EXPERIMENTAL STUDY OF THERMAL PLASMA FLOW AND HEAT TRANSFER IN A TUBE

Xi Chen, Lan Yu and Bingzhi Su

Department of Engineering Mechanics
Tsinghua University , Beijing 100084, China

An experimental study has been conducted concerning the flow and heat transfer for a d.c. arc argon plasma jet issuing into a water-cooled tube. It is shown that the gas static pressure in the tube may increase, decrease or even keep constant along the tube axis, depending on the flow regime, while the heat flux increases with increasing arc current or flow-rate, and decreases with the axial distance from the tube inlet.

1. INTRODUCTION

Knowledge concerning the fluid flow and heat transfer for a thermal plasma issuing into a tube is important for many applications, since the energy efficiency and gas cooling rate within a plasma reactor are all associated with them. Research efforts in this subject will also throw a light on the interaction between a thermal plasma and a cold wall, which has been considered to be an extremely complicated and unsolved basic problem in low-temperature plasma physics.

Some experimental and modeling results were presented in Refs.[1,2]. It was reported that the measured gas static pressure within a water-cooled tube first decreases and then increases with the axial distance from the tube inlet. Such a static pressure variation is markedly different from that for the case of ordinary-temperature gas tube-flow and can be attributed to the special feature of thermal plasma. This pressure variation was also predicted by a numerical simulation for higher plasma temperatures associated with appreciable ionization degree, although quantitative agreement between the predicted and experimental results is not well satisfactory [1,2].

Recently, an experimental/modeling study has been conducted in our Lab concerning the flow and heat transfer for a d.c. arc argon plasma jet issuing into a water-cooled tube. Some results obtained in this experimental study are somewhat different from those reported in Refs.[1,2] and will be presented in this paper.

2. EXPERIMENT

A water-cooled copper tube of 8 mm i.d. and 400 mm length is fit co-axially with the anode-nozzle (with 8 mm i.d. exit) of an argon d.c. arc plasma torch (Fig.1). The arc current used in the experiment is within the range of 80 to 280 A, while the argon flow-rate varies from 0.34 to 2.30 STP m^3/h to cover all the laminar, transitional and turbulent flow regimes. The gas static pressure within the tube has been measured by a manometer as a function of the axial distance (x) from the exit of the plasma-jet generator or the tube inlet for these different flow regimes. It is found that for laminar flow regime at low flow-rates associated extremely low gas-flow noise level, the measured gas pressure increases with increasing axial distance x (Fig.2). This result is roughly consistent with those reported previously at low plasma temperatures [1,2]. On the other hand, for the turbulent flow regime associated with much higher noise level, the measured gas pressure assumes a quite different variation. Namely, the pressure decreases with increasing axial distance x (Fig.3). At moderate flow-rates, i.e. within the transition regime from laminar to turbulent flow regime, gas pressure may increase, decrease or even keep constant along the tube axis, depending on the gas flow-rate (Fig.4).

Heat flux distributions along the tube wall have been measured by two methods for different gas flow-rates and different arc currents. The first method is a steady one by using the setup shown in Fig.1, in which a calorimetric procedure is used to determine the local heat flux. Namely, the mass-flow-rate (G) and temperature rise of the cooling water from the inlet to the outlet of each tube section (ΔT) are measured and the average value of the local heat flux over the inner surface of the tube section $\bar{q}$ is thus calculated by

$$\bar{q} = GC_W \Delta T / F \tag{1}$$

in which C_W is the specific heat of water, and F is the area of inner surface of the tested tube section. The water-cooled tube used in the steady heat transfer experiments is divided into 12 sections with different lengths and insulated each other. Because the local heat flux decreases rapidly with the axial distance within the region near the tube inlet, the length of the tube section near the inlet is designed to be comparatively short, and then increases gradually with increasing distance from the tube inlet.

The second experimental method for heat transfer is an unsteady one, in which an uncooled copper tube with 8 mm i.d. and thin wall is forced to surround abruptly the plasma jet and its wall temperatures at different distances from the tube inlet are measured and recorded as function of time by a minicomputer. The local heat flux distribution can be easily obtained by a local heat equilibrium consideration if axial heat conduction along the tube wall and other heat losses are ignored. For a fixed distance x, the local heat flux is calculated by

$$q = \rho C \delta \left(\frac{dT}{d\tau} \right) \qquad (2)$$

in which ρ and C are copper density and specific heat, δ is the thickness of the tube wall, while $dT / d\tau$ is the temperature rising rate of the tube wall., Both the steady and unsteady methods demonstrate that the local heat flux density always increases with increasing arc current or increasing gas flow-rate. Along with the increase of the axial distance from the torch exit, the measured local heat flux density decreases rapidly at first and then its rate of decrease reduced gradually. Some typical experimental results are presented in Fig.5. The measured heat fluxes by using the steady and unsteady methods are totally consistent except for near the tube inlet, where the heat fluxes measured by unsteady method is somewhat lower than their counterparts obtained by the steady method as shown in Fig.6. An analysis including axial heat conduction and other heat losses shows that such a contradiction can be mainly attributed to the effect of the axial heat conduction along the tube wall in the unsteady measurements.

In a few experiments, a negatively biased voltage has been applied between the tube section under study and the torch anode and effect of the applied voltage on the wall heat flux and gas static pressure is studied. Experimental results show that the negatively biased voltage can slightly enhance the heat flux to the tube section, but the applied voltage almost does not affect the axial gas static pressure distribution within the tube.

3. DISCUSSIONS AND CONCLUSIONS

Axial variation of gas static pressure within the tube is determined by two factors. The first is the decrease of gas average temperature with increasing axial distance from the tube inlet due to heat transfer from gas to water-cooled tube. Decrease in gas temperature will result in the increase of gas density and the decrease of gas velocity for a fixed mass flow-rate. If only this factor is important, gas pressure will increase along the tube axis. The second factor which affects the gas static pressure is the friction force at the tube wall. Friction loss will obviously result in the decrease of gas momentum or pressure along the tube axis. From the experimental results plotted in Figs.2-4, it seems that the first factor (heat transfer to wall causes temperature reduction) is predominant for laminar regime, while the second factor (wall friction) is determining for turbulent regime. Both factors have comparable effects on the pressure variation for transition regime.

The decrease of local heat flux to the tube wall along the axial direction shown in Fig.5 can be easily explained by the reduction of both gas temperature and velocity with increasing axial distance from the tube inlet.

Fig.7 and Fig.8 compared the experimental and modeling results for a laminar regime. The modeling work is concerned with the simultaneous solving of 2D (axisymmetrical) continuity, momentum and energy equations by using SIMPLEC algorithm [3] and based on LTE assumption. It can be seen that agreement between the modeling and experimental data is good for both heat flux and gas pressure distributions.

The phenomenon that gas static pressure first decreases and then increases with the axial distance from the tube inlet reported in Ref.[1,2] is not observed even for laminar regime in the present experiment. This difference can be explained by the fact that the plasma temperatures at the tube inlet involved in this experiment is comparatively low (lower than 12000 K). According to the numerical results of Ref.[2] and ourselves, gas pressure will increase with increasing axial distance at comparatively low incoming plasma temperatures, which is consistent with the present experimental results for laminar regime. Owing to the same reason, it has been observed that a negatively biased voltage has only little effect on heat transfer and flow within the tube.

ACKNOWLEDGMENT

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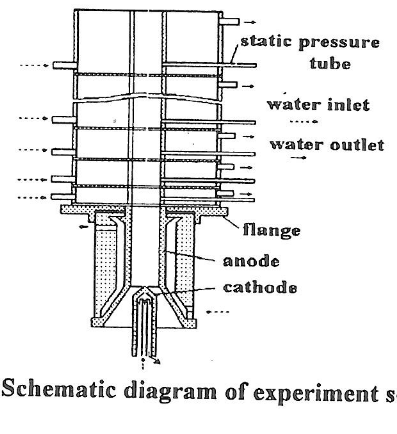

Fig. 1 Schematic diagram of experiment setup

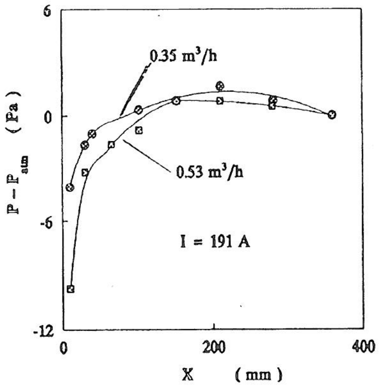

Fig.2 Measured axial static pressure variation (laminar regime)

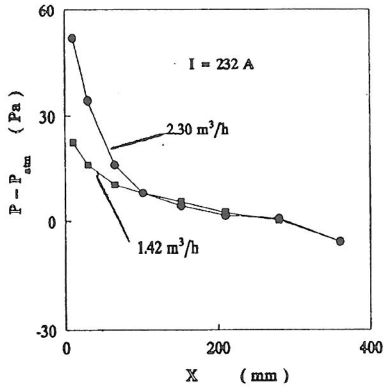

Fig.3 Measured axial static pressure variation (turbulent regime)

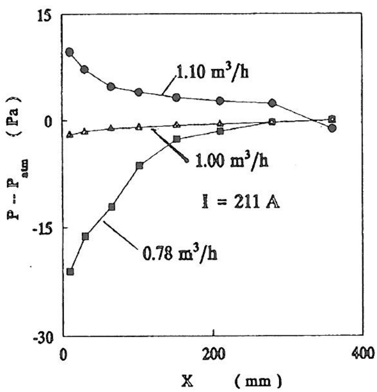

Fig.4 Measured axial static pressure variation (transition regime)

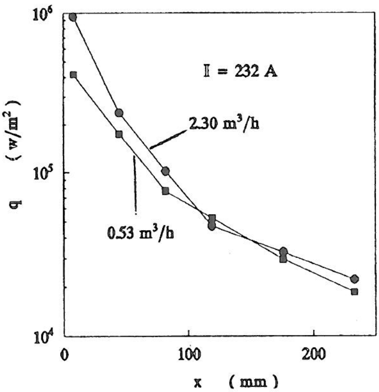

Fig.5 Measured axial heat transfer flux variation (laminar and turbulent regime)

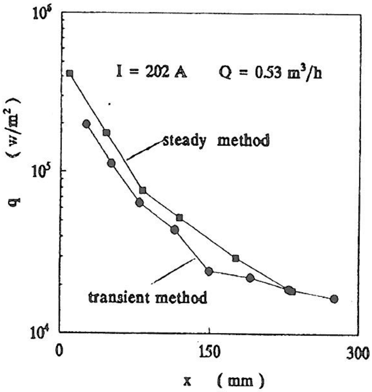

Fig.6 Comparison of the measured heat flux by steady and transient methods

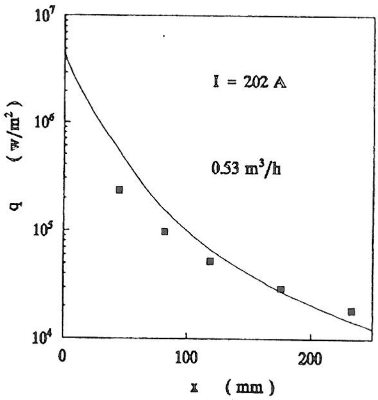

Fig.7 Comparison of the predicted heat flux distribution (line) with experimental data(dots)

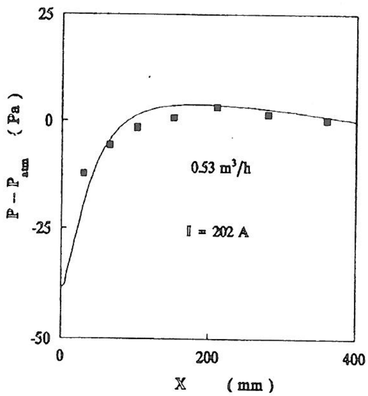

Fig.8 Comparison of predicted static pressure distribution (line) with experimental data (dots)