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SHORTER COMMUNICATIONS

TEMPERATURES IN A PLASMAJET†

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NOMENCLATURE

i, intensity of spectral radiation;
r, radius;
A_n^m, probability of transition from state m to state n;
g_m, degeneracy of the state m;
m_e, mass;
k, Boltzmann's constant;
T, absolute temperature;
n, particle density;
h, Planck's constant;
E, energy level;
Z, partition function;
ν, frequency of radiation.

Subscripts
e, electron;
0, neutral particle;
I, ionization;
n, lower energy level.

Superscripts
0, neutral particle;
+, ion;
i, internal;
m, higher energy level.

PLASMA generators are in frequent use as engineering tools for various high temperature operations. It is important in such applications that the engineers know how the generator output varies with the input parameters of current and mass flow. The abbreviated results of a study to this end are presented in this note.

The Thermal Dynamics Corporation F-40 plasma torch used for this investigation produces a field free plasma with a maximum temperature of about 13000 K depending on current and mass flow. Operation for this investigation was always in the open so that the jet exhausted into the atmosphere. The device is capable of fairly stable operation with argon over a current range of 200–600 A and a mass flow range from 10 to 130 g/min. Operation at the upper current limit was not feasible for prolonged periods of a half hour or more since severe Joule heating in the uncooled leads and terminal connections was encountered.

The temperatures were measured using a spectrograph and interpreting the resultant line intensity distributions using well known methods. These are described in [1].

It can be shown by an indeterminate error analysis that the off-axis peaking method and the ion-neutral comparison method are the most accurate to use for our purposes. Since the peak temperatures for this investigation are lower than those required for using the off-axis peaking method directly, it was decided to use the ratio of intensities of an ion line to a neutral line at a certain point in the source to determine the temperature at that point. This is a markedly temperature sensitive method and may be used down to a temperature of about 11000 K where the ion line becomes indistinguishable from the background continuum. Although the ion lines were all very weak for this investigation, it was possible, by careful masking of the exit slit, to obtain measurable values of their intensities. The equation used for this is

$$\frac{i^+(r)}{i^0(r)} = \frac{2(A_n^m g_m \nu)^+ (2\pi m_e kT)^{\frac{3}{2}}}{n_e(T)(A_n^m g_m \nu)^0 h^3} \exp\left[-(E_I + E_m^+ - E_m^0)/kT\right]. \tag{1}$$

Here + denotes the ions, 0 the neutrals and $i(r)$ is the emission coefficient of a spectral line which is a function of temperature. The temperature in turn is a function of the radius. The electron density, n_e, is also a function of temperature for a given pressure; A_n^m is the transition probability for the line in question (corresponding to a spontaneous transition from a state m to one of lower energy n). The statistical weight or degeneracy of the mth energy level is denoted by g_m and ν is the frequency corresponding to the transition. The electron mass is indicated by m_e, h is Planck's constant, k is Boltzmann's constant and T is the absolute

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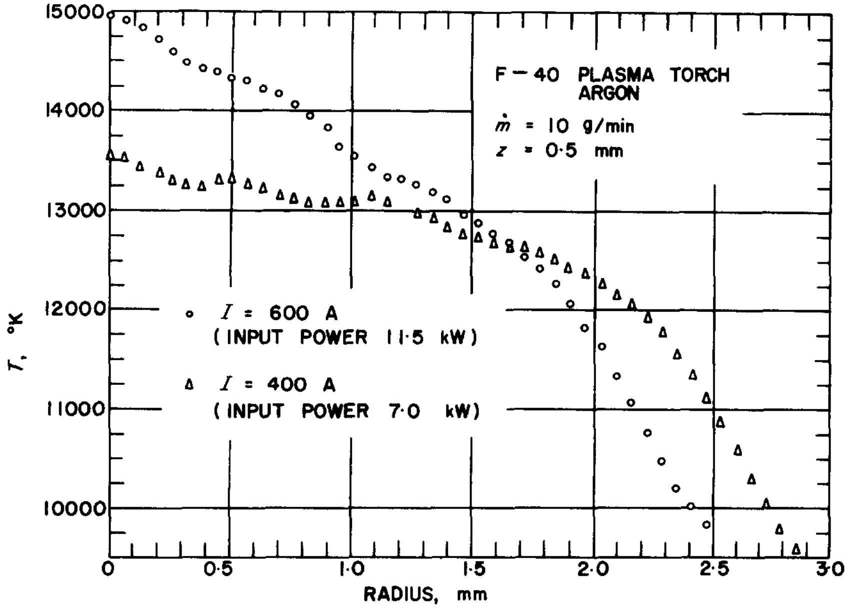

FIG. 1. Temperature distribution at various currents for the low mass flux jet.

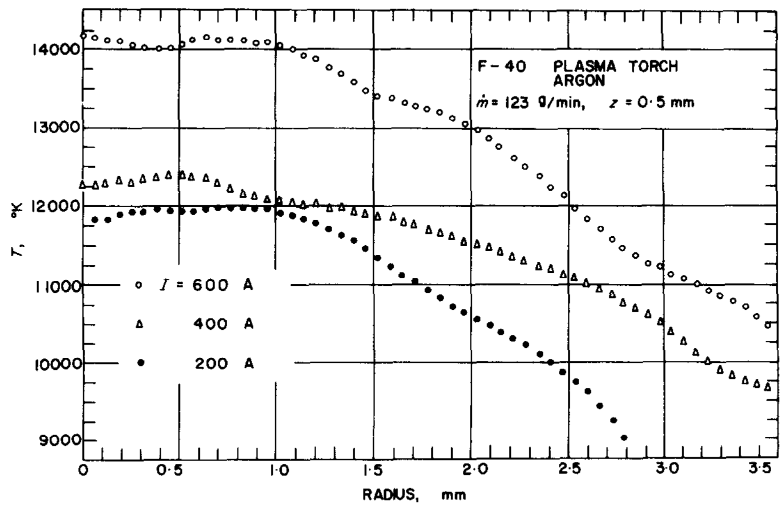

FIG. 2. Temperature distribution at various currents for the high mass flux jet.

temperature. E_I is the ionization energy and E_m is the energy corresponding to the mth excited state of the particle in question.

At radii where the temperature is below 11000 K and equation (1) is no longer applicable, the off-axis peaking method can be used down to temperatures of about 9000 K. For this purpose, a temperature above 11000 K obtained from equation (1) is used as the reference temperature T^* at its particular radius r^*. The ratio of the line intensities $i(r)/i(r^*)$ determines the relation

$$\frac{i(r)}{i(r^*)} = \frac{n_0(T)\,Z_0^i(T^*)}{n_0(T^*)\,Z_0^i(T)} \exp\left[\frac{E_m}{kT^*} - \frac{E_m}{kT}\right]. \qquad (2)$$

Here n_0 is the neutral particle density and Z_0^i is the electronic partition function, both of which are functions of the temperature. The temperatures for radii $r > r^*(T < T^*)$ are then obtained from equation (2).

The temperatures in the jet outside of the nozzle were everywhere lower than the normal or critical temperature needed to employ the off-axis peaking method to determine the temperature distribution. That is to say that nowhere in the jet was it possible to fix the temperature by finding the radius at which the intensity of a spectral line peaked. This occurs at about 15000 K for the neutral argon lines at atmospheric pressure. All radial intensity distributions peaked at the axis. A few instances arose where an off-axis peak would be found at a section 5 mm or so from the nozzle exit, but these were cases where the ion line and continuum intensities were close together in magnitude and so there was a large error associated with the net line intensity. Also the rather flat profiles of the high mass flux jet sometimes suffered from insufficient symmetry and made an accurate determination of the net line intensity difficult.

Further evidence that the temperatures are not as high as 15000 K is afforded by the spectrograms of the plasma jet. These are shown in [2]. In the neighborhood of 15000 K, the ion line 4806·90A should have about the same local intensity as the neutral lines 4259·36 A and 4158·59 A. Although the spectrograms indicate only lateral intensities, where the optical depth and inhomogeneity must still be accounted for, it was apparent that the ionic line intensities were nowhere near as strong as the neutral line intensities. In the temperature region of 13000 K, the line 4806·90 A has a local intensity that is about one sixth that of the neutral line 4259·36 A.

Since the radial intensity distributions peaked on the axis, the ion-neutral method was chosen for all initial temperature distributions. The pair consisting of the 4806·90 A ion line and the 4259·36 A neutral line were chosen for subsequent use. That particular ion line is the strongest one available, a necessary requirement at these relatively low temperatures, and the neutral line is the best available in the same part of the argon spectrum which does not have too close neighbors and for which the transition probability is known.

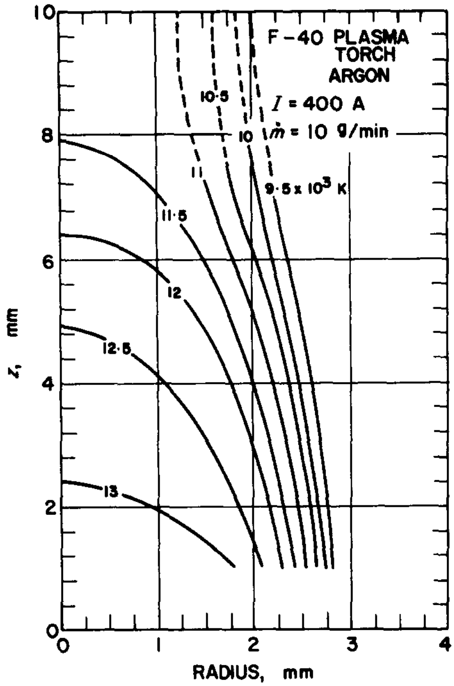

FIG. 3. Isotherms of the low mass flux plasma jet.

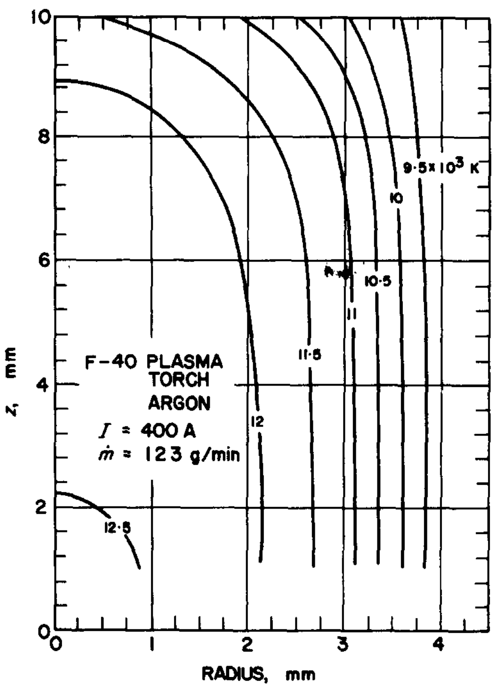

FIG. 4. Isotherms of the high mass flux plasma jet.

The ion line intensities become too weak to be measured accurately when the temperatures drop to below 11 000 K. This precludes using the ion-neutral pair for determining temperatures except near the jet axis. For this reason the temperature determined by the ion-neutral method is used as the reference temperature in equation (2). The final temperature distribution is then obtained by the method based on equation (2) which is useful out to the region where the temperature drops to 9000 K. This is the lower limit to which the assumption of thermodynamic equilibrium may still be applied.

Figures 1 and 2 show the change in radial temperature distribution for different currents. The mass flow rates given correspond to extreme operating conditions. The low mass flux case was not run at 200 A as was the high mass flux case since the stability here was too poor for spectrometric measurements. It is interesting to note the crossing of the profiles for the low mass flux case where the flow is laminar and presumably the arc column is very well defined. As the self-magnetic field is increased with increasing current, a certain radial pressure gradient is developed. This pressure gradient makes the actual arc radius smaller. This effect would not be so noticeable in the high mass flux case where the flow is turbulent and the turbulent diffusion of energy would be much more significant than retardation due to magnetic pressure on the column. The relative proximity of the 200 A and 400 A profiles for small radii in Fig. 2 is probably due to experimental errors since if one were to fit an appropriate second or third degree curve to the data, the curves would be somewhat further apart in the 1 mm region.

The temperature distributions as functions of radius and axial position are given as isotherms in Fig. 3 for the low mass flux jet and in Fig. 4 for the high mass flux turbulent jet. The current of 400 A was chosen for these measurements because the stability was best here for both cases and therefore the results would be more meaningful. The data for $z > 8$ mm in Fig. 3 are somewhat in doubt because of the low ion intensities at this distance

REFERENCES

1. W. FINKELNBURG and H. MAECKER, Elektrische Bogen und Thermisches Plasma, *Handb. Phys.* **22**, 254–444 (1956).
2. C. J. CREMERS and E. PFENDER, The thermal characteristics of a high and low mass flux plasma jet, USAF Office of Aerospace Research, ARL 64-191 (1964).

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PATTERNS OF FREE CONVECTION FLOW ADJACENT TO HORIZONTAL HEATED SURFACES

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INTRODUCTION

THIS paper is concerned with the free convection flow field adjacent to horizontal, upward-facing heated surfaces having various planforms (square, rectangle, triangle, circle). A flow visualization technique is employed which is an extension of that described by Baker [1]. The fluid motions are made visible by local changes of color of the fluid itself, the color changes resulting from changes in pH (acidic to basic). The aim of the investigation is to provide insights into the nature of the free convection flow field, with particular emphasis on the influence of the shape of the heated surface which generates the flow.

Available experimental information on the heat-transfer characteristics of upward-facing heated surfaces is incomplete and somewhat contradictory. For square plates, McAdams [2], following Fishenden and Saunders [3], provides a correlating equation which differs from that of Mikheyev [4] by 30 per cent. The correlation of Bosworth [5] is in substantial agreement with Mikheyev's, provided that the characteristic dimensions in the respective correlating equations have the same meanings. Temperature and velocity field measurements [6, 7] have been made only for square plates. Information for surfaces other than squares is generally lacking. Flow visualization studies have, apparently, not heretofore been performed.

EXPERIMENTAL APPARATUS

The surfaces employed in the flow visualization studies are