Comparison of electron temperature in DC glow discharge and AC glow discharge plasma

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Abstract. Knowing electron temperature and electron density is important for any plasma related applications. In this research, the electron temperature and electron density of argon plasma generated by low frequency AC power supply and a high voltage DC power supply were investigated. The measurements were compared, both experimentally and theoretically. For the experiment, a long glass cylindrical tube was used as a chamber where the electrodes were placed at 37.5 cm apart. A high voltage function generator power supply was operated at various frequencies and it was also used for DC operation. The electron temperatures were measured by Optical Emission Spectroscopy (OES) technique for different operating pressures of 0.1 mbar, 0.6 mbar and 1.1 mbar. For the simulation, both plasma theory and finite element method were used to simulate dynamics of the plasma in the cylindrical setup. From the experiment, the range of breakdown voltage was found to be between 0.80 to 2.3 kV. The length of DC glow discharge dark regions of the plasma decreases due to increasing in both operating pressure and voltage. AC glow discharge shows positive charge and negative charge swing. From the DC discharge, the maximum value of electron temperature was found to be 0.810 eV and the minimum value was 0.610 eV under the operating pressure 0.1 and 0.6 mbar respectively. From AC glow discharge plasma, the maximum electron temperature was 0.907 eV and the minimum was 0.540 eV under operating pressure 0.1 and 1.1 mbar respectively. Collision loss between ions and electrons causes this variation in the results.
1. Introduction
DC glow discharge plasma and AC glow discharge plasma has been applied in many field applications such as material science modifications [1–3] and water treatments [4,5]. Therefore, understanding characteristics of the plasma such as an electron temperature of plasma is very important.

Many researchers had tried to determine electron temperature of plasma. Garamoon A A et al [6] experimented on the DC glow discharge system operated under operating pressures of the argon gas between 1 – 8 torr. They used optical emission spectroscopy (OES) technique to determine the electron temperature which they found to be between 0.3 – 0.9 eV. Honglertskul K and Ngamrungruj D [7] measured the electron temperature of nitrogen plasma under the different pressures of 0.15, 0.30, 0.44, 0.67, 1.00 and 1.90 mbar, with the operating voltage ranged between 800-1400 V. The electron temperature was found by using OES technique to be 0.8 eV. Kongpiboolkid W [8] studied an argon plasma that is generated by AC glow discharge system. The operating frequency of the AC power supply was varied between 500 – 8000 Hz. The electron temperatures of plasma calculated from experimental results were compared with the simulation results. In the research, a finite element method was used to simulate the dynamics of plasma, and the electron temperatures were found to be between 1.0 – 1.5 eV.

In this research, we attempt to show and compare the characteristics of the plasma in different plasma systems. Moreover, we investigate how operating frequency of AC power supply relates to the characteristics of the plasma. The simulation model, experimental setup, and the measurement methods are described in the following section.

2. Simulation and experiment
A plasma glow discharge system consists of a cylindrical glass tube as shown by diagram in figure 1 is used in the experiment. This cylindrical tube has two parallel electrode plates, and the length of the tube is 47.5 cm. The distance between the electrodes is 37.5 cm. In this research, the plasma glow discharge system was operated with a DC power supply and an AC power supply. Pure argon gas was used as the operating gas. The operating pressure of the argon gas was varied to be 0.1, 0.6, and 1.1 mbar. The frequency of the AC power supply investigated was 20 Hz, 50 Hz and 1000 Hz.

![Figure 1](image_url)  
**Figure 1.** Diagram showing (a) plasma glow discharge system and (b) measurement setup of the setting of the Optical Emission spectrometer (OES).

2.1. DC and AC glow discharge simulation
In the simulation, the characteristics of the plasma were simulated by using finite element simulation software (COMSOL). The dynamics was modeled by using electrostatic theory and transport theory. The theories were combined to calculate parameters of the plasma.

The electrostatic theory was used to calculate the electric field that affected the dynamics of electrons and ions in the plasma, and the equation could be shown as;

\[ E(r, t) = \frac{1}{\epsilon_0} \frac{\partial \phi(r, t)}{\partial t} \approx \frac{1}{\epsilon_0} \frac{\partial \phi(r, t)}{\partial t} \]

\[ \phi(r, t) = \frac{Q}{4\pi \epsilon_0 r} \]

\[ \frac{\partial^2 \phi(r, t)}{\partial r^2} + \frac{1}{r} \frac{\partial \phi(r, t)}{\partial r} = 0 \]

Where, \( \phi(r, t) \) is the electric potential, \( Q \) is the charge, \( \epsilon_0 \) is the permittivity of free space, and \( r \) is the radial distance.
\[
\n\vec{D} \cdot (\varepsilon \vec{E}) = \rho_f
\]

where \(\vec{D}\) is electric displacement field, \(\rho_f\) is charge density in the space, \(\varepsilon\) is permittivity in medium, \(\vec{E}\) is electric field in the medium. The transport theory was used to estimate the characteristics of the plasma such as the electron temperature, number density of ions, and number density of electrons.

The electron transport equations used to explain dynamics of the electron are written as;

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{r}_{en} = R_e - \vec{u} \cdot \nabla n_e
\]

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{r}_{en} + \vec{E} \cdot \nabla = S_{en} - \vec{u} \cdot \nabla n_e + (Q)
\]

where \(n_e\) is number’s density of electrons, in this research used mass of argon, \(n_e\) is energy number density of electron, \(R_e\) is an electron creation rate, \(S_{en}\) is an energy loss/gain from inelastic collisions, \(\vec{u}\) is a vector field ions velocity, \(Q\) is a total heat source, \(r_{en}\) is an electron flux, \(r_{en}\) is an electron energy flux.

The transport of neutral and ion gas in the plasma was also determined by using continuity equation presented by;

\[
\rho \left( \frac{\partial \mathbf{w}_k}{\partial t} + \vec{u} \cdot \nabla \mathbf{w}_k \right) = \vec{v} \cdot \vec{j}_k + R_k
\]

\[
\vec{v}_k = D_k \frac{\nabla w_k}{w_k} + D_k \frac{\nabla M_a}{M_a} + \frac{\nabla T_i}{\rho w_k T_i} - Z_k \mu \cdot (\vec{E})
\]

where \(\vec{j}_k\) is the diffusive flux vector, \(M_a\) is the mean molar mass of the mixture, \(R_k\) is the rate expression for species \(k\), \(\vec{u}\) is mass averaged fluid velocity, \(w_k\) is the mass faction of the \(k^{th}\) species \(\vec{v}_k\) is the diffusion velocity, \(D_k\) is the diffusion coefficient of ion, \(T_i\) is the temperature of the ion, and \(k\) is the number species of ion. In the simulation, the space of the tube was set to be a domain which plasma dynamic was simulated.

The electrodes were set to be at the applied voltage and ground. The surface of the tube was set to have a dielectric value. The boundary condition for plasma was based on recombination process of argon ion and the loss of electrons to the wall due to random motion described by electron flux and the electron energy flux. The dynamics of plasma was simulated and shown the changes in the density of electrons. The result is shown in figure 2.

2.2. Experiment setup and measurement

For experiment, Argon plasma emission was measured by Optical Emission Spectrometer (OES). The electron temperature was determined from the emission spectrum. Each spectrum line can be referred to species of argon ion. However, the OES has a spectral range limit between 200 nm to 1100 nm, therefore the measurement is limited to low temperature plasma. The electron temperature of the argon plasma was calculated by using “Boltzmann plot” method [9], and database of argon’s ions from NIST [10] was used for the plasma temperature calculation. The OES setup is shown in figure 1(b).
3. Results and discussion

From the experiment, pictures of the plasma generated by DC power supply and AC power supply are shown in figure 3 (a) and 3 (b) respectively. For DC glow discharge plasma, the plasma can be seen to be separated in four regions. These regions are cathode glow space, negative glow space, faraday space, and positive column space. The lengths of the dark regions of the plasma can be seen to vary with operating voltage and operating pressure. The also correspond to the changes in the positive column where the positive column increases the dark space is reduced. However, the plasma is generated by using AC power supply can be seen to be different as it is divided in three regions of negative glow space, faraday space, and positive column. The operating with AC frequency causes the negative charge and positive charge of ions of argon to swing due to voltage switching at the electrodes.
The argon spectral emissions measured by OES are shown in figure 4. The species of argon ions can be found from these spectral lines which are emitted by recombination process in the plasma. Figure 4 shows spectral line of Ar I and Ar II in the measurement obtained. Table 1 shows the correlation between operating pressure and breakdown voltage of argon gas for different mode of operations. It was found that the breakdown voltage significantly relate to the electron temperatures that are shown in the table 2.

**Table 1.** Table showing the breakdown voltage obtained experiment under operating pressure 0.1, 0.6, and 1.1 mbar.

| Pressure (mbar) | Breakdown Voltage (kV) |
|----------------|------------------------|
|                | DC Power Supply | Frequency of AC Power Supply |
|                | 10 (Hz) | 50 (Hz) | 500 (Hz) | 1000 (Hz) |
| 0.1            | 0.730   | 1.100   | 1.100    | 1.100     |
| 0.6            | 1.000   | 1.455   | 1.443    | 1.440     |
| 1.1            | 1.475   | 2.233   | 2.230    | 2.165     |

**Table 2.** Table showing comparison of electron temperature between results obtained by experiment and computation under operating pressure 0.1, 0.6, and 1.1 mbar.

| Pressure (mbar) | Electron Temperature (eV) |
|----------------|---------------------------|
|                | DC Power Supply | Frequency of AC Power Supply |
|                | 10 (Hz) | 50 (Hz) | 500 (Hz) | 1000 (Hz) |
| Experiment     | 0.1    | 0.810   | 0.650   | 0.600     | 0.540     | 0.640     |
|                | 0.6    | 0.610   | 0.610   | 0.750     | 0.880     | 0.640     |
|                | 1.1    | 0.640   | 0.970   | 0.935     | 0.890     | 0.750     |
| Computation    | 0.1    | 4.600   | 3.737   | 3.561     | 3.192     | 3.146     |
|                | 0.6    | 1.690   | 2.250   | 2.187     | 2.080     | 1.798     |
|                | 1.1    | 2.505   | 0.997   | 0.997     | 0.909     | 0.9635    |

Considering the DC glow discharge plasma, the electron temperature, obtained from both results decreases when the operating pressure was increased from 0.1 mbar to 0.6 mbar. However, it increased when the operating pressure was increased to 1.1 mbar. It was found that the electron temperature is the highest at 0.1 mbar, and it is the lowest at 0.6 mbar.
The result can be explained by the collision loss effect between ions and electrons as shown by the simulation. However, the actual values of the electron temperature obtained from the experiment and simulation are different. This discrepancy can be explained by the spectral range limitation of OES the mentioned earlier. Therefore it is possible that the plasma in the tube could have higher electron temperature but the value would not exceed that obtained by the simulation. Moreover, the energy loss due to inelastic collisions in the experiment could further add the decrease of the electron temperature.

For the AC glow discharge plasma, the simulation results show that the electron temperature decreased with increasing operating pressure which is different from the experimental results. The simulation results show the electron temperature decreased when the operating pressure is increased. It is possible to explain that increasing of the operating pressure causes more collision of both ions and electrons in the AC system which the electron and ions could not gain high momentum thus the average electron temperature is relatively low in comparison to the DC glow discharge plasma. By further increase in the operating frequency it can be seen that the electron temperature to further decrease. This confirms that the plasma loses more energy as it oscillates and collides more frequently.

It is interesting to note that for the operating frequency of 1000 Hz and operating pressure of 1.1 mbar the electron temperature is higher when the operating frequency is 500 Hz and under the same pressure as the breakdown voltage are different.

4. Conclusions

The electron temperature of plasma generated from DC glow discharge and AC glow discharge was investigated. The results of both were compared. The finite element method was used to simulate the dynamics of plasma and it also was used to calculate the electron temperature of the plasma. From the experiment, the electron temperature was determined by using the “Boltzmann plot method that the spectral line of both Ar I and Ar II detected by using OES was investigated. The operating pressures investigated in the research were 0.1 mbar, 0.6 mbar and 1.1 mbar. The operating frequencies of AC plasma studied were 10 Hz, 50 Hz, 500 Hz and 1000 Hz. It was found that;

(1) The plasma generated from DC power supply and AC power supply shown in figure 1 and figure 2 were different. The DC glow discharge plasma was separated in four regions. These regions are composed of cathode glow space, negative glow space, faraday space, and positive column space. The lengths of the dark regions of the plasma were varied with different operating voltage and pressure. Increasing in operating both pressure and voltage increased the positive column of plasma which reduces the dark space. The plasma generated by using AC power supply was divided in three regions as negative glow space, faraday space, and positive column. The operating frequency causes the electron and ions to swing due to switching of the voltage on the electrodes.

(2) The electron temperature of plasma generated by DC obtained from the experiment and simulation shows similar tendency. The electron temperature is the highest at 0.1 mbar, and it is the lowest at 0.6 mbar. However, the actual values were different can be due to the limitation of OES measurement that allows determination of electron temperature from Ar I and Ar II species.

(3) The electron temperatures of plasma generated from AC glow discharge were different between simulations and experiment. The electron temperature decreased as the operating pressure increased in the experiment where the simulation results showed that the electron temperature decreased due to operating pressure. This is explained by the energy loss due to collisions. Moreover, increasing in operating frequency also caused to the electron temperature to reduce as the energy is loss due to plasma. From the simulation, the electron temperature under the operating frequency and operating pressure are 1.1 mbar and 1000 Hz was higher than the temperature under the operating frequency of 500 Hz at the same pressure. The reason of the effect was due to the breakdown voltage. In general, the experimental results show that the electron temperature is raised when operating pressure and breakdown voltage increases.
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