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Experimental Performance Analysis of the BUSTLab Microwave Electrothermal Thruster

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Numerous types of in-space propulsion systems have been developed since the 1960s for satisfying the propulsive needs of satellites and spacecraft. Electrothermal thrusters, a subclass of in-space propulsion systems, produces thrust by the thermal expansion of the propellant heated using electrical energy. Resistojets and arcjets are the kinds of electrothermal thrusters that have been used on various space platforms to date. Resistojets use heater elements, and arcjets use DC or AC arc to heat the gas. On the other hand, Microwave Electrothermal Thruster (MET) concept eliminates certain shortcomings of arcjets and resistojets by using a free floating plasma instead of a resistant heater or electric arc for the heating process. In microwave electrothermal thrusters, the goal is to convert a microwave resonant cavity to a heating chamber of a propulsion system and thus heating the propellant to be expelled using free floating microwave induced plasma. This study presents the preliminary experimental results of the prototype microwave electrothermal thruster developed at the Bogazici University Space Technologies Laboratory (BUSTLab). For the presented experiments, Helium gas is used as the propellant for the thruster operating at $2.45\ GHz$ frequency. In the experiments, chamber pressure, propellant mass flow rate and power delivered to the thruster are directly measured, and the chamber temperature, specific impulse, and the thrust values are evaluated by using appropriate equations. For the tests at a delivered power level of $500\ W$, a maximum I_{sp} level of $347\ s$ and thrust level of $266\ mN$ is evaluated.

I. Introduction

Space propulsion systems which are used for the maneuvers of spacecraft in space corresponding to their mission requirements have been researched and developed since the 1960s. Resistojets and arcjets have more commonly been studied as electrothermal systems. Although they have been used on numerous space platforms and still are considered preferable, they have some inherent limitations. Thus, the cathode erosion problem of arcjets and thermal endurance limit of the heater element in resistojets led scientists to search for alternative electrothermal propulsion systems.[1] Microwave electrothermal thruster (MET) is one of the proposed concepts put forward to as a result of such a search.[2] MET concept is expected to eliminate the handicaps of arcjets and resistojets using a free floating plasma instead of a resistant heater or electric arc produced using electrodes. By this concept, it is considered that limiting factors are reduced to only one which is the wall temperature endurance as in all thrusters. The wall temperature limits are also increased by cooling the walls with the propellant gas.

Since it was first proposed by researchers at Michigan State University, researchers at PennState University and elsewhere conduced research on prototypes that operate at different frequencies and power levels.[3,4] Although the MET concept has not yet been used on any space platform, the trends of miniaturizing satellites steer scientist into developing smaller and more compact MET systems by employing higher microwave frequencies.[4,5]

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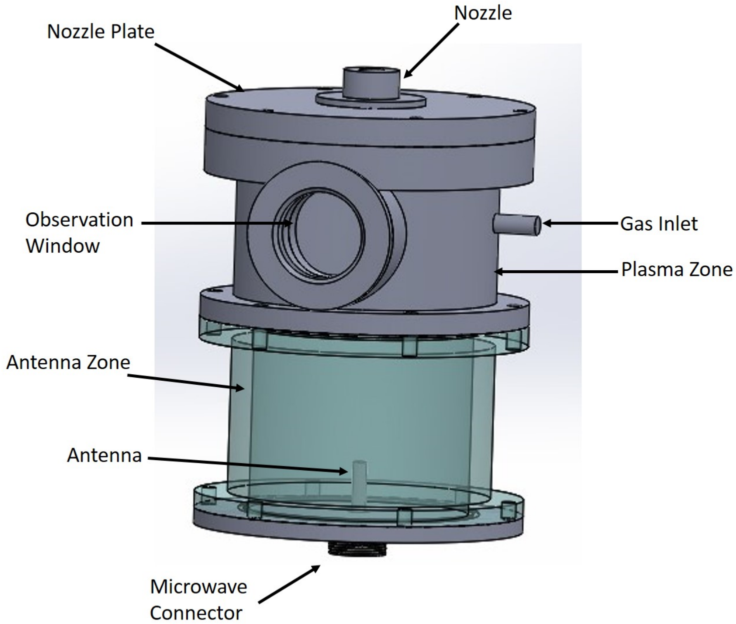

Figure 1. MET Schematic

A MET system uses a free floating plasma produced by microwave radiation. Propellant gas is heated as it swirls around this free floating plasma. Thus the plasma can be thought as a free floating heater element. To produce thrust, usually a conventional converging-diverging is used. When the gas passes through the nozzle, the thermal energy of the gas is transformed into the kinetic energy and the gas expelled at high velocities, producing thrust.

In a MET system, plasma is generated in a resonant cavity which is one of the main parts of the system. A resonant cavity is a structure in which an electromagnetic radiation create a standing wave as all surfaces are closed by conductor boundaries. When the standing wave resonates back and forth inside the cavity, free electrons in the propellant gas are coupled to the electric field of the electromagnetic wave. Coupled free electrons will be accelerated due to the Lorentz force. These energized electrons will interact with neutrals. If the electrons make elastic collisions they would only impart momentum to their collision partner, and no change will occur in their electronic structure. On the other hand, if the electrons have enough energy for an ionization process to take place, an electron will be stripped off from the neutral atom. As a result of these processes, new free electrons and ions will be generated, initiating the formation of a plasma. Plasma will absorbs some amount the energy of the microwave beam depending on its conductivity, and thus the plasma will act as a resistive load.[6] Propellant gas will be heated when interacting with the plasma.

Experimental and numerical research conducted on MET systems indicate that a microwave cavity working at TM_{011} mode is best fitted for MET systems. For the TM_{011} mode, the electric field intensity reaches its peak value at two very ends of the cavity and this formation pattern is the best for reducing the thermal losses to the walls.[7] In this mode of operation, the plasma will form at the locations where the electric field reaches its maximum, and the gas will interact with the plasma and be expelled right after it is heated, thus reducing thermal losses.[4]

Other main parts of a MET system are the nozzle and the microwave coupling probe (antenna). Nozzle is generally attached at one of the ends of the cavity on a nozzle plate as seen in Figure 1.The antenna is designed based on the operating frequency. Generally an antenna with a length of one quarter of the wavelength is used to provide maximum radiation.

A prototype MET thruster operating at 2.45 GHz is designed and developed at the Bogazici University Space Technologies Laboratory (BUSTLab). In this study, in order to understand the system efficiency and performance characteristics, experiments are conducted using Helium gas as the propellant for 400 W and 500 W delivered microwave power levels. Thrust, specific impulse and efficiency values of the BUSTLab MET thruster are evaluated using experimental data and appropriate set of equations.

II. Experimental Setup

BUSTLab MET prototype was designed for 2.45 GHz microwave frequency and power levels of upto 1200 W. A schematic of this thruster is shown in Figure 1. The microwave frequency of 2.45 GHz is chosen due to the availability and low cost of power supplies and other components for this frequency. The BUSTLab MET thruster, seen in Figure 2, consists of resonant cavity, quartz separation plate, nozzle and antenna. The resonant cavity has an inner diameter of 100 mm and a length of 175 mm. These dimensions are chosen for operating in TM_{011} mode at 2.45 GHz frequency. Thruster body is made of stainless steel. Two gas connections holes; one for feeding the gas and the other for pressure measurements are machined on two sides of the cavity.

A 31 mm long ($\lambda/4$) antenna, made of copper, is used as the coupling probe. A quartz plate of thickness of 10 mm is used to separate the antenna zone from the plasma zone. An observation window of 50 mm diameter located on the wall on the plasma zone side of the cavity allows the visual observation of the plasma conditions. A perforated metallic shield is attached on the inner side of observation window to prevent microwave leakage. A converging-diverging nozzle is placed at one side of the resonant cavity. The nozzle is designed to be modular for examining the system characteristics for various nozzle geometries and expansion ratios.

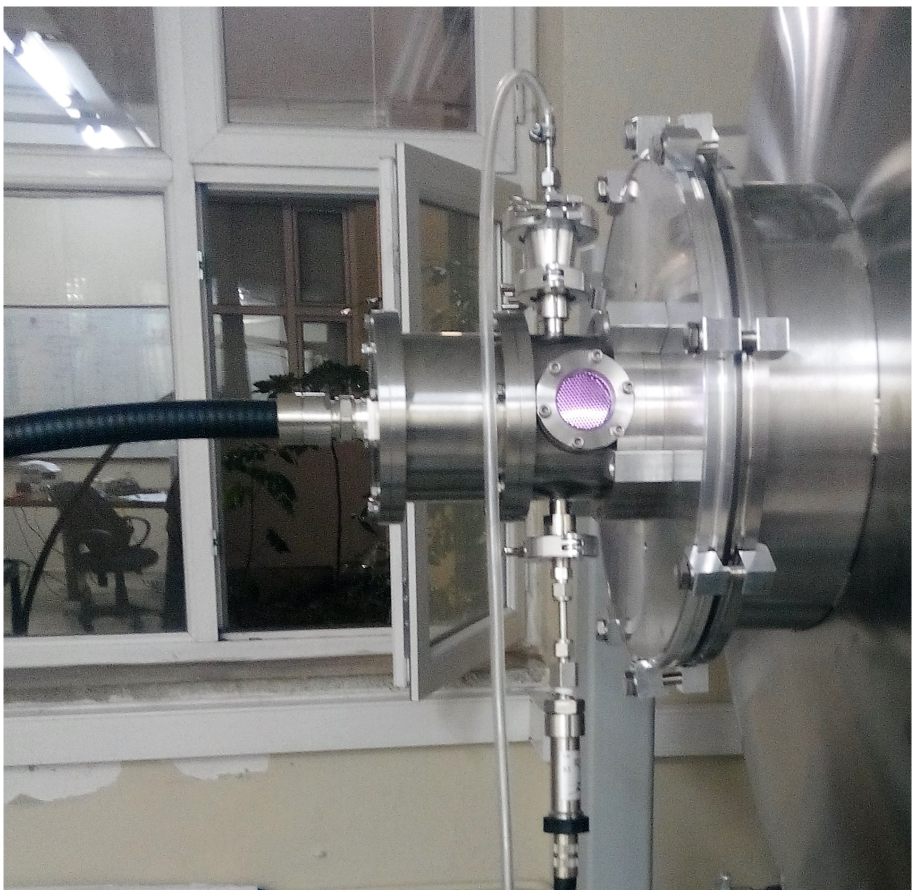

Figure 2. BUSTLab MET thruster attached to one of the ports of the BUSTLab vacuum chamber

The experimental setup consists of the microwave electrothermal thruster, a microwave generator, microwave transmission system, gas feeding system, measurement systems and vacuum system as shown in Figure 3. For the tests, the MET thruster is attached to one of the ISO-320 ports of the BUSTLab vacuum chamber with specially designed flange and clamps as shown in Figure 2. A Richardson power supply, $SM745$, and a 1.2 kW Richardson magnetron head, $MH1.2W-S$, are used as the microwave generator. Microwave generation system enables to set power level at 12 W increments. The microwave transmission system that transfers the microwave energy into the cavity is composed of an isolator, a coupler and a waveguide to coax adaptor. Muegge $MW1003A-210EC$ isolator is used to protect the magnetron head from the reflected power damage. The isolator can protect the system up to 3 kW of reflections. In a MET system reflections can be reduced and the power coupling be increased by employing a tuning system. An Astex $D13604$ two stub tuner is used to tune the system. In order to increase the systems flexibility, transition from waveguide to a coaxial cable is done by a Muegge $MW5002A-260YD$ adaptor. The coaxial cable used in the experiments is capable of transmitting 2.80 kW power at 2.45 GHz with 0.04 dB/m attenuation. The coaxial cable is connected to the transition by a 7/16 connector. The other end of the coax cable is attached to the antenna of the thruster via another 7/16 connector. To measure the delivered and reflected power levels two Booton 52012 power sensors are used.

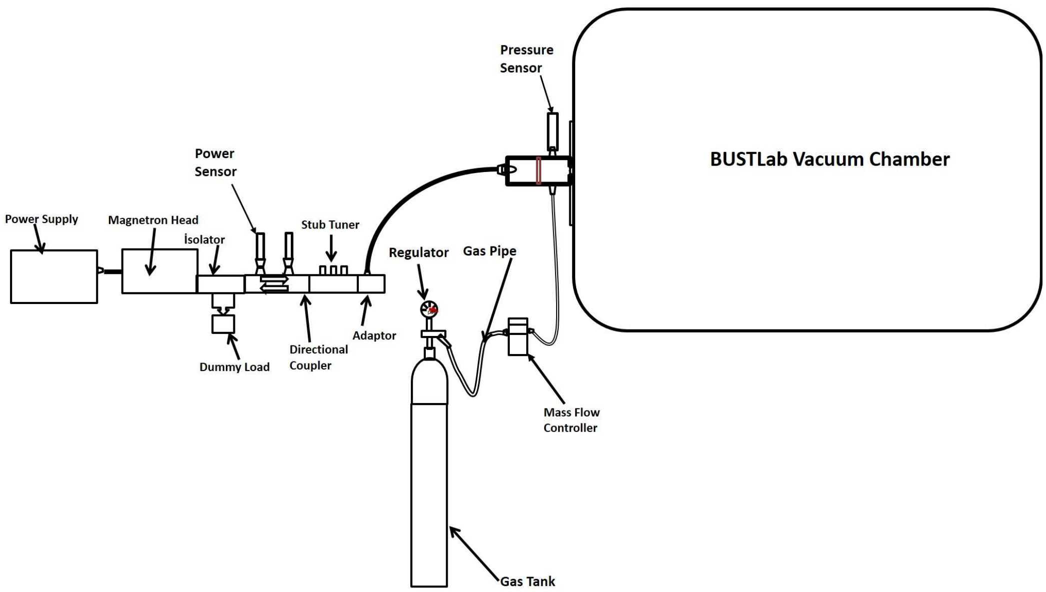

Figure 3. Experimental Setup

Gas feeding system consists of an MKS 579A mass flow controller, piping, and a gas tank. The inner pressure of the plasma zone side of the cavity is measured by a Keller 33X pressure sensor which is attached to the wall of the cavity. The pressure sensor and the two power sensors are connected to a PC with proper RS232 cables data collection. It was observed that at pressures higher than 10 torr initiation of a plasma is difficult unless external electrodes are used.[8] Thus, the cavity inner pressure is reduced through the nozzle opening of the thruster that was exposed to the vacuum conditions of the BUSTLab vacuum chamber. The BUSTlab vacuum chamber is 1.5 m in diameter and 2.7 m in length. The chamber is pumped with a rotary vane pump with roots blower and with two 12 inch cryogenic pumps. The pressure of the vacuum chamber, thus the back-pressure of the thruster, is measured by an MKS-972B pressure sensor.

III. Experimental Results and Discussions

In this study, BUSTLab MET thruster performance parameters are evaluated using the experimental data. The system is operated for mass flow rates of 30 to 84 mg/s and power levels of 400 W and 500 W. The mass flow rates are increased until the plasma is quenched for each power level. Experiments are repeated at least three times for each mass flow rates to ensure the repeatability of the measured results. To start the experiments, vacuum chamber pressure is reduced to 10^{-3} $torr$ level. Then the mass flow rate is increased to a level at which the cavity inner pressure is fixed at 10 $torr$. This mass flow rate level is about 250 $sccm$ for the current tests with Helium. After achieving the proper pressure condition, microwave power is increased to 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. At first a glow discharge that fill the whole cavity forms when the pressure is low. 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. The discharge chamber pressure data for each mass flow rate is recorded.

A second set of experiments are done for determining cold gas conditions. For these tests, after the plasma side of the resonant cavity is evacuated using the pumping mechanism of the BUSTLab vacuum chamber, mass flow is introduced at desired levels and the MET thruster chamber pressure is recorded without supplying any microwave energy.

In a MET system, measuring the gas temperature directly by immersing a thermocouple probe would interfere with the resonance conditions of the cavity. Thus, the chamber gas temperature is evaluated by using the chamber pressure data and adiabatic rocket equations.

Mass flow rate in an adiabatic nozzle can be written as;

$$\dot{m} = A_t p_c k \sqrt{\frac{(2/k+1)^{(k+1)/(k-1)}}{kRT_c}} \tag{1}$$

where A_t is the throat area, p_c is the chamber pressure, k is the ratio of specific heat ratio, R is the specific gas constant and T_c is the chamber temperature. When the mass flow rate for hot gas condition is divided by mass flow rate of cold gas conditions for the same flow rate, a relationship between the hot and cold gas conditions is obtained;

$$\frac{T_{ch}}{T_{cc}} = \left[\frac{p_h}{p_c}\right]^2 \frac{k_h[2/(k_h+1)]^{(k_h+1)/(k_h-1)}}{k_c[2/(k_c+1)]^{(k_c+1)/(k_c-1)}} \tag{2}$$

In this equation the subscripts *cc* and *ch* indicate the cold chamber and hot chamber conditions, respectively. For Helium, which is a monatomic gas, k and R values are constant. So equation 2 reduces to;

$$\frac{T_{ch}}{T_{cc}} \cong \left[\frac{p_{ch}}{p_{cc}}\right]^2 \tag{3}$$

For an ideal rocket that is exhausting to absolute vacuum, the exit velocity can be written as;

$$v_{ex} = \sqrt{2kRT_c(k-1)} \tag{4}$$

using equation 4 and mass flow rate value, the obtained thrust can be evaluated;

$$\tau = \dot{m} v_{ex} \tag{5}$$

and using the calculated thrust value, the specific impulse can be evaluated;

$$I_{sp} = \tau / \dot{m} g_0 \tag{6}$$

where g_0 is the gravity of earth. For a MET system, the coupling efficiency, η_c, is the ratio of absorbed power to the incident power and is written as

$$\eta_c = \frac{P_{inc} - P_{ref}}{P_{inc}} \times\ 100 \tag{7}$$

where the P_{inc} is the incident power and P_{ref} is the reflected power. Thrust efficiency, η_τ is the ratio of the exhaust kinetic energy to the incident power;

$$\eta_\tau = \frac{\tau I_{sp} g_0}{2P_{inc}} \tag{8}$$

Chamber pressure data for cold gas, 400 W and 500 W power levels are measured as described above. It is observed that the pressure increases linearly with increasing mass flow rate for all three operating conditions as seen in Figure 4. Increase in the supplied power level causes the chamber pressure to increase due to the increased electrothermal heating of the propellant gas. The pressure level of 400 W delivered power condition is nearly twice of that of the cold gas condition. On the other hand for a 100 W increment from 400 W to 500 W, the pressure level rises slightly. The plasma can be sustained at a maximum pressure of about 800 *torr* at 500 W power level whereas this value is about 600 *torr* at 400 W.

The chamber temperature is proportional to the square of the chamber pressure as indicated in equation 2. As seen in Figure 5, a peak in chamber temperature is observed corresponding to a given input power for varying mass flow rates. Before the chamber temperature reaches its maximum, the plasma volume contracts with increasing pressure, and the thermal losses will decrease so the temperature of the gas will increase. On the other hand, if the mass flow rate is increased further, the gas cannot be heated to higher temperatures as the gas and the plasma interaction time will decrease. The maximum chamber temperature for 400 W and 500 W delivered power levels are evaluated to be 1030 K and 1114 K, respectively.

As the value of the exhaust velocity is temperature dependent, so is teh value of the specific impulse. As seen in Figure 6, the specific impulse values show a similar trend to that of the temperature. The maximum achievable specific impulse of the system is 334 s for 400 W and 348 s for 500 W levels. These obtained values are in the range of those of resistojets.[9] Evaluated specific impulse values increase for increased power. For the same mass flow rates, the specific impulse values at 500 W level are about 15 s higher than those for 400 W.

The calculated thrust values show a linearly increasing trend for increasing mass flow rate as seen in Figure 7. Thrust values change from 97 mN to 203 mN and 120 mN to 266 mN for 400 and 500 W power levels, respectively. It is observed that the thrust level at 500 W for the same mass flow rate is slightly higher than that of 400 W as seen in Figure 7.

The system coupling efficiency is about % 97 for both power levels. This value is roughly constant since the system is tuned (using a two stub tuber) for every power and mass flow rate value during the experiments. On the other hand, thrust efficiency of the system increases with increasing mass flow rate as tabulated in Tables 1 and 2. As tabulated in Tables 1 and 2, the specific impulse values decrease beyond a peak value while the thrust efficiency keeps increasing. A trade off needs to be done between the higher specific impulse versus higher efficiency when choosing the ideal operating conditions.

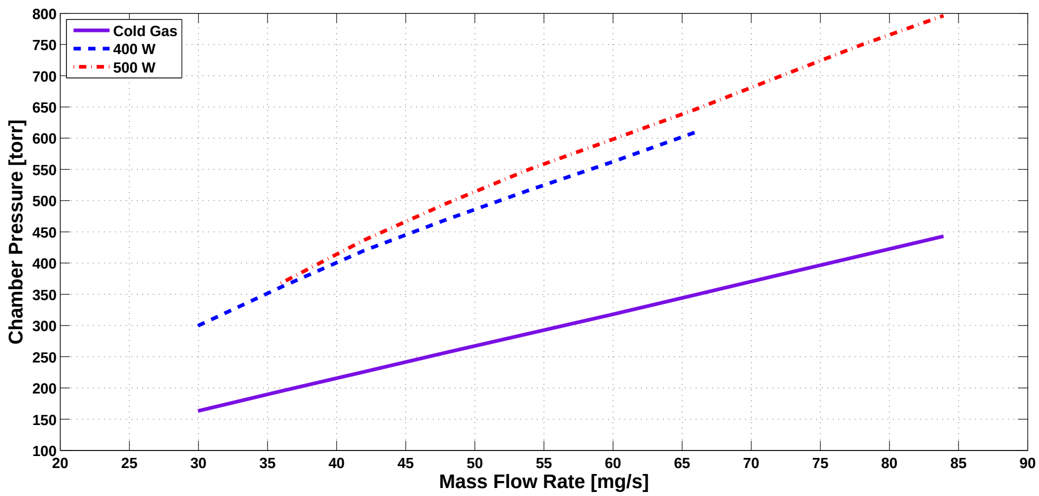

Figure 4. Chamber pressure experimental data for cold gas, 400 W and 500 W microwave power levels.

Table 1. Performance parameters at 400 W incident power

mfr [mg/s]	p_c [torr]	T_c [K]	V_{ex} [m/s]	τ [mN]	I_{sp} [s]	η_c[%]	η_τ[%]
30	300	1005	3240	97	330	98	31
36	361	1025	3272	118	334	98	38
42	420	1030	3281	138	334	98	45
48	470	997	3227	155	329	98	50
54	517	965	3176	171	324	97	54
60	562	932	3120	187	318	97	58
66	609	908	3080	203	314	98	63

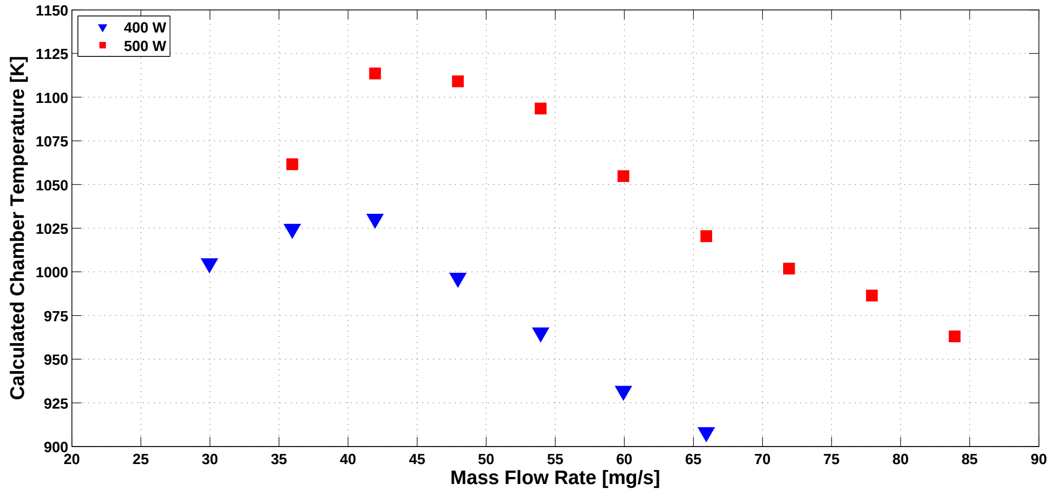

Figure 5. Chamber temperature values at 400 W and 500 W microwave power levels calculated using chamber pressure data.

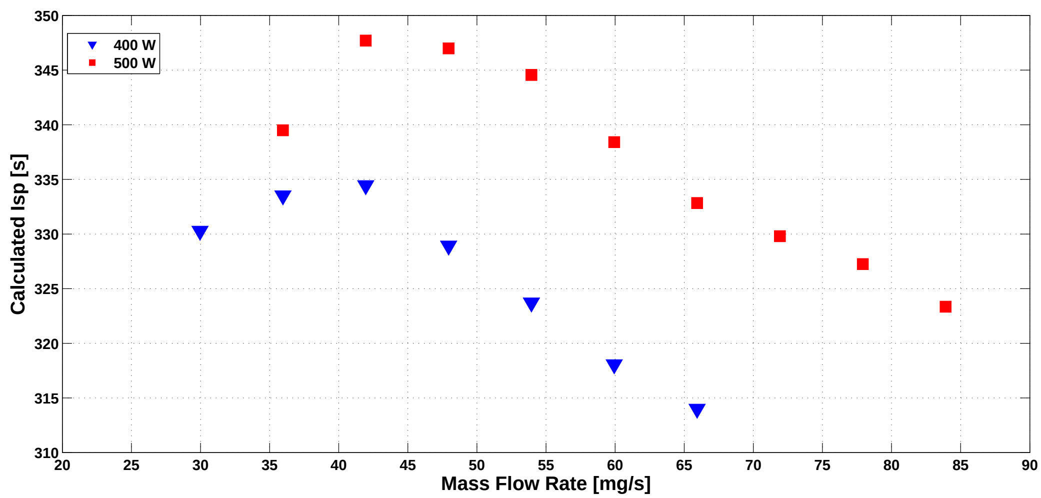

Figure 6. Calculated I_{sp} values at 400 W and 500 W microwave power levels.

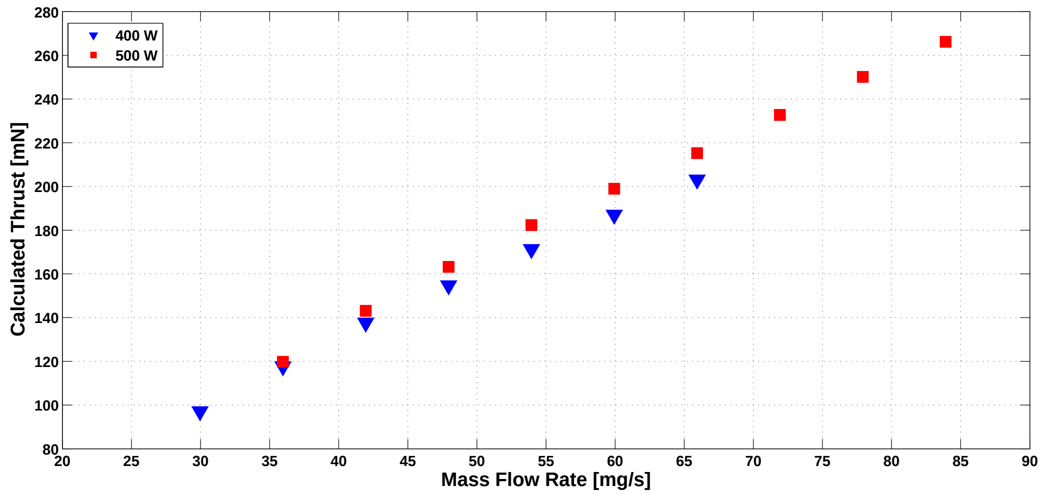

Figure 7. Calculated thrust values at 400 W and 500 W microwave power levels.

Table 2. Performance parameters at 500 W incident power

mfr [mg/s]	p_c [torr]	T_c [K]	V_{ex} [m/s]	τ [mN]	I_{sp} [s]	η_c[%]	η_τ[%]
36	368	1062	3330	120	339	97	40
42	436	1114	3411	143	348	97	49
48	496	1109	3404	163	347	97	56
54	550	1093	3380	182	345	97	62
60	598	1055	3320	199	338	97	66
66	646	1020	3265	215	333	97	70
72	698	1002	3235	233	330	97	75
78	749	986	3210	250	327	97	80
84	796	963	3172	266	323	98	84

IV. Conclusion

Performance characteristics of BUSTLab MET system, designed to operate 2.45 GHz frequency, are examined using experimental data for 400 W and 500 W operating power levels. In the experiments, chamber pressure and power absorbed by the thruster are directly measured, and the chamber temperature, specific impulse, and the thrust are evaluated by using appropriate equations. Maximum I_{sp} level of 347 s and thrust level of 266 mN is assessed. The evaluated I_{sp} values corresponding to the specified power levels are in the range of resistojet thrusters' I_{sp} levels. It is also observed that increasing power levels has a positive effect on performance characteristics. It should be noted that the evaluated values will deviate from the real values because of the ideal expanded nozzle assumption.

Acknowledgements

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References

[1]Whitehair, S., Asmussen, J., and Nakanishi, S., "Demonstration of a New Electrothermal Thruster Concept," *Applied Physics Letters*, Vol. 44, No. 10, 1984, pp. 1014.

[2]Brandenburg, J. E., Kline, J., and Sullivan, D., "The Microwave Electro-Thermal (MET) Thruster Using Water Vapor Propellant," *IEEE Transaction on Plasma Science*, Vol. 33, No. 2, 2005, pp. 776–782.

[3]C. Hawley, M., Asmussen, J., Filpus, J. W., Whitehair, S., Hoekstra, C., and Chapman, R., "Review of Research and Development on the Microwave Electrothermal Thruster," *Journal of Propulsion and Power*, Vol. 5, No. 6, 1989, pp. 703–712.

[4]Micci, M. M., Bil, S. G., and Clemens, D. E., "History and Current Status of Microwave Electrothermal Thrusters," *Progress in Propulsion Physics*, Vol. 1, 2009, pp. 425–438.

[5]Capalungan, Erica E. and Micci, Michael M. and Bilén, Sven G., "The Design and Development of a 30-GHz Microwave Electrothermal Thruster," 32^{th} *International Electric Propulsion Conference*, Wiesbaden,Germany, September 2011, IEPC-2011-162.

[6]Power, J. L., "Microwave Electrothermal Propulsion for Space," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 40, No. 6, 1992.

[7]Mueller, J. and Micci, M. M., "Desing and Performance Characteristics of a New Microwave Electrothermal Thruster," 22^{th} *Electric Propulsion Conference*, Viareggio, Italy, July 1991, IEPC-91-033.

[8]Diamant, K. D., Zeigler, B. L., and Cohen, R. B., "Microwave Electrothermal Thruster Performance," *Journal of Propulsion and Power*, Vol. 23, No. 1, 2007, pp. 27–34.

[9]Martinez-Sanchez, M. and Pollard, J. E., "Spacecraft Electric Propulsion An Overview," *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998, pp. 688–698.