Simulating Experimental Conditions of the HIIPER Space Propulsion Device

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Abstract: The Helicon-Injected Inertial Plasma Electrostatic Rocket (HIIPER) is a two-stage electric propulsion system comprising of a helicon plasma source and an inertial electrostatic confinement (IEC) device for plasma production and acceleration, respectively. Several diagnostics such as a Faraday cup, spherical Langmuir probe, and gridded energy analyzer have been developed for analyzing various properties of the jet. To supplement these experimental analyses, COMSOL has been used to create models of the experiment and diagnostics, analyze the electric potential, and predict the unknown heat impinging on geometrically complex diagnostics. COMSOL results regarding the potentials are presented, and preliminary COMSOL results of the thermal studies are shown and compared with experimental results. These comparisons show agreement between the experimental and computational data.

Keywords: plasma, helicon, inertial electrostatic confinement

1. Introduction

The Helicon-Injected Inertial Plasma Electrostatic Rocket (HIIPER) is an electric thruster used for space propulsion. HIIPER incorporates a high density plasma source known as a helicon, which acts as the ionization stage. In addition, an inertial electrostatic confinement (IEC) device has been modified to accelerate the plasma from the helicon. The IEC is therefore the acceleration stage of the thruster. The helicon source, consisting of an antenna surrounded by magnetic coils, ionizes argon gas. The plasma produced by the helicon then diffuses into the IEC chamber. The 61 cm diameter IEC chamber acts as an anode and houses a 12.5 cm diameter spherical wire grid that acts as a cathode. The ions form a core around the hollow center of the grid, and a small specified asymmetry in the grid causes a thin plasma jet to form[1].

Experiments are normally performed to measure different plasma properties. This is because the non-linear nature of plasmas makes predictive calculations difficult. Simple models have been developed in COMSOL to make preliminary predictions on certain experiments. Examples of early COMSOL simulations to test the feasibility of the experiment included simulating potential profiles of two plasma diagnostics: a spherical Langmuir probe and a gridded energy analyzer.

Furthermore, COMSOL has been used to back-calculate physical properties from experimental measurements. These calculations are not amenable to standard analytic techniques because of non-linear boundary conditions and complex geometries. These studies included the cooling curve and heat load on the Faraday cup plasma diagnostic.

2. Methods

Measuring the plasma properties of HIIPER involves utilizing various specialized diagnostics. These diagnostics are listed below.

2.1 Gridded Energy Analyzer

The gridded energy analyzer (GEA) is a newly constructed diagnostic in the HIIPER laboratory. The GEA consists of a collector plate to measure net current from the plasma and several biased grids that are used to filter ions and electrons of certain energies. This allows for an accurate determination of the ion and electron energy levels present in the jet. An image of the GEA with these various grids is shown in Figure 1.

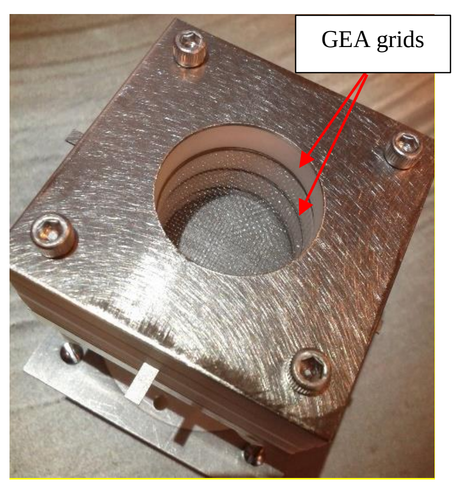

Figure 1. Top view of GEA.

In COMSOL, the experimental setup of the GEA was modeled and added to the IEC simulation that had previously been developed[2-3], and voltage boundary conditions were specified at several locations of interest using the AC/DC module: the IEC grid; the electron repeller grid, which rejects electrons below a certain energy level; the ion sweep grid, which accepts or rejects ions of varying voltages; and the secondary electron repeller, which rejects any secondary electrons that formed in the ion sweep phase. A simplified cut-away image of the GEA and IEC setup is shown below in Figure 2.

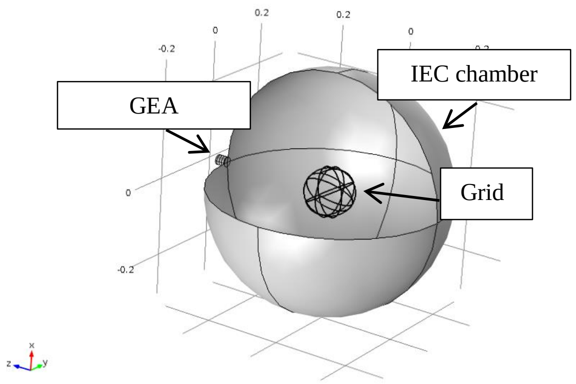

Figure 2. Simplified view of GEA and IEC setup.

The variation of the voltage vs. position from the IEC chamber wall to past the secondary electron repeller was then examined. In particular, the electron repeller and ion sweep voltages were varied so as to determine the behavior of the jet's potential before hitting the electron repeller grid. These results are described in Section 3.1.

2.2 Spherical Langmuir Probe

The spherical Langmuir probe is a spherically shaped electrode placed in the center of the IEC chamber. The Langmuir probe is a solid sphere with no holes, unlike a spherical IEC grid which has openings (holes) between the grid wires. The spherical Langmuir probe is used to mimic the spherical electric potential formed by the IEC grid, and it measures the current from the helicon plasma source. The probe is biased at multiple negative voltages, and the current at those voltages is measured. An image of the spherical Langmuir probe is shown below in Figure 3.

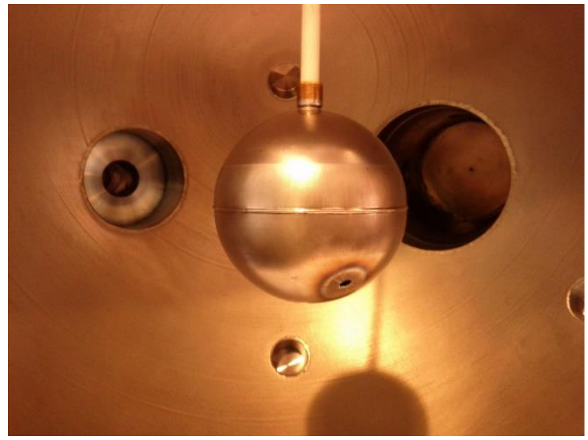

Figure 3. Spherical Langmuir probe inside IEC chamber.

The spherical Langmuir probe model was constructed as shown in Figure 4. The COMSOL simulation modeled the electric potential of the IEC chamber and the dielectric tube, which represents the helicon plasma source. The boundary conditions used in this model were Dirichlet boundary conditions. Voltage was set to -5000 V at the IEC grid and 0 V (ground) at the chamber walls. The helicon dielectric tube was not grounded as it is a dielectric, however the end face of the cylinder was set to 0 V due to it being conducting and grounded.

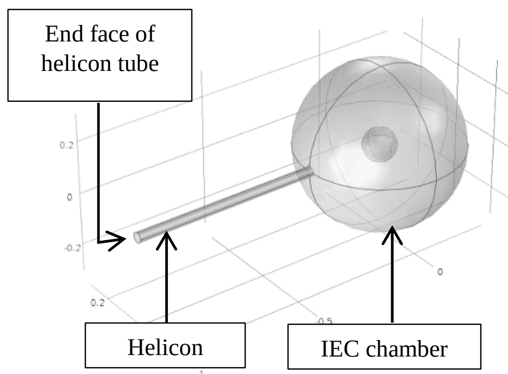

Figure 4. COMSOL model of dielectric tube attached to the IEC chamber.

The reason why negative voltages were used is because biasing the center electrode of the IEC positive requires a very powerful DC power supply. This is because the current flows from the chamber to the center electrode. The chamber has a higher surface area than the center electrode, therefore the current drawn is very large. Furthermore, biasing the center electrode of the IEC negative attracts ions from the helicon. Ions are the species of interest with regard to space propulsion. In addition, the IEC grid normally placed in the IEC is biased negative, and the plasma jet forms when the inner electrode is biased negative.

2.3 Faraday Cup

In simulating the Faraday cup, two separate analyses were conducted. First, the cooling curve, the rate at which the cup cooled after an experiment, was examined. Second, the rate of heating of the cup during jet operation was studied. This allowed for an estimation of the thermal power being input by the jet. Figure 5 below shows an image of the Faraday cup used in the experiments.

Figure 5. Faraday cup (no structure attached).

For both sets of analyses, a model of the actual Faraday cup was created in COMSOL, and it is shown below in Figure 6. Due to the preliminary nature of this work, several aspects were not included in this model, including a plasma shield that protects the Faraday cup from any plasma that did not originate in the plasma beam. In the model shown in Figure 6, the cylinder setup on the top is the actual Faraday cup, and it is made of 304 SS. The metal plates are used as supports for the Faraday cup, and they are made of aluminum. The four cylinders connecting these plates serve as insulators for the Faraday cup and are made of alumina.

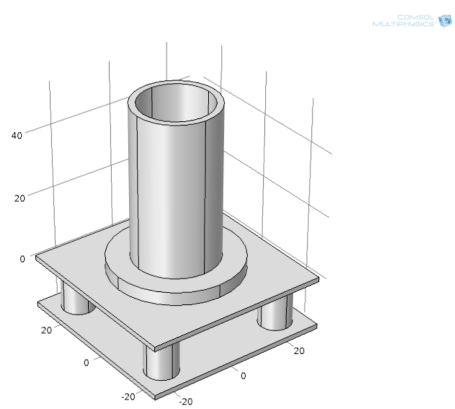

Figure 6. Faraday cup model.

For the cooling curve analysis, the entire model was set with an initial temperature of 94°C, which was determined experimentally. Radiative boundary conditions were set throughout the model. Convection was ignored due to this experiment being in vacuum, and conduction from the Faraday cup to other structural material not included in the model was neglected due to the preliminary nature of these studies. In this cooling analysis, the temperature was plotted as the Faraday cup cooled to ambient conditions. These results are described in Section 3.3.

For the heating portion of this analysis, the same model was used, however different boundary conditions were set: for the area inside the cup, a total thermal power was specified. Then, using experimental data for various IEC power levels, initial temperatures were set throughout the model, and the simulation time was set to equal the experiment duration. Following completion of the simulations, final temperatures and the overall slopes of the temperature-time plots were compared with experimental data. The simulations were then iterated by changing the total thermal power boundary condition until the slopes matched those of the experiment. The resulting thermal powers were then plotted against the corresponding slopes.

3. Results and Discussion

3.1 Gridded Energy Analyzer Results

The electric potential was plotted as a function of position, and it is shown below in Figure 7. The domain of the position is from the chamber wall (at -0.3 m) to past the secondary electron repeller grid (at 0.6 m). The minimum value corresponds to the voltage set at the IEC grid, -5000 V. As position increases, the potential increases until the electron repeller is encountered (set at -1000 V), at which the potential drops. The potential then suddenly rises as the ion sweep grid (500 V) is encountered. The potential then drops slightly due to the secondary electron repeller grid (-45 V), and then it rises to 0 V, which was set as a boundary condition.

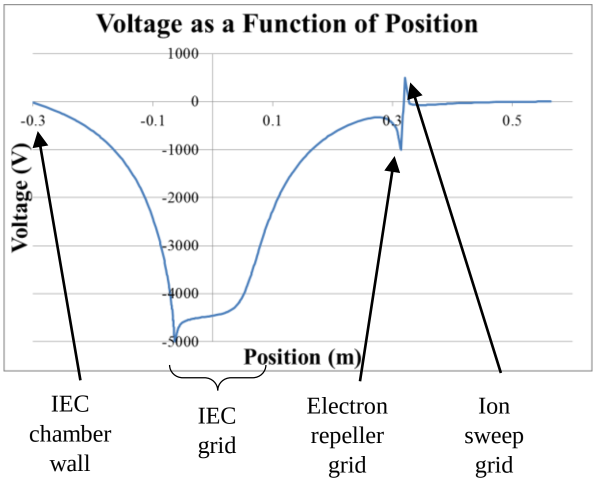

Figure 7. Voltage as a function of position.

This analysis is useful in that varying the electron repeller and ion sweep voltages allows for estimating the peak voltage inside the chamber near the electron repeller grid. Several of these studies were examined, with different electron repeller and ion sweep voltage combinations, and they are currently being used in the experimental analysis.

3.2 Spherical Langmuir Probe Results

The objective of this simulation was to find the voltage drop in the helicon dielectric tube when the spherical Langmuir probe is biased. The reason why this is important is to see if the ions in the helicon plasma will be drawn to the spherical probe when the probe is biased. The simulation gives an initial idea of the voltage drop expected within the helicon dielectric tube connected to the IEC. The results shown in Figure 8 reveal that a ~25 V voltage drop occurs in the helicon dielectric tube when the spherical Langmuir probe bias is at -5000 V. Note that the position is with respect to the center of the IEC chamber, and to reiterate, the IEC chamber has a radius of 0.3 m.

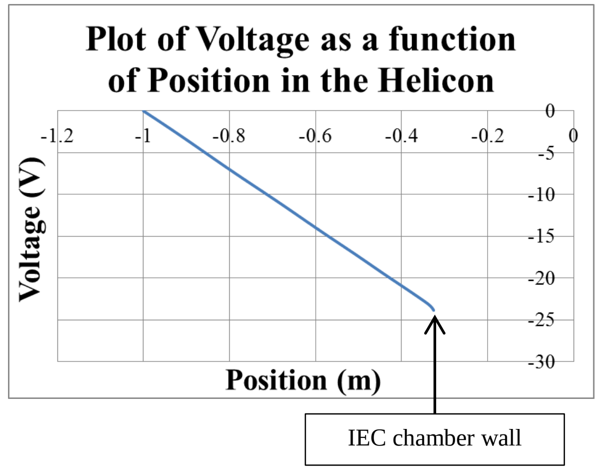

Figure 8. Voltage as a function of position in the helicon dielectric tube.

3.3 Faraday Cup Results

The cooling curve was plotted against time and compared with experimental data. This comparison is shown below in Figure 9. The results show a correspondence with the final temperatures, however the exact behavior of the curves do not match perfectly. This could be due to approximations made in boundary conditions, as the model used did not take into account the more complicated aspects of the Faraday cup, such as the plasma shield, as discussed above.

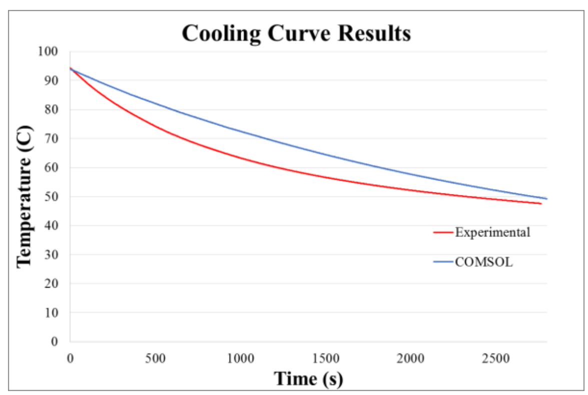

Figure 9. Cooling curve results.

For the heating portion of the study, the input thermal power values for different cases were then plotted against their respective changes in temperature over time (termed the “slope”). The different cases were of the IEC grid at 50 W, 100 W, 150 W, 200 W, and 250 W. The correlation of the thermal power to the slope is shown below in Figure 10. The relation between the thermal power and the slope allows for thermal power predictions, given data on temperature rise over time.

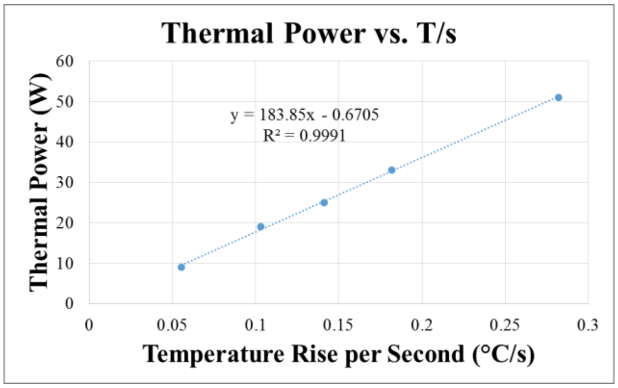

Figure 10. Thermal power vs. slope.

4. Conclusions

COMSOL was utilized to solve two different types of physics problem. The first physics type was the use of electrostatics to model the electric potential throughout the IEC and the GEA. In addition to modeling the GEA, the electric potential in the helicon dielectric tube was also simulated. This helicon tube potential drop was caused by a biased spherical Langmuir probe. These electrostatic simulations did not contain plasmas and were used to give preliminary results and ideas on how the plasma behaves under certain voltage profiles. The second physics type was heat conduction of a geometrically sophisticated object, the Faraday cup. The Faraday cup was hit with a plasma beam, and COMSOL was used to estimate the thermal power of the plasma beam. Multiple physics were taken into account such as heating (due to the plasma beam) and cooling (due to radiation heat transfer) which occur at the same time. The results from the COMSOL Faraday cup simulations generated a cooling curve which was compared with experimental data, and they also allowed for the generation of a heating calibration curve. Using this calibration curve, predictions can be made about plasma beam thermal power.

5. References

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6. Acknowledgments

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