Emission Spectrum Analysis of Magnetic Field Controlled Plasma One-Dimension Jet Array

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Abstract: For the purpose of studying the discharge plasma parameter of the plasma produced in jet array, emission spectrums are taken advantage of judging the changes of plasma electron temperature and electron density. An optical fiber spectrometer is adopted to record the emission spectrum emitted in a homemade one-dimension jet array discharge plasma system. The research findings show that the electron excitation temperature increase with the flow rate of discharge gas. Plasma electron density decreases first and then increases with the velocity of discharge gas flow. It has a minimum value when the flow rate is 5 liters per minute. These are useful to investigate magnet confined plasma jet array further.

1 INTRODUCTION

Atmospheric pressure plasma jet has the following advantages, such as low discharge gas temperature, convenient discharge equipment, easily producing a large number of highly controllable chemically active particles and unrestricted size and shape of the material to be treated, so it has a wide range of applications in many areas, for example, biomedical field, material surface treatment field and organic waste gas treatment and so on (**Tendero, 2006, Park, 2018**). Its shortcoming is small volume of plasma. So many researchers have combined several small-scale plasma jet elements into a parallel array which is called jet arrays (**Lu, 2012, Cao, 2009, Lu, 2011**). The jet arrays can be classified two types based on dimension. One is one-dimensional jet array and the other is two-dimensional jet array.

Although the magnetic field confined discharge structure has been testified to promote the discharge effect in dielectric barrier discharge (**Rong, 2006, Wang, 2011**), only a few researchers have studied the influence of magnet on discharge plasma. Hu et al (**Hu, 2013)** investigated the influence of external magnetic field on DC arc plasma jet and found that the arc root turns, the curve of the volt-ampere and power of plasma torch increasing with magnetic field. There are no more reports about introducing the magnetic confinement into the plasma jet array in the other existing studies. Here, the emission spectrum of discharge plasma is analyzed to obtain the plasma electron excitation temperature and electron density by means of one-dimensional plasma jet array discharge system.

2 EXPERIMENTAL PROCEDURE

The experimental procedure includes a discharge process done in a homemade experimental system and spectral testing process carried out by an optical fiber spectrometer.

2.1 Experimental System

Figure 1 is the schematic diagram of the jet array experimental system established in this study. The fluidic array reactor is composed of three single

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fluidic units arranged in parallel, and the spacing between quartz tubes is 2 mm. The electrode structure of single jet unit are two copper rings. The ring electrodes are wrapped outside the quartz tube. Each jet unit is composed of quartz tube, low voltage electrode and high voltage electrode. The size of quartz tube is 4 mm in outer diameter, 2 mm in inner diameter, and 100 mm in length. The electrode rings are cut from a copper pipe with the size of 6 mm in outer diameter, 4 mm in inner diameter and 30 mm in length. The distance between the outer side of the high voltage electrode and the quartz nozzle is 50 mm. The experimental gas is He gas (99.99% volume fraction), which is controlled by LZB-10WB flowmeter and passed into the quartz tube. The measuring range of the flowmeter is 5 ~ 45 L/min. A power supply with 0 ~ 15 kV and 0 ~ 35 kHz is adopted here. The high voltage electrode is connected to high voltage terminal of the power supply. The ground electrode is connected to the earth with a long wire. The voltage waveform is measured by a Tek P6015A probe. The discharge current is gotten by connecting a 50 Ω non inductive resistor R in discharge circuit of one-dimensional jet array. The transfer charge in the discharge space is connected in series with one non inductive measurement capacitance C of 0.0068 μF in the discharge circuit. The discharged voltage-current waveform graphics and voltage-charge Lissajous images are recorded by TDS1052B (50MHz, 1GS/s) digital oscilloscope. The emission spectrums are obtained by means of a spectrometer with the type of AvaSpeec-USB2-DT. The spectral wavelength measured is in the range from 200 nm to 840 nm, and the optical resolution of the spectrometer is 0.75 nm.

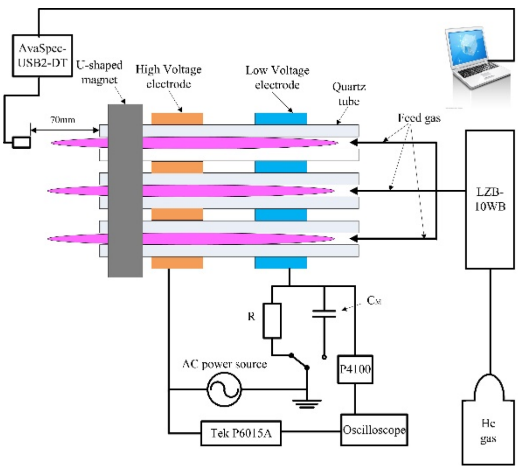

Figure 1: The discharge experimental system.

2.2 Measurement

The emission optical spectrums are measured by putting an optical fiber probe 70 mm from the quartz nozzle in different discharge conditions. The AvaSpeec-USB2-DT spectrometer is connected to a computer with a USB interface. The spectrum can be obtained by means of the corresponding software.

The velocity of flow of the discharge gas can be measured by the LZB-10WB flowmeter. The peak value of discharge voltage is 15kV, and the discharge frequency is 28.3 kHz.

Emission spectroscopy is a diagnostic method of high precision for measuring the electron excitation temperature and electron density (**Song, 2021**).

2.2.1 Diagnostic Method of Electronic Excitation Temperature

Boltzmann slope method is the main method for diagnosing electron excitation temperature. It is approximately considered that the plasma jet array is in LTE state. The relative spectral intensity of a particle in the excited state when it transitions to a lower energy level can be described as follows:

$$I = \frac{1}{4\pi}\frac{hc}{\lambda}AN\frac{g}{Z}\exp(-\frac{E_k}{kT_e}) \qquad (1)$$

Where, the parameters are Planck constant number h, vacuum light speed c, spectral line wavelength λ, transition probability A, total atomic density N, statistical weight g, distribution function Z, excitation energy E_k, Boltzmann constant k and electron excitation temperature T_e.

We can get the following formula by taking the logarithm of both ends of formula (1) at the same time.

$$\ln\frac{I\lambda}{gA} = -\frac{E_k}{kT_e} + \ln(\frac{hcN}{4\pi Z}) \qquad (2)$$

It can be seen from formula (2) that as long as the abscissa Boltzmann fitting diagram is obtained with ln(Iλ/gA) as the vertical coordinate and E_k as abscissa. The electron excitation temperature can be achieved by fitting the slope of the straight line. Here we use multi spectral lines of He Ⅰ at 471.3 nm, 667.8 nm, 706.5 nm and 728.1 nm to calculate electron excitation temperature. And the associated parameters are listed in table 1.

Table 1: The associated parameters for calculating electron excitation temperature.

λ/nm	g*A	E_i/eV	Transition

471.3	1.58 x 10^7	23.59	$2p^3$ - $4s^3$
667.8	3.18 x 10^8	23.09	$2p^1$ – $3d^1$
706.5	4.64 x 10^7	22.71	$2p^3$ - $3s^3$
728.1	1.82 x 10^7	22.92	$2p^1$ - $3s^1$

2.2.2 Diagnostic Method of Electronic Density

Stark broadening has become the main tool to calculate the electron density because it depends primarily on the electron density of the plasma. When only Stark widening is considered and the other widening mechanisms are ignored, and the electron density is more than 5 x 10^{14} cm^{-3}, the expression between stark broadening of the half height and full width of the H_α spectral lines (FWHM) and electron density is as follows (**Feng, 2021**):

$$N_e = 10^{17} \times \left(\frac{\Delta\lambda_s^A}{1.098} \right)^{1.47135} \quad (3)$$

Where, Ne is the electron density, $\Delta\lambda_s^A$ is the full width at half area of the spectral line.

3 SPECTRUM ANALYSIS

3.1 Jet Plasma Emission Spectrum

Figure 2 shows some emission spectrum obtained by the AvaSpeec-USB2-DT spectrometer at different flow rates of 4L/min, 6L/min and 7L/min of the discharge gas He. As shown in figure 2, the spectrum of the plasma in jet array include many spectral lines. The higher spectral line positions are 308.9 nm, 313.6 nm, 315.9 nm, 337.1 nm, 357 nm, 375.3 nm, 380.3 nm, 399.6 nm, 405.8 nm, 425.9 nm, 656.3 nm, 706.5 nm, 728.3 nm, 750.4 nm and 777.4 nm. There are different spectral line intensities at different gas flow rates.

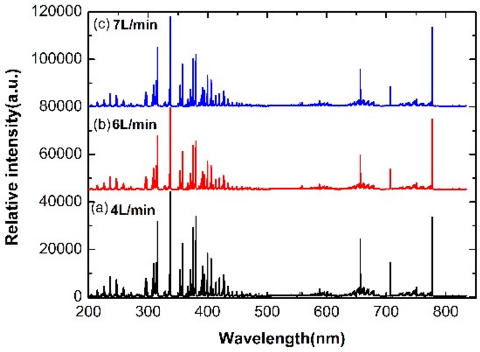

Figure 2: The full emission spectrum of helium plasma jet array in magnetic confinement at different gas flow rate.

In order to obtain the atomic spectral lines and ion spectral lines of the emission spectrum, emission spectroscopy of 6L/min flow rate is analysed and shown in figure 3.

As shown in figure3, the OH radical's spectra is found in 306 ~ 315 nm interval. The first negative system of N_2^+ ion and the second positive system of N_2 molecule appear in the interval of 300 ~ 450nm. It is also found the O atomic line at 777.4 nm. The atomic spectral lines are determined by means of the NIST atomic spectral database (**Deng, 2018)**. Due to the jet array plasma opened to the atmosphere air, the spectral lines of N_2^+ ion, N_2 molecules and O atoms appear. In addition, strong Balmer family line (Hα) is also found.

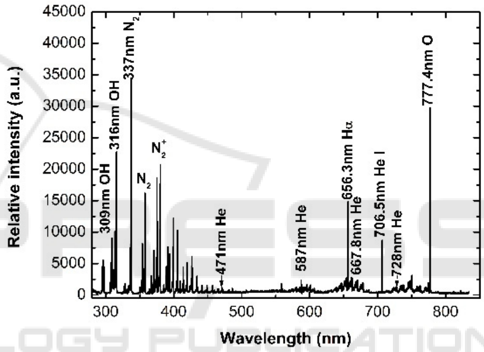

Figure 3: The emission spectrum of jet array at 6L/min.

Due to the inelastic collision of high-energy electrons with nitrogen molecules and oxygen molecules, N_2, N_2^+ and oxygen atoms are produced. A great quantity of metastable helium atoms produced in the plasma because of collisions. The metastable helium atoms will also be violent with oxygen molecules and nitrogen molecules inelastic collision. The occurrence of OH group and H (Hα) is due to the ionization of H_2O in the air.

3.2 Application of Emission Spectrum

3.2.1 Electron Excitation Temperature

According to formula (2), table 1 and the emission spectrum measured at different flow rate of helium, we can obtain the electron excitation temperature of discharge plasma jet array. The changes of the electron excitation temperature with the error of 10 percent are depicted in figure 4.

As illustrated in figure 4, the electron excitation temperature increase with the discharge gas flow rate which is in accordance with the study of wu et al (**Wu, 2015**). The jet length of the array becomes longer with the flow rate increasing in the experimental conditions. According to discharge theory, free electrons in the discharge region can be accelerated to a higher speed under the combination effect of electric field and magnetic field confinement. As a result, free electrons get more energy from the external electric field and make more collisions with other particles in discharge area. So the excitation temperature of the electrons will show an upward trend. Moreover, active particles in discharge plasma can reduce the breakdown electric field, but the increase of discharge gas helium flow causes the Penning ionization process weakening and the quenching of the active particles remaining in the last discharge because of the involvement of a large number of diatomic molecules N_2 with high vibrational dynamics. Therefore, the increase of the flow velocity of discharge gas helium leads to the breakdown electric field increasing. The larger the breakdown electric field is, the greater the average energy (electron temperature) of electrons in the plasma is. With the enlargement of the flow rates of discharge gas helium, the discharge power also raises and the electrons can accrue more energies. Consequently, the electron temperature raises with the increase of the flow rate of helium gas. The similar experimental results are reported by Wang et al (**Wang, 2018**).

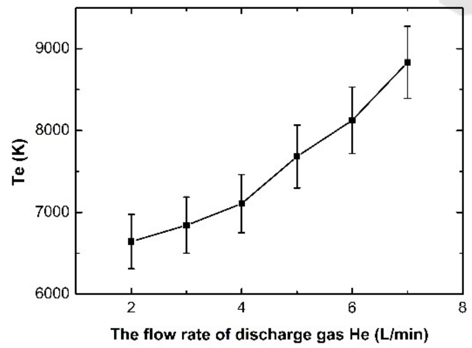

Figure 4: The changes of electron excitation temperature.

3.2.2 Plasma Electron Density

In order to analyse the changes of electron density in different conditions of the plasma jet array, we record the relative intensity of the spectral line of Hα at 656.3 nm. It is used to evaluate electron density because of its stabilization at different electron temperature. According to formula (3), electron density at different flow rate of discharge gas helium is computed and shown in figure 5. It can be seen that electron density decrease first and then increase as the helium flow rate increasing. It has a minimum value at 5 litres per minute. In case of low discharge gas flow rate, the electron and particles produced in discharge are mainly in discharge area. As the increasing of flow rate, lots of high energy electron is blown out the quartz tube. So the electron with more energy left in discharge decreases. So the electron density decrease. The electron density drops to the lowest at the flow rate of 5 litres per minute. When the flow speed is more than 5 litres per minute, the helium flow is strong enough to prevent particle dispersion and the high energy electron is main in the length of discharge channel. So stark broadening adds the FWHM of the Lorentz profile. Thus, electron density increases slightly when the flow rate is greater than 5 liters per minute.

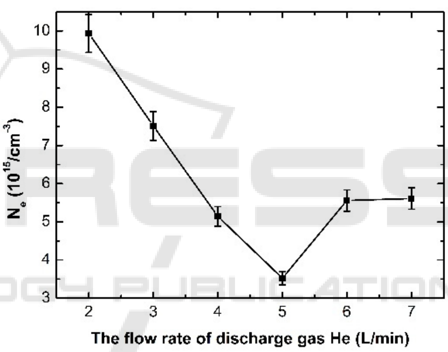

Figure 5: The changes of plasma electron density.

4 CONCLUSIONS

A magnet controlled unidimensional plasma jet array discharge system has been established. It includes three quartz tubes in line arrangement, a power supply and corresponding measuring devices. It can run on atmospheric pressure. With the help of the jet array system, the effect of helium flow velocity on plasma parameters has been discussed. From the experimental results, the plasma parameters are changed with gas flow velocity in the range of 2 liters per minute to 7 liters per minute. Meanwhile, discharge emission spectrums are used to compute electron temperature and electron density. This research shows that electron temperature increase with gas flow rate increasing, and the electron density decrease first then increase with helium flow rate under magnetic constraint.

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