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Microwave Electrothermal Thruster Optimization via Simulations

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ABSTRACT

This thesis presents the setup and simulation results for a 2.45-GHz Microwave Electrothermal Thruster (MET) for the purpose of understanding some design possibilities for the thruster. The simulations in this thesis were performed using COMSOL Multiphysics. These simulations were created to study the effects of different operational conditions for the MET. The electric field intensity in the MET cavity, the electron density in the cavity, and the power loss during operation are strong indicators of MET performance. These three characteristics were used to find desirable operational conditions for the MET. The propellant injectors were modeled to be near the midplate in this thesis, but the results obtained from this injector placement are not promising. Hence, the injectors should be maintained at their nominal location near the nozzle.

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Chapter 1

Introduction

The Microwave Electrothermal Thruster (MET) is one type of Electric Propulsion (EP) system that is in development for use in satellites for attitude control, maneuvers, and formation flight. The MET uses an electromagnetic resonant cavity to ignite and sustain a free-floating plasma in a propellant gas. The heated propellant is then accelerated through a nozzle to generate thrust on the order of millinewtons. The heating mechanism of this system is like that of an arc jet, in which a propellant gas is heated by an arc discharge between two electrodes. The MET has a longer lifetime than an arc jet because the plasma is free-floating, avoiding the electrode erosion that is the main lifetime limitation of an arc jet. This thesis presents simulation results based on the 2.45-GHz MET developed at The Pennsylvania State University.

The Importance of Electric Propulsion

The demand for EP thrusters has skyrocketed because they are more efficient and have much higher specific impulses than thrusters that employ traditional chemical propulsion. Specific impulse is a measure of how efficiently a propulsion system can generate thrust. Chemical propulsion systems are limited by the energy released in the exothermic reactions of their propellants, which is why chemical systems are called energy-limited systems. EP systems are limited by several factors as well, but one of the primary limitations is the amount of power that can be provided to the system. Theoretically, EP systems can be provided any amount of required power. However, in reality the amount of power an EP system can receive is limited by the materials of which the system is made (because the materials used can only withstand a certain amount of power), and by what can be generated by the spacecraft.

EP systems do not provide nearly as much thrust as chemical systems, so they will likely never be used to launch from the Earth's surface. Instead, EP systems are used for attitude and orbit control of Earth-orbiting satellites and for deep-space-probe missions [1]. More advanced EP systems are being developed that will allow for more ambitious space missions.

There are several types of EP thrusters: arc jet, Hall thruster, pulsed-plasma thruster, magnetoplamsadynamic thruster, field-emission electric propulsion thruster, and the ion thruster [2]. The thruster that will be discussed in this thesis is a type of arc jet.

Introduction to the MET

There are several ways to generate plasma in an EP thruster: electron discharge (i.e., arc), thermionic, rf heating, and microwave frequency electromagnetic waves. The microwave electrothermal thruster (MET) simulated in this thesis is a type of arc jet that utilizes microwave power to excite electrons and generate plasma rather than an electric arc. The generated plasma is then expanded through a nozzle, generating thrust. METs mitigate the lifetime issues associated with electron discharge thrusters, but they only operate under certain conditions [2]. The microwave frequency must be resonant in the cavity and the plasma density high enough to absorb the microwave power. When the conditions are correct, the microwave energy is coupled to the plasma by resonant heating of the electrons through collisions.

Research on MET systems began in the 1980s, yet they have just achieved their first use on a satellite in space. METs and other EP systems will be used in future space missions instead of chemical systems because they utilize much less propellant. This will save space on spacecraft, on which space is generally very limited, and greatly reduce the mass of the spacecraft as compared to chemical systems.

The propellant is injected into the cylindrical microwave chamber tangentially, allowing the gas to breakdown into plasma. The heated plasma is then expanded out of a nozzle to produce thrust [3]. METs produce a very small amount of thrust, so these thrusters are meant to be used over longer periods of time to generate significant thrust. This could be an issue, because in emergency situations the MET may not be able to provide enough thrust to perform a maneuver in time.

The electric field that is produced near the nozzle initiates and sustains the plasma formation in the MET, so the thruster's performance largely depends on the electric field intensity in the chamber [3]. MET designs with empty chambers allow plasma formation near the antenna, so a dielectric insert was introduced to confine the plasma towards the nozzle end [3].

Previous Research

There has been a lot of previous research conducted at Penn State on the MET. The first MET design operated at a microwave frequency of 2.45 GHz, and this is what determined the size of the MET cavity. METs are resonant structures so the electric field interactions with the plasma largely depend on the size and shape of the MET. Hence, this thruster was designed to have a chamber diameter of 10 cm and a chamber length of 15.75 cm and received an input power range of 1 kW to 2.5 kW [4].

The 2.45-GHz MET has been tested with ammonia as the propellant, and the MET demonstrated a specific impulse of 400 seconds [1]. The ion thruster was also tested with simulated hydrazine decomposition products and demonstrated a specific impulse of 425 seconds [1]. The MET was then developed to operate at different microwave frequencies with many different propellants. One design operated at a frequency of 7.5 GHz and 100 W of power and achieved a specific impulse of 220 seconds [1]. Preliminary designs were created for an MET to operate at 8.4 GHz with 350 W of power.

A 14.5-GHz MET was also designed to operate at low power with helium as propellant. Initially the MET demonstrated a specific impulse of 197 seconds with 14.3 W of power [5]. After some improvements were made to the thruster, the MET demonstrated a specific impulse of 423 seconds with 70 W of input power [6].

Designs for a 17.8-GHz MET were also created to use superheated water vapor as a propellant. These designs were meant for use on a 3U CubeSat (7). This thruster was also tested with ammonia as propellant at 32 W of input power and demonstrated a specific impulse of 202 seconds [8, 9].

Research Scope and Thesis Overview

This thesis serves to assist in optimizing a miniature MET. A lot of research and optimization has been previously performed on METs, and simulations were created and analyzed in COMSOL Multiphysics to further optimize the current 2.45-GHz MET. COMSOL Multiphysics simulations were also done to help understand phenomena observed in the lab.

The theory behind the 2.45-GHz MET is explained in Chapter 2. The design of the thruster and the setup for the simulation are presented in Chapter 3. In Chapter 4, the simulation results are shown and discussed. Chapter 5 includes research conclusions and recommendations.

Chapter 2

Background

Microwave frequency ranges between 0.3 GHz and 300 GHz of the electromagnetic spectrum. To generate plasma in an MET, microwave power is introduced into its cylindrical cavity, heating a propellant. The MET operates in the TM^z resonant mode, so the understanding of its operation starts with solutions to Maxwell's equations for the TM^z resonant mode [10].

TM^z_{011} Resonant Cavity Field Theory

The MET has a cylindrical cavity, hence the solutions for the fields inside of the MET are easier to solve in cylindrical coordinates. Figure 1 shows the MET's cavity components in the cylindrical coordinate system. For the TM^z_{011} resonant mode, the equations governing the components of electric and magnetic fields in the MET for a homogenous, source-free, lossless medium are [11]:

$$E_\rho = j\frac{B_{011}}{\omega\mu\varepsilon}\frac{\pi\chi_{01}}{ah}J_0'\left(\frac{\chi_{01}}{a}\rho\right)\sin\left(\frac{\pi z}{h}\right) \quad (1.1a)$$

$$E_\phi = 0 \quad (1.1b)$$

$$E_z = -j\frac{B_{011}}{\omega\mu\varepsilon}\left(\frac{\chi_{01}}{a}\right)^2 J_0'\left(\frac{\chi_{01}}{a}\rho\right)\cos\left(\frac{\pi z}{h}\right) \quad (1.1c)$$

$$H_\rho = 0 \quad (1.2a)$$

$$H_\phi = -\frac{B_{011}}{\mu}\frac{\chi_{01}}{a}J_0'\left(\frac{\chi_{01}}{a}\rho\right)\cos\left(\frac{\pi z}{h}\right) \quad (1.2b)$$

$$H_Z = 0 \quad (1.2c)$$

These equations can be solved to yield an expression for the resonance frequency for a given radius-to-height ratio [11]:

$$(f)_{011}^{\mathrm{TM}^z} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{\chi_{01}}{a}\right)^2 + \left(\frac{\pi}{h}\right)^2} \quad (1.3)$$

where μ and ε represent the relative permeability and permittivity of the gas in the chamber, respectively. For the $\mathrm{TM}^z{}_{011}$ resonant mode, $\chi_{01} = 2.4049$.

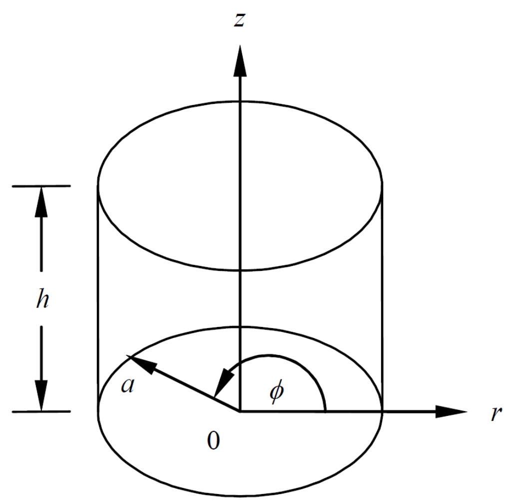

Figure 1. Cylindrical coordinate system for MET cavity [1]

Varying the height-to-radius ratio, h/a, alters the electric field strength at the endplates relative to that of the midplane. The relation for this ratio is [11]:

$$\left|\frac{E_Z|_{\rho=0,z=h}}{E_\rho|_{\rho=a,z=h/2}}\right| = \left[\frac{\chi_{01}}{\pi}\frac{J_0(0)}{J_1(\chi_{01})}\right]\left(\frac{h}{a}\right) = 1.472\left(\frac{h}{a}\right) \quad (1.4)$$

For the 2.45-GHz MET, the ratio $h/a \approx 3$. Altering the dimensions of the chamber by the smallest amount will change the resonant frequency. Adding a dielectric plate at the mid-plane, which is typical in the MET, adds further complexity to determining the dimensions of the cavity. The resonant wavenumber is defined by:

$$\beta_{\mathrm{res}}^2 = \omega_{\mathrm{res}}^2\mu\varepsilon = \beta_\rho^2 + \beta_z^2 \quad (1.5)$$

With the addition of a dielectric plate, the fields are governed by [6]:

$$\frac{\beta_{z,d}}{\varepsilon_d}\tan(\beta_{z,d}t) = \frac{\beta_{z,g}}{\varepsilon_g}\tan\left(\beta_{z,g}(t-h)\right) \quad (1.6)$$

$$\beta_{z,d} = \sqrt{\beta_{d,\text{res}} - \beta_r^2} = \sqrt{\omega_{\text{res}}^2 \mu_d \varepsilon_d - \left(\frac{\chi_{01}}{a}\right)^2} \tag{1.7}$$

$$\beta_{z,g} = \sqrt{\beta_{g,\text{res}} - \beta_r^2} = \sqrt{\omega_{\text{res}}^2 \mu_g \varepsilon_g - \left(\frac{\chi_{01}}{a}\right)^2} \tag{1.8}$$

The dielectric plate, which is made of fused quartz, has $\varepsilon_d = 4.2\varepsilon_0$ and lowers the cavity's resonance frequency. The height of the cavity was therefore reduced to account for the plate. The value of ε_g is set to equal ε_0.

The dielectric plate thickness also has an impact on the resonance frequency of the cavity, so the height-to-radius ratio of the cavity must also be altered. The quartz plate has a thickness $t = 1/16''$ or 1.5875 mm. With this thickness, equations (1.6) through (1.8) give a radius of $a = 50.8$ mm, and the optimal height of $h = 157.5$ mm was found using COMSOL Multiphysics. The height-to-radius ratio was altered to $h/a \approx 3.1$.

Transmission Line Theory

To optimize the performance of an MET, we must understand the method of power transfer from the microwave source to the MET. There are three primary types of transmission lines [12]. The first in the waveguide, which can handle high power levels with low loss, but they tend to be more expensive and are also larger in size. The second type of transmission line is the coaxial line, which are compact and inexpensive [10]. The planar transmission line is the last type of transmission line. This transmission line is primarily used in microwave circuitry because they are compact and inexpensive.

A transmission line can be characterized using three properties: propagation constant, characteristic impedance, and, if the line has loss, attenuation. The propagation constant for the

$TM^z{}_{011}$ mode is β. The characteristic impedance of a line is represented by Z_0, and is determined using the ratio of voltage to current for the wave traveling through the line [12]. The attenuation is the rate of decay of a signal in the line and is represented by the variable α. This parameter should be minimized to optimize the MET.

Wave propagation along transmission lines can be categorized into three types: transverse electromagnetic (TEM), transverse electric (TE), and transverse magnetic (TM). Transmission lines with two conductors can support TEM wave propagation, whereas transmission lines with one conductor can only support TE or TM wave propagation.

Matching the MET's load impedance with the characteristic impedance of the transmission line is essential for optimal performance of the MET. Matching the load and line impedance allows for the most power transfer from the transmission line to the MET. If the impedance of the load and the line are poorly matched, then part of the traveling wave is reflected. The voltage reflection coefficient, Γ, represents the amplitude of the reflected voltage normalized to the amplitude of the incident voltage [12]:

$$\Gamma = \frac{Z_{\mathrm{L}} - Z_0}{Z_{\mathrm{L}} + Z_0} \tag{1.9}$$

When there is no reflected wave, Γ equals zero. For this to occur, Z_{L} and Z_0 must be equal. A standing wave is the superposition of the incident and reflected wave along the transmission line. The incident and reflected power can be defined by [12]:

$$P_{\mathrm{inc}} = \frac{1}{2}\frac{\left|V_{0,\mathrm{inc}}\right|^2}{Z_0} \tag{1.10}$$

$$P_{\mathrm{ref}} = \frac{1}{2}\frac{\left|V_{0,\mathrm{inc}}\right|^2}{Z_0}\left|\Gamma^2\right| \tag{1.11}$$

The incident power minus the reflected power is defined as the average power on the transmission line [12]:

$$P_{\text{avg}} = P_{\text{inc}} - P_{\text{ref}} = \frac{1}{2}\frac{|V_{0,\text{inc}}|}{Z_0}(1 - |\Gamma^2|) \tag{1.12}$$

If the impedance of the load and the impedance of the transmission line are poorly matched, not all of the power put into the system is delivered to the load. Return loss is the term used to describe the power loss that is caused by poorly matched loads and lines [12]:

$$\text{RL} = -20\log|\Gamma| \tag{1.13}$$

Plasma Theory

The MET utilizes plasma to heat the propellant. Thus, to optimize the design of an MET, it is essential to understand plasmas. Plasmas are very complex, so only a brief explanation of their characteristics is included in this thesis.

In *Introduction to Plasma Physics and Controlled Fusion*, Chen defines a plasma as a quasi-neutral gas consisting of neutral and charged particles [13]. Quasi-neutrality means the plasma charges are balanced (neutral) overall, while small, concentrated areas of charge may exist within the plasma, but charges redistribute to shield this perturbation from the bulk plasma to maintain neutrality. These concentrations also give rise to electric fields, and the electric flow in the plasma caused by the electric fields give rise to magnetic fields. Now all particles in the plasma are affected by the fields that the moving particles create in the plasma.

Plasma exists in many different places in nature: within stars, lightning bolts, the *aurora borealis*, and Van Allen radiation belts [13]. Plasmas can shield out electric potentials, and this is an essential characteristic to understand about plasma. The thickness of the shielding within a plasma is a function of the Debye length, λ_{D}. There are a few criteria that must be met for an ionized gas to be considered a plasma. The first requires that [13]

$$\lambda_{\mathrm{D}} \ll L \tag{1.14}$$

This criterion states that the fields in concentrated areas of charge in the plasma should be shielded by the gas within short distances compared to the size of the plasma. The next criterion states that there must be enough particles in the charged gas to create the shielding [13], i.e.,

$$N_{\mathrm{D}} \gg 1 \tag{1.15}$$

These two criteria are required such that the plasma is quasi-neutral. The final criterion requires a relation between the frequency of collisions with neutral atoms in the plasma, ω_{c}, and the mean time between those collisions, τ_{c}, be met:

$$\omega_{\mathrm{c}}\tau_{\mathrm{c}} > 1 \tag{1.16}$$

When this condition is met, the motion of the charged cloud is controlled by electromagnetic forces [13].

Now that plasma has been defined, the generation of the plasma can be understood. Plasma formation generally occurs by breakdown ionization. When a strong electric field is present, electrons can be stripped from their molecules resulting in two charged particles: free negatively charged electrons and positively charged ions. Gas breakdown, or plasma formation, is designed to occur in the center of the MET cavity near the nozzle entrance by concentrating the electric field at that location. As addressed previously, a dielectric plate is required to keep the plasma from forming close to the antenna.

The forces that affect the charged particles follow the Lorentz Law:

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{1.17}$$

As shown by the expression, the force a particle experiences depends on its charge. The electric and magnetic fields force the electrons and ions in opposite directions. Gaseous breakdown generates a plasma when the rate of ionization is greater than the rate of recombination. Plasma is sustained if the ionization rate remains greater than the sum of both the rate of diffusion and the rate of recombination. Diffusion occurs when electrons are absorbed by the cavity walls instead of colliding with molecules inside of the cavity. Recombination occurs when an ion collides with a low velocity electron and forms a neutral atom. The rate of diffusion and recombination can be minimized with the presence of a magnetic field.

Whether or not the ionization rate remains greater than both the rate of diffusion and the rate of recombination combined depends on the losses of the system. Vibrational and rotational modes of the particles and molecules could absorb extra energy in the system, and energy can also be lost in the excitation of electrons in existing molecules. Considering these factors, one can see that choosing a propellant that is light and has a less complex molecular structure will improve the MET's performance.

Ionization is mostly maintained through inelastic collisions between the free electrons and the neutral particles in the gas. The collision is called inelastic because kinetic energy is not conserved in the collision [6]. Most of the kinetic energy is conserved, and if enough of the kinetic energy is conserved, the neutral atom is ionized.

Chapter 3

Numerical Modeling of the MET

Numerical electromagnetic modeling of the 2.45-GHz MET was performed using COMSOL Multiphysics, a commercial finite element analysis (FEA) software. COMSOL Multiphysics was used to find numerical solutions for the electric field intensity within the MET cavity, the electron density throughout the cavity, and losses of the system. These are three of the essential factors driven by the electromagnetics of the MET to consider during their design. The electric field intensity solution helps understand where the electric field becomes the most intense within the cavity, because this is one of the factors that drives where the plasma is generated. Solving for electron density helps to understand the plasma formation in the cavity. Plasma formation is driven by excited electrons and inelastic collisions. The solutions for the losses in the system are important because this helps to understand where and how much energy is being lost in the system, which reduces overall efficiency.

Simulation Setup

The RF (radio frequency) module of COMSOL Multiphysics was used to generate a 2D axisymmetric model of the 2.45-GHz MET using argon propellant. The MET is essentially symmetric inside the chamber (except for propellant injectors, which are only at specific orifice ports, and a symmetrical simulation does not fully capture their effects), and 3D solutions are much more computationally intensive to obtain. The shapes of some components are slightly simplified to speed up the computation process. Only the inside of the MET cavity was included in the model, along with the coaxial antenna. The walls are considered to have no thickness.

Figure 2 shows the dimensions and entire geometry of the model. The height and the radius of the MET cavity are represented by h and a, respectively. The quartz separation plate height is represented by h_s and the radius is represented by t_s. The antenna radius and thickness are represented by r_c and t, respectively, and h_a and r_a represent the height of the antenna and the radius of the antenna, respectively. The coaxial port height is represented by h_p and the radius is represented by r_p. The antenna insulator (Teflon®) height is represented by h_T.

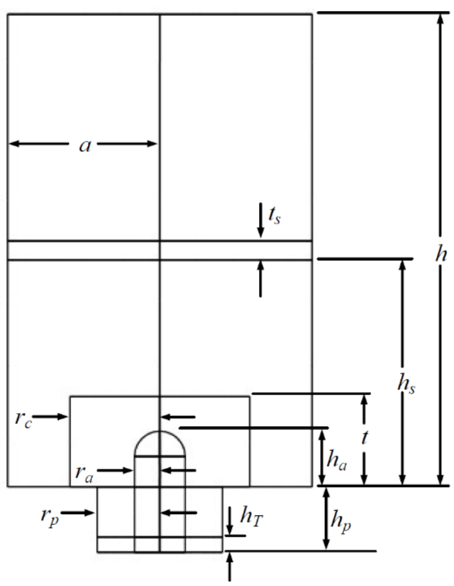

Figure 2: MET geometry [1]

The cavity of the MET is broken into three subdomains. The first subdomain is the part of the cavity that is filled with air and has a relative permittivity of 1.0 (this subdomain could also be modeled as a vacuum). The second subdomain is the fused quartz dielectric plate at the midpoint of the cavity, which has a relative permittivity of 4.2. The coaxial insulator material around the antenna is the third subdomain of the model and has a relative permittivity of 2.0.

For the boundary conditions, the walls and the antenna were modeled as perfect electrical conductors. The model was set to have propellant injectors and a coaxial port at the base of the midplate with varying input power (the arrows in Figure 3 point at this boundary, this is for simulation only as this injector location is not physically possible). A coaxial electron outlet was also created at the top of the cavity. A free tetrahedral mesh of over 30,000 elements was created. This provides a clear numerical solution without sharp discontinuities but is also a relatively small number to allow for a reasonable computation time.

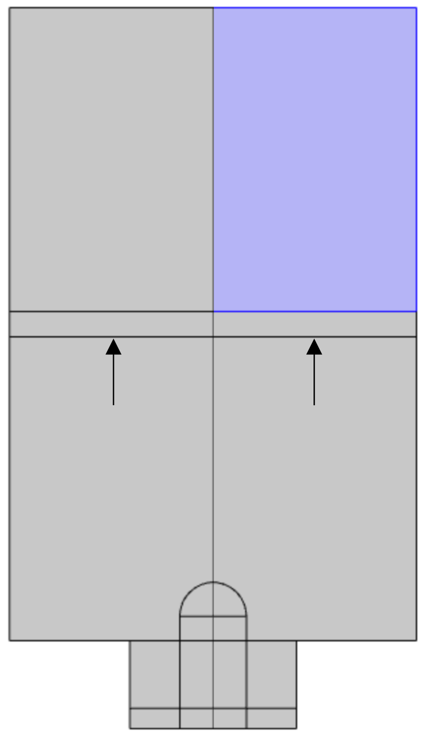

Figure 3. Full MET model

The COMSOL Multiphysics simulations that are presented in the next chapter examine multiple factors of the MET for optimization and for the purpose of understanding certain plasma phenomena. First, two different antenna heights were examined in the MET to understand the effects of different antennas on the electric field intensity and distribution in the cavity. A high electric field near the nozzle end of the thruster is desirable. The MET was also simulated at different input powers to see how input power would change plasma generation and losses in the thruster. Finally, the MET was simulated at different pressures to examine the impact of pressure on the system.

Chapter 4

Computational Results and Discussion

First, two different antenna heights in the MET cavity were simulated to observe the impact of different antennas. The conditions these antennas were evaluated under in the lab are shown in Table 1. These conditions were used to set up the initial simulations of the MET in COMSOL Multiphysics, and then new conditions were evaluated to see if they have a positive impact on the performance of the system. The first parameter that was evaluated was the antenna height, and the impact of its size on plasma generation in the MET. The 14.52-mm antenna is referred to as Antenna 1, and the 17.50-mm antenna is referred as Antenna 2.

Table 1. Lab conditions for MET

Antenna	Height (mm)	Power (W)	Pressure (Torr)	Injection Speed (m/s)
1	14.52	631	16.54	0.0196
2	17.50	586	16.54	0.0196

Antenna Size

The results of the COMSOL Multiphysics simulations suggest that antenna performance depends on the power that is provided to the system (Figure 3). With about half the power (300 W) that was tested in the lab, the shorter antenna generates a more intense electric field near the dielectric plate, which would result in more plasma generation. This is not desirable, however, because the intention is to generate plasma at the nozzle.

The full MET model is shown in Figure 3. In Figure 4, only the top right section of the model is plotted (the section shaded in blue in Figure 3), because this is the region in the cavity where plasma is created, and the model is axisymmetric. The figure shows that Antenna 1

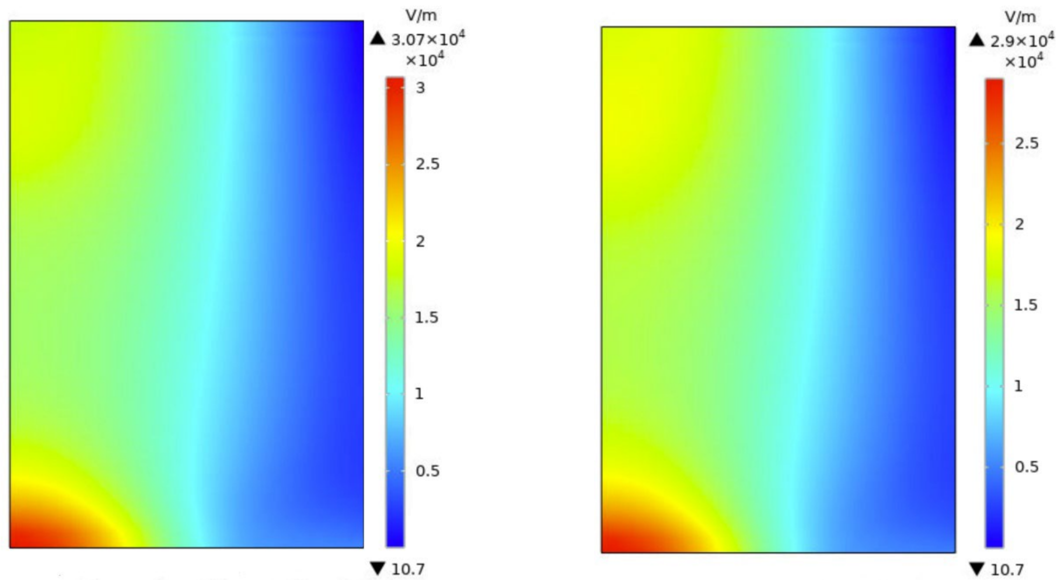

Figure 4. E-field inside plasma region of MET cavity, Antenna 1 (left) and Antenna 2 (right) tested with 300 W, 16 Torr, 0.02 m/s injection speed

generates a slightly more intense electric field close to the dielectric plate, with a maximum of 3.07×10^4 V/m, whereas Antenna 2 generates a maximum 2.9×10^4 V/m electric field. The regions of high intensity are also similar in size. When the MET is provided the same power as in the lab, about 600 W, it can be observed in Figure 5 that the electric field intensity is higher

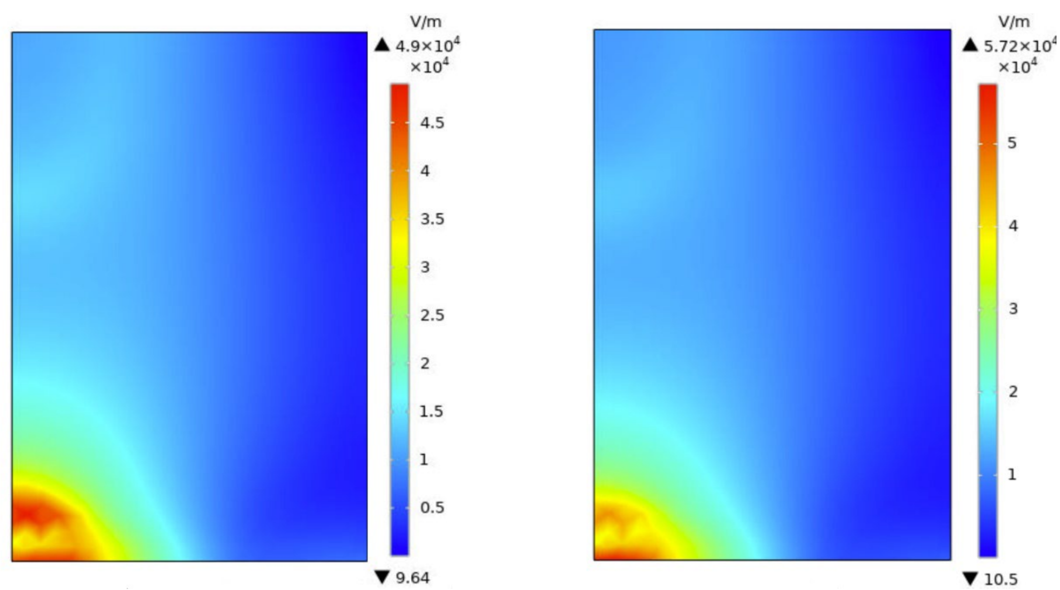

Figure 5. E-field inside plasma region of MET cavity, Antenna 1 (left) and Antenna 2 (right) tested with 600 W, 16 Torr, 0.02 m/s injection speed

for Antenna 2 than for Antenna 1, but the region of high intensity for Antenna 1 is visibly larger than the region of high intensity for Antenna 2. It will be observed later that the plasma generation for these antennas at this power level are similar.

Power

The next parameter that was examined is the power provided to the system. It is predictable that increasing the power level will increase the electric field and, therefore, more plasma will be generated in the MET cavity. But as one can see in Figure 6, which is a surface plot of electron density, the plasma is being generated close to the walls of the MET cavity, and this is not desirable. A high electron density corresponds to a higher chance for inelastic collisions between free electrons and propellant atoms, which is how we see plasma generation

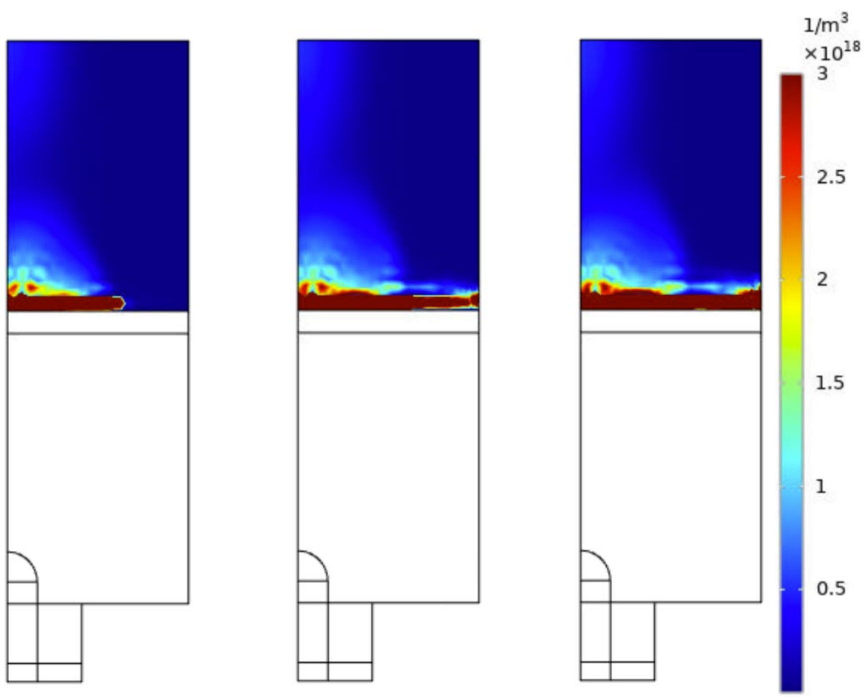

Figure 6. Electron density for antenna 1 at 300 W (left), 600 W (middle), 1 kW (right), 16 Torr, and 0.02 m/s propellant injection speed

in COMSOL Multiphysics. The simulations show that, as power increases, if pressure remains the same, the plasma will start to form close to the walls of the MET.

The results for electron density for Antenna 2 at 300 W, 600 W, and 1000 W at 16 Torr and 0.02 m/s propellant injection speed appear identical to the results for Antenna 1. The difference in length between Antenna 1 and Antenna 2 does not seem to make much of an impact on the solutions for electron density.

Minimizing the power transfer into the cavity during operation is a very important part of optimizing the MET, and more power is transferred when the MET is operating at certain power levels. Figures 7–9 show the reflected power in the first 10 μs of MET operation for three different power levels in decibels (dB). S_{11} is related to Γ in equations (1.9), (1.11), (1.12) and (1.13), and is the reflection coefficient. An S_{11} of 1 (0 dB) means that all input power is reflected, and low S_{11} means that more power is absorbed within the cavity. S_{11} can be used to find the return loss (RL) of the system, which is an indicator of how well a transmission line matches a device. A higher RL means the transmission line and device are well matched, and less power is lost.

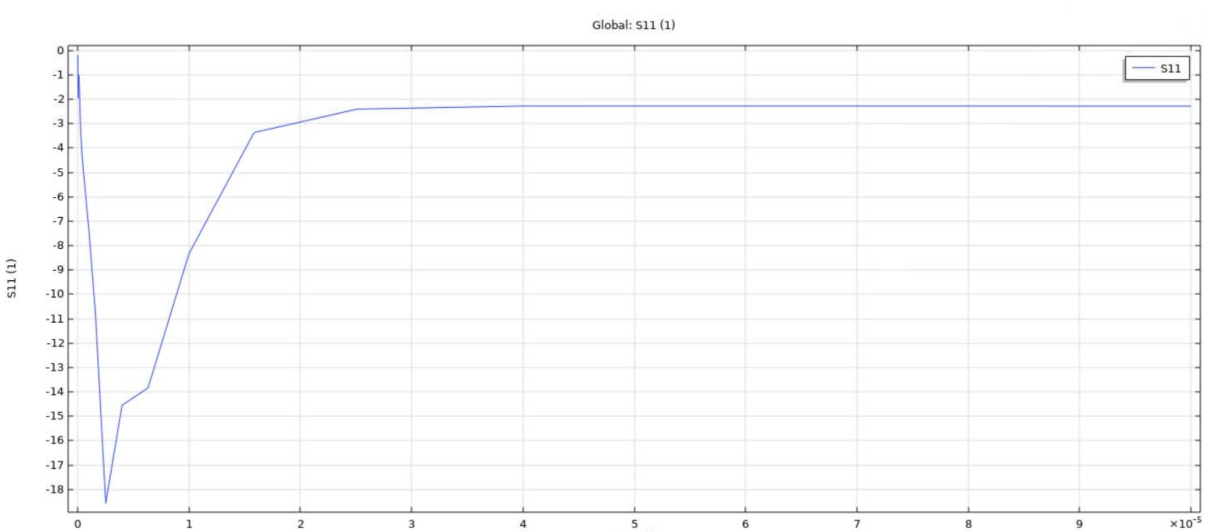

Figure 7. Power lost in transmission line at 300 W input power

At 300 W input power, S_{11} first drops to about −18.5 dB. After about 4 μs, S_{11} settles at a little lower than −2 dB, which means much of the power is reflected.

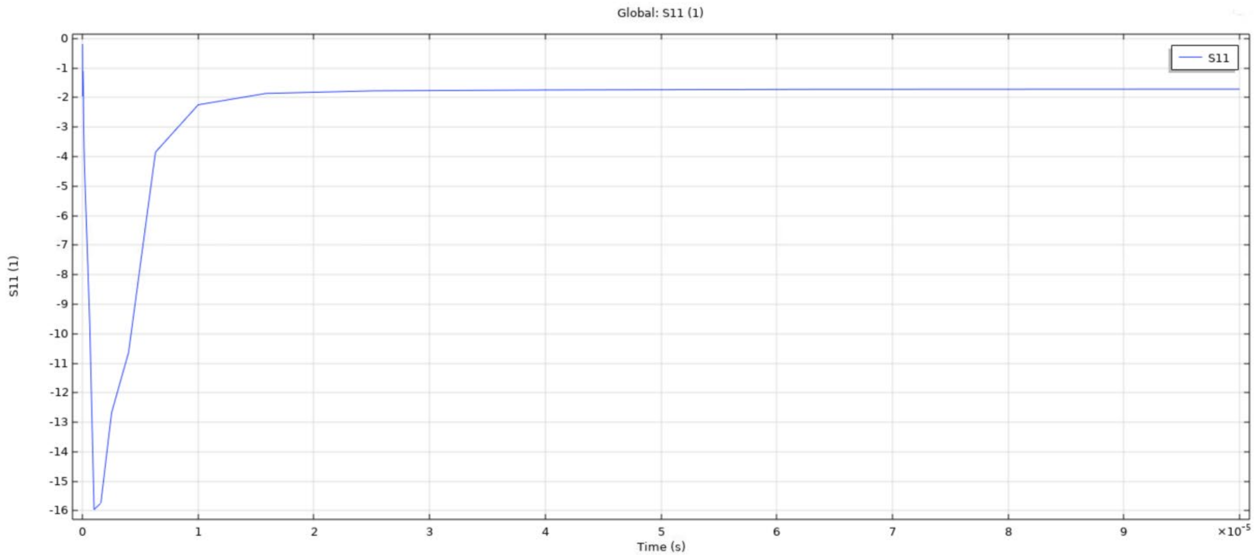

Figure 8. Power lost in transmission line at 600 W input power

For a power input of 600 W, S11 drops very quickly to −16 dB, which is worse than at 300 W and less input power is absorbed within the cavity. After about 2.5 μs, S_{11} settles at a little higher than -2 dB, which is again worse than at 300 W.

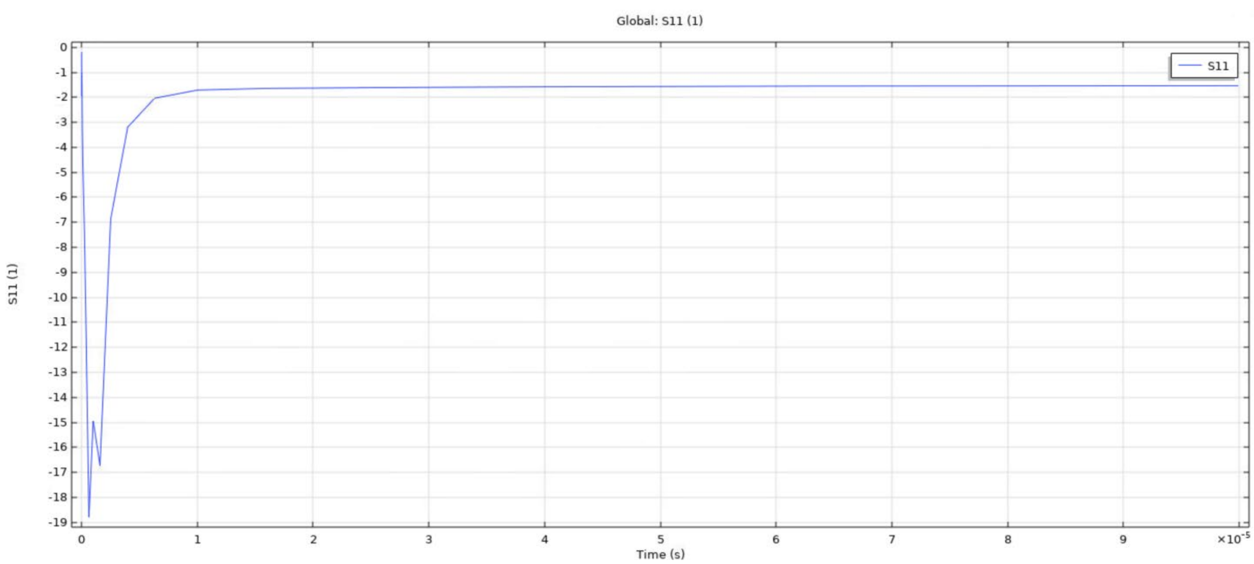

Figure 9. Power lost in transmission line at 1 kW input power

When operating at 1 kW input power, S_{11} drops to −19 dB, so the cavity is absorbing a large amount of power at first. Then after about 40 μs, S_{11} settles at about −1.5 dB. It appears that initially, the power can be absorbed within the cavity, initiating the plasma discharge. Once the discharge is going, the plasma acts to shield the second half of the cavity, in a sense making the cavity appear shorter and, hence, no longer resonant. This explains the large amount of reflected power seen in the simulations.

Pressure

The next object of study was pressure and its effects on plasma generation in the MET. Figure 10 shows that as pressure increases more of the plasma that is generated forms in the center of the cavity relatively far from the MET cavity walls, and this is desirable. However, as one can see in Figure 11, as the pressure is increased, the maximum electric field intensity produced by the same antenna at the same power will decrease.

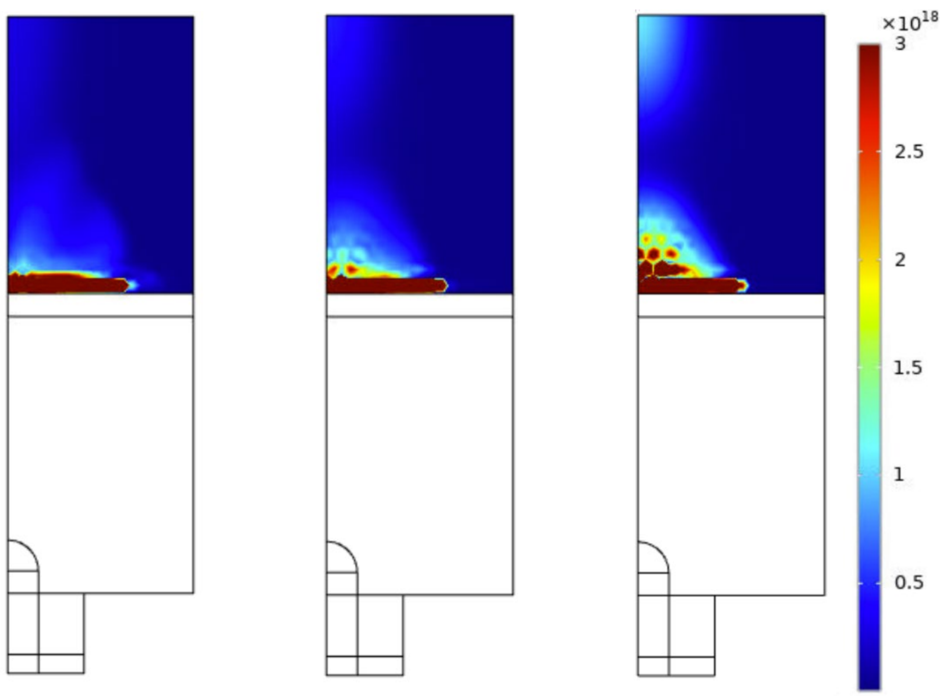

Figure 10. Electron density for antenna 1 at 8 Torr, 16 Torr, and 32 Torr and 300 W, 0.02 m/s propellant injection speed

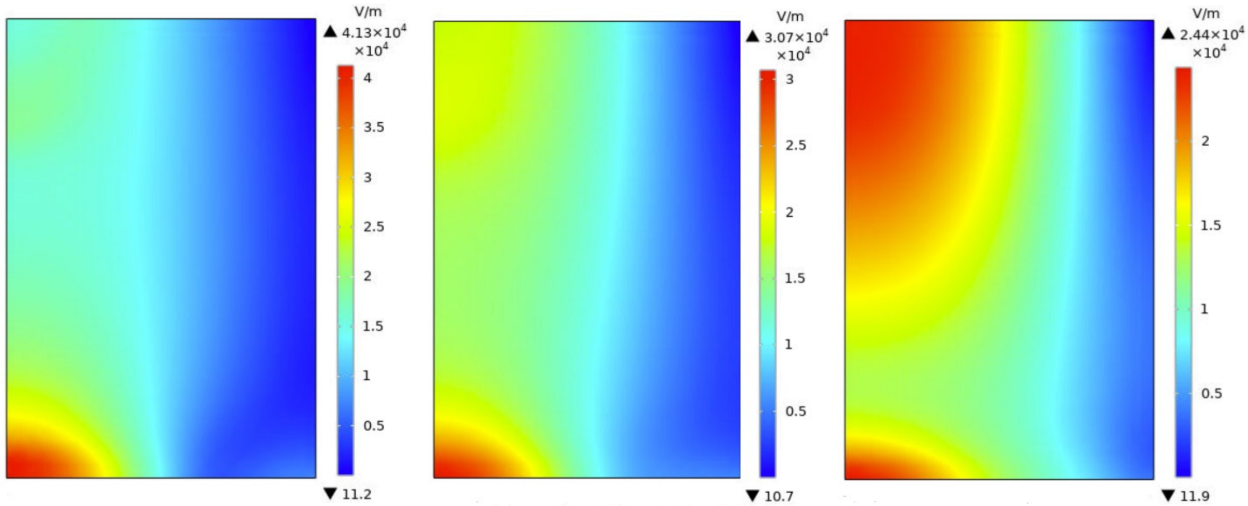

Figure 12. E-field for antenna 1 at 8 Torr (left), 16 Torr (middle), and 32 Torr (right) and at 300 W, 0.02 m/s propellant injection speed

It also seems that increasing the pressure inside of the MET cavity also results in decreased power loss in the system. S_{11} drops below −10 dB for almost the first 2 seconds of operation and takes 4 seconds to settle down to −3 dB.

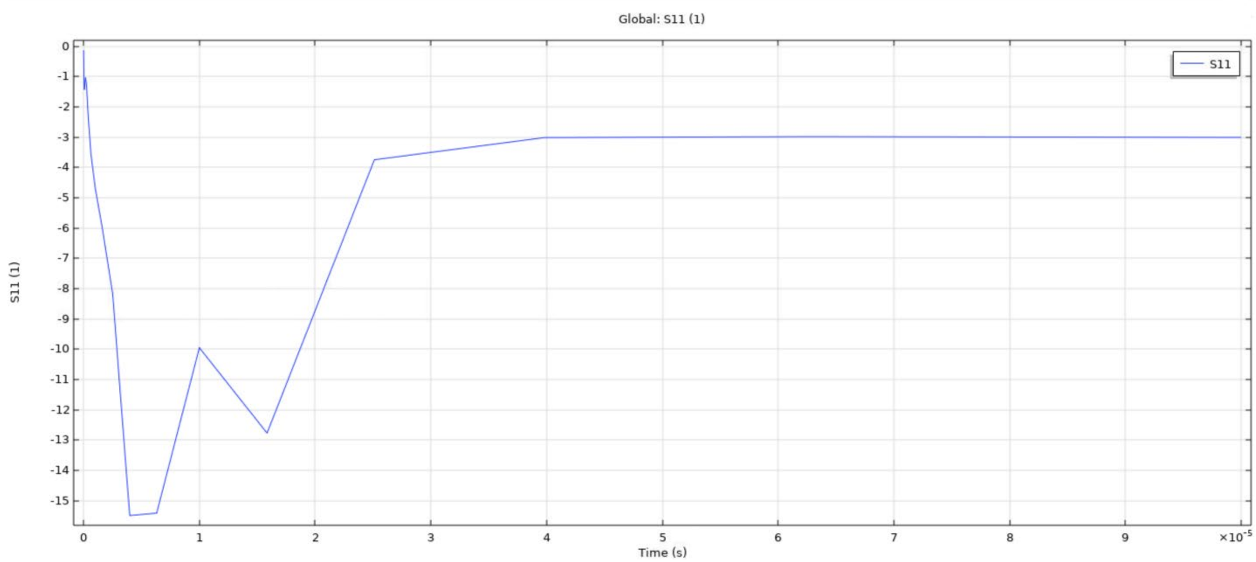

Figure 11. Power lost in transmission line at 300 W and 32 Torr

Propellant Injection Speed

The final parameter that was investigated was the injection speed of the argon propellant. The results from these solutions are not helpful for optimization, however. The MET was tested with three different injection speeds, while keeping all other inputs for the system constant. The MET was simulated with Antenna 1, 300 W of input power, 16 Torr pressure, and 0.02 m/s, 0.04 m/s, and 0.2 m/s injection speed. Figure 13 shows the identical electron density results for these three speeds.

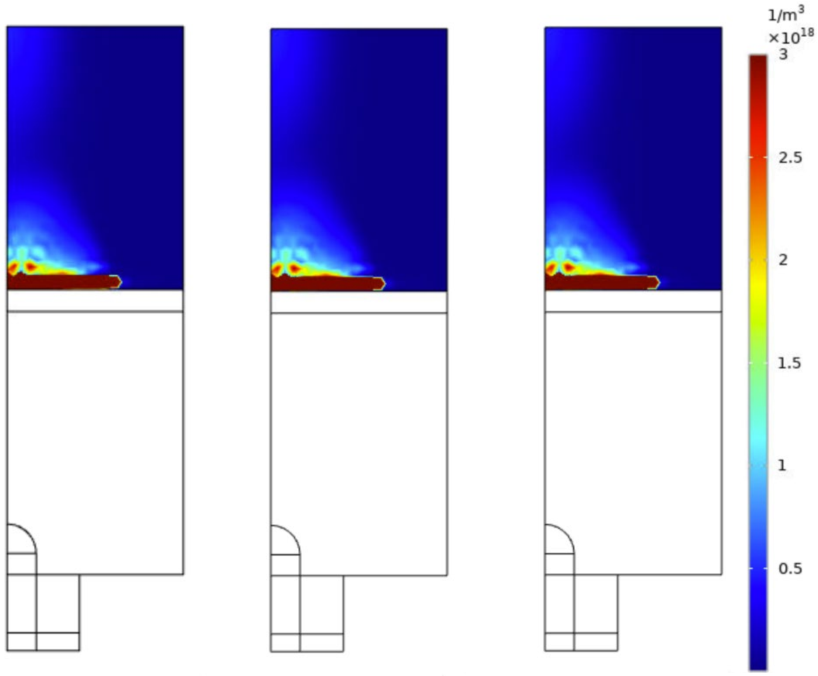

Figure 13. Electron density for antenna 1, 300 W, 16 torr, 0.02 m/s (left), 0.04 m/s (middle), 0.2 m/s (right) injection speed

The results for temperature inside the chamber and losses during operation also remained the same for all three injection speeds. These results show that the solutions from COMSOL Multiphysics are not dependent on injection speed as this simulation has been set up. This could be the result of not including the physics for fluids, which were not included in these simulations.

Chapter 5

Conclusions and Recommendations

EP systems are far more efficient and weigh much less than chemical propulsion systems. The higher specific impulse of EP systems means that EP systems will be used for deep space missions and attitude control of spacecraft. The MET is an EP system that can be used for long-duration missions because there are fewer components that degrade in the system compared to other EP systems.

The designs and operational conditions of a 2.45-GHz MET were studied using COMSOL Multiphysics. Microwave plasma physics and radio frequency physics were used to simulate the MET and observe the impact of different operational conditions for said MET. The results suggest that a shorter antenna performs better overall than a longer one, and that increasing power increases the percentage of power lost during operation. Increasing pressure had mostly desirable results. Plasma was generated in the center of the cavity rather than against the walls, and the increase in pressure also came with a decrease in power loss.

The simulations included in this thesis did not include fluid mechanics, and in future simulations, it should be included. The results of all these tests would change with the addition of fluid mechanics, and the impact of both pressure and propellant injection speed could properly be studied with fluid mechanics. The cavity was also simplified, and a more accurate representation of the MET cavity would yield more accurate results.

This MET was simulated with air inside of the cavity, with the intention of comparing the computational results with the experimental results. For more accurate information about the

MET and its operation in space, it should be simulated as a vacuum inside of the cavity. The MET should also be examined using different propellants. Argon was used in all of the simulations in this thesis, but the MET should be simulated with nitrogen because that is the propellant used in the lab.

The propellant injectors were modeled to be near the midplate for this thesis, but the results obtained from this injector placement are not desirable. Plasma is being generated near the midplate in these simulations, but plasma should be generating in front of the nozzle at the top of the model. Future simulations should have the electron imports and injectors placed at the top of the model, near the nozzle.

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- Simulated electric field and plasma generation using COMSOL Multiphysics
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- Presented my findings weekly in lab meetings

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- Tested the tool in local waterways
- Designed a waterproof casing for the device

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- Recorded experimental data electronically
- Analyzed educational data to help improve future physics education
- Developed codes to categorize student responses in research

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