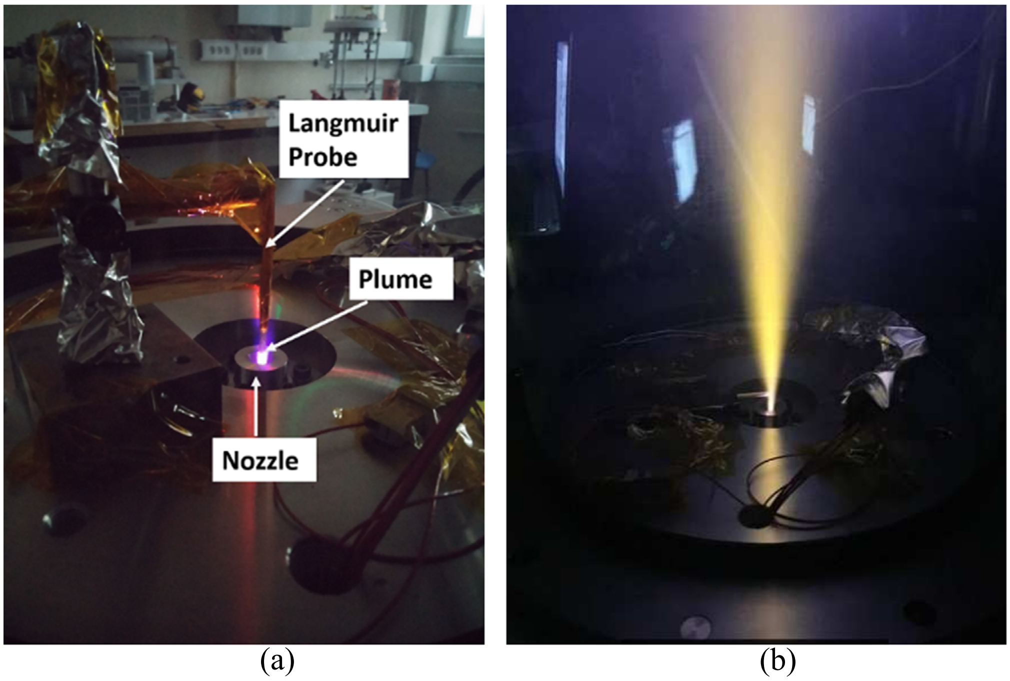

Figure 4. (a) View of the nozzle region of BUSTLab MET in operation with helium propellant, (b) view of nozzle region of the BUSTLab MET in operation with nitrogen propellant.

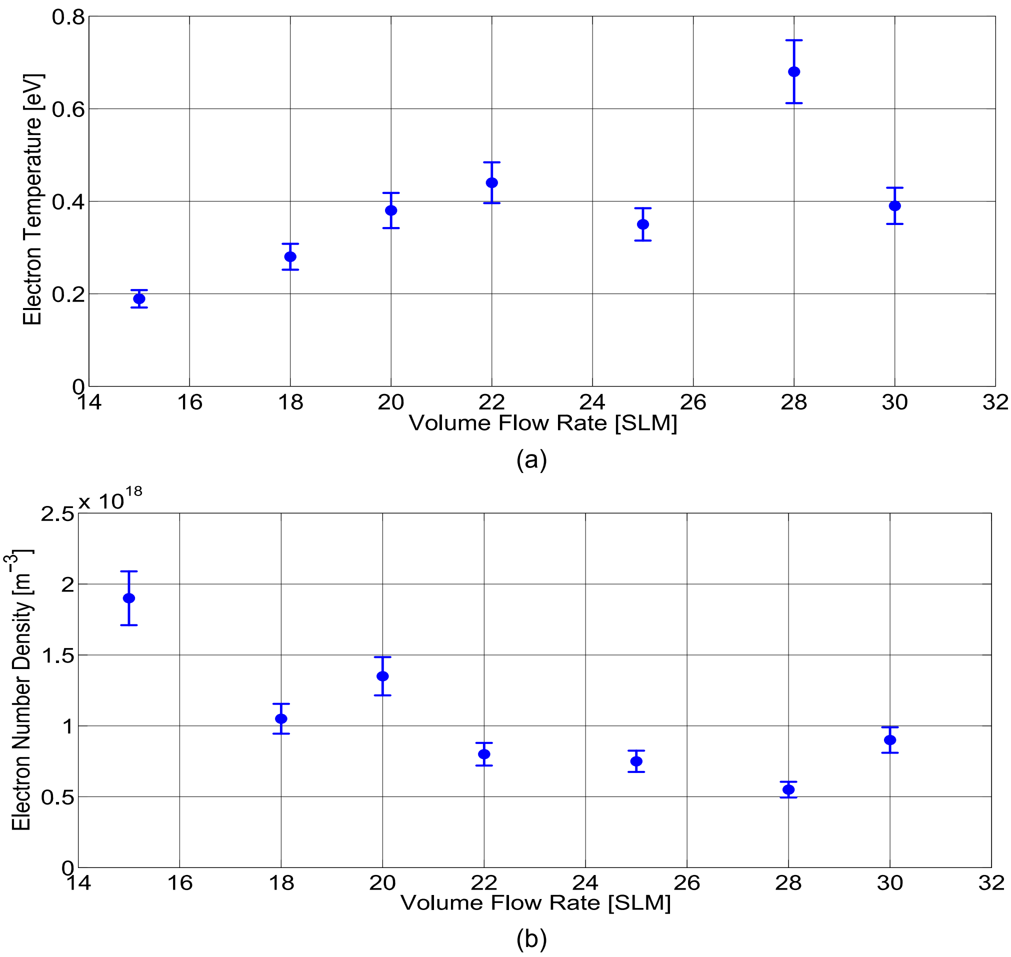

Figure 5. (a) Electron temperature, (b) plasma density of the plume for the thruster operating with helium propellant at 500 W of power.

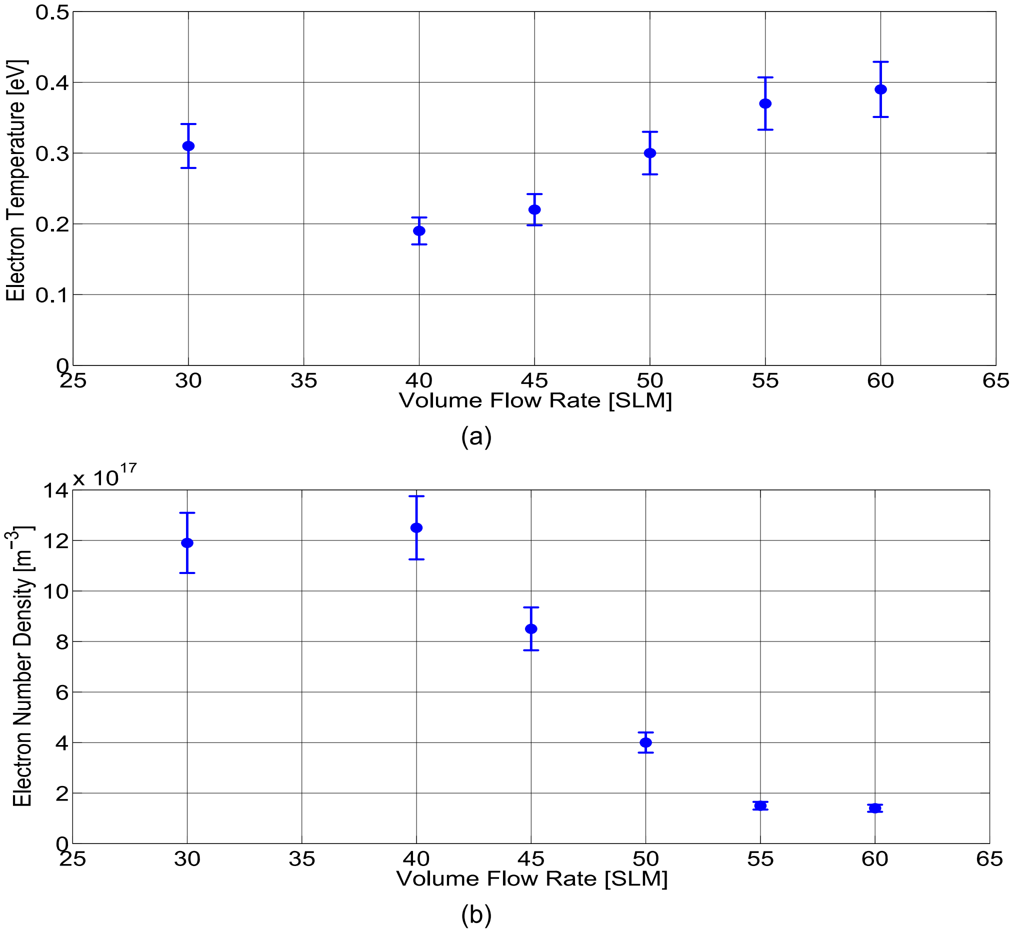

Figure 6. (a) Electron temperature, (b) plasma density of the plume for the thruster operating with argon propellant at 200 W of power.

system reached best power deposition values at argon flow rates between 30 and 60 SLM. The measured electron temperature and plasma density values are shown in figure 6. Electron temperatures are about 0.3 eV and the plasma densities decrease from 10^{18} #/m^3 levels as the gas flow rate is increased.

After these two mono-atomic gases, the third set of measurements are conducted using nitrogen gas; the cylindrical Langmuir probe is used. The first set of measurements for nitrogen gas is done for 300 W of microwave power delivered as the flow rates are varied from 3.5 to 7 SLM. Plasma in the resonant cavity cannot be sustained at higher flow rates as in experiments with monatomic gases. When molecular gases are used, vibrational and rotational modes of excitations result in higher fractional electron energy losses per collision. Therefore discharge of monatomic gases can be maintained at higher cavity pressures, hence at higher flow rates [13]. The measured electron temperature and plasma density values are shown in figure 7. The electron temperatures are measured to be about 0.3 eV and plasma densities are in 10^{17} #/m^3 levels.

To understand the effect of the delivered power, one more set of measurements are done with nitrogen gas at 550 W of microwave power delivered. Increasing the power level increases the volume flow rate level where the maximum power deposition is reached. At this power level, the optimum flow rates are between 7 and 15 SLM. When compared with the measurements at 300 W level, electron temperatures and plasma densities increase as shown in figure 8. For volume flow rates above 13 SLM, the plume plasma temperatures increase to levels above 1 eV. It is observed that as the volume flow rate is increased the plasma density decreases. Since MET thruster needs high flow rates to operate, it is observed that the electron temperatures are well below 1 eV for most of the volume flow rates and power levels where the data was taken. According to the previous studies from the literature [33, 34], the increase in the supplied power results in a decrease in electron temperature. In the current measurements, there has been a limited set of data where different levels of power is delivered for a given propellant flow rate. Therefore, the current data is inconclusive regarding the effect of power delivered on the near exit plane plume plasma electron temperature. The Langmuir probe measurement results show that the exit plane plume plasma densities are in the 10^{17}–10^{18} #/m^3 range.

4. Faraday probe measurements

Faraday probe measurements are performed to evaluate the plume ion charge flux for understanding the possible effects of energetic ions on spacecraft. Although innumerous

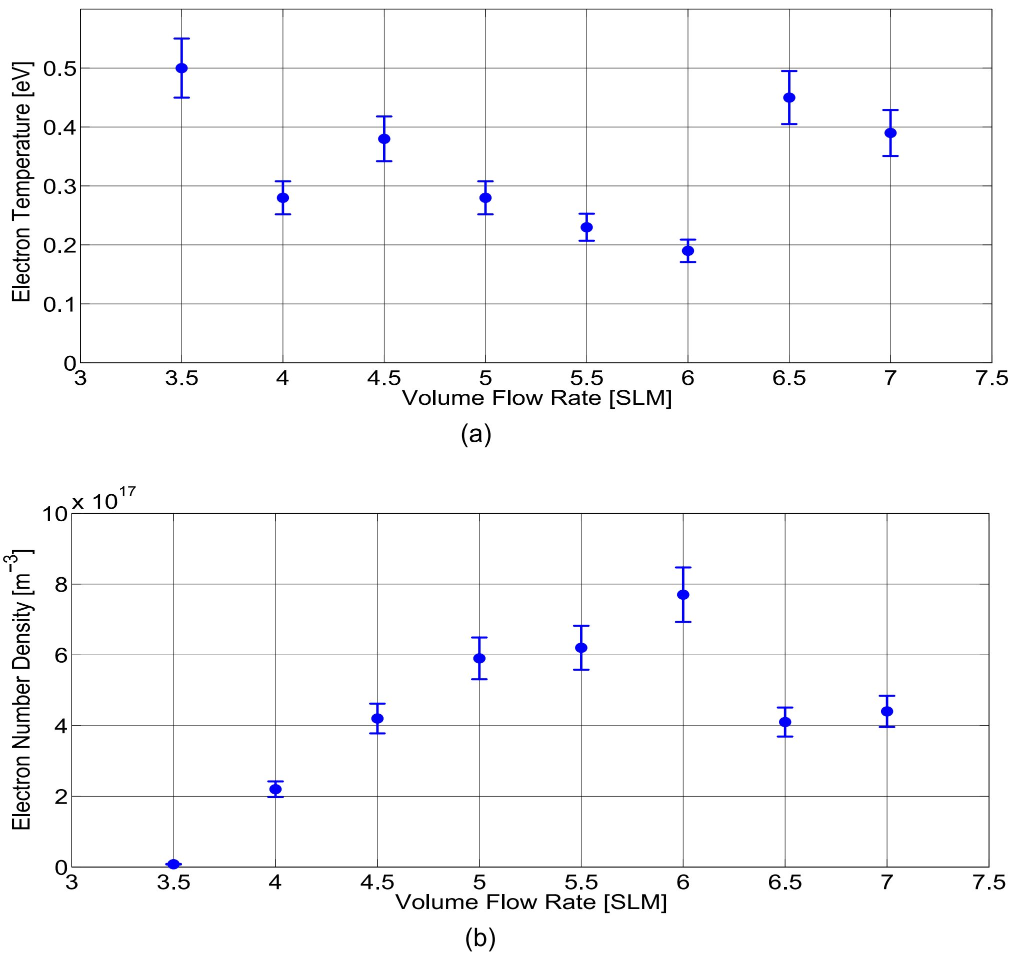

Figure 7. (a) Electron temperature, (b) plasma density of the plume for the thruster operating with nitrogen propellant at 300 W of power.

measurements of plume angular ion current density distribution are conducted on Hall effect thrusters and ion engines, there is inadequate data for other type of thrusters like arcjets, pulsed plasma thrusters, etc [35].

4.1. Faraday probe and experimental apparatus

Different types of Faraday probes have commonly been used to measure the ion charge flux in thruster plumes [6, 35, 36]. In this study an in-house-built Faraday probe with guard ring is used. Detailed methods about probe construction, utilization and selection in addition to data analysis techniques can be found in references [6, 35–37].

A Faraday probe with guard ring is a kind of planar probe encapsulated in a conducting cylinder. Guard ring is biased at the same potential as the collector which prevents the ion collection from the sides of the collector and ensures that the collector front surface is the only collection area. In the built Faraday probe, stainless steel is used as the guard ring and collector material. Guard ring consists of a hollow cylinder and back cap screwed together. The outer diameter of the guard ring is 16 mm and at front plane the inner diameter is 10 mm. Collector has a flat surface with a diameter of 9 mm. Therefore, 0.5 mm gap is provided between the collector and guard ring with this design. A macor ring is used for electrical isolation between the guard ring and the collector as shown in the exploded view in figure 9. A 1/16 inch stainless steel rod that is spot-welded to the collector is employed as the central wire to bias the collector. This central conductor rod is shielded with an alumina tube. In order to bias the guard ring, a stainless steel wire is spot-welded to the bottom cap of the guard ring.

For the Faraday probe experiments, the MET is operated inside the BUSTLab vacuum chamber, which is 1.5 m in diameter and 2.7 m in length, rather than the bell-jar system for the proper placement of the translation stage for the movement of the Faraday probe.

For this setup, the same gas feeding and microwave transmission lines as the bell-jar setup are used. The microwave cable is connected to the chamber using a KF50 flange with a 7/16 DIN feedthrough. SmarAct translation stage is used for the angular sweep of the probe at a set distance from the thruster exit plane. A Keithley 2410 sourcemeter is used to bias the collector and measure the collected ion current. The guard ring is biased using an Ametek DCS 60-18E power supply as seen in figure 10.

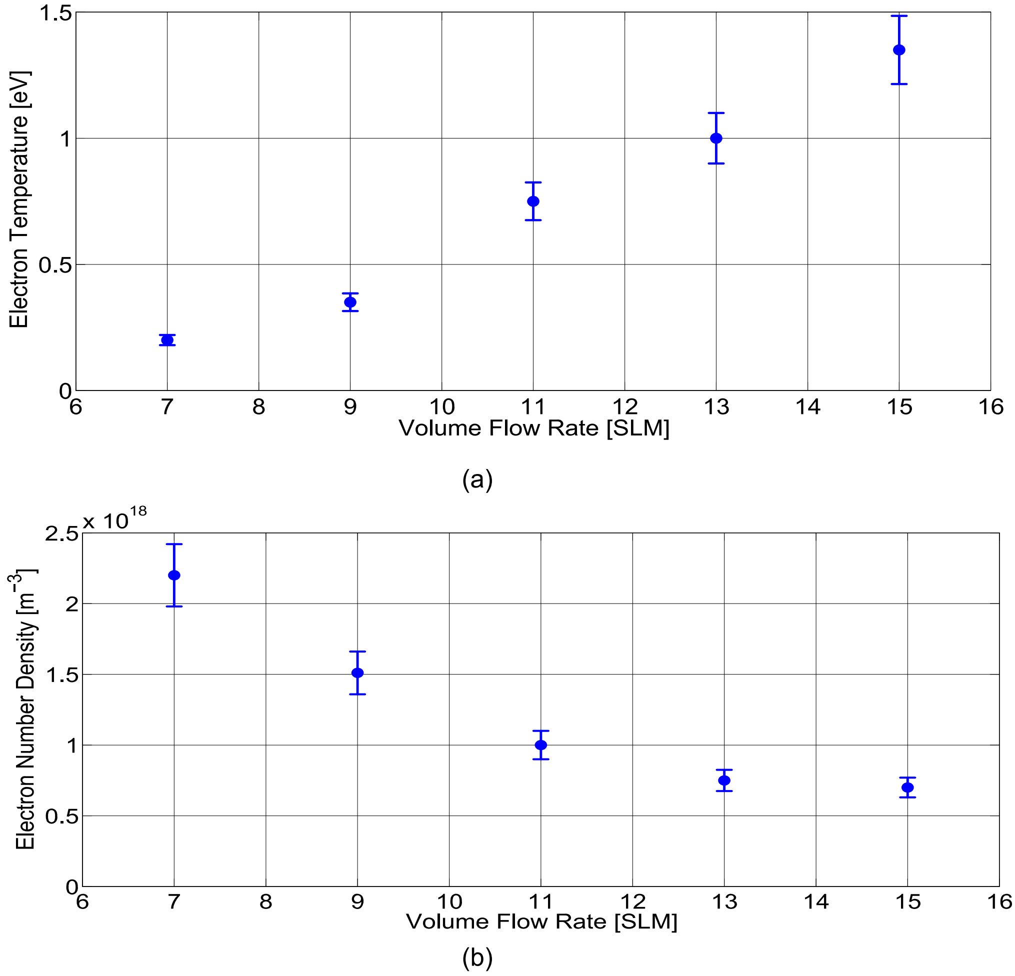

Figure 8. (a) Electron temperature, (b) plasma density of the plume for the thruster operating with nitrogen propellant at 550 W of power.

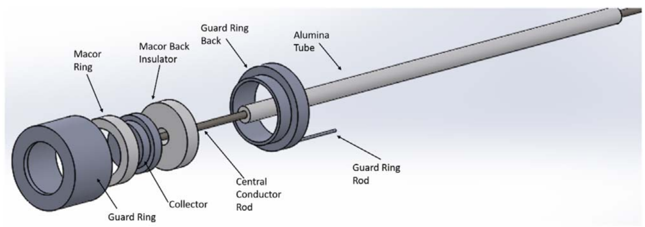

Figure 9. Exploded view of Faraday probe.

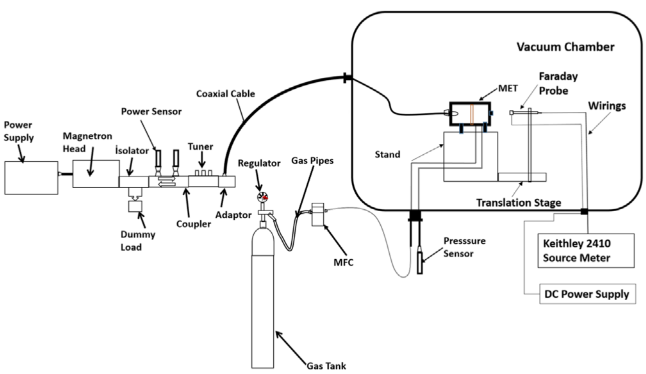

Figure 10. Schematic of vacuum chamber experimental setup.

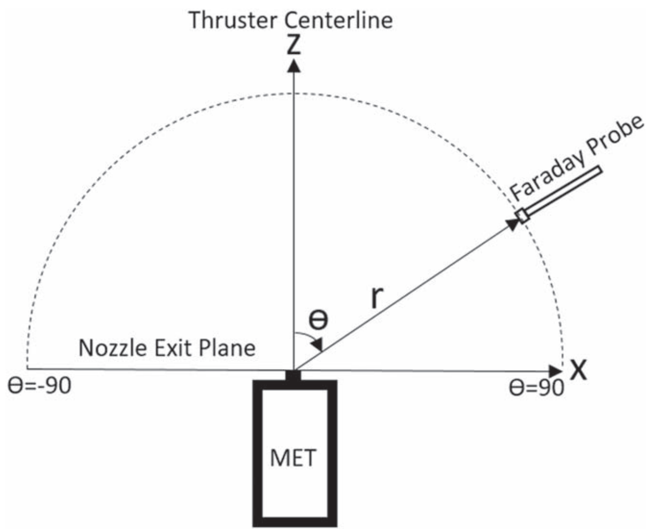

Figure 11. Schematic of coordinate system for Faraday probe measurements.

4.2. Experimental measurements and results

Experiments are conducted for argon and nitrogen gases as the propellant. Hemispherical coordinate system as indicated in figure 11 is used for the plume measurements. Faraday

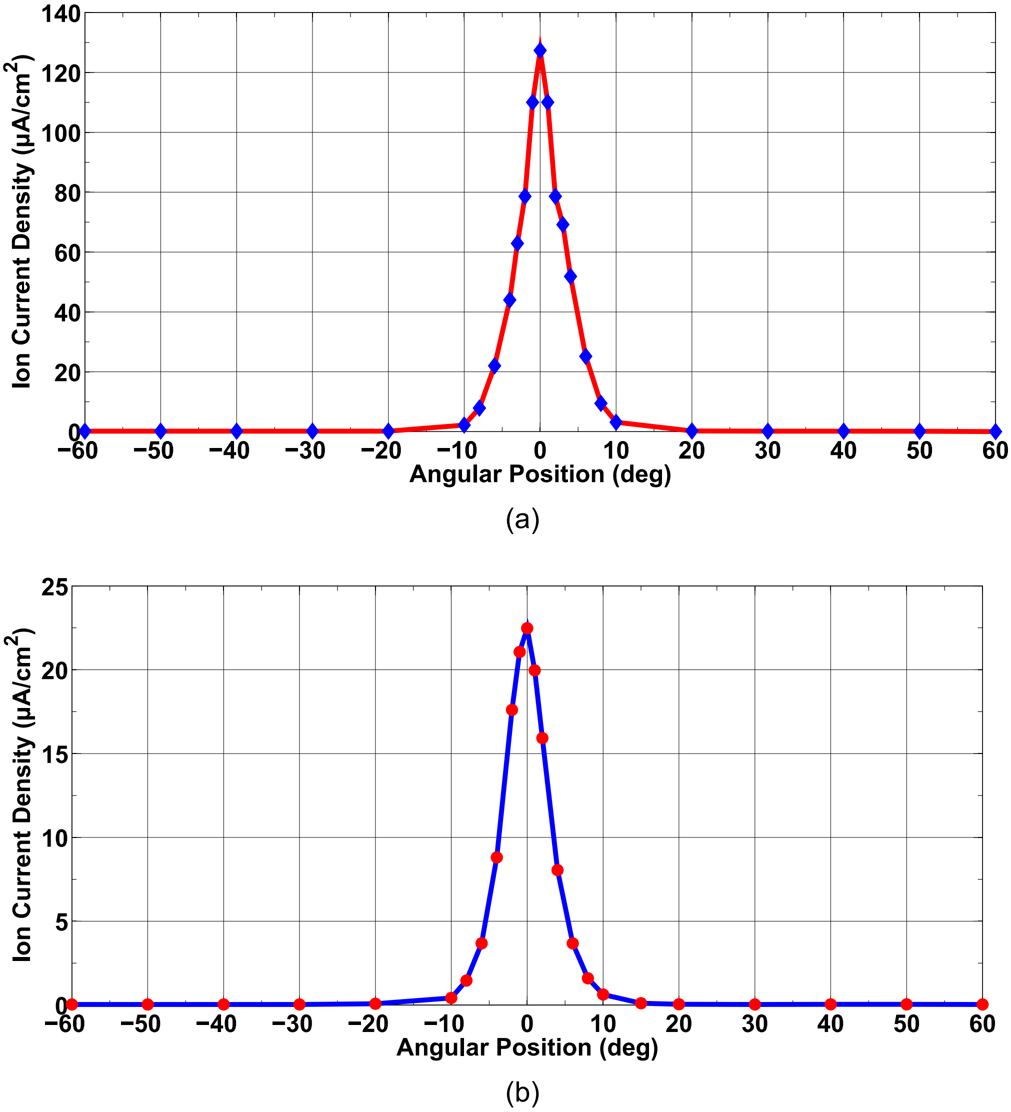

Figure 12. Ion current density as a function of angular position for MET (a) operating with argon at 300 W, (b) operating with nitrogen at 500 W.

probe is centered on the MET z axis at $r = 100$ mm and ion current density is scanned between $\theta = \pm 60^{\circ}$ and at a volume flow rate of 40 SLM. At this operation condition, the gas pressure inside the MET cavity is measured to be 896 Torr where the background pressure is 4.33 Torr. 98% of microwave power is deposited to the plasma for this operation condition. In order to determine the proper bias voltage level, before starting the Faraday probe tests, the bias voltage was swept between −15 and −30 V when the probe is positioned at an angle of 5° with respect to the plume exit centerline. For the tests with argon propellant, MET system is operated at 300 W microwave power level. Based on the changes in the value of measured current, it was decided to bias the probe at −20 V level. For the Faraday probe, both the collector and the guard ring are biased to −20 V. It was observed that the ion current levels are very low outside the $\theta = 10$ degrees region as shown in figure 12(a).

The ion current flux reaches its peak value at the center of thruster plume as expected. The maximum value of the ion current density is about 130 μA cm^{-2} as shown in figure 12(a). The measured ion current density values are more than 50 times less when compared with a standard Hall effect thruster working at 1350 W despite much higher flow rates [6, 35].

Second set of measurements are conducted with nitrogen gas as the propellant. MET system is operated at 500 W microwave power level and at a volume flow rate of 6 SLM. For this operation condition, the gas pressure inside the MET cavity is measured to be 176 Torr where the background pressure was 9×10^{-1} Torr. 98% of the microwave power is deposited to the plasma. Collector and the guard ring are biased to −20 V. Similar to the measurements with argon propellant, it was observed that the ion current density is very low beyond $\theta = 10^{\circ}$ as shown in figure 12(b). The maximum ion current density is measured to be about 25 μA cm^{-2} at the center plane as shown in figure 12(b).

For the argon test, the total beam current and the half angle plume divergence are evaluated to be 14.4 mA and

9.51° respectively. For the nitrogen tests, the total beam current and the half angle plume divergence values are 2.5 mA and 9.76° respectively. These divergence angle values are lower compared to Hall effect thrusters [6, 35, 36].

5. Conclusion

In order to determine the plume characteristics, measurements of the BUSTLab MET thruster plume plasma are conducted using single Langmuir probes and a Faraday probe. During the experiments, it is observed that the plume characteristics of the system vary according to the propellant gas used, the volume flow rate and the delivered power. For helium and argon gases, the plume was relatively faint and had a very short, on the order of 5–10 cm visible part. However, for similar microwave power levels, when the thruster was operated with nitrogen gas, the plume was very luminous and filled the entire length of the 60 cm long Pyrex vacuum chamber.

The measured electron temperatures are generally lower than 1 eV except only for nitrogen gas at 550 W delivered power level. These temperature levels are very similar to values obtained in the plume diagnostics research of arcjets. On the other hand, the plume plasma densities of MET thruster are higher than arcjet plume densities.

The measurements show that MET thruster plume effects on spacecraft will likely be similar to those of the arcjet plume. Based on the Faraday probe measurements, it is observed that the ion flux density is significantly less than that of a typical medium power level Hall effect thruster. Also, the plume divergence angle is much narrower than that of a typical Hall effect thruster.

In conclusion, it is observed that the measured plume ion flux levels are very low for the high volume flow rates used for the operation of this thruster. As expected, the plume of the thruster is mostly neutral. MET plume characteristics is very similar to that of arcjet thruster. So, experimental results show that no severe deterioration of solar panels and surface coating is expected for short duration operations. On the other hand, for longer operation durations, these effects should be considered at thruster integration phase.

Acknowledgments

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