Temperature measurements in a laminar plasma jet generated at reduced pressure

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Abstract: Boltzmann-plot method and double electrostatic probe method were applied to measure the excitation temperature and electron temperature of a DC laminar plasma jet generated at reduced pressure. Results show that excitation temperature at the jet center increases with the chamber pressure and the arc current. However, it is much lower than the electron temperature, indicating that the laminar jet is evidently deviated from the LTE state.

Keywords: laminar plasma jet, low pressure, temperatures measurement

1. Introduction

DC arc plasma jet generated at reduced pressure has the characteristics of large plasma volume, moderate energy intensity and temperature and velocity gradient, which are favorable for depositing large area films/coatings [1-2]. However, this kind of technology still relies more on experiences in practical use, poor understanding of the basic plasma phenomena has been the major obstacles to further development of this kind of technology. Therefore, it is necessary and useful to systematically diagnose the plasma jet parameters, especially the jet temperatures and their distributions on which the process suitability and control depend, for better understanding and use of this kind of plasma jet.

Generally, thermal plasmas produced in high intensity arcs at high pressure environment can be considered in local thermodynamic equilibrium (LTE) state, which is characterized by an approximate equality between heavy particle and electron temperature [3]. In the past decades, many papers have been published to report the measured temperatures of turbulent plasma jets issuing from non-transferred arc plasma torches or the temperatures of the transferred arc plasma [4-6]. While for the plasmas generated at reduced pressure, deviations from the LTE state may occur due to the small electron number density and less collision processes, and in this case, there exist different temperatures, such as the electron temperature T_e, the excitation temperature T_{ex}, the vibration temperature T_v, the rotational temperature T_r and the kinetic temperature T_c of the heavy particles [3]. Different method should be applied to obtain these temperatures. However, the diagnostics work about parameters of the plasma jets generated at reduced pressure has been relatively scarce.

In this study, the excitation temperature and the electron temperature of the DC arc plasma jets generated at reduced pressure were measured by using the Boltzmann-plot method and double- electrostatic probe method, the deviations of the measured temperatures have been analyzed.

2. Experimental details

The non-transferred DC arc plasma torch used for generating the plasma jets at reduced pressures is the same as used in the former work [7], which mainly contains an anode, a cathode and a three-piece inter-electrode insert. The plasma torch is installed on the top of the vacuum chamber, and the jet is issuing freely into the vacuum chamber. Plasma jets were generated with pure argon gas at gas flow rate of 1.25×10^{-4} kg/s, arc currents of 80 A to 110 A and chamber pressure of 170 Pa to 2000 Pa, where the laminar flow regimes can be achieved.

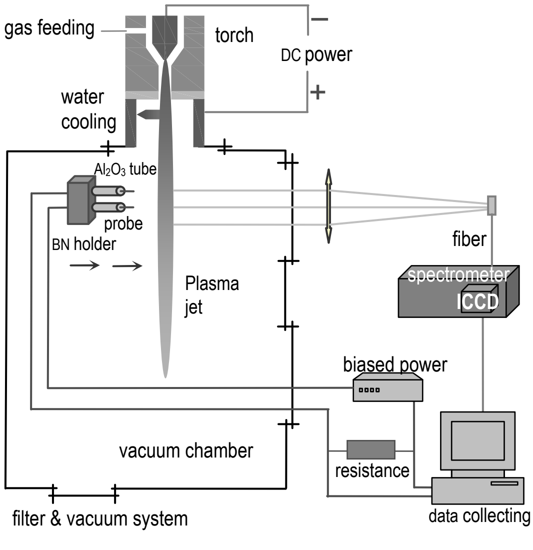

Fig. 1 Schematic diagram of the experimental setup.

The schematic diagram of the experimental setup is shown in Fig. 1. A double-electrostatic probe system was applied to measure the electron temperature. The probe system mainly consists of five parts, i.e., a double-electrostatic probe, one boron nitride probe holder, a DC bias power supply, a sampling resistance of 10 Ω and an oscilloscope for collecting the voltage signals of the sampling resistance and the biased power supply. The double-electrostatic probe comprises two individual tungsten wire electrodes of 0.3 mm in diameter with an exposed length of 2 mm in the plasma. Other part of each wire is covered by an alumina tube of 0.5 mm in inner diameter, 1 mm in outer diameter and 35 mm in length. The probe head is fixed in a boron nitride holder with a centre distance of 2 mm between the two wires. The holder can move along the axial and radial direction of the jet.

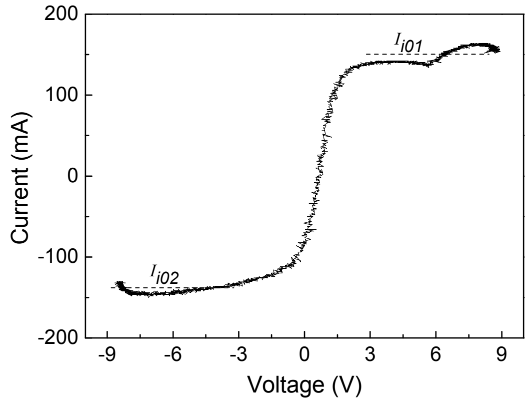

Fig. 2 Typical V-I curve of the double-electrostatic probe method.

According to the following equation, the electron temperature T_e can be derived:

$$\left.\frac{dI_D}{dU_D}\right|_{I_D=0} = \frac{e}{kT_e} \times \frac{I_{i01} \times I_{i02}}{I_{i01} + I_{i02}} \qquad (1)$$

where I_D is the working current on the probe, U_D is the voltage between these two probes, e is the elementary charge, k is the Boltzmann constant, I_{i01} and I_{i02} are the ion saturation current of these two probes. Fig. 2 shows the typical voltage-current (V-I) curve of the double-electrostatic probe used in this experiment. Since the sweeping of the bias voltage was done at the line frequency, the V-I curve represents the data obtained during a 10ms time period, and will show the effect of parameter variation caused by the ripples of the power source. The fluctuations of the ion saturation current on this V-I curve reflects the characteristics of the tri-phase full-wave rectified power supply used to generate the laminar plasma jet [8], so the averaged value of I_{i01} and I_{i02}, dashed line shown in Fig. 2, are used to derived the electron temperature.

The Boltzmann-plot method [3] was used to get the jet excitation temperature, where six ArI spectral lines (675.28 nm, 687.13 nm, 696.54 nm, 706.72 nm, 738.40 nm, 750.39 nm) were chosen in order to draw the Boltzmann-plot curve by the following equation:

$$\ln\left(\frac{\varepsilon_\lambda \cdot \lambda}{A_{ul} \cdot g_u}\right) = -\frac{E_u}{kT_{\mathrm{ex}}} + \ln\left(\frac{hc}{4\pi} \cdot \frac{n_i}{Z_i}\right) \qquad (2)$$

where ε_λ is the light emission coefficient, λ is the wave length, A_{ul} is the corresponding transition probability, g_u is the statistical weight of the upper excited state u, E_u is the energy of the upper excited state u, k is the Boltzmann constant, T_{ex} is the excitation temperature, h is the Planck constant, c is the light velocity, n_i is the population of the chemical species i and Z_{i} is the partition function of the chemical species i, The spectroscopic parameters of the selected ArI spectral lines are taken from the atomic database of NIST [9]. Fig. 3 shows the typical Boltzmann-plot curve for the six selected ArI lines, where the slope of the fitted straight line is proportional to $-1/(kT_{ex})$. The exposure time for getting the integrated intensities of each ArI spectral line was 100 ms in this experiment, and it takes about three minutes to obtain all six data because of the long time needed for grating adjustment and data saving. Therefore, the fluctuations of the plasma jet originated from the power supply will not affect the measured excitation temperature, which represents the averaged value in this period.

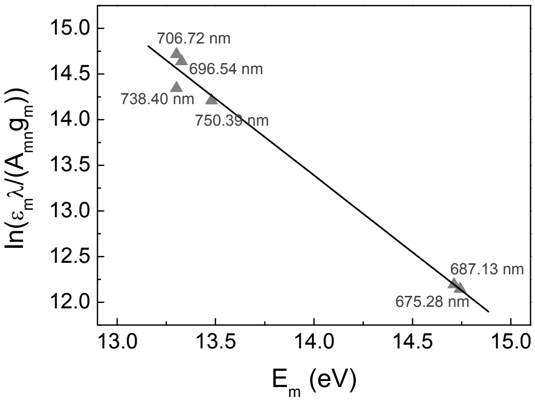

Fig. 3 Typical Boltzmann-plot curve for the six selected ArI lines.

The measurement system consists of a spectrometer with focal length of 550 mm, an ICCD detector with accurate exposure time and the external optical imaging and transmission setup, which include a lens with focal length of 300 mm and an optical fiber of 0.2 mm in diameter. The image of the plasma jet is formed on the frontal end of the optical fiber through the lens, and is transmitted to the slit of the spectrometer by the fiber. The ICCD can detect the light intensities eventually.

3. Results and discussions

Fig. 4 plots the distributions of the measured electron temperature and the excitation temperature of the argon plasma jet at arc current of 80 A. For the electron temperature, the chamber pressure is fixed at 170 Pa, and the measured jet cross section is at the torch exit. For the excitation temperature, the chamber pressure increases from 170 Pa to 2000 Pa, and the measured jet cross section is 10 mm from the torch exit. The spread in the electron temperature might have been caused by the instantaneously collected data by the fast response electrostatic probe, and the dashed curve represents the averaged value of the measured electron temperature. It is seen that the deviations of the measured electron temperatures can be up to 10%, probably due to the fluctuations of the rectified power supply [8]. In order to obtain the electron temperature, the value of dU_D/dI_D at the zero current point, the ion saturation currents I_{i01} and I_{i02} are used.

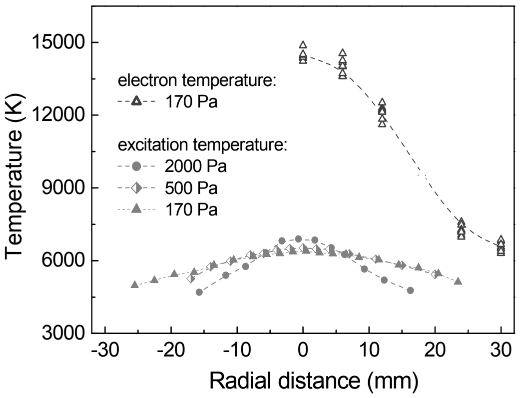

Fig.4 Distributions of the electron temperature at the torch exit and the excitation temperature of the argon plasma jet at the distance of 10 mm from the torch exit (arc current 80 A, chamber pressure 170 Pa).

It is seen that the electron temperature at the jet center can be up to 14500 K, while it decreases to about 6600 K at the radial distance of 30 mm, the mean temperature gradient is about 260 K/mm. The excitation temperature at the jet center is about 6400 K at the chamber pressure of 170 Pa, and the mean radial gradient is about 55 K/mm, which is much smaller than that of the electron temperature. The excitation temperature increases to 6900 K when the chamber pressure regulated to 2000 Pa. It is also clearly seen that with increase in the chamber pressure, the mean radial gradient of the excitation temperature increases to about 65 K/mm at the chamber pressure of 500 Pa, increasing to 130 K/mm when the chamber pressure is 2000 Pa.

Fig. 5 provides the axial distributions of the measured electron temperature and the excitation temperature at arc current of 80 A and chamber pressure of 170 Pa. Both the temperatures decrease with the increase of axial distance between the torch exit and the measured point. For the averaged electron temperature, it decreased from 14500 K at the torch exit to about 9300 K at the axial distance of 75 mm. The mean gradient is about 70 K/mm, which is much smaller than the mean radial gradient of the averaged electron temperature of 260 K/mm. For the excitation temperature, the mean axial gradient is just about 20 K/mm, it is still smaller than the mean radial gradient of 55 K/mm. These characteristics indicate that the laminar jet keeps high temperature and kinetic energy along the jet axis for a large distance.

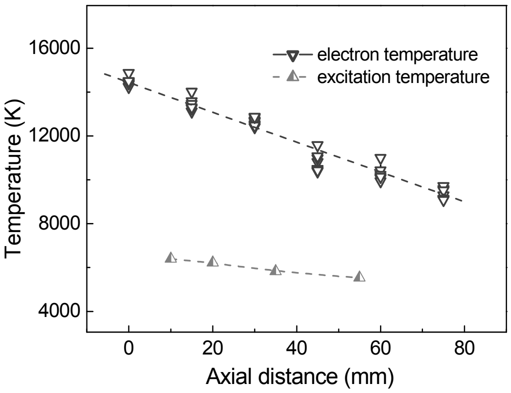

Fig. 5 Distributions of the electron temperature and excitation temperature along the jet axis at chamber pressure of 170 Pa.

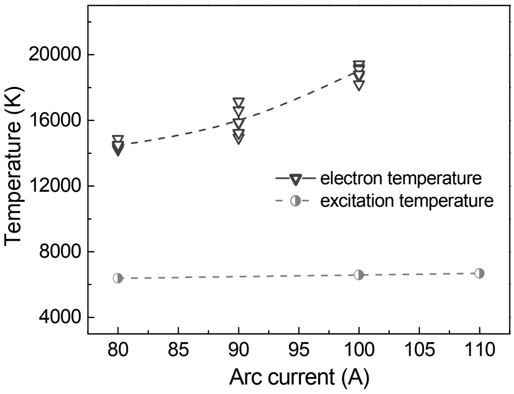

Fig. 6 Dependence on arc current of the electron temperature (torch exit), excitation temperature (axial distance 10 mm) at chamber pressure of 170 Pa.

The changes of the electron temperature and the excitation temperature as a function of the arc current are show in Fig. 6. The gas flow rate is 1.25×10^{-4} kg/s, and the chamber pressure is 170 Pa. It is obvious that electron temperature increases with increasing arc current, when the arc current increases to 100 A, the electron temperature can be up to 19000 K. Though the variations of the excitation temperature are not as evident as the electron temperature, they also increase with the arc current. The input power increases with the increase of the arc current, which can lead to increase of the temperature.

From Fig. 4 to Fig. 6, it is clear that the electron temperature is much higher than the excitation temperature under similar working conditions, which indicate that the plasma jet is evidently deviated from the local thermodynamic equilibrium state, which is different from the arc plasma jet generated at atmospheric pressure. The moderate temperature and existence of active particles of the laminar plasma jet generated at reduced pressure could be favorable factors for material processing.

4. Conclusions

In this research, the electron temperature and excitation temperature of the non-transferred DC argon plasma jet generated at reduced pressure have been measured and analyzed. Experimental results show that the jet center electron temperature near the torch exit is up to 14500 K at arc current of 80 A and chamber pressure of 170 Pa, while the excitation temperature is about 6400 K at similar working conditions. Both temperatures increase with increasing arc current. The axial gradients of the electron temperature and the excitation temperature are much smaller than the radial gradients. The excitation temperature is much lower than the electron temperature at similar working conditions, which indicate that the plasma jet is evidently deviated from the local thermodynamic equilibrium state under these working conditions.

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