Anode Current Distribution in a Moving Arc

M.G. Drouet,* R. Beaudet,† and R. Jutras‡
Institut de recherche de l'Hydro-Québec,
Varennes, Québec, Canada

Two new measuring techniques are discussed. They give, respectively, the distributions of the arc current in the directions parallel and transverse to the arc motion. They are applied to measurements on an arc, 1.6 mm in length, burning at up to 700 A, in air at atmospheric pressure, between 2 parallel copper electrodes and driven, at up to 200 ms^{-1}, by a transverse magnetic field. The measured distribution profiles are nonsymmetrical in both directions. The current density at the arc foot is much larger than previously reported for the arc column. The transverse profile is characterized by a high-current core with 2 low-current wings.

Introduction

VARIOUS techniques have been proposed and used, in the past, to determine the characteristics of an arc burning between two electrodes. These techniques which use current transformer,[1-3] wire probes,[4] spectroscopy,[5-7] or shock waves[8] are applicable, in general, to the study of the conditions in the positive column of the arc.

In this paper, on the contrary, the 2 techniques, which are discussed, are applicable to the study of the arc at the electrode surface. These 2 techniques give direct or semidirect oscillographic displays of the amplitude of the distribution of the arc current. The arc is moving in the x direction, on thelectrode surface, driven by a gas flow or a transverse external magnetic field. The arc is free to expand in both the x and y directions parallel to the electrode surface. The current density, in the arc itself, is a function of position. Let x,y) be the current density in the arc at the electrode surface. The total arc current I_o corresponds to the integral of $J(x,y)$ over the electrode surface:

$$I_0 = \int J(x,y)\ dy \tag{1}$$

$$\mathcal{J}_x(x) = \int J(x,y)\ dy \tag{2}$$

$$\mathcal{J}_y(y) = \int J(x,y)\ dx \tag{3}$$

The quantity $\mathcal{J}_x(x)$ expresses how the total arc current I_0 is distributed along x, the direction of motion of the arc, while the quantity $\mathcal{J}_y(y)$ expresses how the total arc current I_0 is distributed along y, the direction transverse to the arc motion. The method of measurement of the distribution $\mathcal{J}_x(x)$ has been reported recently.[9] It will be reviewed here briefly. The main object of this paper is to report on the second techniques and to interpret the combined results obtained using both techniques.

Distribution of the current in the direction of the arc motion $\mathcal{J}_x(x)$

Measuring method

The electrode is split across in the y direction, and this slit is connected to a cylindrical cavity located a short distance below the electrode surface as shown on Fig. 1. As the arc is driven across the slit, the current on the left side of the slit, I_ℓ decreases and that on the right side, I_r increases. If the total current I_o is constant, the rate of current transfer at the slit, dI/dt, is related to the value, at the slit, of the quantity $\mathcal{J}_x(x)$ as follows,

$$(dI/dt) = \mathcal{J}_x(x)\ \mathcal{V}_x \tag{4}$$

where $\mathcal{V}_x$ is the velocity of the arc in the direction x. However, as the current is transferred from left to right of the slit, there is a variation of the magnetic flux inside the cavity. This variation of the magnetic flux can be measured using a small coil inserted in the cavity. If the coil circuit has a sufficiently large impedance, so that the current induced in the coil does not affect the variation of flux in the cavity, and, furthermore, if the coupling between the coil and the electrode is independent of frequency, then the voltage $V(t)$ induced in the coil can be expressed as follows

$$V(t) = M\ dI/dt \tag{5}$$

where M is the mutal inductance between the coil and the electrode. Using Eq. (4) we obtain,

$$\mathcal{J}_x(x) = C\ V(t) \tag{6}$$

where C is a constant which depends on the values of both the mutual inductance M and the arc velocity. This last result indicates that direct oscilloscope display of the distribution $\mathcal{J}_x(x)$ can be achieved; i.e., the voltage pulse induced in the coil is directly related to the distribution $\mathcal{J}_x(x)$ of the current in the arc. The general case in which the coupling between the coil and the electrode is not independent of frequency has been considered in details in Ref. 9. In our case the transfer impedance between the coil and the cavity was measured and

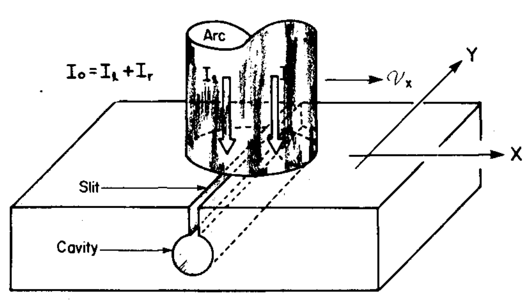

Fig. 1 Position of the slit and of the cavity.

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*Senior Research Physicist.

†Junior Research Physicist.

‡Member of the Technical Staff.

found to be independent of frequency, and the use of Eq. (6) is well justified.

Experimental arrangement

In our experiment the arc is driven by a transverse magnetic field, however, and as pointed out earlier on, the technique is also applicable for the diagnostic of an arc driven by a gas flow. The experimental set up used is shown in Fig. 2. The arc is produced in air at atmospheric pressure between 2 parallel rail electrodes. Electrodes of commercial purity copper are used; they are separated by 1.6 mm to form the arc gap. The beam of a CO_2 TEA laser, focussed between the electrodes at one end, is used to initiate the arc. The arc produced is driven along the electrodes by a transverse magnetic field established by 2 coils located on each side of the electrode arrangement; the value of this magnetic field can be adjusted from 400-1600 gauss. The arc current is supplied by a 0.04 F capacitor charged as high as 400 v, and the arc current is limited by an adjustable resistance. Depending on the value of this resistance the value of the arc current is set in the range of 200-800 amp. Both the values of the arc current and of the transverse magnetic field remain quasi-constant; i.e., within 1%, during the measurement of the distribution justifying the assumptions of constant current, $dI_o/dt=0$, and constant arc velocity made in the derivation of Eq. (6). The arc current is measured using a calibrated current transformer and is displayed on the oscilloscope together with the arc voltage. The arc velocity is determined from the record of the motion of the arc as a function of time obtained with a TRW streak camera. The design and the dimensions of the cavity are shown on Fig. 2. The slit is 0.05 mm wide, and a mylar sheet is inserted into it to assure that no contact exists between the 2 sections of the electrode. The pick up coil is a one turn copper wire loop placed on the electrode side surface, vis-a-vis the cavity as shown in Fig. 2. The coil is insulated from the electrode by a 0.025-mm-thick mylar sheet and is connected to the oscilloscope across a 50 Ω resistance which is large enough to satisfy the assumption made prior to Eq. (5); i.e., $2\pi f_{max} L \ll R$, where L ($2\ 10^{-9} H$) and R(50 Ω) are, respectively, the inductance and the resistance of the coil circuit, and f_{max} is the highest frequency Fourier component of the voltage pulse (200 kHz).

The measurements are performed only after the polished electrode surfaces have been oxidized by many passages of the arc. This conditioning requires about 50 shots, after which there is little change in arc behavior from shot to shot as far as arc current, arc voltage, and arc velocity are concerned.

Results

A typical oscillographic recording of the voltage pulse induced in the coil, $V(t)$, as a 700 A arc was driven across the slit, is shown on Fig. 3a. In that particular case the slit was at the anode. The pulse shape is characterized by a sharp rise and a slower decay. The pulse is quite smooth and occurs in less than 50 μs in these particular conditions. These experimental conditions are given in Fig. 3c which displays the amplitutes of the arc current I_o, arc voltage V_o, and transverse driving

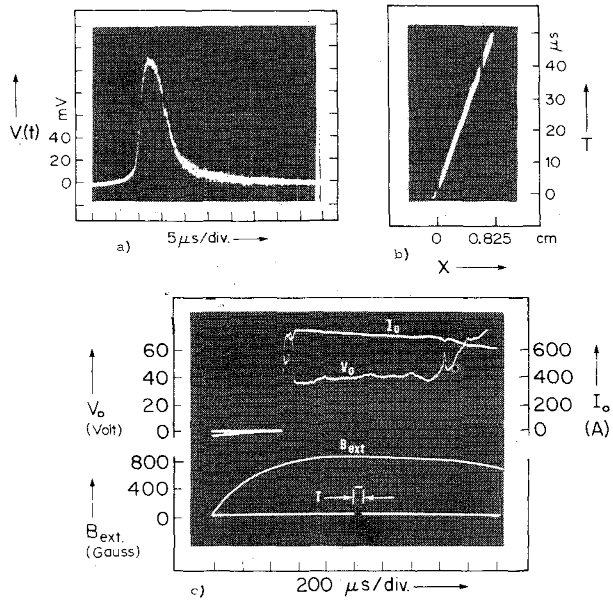

Fig. 3 Experimental results.

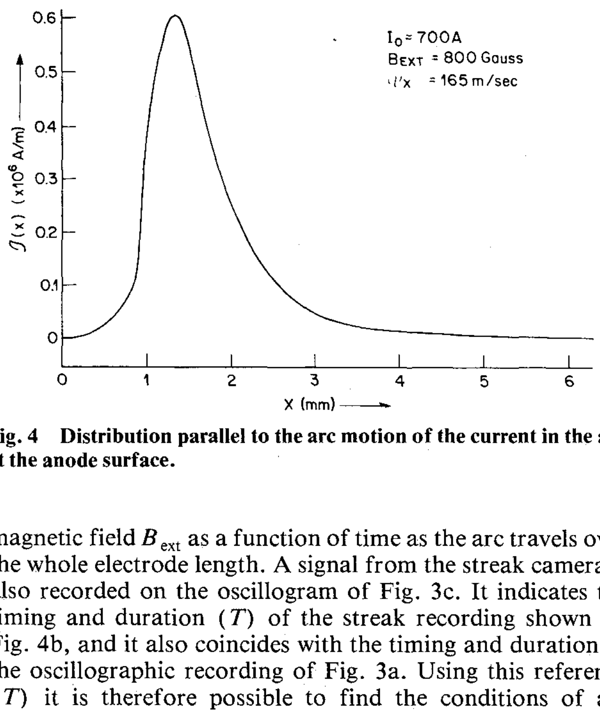

Fig. 4 Distribution parallel to the arc motion of the current in the arc at the anode surface.

magnetic field B_{ext} as a function of time as the arc travels over the whole electrode length. A signal from the streak camera is also recorded on the oscillogram of Fig. 3c. It indicates the timing and duration (T) of the streak recording shown on Fig. 4b, and it also coincides with the timing and duration of the oscillographic recording of Fig. 3a. Using this reference (T) it is therefore possible to find the conditions of arc current, arc voltage, transverse magnetic field, and arc velocity which correspond to the voltage pulse $V(t)$ recorded on Fig. 3a. It is also possible from these records to evaluate the variations of the arc current, dI_o/dt, and of the arc velocity during the recording of the voltage pulse $V(t)$. Both variations are found to be smaller than 1%.

The value of the arc velocity is obtained from the slope of the luminous streak on the photograph (Fig. 3b) knowing the time duration of the display and the distance between the 2 vertical dark lines on the recording. These 2 dark lines are produced by 2 vertical markers located near the electrodes, between them and the camera, separated by 6.5 mm and equidistant from the slit-cavity arrangement so that the streak recording shows the luminous appearance of the arc before, during and after the actual probing of the arc by the slit-cavity arrangement. In the case illustrated, the value of the velocity $\mathcal{V}_x$ is approximately 165 ms^{-1}; it is comparable to that reported in the literature for similar experimental conditions.[10] The width of the trace along the x-axis on the streak recording gives an idea of the size of the luminous region of the arc and

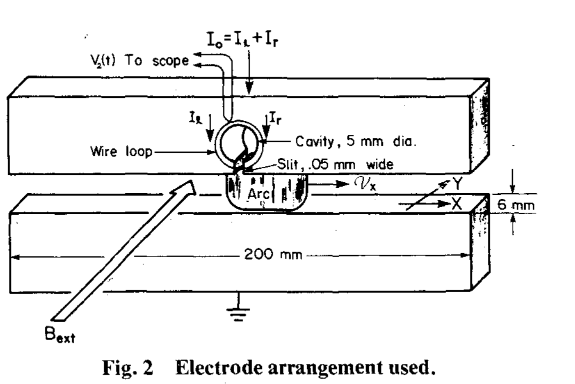

Fig. 2 Electrode arrangement used.

of the behavior of the arc during its probing by the slit. There is no indication, on the recording, of any perturbation of either the arc velocity or the luminous width of the arc caused by the presence of the measuring device in the electrode.

We shall now proceed to derive the distribution $\mathcal{J}_x(x)$ corresponding to the experimental conditions indicated on Fig. 3c from the measured voltage pulse as given on Fig. 3a. The results of measurement of the transfer impedance have indicated, to a very good degree of approximation, that the mutual inductance M between the electrode and the coil in independent of frequency. Using the values estimated for M (1.12 ± 0.03, $10^{-9} H$) and for the arc velocity, $\mathcal{V}_x$, we have determined the shape of the distribution, parallel to its motion, of the current in the arc $\mathcal{J}_x(x)$; it is shown on Fig. 4. We will note, as an additional check on the results, that the value of the area below the $\mathcal{J}_x(x)$ curve is equal to the value of I_o as it should according to Eq. (1).

Distribution of the current in the direction transverse to the arc motion $\mathcal{J}_y$ (y)

Measuring method

In this case one of the electrode is made of strips oriented in the direction of the arc motion. The technique is illustrated on Fig. 5. The geometry shown on Fig. 5a, commonly used for the study of arc driven between 2 rails electrodes, is replaced by that illustrated on Fig. 5b. The strips, in contact with the arc, are insulated from one another and each one is connected to the power supply through a shunt. The shunts are used to determine the value of the current corresponding to each strip and in this way the distribution $\mathcal{J}_y(y)$ of the total arc current in the direction transverse to the arc motion.

Experimental arrangement

The experimental arrangement is identical to that described in the preceeding chapter, apart from the fact that one of the electrodes is made of metal strips, each of them being grounded through a low resistance shunt as discussed earlier. For our measurements, 12 strips are used. To obtain a better definition of the distribution of the current in the arc core, the strips are not of equal thickness. In a symmetric fashion with respect to the mid plane of the electrode their thickness is 0.010, 0.010, 0.010, 0.031, 0.031, and 0.062 in., respectively, the thicker strips being on the outside of the electrode. A mylar sheet 0.001 in. is used to insulate the strips from one another. The total electrode width was therefore 0.319 in. (~8.3 mm). The electrode arrangement is shown on Fig. 6. Each shunt is made of a length of 1 in. of shield of a RG-58 cable soldered on one side to the collector, which is itself grounded, and on the other side to one of the strips. The central wire of the RG-58 cable is also soldered to the strip; it is used to monitor the voltage developed by the current in each strip across the length of cable shield connected to that particular strip. The value of the current is determined knowing the voltage drop and the value of the shunt ($5.10^{-4}\Omega$). In our

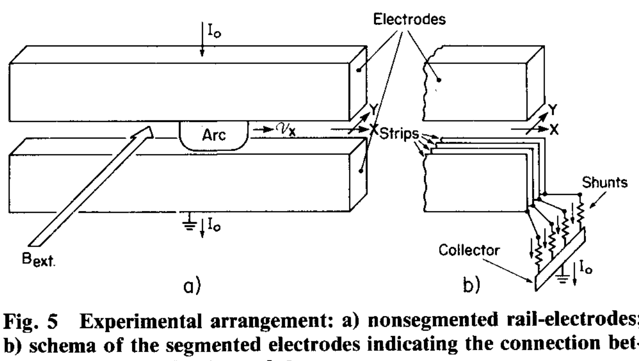

Fig. 5 Experimental arrangement: a) nonsegmented rail-electrodes; b) schema of the segmented electrodes indicating the connection between the individual strips and shunts.

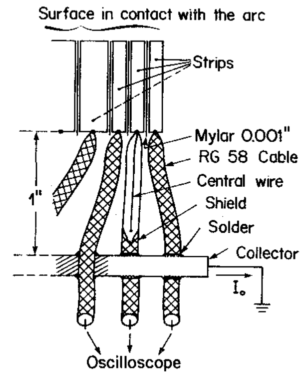

Fig. 6 Detail of the shunts.

case, the 12 RG-58 cables are connected to 2 double beam oscilloscopes used in the chopped mode and a single shot, 12 traces, simultaneous recording of the value of the current in each strip is obtained as a function of time during the travel of the arc from one end of the rail to the other. The value of the total arc current being approximately constant during the experiment, it is not necessary in this case to worry about the frequency response of the probing device. Some comparative measurements of arc velocity and of arc voltage were made for different values of arc current and magnetic field successively with a segmented electrode (12 strips) and with a solid electrode (non-segmented). No difference in the arc voltage and the arc velocity were observed, and to our knowledge the use of this type of segmented electrode does not seem to cause any perturbation of the arc.

Results

Measurements were made at the anode in air, at atmospheric pressure, for a range of values of the arc current

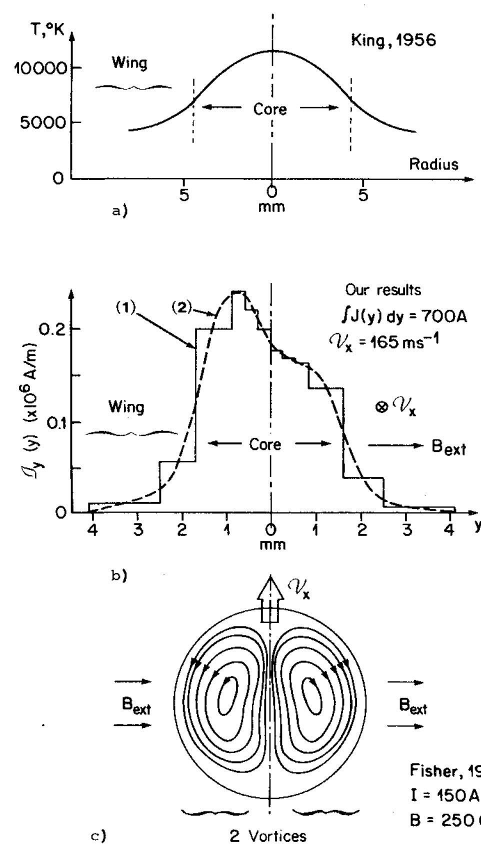

Fig. 7 a) radial temperature distribution in a stationary arc (King, 1956); b) distribution transverse to the arc motion of the current in the arc measured at the anode surface; c) cross-section of the arc indicating the flow lines according to Fisher.[16]

from 200-800 amp and of the magnetic field from 500-1500 gauss. The copper electrodes were separated by 1.6 mm. As indicated 2 simultaneous oscilloscope recordings are made which give simultaneously the values of the current corresponding to the 12 strips during the arc travel between the rail electrodes. For most of the tests we observed that the current distribution remains fairly constant for travel distances of a few tens of mm. A typical $\mathcal{J}_y(y)$ profile, derived from such recordings, for an arc of 700 amp driven at 165 ms^{-1} by a transverse magnetic field of 800 gauss is shown in Fig. 7b. In the curve 1, each level corresponds to a particular strip, the value of $\mathcal{J}_y(y)$ for each strip is determined by dividing the value of the current corresponding to that strip by the width of the strip. The curve 2 illustrates a possible profile of the distribution $\mathcal{J}_y(y)$ of the arc current.

Discussions

Two techniques for the measurement of the distributions at the electrode surface of the arc current in the directions parallel and transverse to the arc motion have been reported. We believe that these 2 techniques could be used to study the characteristics of the anode and cathode§ arc roots and in particular their current distributions, the motion of the arc on the electrode surface, the existence and the value of the current carried by the microcraters in the arc roots and the current density on the electrode surface. The results included in this paper, which are typical of the results obtained in the range of conditions studied, demonstrate some possibilities offered by these techniques.

Current Density

The maximum current density at the anode surface, corresponding to the conditions specified on Figs. 3a and 7b, has been evaluated. It is found to be approximately 5 10^4 A cm^{-2}. A value of 3.4 10^5 A cm^{-2} was found at the anode surface by Shih[3] for a 750 amp stationary free-burning arc. Slovetskii[7] using a conductivity profile determined by spectroscopic means on an arc fairly similar to ours, obtained a value for the current density which is much smaller, 1.6 10^3 A cm^{-2}. It should be noted however that the measurements by Slovetskii correspond to the arc column where the cross section may be much larger than it is at the electrode surface.

Arc Cross Section

Using a "double inversion" method similar to that proposed by Olsen et al.[11] we intend to resolve the current density distribution in the arc from the measured distributions $\mathcal{J}_x(x)$ and $\mathcal{J}_y(y)$. This study has not been completed yet; however it is clear, from Figs. 4 and 7b, that in our arc conditions, the dimension transverse is much larger than the dimension parallel to the arc motion. Similar observations were made earlier by Guile et al.[6] Roman and Myers,[12] and Benenson and Baker[13] although in different arc conditions. On the basis of these observations it has been generally assumed that the arc boundary should be convex and symmetrical with respect to the directions of arc motion and magnetic field, and that the cross section would be elliptical with the major axis transverse to the arc motion. Although our measurements confirm that the arc has a much wider overall dimension normal to motion than that in the direction of motion they show that in our operating conditions, at the anode, the distributions of the current are, on the contrary, not symmetrical with respect to the directions of either the magnetic field (Fig. 4) or the arc motion (Fig. 7b).

Over the range of conditions studied the distribution $\mathcal{J}_x(x)$ was always characterized by the presence of a tail. The extent of this tail was found to depend, in particular, on the velocity of the arc, the distribution $\mathcal{J}_x(x)$ being more and more constricted as the velocity is increased at constant total arc current. The nonsymmetry of the arc with respect to its direction of motion is discussed.

Shape of the Transverse Distribution $\mathcal{J}_y(y)$

On Fig. 7b we observe the presence of low current wings on each side of the core of the transverse distribution. These wings contribute greatly to increase the total width of the distribution without carrying much of the arc current. The overall shape of the transverse distribution suggests a comparison with the shape of the theoretical and experimental temperatures profiles reported for the case of stationary arc burning in air as shown on Fig. 7a. According to King[14] and Frind[15] the particular radial temperature profile of the stationary arc burning in air must be attributed to the dissociation and recombination phenomena occurring in the region around the high temperature central core, and they result from an effective energy transfer from the central arc core.

In a moving arc, such as the one studied here, it has often been considered that the energy transfer processes would be different, in particular the energy transfer by convection should be important. However, the presence of the low current wings indicates that the processes of recombination and dissociation in a moving arc may also contribute appreciably to the energy transfer. More studies and measurements are needed to check this first interpretation of our results.

Nonsymmetry of the Transverse Distribution

In addition to the presence of low-current wings, we observe that the shape of the core of the transverse distribution is strongly nonsymmetrical. From shot to shot the current carried in the left or right sides may be up to twice as much that carried on the other side. We ruled out any preferential attachment to one or more of the metal strips because the asymmetry did not show any preference for the left or right side of the electrode. Furthermore, as pointed out earlier, the profile, and therefore this nonsymmetry, remains fairly similar for arc travel distances of several tens of mm. In our operating conditions, the nonsymmetry of the distribution appears to us to be a characteristic of the moving arc. We suggest that this observation could be interpreted in terms of the presence of a double vortice in the arc as predicted by many theoretical works, e.g., Fisher,[16] in spite of the fact that most of these works do not envisage the possibility of a nonsymmetrical arc. Our tentative interpretation goes as follows: the existence of two vortices in the arc would divide effectively the arc in 2 regions right and left on Fig. 7c. The left and right sides of the arc would not be connected by any flow line as indicated on this figure. The energy exchange between these 2 regions cannot occur by convection, it will occur by processes such as radiation and conduction across the flow lines. If these energy transfer processes are not major terms in the energy balance, a large difference in temperature could exist between the 2 regions. This, in turn, would result in different values of the conductance and therefore of the current carried by each side, left and right of distribution. The situation is unstable because any increase in temperature in one of the two regions of the arc results in an increase of conductance and therefore of current in that region which in turn causes an additional increase of temperature. This unstable condition favoring a continual increase in temperature may be limited by either or both the facts that: a) conduction and radiation transfers increase with temperature; and b) the velocity and the arc diameter of the favored region increase and therefore the convection losses also increase. More studies and measurements are also needed to check this tentative interpretation of the results.

§Measurements of $\mathcal{J}_x(X)$ at the cathode have also been reported (closure Ref. 9).

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