



## Temperature measurements in a laminar plasma jet generated at reduced pressure

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### ABSTRACT

Double electrostatic probe method and Boltzmann-plot method are applied to measure the electron temperature and the excitation temperature of a DC laminar argon plasma jet generated at reduced pressure. Attempts are also made to measure the gas temperature by using a pair of WRe-5/26 thermocouple. Experimental results show that the measured excitation temperature at the jet center increases with the vacuum chamber pressure and the arc current, but is appreciably lower than the measured electron temperature, indicating that the plasma jet under study is evidently deviated from the LTE state. The temperature indicated by the thermocouple probe is much lower than the measured excitation temperature and electron temperature. Theoretical analysis shows that the thermocouple method intended for gas temperature measurement contains very large errors due to rarefied-gas heat transfer effects, and thus is unsuitable for this purpose.

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### 1. Introduction

DC arc plasma jet generated at reduced pressure has the features of large plasma volume, moderate energy density and comparatively small temperature and velocity gradients, which are favorable for depositing large area films/coatings [1–3]. However, this kind of surface-processing technology still relies more on operators' experiences in practical use, poor understanding of the basic plasma phenomena has been the major obstacles to further development of the technology. Therefore, it is 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 atmospheric pressure can be considered to be in local thermodynamic equilibrium (LTE) state, which is characterized by approximately equal heavy-particle and electron temperatures [4]. In the past decades, many papers have been published to report the measured results about the temperatures of turbulent plasma jets issuing from non-transferred arc plasma torches or the temperatures of the transferred arcs operating at

atmospheric pressure [5–7]. However, for the plasmas generated at reduced pressure, deviations from the LTE state may occur since lower electron number density and lesser collisions between gas particles are involved. For this case, the plasma is often characterized by means of several different temperatures, such as the electron temperature  $T_e$ , the excitation temperature  $T_{ex}$ , the translational temperature of heavy particles  $T_c$ , the vibration temperature  $T_v$ , and the rotational temperature  $T_r$  [4]. Different methods are usually required to measure the different temperatures. However, so far diagnostic research about the parameters of the plasma jets generated at reduced pressure is relatively scarce.

A specially designed non-transferred DC arc argon plasma torch with a large anode-nozzle exit diameter for use in reduced pressure environment has been constructed [8–12] and employed in this study. The electron temperature and the excitation temperature of the DC arc plasma jets generated at reduced pressure are measured by using the double electrostatic-probe method [13,14] and the spectroscopic-intensity Boltzmann-plot method [4] respectively, and the thermocouple method is also used as an attempt to measure the gas temperature. The reason for the significant deviation of the gas temperature indicated by the thermocouple reading from the measured excitation temperature has been analyzed based on a theoretical analysis considering the rarefied-gas effects on heat transfer from the low-pressure plasma flow to the thermocouple.

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## 2. Experimental details

The non-transferred DC arc plasma torch employed for generating the plasma jet at reduced pressures is the same as that used in the former work [8–12], which mainly contains an anode, a cathode and a three-piece inter-electrode insert. The plasma torch is installed on the top of a vacuum chamber, and the plasma jet is issuing freely into the vacuum chamber. The diameter and height of the vacuum chamber are 650 mm and 450 mm, respectively. Plasma jets are generated using argon as the working gas with flow rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A–110 A and vacuum chamber pressure of 170 Pa–2000 Pa, where the laminar flow regime is achieved. Photos of the laminar plasma jets for different arc currents and chamber pressures [8] show that the volume of the luminous region of the plasma jet does not increase obviously with increasing arc current, but the jet center region looks somewhat brighter at higher arc current. At higher chamber pressure, the size of luminous region of the plasma jet is appreciably reduced but the jet central region becomes much brighter, indicating the notable decrease of the plasma volume and the appreciable increase of the plasma temperature and its radial gradient at higher gas pressure.

The schematic diagram of the experimental setup is shown in Fig. 1. A double electrostatic probe system has been applied to measure the electron temperature  $T_e$ . The probe system mainly consists of five parts, i.e., two fine-wire electrodes for the double electrostatic probe, one boron nitride probe holder, a DC bias power supply, a sampling resistance of  $10 \Omega$  and an oscilloscope for collecting the voltage signals across 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 flow. Other surface of each tungsten wire is covered by an alumina tube of 0.5 mm inner diameter, 1 mm outer diameter and 35 mm length. The probe head is fixed in the boron nitride holder with a center distance of 2 mm between the two tungsten-wire electrodes. The holder can move in the axial and radial direction of the plasma jet. According to the theory of the double electrostatic probe [13,14], the electron temperature  $T_e$  can be deduced from the measured voltage-current

(V–I) characteristic curve and the electron temperature is presented here as the averaged value of at least five measured data at each spatial position.

The spectroscopic measurement system consists of a spectrometer with focal length of 550 mm, an ICCD detector, an external optical imaging and transmission part including 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 then transmitted to the slit of the spectrometer by the optical fiber. The ICCD can detect the light intensities of chosen spectral lines eventually.

The Boltzmann-plot method [4] is used to obtain the excitation temperature  $T_{ex}$  of the plasma jet. Six ArI spectral lines (675.28 nm, 687.13 nm, 696.54 nm, 706.72 nm, 738.40 nm, and 750.39 nm) have been employed to draw the Boltzmann-plot line, and the electron temperature is determined from the slope of the fitted straight line. The spectroscopic parameters of the selected ArI spectral lines are taken from the atomic database of NIST [15]. The exposure time for getting the integrated intensities of each ArI spectral line is set to 100 ms in this experiment.

A thermocouple probe made of 0.2 mm diameter WRe-5/26 wires is used in an attempt to measure the gas temperature. A two-hole ceramic tube with outer diameter of 4.1 mm was used to fix the thermocouple wires and support the thermocouple. The distance between the thermocouple ball-shaped junction and the frontal end of ceramic tube is taken to be 4 mm in order to reduce the conduction loss along the thermocouple wires. The ceramic tube was tied to a water-cooled holder which can move in the axial and radial direction of the plasma jet. Initially, the thermocouple was located outside the plasma jet, and it is moved to a desired measurement position quickly by means of the translation mechanism for measuring the local gas temperature. The temperature indicated by the thermocouple probe is denoted as  $T_p$  in this paper. A data-collecting system with sampling rate of 1 kHz was used to record the temperature evolution history from the value before putting the thermocouple into the plasma jet to the equilibrium temperature finally reached at the measuring position. Experimental results show that due to the existence of the thermal inertia

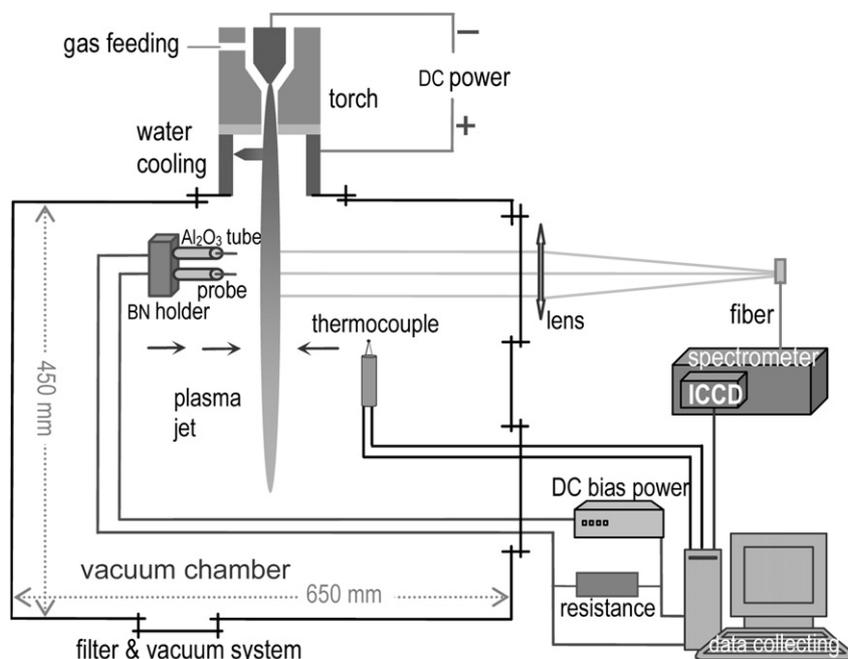


Fig. 1. Schematic diagram of the experimental setup.

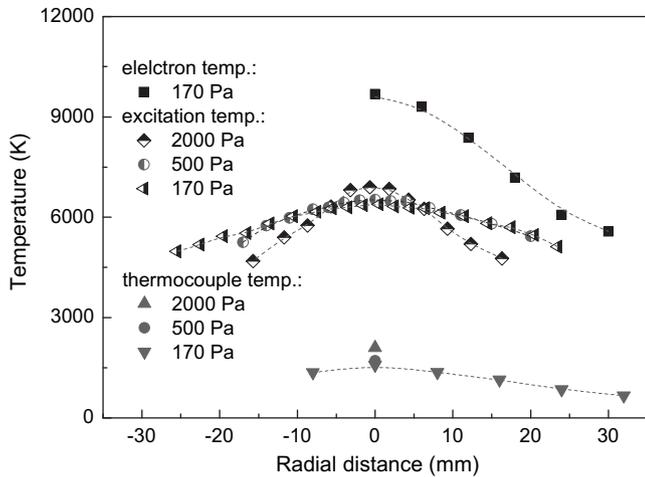


Fig. 2. Radial distributions of the measured electron temperature, excitation temperature and gas temperature of the laminar argon plasma jet for the case with argon flow-rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A and axial distance of 10 mm.

of thermocouple probe, it takes about 4.5 s for the thermocouple probe to achieve the equilibrium temperature, i.e., achieve such a state where the heat flux due to the convective heat transfer from the plasma jet to the ball-shaped junction of the thermocouple is equal to the radiation heat loss from the thermocouple junction to the cold surrounding plus the conductive heat loss (if any) from the thermocouple junction to the ceramic tube along the thermocouple wires. Hence, in this study, the thermocouple stay time at each spatial position is always adopted to be at least 5 s to get the steady temperature  $T_p$ .

### 3. Results and discussions

#### 3.1. Measured electron temperature, excitation temperature and gas temperature

Fig. 2 plots the measured radial distributions of the electron temperature  $T_e$ , the excitation temperature  $T_{ex}$  and the gas temperature  $T_p$  of the argon plasma jet for the case with a fixed axial distance of 10 mm and a constant arc current of 80 A. For the  $T_e$  measurements, the vacuum chamber pressure is fixed at 170 Pa, while the chamber pressure varies from 170 Pa to 2000 Pa for the  $T_{ex}$  and  $T_p$  measurements. It is clearly seen that the values of  $T_e$  are much greater than those of  $T_{ex}$ , while the values of  $T_p$  are much lower than those of  $T_e$  and  $T_{ex}$ . The electron temperature  $T_e$  is as high as 9600 K at the jet center, while it decreases to about 5600 K at the radial position of 30 mm, i.e. the mean radial temperature gradient is about 130 K/mm. The excitation temperature  $T_{ex}$  at the jet center is about 6400 K for the chamber pressure of 170 Pa, and its mean radial gradient is about 55 K/mm, which is appreciably smaller than that of  $T_e$ . When the chamber pressure increases to 2000 Pa, the excitation temperature at the jet center increases to about 6900 K. It is also clearly seen that with the increase of the chamber pressure, the mean radial gradient of  $T_{ex}$  increases. It increases from about 55 K/mm at the chamber pressure of 170 Pa to about 65 K/mm at 500 Pa, and then to 130 K/mm at 2000 Pa. The temperature measured by the thermocouple is about 1600 K at the jet center and decreases to 620 K at the jet edge when the chamber pressure is 170 Pa, and the radial gas temperature gradient is about 30 K/mm.

Fig. 3 provides the measured results about the distributions of  $T_e$ ,  $T_{ex}$  and  $T_p$  along the jet axis for the case with a fixed chamber pressure of 170 Pa and a constant arc current of 80 A. It is seen that

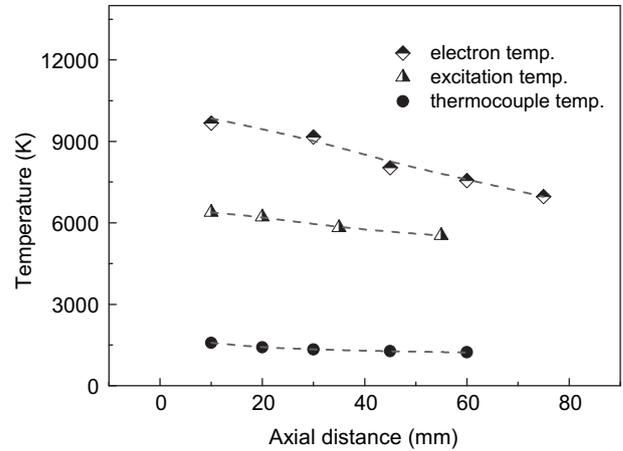


Fig. 3. Axial distributions of the electron temperature, excitation temperature and gas temperature measured at the jet axis for the case with argon flow-rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A and chamber pressure of 170 Pa.

all the three kinds of temperatures decrease with increasing axial distance between the torch exit and the measured position. For the electron temperature  $T_e$ , it decreased from 9600 K at the axial distance of 10 mm to about 7000 K at the axial distance of 75 mm. The mean axial gradient of the electron temperature is about 40 K/mm, which is much smaller than its mean radial gradient 130 K/mm. The mean axial gradient of the excitation temperature  $T_{ex}$  is about 20 K/mm and smaller than its mean radial gradient of 55 K/mm. The averaged axial gradient of the gas temperature  $T_p$  is about 6.5 K/mm, which is also much smaller than its radial gradient 30 K/mm. The smaller axial gradients of temperatures  $T_e$ ,  $T_{ex}$  and  $T_p$  indicate that the laminar plasma jet may preserve its state of high temperature along the jet axis for a large distance.

The variations of  $T_e$ ,  $T_{ex}$  and  $T_p$  with the arc current are shown in Fig. 4 for the case with a fixed chamber pressure of 170 Pa. It is clearly seen that the electron temperature  $T_e$  increases with increasing arc current. When the arc current is increased from 80 A to 100 A, the electron temperature increases from 9600 K to 13000 K. The variations with the arc current of the excitation temperature  $T_{ex}$  and the gas temperature  $T_p$  are not as appreciable as the electron temperature  $T_e$ , but they also increase with the arc current. With the increase of the arc current, the input power and

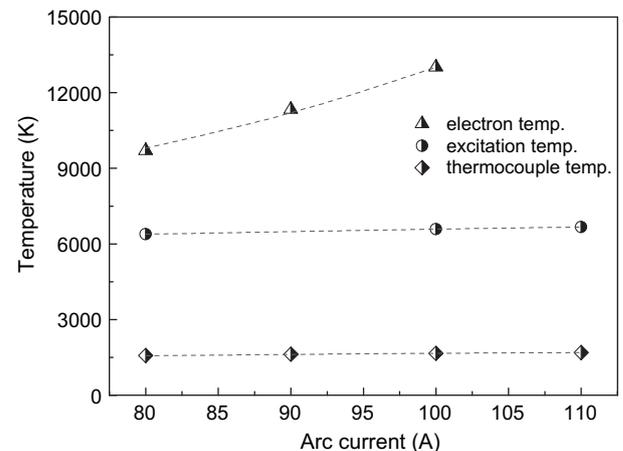


Fig. 4. Variations with the arc current of the measured electron temperature, excitation temperature and gas temperature for the case with argon flow-rate of  $1.25 \times 10^{-4}$  kg/s, chamber pressure of 170 Pa and axial distance of 10 mm.

thus the jet temperature increase, which is consistent with the observation from the photos of the laminar plasma jet [8] mentioned above.

From the measured results presented in Figs. 2–4, it is clear that the electron temperature  $T_e$  is significantly higher than the excitation temperature  $T_{ex}$  and very much higher than the measured thermocouple temperature  $T_p$  under the same working conditions. The plasma jet generated at reduced pressure is evidently deviated from the local thermodynamic equilibrium state, which is different from the arc plasma jet generated at atmospheric pressure.

### 3.2. Discussion on the measuring error of the gas temperature using the thermocouple

The measured results show that the temperature  $T_p$  is much lower than the excitation temperature  $T_{ex}$ . It is believed that such a significant difference between  $T_{ex}$  and  $T_p$  is mainly due to the fact that large systematic error exists in attempting to measure the gas temperature by the thermocouple method under the present conditions, as shown by the following analysis.

Suppose a typical value of the measured temperatures  $T_p$  presented in Figs. 2–4 is taken to be 1600 K at the jet center for the case with the argon mass flow rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A and chamber pressure of 170 Pa, and assume that this temperature were the true gas temperature. From the well-known equation for the sound speed of perfect gas  $a_s = (\gamma RT)^{1/2}$  (where  $T$ ,  $R$  and  $\gamma$  are the gas temperature, ideal gas constant and specific heat ratio, whereas  $a_s$  is the sound speed), the sound speed corresponding to 1600 K argon would be about 742 m/s. Former velocity measurement by means of an electrostatic probe method [16] of the laminar plasma jet issuing from the same plasma torch under the same working conditions (argon mass flow rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A and chamber pressure of 170 Pa) showed that the measured mean velocity at the jet center was about 1200 m/s. Hence, if the gas temperature were indeed 1600 K, the Mach number (=velocity/sound speed) at the center of the measuring section would have been about 1.6, i.e. the flow of the laminar plasma jet at the measuring position would have been supersonic for this case. However, when we inserted a tungsten stick of 1.5 mm diameter into this laminar plasma jet, there was not any indication of occurrence of Mach waves, as demonstrated in Fig. 5(a). As a comparison, Fig. 5(b) shows a photo which demonstrates that when a tungsten stick is inserted into a truly supersonic plasma flow, Mach waves appear around the tungsten stick, as expected. This fact tells us that the laminar plasma jet shown in

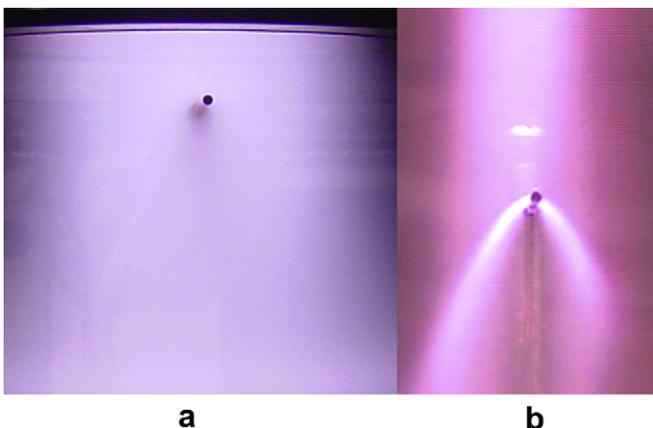


Fig. 5. Photographs obtained when a tungsten stick is inserted into (a) the laminar argon plasma jet at chamber pressure of 170 Pa and (b) a supersonic plasma jet.

Fig. 5(a) must not have been supersonic, i.e. the local sound speed must have been much higher than 742 m/s and the actual gas temperature must have been much higher than the 1600 K measured by the thermocouple. Since the local sound speed must have been higher than the gas flow velocity 1200 m/s, correspondingly the gas temperature must have been at least higher than about 4200 K, i.e. the gas temperature measured directly by the thermocouple must have contained large error for the present reduced pressure case.

A most likely reason for the existence of such a large error in the measured gas temperature by thermocouple for the present reduced pressure case is that the convective heat transfer from the flowing gas to the thermocouple is reduced significantly at low gas pressure. It is well known that the indicated temperature of the thermocouple is the result of heat balance at the thermocouple surface involving several different heat transfer mechanisms. If we ignore the conductive heat transfer along the thermocouple wires, the heat flux due to the convective heat transfer from the flowing plasma to the thermocouple would be equal to that due to the radiative heat loss from the thermocouple to the cold environment at steady state. The heat flux due to the radiation heat loss from the thermocouple surface  $q_r$  (in W/m<sup>2</sup>) can be calculated by  $q_r = \varepsilon \sigma T_p^4$ , where  $\varepsilon$  is the emissivity of the thermocouple material and  $\sigma$  is the Stefan–Boltzmann constant. On the other hand, when the gas flow temperature is about 5000 K and the gas pressure is 170 Pa, the Knudsen number (Kn) would be larger than 1 and thus the convective heat transfer from the flowing gas to the thermocouple junction should be treated as a rarefied-gas heat transfer problem. For the free-molecule regime, Ref. [17] derived the expressions for the heat fluxes to a cylindrical wire due to atoms, ions and electrons, respectively. For the case studied here, degree of ionization of the gas is small and thus the heat transfer will be dominated by argon atoms. Hence, the convective heat flux from the flowing gas to the cylindrical wire surface  $q_c$  (in W/m<sup>2</sup>) can be calculated by [17]:

$$q_c = ap_\infty \sqrt{\frac{kT_\infty}{2\pi m}} e^{-S^2/2} \left\{ \left( 2 + S^2 - 2\frac{T_w}{T_\infty} \right) I_0 \left( \frac{S^2}{2} \right) + \left( \frac{5}{2} + S^2 - 2\frac{T_w}{T_\infty} \right) S^2 \left[ I_0 \left( \frac{S^2}{2} \right) + I_1 \left( \frac{S^2}{2} \right) \right] \right\} \quad (1)$$

where  $a$  is the thermal accommodation coefficient at the thermocouple surface,  $p_\infty$ ,  $T_\infty$ , and  $U_\infty$  are the static pressure, temperature and velocity of the flowing gas,  $k$  is the Boltzmann constant,  $m$  is the argon atom mass,  $T_w$  is the wire surface temperature (here  $T_w = T_p$ ),  $S = U_\infty / (2kT_\infty/m)^{1/2}$  is the so-called speed ratio, whereas  $I_0(z)$  and  $I_1(z)$  are the zero-order and first-order modified Bessel function, respectively.

When the heat transfer processes reach the steady state, the convective heat flux  $q_c$  is equal to the radiative heat flux  $q_r$ , and thus the temperature of the oncoming gas flow can be deduced from the measured temperature  $T_p$ . For the typical case with measured temperature  $T_p = 1600$  K and gas flow velocity  $U_\infty = 1200$  m/s, Fig. 6 shows the variations with gas-flow temperature of the convective and radiative heat fluxes using the thermal accommodation factor  $a$  and the material emissivity  $\varepsilon$  as two parameters. One can see from Fig. 6 that reliable data of the emissivity of the thermocouple material and the thermal accommodation coefficient at the thermocouple surface are required for accurately deducing the gas flow temperature from  $q_c = q_r$ . The deduced gas temperature will decrease with decreasing emissivity  $\varepsilon$  and increase with decreasing thermal accommodation coefficient  $a$ . If the thermal accommodation coefficient  $a$  of the WRe-5/26 thermocouple surface is taken to be 1.0 and the tungsten emissivity  $\varepsilon$  is taken to be

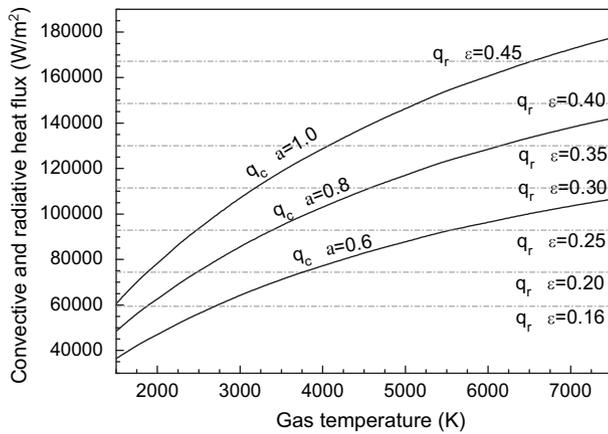


Fig. 6. Variations of the convective and radiative heat flux with gas temperature  $T_\infty$ .  $T_p$ ,  $u_\infty$  and  $p_\infty$  are taken to be 1600 K, 1200 m/s and 170 Pa, respectively, in the calculation.

0.4 [18], the gas temperature  $T_\infty$  deduced from Fig. 10 is 5100 K. On the other hand, when  $a = 0.8$  and  $\varepsilon = 0.35$  are adopted, the deduced gas temperature  $T_\infty$  would be 6100 K. Although the uncertainty in  $\varepsilon$  and/or  $a$  influences the value of the deduced gas temperature, the deduced gas temperature  $T_\infty$  is always much higher than the temperature  $T_p$  measured by the thermocouple. It means that the temperature measurement using the WRe-5/26 thermocouple at low gas pressure always contains large measuring errors, and the  $T_p$  value given by the thermocouple cannot be taken directly as the gas temperature.

#### 4. Conclusions

In this study, the electron temperature and the excitation temperature of the non-transferred DC argon plasma jet generated at reduced pressure are measured by using double electrostatic probe method and the spectroscopic-intensity Boltzmann-plot method, respectively. Attempts are also made to measure the gas temperature by using a pair of WRe-5/26 thermocouple. Experimental results show that the electron temperature is as high as 9600 K for the case with gas flow rate of  $1.25 \times 10^{-4}$  kg/s, arc current of 80 A and vacuum chamber pressure of 170 Pa, while the excitation temperature and the thermocouple temperature are about 6400 K and 1600 K respectively at the same working

conditions. These three kinds of temperatures all increase with increasing arc current and decrease with increasing axial distance. The measured electron temperature is much higher than corresponding excitation temperature, indicating that the low-pressure plasma jet is evidently deviated from the local thermodynamic equilibrium state under the present experimental conditions. Theoretical analysis based on a rarefied-gas heat transfer approach shows that temperatures of the WRe-5/26 thermocouple probe would have values very much below the gas stream temperature under these conditions, and thus cannot represent actual temperature of the gas.

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