Characteristics of Ar Plasma Jet Generated by 50 Hz Alternating Current

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Abstract. Plasma jet generated by dielectric barrier discharge system has gain importance in surface modification processes. Characteristics of plasma of the plasma jet depend on type of gas, flow rate of gas, design of electrodes, power and frequency of the power source. In this research, the argon gas is flowed through a hollow tube is investigated. Alternating high voltage power supply connected to electrodes is operated with frequency of 50 Hz. It was found that the lengths of the plasma jet generated by this system ranges from 0.5 cm and 1 cm. The minimum and the maximum electron temperature of the plasma was 0.44 eV and 0.86 eV respectively. The electron temperature increased as the applied voltage was increased. However, the electron temperature decreased when the operating voltage was increased above 6.5 kV to 7.5 kV. It can be explained by the effect of arcing between the electrodes which causes the lost in energy. Also, increasing of the flow rate over a critical limit produces turbulence that also causes reduction in electron temperature of the plasma jet.

Keywords: Plasma jet, electron temperature of plasma jet

1. Introduction
Plasma jet is a type of cold plasma that can be generated by feeding gas through powered electrodes. The plasma can be produced under atmospheric pressure condition. The plasma jet has been applied in many fields of science, especially in material treatment and processing such as treatments of wood surface [1], healthcare and medicine [2], wastewater treatment and pollution control [3,4], as well as polymer surface treatment [5].

In order to effectively conduct different type of treatment for each different application, it is important to be able to control the properties of plasma. Evaluating plasma parameters such as plasma temperature and plasma density are the most essential in many cases. In this work, the electron temperature and the electron density were investigated. Argon gas was used as the operating gas for generating plasma jet from a discharge plasma system. Alternating current high voltage power supply with applied frequency
of 50Hz was used as the main source of power for the system. Optical spectroscopy method was considered for electron temperature of plasma and number density of electron measurement and calculation.

2. Experiment procedures
The atmospheric pressure plasma jet system consists of a cylindrical borosilicate glass insulator tube with outer diameter of 5 mm, inner diameter 3 mm and length of 152 mm. Diameter of inner electrode is 1.5 mm as shown in Figure 1. The argon gas was used in this work and the gas flow rate is controlled by using a volume flow meter. The frequency of alternating current high voltage power supply used in this research is 50 Hz. The range of operating voltage applied to generate plasma was between 5kV and 7.5 kV. Within the tube consists of an inner solid electrode with diameter of 1 mm. A copper wire is wound around this tube as shown in Figure 1. The gap between the inner electrode and the outer electrode is about 0.5 cm.

The electrical power transferred to the plasma source was estimated by using the difference between the input power and the electrical power on a resistor. Differential voltage between point A to B ($V_{AB}$), between point B to C ($V_{BC}$), and between point A and C ($V_{AC}$) were measured as shown in Figure 1. Current of the circuit $I$ through the resistor which has resistance $R$ can be determined by using ohm’s law that its equation can be show as:

$$I = \frac{V_{AB}}{R}. \quad (1)$$

The differential voltage $V_{BC}$ represents the high voltage source of the system, and $V_{AC}$ is the voltage across electrodes. Electrical power dissipated in the resistor $P_R$ can be calculated by using equation as follow;

$$P_R = I^2 \times R. \quad (2)$$

For plasma properties measurement, Ocean optical spectrometer (HR4000) was used to measuring spectrum lines which are emitted from the plasma. The plasma parameters such as electron temperature ($T_e$) and electron density ($n_e$) that represent the characteristic of plasma were evaluated based on Boltzmann plot [6,7,8], using the equation as shown in equation (3). The equation shows the relationship between intensity of spectrum line chosen and electron temperature. The Boltzmann plot was used under the assumption that the plasma is completely in local thermodynamic equilibrium (LTE) condition. However, plasma jet is non-LTE therefore we will only approximate the electron temperature by using this equation.

$$\ln \left[ \frac{I_\lambda}{gA} \right] = -\frac{1}{k_B T_e} E + \ln \left( \frac{4\pi Z}{hcN_0} \right) \quad \text{hcN}_0$$

Where, $I$ is the intensity of selected spectral line, $k_B$ is the Boltzmann constant, $E$ is the excited state energy or energy level of the upper state for emission, $g$ is the statistical weight, $A$ is the transition probability, $h$ is Planck constant, $Z$ is partition function, $c$ is speed of light, and $N_o$ is total species population, $\lambda$ is wavelength of spectral line. For Equation 3, the Boltzmann distribution was rearranged to be a linear plot, thus the terms observed in the right part will straightforwardly shows that the slope can be used to determine $T_e$ of the plasma.
The range of spectrum line recorded was between 200 nm and 1100 nm. These spectrum line represent emission of Ar I and Ar II which were selected. Excited energy, transition probability and statistical weight were found for these values from NIST Atomic Spectra Database [8]. The electron density $n_e$ was determined by using corona equilibrium model [9]. The equation can be written as:

$$\frac{N_{i+1}}{N_i} = 1.27 \times 10^5 \left(\frac{T_{ev}}{\chi_i}\right)^3 \exp\left(-\frac{\chi_i}{T_{ev}}\right)$$

where

$N_i$, $N_{i+1}$ is a number density of ion at state $i$ and $i+1$ respectively.

$\chi_i$ is an ionization energy in a state $i$.

$T_{ev}$ is an electron temperature of plasma.

3. Experiment results

Argon plasma jet generated under 50 Hz operating frequency and 1 l/min flow rate of argon gas is shown in Figure 2.

![Figure 2. A photographic image of the plasma jet.](image)

It could be shown that the plasma jet could be generated when the applied voltage was raised to more than 4.5 kV under the flow rate of less than 1 l/min. The relationship of power dissipated on the resistor, electrical power transferred from the plasma source, and the input power with the applied voltage are shown in Figure 3. From the result, the transferred power increases as applied voltage was increased. By assuming the plasma jet tube behaves like a capacitor, therefore by increasing input voltage causes it to have more charge. Considering the operating voltage over 7.5 kV, the plasma behaves like a conduction wire that connects both electrodes, therefore the plasma causes arcing between the electrodes. From the results, it can be seen that the input power used to generate argon plasma jet ranges between 1.95 W and 3.5 W, and the power dissipated to plasma jet tube was between 1.85 W and 3.27 W respectively.

![Figure 3. Input Power, dissipated power on resistor and Dissipated power on plasma jet tube system.](image)

The spectrum lines emitted from the argon plasma measured by optical spectroscopy is shown in Figure 4. The range of wavelength of the spectrum lines can be divided into two groups. The spectrum range between 300 and 400 nm were generated from species of ArII, and the spectrum range between 680 and 850 nm were from species of ArI. In this experiment, the height of spectrum lines referred to
the intensity of spectrum. It can be seen that the height of the lines generated from ArI group is higher than the lines generated from ArII.

![Figure 4. Spectrum lines of Ar plasma jet.](image)

The relationship between electron temperature and the voltage across the electrode is shown in Figure 5, and the range of electron temperature is between 0.44 eV to 0.86 eV. From the results, the voltage across of 6.5kV generates the maximum electron temperature. Considering range of applied voltage between 5.5 kV to 6.5 kV, we can see an increase in electron temperature due to increasing in the applied voltage, but at a higher voltage the electron temperature decreases.

The effect may be explained by the breakdown potential voltage of the gas to become plasma is higher, thus the kinetic energy of the electrons naturally increases. However, when the voltage was raised to 6.5 kV, the electron temperature decreases as there were more electrons and more collision loss. Once the voltage was increased to over 7.5 kV, the arcing between the electrodes appeared.

![Figure 5. Electron temperature and voltage across electrode.](image)

The relationship of number density of electron per number density of ion and applied voltage is shown in Figure 6. Trend of electron temperature and the ratio shown in Figure 6 are similar. Explanation for the similarity can be that, the majority of the species of argon ion generated in this experiment was ArI, and the input power was not enough to generate the higher species of argon ions.

![Figure 6. Number density of electron/Number density of argon gas and voltage](image)
4. Research discussion and conclusions
In this research, we have demonstrated that argon plasma jet can be produced under atmospheric condition by using alternating current power supply at 50 Hz. The range of operating voltage was between 5.5 kV and 7.5 kV. The electron temperature can be determined by Boltzmann plot method from spectral line of both Ar I and Ar II using optical spectroscopy method. The number density of electrons per number density of ions could be calculated by using coronal equilibrium in correlation with the electron temperature. From the results, both electron temperature and the number density ratio increased due to increasing operating voltage between 5.5 kV and 6.5 kV, and they decreased when the range of the voltage was higher between 6.5 kV to 7.5 kV. The majority of argon ion species of the plasma jet was Ar I. The power transfer to plasma jet system were between 1.85 W to 3.27W. The electron temperature measured were ranging between 0.44 eV to 0.86 eV and the number density of electron to number density of argon gas were about $9.7 \times 10^{-12}$ to $6.3 \times 10^{-4}$ m$^{-3}$.

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