Comparison of Plasma Diagnostics of a Helicon Thruster using Argon and Water Vapor with Helium

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Abstract: A comparison of the performance of a helicon thruster using argon or water vapor propellant with and without smaller concentrations of helium is presented. Measurements of electron temperature were collected using a retarding potential analyzer, a Langmuir probe, and emission spectroscopy. The primary propellants were tested alone and mixed with helium as a seed gas so that emission spectra analysis could be conducted with a helium collisional-radiative model. If the addition of helium does not have a significant effect on the plasma parameters, this diagnostic method can be used to determine performance characteristics with complex propellants.

Nomenclature

\[ A_{ji} = \text{transition probability from state } j \text{ to state } i \]
\[ C_{ij} = \text{Collisional excitation rate between particles in lower state } i \text{ and higher state } j \]
\[ C_{i-ion} = \text{ionization rate for particles in state } i \]
\[ C_{ij}^{-1} = \text{Collisional de-excitation rate between particles in higher state } j \text{ and lower state } i \]
\[ E_e = \text{electron energy} \]
\[ I_{ij} = \text{emission line intensity} \]
\[ k_B = \text{Boltzmann constant} \]
\[ m_e = \text{electron mass} \]
\[ m_i = \text{ion mass} \]
\[ n_i = \text{particle number density in state } i \]
\[ T_e = \text{electron temperature} \]
\[ S = \text{inner surface area of the tube} \]
\[ V_{\text{float}} = \text{Langmuir probe floating potential} \]
\[ V_{\text{max}} = \text{potential at which Gaussian peak occurs} \]
\[ V_{\text{space}} = \text{Langmuir probe space potential} \]
\[ \sigma_{ij} = \text{collisional cross section for the transition from state } i \text{ to } j \]

I. Introduction

A radio frequency (RF) powered helicon thruster was developed to research its suitability for use as a low thrust electric space propulsion system. The helicon plasma source was first proposed as a propulsion system by Charles and Boswell.1 They investigated a current-free double layer as the particle acceleration mechanism in their Chi-King experiment.2 3 The current-free double layer accelerates the ions in the plasma, producing thrust. Chen later proposed the acceleration mechanism is a free standing sheath identical to that which forms at a physical boundary in the plasma.4 The helicon thruster has several advantages over other electric propulsion systems. The

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RF antenna powering the thruster is not immersed in the plasma, making it less susceptible to erosion, and the exhaust is neutral, eliminating the need for an external electrode. Helicon waves have a higher ionization efficiency than capacitive or inductive coupling, requiring less energy per ion.

The purpose of this paper is to compare results from three different plasma diagnostics for use in determining the performance of a helicon thruster utilizing argon and water vapor with helium gas as a marker. The diagnostic tools used were a retarding potential analyzer (RPA), a Langmuir probe, and emission spectroscopy. A comparison of plasma parameters for argon and water vapor with and without helium added to the plasma is presented.

II. Experimental Set Up

The helicon thruster shown in Fig. 1 is housed in a 60 cm diameter, 1 m long vacuum chamber. The thruster itself consists of a 40 cm long, 2 cm diameter quartz glass tube surrounded by a single turn helical copper antenna and with a gas inlet at one end. The antenna is connected to an 1100 W RF power source through a matching network. Current running through the antenna creates a time varying magnetic field resulting in a curling electric field that accelerates free electrons in the gas to ionization energy. Three 6 cm diameter Helmholtz coils centered at the antenna provide the axial magnetic field, allowing for the formation of helicon waves. The coils yield a magnetic field strength of about 200 Gauss with 10 Amps of current. A retarding potential analyzer (RPA) is placed 7.6 cm downstream of the thruster exit. A Langmuir probe is exposed to the plasma in the thruster through a hole in the quartz tube in the center of the antenna. Emission spectra are collected through a fiber optic cable placed at the antenna center and connected to the spectrograph. Figure 2 shows an image of the helicon thruster running with argon gas. The blue color in the antenna center indicates a higher number of argon ions.

![Figure 1. Helicon thruster schematic.](image-url)
III. Plasma Diagnostics

The RPA designed for this experiment is based on RPAs used to measure plasma characteristics in Hall thrusters.\textsuperscript{5,6} An additional electron suppression grid was added before the collector plate to repel secondary electrons that would hit the plate and skew the ion current readings. The RPA measures the ion current as a function of discriminator grid voltage. Differentiating this current-voltage (I-V) curve results in a Gaussian distribution, the peak of which can be used to find the electron temperature of the plasma. The voltage at which this peak occurs, $V_{\text{max}}$, can be used to calculate the electron temperature using the following equation,

\[
T_e = \frac{2V_{\text{max}}}{1 + \ln \left( \frac{m_i}{2\pi m_e} \right)}
\]

where the free standing sheath acceleration model proposed by Chen (Ref. 4) has been assumed. Figures 3 and 4 show an example of an I-V curve and its derivative for a test with argon gas. The peak in the current derivative curve is located around 52 V, which equates to an electron temperature of about 10 eV for argon.

Figure 3. RPA I-V curve for argon at 0.002 mbar pressure, 200 W RF power, 200 G axial magnetic field.

Figure 4. RPA I-V derivative curve for argon at 0.002 mbar pressure, 200 W RF power, 200 G axial magnetic field.
The RF compensated Langmuir probe design was based on a probe used by Chen. The Langmuir probe returns a plot of electron current as a function of probe voltage. This relationship is used to determine the electron temperature of the plasma. Figures 5 and 6 show an example of a Langmuir probe I-V curve and its derivative for an argon gas test. The floating potential, \( V_{\text{float}} \), is the zero current crossing on the I-V plot, -3V in Fig. 5, and the space potential, \( V_{\text{space}} \), is the location of the minimum of the \(-dI/dV\) curve, 71 V in Fig. 6. The electron temperature is calculated using the following equation from Ref. 7, and has a value of 14 eV.

\[
T_e = \frac{2(V_{\text{space}} - V_{\text{float}})}{\ln\left(\frac{2m_i}{\pi m_e}\right)}
\]

\[ (2) \]

Emission spectroscopy is advantageous for plasma diagnostics because it is non-invasive and requires only a line of sight. Unlike the RPA and Langmuir probe, different species, doubly versus singly ionized particles or even neutrals for example, within the plasma can be identified. The disadvantage is that analysis of the spectra is complicated. This analysis was accomplished by developing a collisional-radiative (C-R) model, a technique which has been implemented with other helicon plasma experiments. Both the argon and helium C-R models predict the emission spectra for a user specified electron temperature and electron density by calculating the population densities of particles in different energy states based on various transitions. Those transitions are as follows: electron induced excitation and de-excitation collisions, electron induced ionization collisions, spontaneous de-excitation, and recombination at the tube walls. Each of these transitions equates to a rate of particles entering or leaving a given energy state. Summing all the possible transitions to and from any state, \( m \), gives the total rate of change of the population density of a particle in state \( m \) per unit time,

\[
\frac{dn_m}{dt} = \sum_{j<m} n_j n_e C_{jm} - \sum_{k>m} n_m n_e C_{mk} + \sum_{l>m} A_{lm} n_k - \sum_{j<m} A_{jm} n_m + \sum_{k>m} n_k n_e C_{km} - \sum_{j<m} n_m n_e C_{ji} - n_m n_e C_{m-\text{ion}} + \sum_i S_{ln_i} \sqrt{\frac{k_B T_e}{m_i}}
\]

\[ (3) \]

where \( j \) represents all the energy levels below state \( m \), \( k \) represents all the energy levels above state \( m \), and \( l \) is the total number of energy states. The collisional rates are a function of the collisional cross sections and therefore a function of electron temperature, given by the following equation for collisions resulting in an energy level transition from state \( i \) to state \( j \):
\[ C_{ij} = \int_{0}^{\infty} \frac{2E_e}{\sqrt{\pi(k_B T_e)^{3/2}}} \exp\left(\frac{-E_e}{k_B T_e}\right) \sigma_{ij} dE_e \]  

(4)

The atomic spectral data used in the C-R model, such as spectral lines, transition probabilities, and atomic energy levels came from the NIST atomic database.\textsuperscript{10} Collisional cross sections for each energy state as a function of electron energy were computed using parameters and formulas found in the literature.\textsuperscript{11,12} In steady state, the population number density rate, \(dn_m/dt\) is zero and the right hand side of the equation can be written as a square \(N\times N\) matrix, where \(N\) is the number of total states for both neutral particles and singly ionized particles. This square matrix is multiplied by an array of \(n_m\), the number density at each state. The number density array is the unknown and is computed by finding the null space of the rate matrix. The intensity of an emission line corresponding to a transition from level \(j\) to level \(i\) is given by the number density at given energy state and the transition probability,

\[ I_{ij} = n_j A_{ji} \]  

(5)

Figure 7 shows a simulated argon and helium spectrum; a plot of emission line intensity as a function of wavelength.

Figure 7. Simulated spectra from argon and helium C-R models for an electron density of \(10^{18}\) m\(^{-3}\) and an electron temperature of 15 eV.

Comparison of the simulated data to the helicon plasma spectrograph data is done by computing line intensity ratios. The intensity ratios of pairs of prominent emission lines are plotted as a function of electron temperature and the temperature yielding the closest match to the line ratio in the data is assumed to be the electron temperature of the plasma. The Helium C-R model is much less complicated than the argon model since there are fewer transitions and more complete and accurate cross section data are available. Analysis using the helium model is therefore easier and should yield better estimates of the electron temperature and density, so helium was added to the propellant as a seed gas for analysis purposes. The ratios of the helium emission lines visible in the spectra were compared to a series of C-R model generated spectra for a range of electron temperatures and densities to find the closest fit. Because a water vapor C-R model would be very complex and rely on sparse collisional cross section data, the estimate of electron temperature would not be very accurate. If the helium C-R model can return a more precise temperature estimate for the argon and helium plasma, then the same type of analysis can be used to determine the electron temperature of a water vapor plasma seeded with helium. Assuming the addition of helium to the propellant does not significantly affect the RPA and Langmuir probe measurements, the performance characteristics of the thruster propelled by pure argon and water vapor can be determined from the plasma parameters obtained from the seeded gas.
IV. Results

The use of multiple plasma diagnostics is intended to make the estimate of electron temperature more accurate and to provide corroboration among the different techniques. The following results show the effect on each diagnostic of adding helium gas to argon and water vapor propellant.

A. RPA Results

The RPA current-voltage and derivative curves in Fig. 8 through 11 show a comparison of the helicon thruster operating with pure argon or water vapor and argon or water vapor mixed with helium. The plots for 100% argon and 75% argon with 25% helium (by number) in Fig. 8 and 9 show the average of five consecutive RPA tests (the darker line), the smoothed fit to the data (the brighter line), and the standard deviation for the five tests (the error bars). The maximum difference between the currents for each propellant case is around 8% lower current for the pure argon test. This deviation of 8% was also found in the RPA current readings between different tests with the same concentration of argon and helium with the same pressure, RF power, and magnetic field strength, indicating that adding helium to the argon propellant does not contribute to a significant change in the ion current at the thruster exit. The peaks of the Gaussians in the derivative plots (Fig. 9) show a $V_{\text{max}}$ of 52 V for both gases, yielding an electron temperature of 10 eV.

The current-voltage curve in Fig. 10 shows a comparison between water vapor and water vapor mixed with helium with a ratio of 80% water vapor to 20% helium. This plot also shows the average of five tests, the smoothed data and the standard deviation. The water vapor pressure is more difficult to hold constant because the gas is not stored in a regulated tank like the argon, so the data show more fluctuation than the argon. The derivative of the unsmoothed current does not clearly show the peaks so only the derivatives of the smoothed curve fits are shown in Fig. 11. The maximum difference between the currents for each propellant case is higher than that for the argon tests at 14%, but still within a few percent of the deviation between separate tests with identical conditions. The water vapor current curves show two steep drops instead of one, resulting in two peaks in the derivative plots in Fig. 11. The electron temperature estimate from the first peak is less than 1 eV for the water vapor test and 2 eV for the water vapor/helium test. The temperature estimate from the second peak is 13 eV and 12 eV respectively. Multiple peaks could indicate the presence of particles with two different energy distributions. The argon tests show a smaller initial drop which may also be a lower energy particle distribution, but it is not as clear as the water curves.
B. Langmuir Probe Results

Figures 12 through 15 show the electron current to the Langmuir probe tip as a function of voltage and the negative of the derivative of the current as a function of voltage for each propellant with and without the helium seed gas. Figures 12 through 14 show an average of 10 consecutive probe tests (the darker line), the smoothed fit to the data (the brighter line), and the standard deviation (the error bars). The water vapor data had more outliers because of small pressure fluctuations so only the derivative of the smoothed data is plotted in Fig. 15. For the pure argon and the 75% argon / 25% helium tests, $V_{\text{float}}$ is -12 V. The argon/helium mix current is 12% lower than the argon current at its maximum deviation. As with the RPA tests, the same deviation between two tests of the same argon/helium gas mix at the same test conditions was nearly the same, 11%. The maximum difference between the water vapor and water vapor / helium mix current is larger than the argon deviation at 20%, but this may be attributed to the larger deviation from the average current. Determining $V_{\text{space}}$ is more difficult since there are two minimum peaks with overlapping error bars in the derivative curves in Fig. 13 and 15. Taking the first minimum at a $V_{\text{space}}$ of 67 V for the pure argon test and 70 V for the argon / helium mix test indicates an electron temperature of 15 eV. The second minimum at 95 V for argon and 98 V for argon / helium mix would estimate an electron temperature of 20 eV. The water vapor tests are less consistent. $V_{\text{float}}$ is 11 V for the water vapor test and 21 V for the water vapor / helium mix. $V_{\text{space}}$ according to the first minimum peak is 48 V for water vapor and 60 V for water vapor / helium, resulting in electron temperatures of 7 eV and 8 eV. The second minima occur at 78 V for water vapor and 95 V for water vapor / helium, which would estimate electron temperatures of 14 eV and 15 eV. These temperatures are higher than those estimated by the RPA. One possible cause is that the Langmuir probe is positioned in the center of the antenna, while the RPA is in the exit plume. There could be additional heating from the close proximity to the antenna, causing the Langmuir probe to show higher electron temperatures. The variation in the derivative curve for the Langmuir probe data is also small, on the order of 1% to 3% of the electron current values, which contributes to the difficulty in determining a definite minimum. However, the addition of helium to the argon does not appear to affect the electron temperature estimates from the Langmuir probe significantly more than the deviation between separate thruster tests.
C. Emission Spectroscopy Results

The electron temperature estimate from the emission spectroscopy analysis is highly dependent on the accuracy of the collisional cross sections and therefore, the error in the estimate is large. Figure 16 shows the spectra collected from a test utilizing a mix of 75% argon and 25% helium gas by pressure and a test utilizing only argon. The helium emission lines visible in this range at 492 nm, 502 nm, and 505 nm appear in the spectrum for the argon/helium mix in light blue on the plot. All argon emission lines in the range displayed in the plot (480-520 nm) are singly ionized argon (Ar+) lines. This is supported by the observed blue color inside the thruster antenna (see Fig. 2). Iterating the helium C-R model to find the closest line ratio matches for the 502 nm and 505 nm lines
returned a value of $10^{16}$ m$^{-3}$ for electron density and 9 eV for electron temperature. This is within 1 eV of the electron temperature estimates from the RPA, shown in Fig. 9.

The water vapor spectra comparison is shown in Fig. 17. The only emission line visible in this wavelength range for the pure water vapor test, plotted in blue, is the hydrogen Balmer line (H-$\beta$) at 486 nm. The water vapor / helium mix spectrum shows the H-$\beta$ line as well as helium lines at 492, 502, and 505 nm. Iterating the helium C-R model to find the closest line ratio matches for the 502 nm and 505 nm lines returned a value of $10^{16}$ m$^{-3}$ for electron density and 10 eV for electron temperature. This estimate is 2 to 3 eV lower than the water vapor RPA prediction and in between the two possible estimates from the Langmuir probe. An indication of a large potential error in the C-R model analysis is a lack of an intercept between the model line ratios and the data line ratio for some of the line pairings. For the tests shown here, the helium line ratios examined were 492 / 502 nm, 492 / 505 nm, and 502 / 505 nm. Only the 502 / 505 nm ratio matched the data for any combination of electron density and temperature.

Figure 16. Spectra for argon and 75% argon / 25% helium at 0.002 mbar pressure, 200 W RF power showing Ar+ emission lines and helium emission lines at 492 nm, 502 nm and 505 nm.

Figure 17. Spectra for water vapor and 80% water vapor / 20% helium at 0.005 mbar pressure, 200 W RF power showing the H-$\beta$ line at 486 nm and helium emission lines at 492 nm, 502 nm and 505 nm.
To demonstrate the effect of adding helium gas to the water vapor on the emission line intensity, spectra taken with a coarser grating for tests with and without the seed gas are shown in Fig. 18. The hydrogen emission line intensities from the mixed gas are about 5% higher than the intensities from the water vapor alone. This is a small difference and with the intensity deviation between separate tests run at identical conditions.

![Spectra](image)

**Figure 18.** Spectra for water vapor and 80% water vapor / 20% helium at 0.005 mbar pressure, 200 W RF power showing hydrogen emission lines at 486, 434 and 410 nm, and helium emission lines at 588, 505, 502, 492, 471, 447 and 439 nm.

**V. Discussion**

Although there is some consistency between the results from the RPA and helium C-R model, the discrepancies in the estimate of electron density and temperature across all diagnostics indicate that more work needs to be done. Each diagnostic has advantages and disadvantages. The RPA must be located in the thruster exit plume and therefore does not measure the same plasma as the spectrograph and Langmuir probe. The RPA analysis assumes a uniform plasma and ion acceleration via a free standing sheath. Visual inspection of the thruster indicates that the plasma throughout the quartz tube is not uniform. The color and intensity change from the center of the antenna, downstream in the tube, and at the thruster exit. The RPA measurements may not corroborate those from the other diagnostics because of this plasma non-uniformity. The presence of more than one Gaussian distribution in the RPA current derivative indicates that there are particles with multiple energy distributions in the plasma and may invalidate the sheath assumption. The Langmuir probe is invasive and susceptible to RF and magnetic fields. It is RF compensated, but magnetic fields can alter the electron temperature and density measurements. An uncompensated probe will be tested in the thruster to compare the electron temperature estimates and verify that the probe is compensating properly for the RF field. This may resolve discrepancies between the emission spectroscopy results and the Langmuir probe results.

Emission spectroscopy is not affected by RF or magnetic fields, but the C-R model is dependent on collisional cross section data and models that may not be accurate or may not exist for certain energy states. There are several assumptions made for the argon and helium C-R models that may need to be reconsidered. The plasma in the volume seen by the spectrograph is assumed to be uniform and quasi-neutral. The plasma is assumed to be optically thin; meaning any radiation created in the plasma will leave the volume and not be reabsorbed. The electron distribution function is assumed to be Maxwellian. The only mechanism for ion neutralization is recombination at the tube walls, since there is negligible three body recombination. Lastly, only certain transitions are modeled and others, like photo-absorption and radiative recombination of electrons, are considered negligible. Because of the complex and non-uniform nature of the plasma, these assumptions may need to be reevaluated.
VI. Conclusion

A helicon thruster was tested with argon and water vapor seeded with helium to quantify the performance. Measurements of the plasma using an RPA, Langmuir probe, and emission spectroscopy showed small variation in measurements taken for the seeded and unseeded propellants, but the difference is within the range of deviation between separate tests of the thruster at identical conditions with identical propellants. Despite discrepancies between diagnostics, adding helium to the propellant does not appear to have a significant effect on the electron temperature estimates and could be a promising technique for determining plasma parameters using emission spectroscopy. Establishing a method for corroborating the plasma diagnostics will help validate results from helicon thruster tests with more complex propellants. The performance metrics calculated from these tests will be used to measure the loss in performance for propellants that are harder to ionize. Because of the difficulty in matching the helium line ratios to the data, the C-R models will be revisited. Being able to use helium as a seed gas and leveraging the simpler helium C-R model would be beneficial in analyzing more complicated propellants.

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References