Measured temperature of a laminar plasma jet by using thermocouple at reduced pressure

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Abstract: Attempts were made to measure the gas temperature of a DC arc laminar plasma jet generated at reduced pressure by using a pair of WRe-5/26 thermocouple. Results show that the measured temperature is much lower than the value measured by using the spectral method. Theoretical work considering rarefied-gas heat transfer effects has been carried out to analyze the measured error of the thermocouple.

Keywords: laminar plasma jet, temperature measurement, reduced pressure, heat transfer

1. Introduction

Thermal plasma generated at reduced pressure has been widely used in material processing for several decades, such as fast deposition of the high quality diamond films, SiC films and ceramic coatings [1-3]. Temperature of the plasma jet is an important and fundamental parameter which can affect the material processing quality. Generally, at atmospheric pressure, thermocouple can be used to measure the gas temperature if the gas temperature and velocity are not too high. However, there may exist large measuring error in low pressure and high temperature environments due to the complex heat transfer processes being involved, such as the convective heat transfer from the plasma jet to the thermocouple wires, the radiant heat loss from the thermocouple and the heat conduction along the thermocouple wires.

A specially designed non-transferred DC arc plasma torch with a large anode-nozzle exit diameter for use in reduced pressure environment has been constructed [4]. In this study, the thermocouple method was used as an attempt to measure the gas temperature of the laminar plasma jets generated with this plasma torch, and the theoretical study considering rarefied gas heat transfer effects is carried out to analyze the measured error of the thermocouple.

2. Experimental details

The plasma jets were generated with pure argon at the flow rate of 1.25×10^{-4} kg/s, arc current of 80 A and chamber pressure from 170 Pa to 2000 Pa, where the laminar flow regime can be achieved. Fig. 1 compares the photos of the laminar argon plasma jets generated at chamber pressures of 170 Pa and 2000 Pa, respectively, which were taken by an ordinary digital camera. It is clearly seen that at higher chamber pressure, the size of luminous region of the plasma jet is reduced, but the jet central region becomes much brighter, indicating the notable decrease of the plasma volume and the increase of the temperature and its radial gradient at higher gas pressure.

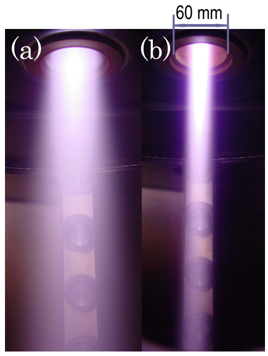


Fig.1 Photographs showing the appearance of the pure argon plasma jets generated at chamber pressure of 170 Pa (a) and 2000 Pa (b).

A pair of WRe-5/26 thermocouple with wire diameter of 0.2 mm was used to measure the gas temperature. The diameter of the ball-shaped junction of the thermocouple is 0.6 mm. 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 junction and the frontal end of ceramic tube is set 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 along the jet axial or in the radial direction. Initially, the thermocouple was located far from the plasma jet, and then it is moved to a desired measurement point quickly and accurately by means of the translation mechanism. The gas temperature measured by the thermocouple is denoted as T_{pa} in this paper.

A data-collecting system with sampling rate of 1 kHz was used to record the temperature variation process from the value before setting the thermocouple into the plasma jet to the equilibrium temperature finally reached at the measuring position.

Fig. 2 plots the temperature evolution curve of the thermocouple when it moves to and then stays at the jet center. In the measurement, the axial distance between the plasma torch exit and the thermocouple junction is 20 mm, and the chamber pressure is 170 Pa. It is seen that after the thermocouple arrives at the measurement location, the thermocouple temperature gradually increases from about 500 K to a steady level of about 1400 K within 4.5 s. This experimental results demonstrates that due to the existence of the thermal inertia of thermocouple probe, the heat transfer processes require about 4.5 s to achieve the steady state, i.e., achieve such a state where the heat flux due to the convective heat transfer from the plasma jet to the thermocouple junction 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 position is always adopted to be at least 5 s to get the balanced temperature of T_{pa}..

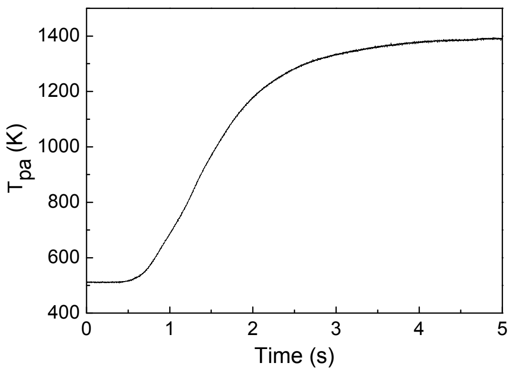


Fig. 2 Temperature evolution curve.

3. Results and discussions

Fig. 3 shows the measured radial distributions of T_{pa} for two different axial distances (i.e. 10 mm and 20 mm) between the torch exit and the thermocouple junction, for the chamber pressure of 170 Pa. When the axial distance is 10 mm, the maximum temperature measured at the jet center is about 1600 K and the temperature decreases to 620 K at the jet edge. The radial temperature gradient is about 30 K/mm. When the axial distance is increased to 20 mm, the temperature curve changes from 1400 K at the jet center to about 620 K at the jet edge, and the radial temperature gradient is about 24 K/mm.

The variations of the gas temperature T_{pa} measured by the thermocouple at the jet center with the axial distance and with the chamber pressure are shown in Fig. 4. It is seen that when chamber pressure increases from 170 Pa to 2000 Pa, the measured temperature T_{pa} increases from 1600 K to about 2170 K. This result is qualitatively consistent with that shown in the photos of Fig. 1, which show that the jet center becomes brighter at higher chamber pressure. Fig. 4 also show that the measured temperature T_{pa} decreases along the jet axis, and the averaged axial temperature gradient is only about 6.5 K/mm which is much lower than the radial temperature gradient.

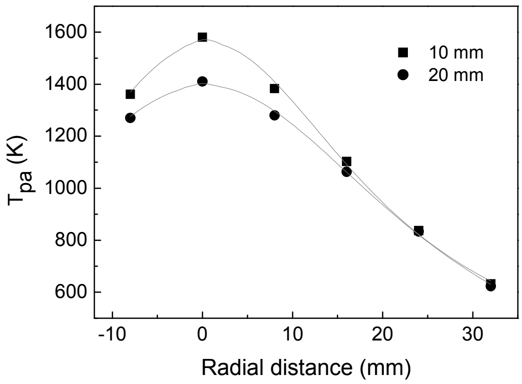


Fig. 3 Radial distributions of the measured temperature at the measuring section with axial distance of 10 mm and 20 mm between the torch exit and the thermocouple junction.

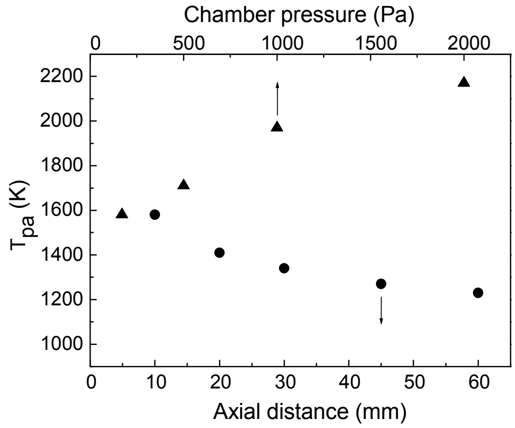
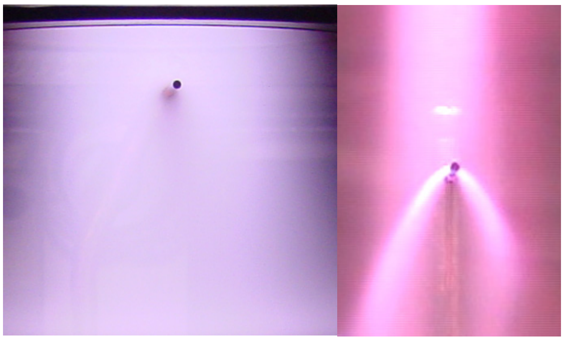


Fig.4 Variations of the measured temperature at the jet center with the axial distance and the chamber pressure.

By using the sound velocity equation of the prefect gas $a=(\gamma RT)^{1/2}$, the sound velocity for pure argon gas of 1600 K is about 735 m/s, that means if the measured temperature T_{pa} is equal to the real gas temperature, the sound velocity in that case is indeed 735 m/s. Former experimental work about the measured velocity of the laminar jet at the torch exit with the gas mass flow rate of 1.25×10^{-4} kg/s, arc current of 80 A and chamber pressure of 170 Pa showed that the measured mean velocity was 1200 m/s by means of the electrostatic probe method [5]. Thereby, the Mach number is about 1.6, indicating supersonic flow of the laminar jet in this typical case. However, there wasn't any indication of supersonic flow characteristics when a tungsten stick of 1.5 mm was inserted into the laminar jet at the same working conditions mentioned above (Fig. 5 (a)), that is, if the plasma jet flow were supersonic, Mach waves would have appeared distinctly when the tungsten stick was inserted (Fig. 5(b)). The calculated Mach number and the jet photo seem incompatible to each other. Also, the temperature measured by the thermocouple is very much lower than the gas temperature (~6000 K) measured through the oxygen spectral line absorption spectral, where just 4.5% volumetric fraction of oxygen was added into the laminar jet [6].



(a) (b)

Fig.5 Photo of a tungsten stick inserted into (a) a laminar plasma jet at the same working conditions of Fig. 3 and (b) a supersonic plasma jet flow.

From the above mentioned discussions, it can be deduced that large errors may exist in the thermocouple measurements under the present reduced pressure conditions. A possible reason is that since the convective heat transfer from the flowing gas to the thermocouple may be small at low gas pressure, the radiation loss of the thermocouple may lead to appreciably lower temperature measured by the thermocouple.

Theoretical analysis is thus conducted in the following to estimate the measured error of the thermocouple. It is noted that the measured temperature by the thermocouple is only the result of heat balance involving several different heat transfer mechanisms at the thermocouple surface. If we ignore the conductive heat transfer along the thermocouple wires, the heat flux due to the convective heat transfer from the flowing gas to the thermocouple will be equal to that due to the radiative heat transfer from the thermocouple surface 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^2) can be calculated by

$$q_r = \varepsilon \sigma T_{pa}^4 \qquad (1)$$

where ε is the emissivity of the thermocouple material, whereas σ is the Stefan- Boltzmann constant.

On the other hand, when the gas flow temperature is about 5000 K and gas pressure is 170 Pa, the Knudsen number (Kn) defined as the ratio of the mean free length of gas particles to the thermocouple-wire diameter (0.2 mm) is about 7 and thus the convective heat transfer from the flowing gas to the thermocouple is expected to happen in the near-free-molecule flow regime [7]. Hence, one should use the rarefied-gas heat transfer approach to calculate the heat flux of the convective heat transfer for the gas flowing cross the thermocouple wires. Similar problem was studied in Ref. [7], in which the expressions were derived for the local heat fluxes and for the circumferentially averaged heat fluxes due to atoms, ions and electrons, respectively.

For the case studied here, the gas ionization degree is small and thus the heat transfer will be dominated by argon atoms. Hence, the heat flux from flowing argon to the cylindrical wire surface q_c (in W/m^2) can be expressed as [7]:

$$q_c = a p_\infty \sqrt{\frac{kT_\infty}{2\pi m}} e^{-S^2/2} \left\{ \left(2 + S_h^2 - 2\frac{T_w}{T_h} \right) I_0\left(\frac{S^2}{2}\right) + \left(\frac{5}{2} + S^2 - 2\frac{T_w}{T_h} \right) S^2 \left[I_0\left(\frac{S^2}{2}\right) + I_1\left(\frac{S^2}{2}\right) \right] \right\} \qquad (2)$$

where a is the thermal accommodation coefficient of the thermocouple surface, p_∞ is the static pressure of the flowing gas, k is the Boltzmann constant, m is the argon atom mass, $S=U_\infty/(2kT_\infty/m)^{1/2}$ 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.

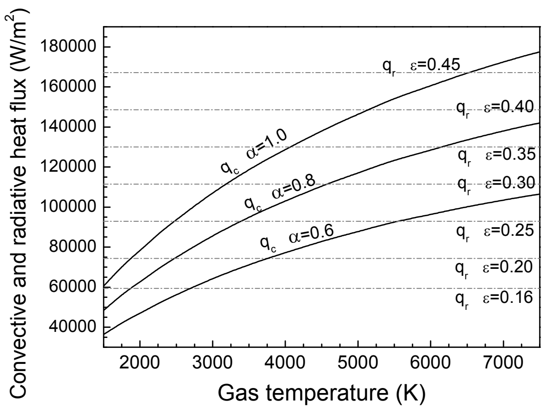


Fig. 6 Variations of the convective and radiative heat flux with gas temperature. (T_{pa} 1600 K, u_∞ 1200 m/s, p 170 Pa).

When the heat transfer processes achieve the steady state, the convective heat flux q_c will be 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_{pa}. For the typical case with measured temperature T_{pa}=1600 K, gas flow velocity U_∞=1200 m/s, Fig. 6 shows the variations of the convective and radiative heat fluxes with gas flow temperature taking the thermal accommodation factor a and the material emissivity ε as the parameters. One can see from Fig. 6 that if the thermal accommodation coefficient of the WRe-5/26 thermocouple surface is taken to be 1.0 and the tungsten emissivity is taken to be 0.4 [8], the gas temperature deduced from Fig. 6 is 5100 K. The deduced gas temperature will decrease with decreasing emissivity ε and increase with decreasing thermal accommodation coefficient a, and large variations in the value of the deduced gas temperature can easily happen. Hence, reliable data of the emissivity of the thermocouple material and the thermal accommodation coefficient at the thermocouple surface are necessary for the accurate deduction of the gas flow temperature from q_c=q_r. However, the deduced gas temperature is always much higher than the temperature measured by the thermocouple, although the deduced gas temperature contains uncertainty in ε and a values. It means that the temperature measurement using the WRe thermocouple at low gas pressure always contains large measuring errors, It cannot be used directly as the gas temperature.

4. Conclusions

Attempts were made to measure the gas temperature of a DC arc laminar plasma jet generated at reduced pressure by using a pair of WRe-5/26 thermocouple. Results show that the measured temperature increases with increasing chamber pressure, and decreases with increasing axial distance from the torch exit to the thermocouple junction. The measured temperature at the jet center is about 1600 K at arc current of 80 A, gas flow rate of 1.25×10^{-4} kg/s and chamber pressure of 170 Pa, and this value is much lower than the measured one obtained by using the spectral method. Theoretical analysis using a rarefied-gas heat transfer approach shows that the measured gas temperatures using the WRe-5/26 thermocouple are always much lower than the actual gas temperature and thus contain large errors.

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References

[1] H. Murakami, K. Higuchi, T. Yoshida, Nippon Kinzoku Gakkaishi/Journal of the Japan Institute of Metals 56(4), 452(1992).

[2] W. X. Pan, F. X. Lu, W. Z. Tang, G. F. Zhong, Z. Jiang, C. K. Wu, Diamond and Related Materials 9(9-10), 1682(2000).

[3] J. H. Ouyang, S. Sasaki, K. Umeda, Surface & Coatings Technology 137(1), 21(2001).

[4] W. X. Pan, X. Chen, X. Meng, T. Li, C. K. Wu, In: Proceedings of the 17th International Symposium on Plasma Chemistry. 2005, Paper No. 438.

[5] W. X. Pan, Z. Y. Guo, X. Meng, H. J. Huang, H. J. Huang, In: Proceedings of the 2nd International workshop on non-equilibrium Flows, Lijiang, 2008.

[6] H. L. Liu, X. Meng, F. Li, X. L. Yu, W. X. Pan, J. Fan, In: Proceedings of the 2nd International workshop on non-equilibrium Flows, Lijiang, 2008.

[7] X. Chen, Journal of Physics D: Applied Physics 30, 1885(1997).

[8] R. D. Larrabee, The spectral emissivity and optical properties of tungsten, Technical report 328 in MIT, 1957.