Langmuir probe plasma diagnostics to investigate the dielectric properties of cryogenic gas mixtures

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Abstract. Use of the Langmuir probe plasma diagnostics to investigate the dielectric properties of gas mixtures is discussed as a continuation of our previous experimental and theoretical work on understanding the dielectric strength of helium gas mixtures for superconducting and other cryogenic applications. Here we report the results of Langmuir probe experiments conducted on the gas mixtures to obtain plasma parameters including plasma density and the electron temperature. The experimental procedure used in the Langmuir probe plasma measurements, the derivation of the plasma characteristic parameters, and the implications of the results to the dielectric characteristics are discussed. The plasma characteristics obtained under various discharge power, gas pressure, and gas composition are also discussed. The results support the findings of our previous theoretical and experimental studies that showed substantial enhancement of dielectric strength of He gas obtained by the addition of small mol\% of H\textsubscript{2} and relate the enhancements to the plasma characteristics observed.

1. Introduction

Liquid nitrogen (LN2) has been the standard cryogen for high temperature superconducting (HTS) power applications, but gaseous helium (He) is being studied as an alternative to LN2 for naval and aerospace applications because of its wider operating temperature range and potential to allow higher power densities [1–2]. However, one of the drawbacks of He is its low dielectric strength compared to that of LN2. In an attempt to overcome this drawback and identify means of enhancing the dielectric strength of He, we have been engaged in systematic theoretical and experimental studies [3–6]. We have reported on substantial enhancements in the dielectric strength of He by the addition of small mol\% of H\textsubscript{2} experimentally and later developed theoretical understanding of the enhancements through the Boltzman analysis [3–6].

This study is on the use of plasma experiments as means to understanding the dielectric properties of gas mixtures. Plasma is ionized gas consisting of electrons, ions, and neutrals species. Dielectric breakdown phenomena in gases is in the form of plasma. Hence plasma studies shed light on fundamental phenomena related to the dielectric characteristics of gas mixtures. Plasma is initiated by electrons and the electron energy distribution is effected by various electron heating mechanisms. Among the electron heating mechanisms, secondary emission heating plays a crucial role in the
production of plasma and in the electron heating in high pressure dc discharges (i.e., dielectric breakdown) as well as in low pressure (in the range of mTorr) dc glow discharges. We generated a low-pressure dc plasma with various compositions of helium and hydrogen gas mixtures and measured the I-V characteristic curves of the plasma by a Langmuir probe inserted in the plasma. The I-V characteristic curves are used to derive the electron energy distribution function (EEDF). Differentiation of the I-V characteristic curves twice with respect to the probe voltage results in the EEDF. The EEDF contains the complete set of plasma information. By using EEDF and the electron scattering cross section data of the constituent gas species, plasma density, effective electron temperature, and the rate coefficients of electron kinetic processes including ionization and attachment processes can be obtained. An analysis of the results of plasma experiments show that when H₂ is mixed with He, the plasma density, effective electron temperature, and ionization rate constant are decreased while the attachment rate constant is increased.

![Figure 1. Experimental setup for plasma measurements.](image)

2. Experimental Procedure

Figure 1 shows the experimental setup used for the dc plasma experiments. Experiments were conducted in a plasma chamber made a cylindrical borosilicate glass (Pyrex) tube with dimensions of 51 mm in diameter and 400 mm in length. The chamber is equipped with an anode and cathode made of stainless steel on both ends. A negative dc voltage of -300 to -400 V was applied to the cathode through a dc power supply keeping the anode grounded. A mass flow controller (MFC) was used to supply a constant gas flow of 5 sccm (standard cubic centimeter per minute) while the gas pressure was maintained at 40 mTorr (5.33 Pa) by a calibrated absolute capacitance manometer (MKS Baratron). A single Langmuir probe with a tip made of 0.125 mm diameter and 1 cm long cylindrical tungsten wire was placed at the center of the positive column of dc plasma generated by 100:0 and 96:4 He-H₂ mixtures by molar ratio. The current-voltage (I-V) characteristic curve of the plasma were measured through a digital multimeter (Rigol DM3058E) by sweeping the probe voltage from -50 to 0 V. Rp is a parallel resistor, which was used to achieve four-quadrant power supply with a two-quadrant power supply, and Rb is a resistor that stabilizes the dc plasma discharge. Ip is the probe current and Id is the discharge current of the plasma.

When the probe voltage is strongly negative, probe current is mainly ionic. Ions have substantially larger mass and lower velocities than electrons and thus result in smaller current magnitudes. As the probe voltage is increased, at a particular voltage the ionic current is equal to electronic current. The potential corresponding to this point is called the floating potential at which the net current is zero. As the probe voltage is further increased, the electron current increases exponentially until the probe voltage reaches the plasma potential. At plasma potential the probe potential and plasma potential are equal indicating the absence of electric potential gradient between them. Due to the lack of potential gradient
between the probe tip and plasma, electrons of any energy can enter the probe. That is, electron current is determined by the surface area of the probe. However, a further increase in the probe potential increases the probe sheath thereby increasing the effective surface area of the probe. Increased probe surface area enables the probe to collect more electrons and thus the probe current further increases (figure 2).

The measured I-V characteristic curves are differentiated twice with respect to the probe voltage to obtain the electron energy probability function (EEPF) based on the Druyvesteyn formula shown below [7].

\[
f(\varepsilon) = 2(2m_e)^{1/2} \left( \varepsilon^3 A \right)^{1/2} \frac{d^2 I_p}{dV_p^2}
\]

where \( m_e \) is the electron mass, \( e \) is the elementary charge, \( I_p \) is the probe current, \( V_p \) is the probe voltage, and \( A \) is the surface area of the probe tip.

![I-V Curve Example](image1.png)

**Figure 2.** EEPF is calculated from the measured I-V characteristic curve based on the Druyvesteyn method.

Once the EEPF is obtained, the electron energy distribution function (EEDF) is derived by the following relationship.

\[
F(\varepsilon) = \sqrt{\varepsilon} f(\varepsilon)
\]

Then, the plasma density \( n \) and the effective electron temperature \( T_{\text{eff}} \) can be obtained by integrating the EEDF as follows.
\[ n = \int_{0}^{\infty} F(\varepsilon) d\varepsilon \]  

(3)

\[ T_{\text{eff}} = \frac{2}{3} \langle \varepsilon \rangle = \frac{2}{3n} \int_{0}^{\infty} \varepsilon F(\varepsilon) d\varepsilon \]  

(4)

Note that \( \langle \cdot \rangle \) is a symbol for average. Furthermore, rate coefficients can be calculated by using the EEDF and the electron scattering cross sections of constituent gases as follows.

\[ K_j = \langle \varepsilon \sigma_j(\varepsilon) \rangle = \frac{1}{n} \int_{0}^{\infty} \varepsilon \sigma_j(\varepsilon) F(\varepsilon) d\varepsilon \]  

(5)

The relative dielectric strength of gas mixtures can be observed by comparing \( n \), \( T_{\text{eff}} \), and \( K_j \), but only under the identical conditions of discharge power and gas pressure since these conditions influence the plasma parameters. In many cases, effective electron temperature \( T_{\text{eff}} \) could be sufficient in assessing the dielectric strength of gas mixtures. With high \( T_{\text{eff}} \), the rate of ionization collisions increases leading to electron multiplication or avalanche that precedes a dielectric breakdown event. Therefore, gas mixtures with lower \( T_{\text{eff}} \) generally show high dielectric strength.

**3. Results**

**3.1. EEPF and Gas Pressure**

Figure 3 shows the variation of EEPF at different gas pressures. The high electron energy tail of the EEPF (i.e., the values of EEPF at high electron energy) decreases more rapidly as the gas pressure is increased. The steeper negative slope of EEPF indicate fewer number of high energy electrons, which
is mainly due to increased electron energy dissipation caused by increased electron-to-neutral particle collisions. As a result, measured effective electron temperature $T_{\text{eff}}$ decreases from 8.95 eV to 8.07 eV. Unlike $T_{\text{eff}}$, plasma density $n$ increases with gas pressure. The mean free path of ions reduces at higher gas pressure and thus reduces the leakage of electrons and ions through the chamber wall. The reduction of electron and ion leakage increases plasma density. The experimental results indicate that the gas pressure should be maintained at a constant value when observing the relationship between EEPF and the gas composition.

3.2. EEPF and Discharge Power

Figure 4 shows the variation of EEPF at various gas discharge powers. The EEPF gradually becomes straighter, which indicates that the EEPF is approaching closer to the Maxwellian distribution, as the discharge power is increased. The Maxwellianization of the EEPF is caused by increased electron-to-electron collisions because $n$ increases with the discharge power. Unlike $n$, the measured values of $T_{\text{eff}}$ decrease at higher discharge power, which might be caused by the Maxwellianization of the EEPF. These results indicate that the discharge power should also be maintained at a constant value when observing the relationship between EEPF and the gas composition.

3.3. EEPF and Gas Composition

Figure 5 compares the EEPF of the studied two gas mixtures - 100:0 and 96:4 He-H₂ in molar ratio. As seen in the figure, the measured EEPF of the He-H₂ mixture with 96:4 molar ratio shows higher values in the lower range of electron energy and lower values in the higher range of electron energy than that of the mixture with 100:0 molar ratio. Accordingly, the $T_{\text{eff}}$ of the 96:4 He-H₂ mixture (8.82 eV) is lower than that of the 100:0 mixture (9.75 eV). In addition, the $n$ of the 96:4 mixture is lower than that of the 100:0 mixture.

![Figure 5. The variation of EEPF caused by gas composition.](image_url)
The reduction in both $T_{\text{eff}}$ and $n$ is mainly due to the reduction of ionization efficiency (i.e., collision efficiency) that can be attributed to the numerous excitation electron scattering cross sections of H$_2$ in the 96:4 He-H$_2$ gas mixture. Figures 6 and 7 compare the electron scattering cross sections of He and H$_2$. As seen in the figure, H$_2$ has more abundant inelastic collision cross sections than He, which significantly dissipate electron energy. The results also support our previously reported theoretical and experimental studies that showed dielectric strength improvements when H$_2$ was added to He gas [3–6].

4. Discussion
One might wonder if the plasma experimental measurements conducted at 30–50 mTorr (10 mTorr = 1 Pa) represents the dielectric breakdown phenomena occurring at atmospheric and above-atmospheric pressures. The experiments in the pressure range of several mTorr do result in information relevant to high pressure dielectric behaviour as long as the discharge power and the gas pressure, which alter EEPF, are maintained while only gas composition is changed, and the resulting measurements could be used for evaluating the dielectric strength variation in gas mixtures. Also, the Langmuir probe plasma diagnostics method used in this study is applicable to gases at cryogenic temperatures since the breakdown phenomena is dictated by electron–neutral interactions, which is not significantly affected by gas temperature. In fact, neutral gas particle velocity at ambient is already substantially slower than those of electrons that often they are assumed to be stationary.

5. Conclusion
We used dc plasma characteristics for studying the dielectric properties of gas mixtures. Langmuir probe was used to measure the EEPF of He-H$_2$ plasma. EEPF was affected by gas pressure and discharge power. Hence, we maintained both gas pressure and discharge power at constant values while measuring the EEPF of the two gases, pure He and and 96% He + 4% H$_2$ mixture. The results of the study showed reductions in both the electron temperature and plasma density, which are both signs of dielectric strength improvement in the case of 96:4 He-H$_2$ gas mixture. This study - as a part of our broad investigation in understanding the dielectric strength of gas mixtures and to develop gas-cooled HTS power devices for MVDC systems on electric ships, aircrafts, and other applications - provided the relationship between the plasma characteristics and the dielectric strength of gas mixtures.
6. References

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