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Transverse Magnetic Field Effects on a Cross-Flow Arc

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Experiments were conducted upon an 80 amp, 1.1 atm argon cross-flow arc in a constant velocity mainstream flow of 182.8 cm/sec; electrode spacing was held constant at 6.3 mm. Applied transverse magnetic fields ranged from the zero-balanced mode ($B = 0$) to the balanced configuration ($B = 11.2$ gauss). Isotherm distributions were obtained in several horizontal planes; cross-sectional shapes and profiles were thereby inferred. The arc cross-sectional shape was found to be noncircular in all cases. For the zero-balanced mode, the major axis of the cross-sectional shape was in the direction of flow; for the balanced configuration, the major axis was in the direction transverse to the flow. The experimental results indicated that the influence of the magnetic field was perceived throughout the plasma. For the zero-balanced mode, the effects of forced convection were found principally in the outer region; the inner core was approximately circular in cross section.

Introduction

IN applications associated with cross-flow plasmas (e.g., heat sources, switch gear, thrusters) the pin array is generally employed for fixed arc attachments and the rail or annular arrangement for nonstationary arcs. When a transverse magnetic field is applied to the pin electrode array, the arc column will be forced either upstream or downstream (generally the arc attachments remain stationary on the electrode). Thus, stable operation of the plasma may be achieved over a wider range of speeds (for a given arc current) or arc extinction may be advanced. For the rail or annual electrode arc, the applied transverse magnetic field will cause the entire arc to move; such an arrangement has been employed to more uniformly heat a moving stream. The processes associated with the operation of the cross-flow arc, whether in the presence of or in the absence of an applied transverse magnetic field, are not yet well understood theoretically although considerable knowledge, of at least a qualitative nature, has been obtained. Similarly, quantitative experimental information with respect to the characteristics of such plasmas (e.g., local temperature distribution, particle density distribution, cross-sectional shape, profile, extinction criteria) has been difficult to obtain, particularly with respect to diagnostics within the arc. This comes about, for the case of spectroscopic diagnostics, as a consequence of the observed absence of circular symmetry in cross section. Only recently have experimental techniques and methods of data reduction been developed for this asymmetrical plasma configuration.

Analytical studies have considered either the zero-balanced ($B = 0$) cross-flow configuration or the balanced arc; operationally (for a pin array), the balanced condition is defined as that at which the arc visually appears colinear with or parallel to the electrode centerline. The most comprehensive analyses of the zero-balanced ($B = 0$) configuration[1,2] have considered the case of the plasma in a very low Mach number flowfield. The arc was assumed to be circular or one-dimensional wedge-like in cross section. Azimuthal dependence of all variables was thus neglected. With the exception of electrical conductivity, all gas properties were assumed to be constant. Electrical conductivity was represented by the linear discontinuous model. Flow through the arc column was specified and, for the case considered in detail, assumed to be zero. With these assumptions, the equations of motion, the energy equation, etc. became uncoupled. Determination of the temperature field required the solution of the energy equation only. Results of the analyses showed that: 1) curvature of the arc profile increased the temperature gradients upstream of the center of the arc with respect to those downstream of the center; and 2) the maximum temperature was located slightly upstream of the center of the arc. The radius of curvature of the plasma was also determined in terms of the operating parameters.

Similarly, analyses of the balanced cross-flow arc[3–8] have not coupled the fluid mechanic and thermodynamic interactions. In Ref. 3 a low power plasma in low Reynolds number flow was considered. With the assumption of Stokes flow within the arc and Oseen flow exterior to the plasma, a circu-

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lar boundary isotherm was obtained. Although flow through the plasma was permitted, the formulation required the specification of one additional boundary condition. Thus, unique solutions were not obtained. Possible flow patterns within the arc were suggested. In Ref. 4 solution for either the velocity or the temperature (heat flux potential) was obtained upon the assumption of one of the fields. Coupling of the equations of motion and the energy equation, so that a solution could be determined in an iterative fashion, was suggested but not carried out. In Ref. 5, an extension of Ref. 3, solution for the velocity field was sought through introduction of an additional interaction zone between the previously considered[4] arc interior and external fields. In Ref. 6, a higher Reynolds number, boundary-layer type analysis was considered for the region at the outer edge of the plasma cross section. A circular arc configuration, impervious to the mainstream flow, was assumed; the stagnation region was investigated. Possible isotherm and (double vortex) flow patterns were suggested. The proposed interior isotherms were noncircular, with major axis in the direction transverse to the flow. Similarity rules were also obtained. In Ref. 7 an arc impervious to the mainstream flow was assumed; the boundary isotherm was assumed to be circular. Temperature distributions were obtained to first order in velocity, neglecting inertia terms within the plasma. The (computed) interior isotherms were generally noncircular, with major axis in the direction transverse to the flow. The velocity solution (double vortex) was found using the zeroth order temperature solution. In Ref. 8 a relation was obtained between the applied transverse magnetic field, arc current, and velocity; zero flow through the plasma was assumed.

Experimentally determined temperature distributions within zero-balanced ($B = 0$) plasmas have been reported recently.[9-11] Spectroscopic diagnostics within the cross-flow plasma are made more complex as a result of the absence of circular symmetry in cross section. Quantitative determination of, say, temperature within the arc requires 1) observation of the plasma about many azimuthal locations—an optical system was developed for this purpose[9-11] and was employed in the present work; and 2) a method for inverting the experimentally obtained integrated intensity distributions of radiation so as to determine the local distribution of emission coefficients (from which the local temperatures may be calculated); such a method has been developed[12,13] and was employed herein. The experimental results[9-11] demonstrated that the zero-balanced configuration was indeed noncircular in cross section, with major axis in the direction of flow. Velocity was found to exert a profound influence upon the temperature distribution and cross-sectional shape within the arc.[11] Along the mirror plane of symmetry in cross section, the observed temperature gradients and the location of the maximum temperatures were in qualitative agreement with analyses.[1,2]

Previously reported experimental investigations of the steady-state cross-flow plasma in the presence of a transverse magnetic field have studied the balanced configuration.[14,15] Both studies were qualitative in nature in that the plasma profile and cross-sectional shape were estimated from photographs taken at two azimuthal angles about the arc. On this basis, the plasma was found to be noncircular, with major axis in the direction transverse to the flow. Temperature distributions within the plasma were not obtained. Studies of rail mounted cross-flow arcs (either stationary[16] or moving[17]) have also been qualitative in the sense that diagnostics within the plasma have not been carried out.

The present paper is an experimental investigation of the effects of applied transverse magnetic fields upon the temperature distribution within a steady-state, stationary cross-flow plasma. Arc cross-sectional shape and profile were inferred from the temperatures. The experiments were conducted upon an 80 amp, 1.1 atm argon arc in a constant mainstream velocity flowfield of about 6 fps (182.8 cm/sec). Electrode spacing was maintained constant at 6.3 mm. Temperature distributions were obtained in several horizontal planes within the plasma. The temperatures were determined using the Kramers-Unsold equation for radiation in the argon continuum. Experiments were conducted over the range of magnetic fields from zero-balanced ($B = 0$) to balanced ($B = 11.2$ gauss) modes.

Experimental Arrangements and Procedures

Test Facility

The experiments were conducted in an open circuit tunnel; all flow passages were $1\frac{7}{8}$ in. $\times$ $1\frac{7}{8}$ in. cross section. The power supply consisted of two direct current welders extensively filtered to reduce ripple. Arc initiation was accomplished using a high frequency starter.

The aluminum test section, 12-in. long, contained water-cooled top and bottom walls. A 9 in. viewing window was installed in one side wall to permit observation of the plasma over a wide range of azimuthal angles. A black anodized aluminum insert was placed into the rear side wall. A viewing port was located in the top wall so that the plasma could be observed from a rearward-like position.

The transverse magnetic field was applied using a Helmholtz-like pair of coils whose axis was located normal to both the tunnel and electrode centerlines. The inside diameter of the coils, 23 in., was selected so as to accommodate the entire optical system within the interior. At the edge of a cube, 0.50-in. in length of side, centered with respect to the tunnel and the electrode centerlines, the transverse field was calculated to be uniform to within $\pm 0.1\%$; at the corners of the cube, the radial field was calculated to be $\pm 0.3\%$ of the tranverse field.

The anode contained a 90°, conically tipped OFHC insert (0.250 in. base diameter). The 0.090-in.-diam tantalum cathode insert was $\frac{1}{4}$-in. long. The latter was terminated with an (initially) 120° conical tip. During operation, arc attachment at the cathode resulted in local melting at the tip and formation of a hemispherical zone. For purposes of facilitating the spatial location of data points in the data reduction procedure, a notch, 0.015-in. deep and 0.030-in. long, was fabricated 0.100 in. from the tip.

The test facility is discussed in more detail.[9-11,18]

Optical System

The optical system developed[8-11] permitted simultaneous observation of the plasma at twelve azimuthal locations. The system contained three components. 1) Primary mirrors; the twelve (front surface) mirrors were aligned to view the plasma at azimuthal angles determined to within $\pm 0.1°$. Eleven of the mirrors were oriented in a common horizontal plane. The twelfth mirror, which observed the arc from a rearward-like position through the viewing port in the top wall, was not oriented in the same plane as the mirrors previously cited. The twelfth mirror was used principally to determine the existence of a mirror plane of symmetry in cross-section. 2) Secondary mirrors; these (front surface) mirrors compacted the images of the arc for placement upon the 4 in. $\times$ 5 in. negative film. 3) Detector; this arrangement included a) the camera, and b) the narrow band optical interference filter (centered at about 4945 Å (normal incidence), in the argon continuum; 12.5 Å bandwidth).

A negative contained, then, twelve images of the arc. Associated with a given image were the calibration data for both the optics and the portion of the film appropriate to that image.

The arrangement developed was, thus, approximately equivalent to the simultaneous use of twelve monochromators, each of which observed the plasma at a known azimuthal location. Details of the optical system are discussed more completely in Refs. 9–11, 18.

Optical System Calibration and Data Reduction

In order to determine quantitatively the local temperature distribution within the arc, it was necessary to obtain an absolute calibration of the optical system. Calibration data were obtained with a tungsten strip projection lamp, using published spectral emissivities.[19] Brightness temperature was determined using an optical pyrometer.[20] The calibration data points were placed in the immediate vicinity of each of the eleven images of the plasma. The darkening of the film, due to each calibration data point, was determined with a microdensitometer. From the characteristics of the calibration lamp and the optical pyrometer, the energy emitted by the source was determined; thus, for each image of the arc, the appropriate calibration curve was obtained. Film exposure times and lens settings were identical for both calibration and test runs.

From the (microdensitometer) measured density of any point in a given image of the arc, together with the calibration curve appropriate for that image, the absolute integrated intensity of the radiation was determined through the inverse of the calibration procedure. Microdensitometer scans [with real space (arc space) scanning slit dimensions 1.09 mm height by 21.25 microns width] of each image were obtained in as many as three horizontal planes whose scan centerlines were located 1.46 mm (scan 1), 2.55 mm (scan 2), and 3.64 mm (scan 3) above the anode tip.

The inversion method for asymmetrical plasmas[12,13] was employed to determine the local distribution of emission coefficients. The method required the existence of a mirror plane of symmetry in cross section. Microdensitometer scans indicated that this requirement was satisfied in all tests.

The Kramers-Unsold equation for continuum radiation was employed to determine the local temperatures within a cross section. The frequency independent form was used. For atmospheric pressure co-axial argon plasmas having about the same current levels and with centerline temperatures of about 10,000K,[21] the temperature calculated according to the frequency independent Kramers-Unsold equation were in good agreement (within about ±60K) with those determined from line radiation measurements. Self-absorption has been found to be negligible for atmospheric argon plasmas in the wavelength region employed.[22] A mirror plane of symmetry in cross section has been observed.

The data reduction procedure has been largely computerized to facilitate the calculations. One result of the program is the computer-plotted isotherm distribution, obtained in a given horizontal plane. Isotherm distributions presented herein employ a polar coordinate system. A requirement of the inversion method[12,13] is that the origin of the coordinate system be close to the location of the maximum temperature. For plasmas having noncircular cross sections, the location of the maximum temperature is not known a priori. For all cases considered herein, the location of the coordinate system was found to be within ±0.4 mm of the location of the maximum temperature, thereby satisfying the requirements of the inversion method. Solely for convenience in presenting the isotherm distributions, the origin of the coordinate system in the graphs has been placed at the location of the maximum temperature.

Uncertainties in the determination of arc temperatures include: calibration procedure (determination of brightness temperature (±110K), emissivity of the tungsten filament (±55K), influence of parameters in the inversion method (±20K), calibration of the narrow band interference filter and of the neutral density filters employed during calibration (±80K), simplifications associated with the observed mirror plane of symmetry in cross section (±100K), repeatability of the temperature distributions for a given operating condition

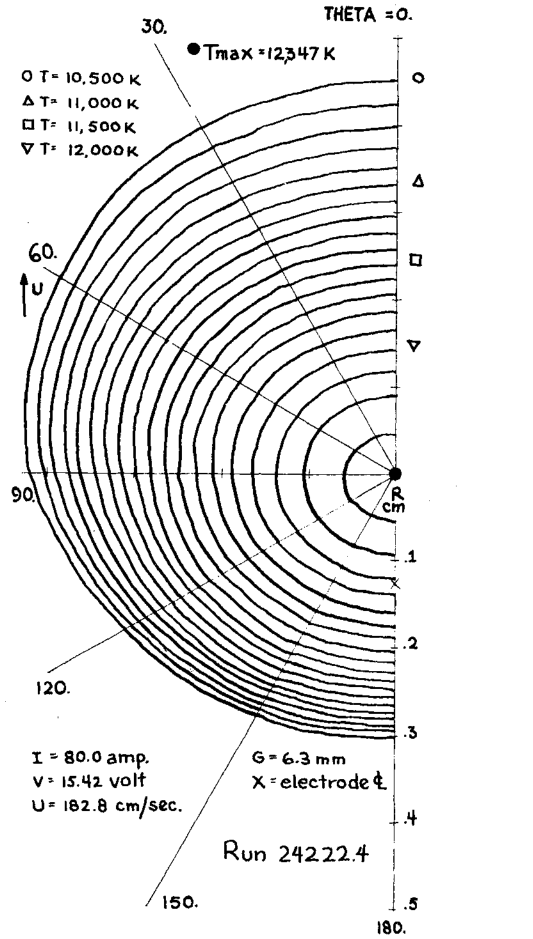

Fig. 1 Isotherm distribution, 2.55 mm above anode, B = 5.5 gauss.

(±100K), and differences between temperatures determined according to Kramers-Unsold continuum and line radiation (±60K). Thus, temperatures within the arc are believed determined to within about ±525K. The optical system calibration and the data reduction procedures are discussed in detail in Refs. 9–11, 18.

Discussion of Results

Isotherm distributions determined for the zero-balanced (B = 0) configuration were similar to those obtained previously.[9–11,23] Application of transverse magnetic field results in pronounced changes in the isotherm distributions and in the inferred cross-sectional shapes and arc profile. The isotherm distributions for various applied fields are presented in Figs. 1–5. In Figs. 1, 2, and 4, the distributions (scan 2) are shown for the intermediate-balanced modes (B = 5.5 and 8.3 gauss) and the balanced configuration (B = 11.2 gauss), resoectively. Isotherm distributions for the balanced mode, scans 1, 2, and 3, are presented in Figs. 3–5, respectively. The balanced condition was considered to have been achieved when the upstream edge of the arc was observed visually to be parallel to the electrode centerline (arc attachments remained on the tips of the electrodes). For this case the downstream edge of the plasma appeared somewhat cusp-shaped.[15] The influences of electrode spacing, arc current, and flow velocity were factors which contributed to observed lack of uniformity along the length of the arc column.

In Figs. 1, 2, and 4 (scan 2), the plasma is found to be noncircular, with major axis in the direction transverse to the flow. A measure of the local shape of the cross section may be obtained from the fineness ratio F_α. The fineness ratio is defined, $F_\alpha \equiv W/L$, where W = distance, along angle α, from

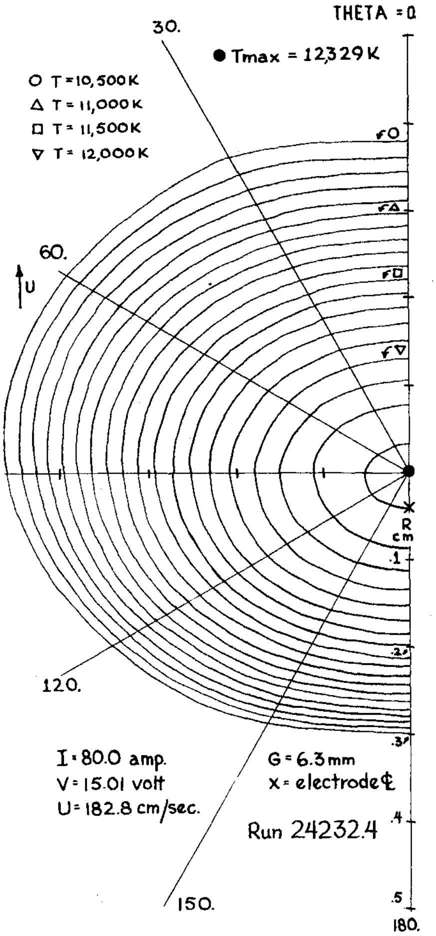

Fig. 2 Isotherm distribution, 2.55 mm above anode, B = 8.3 gauss.

the location of the maximum temperature to a given isotherm and L = distance between the intercepts of a given isotherm, along the mirror plane of symmetry (the line $\theta = 0° - 180°$). Values of $F_\alpha \approx 0.50$ about the arc indicate the given isotherm to be nearly circular with respect to the maximum temperature. Marked lateral broadening of the arc occurs upon application of the transverse field. The broadening is particularly evident for $\theta = 90°$ ($0.56 \leq F_{90} \leq 0.68$) and, as well, generally remains significantly large in the range $60° \leq \theta \leq 120°$ (F_{60}: 0.50–0.66; F_{120}: 0.48–0.57). Further, the influence of the magnetic field penetrates the entire cross section as evidence by similar, large values of $F\alpha$, in the range $60° \leq \theta \leq 120°$, for both the inner and outer isotherms (e.g., in Fig. 2 for the 12,100K and 10,500K isotherms, respectively—F_{60}: 0.60, 0.66; F_{90}: 0.68, 0.67; F_{120}: 0.62, 0.58).

The maximum value of F_{90} ($F_{90} = 0.68$) is obtained for an intermediate-balanced mode (B = 8.3 gauss). The balanced mode, however, forces the downstream, outer isotherms inward; this is evident from Figs. 2 and 4. The observed isotherm distribution are, of course, the results of the interactions of the (magneto) gasdynamic and thermodynamic aspects.

The persistence of similar, high values of F_{90} for both the inner and outer isotherms, irrespective of the magnitude of the (non-zero) applied magnetic field, suggests that, in contrast to the a priori assumptions of the analyses of the balanced arcs,[4–8] the arc "boundary," however defined, is not circular (even for the balanced mode).

Along the mirror plane of symmetry, the temperature gradients upstream of the center of the arc are greater than those downstream of the center; the maximum temperature is located upstream of the center of the arc. The maximum temperature gradients are located on the mirror plane of symmetry, in the upstream direction ($\theta = 180°$).

Arc voltage decreased as the field strength was increased. To a first approximation, this is associated with the reduction in arc length with increasing field. The characteristic length (along the mirror plane of symmetry) of the outer isotherm decreased as the field increased in the range $0 \leq B \leq 8.3$ gauss. The length increased slightly in achieving the balanced configuration; this increase is associated principally with an outward flaring of the 10,500K isotherm in the region $0° \leq \theta \leq 30°$ (Fig. 4). The characteristic length of the inner isotherm increased in the range $0 \leq B \leq 5.5$ gauss, and decreased thereafter, $5.5 \leq B \leq 11.2$ gauss. The maximum temperature increased in the range $0 \leq B \leq 5.5$ gauss, and decreased thereafter. The behavior cited above is the result of the balance between power density input and the energy exchange processes associated with arc curvature, cross-sectional shape, and flowfield internal and external to the arc, as influenced by interaction with the applied magnetic field.

The isotherm distributions for the balanced configuration, Figs. 3–5 (scans 1, 2, and 3, respectively), exhibit similar lateral broadening characteristics as described above for the scan 2 cases (Figs. 1, 2, and 4) (the lateral broadening in scan 3 is significantly less than those determined from scans 1 and 2; scan 3 tends to approximate a circular distribution of the isotherms). The magnitude and extent of the lateral broadening suggests that, as noted earlier for the (generally) intermediate-balanced modes, the "boundary" of the balanced arc is not circular, in contrast to the a priori analytical assumptions.[4–8] The observed lateral broadening is qualitatively similar to that calculated[7] or suggested[6] for the interior isotherms of balanced arcs. The fineness ratio in the transverse direction, F_{90}, is expected to increase according to both analysis[7] (referring here to the interior isotherms) and initial

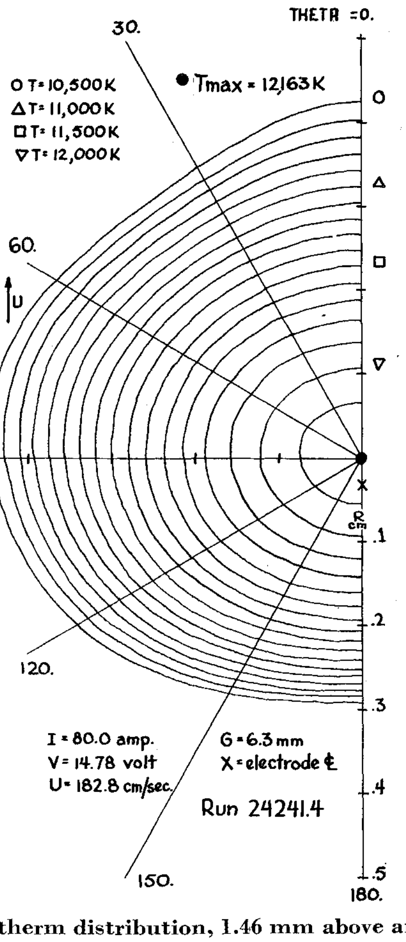

Fig. 3 Isotherm distribution, 1.46 mm above anode, B = 11.2 gauss.

qualitative measurements.[14] Consequently, as the present experimental results indicate, analyses of the balanced arcs should obtain the arc cross-sectional shape, temperature and flowfields as results of a coupled treatment rather than by assuming a prior one or more of these aspects.

The arc cross-sectional shape decreases markedly in area from scan 1 to scan 3, leading to a progressive increase in maximum temperature in this direction. For the balanced mode, the behavior of the temperature gradients and the location of the maximum temperature is as described above for the scan 2 cases (Figs. 1, 2, and 4).

The Reynolds number of these configurations, based upon film temperatures and nominal characteristic lengths, is about 35. Thus, comparisons with certain analyses, e.g., Ref. 7, would be appropriate provided: 1) the analyses considered the coupled problem, as noted earlier; and 2) relatively uniform (along their length) arcs were observed experimentally. On these bases, qualitative comparisons only are feasible. Qualitative agreement is found between theory[7] and the present experiments in the observation of noncircular (interior) isotherms whose major axes are in the direction transverse to the flow. The present experiments suggest strong persistence of the magnetic field, such that the arc "boundary," however defined, is not circular. The present experiments indicate that noncircularity is found to a much larger extent than predicted by theory.[7]

The arc profile, obtained as described earlier for the zero-balanced ($B = 0$) mode, is shown in Fig. 6. In Refs. 24 and 25 it is contended, through considerations of arc curvature and through stability conditions, that a balanced arc cannot be straight. In Fig. 6, the location of the maximum temperature is approximately a straight line parallel to the electrode centerline; the upstream isotherms are more or less straight lines. The present results, while not conclusive in this aspect, suggest, at least tentatively, that the degree of straightness of the balanced arc may not be a dominant factor in determining the arc profile, i.e., a relatively small amount of curvature may satisfy stability criteria. Clearly, longer arcs, more uniform along their length, are required to delineate the significance of curvature with respect to stability and straightness.

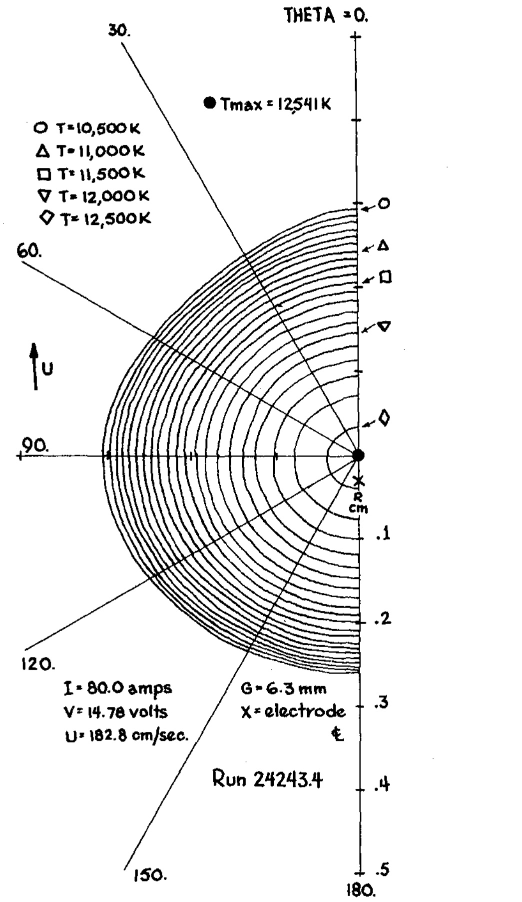

Fig. 5 Isotherm distribution, 3.64 mm above anode, B = 11.2 gauss.

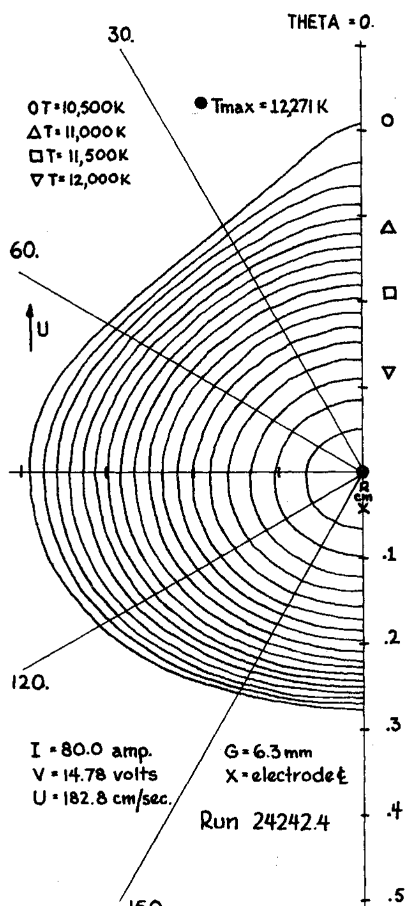

Fig. 4 Isotherm distribution, 2.55 mm above anode, B = 11.2 gauss.

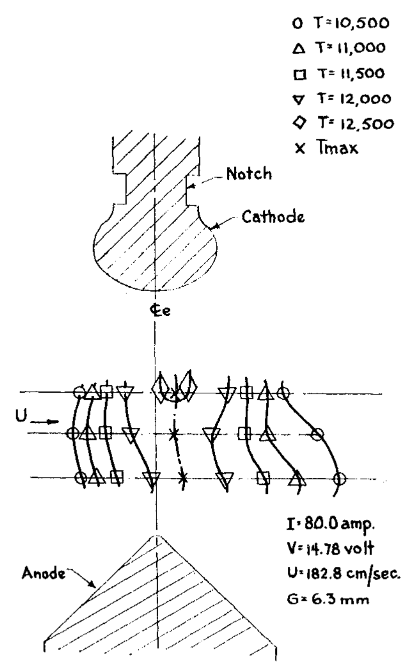

Fig. 6 Arc profile, B = 11.2 gauss.

Conclusions

Isotherm distributions and the inferred cross-sectional shapes and profiles have been obtained experimentally for cross-flow plasmas operated with applied transverse magnetic fields ranging from the zero-balanced mode ($B = 0$) to the balanced configuration ($B = 11.2$ gauss). In all cases, the arc cross-sectional shape was found to be noncircular. For the zero-balanced mode, the major axis was in the direction of flow; for the balanced configuration, the major axis was in the direction transverse to the flow. The effects of forced convection (for the zero balanced mode) were confined primarily to the outer region of the arc. The influence of the magnetic field was perceived throughout all such plasmas. The experimental results for the balanced configuration indicate that the arc "boundary" is not circular. The results also demonstrate that analytical studies (of either the zero-balanced mode or the balanced configuration) should obtain the arc cross-sectional shape, flow and temperature fields as results rather than as (one or more) a priori assumptions.

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