Evaluation of Plasma Properties in a Microwave Electrothermal Thruster Resonant Cavity Using Two Fluid Global Model

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A microwave thermal thruster (MET) is a type of electric thruster where the propellant is heated via microwave energy inside a properly designed resonant cavity and then the gas is expanded through a conventional converging-diverging nozzle to produce thrust. Thus, in a microwave electrothermal thruster a microwave resonant cavity acts in a similar fashion to the combustion chamber of a chemical propulsion system. Inside the resonant cavity a free floating plasma, generated by the microwave energy deposition into the gas, heats the gas before the gas is expelled. This study presents a two fluid global model which aims to provide a better understanding of the propellant heating mechanism in the microwave resonant cavity of a MET. COMSOL Multiphysics, a finite element software, is used to solve the appropriate equations to determine the thruster performance and plasma parameters, and the results are presented.

I. Introduction

Many types of electric propulsion systems have been developed since 1960s to produce thrust for in-space maneuvers of spacecraft. Electrothermal systems are among the pioneers of these kinds. Although they provide relatively lower specific impulse compared to that of electrostatic or electromagnetic systems, they have already been used on many space platforms. Resistojets and arcjets are the well-known electrothermal systems. Resistojets use resistive heater elements and arcjets employ DC or AC arc to heat the propellant. Thrust is obtained when the energized gas is expelled through a conventional nozzle as in chemical thrusters. On the other hand these two systems have some inherent handicaps. The thermal endurance of the heater element is a temperature limiting factor for resistojets. Propellant gas can be heated up to a temperature lower than this temperature limit. For arcjets, the cathode suffers significant erosion problems because of the ions striking on the tip when the thruster is in operation.[1] After a certain time of operation, the cathode length is reduced to a level at which the arc can no longer be generated. This is the major lifetime limiting factor for arcjets.

As a subclass of electrothermal thrusters, Microwave Electrothermal Thruster (MET) concept is put forward in 1980s.[2] Using this concept, researchers aimed to eliminate the inevitable handicaps of resistojets and arcjets mentioned above. Since METs use free floating plasma they do not have a heater thermal endurance limit or a cathode erosion problem. Only limit of this type is the wall temperature endurance as in all thrusters but can be overcome to a certain extend by means of cooling techniques.

Microwave electrothermal thrusters consist of four main parts which are microwave generator, resonant cavity, separation plate and the nozzle. In a microwave electrothermal thruster resonant cavity, energy carried by the microwave beam is transferred into the thermal energy of the gas via free floating plasma. When the microwave is transmitted into the cavity it starts to bounce back and forth, and the free electrons in the propellant gas are coupled the electric field of the wave. Thus, electrons are accelerated in accordance

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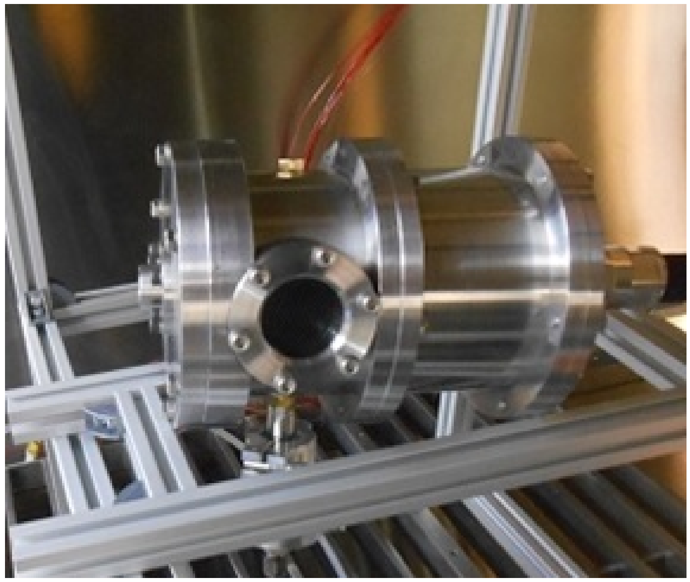


Figure 1. BUSTLab microwave-electrothermal-thruster on a stand inside the BUSTLab vacuum chamber

with the Lorentz force. At this point there are two probable interactions between the electrons and the heavy species (neutrals, ions or free radicals).[3] Fist one is the elastic collisions by which only the kinetic energy is transferred. Second one is the inelastic collisions by which the excitation or ionization of the heavy species occur. Molecular or electronic structure of the gas can be changed by this kind of collisions. If electron energy is higher than the ionization threshold energy of the gas, an electron is stripped off from the neutral atom and a new free ion-electron pair is created.

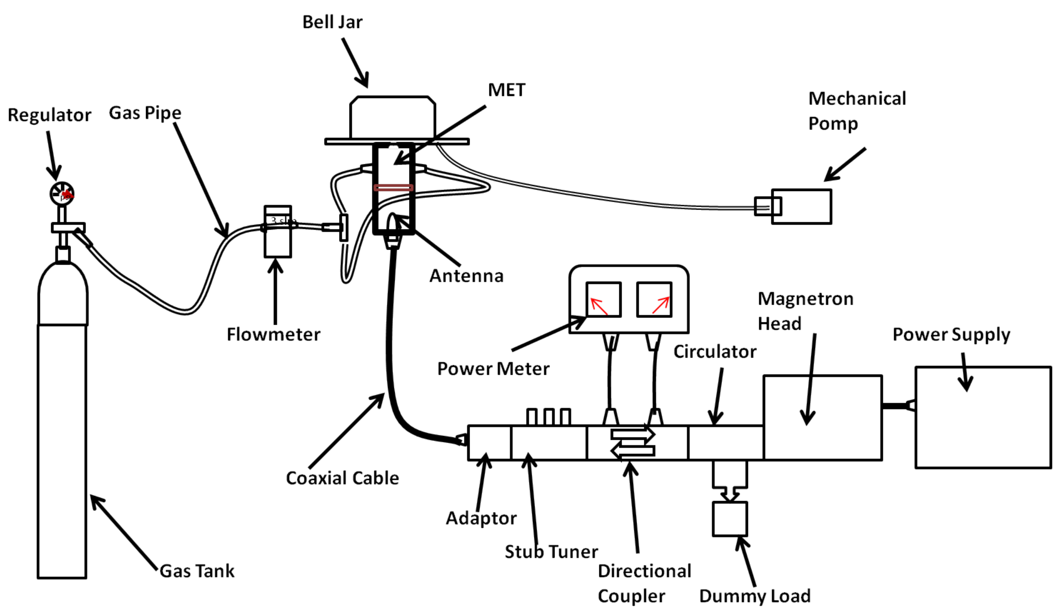


Figure 2. Experimental Setup

When the number density of the electrons reach a breakdown threshold level, plasma discharge begins. After this point, plasma acts as a resistive load and absorbs microwave energy. The gas is heated when swirling around or passing through the plasma. After the gas heats up, the gas thermal energy transforms into the kinetic energy when expelled through a conventional nozzle as in other electrothermal thrusters mentioned above.[3,4]

In preliminary studies, researchers focused on defining the working principles of this system and the energy transfer mechanisms from microwave to the gas. Prototypes consisted of cylindrical quartz tube and a resonator integrated to this tube was used. At first, characteristics of the plasma and efficiency of the concept[5–8] are studied. Coupling efficiencies of %40 to %95 are measured for systems using different types of gases.[5–8] Besides, systems are designed using resonant cavities which work in different TM or TE modes. TM_{011} is determined as the optimal mode. Using this mode the plasma can be generated at the upstream region of the nozzle plate so the gas can be expelled as soon as it is heated and the heat transfer losses are minimized. Also, the stabilization of plasma is investigated by M. Micci from Penn State University using bluff body in the flow region.[9] Later, the stabilization of plasma using vortex flow pattern is proposed by Sullivan and Micci.[10,11] Also, a new prototype that does not employ a quartz tube for stabilization is designed.[10,11] Penn State University researchers have developed thrusters working at 2.45, 7.5 and 14.5 GHz resonant frequencies.[12] Microwave electrothermal thruster using water vapur as propellant is tested by Brandenburg et al.[2]

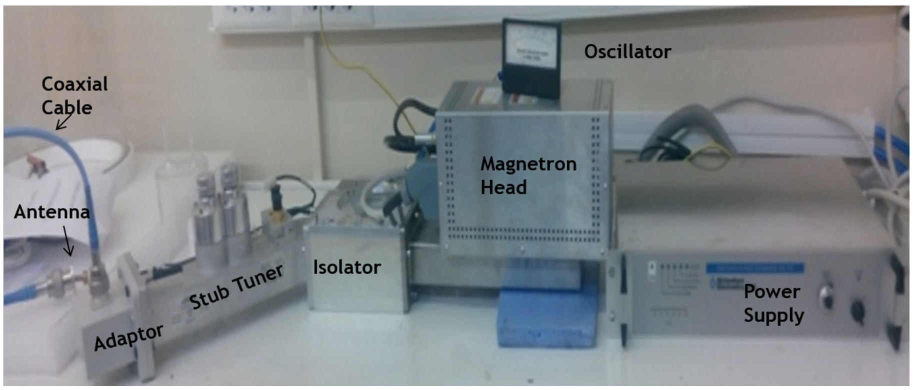


Figure 3. Transmission Line

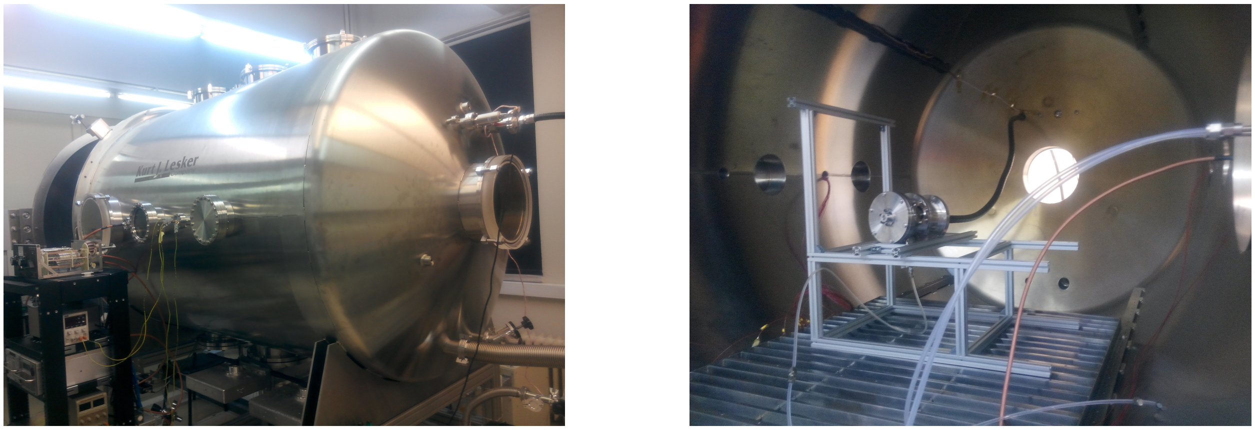
Although there are numerous experimental research to understand the energy transfer mechanisms in microwave electrothermal thrusters, only a few numerical studies are performed to date. A non-equilibrium 3-D plasma model employing Maxwell's and Navier-Stokes equations together is studied by Chiravalle et al.[13]

In this study, a global model is proposed to define the plasma characteristics in the microwave electrothermal thruster resonant cavity. Even though the 0-D models do not give accurate solutions as in multi-dimensional models, they give good insights of physics of the processes within a shorter time. In this study, plasma density, plasma temperature, neutral gas temperature in a microwave thruster resonant cavity operating at 2.45 GHz frequency and the power level of 1 kW are evaluated.

II. BUSTLab MET Thruster

At the Bogazici University Space Technologies Laboratory (BUSTLab) a prototype microwave electrothermal thruster (MET) has been designed, manufactured and tested. This prototype MET, a picture of which is shown in Figure 1, is designed to operate at 2.45 GHz frequency and at power levels of up to 1 kW. The delivered power level can be adjusted at 10 W increments. Argon gas is used as the propellant. The prototype MET is made of stainless steel. The nozzle of the MET is designed to be modular for examining the system characteristics for various nozzle geometries and expansion ratios.

Experimental set up consists of four main subsystems; microwave electrothermal thruster, microwave generation and transmission system, gas feeding system and vacuum system as shown in Figure 2. Microwave electrothermal thruster has three main parts that are resonant cavity, antenna and the nozzle plate. The resonant cavity of the thruster is designed to operate at TM_{011} mode at 2.45 GHz resonant frequency. 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 reflected power



(a) BustLab Vacuum Chamber Facility

(b) MET integration to the vacuum chamber

Figure 4. MET's first test inside the vacuum chamber

a simple oscillator is used. The oscillator diode is connected to the connector of the isolator. 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. The other end of the coax cable is attached to an antenna via another 7/16 connector. A picture of the microwave power generation and transmission system is shown in Figure 3. Gas feeding system consists of a mass flow controller, piping and a gas tank. The vacuum system consists of a mechanical pump, a bell jar and the base plate on which the thruster is attached.

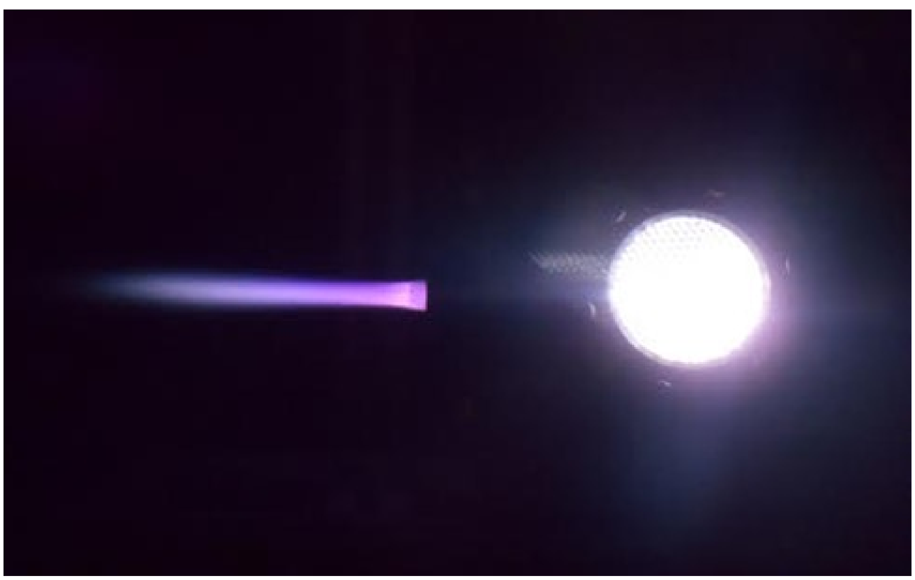


Figure 5. Plasma plume of MET operating inside the BUSTLab vacuum chamber

MET is also tested inside the BUSTLab vacuum chamber as shown in Figure 4(a). This chamber is 1.5 m in diameter and 2.7 m in length. The MET prototype is placed on a stand as shown in Figure 4(b) and the propellant gas is fed through swagelok pipes attached to the near wall of the vacuum chamber. Microwave is carried to inside of the chamber using a 7/16 power feedthrough and coaxial cables. Mass flow rate to the thruster is regulated between 2 to 30 l/m and the power level is adjusted between 70 to 550 W. A picture of the thruster operating inside the chamber is seen in Figure 5.

III. Two Fluid Global Model

Microwave electrothermal thruster uses microwave induced plasma to heat the gas. Experiments conducted to date show that microwave thrusters can be modelled as atmospheric pressure discharges.[14] In a global or 0-D model, spatial variations of the plasma properties are not taken into account, and volume averaged properties are used in calculations.

The model discussed in this study is developed for the analysis of the BUSTLab prototype microwave electrothermal thruster described in the previous section. A more detailed discussion about the developed model is presented in an earlier work.[15] In the model, the nozzle of the system is assumed to be optimally expanded, thus the effective exhaust velocity is taken to be equal to the exhaust velocity. Energy loses of the flow in the nozzle are not taken into consideration. Temperature of the background gas is assumed to be uniform in all plasma sections. In addition, the temperature of ions and neutrals are taken to be the same as in two fluid models for atmospheric pressure plasmas.[16,17] Since the gas velocity in the plasma filled section of the cavity is very low in comparison to the velocities in the nozzle, the static pressure in the nozzle inlet is considered to be equal to the stagnation pressure. Argon propellant is assumed to behave as an ideal gas, and the specific heat ratio is assumed to be constant. The species in the plasma are considered to have Maxwellian velocity distribution. Also, the plasma is considered to be quasi-neutral.

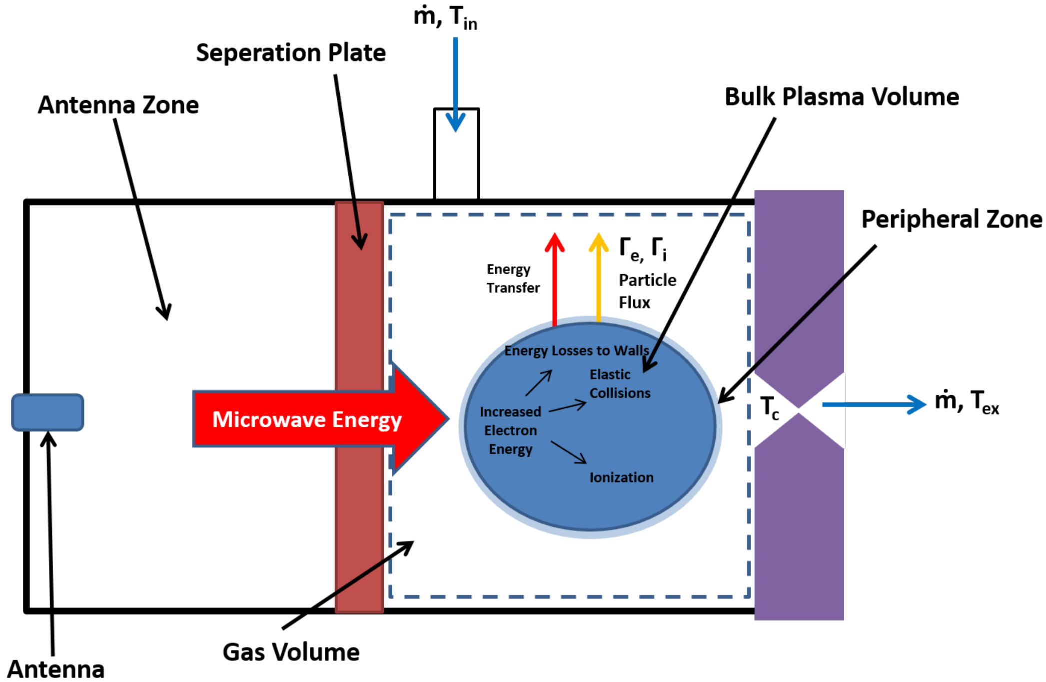


Figure 6. Schematic of the mass and energy transport for the plasma in the resonant cavity of MET

In the two fluid model three sets of equations are used to determine the properties of the plasma. Thus, one set is for electron fluid properties, second one for heavy particles properties and the last one is to determine the flow characteristics in the nozzle section. The first set of equations are used to determine the plasma parameters to investigate the energy transfer mechanisms of microwave power to the propellant gas. Elastic collisions are the main power absorption mechanism in the plasma. Electrons transfer some amount of their energy to the heavy particles when collisions occur. As a result, the heavy particles are energized and heated.[4] Besides, some amount of energy used for ionization and excitation processes which are necessary to maintain the plasma discharge. In the microwave thruster tests conducted at BUSTLab, it is observed that the discharge will be maintained below 100 W level at atmospheric pressures. Energy absorbed for ionization is transferred back to the gas as a result of the recombination and de-excitation processes. Also, another energy loss mechanism is the energy carried out of the plasma by the escaping electrons and ions. These ions and electrons deposit some amount of their energy to the walls when they strike the walls and cool down. The energy balance for the electrons have this power input, P_{dep}. Electrons are energized because of the Lorentz force which results from the electric field inside the cavity. The ions are heated by electron-ion elastic collisions, $n_e n_i \langle\sigma_{ei} v_e\rangle \delta \frac{3}{2} k_b (T_e - T_c)$, and the neutrals are heated by electron-neutral elastic collisions, $n_e N \langle\sigma_{ea} v_e\rangle \delta \frac{3}{2} k_b (T_e - T_c)$. Although some energy is gained by recombination and de-excitation processes, this is much smaller compared to the energy gained by elastic collisions.[18] Thus, the power deposited to the gas is equal to the power gained by elastic collisions. This can be formulated as;

$$P_{dep} = \underbrace{\forall_p n_e \left(n_i \left\langle\sigma_{ei} v_e\right\rangle + N \left\langle\sigma_{ea} v_e\right\rangle\right) \delta \frac{3}{2} k_b (T_e - T_c)}_{Elastic\ Collision\ Loss} \tag{1}$$

where $\delta = \frac{2m_e}{M}$ is the average fraction of energy loss by the electrons in an elastic collision with a heavy particle. Also, $\langle\sigma_{ei} v_e\rangle$ and $\langle\sigma_{ea} v_e\rangle$ are electron-ion and the electron-neutral rate coefficients for elastic momentum transfer collisions averaged over Maxwellian electron energy distribution and are written as;[18]

$$\langle\sigma_{ei} v_e\rangle = 2.91 \times 10^{-12} \frac{ln\Lambda}{T_{eV}^{1.5}} \quad [m^3 s^{-1}] \tag{2}$$

$$\langle\sigma_{ea} v_e\rangle = (0.084 + 0.537 T_{eV} + 1.192 T_{eV}^2) \times 10^{-14} \quad [m^3 s^{-1}] \tag{3}$$

where $ln\Lambda$ is the Coulomb logarithm.

The total power needed to reach the desired chamber temperature is the sum of the power that is deposited to the gas by the electrons, power lost to the walls and power used for inelastic collisions:

$$P_{Total} = P_{dep} + P_{loss} + P_{Inelastic\ Collision} \tag{4}$$

Because of the potential difference as a result of the plasma sheath formation on the walls, the electrons and ions carry some amount of energy out of the plasma when they strike on the walls of the cavity.[19] Every electron leaving the plasma and striking on the walls carries off an energy of 2 T_{eV}, and for an Argon ion leaving the plasma and striking on the walls, the energy carried away will be 5.2 T_{eV}.[20]

In our model, there are two main reactions in the plasma zone. These are electron impact ionization and excitation processes. The total power for the inelastic collisions is equal to the sum of the excitation and ionization losses;

$$P_{Inelastic\ Collision} = \forall_p (\underbrace{k_{exc} U_{exc} n_e N}_{Excitation} + \underbrace{k_{iz} U_{iz} n_e N}_{Ionization}) \tag{5}$$

where k_{iz} and k_{exc} are the ionization and the excitation rate coefficients, respectively. Curve fits for k_{iz} and k_{exc} are taken from Lieberman et al.;[20]

$$k_{iz} = 2.34 \times 10^{-14} (T_{eV})^{0.59} exp(\frac{-17.44}{T_{eV}}) \quad [m^3 s^{-1}] \tag{6}$$

$$k_{exc} = 2.48 \times 10^{-14} (T_{eV})^{0.33} exp(\frac{-12.78}{T_{eV}}) \quad [m^3 s^{-1}] \tag{7}$$

If the recombination is neglected, the electron continuity equation for steady state can be expressed as

$$\nabla^2 n + \frac{\nu_{iz}}{D} n = 0 \tag{8}$$

where the ν_{iz} is the ionization frequency.[20,21] D is the diffusion coefficient which is assumed to be equal to the ambipolar diffusion coefficient, the form of which is adapted form Jonkers et al.[18] Using the continuity equation along with the appropriate flux equations for a cylindrical geometry, expressions for the total flux to the cavity surfaces, Γ_T, and the volume averaged electron density, n_e, can be obtained as presented in detail in;[15]

$$\Gamma_T = \frac{4D\pi^2 R^2 n_0 J_1(\chi_{01})}{\chi_{01} L} + 4DL\chi_{01} n_0 J_1(\chi_{01}) \tag{9}$$

$$n_e = \frac{4LR^2 n_0 J_1(\chi_{01})}{\chi_{01} \forall_p} \tag{10}$$

where n_0, J_0 and the χ_{01} are electron number density at the center of the plasma, zeroth-order Bessel function of the first kind and the first zero of the J_0, respectively. Also, L is the length of the plasma zone, R is the radius of the cavity, and $\forall_p$ is the volume of the cavity.

To maintain quasi neutrality and continuity, the total volume ionization inside the plasma zone is set equal to the total ion loss out of the plasma zone. Losses because of the diffusion dominate the losses due to three body recombination in atmospheric pressure discharges.[18] So, the recombination losses are neglected. On the other hand, diffusion term is included in the total flux equation. The total flux is balanced with the total generation as;

$$\forall_p n_e N k_{iz} = \Gamma_T \tag{11}$$

By plugging in the expressions obtained for Γ_T in Equation 9, and n_e in Equation 10 into Equation 11, the following relation is obtained;

$$k_{iz} = \frac{D}{N}\left(\frac{\pi^2}{L^2} + \frac{\chi_{01}^2}{R^2}\right) \tag{12}$$

The neutral density can be obtained by using Dalton's law as;

$$N = \frac{p_c}{k_B T_c} - n_e\left(1 + \frac{T_e}{T_c}\right) \tag{13}$$

To compute the heavy particle's temperature in the chamber, it is assumed that the flow characteristics are similar to that of the turbulent flow in a circular pipe, and the main heat transfer mechanism is the convective heat transfer in the chamber. Also, the elastic collisions are assumed as the heat source in the chamber. The energy equation for the heavy particles are written as;

$$A_c h(T_c - T_w) = P_{dep} \tag{14}$$

where h is the convection coefficient, T_c is the chamber temperature, A_c is the chamber cross sectional area and P_{dep} is the power deposited to the gas by elastic collisions. To determine the convection coefficient Reynold's number is defined as;

$$R_e = \frac{4\dot{m}}{\pi D_c \mu} \tag{15}$$

where D_c is the diameter of the chamber, $\dot{m}$ is the mass flow rate and μ is the dynamic viscosity. Heat convection coefficient is determined as;

$$h = \frac{N_u \lambda_g}{D_c} \tag{16}$$

where N_u is the Nusselt number and λ_g is the conduction coefficient. The conduction coefficient is taken from the literature.[17] The Nusselt number for turbulent flow in the pipe is evaluated using Equation 17:

$$N_u = 0.023 R_e^{4/5} P_r^n \tag{17}$$

where P_r is the Prandlt number:

$$P_r = \frac{\mu C_p}{\lambda_g} \tag{18}$$

where C_p is the specific heat at consant pressure.

Another set of equations are used to evaluate the flow properties through the nozzle. These set includes the ideal rocket equations which are derived by assuming that the flow in the nozzle is isentropic. This set of equations are used to determine the mass flow rate provided the specific chamber conditions. Also, the produced thrust is evaluated in terms of these chamber conditions. In the model, BUSTLab MET nozzle dimensions are used to determine the exit pressure, temperature and Mach number values. Nozzle is assumed to be ideal expanded for the given conditions. The exit Mach number is evaluated iteratively for a known nozzle exit to throat area ratio, A_{ex}/A^*, by using the well know relations.[22] Similarly, exit temperature, pressure and velocity values are calculated. Mass flow rate is a function of the throat area, chamber pressure and temperature and defined as;[22]

$$\dot{m} = A^* p_c k \sqrt{\frac{(2/k+1)^{(k+1)/(k-1)}}{k R_g T_c}} \tag{19}$$

where k is the specific heat ratio and R_g is the specific gas constant.

For an optimum expanded nozzle, the thrust due to the pressure, $A_{ex}(p_{ex} - p_a)$, is neglected and the thrust equation reduces to;

$$\tau = \dot{m} v_{ex} \tag{20}$$

Table 1. **System Comparison Table**[23]

$p_c[kPa]$	$T_c[K]$	$T_{ex}[K]$	$p_{ex}[Pa]$	$v_{ex}[m/s]$	$\dot{m}[mg/s]$	$\tau[mN]$	$n_e[10^{19}/m^3]$	$T_e[K]$
25	1000	13	0.48	1016	23	23	1.51	8625
50	1800	24	0.96	1363	34	46	1.56	8592
100	2200	29.3	1.93	1507	62	93	1.17	8241
150	3000	40	2.89	1760	79	140	1.27	8173
200	4000	53	3.87	2032	92	187	1.55	8176
250	3000	46	4.83	1759	133	233.9	0.868	7848

IV. Results and Discussions

Three sets of equations are solved to determine the thruster performance parameters and plasma parameters in the cavity by using COMSOL software 0-D solver. In the model chamber pressure, chamber temperature, throat area and the area ratio are set to a constant value. Calculations are performed for 25, 50, 100, 150, 200 and 250 kPa chamber pressure levels. Exit Mach number, pressure, electron temperature, electron number density, mass flow rate, thrust and exit velocity calculations are performed. The obtained results are presented in Table 1.

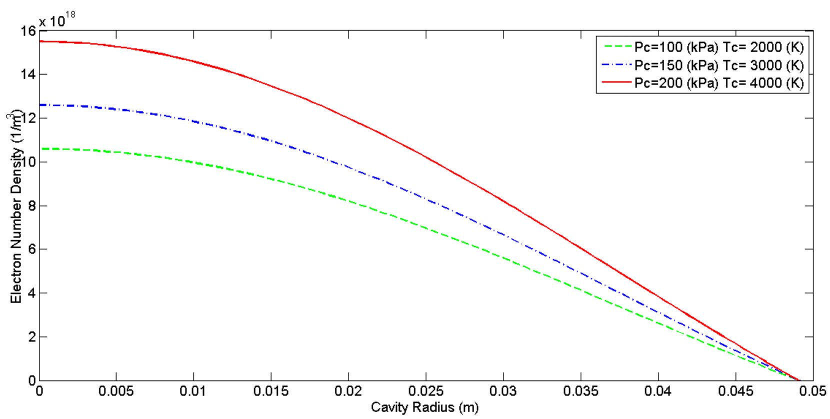


Figure 7. Electron Density Radial Distribution

Steady state solution of electron continuity equation for cylindrical volume is used in the model to evaluate volume averaged density. According to this solution, maximum plasma density will be at the center of the cavity. But, experiments conducted to date show that the plasma will be generated at the place where the maximum electric field is located.[4,24] But in a global model, place of the plasma is not taken into consideration and it is proper to use volume average of the plasma density. To evaluate plasma parameters a second set of equations, which include particle and energy balance equations for electrons, are used. For increasing pressure levels electron number density is on the order of 10^{19} m^{-3} and electron temperatures are about 0.7 eV. These two values changes slightly with increasing chamber pressure and temperature as shown in Table 1. Electron number density distributions are given in Figures 7 and 8 in accordance with the equations. Number density reaches its maximum at the center of the cavity and decreases gradually towards the walls. However, experiments conducted to date show that a streamer form of the plasma is observed at pressure levels higher than the atmospheric pressure.[25] Also, the experiments conducted at BUSTLab facilities show that the plasma distribution is not smooth as in this calculations. Arc shaped plasma formation is observed in the cavity. Thus, an arc is in the middle of the cavity and a very bright plasma is observed around it. This formation coincides with the literature rather than the calculations.

Although the gas temperature increases with the chamber pressure, experiments conducted by Clemens[23] show that there is a pressure threshold above which the gas temperature decreases with increase in pressure.

Because the plasma is getting closer to the nozzle after that threshold and the gas is expelled before being heated to higher temperatures. This process also affects the electron densities and temperatures as seen in Table 1.

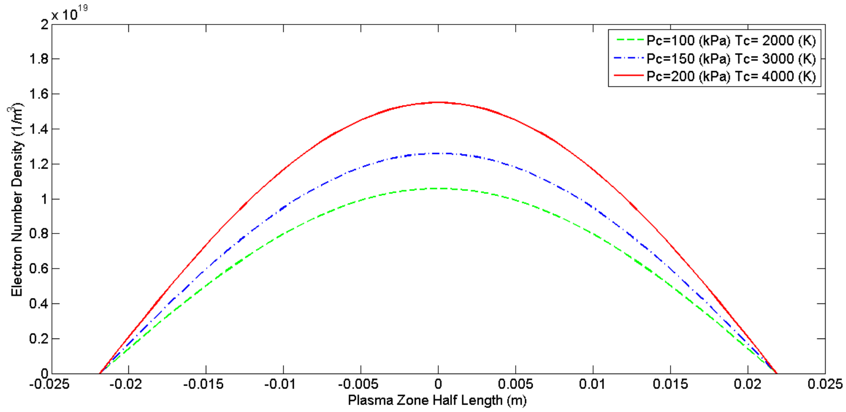


Figure 8. Electron Number Density Axial Distribution

V. Conclusion

This study presents a two fluid global model which aims to provide a better understanding of the propellant heating mechanism in the microwave resonant cavity of a MET. 0D solver of the COMSOL Multiphysics, a finite element software, is used to solve the appropriate equations to determine the thruster performance and plasma parameters, and the results are presented. Equations to define power absorption mechanisms in a MET cavity are presented. For an assumed geometry, cavity temperature and pressure values, relevant plasma and operational parameters are calculated. Also, radial and axial distributions of expected electron density results are presented.

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References

[1]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.

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

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

[6]Whitehair, S and Frasch, L L and Asmussen, J, "Experimental Performance of A Microwave Electrothermal Thruster With High Temperature Nozzle Materials," 19^{th} *International Electric Propulsion Conference*, Colorada Springs, Colorado, July 1987, AIAA-87-1016.

[7]Haraburda, S. and Hawley, M., "Investigation of Microwave Plasmas Applications in Electrothermal Thruster Systems," 25^{th} *Joint Propulsion Conference*, Monterey, CA, USA, July 1989, AIAA-89-2378.

[8]Balaam, Philip and Micci, Michael M, "Performance Measurement Of a Resonant Cavity Electrothermal Thruster," 22^{th}

International Electric Propulsion Conference, Viareggio, Italy, October 1991, IECP-91-031.

[9]Balaam, P. and Micci, M. M., "Investigation of Free Floating Resonant Cavity Microwave Plasmas for Propulsion," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 103–109.

[10]Sullivan, D. J. and Micci, M. M., "Development of a Microwave Resonant Cavity Electrothermal Thruster Prototype," 23^{rd} *International Electric Propulsion Conference*, Seattle, WA, USA, July 1993, pp. 337–354.

[11]Sullivan, Daniel J and Kline, John and Philippe, C. and Micci, Michael M., "Current Status of the Microwave Arcjet Thruster," 31^{th} *Joint Propulsion Conference*, San Diego,CA, July 1995, AIAA-95-3065.

[12]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.

[13]Chiravalle, V. P. and Miles, R.B. B and Choueiri, E Y, "A Non-Equilibrium Numerical Study of a Microwave Electrothermal Thruster," 38^{th} *Joint Propulsion Conference*, Indianapolis,IN, July 2002, AIAA-2002-3663.

[14]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.

[15]Yildiz, M. S. and Celik, M., "Global Energy Transfer Model of Microwave Induced Plasma in a Microwave Electrothermal Thruster Resonant Cavity," 34^{th} *International Electric Propulsion Conference*, Kobe, Japon, July 2015, IEPC-2015-266.

[16]Baeva, M. and Bösel, A., "Modeling of microwave-induced plasma in argon at atmospheric pressure," *Physical Review E*, Vol. 85, No. 5, 2012, pp. 1–9.

[17]Martinez, E. C., Kabouzi, Y., Makasheva, K., and Moisan, M., "Modeling of microwave-sustained plasmas at atmospheric pressure with application to discharge contraction," *Physical Review E*, Vol. 70, Dec. 2004.

[18]Jonkers, J., Sande, M. V. D., Sola, A., Gamero, A., and Mullen, J. V. D., "On the differences between ionizing helium and argon plasmas at atmospheric pressure," *Plasma Sources Science and Technology*, Vol. 12, No. 1, Feb. 2003, pp. 30–38.

[19]Lee, C. and Lieberman, M., "Global model of Ar, O2, Cl2, and Ar/O2 highdensity plasma discharges," *Journal of Vacuum Science & Technology A*, Vol. 13, No. 368, 1995.

[20]Lieberman, M. A. and Lichtengberg, A. J., *Principles of Plasma Discharges and Materials Processing*, John Wiley & Sons, Inc., 2nd ed., 2005.

[21]Piel, A., *Plasma Physics*, Springer, 2010.

[22]Sutton, G. P. and Biblarz, O., *Rocket Propulsion Elements*, John Wiley & Sons, Inc., New York, 7th ed., 2000.

[23]Clemens, D. E., *Performance Evaluation of the Microwave Electrothermal Thruster Using Nitrogen, Simulated Hydrazine and Ammonia*, Ph.D. thesis, Pennsylvania State University, 2008.

[24]Chianese, S. G. and Micci, M. M., "Microwave Electrothermal Thruster Chamber Temperature Measurement and Performance Calculations," *Journal of Propulsion and Power*, Vol. 22, No. 1, 2006, pp. 31–37.

[25]ZHU, G.-q., *Modeling of plasma dynamics and pattern formation during high pressure microwave breakdown in air*, Ph.D. thesis, Universite de Toulouse, 2012.