Heat Transfer from a dc Laminar Plasma-Jet Flow to Different Solid Surfaces *

MENG Xian(孟显), PAN Wen-Xia(潘文霞), WU Cheng-Kang(吴承康)
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080

(Received 11 December 2002)

The heat flux distributions were measured by using transient method for an argon dc laminar plasma-jet flow impinging normally on a plate surface embedded with copper probes. Different powders were coated on the probe surfaces and the effect of powder coatings on the heat transfer from jet flow to the probe surface was examined. Experimental results show that the maximum values of the heat flux to the probe increase with the coating of fine metal powders, while for the surfaces coated with fine ceramic powders, the maximum values of heat flux decrease, compared with that to the bare copper probe surface.

PACS: 52.50.−b, 52.40.−w

An effective utilization of thermal plasma sources requires a thorough understanding of the heat transfer mechanism from the jet flow to materials, which is a critical problem in most plasma-material processing, such as plasma spray and materials surface modification. There have been several research works on the heat transfer process[1−6] in recent decades. Pfender and co-workers[1−3] measured the energy transport from the plasma to the wire probe by sweeping the wire through a free-burning arc, or by using a water-cooled copper tube and a tube with pyrex-coated surface in argon atmosphere at atmospheric pressure. Kanzawa *et al.*[4] measured the heat flux to platinum- and silica-coated wires in rarefied argon plasma jet. Chen *et al.*[5] measured the heat transfer for an argon dc plasma jet impinging normally upon a flat plate in air atmosphere. The above works were carried out under transferred arc conditions or non-transferred turbulent jet-flow conditions, where flow fluctuation prevails.[7] Laminar plasma has a long jet length with characteristics of stable flow field and low-energy gradient in its axial direction, which could result in high reliability for materials surface processing.[8] Meng *et al.*[6] performed some simulation and experimental work about the heat transfer characterization of argon dc laminar plasma jets impinging on a copper plate at atmospheric pressure.

In this Letter, we focus our efforts on studying the heat transfer mechanism from argon dc laminar-flow plasma jet to copper probes coated with different material powders by using transient method. The dc laminar plasma jet used here is generated within the parameter range as the same as those in Refs. [6,8].

The schematic diagram of the transient method measuring the heat flux is shown in Fig. 1. The method is similar to our previous work[6] with differences as follows: firstly, five 0.8-mm-diameter, 0.8-mm-length short copper slugs numbered 1, 2, 3, 4, and 5 were embedded linearly in the flat surface as heat-flux measuring probes, and their sides and backs were insulated thermally with ZrO_2 powder. Secondly, five Nickel/Chromium-Nickel/Aluminium thermocouples attached at the back surface of the probe were used to obtain the temperature variation data during the plate sweeping across the laminar jet. Thirdly, fine powders of Cu, Al, ZrO_2, Al_2O_3, SiC, and SiO_2, etc. were coated at the surfaces of probes 1, 3, 5 (as experimental probes) respectively using an Na_2SiO_3 solution binder, with probes 2 and 4 as reference probes without any powder coating. Scanning electron microscope (SEM) images of the powder coating surfaces with Al, SiO_2, and ZrO_2 are shown in Fig. 2, which shows that the particle sizes are generally less than 20 for all kinds of powders. The measured back surface temperature is considered equal to the front surface temperature of the probe for the high thermal conductivity of copper [398]. The sweeping velocities were chosen to be from 183 mm/s to 245 mm/s. The input power to generate plasma jet was 7 kW. The working gas was argon at a feeding rate of 9.0×10^{-5} kg/s.

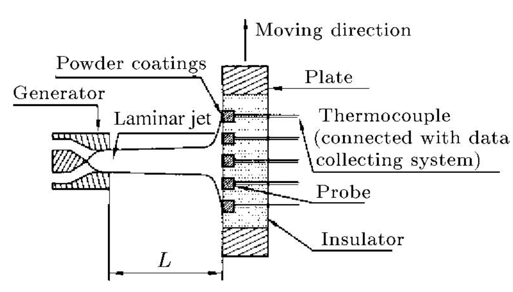

Fig. 1. Schematic diagram of the transient method.

A temperature-response curve of the probe sweeping across the laminar flow plasma-jet was obtained, and heat flux distribution can be obtained by differentiating the temperature with respect to time according to the response curve.[5,6] Fig. 3 shows distributions of heat flux at different velocities and at the distance

* Supported by the National Natural Science Foundation of China under Grant Nos 59836220 and 50276065.

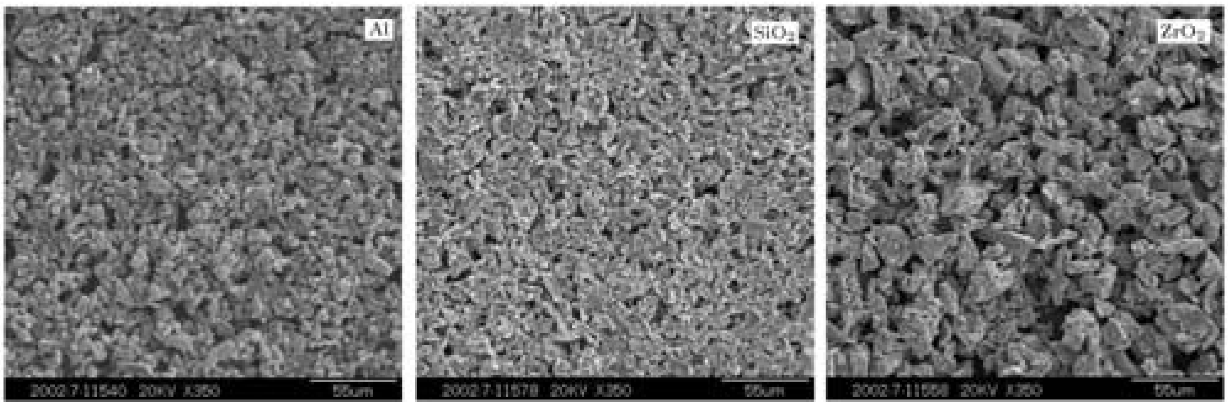

Fig. 2. SEM photos of Al, SiO_2 and ZrO_2 coatings.

axial L of 15 mm derived from probe 2. It is evident that the maximum heat flux corresponding to the jet centre increases as the sweeping velocity decreases. This phenomenon is consistent with the results in Refs. [1,2], which could infer that the frozen boundary layer existed during the heat transfer process, because the heat flow from the jet had more time to reach the probe surface with the sweeping velocity decreasing. The heat flux values become similar to each other for the three curves with the increasing radial distance, so in the following discussion, we would just consider the maximum heat flux at the jet centre. The experimental data showed that the maximum heat flux resulted in probe temperature of 200°C to 420°C for different sweeping velocities, axial distances and surface coatings. In this temperature range, the theoretical thermal conductivities of Cu, Al, SiC, Al_2O_3, ZrO_2, and SiO_2 decreased in turn.[9]

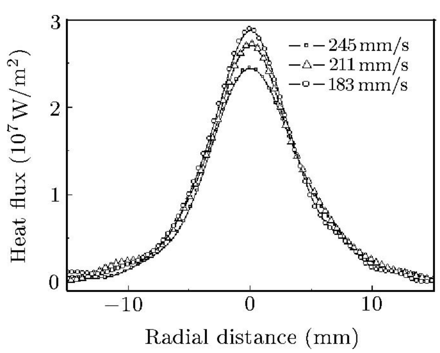

Fig. 3. Distributions of heat fluxes on the plate surface at different sweeping velocities and axial distance L of 6 mm, derived probe 2.

The five probes were used simultaneously in this work. Accordingly, sensitivities of each probe with thermocouple should be calibrated to obtain the comparable data. Figure 4 shows the maximum heat flux values derived from the five bare probes, by sweeping the flat plate across the laminar jet for 12 times at axial distance of 6 mm and velocity of 245 mm/s. The response coefficient of each probe can be obtained by processing the results in Fig. 4. That is, for each probe, a mean value of the maximum heat flux

$$\bar{q}_t = \sum_{n=1}^{5} \bar{q}_n/5, \bar{q}_n \quad (n = 1, 2, \cdots 5),$$

at the jet centre, can be calculated by averaging the experiment data. The response coefficient α_n of each probe was defined as $\alpha_n = \bar{q}_n/\bar{q}_t$ $(n = 1, 2, \cdots 5)$, and the values were $a_1 = 0.94$, $a_2 = 0.83$, $a_3 = 1.28$, $a_4 = 0.88$, $a_5 = 1.25$, respectively. The response coefficients were valid for the maximum heat flux.

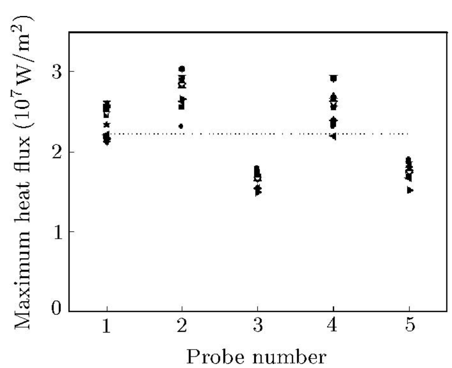

Fig. 4. Maximum heat flux of the five probes.

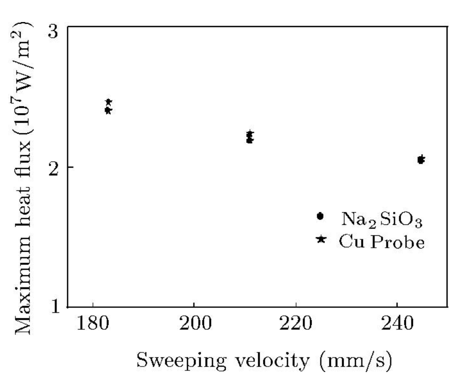

Fig. 5. Effect of binder on maximum heat flux. Na_2SiO_3: the result with binder coatings. Cu probe: the result with bare copper surfaces.

Figure 5 shows the maximum heat flux changing with the sweeping velocities, where surfaces of probes 1, 3, and 5 were just coated with binder, and surfaces of probes 2 and 4 were uncoated as reference ones, in order to analyse whether the binder has effect on heat transfer from the laminar jet to probe surface. The results show that the binder coating had little effect on the maximum value of the heat flux. Thus, the effect of the binder on heat transfer can be neglected.

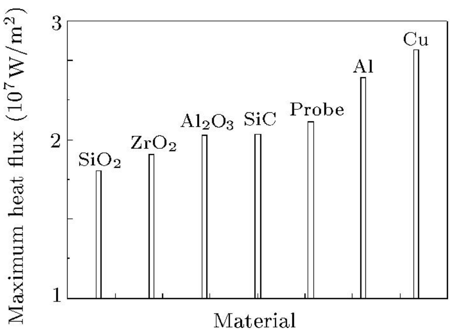

Fig. 6. Comparison of the maximum heat fluxes at the sweeping velocity of 245 mm/s and the axial distance of 6 mm.

The comparisons of the maximum heat flux from laminar jet to solid surfaces with different material coatings are shown in Fig. 6. The thickness of powder coatings was about two times of its particle size, and the maximum heat fluxes were the measured mean values. For the refractory coated surfaces, the maximum values are smaller than that of the bare copper surface. The lower the thermal conductivity of the material is, the lower the maximum heat flux appears. While for the metal powder coated surfaces, the maximum values are higher than that of the bare copper surface. This could be explained by increasing surface area for heat transfer when metal powder is coated on the probe surface. However, for the refractory powder coated surfaces, low thermal conductivity of the materials might play an important role for the heat transfer process, though the heat transfer areas also increased. The comparison of maximum heat flux at different distances and with different coatings is shown in Fig. 7. The maximum heat flux decreases with increasing the axial distance, which is due to decreasing the jet energy distribution with the increasing of the axial distance.[6,8] For a fixed axial distance, the maximum heat flux changes with different coatings as the same tendency shown in Fig. 6.

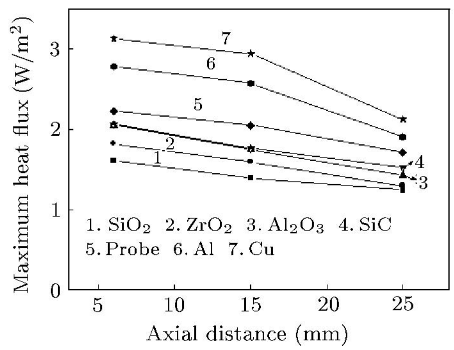

Fig. 7. Comparison curves of maximum heat fluxes at sweeping velocity of 245 mm/s and different axial distances.

In summary, the sweeping velocity can affect the heat transfer from laminar plasma jet to probe surface. For the refractory powder coated surfaces, the maximum heat flux is smaller than that to the bare copper surface. For the metal powder coated surfaces, the values are higher than that to the bare copper surface.

References

[1] Pfender E 1976 *Pure Appl. Chem.* **48** 199
[2] Petrie T W and Pfender E 1972 *Warme-und Stoffubertragung* **5** 85
[3] Meyer T N and Pfender E 1973 *Warme-und Stoffubertragung* **1** 25
[4] Hayashi T, Honda T and Kanzawa A 1978 *Heat Transfer-Japanese Res.* **7** 53
[5] Chen X, Han P, Li H P and Ye X H 1999 *Proc. ISPC* 14 **1** 61
[6] Meng X, Pan W X, Zhang W H and Wu C K 2001 *Plasma Sci. Tech.* **3** 953
[7] Zhao W H, Tian K, Liu D and Zhang G Z 2001 *Chin. Phys. Lett.* **18** 1092
[8] Pan W X, Zhang W H, Zhang W H and Wu C K 2001 *Plasma Chem. Plasma Process.* **21** 23
[9] Zhou Y 1995 *Ceramic Materials* 1st edn (Harbin: Harbin Institute of Technology Press) 459 (in Chinese)