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Concentration of a plasma energy flow by a blowing gas

When a thermal plasma flow is being used for treatment of a material, it is necessary to control the energy flow density. While in plasma cutting, it is desirable to concentrate the heat flux from a plasma to a flat plate. Experiments were carried out on the concentration of the energy flow density of a thermal argon plasma and the concentration of the heat flux from a plasma jet to a flat plate by an injected gas blowing radially inwards through a slit around the nozzle outlet. The Q-value, which is analogous to the sharpness of the resonance curve of an electrical circuit, and which is defined as the ratio of the maximum energy flow to its half width, was used to evaluate the degree of concentration achieved. Both Q values attained maxima with a radially blowing gas at about the same rate of flow.

Introduction

The two features of a thermal plasma are its high temperature and its highly active character due to being itself the source of the radicals. Applications in which use is made of these two features include cutting and welding, using arc plasmas, plasma spray coating, and the manufacture of acetylene by a high-temperature chemical reaction. For a thermal plasma to be used in this way, it is necessary to control the energy flow density. In plasma cutting, *e.g.*, the shape of the cutting surface, the fineness of the cutting need to be taken into account, with a high and concentrated energy flow density of the plasma flow being desirable. In plasma spray

coating, in which powders or a wire are melted in a plasma, minute changes in the spraying conditions produce wide variations in the quality of the sprayed film. The hot region of the plasma should therefore be as large as possible and the energy flow density as uniform as possible. The energy flow density of a plasma can be controlled hydrodynamically, thermally, magnetically, or mechanically. The method used below is to constrict the plasma flow by means of a blowing gas.

The experimental and analytical work on the temperature and velocity distributions of a free-burning arc have been reported by McKelliger *et al.* [7] and Hsu *et al.* [4,5]. However, little work has been done on the interaction between a plasma flow and a surrounding flow, apart from the reports of Chen and coworkers [1,2], who studied the injected flow into an arc inside a water-cooled tube, and Suzuki *et al.* [8], who studied a gas-stabilized free-burning arc.

This article describes some experiments on the concentration of the enthalpy flow from a plasma flow and the heat flux from a plasma flow to a

flat plate by means of a gas blowing radially inwards around the nozzle outlet of the plasma jet.

1. Experimental apparatus and procedure

1.1. Plasma jet generator

The plasma jet generator used in the experiments is shown in Figure 1. The anode consisted of a copper throat tube in the form of a nozzle with an inside diameter of 8 mm, while the cathode was a tungsten rod 6 mm in diameter. A plasma jet was generated by means of an arc discharge between the two electrodes. The discharging gas was argon, which flowed into the discharge chamber at a constant rate of flow regulated by a rotameter. The rate of flow of the plasma jet was 10 liter/min at 300 K and 1 atm, while the discharge current was 200 A, the discharge power being 3.2 kW. A stable plasma jet of $\sim$ 10,000 K was obtained with these conditions. The generator was protected against excessive heat by water-cooling the two electrodes.

The radial coordinate r is the radial position in the plasma jet generator, while the axial coordinate z is the height above the nozzle outlet.
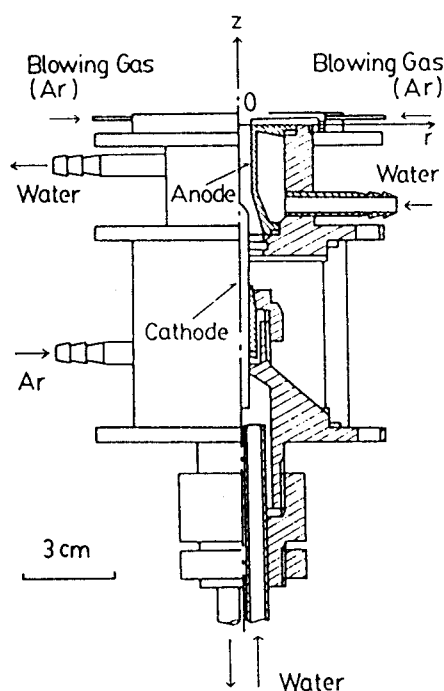

Fig. 1. Sectional diagram of plasma generator.

1.2. Radially blowing gas

The concentration of the plasma flow and the heat flux from the plasma jet to a flat plate was accomplished by blowing argon inwards at right-angles to the plasma jet uniformly from a circumferential slit. The circumferential slit was located at a radius r of 8 or 10 mm, and at a height z of 3-4 mm. This radial inward flow is referred to hereunder as the radially blowing gas. The argon gas at room temperature flowed through a rotameter and then through four holes on the outside of the blowing apparatus affixed to the plasma jet nozzle outlet. In this way, the blowing gas was certain to be entering the apparatus uniformly with axial symmetry. The rate of flow of the radially blowing gas was 0.15 liter/min.

1.3. Determination of the temperature and velocity distributions

1) Measurement of the temperature

The temperature distribution in the plasma jet was determined by measuring the heat flux from it into a small sphere [6]. The apparatus is shown in Figure 2. A 0.85-mm-diameter copper sphere was swept vertically through the plasma jet flow, and the increase in the temperature was measured on a copper-constantan thermocouple (diameter of wire 0.2 mm). These measurements were carried out by varying the distance from the axis of the plasma jet. The heat balance between the plasma jet and the probe is

$$\pi D^2 h\,(\,T_p-\,T_{cu}\,)= \rho_{cu}\,C_{pcu}\,\frac{dT_{cu}}{dt}\,\frac{\pi}{6}\,D^3 + Q_{loss}$$

$$Q_{loss}= Q_{cond}+ Q_{rad} \qquad (1)$$

The left-hand side of the upper equation represents the heat flowing in from the plasma jet; the first term on the right-hand side represents the rise in temperature of the copper sphere, and the
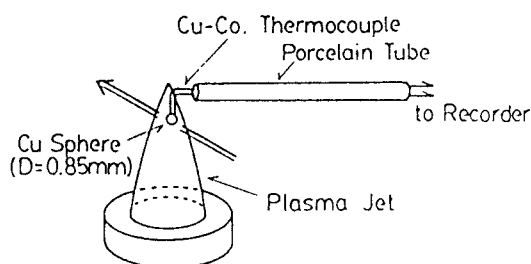

Fig. 2. Experimental apparatus for measurement of plasma temperature.

second term the heat flowing away from the copper sphere Q_{loss}. Q_{loss} is considered to be composed of the heat flowing into the lead wire Q_{cond} and the heat radiated from the copper sphere Q_{rad}. Q_{loss} is at its maximum extent as the probe passes the center of the plasma jet. Estimating the maximum Q_{loss}, the temperature T_{Cu} of the copper sphere as it passes the center of the plasma jet is 450 K. At this point, Q_{rad} is very small, only $\sim 10^{-4}\%$ of the total heat inflow. It is difficult to evaluate Q_{cond}, but it can be no more than 0.9% at the most.

The sweep rate of the copper sphere was 8 cm/s. With the velocity of the plasma jet reaching as high as 125 m/s in these experiments, the probe can reasonably be taken to be stationary. The heat transfer coefficient h in Equation (1) was therefore calculated on the basis of a Nusselt number for heat transfer to a stationary sphere, given by

$$Nu = 2 + 0.6\,Pr^{1/3}\,Re^{1/2} \qquad (2)$$

The values of the physical properties used were those corresponding to the film temperature, which was the average of the plasma temperature T_P and the temperature T_{Cu} of the copper sphere. The temperature T_P of the plasma jet was determined in the above manner. Since Equation (2) contains the Reynolds number, the Nusselt number is a function of the velocity of flow.

In the calculation of T_P, the following assumptions were made:

(1) The probe caused negligible disturbance in the field of the plasma jet;

(2) The temperature inside the copper sphere was uniform.

As far as the first of these assumptions is concerned, the fact that the procelain tube of outside diameter 1 mm, which formed the support for the copper sphere, was 10 mm downstream from the copper sphere in the direction of flow of the plasma jet, coupled with the fact that the plasma jet reached a velocity of 125 m/s, made it reasonable to assume that the probe had very little effect on the flow. Furthermore, the maximum rise in temperature during the passage of the center of the probe was 150 K, for which the corresponding heat inflow was 1.3 W. Since the enthalpy flux of the plasma jet was 1 kW, the effect of the probe on the enthalpy flux could be taken as being very slight. The basis of the second assumption was the high thermal diffusivity of the copper, viz., $1.12 \cdot 10^6\,m^2/s$. With a Biot number as low as $2 \cdot 10^{-3}$ in these experiments, it is reasonable to assume a uniform temperature inside the copper sphere.

2) Measurement of the velocity

The velocity was determined by measuring the dynamic pressure of the plasma jet with a water-cooled Pitot tube. The experimental apparatus is shown in Figure 3. The measurements were made, using a water manometer, with the water-cooled Pitot tube at right-angles to the plasma jet flow. Since the Pitot tube had a factor of ~ 1 [3], the effect of density variations due to a difference in temperature between the tip and the interior of the water-cooled Pitot tube was negligible. The velocity U_P of the plasma jet was calculated from

$$U_P = [\, 2(P_t - P_a)/\rho_{Ar}\,]^{1/2} \qquad (3)$$

where ρ_{Ar} is a function of T_P.

Equations (1)–(3) were used to determine the temperature and velocity distributions of the plasma jet. As the Nusselt number is a function of the velocity, and U_P a function of the temperature, implicit functions had to be used.

1.4. Measurement of the heat flux to a flat plate

Figure 4 shows the probe used to measure the heat flux distribution from the plasma to a flat plate at right angles to the plasma jet. The probe consisted of a copper disk, 105 mm in diameter and 20 mm thick, split into two half-moons thermally insulated from one another by a 0.3-mm-thick
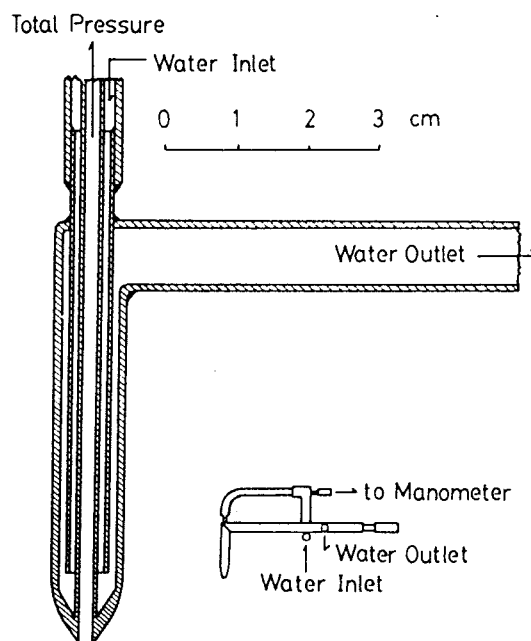

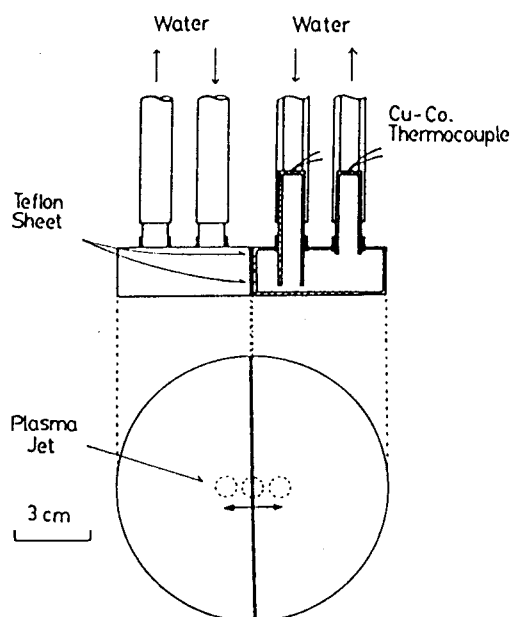Fig. 3. Schematic drawing of water-cooled Pitot tube.

Fig. 4. Schematic drawing of calorimetric probe for plasma heat flux distribution.

Teflon sheet. Insulation was wound round the side of the disk to prevent loss of heat to the surroundings. With bcooling water flowing through each half of the disk, the heat flux to each was determined by measuring the difference in the inlet and outlet temperatures, using a copper-constantan thermocouple. Measurements were made in this way every 1 mm across the diameter of the plasma jet, and the heat flux distribution was determined from the change in the measurements at 1 mm intervals. The data so obtained were the integral values of the radial distribution of the heat flux to the plate at right-angles to the direction of movement of the probe. The Abel inversion was used to convert these integral experimental values to the radial distribution.

2. Experimental results and discussion

2.1. Definition of the Q value

The flow of energy in the plasma jet was evaluated as the enthalpy flow distribution. The enthalpy flow is here defined as the product of the enthalpy, the density, and the velocity. The Q value is defined as the maximum value of the enthalpy flow divided by the peak width at half this maximum value, i.e., the half-width.

The Q value of the heat flux to the flat plate is similarly defined as the maximum value of the

heat flux to the plate, as determined from its radial distribution divided by its half-width.

2.2. Plasma jet flow

1) Temperature and velocity distributions

Figures 5 and 6 show the experimental temperature and velocity distributions. When $z = 10$ mm, the temperature in the center of the plasma is $\sim 9,000$ K and the velocity is ~ 125 m/s. Near the center, both values are higher the closer to the nozzle, and decrease sharply in the radial direction.
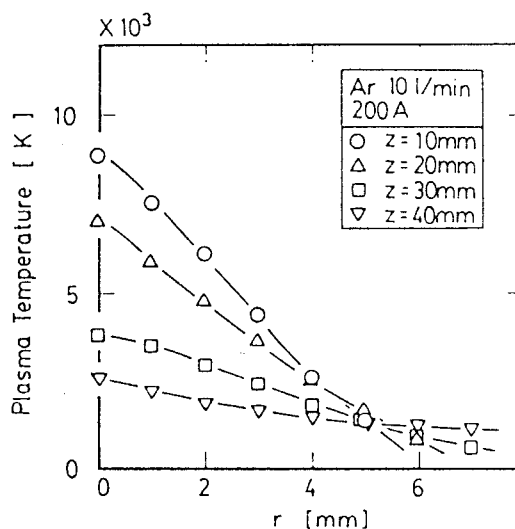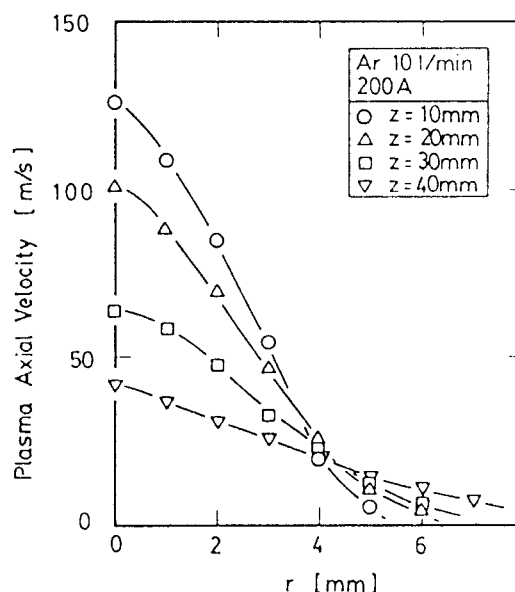

Fig. 5. Plasma temperature distribution.

Fig. 6. Plasma axial velocity distribution.

2) Enthalpy flow distribution

Figure 7 shows the enthalpy flow distribution as determined from the temperature and velocity distributions, which two distributions it is seen to resemble.

3) With a radially blowing gas

Figure 8 shows the enthalpy flow distribution in the presence of a radially blowing gas to concentrate the plasma flow, as determined in a similar way to 2) above. The value in the center is 16.2 W/mm^2 with no blowing gas, rising to 23.7 W/mm^2 with a blowing gas of 3 liter/min. The half-width is 6.6 mm with no blowing gas, falling to 5.0 mm when a blowing gas with a rate of flow of 3 liter/min is used. This indicates the constricting effect a blowing gas at a rate of flow of 3 liter/min has on the enthalpy distribution of a plasma jet, compared with no blowing gas.

4) Q value of the plasma jet

Figure 8 shows how the plasma flow was effectively concentrated by a radially blowing gas. The extent to which a blowing gas is able to concentrate a plasma flow in this way is
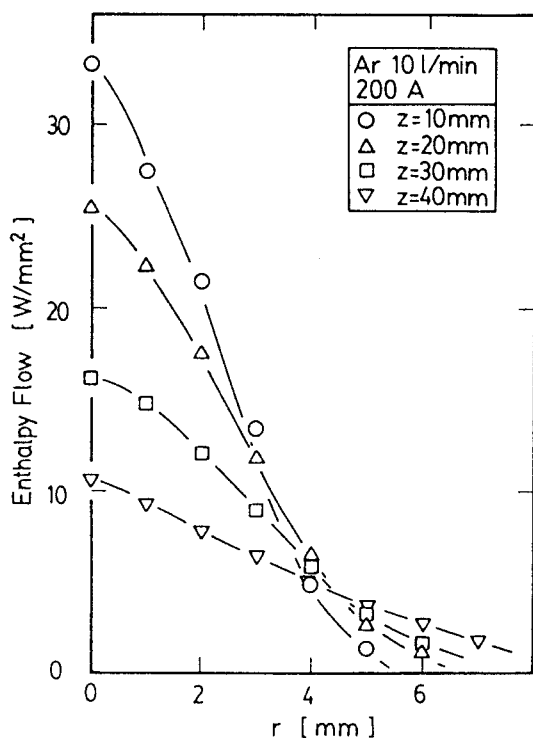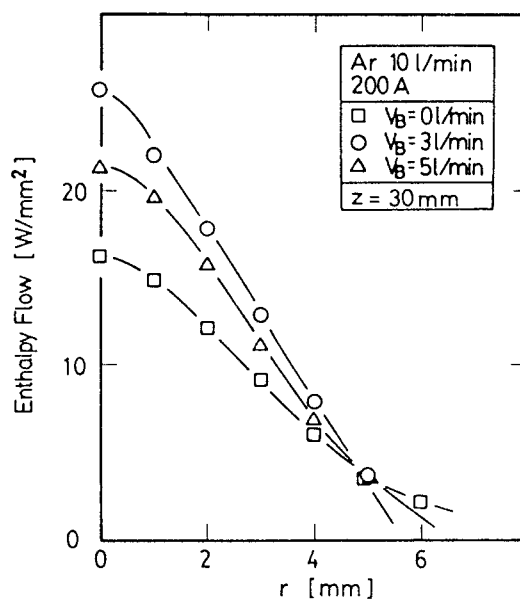
Fig. 8. Variation of enthalpy flow distribution with blowing gas flow rate.

evaluated in terms of the Q value. Figure 9 shows the relationship between the rate of flow of the radially blowing gas and the Q value. The Q value at ~ 3 liter/min is considerably higher at $z = 30$ mm than at $z = 10$ mm. The maximum Q value at ~ 3 liter/min at $z = 30$ mm is 4.9 W/mm^3, around twice the Q value with no blowing gas, *viz.*, 2.4 W/mm^3. The distance from the nozzle outlet to the tip of the brilliant white flame indicating the hot region of the plasma jet is 15.5 mm, which
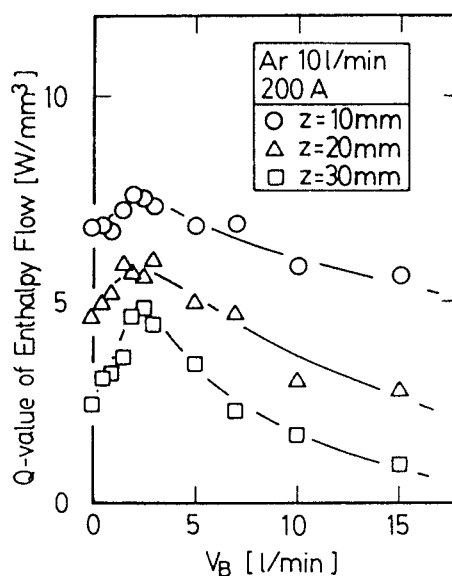
Fig. 7. Enthalpy flow distribution.

Fig. 9. Variation of Q-value of enthalpy flow with blowing gas flow rate.

increases to 21.7 mm with the blowing gas at 3 liter/min. For flow rates of the radially blowing gas above 7 liter/min, the Q value is lower than in the absence of the blowing gas. The explanation for this is that, at higher flow rates, the blowing gas cooled the plasma flow, thereby shortening the flame and reducing the Q value.

2.3. Heat transfer to the flat plate

1) Heat flux distribution

Figure 10 shows the heat flux distributions to the plate, as calculated by the Abel inversion for $z = 10$, 20, 30, and 40 mm. The heat transfer efficiency to the plate based on the electrical power input of the plasma jet is 30% at 10 mm, 22% at 20 mm, 18% at 30 mm, and 16% at 40 mm.

2) Radially blowing gas

Figure 11 shows the effect of the rate of flow of the radially blowing gas on the heat flux to the plate. The data shown are for $z = 30$ mm, for which the increase in the Q value in Figure 9 was quite pronounced. As with the enthalpy flow distribution of the plasma flow in Figure 8, the heat flux near the center of the plasma is higher
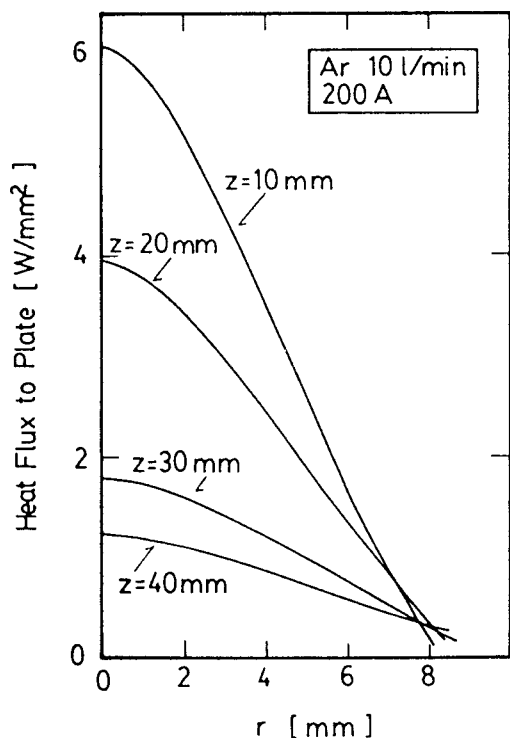
for a flow rate of the blowing gas of ~ 3 liter/min than with no blowing gas. Obviously, the heat flux to the plate can be concentrated by an appropriate choice of flow rate of the blowing gas.

3) Q value of the heat transfer to the plate

Figure 12 shows the relationship between the rate of flow of the radially blowing gas and the Q value of the heat transfer to the plate. There is little difference between the blowing locations
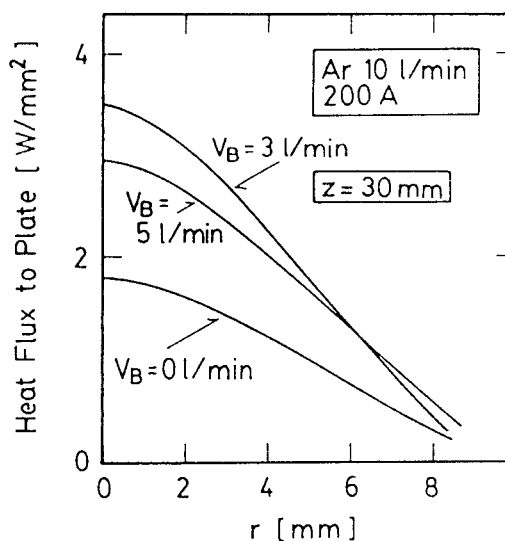
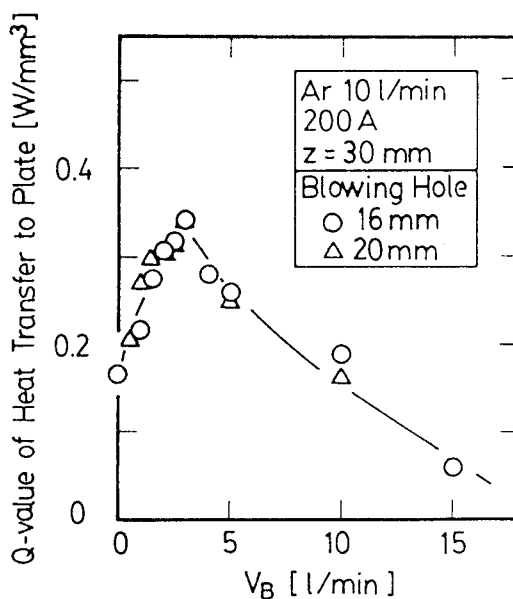**Fig. 11.** Variation of heat flux distribution to plate with blowing gas flow rate.

Fig. 12. Variation of Q-value of heat transfer to plate with blowing gas flow rate.

Fig. 10. Distribution of heat flux on plate.

at a radius of 8 and 10 mm. The maximum Q value occurs at a flow rate of the blowing gas of $\sim$ 3 liter/min. This maximum Q value of 0.35 W/mm^3 is about twice the Q value in the absence of a blowing gas, viz., 0.17 W/mm^3. This is similar to the trend of the experimental results for the Q value of the plasma jet flow in Figure 9. Thus, a radially blowing gas raises the Q value of heat transfer to a plate.

2.4. Effect of a radially blowing gas

In the foregoing experiments, it was shown that the Q value of the enthalpy flow of the plasma jet and the Q value of the heat transfer to the flat plate both attained maxima for a particular rate of flow of the radially blowing gas. The reason for this increase in the energy flow density under the influence of a radially blowing gas is now considered.

The temperature and velocity distributions of a free-jet plasma are spread out radially. As a result of the energy imparted to the surrounding gas, the energy distribution of the plasma jet is spread out flatter. Owing to the outward radial flow of the plasma jet, there is a decrease in the energy flow density. However, in the case of plasma flow in a tube, the wall of the tube restricts the radial outward flow of the plasma flow, producing an elongated bright white flame indicating the hot region. Looking at the present experimental results in the light of this, the radially blowing gas was presumably able to suppress the radial outward flow of the plasma jet and, hence, was able to concentrate the enthalpy flow distribution of the plasma jet and the heat flux to the plate. The experimental results indicated that the control of the radial outward flow of a plasma jet is a remarkably effective way of increasing the energy flow density.

Although a water-cooled tube can be used to suppress the radial outward flow of the plasma flow, this is inconvenient in plasma processing applications, e.g., plasma cutting. An alternative method is a radially blowing gas as used in these experiments, which concentrates the energy flow density of the plasma flow. This method is quite suitable for plasma processing.

Conclusions

There is a need in plasma processing to control the energy flow density of the plasma flow.

A radially blowing gas at the nozzle outlet of the plasma jet was capable of concentrating the

plasma jet flow. Both the Q value of the enthalpy flow of the plasma jet and the Q value of the heat flow to the plate attained maxima at a certain flow rate of the blowing gas. Of the various methods available for concentrating a plasma flow, a radially blowing gas was shown experimentally to be able to increase the energy flow density of the plasma flow using a simple type of apparatus.

Topics for further study include the optimum conditions of position, direction, and rate of flow of the blowing gas, the type of blowing gas, as well as the governing equations for the plasma jet region.

Nomenclature

Bi	....	Biot number
C_p	....	specific heat at constant pressure, J/kg·K
D	....	diameter, m
h	....	heat transfer coefficient, W/m^2·K
Nu	....	Nusselt number
P_t	....	total pressure, Pa
P_a	....	atmospheric pressure, Pa
Pr	....	Prandtl number
Q_{con}	....	conductive heat loss from copper sphere, W
Q_{loss}	....	total heat loss from copper sphere, W
Q_{rad}	....	radiative heat loss from copper sphere, W
Re	....	Reynolds number
r	....	radial coordinate, m
T	....	temperature, K
t	....	time, s
U	....	axial velocity, m/s
V_B	....	blowing-gas rate of flow, liter/min
z	....	axial coordinate, m
ρ	....	density, kg/m^3

Subscripts

Ar	....	argon
Cu	....	copper
P	....	plasma

Literature cited

1. Chen, D. M., Hsu, K. C., and Pfender, E., *Plasma Chem. Plasma Process.* 1, p. 295 (1981).
2. Chen, D. M., Hsu, K. C., Liu, C. H., and Pfender, E., *IEEE Trans. Plasma Sci.* PS-8, p. 425 (1980).

3. Chue, S. H., *Progress in Aerospace Science* **16**, p. 147 (1975).
4. Hsu, K. C., Etemadi, K., and Pfender, E., *J. Appl. Phys.* **54**, p. 1293 (1983).
5. Hsu, K. C. and Pfender, E., *J. Appl. Phys.* **54**, p. 4359 (1983).
6. Kanzawa, A., *Kagaku Kogaku* **36**, p. 1004 (1972).
7. McKelliget, J., Szekely, J., Vardelle, M., and Fauchais, P., *Plasma Chem. Plasma Process.* **2**, p. 317 (1982).
8. Suzuki, M., Etemadi, K., and Pfender, E, *Kagaku Kogaku Ronbunshu* **11**, p. 413 (1985).