Heat Flux Characterization of DC Laminar-plasma Jets Impinging on a Flat Plate at Atmospheric Pressure

MENG Xian (孟显), PAN Wen-xia (潘文霞), ZHANG Wen-hong (张文宏), WU Cheng-kang (吴承康)
Institute of Mechanics, the Chinese Academy of Sciences, Beijing 100080, China

Abstract By using steady and transient methods, the total heat fluxes and the distributions of the heat flux were measured experimentally for an argon DC laminar plasma jet impinging normally on a flat plate at atmospheric pressure. Results show that the total heat fluxes measured with a steady method are a little bit higher than those with a transient method. Numerical simulation work was executed to compare with the experimental results.

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1. Introduction

Thermal plasmas of very high-energy intensity can provide special conditions for materials processing. It can be used to promote the surface capabilities, such as wear resistance, heat resistance and erosion resistance etc. Heat flux, as an important parameter of jet-surface interaction, plays an important role in materials processing and could determine the scope of application of the plasma jet. DC laminar plasma jets with good flow stability were generated at atmospheric pressure with a specially designed torch [1], and preliminary analysis on the flow field indicates that the low temperature gradient along the jet axis could enhance the controllability of processing on material surface. But so far the systematic research on the flow field of laminar plasma jets and interactions between laminar plasma jets and materials has been seldom done.

In order to reveal the feasibility and advantages of the laminar plasma jet for processing on material surface, the total heat fluxes for a DC arc laminar plasma jet impinging on a flat plate are measured with a steady method, and the heat flux distributions on the plate surface are measured with a transient method in this work. The measured results are compared with corresponding modeling results.

2. Methods for measuring the heat flux

2.1 Methods

There are many methods to measure the heat flux [2~5] according to the different purposes and different conditions. For the high heat-flux measurement, both steady-state and transient methods have been used.

2.1.1 Steady method

A water-cooled flat plate of 120 mm in diameter was used to obtain total heat fluxes by measuring

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the temperature rise and flow rate of the cooling water. By using the equation $W = C_w Q \Delta T$, the total heat flux W can be easily obtained, where C_w is the heat capacity of water, Q and ΔT are the flow rate and the temperature rise of the cooling water respectively. Since the plate receives heat over a large area, the heat flux distribution can not be measured.

2.1.2 Transient method

In a transient method, a small or thin-wall sensor of high thermal conductivity is usually used as a heat flux probe, which has the feature of simplicity in its structure and high sensitivity. The transient method has often been used to measure the distribution of the heat flux.

A schematic diagram of the transient method is shown in Fig. 1. A 1 mm diameter and 1 mm length copper slug was embedded in the flat surface, and insulated thermally with ZrO_2 powder on its sides and back. A pair of copper-constantan thermocouple wires of 0.1 mm in diameter was welded onto the rear surface of the slug. A data-collecting system with a response speed of 1000/s was used to obtain the probe temperature variation during the plate sweeping across the jet at a velocity of about 0.1 m/s. The input power to generate plasma jets was 8 kW. The working gas was argon at a feeding rate of 130 cm^3/s.

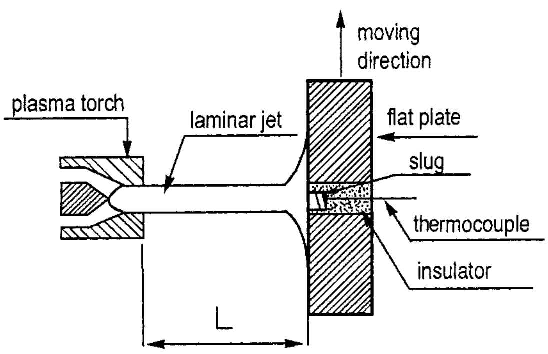

Fig.1 A schematic diagram of the transient method.

Fig. 2 shows a temperature response curve when the plate was put about 20 mm ahead of the laminar plasma torch. Fast Fourier Transformation (FFT) was performed to filtrate the noise signals and thus can get a smoothed output curve. By differentiating the temperature with respect to time in the smoothed curve and using the following equation, we can get the heat flux distribution q:

$$q = \delta \rho C_p dT/d\tau \quad (1)$$

where δ is the length of the slug, ρ and C_p are the density and heat capacity of the slug material, dT is the temperature rise within the time $d\tau$. Due to the high thermal conductivity of copper (k=398 W/(m·K)), the low thermal conductivity of ZrO_2 (k=1.68 W/(m·K)) and the small length of the slug, the measured heat flux distribution could be approximately correspondent to that on the front surface of the plate.

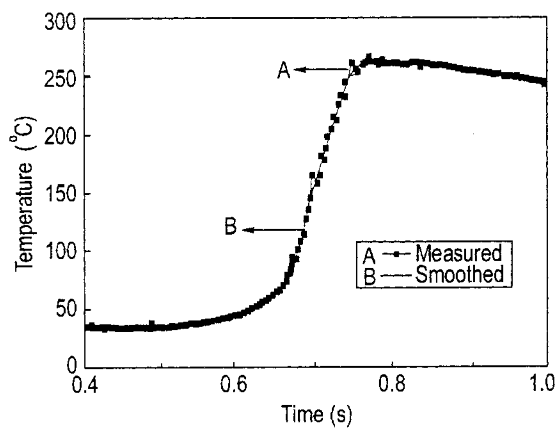

Fig.2 The temperature-response curve and the FFT-smoothed curve.

2.2 Results

Fig. 3 plots the distributions of the measured heat fluxes derived from Eq.(1) at different axial distances. It is found that the maximum value of the heat flux decreases with the increase in axial distance of the plate. The distribution curves do not expand too much in the radial direction with the increase in the distance. This fact demonstrates that the jet diameter almost keeps the same along the jet axis. The radial distribution of the heat flux is approximately symmetrical about the jet axis, by which the symmetry of the laminar plasma jet about the axis could be demonstrated. The pulsation of the flow on the slug surface could lead to a little fluctuation of the heat flux at locations far from the central region.

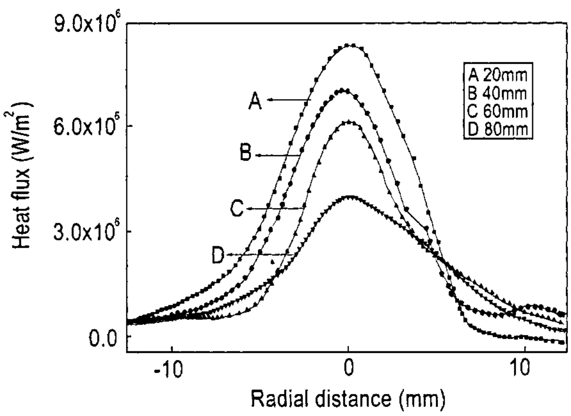

Fig.3 The distributions of heat fluxes on the plate surface with the transient method for different axial distances.

3. Numerical simulation

In order to better understand the flow characteristics of the laminar plasma jet and analyze the possible effects of the laminar plasma jet on the materials surface processing, an Approximate Box Relaxation method [6,7] was used to simulate the laminar plasma jet flow impinging on the flat plate at atmospheric pressure.

3.1 Governing Equations

Basic assumptions used in this study are as follows:

(a) the plasma is in the local thermodynamic equilibrium state;

(b) the plasma is optically thin, i.e., only the radiation loss from the plasma is considered;

(c) the jet flow is steady and symmetrical with respect to the torch axis.

According to the above assumptions, the general form of the governing equations can be written as

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x}(\rho u\phi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v\phi)$$

$$=\frac{\partial}{\partial x}(\Gamma_\phi\frac{\partial\phi}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_\phi\frac{\partial\phi}{\partial r})+S_\phi, \quad (2)$$

where ρ is the gas density, Γ_ϕ is the corresponding diffusion coefficient, S_ϕ is the source term; u and v are the axial and radial velocity components; x and r are the distances in the axial and radial directions respectively. Table 1 shows the different terms, where h is the specific enthalpy, Ur is the radiation power per unit volume of plasma, and μ is the plasma viscosity. The gas properties are taken from the work of Boulos, Fauchais and Pfender [8].

3.2 Computational domain and boundary conditions

The computational domain is shown in Fig. 4. The inside radius of the torch exit AB is R_i=3.3 mm, and AC is 35 mm. The boundary conditions are as follows:

a) BC, EF

$$u_w=v_w=0,\quad T_w=300K,$$

where u_w , v_w are the axial and radial velocity on the wall surface, and T_w is the temperature of the wall surface.

b) AF

$$v=0,\quad \frac{\partial u}{\partial r}=0,\quad \frac{\partial h}{\partial r}=0.$$

c) CD, DE

$$\frac{\partial(\rho vr)}{\partial r}=0,\quad \frac{\partial u}{\partial r}=0,\quad \frac{\partial h}{\partial r}=0.$$

d) AB

the axial velocity and temperature profiles at the torch exit section were not measured experimentally and were taken to be in the following form [9]:

$$u = u_0[1 - (\frac{r}{R_i})^n], \quad v = 0,$$

$$T = (T_0 - T_w)[1 - (\frac{r}{R_i})^m] + T_w.$$

where the parameters u_0, T_0, n and m are related to argon mass flow rate and net torch power, and according to the experimental conditions of a jet power of about 1.3 kW and mass flow rate of 130 cm^3/s, the parameter values used in the present simulations were estimated to be $u_0 = 240$ m/s, $T_0 = 11500K, n = 2, m = 3.8$.

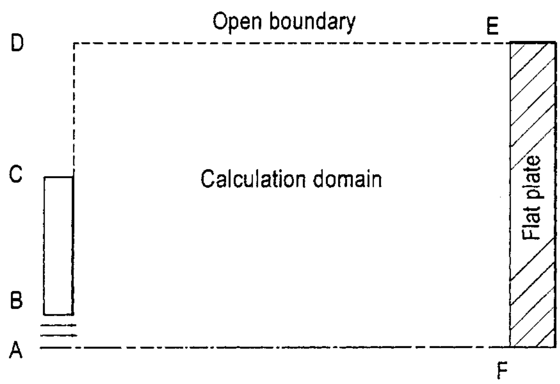

Fig.4 The calculation domain.

3.3 Results

Computed radial distributions of the heat flux on the plate surface are plotted in Fig. 5 for the distance between the torch nozzle and the plate surface being 20 mm, 40 mm, 60 mm and 80 mm, respectively. Heat fluxes at the jet center decrease with the increase in the distance from the torch exit, while the distribution curves of the heat fluxes expand only slightly in the radial direction, implying that the diameter of the laminar plasma jet expands only slightly with the increase in distance.

The computed heat flux distribution is compared with corresponding experimental one in Fig. 6 at an axial distance of 20 mm. It is shown that the maximum heat flux is a little bit higher than the experimental value and the computed distribution curve is somewhat wider than the measured one along the slug surface. This is just a rough comparison, because some assumptions were used in the simulation work, and errors also existed in the measurement method.

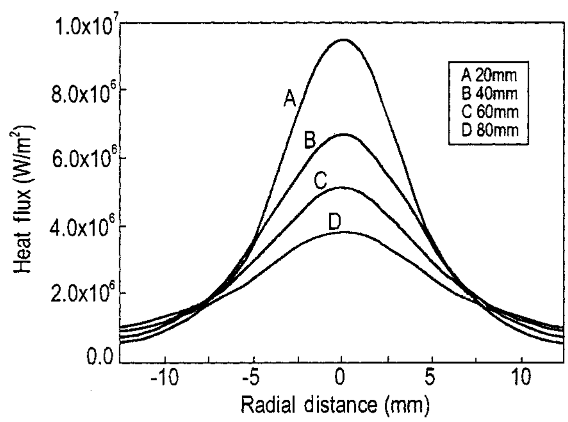

Fig.5 Distributions of the heat flux on the plate surface with the simulation method for different axial distances.

Table 1. Terms in the governing equations

	ϕ	Γ_ϕ	S_ϕ
Continuity	1	0	0
Axial momentum	u	μ	$\frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\mu\frac{\partial v}{\partial x}) - \frac{\partial P}{\partial x}$
Radial momentum	v	μ	$\frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}(r\mu\frac{\partial v}{\partial r}) - \frac{2\mu v}{r^2} - \frac{\partial P}{\partial x}$
Enthalpy	h	μ/P_r	$-Ur$

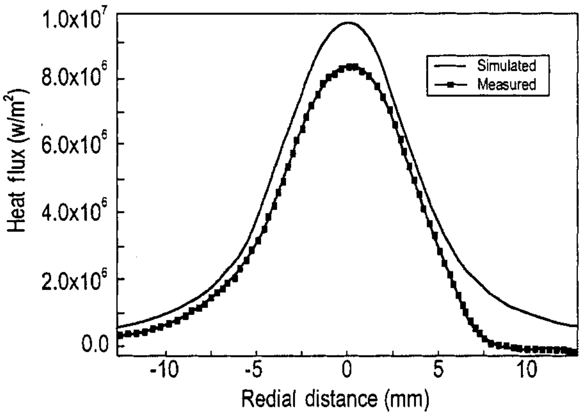

Fig.6 A comparison of heat fluxes on plate surface of the simulation result with that of transient method at an axial distance of 20mm.

4. Comparison of the computed and measured total heat fluxes

By integrating the heat flux distribution, the total heat fluxes at different axial distances can be obtained. Fig. 7 shows the changes of the total heat fluxes obtained by different methods for different plasma conditions. Curve A was obtained by using the steady method for the turbulent plasma jet with a gas flow rate of about 240 cm^3/s. Curves B, C and D were obtained by using the simulation method, the steady method and the transient probe, respectively, for the laminar plasma jet with the same gas flow rate of about 130 cm^3/s.

The total heat fluxes of the turbulent plasma jet decrease sharply along the jet axis, while those for the laminar plasma jet decrease slowly. The latter is in agreement with the computed distribution of temperature which shows a relatively low temperature gradient along the jet axis of the laminar plasma jet [6]. The great difference in the temperature gradient between turbulent and laminar jets indicates that the turbulent jet has a short high-temperature region in the axial direction while the laminar jet has a much longer high-temperature region. For materials surface processing, a long high-temperature region could make the processing easily controlled, and it could be the distinguished advantage of the laminar plasma jet.

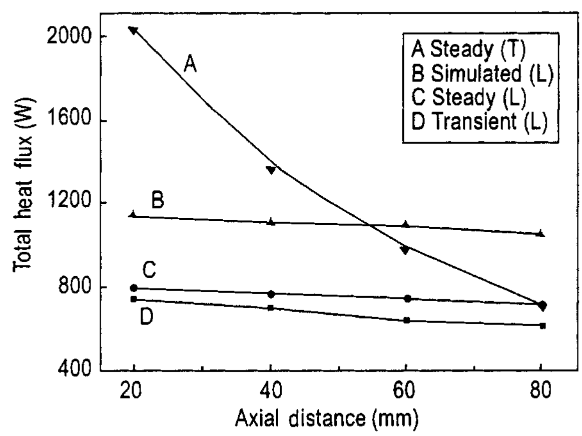

Fig.7 The comparison of the total heat fluxes obtained by different methods. L: laminar jet. T: Turbulent jet.

It has been found that the computed total heat fluxes are less than 1.3 kW. This could be due to the data processing method where just the central regions of the heat flux were integrated to get the total heat flux. It is also found that the simulated results are much higher than the measured ones.

Under the same laminar plasma conditions, the total heat fluxes measured with the steady method are about 5~15% larger than those measured with the transient method, and the difference increases with the increase in the distance from the torch exit. The measurement errors could lead to the lower results from the transient method, such as the response time of the thermocouple, the heat transfer through the copper slug to the surroundings. And the data-processing of FFT smoothing, differentiating and integrating could also affect the accuracy of the transient results.

5. Conclusions

Steady and/or transient methods were used to measure the total heat fluxes and/or the heat flux distributions, and numerical simulation work was also executed to compare with the measured results. Main conclusions obtained from this study are as follows:

(1) The heat flux measured by the transient method shows a decreased maximum value and slightly expanded radial distribution with the increase in the distance between the torch nozzle exit and the plate surface.

(2) The distributions of the heat flux obtained by the simulation and the transient method show an identical trend of variation.

(3) The total heat fluxes measured with the steady method are about 5~15 % higher than corresponding results with the transient method. The difference could be due to the errors in measurements, especially in the transient method.

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E-mail address of MENG Xian: mengxian@btamail.net.cn