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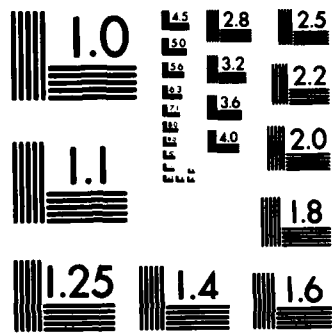
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MEASUREMENT OF LOCAL HEAT FLUX DENSITY AND LOCAL ION SATURATION CURRENT DENSITY IN A PLASMA JET

by

Chen Xi and Zhou Mingde



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MEASUREMENT OF LOCAL HEAT FLUX DENSITY AND LOCAL ION SATURATION CURRENT DENSITY IN A PLASMA JET

Chen Xi and Zhou Mingde

We measured the local heat flux density and local ion saturation current density at a cylindrical probe exposed to the circumferential flow of the plasma jet. The experimental apparatus is shown in Fig. 1. The plasma jet generator employed a design with a tangential inlet and a relatively large

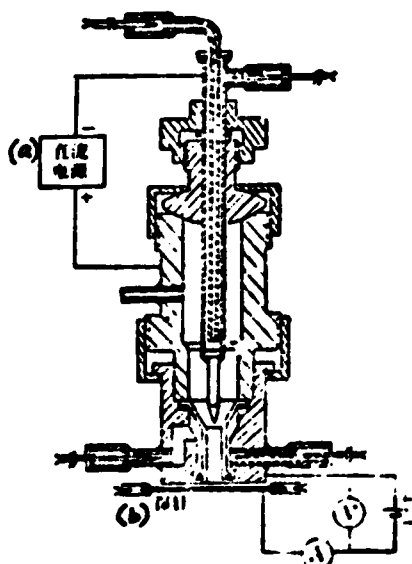


Fig. 1. Simple diagram of the experimental apparatus. Key: (a) dc power source; (b) probe.

length-diameter ratio (30/8 mm) of the anode nozzle. Operation was stable and the axial symmetry of the outlet parameters was good. Operating current was 200 A, arc voltage was approximately 16 V, the working medium was argon, the flow rate was 0.35 m³/h, and observation of appearance and noise measurement proved that the flow was laminar. The cylindrical part of the probe was a nickel tube with an outside diameter of 0.8 mm and a wall thickness of 0.1 mm. The flow rate of the cooling water was approximately 2 g/s, and during the tests the flow rate was

determined by measuring the time required for a certain volume of water to pass through. The rise in cooling water temperature was measured using two shielded EU thermocouples attached to the probe outlet and inlet (connected to form a difference thermocouple). In order to decrease the thermal inertia of the probe, the thermojunctions of the thermocouples were directly exposed to the water. The tests indicated that probe response was rapid and that the time constant was on the magnitude of a second. In order to decrease the measurement error for rise in cooling water temperature the two thermocouples were made from the same section of thermocouple filament, that is, the filament was divided into two and each soldered at the same cut-off point of the shielded filament, thereby ensuring that the material composition at the thermojunction of the two thermocouples were the same, which avoids measurement error which can arise from nonuniformity in thermocouple material. Specialized tests indicated that with the cold junction at room temperature, when the thermojunctions of the two thermocouples were placed in boiling water the difference in thermocouple output was zero. This illustrates that the above described measures are quite effective.

The amount of accumulated heat flux transferred to the probe by the plasma jet was determined by the flow rate and temperature rise of the cooling water. This probe was also used as an electrostatic probe (also called a Langmuir probe). We applied a -30 V dc voltage between the probe water line and the generator anode (the water line has a negative offset and tests indicate that an ion current at -30 V is already at saturation) and measured the accumulated ion saturation current collected by the probe under corresponding conditions.

Using the above described procedure, under conditions where the cooling water line is placed in a horizontal position and perpendicular to the axis of the plasma jet, we used a precise coordinate device which allowed the probe to make horizontal movements (ensuring that the plane of movement of the water line and the cross section of the generator outlet would be parallel) and simultaneously

measured the accumulated heat flux $Q(x)$ and the accumulated ion saturation current $J_{is}(x)$. The results are shown in Fig. 2. Here horizontal coordinate x is the distance between the centerline of the probe and the axis of the plasma jet. From Fig. 2 it can be

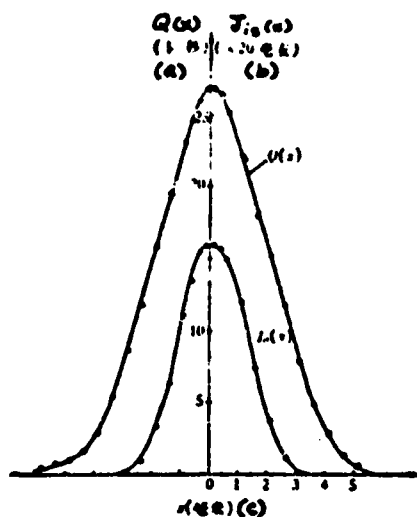


Fig. 2. The distribution of accumulated heat flux $Q(x)$ and accumulated ion saturation current $J_{is}(x)$ (probe centerline to generator outlet is 3.1 mm). Key: (a) cal/s; (b) $\times 29$ mA; (c) mm.

be seen that the distribution curves of $Q(x)$ and $J_{is}(x)$ are nearly symmetrical, which indicates that the axial symmetry of the generator outlet parameters is good. Therefore, we can use Abel's transformation and by the distribution of $Q(x)$ and $J_{is}(x)$ obtain the corresponding distribution of mean local heat flux density $q(r)$ and local ion saturation current density $j_{is}(r)$ about the circumference of the cylinder (which are given in cal/mm²s and mA/mm², respectively):

$$q(r) = -\frac{1}{\pi^2 d_0} \int_r^{\infty} \frac{Q'(x) dx}{\sqrt{x^2 - r^2}} \quad (1)$$

$$j_{is}(r) = -\frac{1}{\pi^2 d_0} \int_r^{\infty} \frac{J'_{is}(x) dx}{\sqrt{x^2 - r^2}} \quad (2)$$

Here r represents the radial distances between the local site and the jet axis, d_0 is the outside diameter of the probe water line, R and R' are the radii of the jet regions which contribute to heat transfer and current accumulation, respectively, $Q'(x) = dQ/dx$ and $J'_{is}(x) = dJ_{is}/dx$ are, respectively, the accumulated heat flux and accumulated saturation current derivatives with respect to x . We employed coefficient tables and numerical solutions for differential-integral equations of the form of expressions (1) and (2), which were recommended in [1]. Figure 3 shows the distribution of local heat flux density $q(r)$ and local ion saturation current density $j_{is}(r)$, which were obtained from the test results of the heat flux quantities in Fig. 2.

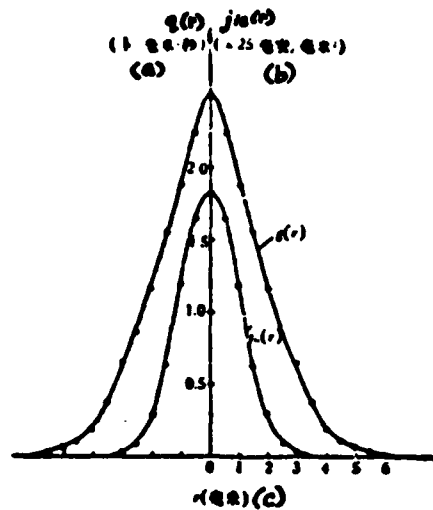


Fig. 3. The distribution of local heat flux density $q(r)$ and local ion saturation current density $j_{is}(r)$. Key: (a) cal/mm²s; (b) x25 mA/mm²; (c) mm.

From Fig. 3 it can be seen that the radial distribution of local heat flux density and ion saturation current density in the plasma jet are extremely nonuniform. This reflects the nonuniformity of the generator outlet parameters (temperature, velocity, etc.) along the radial distribution. The region where ion saturation current density is noticeably not zero must be much narrower than the region where heat flux density is noticeably not zero. This is reasonable and because the degree of ionization upon dropping to 6000°K is already too low, the collected ion saturation current can be practically zero, but now the amount of heat transfer can be quite sizeable.

The method of measurement used in this work is similar to that used in [2] in which heat transfer from freely arcing arc column region plasma to the cylinder was investigated. Our tests indicate that it can also be used for investigation of heat transfer under conditions of free jets of plasma.

As practical examples of this kind of measurement, we can calculate the temperature distribution and electron density distribution at the plasma jet generator outlet measurement plane by the

test results of the ion saturation current density in Fig. 3. It is assumed that the plasma at the measurement cross section is in a state of thermodynamic equilibrium, i.e., a condition in which the Saha equation and the Boltzmann equation hold true, and that a unit value relationship exists between plasma temperature and electron density. Applying the theoretical results of a cylindrical electrostatic probe under conditions of dense plasma which was initially derived by Lam and which was recommended in [4],

$$j_{is} = \frac{2\sqrt{2}}{\pi} n_e \sqrt{\frac{e\mu_i v k T_e}{d_0}} \quad (3)$$

Figure 4 shows the plasma temperature and electron density distribution which was calculated by the test results of the j_{is}

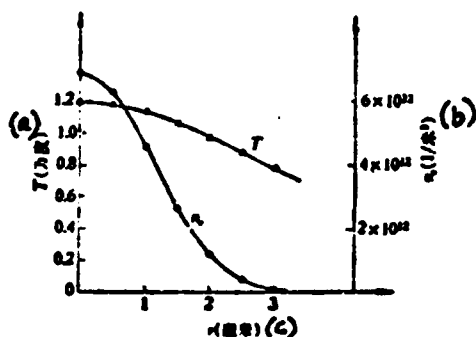


Fig. 4. The distribution of temperature and electron density of plasma at the measurement cross section. Key: (a) 10,000°; (b) m^3 ; (c) mm.

distribution in Fig. 3. In expression (3), e is electron charge, μ_i is the mobility of argon ions at the surface temperature of the water line, k is the Boltzmann constant, T_e and n_e are electron temperature and electron density, respectively, when the plasma is not disturbed by the probe. Under conditions of local thermodynamic equilibrium, T_e will also be the thermodynamic temperature of the plasma. With respect to argon, the relationship

between plasma temperature and electron density has already been given in Olsen's list [6]. Furthermore, v is plasma velocity which can be determined, using the experimental calculation method, by the flow rate of the generator working medium and the calculated mean value of outlet temperature.

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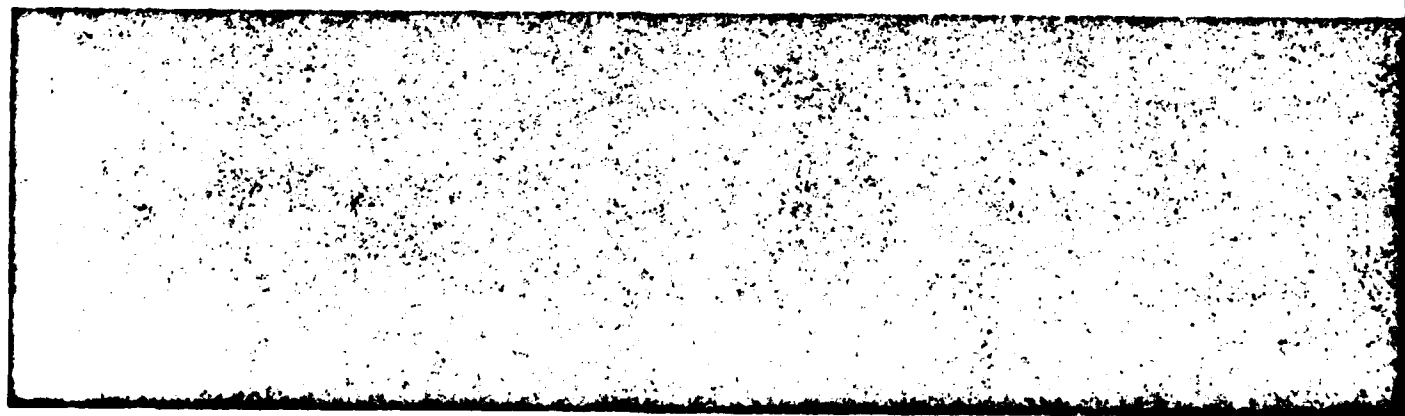
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