Preliminary Thrust Measurement Results of the BUSTLab Microwave Electrothermal Thruster

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In a microwave electrothermal thruster (MET), microwave energy is used to heat the propellant gas using a free floating plasma generated inside a resonant cavity. The heated gas is then expanded through a converging-diverging nozzle and thrust is produced. Microwave electrothermal thrusters are able to produce a few mN to a few hundred mN levels depending on the size and the power levels of the thruster. A prototype microwave electrothermal thruster is designed, manufactured and tested at Bogazici University Space Technologies Laboratory (BUSTLab). This thruster operates at 2.45 GHz frequency. In this paper we present the preliminary thrust measurements of the BUSTLab MET system running on Argon gas for a power level of 200 W.

I. Introduction

Microwave Electrothermal Thruster (MET) is a type of in-space propulsion system where a free floating plasma is used to heat the propellant gas. The MET concept is proposed to eliminate some of the handicaps of resistojets and arcjets which produce similar levels of thrust. For resistojet systems, the maximum thermal endurance level of the resistance element is a limiting factor. On the other hand the cathode erosion problem is a life time limiting factor for arcjets. With the MET concept it is considered that these drawbacks can be removed employing a free floating plasma rather than a heater element or a cathode. In typical chemical thruster systems a combustion chamber is used for heating the gas, whereas in MET systems a resonant cavity is used as the heating chamber. A free floating plasma is formed inside the resonant cavity, and this free floating plasma acts as a heating element. In MET systems:

- First, a standing wave is formed when the microwave is transmitted into the cavity and the free electrons in the propellant gas are accelerated by the electric field. The thermalized electrons collide with the neutrals and new free electrons are produced. After successive collisions plasma is formed and it absorbs the microwave energy due to its resistivity.
- Then the gas heats when it flows around a hot plasma.
- The thermal energy of the gas is transferred into the kinetic energy while being expelled from a conventional nozzle[1]

To date METs working in frequencies of 0.915 MHz to 17.8 GHz have been designed and tested.[2–5] Increasing the operational frequency results in a reduction in size of the thruster cavity because of the decreased wavelength. Power levels of smaller METs are also lower than the larger ones. In thrusters developed to date, the applied powers have been changed from a few Watts to 50 kW levels.[6,7] Also various kinds of propellants like He, N_2, N_2O and water have been tested.[2,8] METs have not been used on any space platform yet. For MET systems specific impulse levels of upto 800 s are achieved in experiments.[2]

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A prototype microwave electrothermal thruster is developed at BUSTLab.[9–11] The BUSTLab MET system mainly consists of a resonant cavity which is designed to operate at TM_{011} mode for 2.45 GHz frequency, a nozzle plate with a modular nozzle, an microwave applicator that transmits microwave powers up to 1000 W level as shown in Figure 1. The resonant cavity chamber is made of stainless steel. A separation plate made of quartz, with a thickness of 10 mm, is placed between the antenna zone and the plasma zone to prevent antenna from damage due to contact with the plasma discharge. An observation window is opened at the side of cavity to observe the plasma formation.[10] A copper antenna of 31 mm in length ($\lambda/4$) is used as the coupling probe. The converging-diverging nozzle is conical in shape with an exit to throat area ratio of 50.

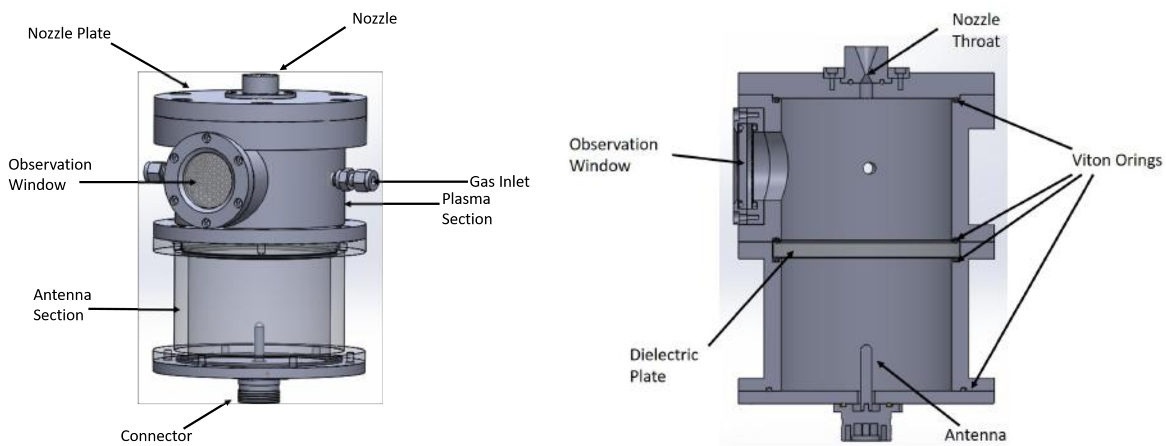

Figure 1. BUSTLab MET

This study presents the results of the thrust measurements of the BUSTLab MET using a thrust stand which is recently built at BUSTLab. The comparison of the experimental data with the predicted thrust levels based on the chamber pressure and plume exit plane temperature measurements are also made.

II. Experimental Setup

The thrust measurements of the BUSTLab MET prototype are conducted inside the BUSTLab vacuum chamber, which is 1.5 m in diameter and 2.7 m in length.[12]

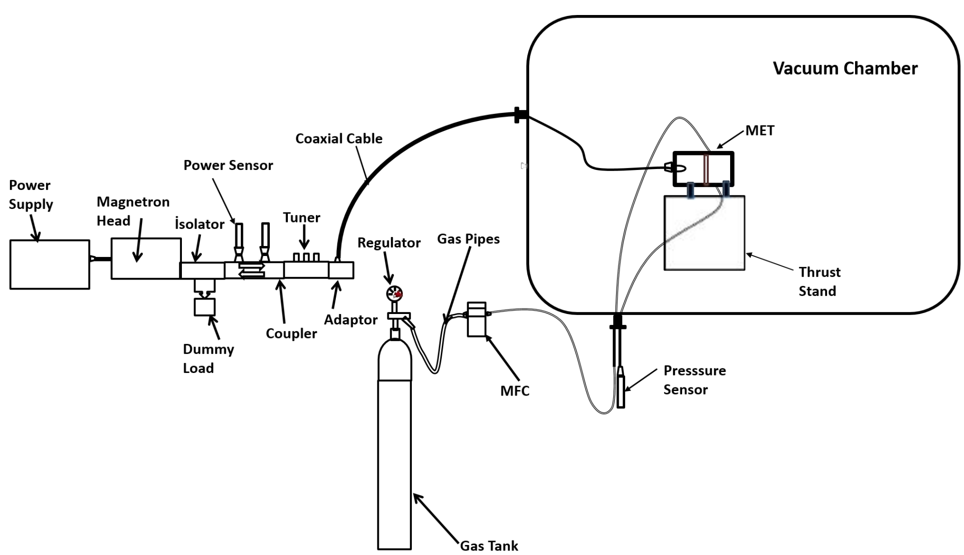

Figure 2. Schematic view of the experimental setup

The experimental set up consists of microwave electrothermal thruster, microwave generation and transmission system, gas feeding system, thrust stand and the vacuum chamber as shown in Figure 2. For the generation of the microwave power a Richardson $SM745$ power supply and a 1.2 kW Richardson $MH1.2W-S$ magnetron head are used. In order to protect microwave generation system a Muegge $MW1003A-210EC$ isolator is added to the transmission line. This isolator can protect the system up to 3 kW of reflected power levels. In order to increase the system efficiency by minimizing the reflected power when maximizing the coupling power an Astex $D13604$ two stub tuner is used. To measure the amount of the incident and reflected power two Booton 52012 sensors are used. The sensors are attached to the nodes on the coupling systems. To achieve system flexibility while integrating the thruster system to the vacuum system it is more appropriate to use a coax cable rather than a rigid waveguide system. Thus, a transition system is needed to transfer energy from the waveguide component to a coax cable. For transition from a WR340 waveguide to a coax cable a Muegge MW5002A-260YD coax transition is used. The coaxial cable is connected to the transition by a 7/16 microwave connector. Cable is passed through a QF50 vacuum feed through into the chamber. And other end of the coax cable is attached to an antenna via another 7/16 connector to the thruster. A picture of the microwave power generation and transmission system is shown in Figure 3. Gas

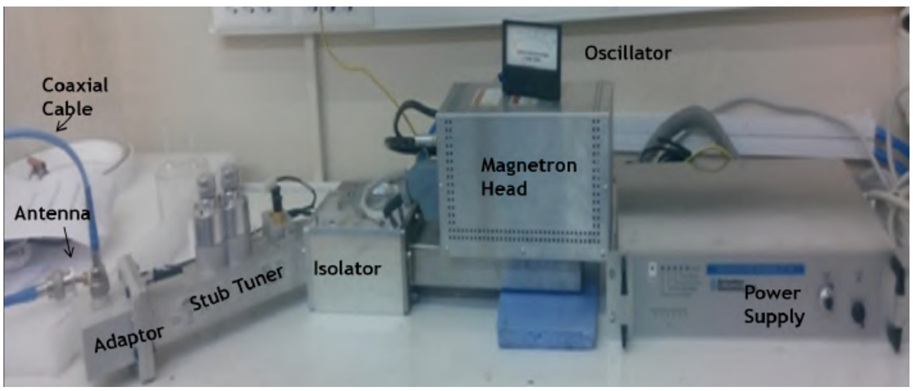

Figure 3. Picture of microwave power generation system.

feeding system consists of a mass flow controller, piping and a gas tank. MKS mass flow controller is used to adjust the mass flow in to the thrust chamber. Mass flow rate to the thruster is regulated between 6 to 30 standart liter per minute (slm).

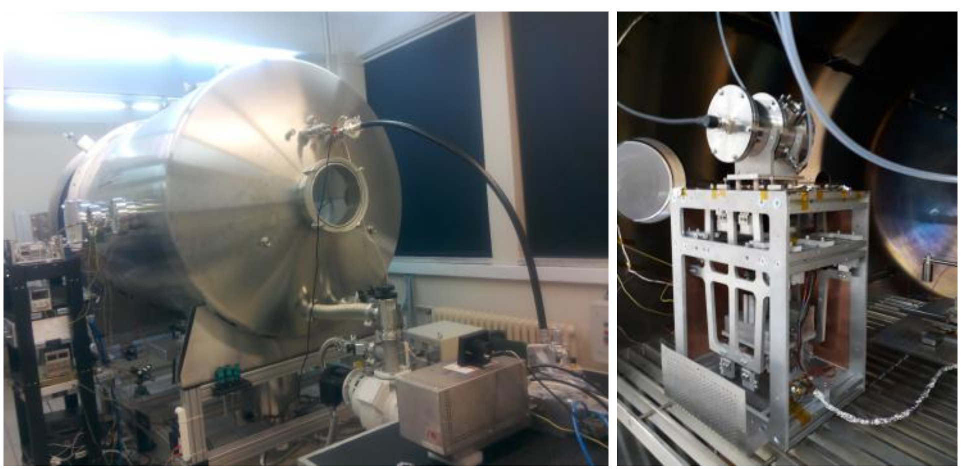

Figure 4. a) BUSTLab vacuum chamber b) MET on thrust stand before tests,

For the thrust tests the MET prototype is placed on a stand as shown in Figure 4 and the propellant gas is fed through 1/4" stainless tubes and swagelok connectors attached to the near wall of the vacuum chamber. A picture of the thruster operating inside the chamber is seen in Figure 5. To measure the thrust chamber inner pressure a Keller 33x pressure sensor is used. The pressure sensor is also attached to the swagelok pipes, one end of which is connected to the MET wall, outside the chamber.

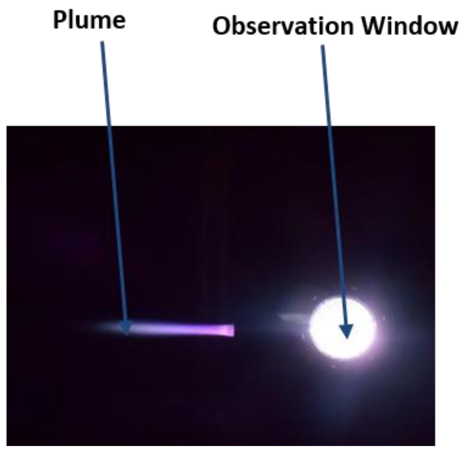

Figure 5. Plasma plume of MET operating inside the BUSTLab vacuum chamber

III. Thrust Stand

Thrust measurements are conducted with an inverted pendulum type thrust stand. The schematic and photo of the BUSTLab thrust stand, with BUSTLab MET on it, is shown in Figure 6. The thrust stand consists of two parallel pendulum arms and two horizontal plates, which are assembled with thin flexural steel plates. Weight of the thruster is balanced with counterweights. Thrust stand is insulated from the plasma in the vacuum chamber and microwaves with copper shields. A 3D rendering of the MET system on the thrust stand inside the vacuum chamber is shown in Figure 7.

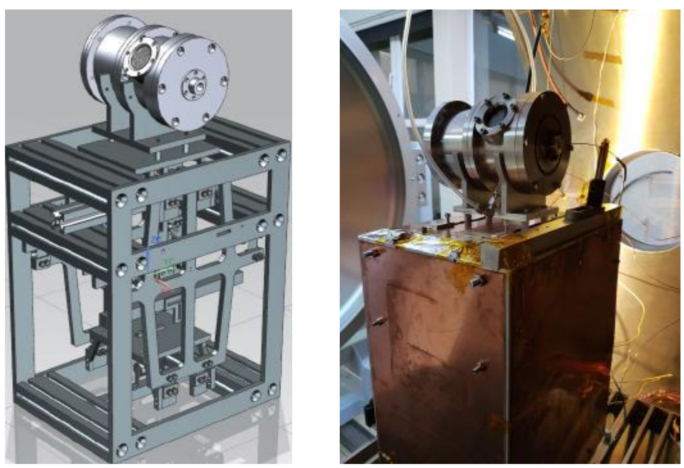

Figure 6. a) Schematic of the BUSTLab MET on the thrust stand, b) MET on thrust stand before tests

The thrust stand utilizes an LVDT linear displacement sensor, which measures the deflection of the pendulum. Calibration of the thrust stand is performed by applying a force through a pre-calibrated load cell. During the calibration process, a linear stage pushes the load cell to the upper plate of the thrust stand. Deflection of the pendulum is measured with the LVDT. Thrust forces up to 500 mN can be measured by the thrust stand with an uncertainty of around %10. Utilization of the load cell provides in situ calibration during the tests, therefore the effects of the thermal drifts can be observed. Measurement range and sensitivity of the thrust stand can be changed by adjusting the counterweight mass.

Gas pipes and microwave cable adds additional stiffness to the system, therefore counterweights are placed according to this effect. During the transient phase at the beginning of the operation, the microwave cable expands thermally, hence a thermal drift occurs within the system. This thermal drift is eliminated by moving the thrust stand with a linear stage that is placed under the thrust stand. After reaching the thermal steady state the thrust stand is shifted to a new position, so that the effect of the thermally expanded cable is eliminated. After this operation, calibration is repeated. During the tests it was observed that the thermal drifts do not affect the stiffness of the system. However during this process the zero-thrust reference point changes, which prevents the determination of absolute applied thrust. Therefore, thrust measurements are conducted by measuring the displacement with the LVDT first, and then by measuring the zero-thrust displacement point by turning off the power input and propellant gas flow to the thruster. As both measurements are conducted one after the other rapidly, thermal drift is assumed to not affect the measurement. For each measurement this process is repeated. The thrust stand responses highly linearly with respect to the applied force. Also, hysteresis between measurements is negligible.

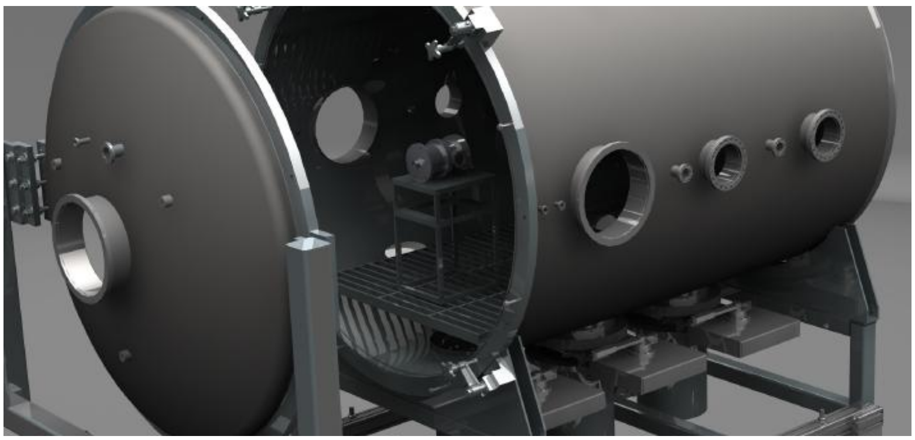

Figure 7. 3D rendering of the MET system on the thrust stand inside the vacuum chamber

IV. Thrust Measurements

The BUSTLab MET system is operated using Argon gas for mass flow rates of 178 to 356 mg/s and at a power level of 200 W. To start the experiments, vacuum chamber pressure is reduced and the resonant cavity is evacuated. Then the mass flow rate is introduced to a level at which the cavity inner pressure is at about 10 torr. This mass flow rate level is about 150 *sccm* for the current tests with Argon.

Table 1. Performance parameters for cold gas case and the case of 200 W of power delivered

	Cold Gas		Hot Gas	
mfr [mg/s]	p_c [torr]	τ [mN]	p_c [torr]	τ [mN]
178	252	85	405	170
208	300	102	480	180
237	347	120	570	220
267	393	138	634	250
297	440	150	700	260
327	486	168	760	270
356	534	187	830	280

After achieving the proper pressure condition, microwave transmission is started at the desired power level. Before the plasma is formed nearly %50 of the incident microwave energy is reflected back. With the commencing of plasma, reflections decrease significantly. First a glow discharge that fills the whole cavity forms when the pressure is low. Then the mass flow rate is set to the desired value. It is observed that with increasing mass flow rate, thus pressure, the plasma volume contracts and moves towards the nozzle inlet region on the central axis. The system is tuned using two stub tuner if the reflections are still high. Chamber pressure data for each mass flow rate is recorded.

For each gas flow rate, the thrust is measured for the case of no microwave energy deposition (cold gas case), and for the case of 200 W of microwave power delivered to the gas. The measured thrust values versus mass flow rate are shown in Figure 8 for cold gas and 200 W power delivered cases. For the given flow rates, the chamber pressure and the measured thrust levels are presented in Table 1 for the same two cases.

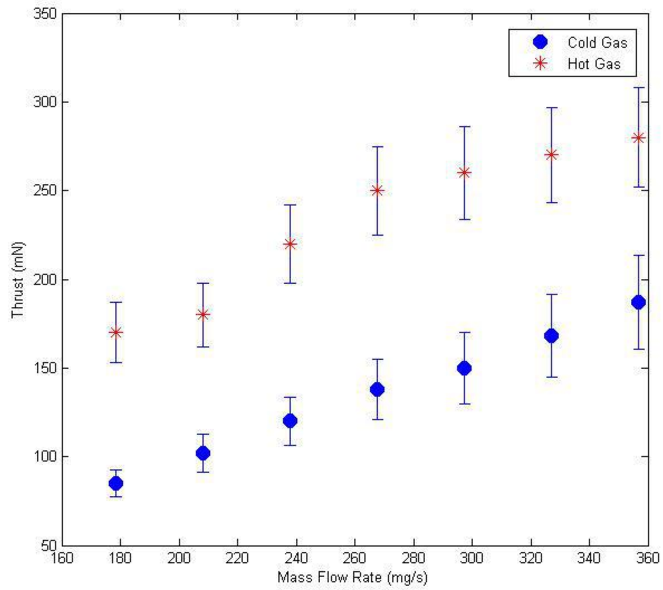

Figure 8. Thrust vs. mass flow rate for the cold gas case and for the case with 200 W of power delivered

During the thrust measurements the pressure inside the resonant cavity, the temperature at the exit plane plume region and the background pressure of the vacuum chamber were recorded. The obtained data is then used to predict the thrust level as explained in an earlier work.[11]

V. Conclusion

Preliminary thrust measurements of a prototype microwave electrothermal thruster running on Argon gas are made. The thrust measurement results for the cold gas case and the case with 200 W of microwave power delivered to the thruster are presented.

Acknowledgments

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