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Fluid Transpiration through Anodic Boundary of an Electric Arc

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Consideration of the distribution of dissipated energy in a free-burning arc indicates that the major portion of the input energy is concentrated at the anode-gas interface This leads to the concept of intıoducing a working fluid into the arc via the anodic boundaıy by transpiration through a porous anode Using porous graphite of sufficiently fine pore size and an inert gas medium, this technique is shown to be successful in generating a sustained plasmajet without a water-cooled channel or other thermal constraint At power levels <10 kw, energy transfer to the gas is in the range 70 8 to 88 5% of input The observed effects of gas flow on arc terminal characteristics are a rise in anode fall voltage and a decrease in incremental arc resistance Evidence for an apparent transition in anode fall mechanism at a specific flow rate is also presented Transient voltage probe studies of the flame reveal a complex structure for the axial potential distribution in the region of the anode

I Introduction

THE use of an electric arc as a pıimary energy source for heating streams of fluids has stimulated investigations of the basic energy transfer mechanisms occurring within the gas discharge zone Whereas the literature is replete with articles on the energetics and processes of the stationary arc discharge,[1] the behavior of an arc under forced convection of a fluid stream has received relatively scant attention despite its importance in the field of plasma generation The work reported thus far in this area has dealt largely with the technique of generating plasmajets, which involves passing a stream of fluid through the arc column As shown by the original work of Gerdien and Lotz[2] and later by Maecker[3] and others,[4 5] the concentration of appreciable amounts of enthalpy in the effluent jet requires the application of constraints on the column boundary This is accomplished by enveloping the column with a vortex of working fluid (the "vortex-stabilized" arc) or by establishing the column in a narrow channel with cooled walls (the "wall-stabilized" arc) In either case the conduction column is immobilized by thermal constriction with respect to radial displacement, thus permitting the convection of fluid through the hot plasma in the column without causing instability or flame-out

The use of this technique as a research tool in high-temperature science has become commonplace For some purposes, however, this method of heating fluids has some limitations For example, except at very low flow rates, the plasmajet is turbulent At low flow rates, on the other hand, problems are encountered in sustained operation with regard to electrode erosion and contamination of the jet, unless the arc is operated at relatively low power

The present paper is concerned with a new method of energizing a stream of fluid by means of an electric arc without the application of thermal constraints on the arc column

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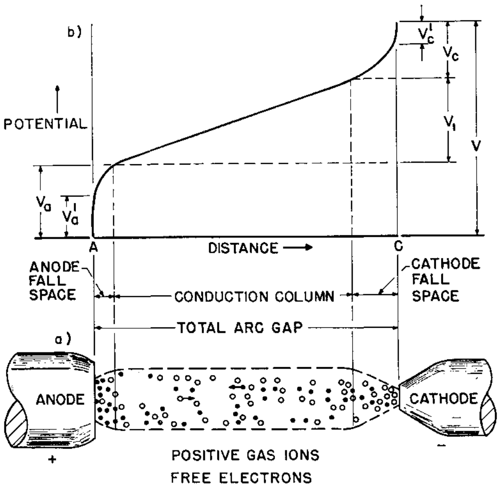

Fig 1 a) Gas conduction zones and b) axial potential distribution of a typical (low-intensity) arc

This consists of injecting the fluid into a free-burning arc via the anodic boundary by transpiration through a porous anode The basis for this approach and experimental results on its effect on arc behavior are presented in the following

II Basis for Fluid Transpiration through a Porous Anode

In any discussion involving energy transfer in an arc discharge, a feature of particular importance is the voltage distiibution in the space between the electrodes This is determined largely by the local charged-particle densities, and under practically all conditions of arc operation it is characterized by three distinct zones The three zones of a typical arc discharge are illustrated in Fig 1a and the corresponding axial voltage distribution in Fig 1b The two fall spaces near the electrodes are concerned with charge and energy transport at the electrode-gas interfaces and are each composed of a very narrow sheath ($\sim$1 mean free path) across which a precipitous voltage drop occurs, followed by a wider transition region in which the voltage gradient decreases until it reaches the value prevailing in the arc column The column extends over most of the interelectrode space and is characterized by a low and constant voltage gradient

Since the arc current flows through all three regions in series, the local ohmic dissipation follows the voltage distribution curve shown in Fig 1b Thus, the amounts of power dissipated in the vicinity of the cathode and anode surfaces are equal to the respective sheath voltages (V' and V_a') times the arc current, whereas the product of the arc current times the sum of the potential drops across the column and both transition regions represents the power dissipated in the interelectrode space From this one might assume that, in a free-burning, low-intensity arc, roughly 10% of the total input energy would be transferred to each electrode, and the remainder would be lost to the surrounding medium However, in addition to this several secondary transfer processes occur which radically affect the regional dissipation of energy so as to increase the thermal loading of the anode For example, if I = the arc current, then the power IV', dissipated at the cathode surface, is reduced by a factor $\alpha I \phi$, where α is the fraction of the cathode current which is carried by emitted electrons,§ and ϕ is the work function of the cathode material This term represents the power absorbed and the consequent cooling by the electron emission process at the cathode surface Conversely, the power transferred to the anode due to the sheath dissipation, namely, IV_a', is increased by a factor $I\phi_a$, where ϕ_a is the work function of the anode material and where the total arc current is used because all of the current across the anode boundary is carried by electrons This term represents the heat of condensation of the electrons entering the anode surface, which contributes to the heat flux into the anode

In addition to the foregoing effect, a considerable portion of the energy normally dissipated in the column region is also transferred to the anode by the mechanism of autogenous convection, which refers to a natural streaming motion of the hot plasma inside the column travelling from cathode to anode The explanation for this phenomenon was given by Maecker[6] It is caused by the pronounced contraction of the conduction zone in front of the cathode surface The cathode transition region therefore represents a zone in which the current density is changing rapidly, and consequently the self-magnetic field associated with the current is inhomogeneous and has a gradient (in the direction of diminishing field strength) pointing along the axis away from the cathode Such a field configuration exerts a body force on a conductive fluid in a manner analogous to the magnetic mirror Thus, a pressure gradient is established along the axis of the discharge which imparts a streaming motion to the plasma from the cathode toward the anode, within the column This streaming motion away from the cathode causes an aspiration of gas from the surrounding atmosphere which enters at the base of the cathode constriction (and which, incidentally, has a cooling effect on the neighboring cathode surface) The aspirated gas, after being drawn into the arc, is heated to the column temperature, thus absorbing a consideiable portion of the column energy before impinging on the anode surface The net result is an increase in the heat-transfer rate to the anode

Some energy is also transferred to the electrodes by thermal conduction and radiation However, unless the arc is burning at a pressure of many atmospheres, both of these processes are of minor importance

The combined influence of all of the preceding secondary heat-transfer processes is to shift the over-all heat balance of a normal arc so that most of the arc energy is dissipated at the anode Eckert and Winter[7] have determined that in a typical situation (e g , a free-burning arc near atmospheric pressure) only about 5% of the total arc input power is transferred to the cathode, between 5 and 20% is lost to the surrounding atmosphere from the column, and from 75 to 90% is transferred to the anode Therefore, from the standpoint of the power dissipation of a free-burning arc, the anode is a strategic location for fluid injection Thus a gas stream emerging from a porous anode should be effective in absorbing a large fraction of the input energy and at the same time in reducing the thermal loading of the anode For example, the flow of gas away from the anode surface would intercept the cathode jet and could be made to divert it into the effluent jet Also, transpiration cooling by the injected fluid would regenerate some of the energy that does enter the anode

Another factor of importance is the effect of forced convection on the stability of a free-burning arc Consider, for example, the relationship between the flow field of the cold injected gas and that of the charged particle flux or drift currents in the conduction column Because of the relatively high cross section for neutral-charged particle collisions, the injected gas stream couples strongly with the ions and electrons Therefore, the injected stream will drag ion pairs out of the conduction zone This fluid mechanical loss of ion pairs is a primary cause of instability in arcs subjected to forced convection When the gas flow has an appreciable component orthogonal to the ion drift current, the hydrodynamical interaction causes the column to be deflected in the direction of the flow The behavior of a free-burning arc under the influence of an external, lateral stream of gas was investigated by Thiene[8] With the arc termini fixed

§ For a refractory cathode, α is usually $> \sim 0\ 5$

on small electrodes, the column of a 1-atm arc in argon was found to be severely distorted in the downstream direction in a traverse gas flow of only a few feet per second At a transverse flow velocity above about 5 fps, the arc was blown out In the wall-stabilized arc, the flow-induced instability is inhibited by the confining effect of the channel However, even in this case the column may be stretched along the axis of the constricting channel Using a segmented nozzle, Wheaton and Dean[9] have shown that the positive terminus of the arc moves rapidly down the channel and is ultimately blown out at the nozzle orifice The arc then immediately reignites at the cathode end of the channel, and the process repeats itself Therefore, except at very low flow rates, the confined plasmajet generators (which feature gas flow parallel to the anode surface) operate by rapid successive extinctions and reignitions and generate a noisy and turbulent plasmajet

In contrast to the foregoing situation, the flow configuration involved in the concept of injection through the anodic boundary does not involve gas flow orthogonal to the ion drift current The difference between the two methods of injection is illustrated in the diagrams of Fig 2 In the case of anode injection, it is clear from Fig 2b that, in the region of the anode fall space, the injected gas leaving the anode surface in the perpendicular direction flows parallel to the ion drift current and antiparallel to the electron drift current This type of flow configuration appears to be much more compatible with the gas conduction process in terms of the availability of charge carriers for a free-burning arc Thus, when injected gas traverses the anode fall space, it merely drags the ion pairs into the column at a greater rate, while at the same time it is heated by the counterflow of energetic electrons comprising the electron drift current Since the energy dissipated in the anode region is quite high, the injected gas should be vigorously heated before leaving the arc and would, therefore, emerge as a hot conductive plasma For this reason considerable flow rates could be tolerated without depleting the supply of charge carriers in the conduction zone Accordingly, it was anticipated that this method of introducing the working fluid would permit the convection of appreciable amounts of gas through the arc while the arc is operating in a stable free-burning mode, and that a relatively nonturbulent plasmajet would be generated over a wide range of flow rates

III Description of Experiments

A Porous Anode Technique

A sketch of the porous anode holder is shown in Fig 3 The porous anode material was machined into the form of a cylindrical plug with bevelled sides and held in place by a threaded electrical contact plug that exerted pressure against the rear face A hole bored through the center of the contact plug was used to introduce gas under pressure into the

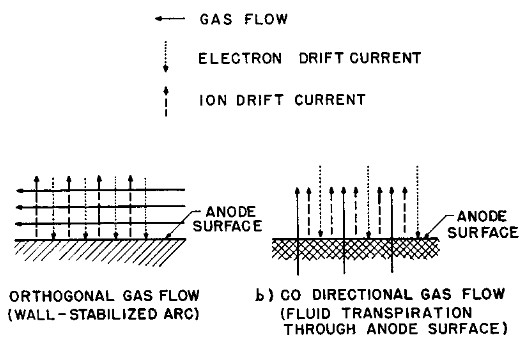

Fig 2 Relative directions of charged particle and fluid flow systems

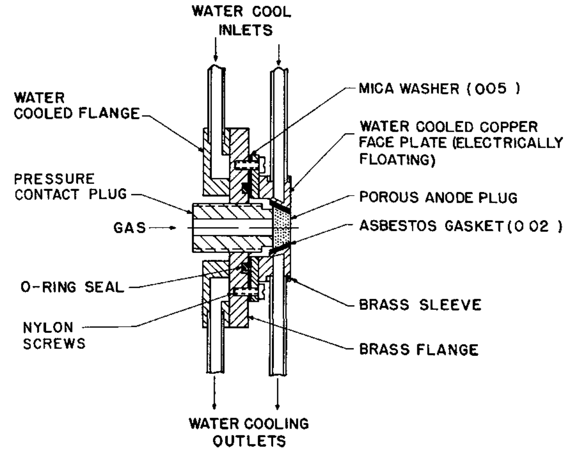

Fig 3 Sketch of porous anode assembly

rear face The anode and contact plug were insulated from the supporting face plate by means of a 0 02-in asbestos gasket With this arrangement, the arc could only terminate on the porous anode plug, thus insuring against any tendency for the arc to jump to the face plate Both structures were water-cooled to protect the "O" ring seals

During the initial search for a suitable porous material, it was observed that the anticipated behavior could not be achieved unless the pore size was sufficiently small (i e , $<\sim 50$ μ at atmospheric pressure) Although the investigation was not extensive enough to arrive at a pore size criterion, it was tentatively assumed that the average pore size should be at least comparable to the thickness of the anode sheath and preferably much smaller than this The logic of this assumption is based on the fact that the anode sheath (which is between 35 and 50 μ for most gases at 1 atm) forms only adjacent to the current-receiving surface Therefore, gas emerging from a hole appreciably larger than the sheath thickness would not penetrate the high-potential gradient region of the fall space On the other hand, if virtually all of the surface outlet orifices are much smaller than the sheath thickness, then the transpired gas must penetrate the sheath where it is rapidly energized This view was borne out by the observation that, when porous anodes were used having pore sizes in excess of 50 μ, the arc was blown out at relatively low gas flow rates, whereas the anode showed evidence of thermal damage On the other hand, when sufficiently fine pore size ($\sim$30 μ or less) was used, the arc was insensitive to the flow rate and continued to burn in a stable fashion as the flow rate was increased, even though the flow velocity was raised to a very high value Indeed, it was found to be impossible to blow out the arc at flow rates up to 1500 g of argon per minute per square centimeter of anode surface When higher head pressures were applied in an attempt to investigate flame-out conditions, the anode plug was blown out of its holder before the arc was extinguished

The first successful experiments[10] were carried out with porous graphite anodes The material used¶ was a commercially available grade of porous graphite Although the pore size of this material varied considerably from one sample to the next, selected specimens were found having an average pore size less than 50 μ This graphite was used almost exclusively during these experiments chiefly because of its ready availability and machineability, and because graphite can sustain an arc with little or no anode cooling In addition, erosion of a graphite anode will not destroy the permeability of the specimen

Using a $\frac{1}{2}$-in -diam anode of NC-50 graphite and a $\frac{3}{8}$-in -diam graphite rod for the cathode the arc was struck in an ar-

¶ Type NC-50 graphite, National Carbon Company

Fig 4 Photograph of plasmajet generated by injecting gas through porous (graphite) anode (argon gas at 1 atm) Flow rate, 7 g/min; voltage, 24 v; current, 90 amps

Fig 5 Photograph of plasmajet at highei flow rate (aigon gas at 1 atm) Flow iate, 30 g/min; voltage, 32 v; cuiient, 105 amps

gon atmosphere, initially with no gas flow A typical low-intensity arc was established at 24 v and 45 amps Then, using argon gas as the transpiration medium, the flow was turned on and gradually increased As soon as the gas was turned on, a well-defined plasma flame appeared which was exceedingly stable under all gas flow conditions Figure 4 is a photograph of the plasma flame produced when the gas flow rate was set at about 7 g of argon per minute It will be observed in the photograph that the axis of the cathode is displaced laterally from that of the anode so that the electrode axes are not collinear This has the effect of causing the cathode jet to merge smoothly with the flow from the anode, producing a relatively nonturbulent flame at approximately 90° to the main discharge The turbulent mixing** of the two opposing streams which results when collinear electrodes are used may, therefore, be avoided

At flow rates higher than 10 or 15 g/min (in argon), it was found desirable to incline the cathode at an angle to the anode axis In this configuration, higher gas flow rates produced a clearly defined cylindrical jet along the axial direction Figure 5 is a photograph of such an arrangement operating with a flow rate of 30 g/min All subsequent experiments were performed with the configuration depicted in Fig 5

In order to test original predictions concerning the effects of transpiration on anode cooling and energy transfer efficiency, measurements were made of anode erosion, anode temperature, and effluent jet enthalpy, for vaiious flow rates The erosion measurements were made by weighing the anodes before and after a 10-min run at various currents and flow rates The iesults are shown in Fig 6 Since the voltage was maintained constant during all of these runs, the current axis is also proportional to the arc power level Note that, in the power range co\ered (2 to 6 kw), the erosion rate (weight loss per unit time) is reduced by a factor of 60 when the flow rate is increased from 0 to 32 g/min

Anode face temperatures were measured by means of a Leeds and Northrup optical pyrometer as a function of gas flow rate The results are presented in the curve of Fig 7 As the flow rate was increased, the anode face was observed visually to darken progressively However, the surface did not darken uniformly, piobably as a result of nonuniformity in the surface distribution of pores Therefore, in making temperature measurements care was taken to focus the optical pyrometer on the brightest point of the active surface so that the values coiiespond to maximum surface temperature At flow rates above 100 g/min, the temperatures indicated in Fig 7 are much below the temperature at which the vapor pressure of graphite becomes too small to account for the observed weight losses This was confirmed by the failure to detect spectroscopically any trace of carbon vapor in the plasma It was, therefore, concluded that, at least at the higher flow rates, the erosion was due to spalling, probably due to thermal shock after ignition To check this point, the erosion rate per unit power input for a 70-sec run was compared with that for a run lasting 33 min, at the same flow rate (100 g/min) A reduction in weight loss per unit time from $18\ 9 \times 10^{-5}$ to $0\ 63 \times 10^{-5}$ g/kw-sec was observed which is consistent with the preceding hypothesis

The effluent jet enthalpy was also measured at several flow rates and arc power levels to determine the fraction of input power transferred to the gas A standard flow calorimeter was used, consisting of a 1-in -i d water-jacketed pipe, 6 ft in length The temperature of the emerging gas was monitored by a thermocouple, and the temperature rise and flow rate of the cooling water was noted when the latter was adjusted so that the gas temperature at the outlet was reduced to room temperature These data, together with the transpiration gas flow rate and arc power input, permitted the jet enthalpy and energy transfer efficiency to be evaluated Typical results are contained in Table 1 The range of overall energy transfer efficiencies (70 8 to 88 5%), in conjunction

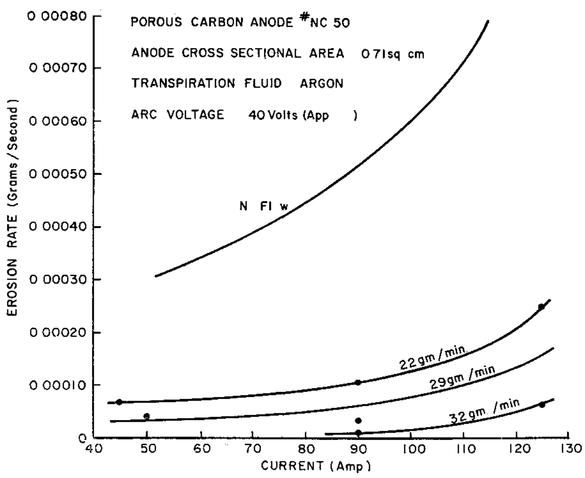

Fig 6 Erosion rate vs cuiient for various flow rates

** See Eckert and Winter,[7] Figs 4–6

Table 1 Total plasmajet enthalpy at various power levels and flow rates (NC-50 graphite anode; argon gas; 1 atm)

Voltage v	Current, amps	Power input, kw	Flow rate, g/min	Max enthalpy (theoretical), kcal/g-mole	Enthalpy (measured), kcal/g mole	Ratio of enthalpy to power input, kcal/g mole-kw	Energy transfer efficiency, %
33 5	200	6 70	478	8 07	7 12	1 06	88 5
34 0	185	6 29	370	9 75	7 65	1 22	78 4
32 5	180	5 85	330	10 2	8 32	1 42	81 6
33 5	200	6 70	268	14 4	10 7	1 60	74 5
35 0	200	7 0	308	13 0	11 4	1 63	87 2
30 5	125	3 81	160	13 8	10 3	2 70	74 5
28 0	100	2 80	79	20 1	14 2	5 07	70 8

with the preceding observations on anode cooling and low erosion, indicates that good heat-transfer characteristics are obtainable with a free-burning (unconstricted) arc by fluid injection through a porous anode

B Effect of Transpiration on Terminal Characteristics

One of the most interesting observations during this study was the effect of gas flow through the anodic boundary on the arc terminal characteristic The type of arc discharge most closely analogous to the present case is the high-intensity arc, in which, by using a sufficiently high current density, a stream of anode vapor is caused to flow into the arc from the anodic boundary Bassett[11] and Finkelnburg[12] have observed an increase in arc resistance occasioned by the onset of vapor flow from the anode surface Reasoning by analogy, the same effect may be anticipated for a gas flowing through a porous anode Thus, it was expected that the arc voltage would rise and the current would fall when the gas flow was turned on However, at a low flow rate, just the reverse occurred, the voltage decreasing from 30 to 24 v and the current increasing from 45 to 70 amp, when the flow rate (of argon) was increased from 0 to 3 g/min Changes of the same direction and magnitude were also observed in helium for the same molar flow rate, indicating that the decrease in arc resistance was not due primarily to the properties of argon

This experiment was carried to higher flow rates in the case of argon Maintaining the arc current constant, the arc voltage was measured as a function of flow rate from 0 to 300 g/min The resultant curve is plotted in Fig 8 It will be noted that, at about 50 g/min flow rate, a minimum in the arc resistance is reached, beyond which it begins to increase with increasing flow rates This portion of the curve is similar to the characteristic of a carbon arc[12] just before vaporization sets in, except that in the carbon arc the decreasing portion is accompanied by a growth in anode spot diameter, whereas in the present case the anode spot diameter remained essentially constant

The most striking change is the sharp rise in the characteristic which occurred at a flow rate of ~100 g/min (Note also that the slope of the anode temperature curve in Fig 7 also bends more sharply at the same flow rate) The steepness and magnitude of the change suggest that some transition in arc mechanism may have been induced at this point Above the "transition" point the resistance continues to increase but with a considerably decreased slope The flow rate required to effect the transition appears to be a function of the arc current, but this relationship remains to be determined quantitatively It should be pointed out that the sudden rise in arc voltage, at the same arc current, represents a considerable increase in power input for a minor increase in flow rate Since the anode temperature continues to decrease at this point, it is reasonable to conclude that this increase in arc power is transferred largely to the gas

The terminal characteristics above the transition point were investigated for arc currents between 75 and 200 amp and flow rates between 100 and 500 g/min The results are presented in the family of curves of Fig 9 Two effects of increasing the gas flow rate in this region are noteworthy The first is that, at a given arc current, the total arc voltage increases with increasing flow rate The second is that the slope of the terminal characteristic decreases with increasing flow rate This behavior is consistent with the hypothesis that gas flow through the anode spot causes a rise in anode fall voltage and a concomitant increase in the rate of ion generation in the sheath region This rise in total arc voltage indicates that the postulated increase in anode fall voltage is the dominating factor An increase in the rate of ion generation with greater gas flow rates and the convection of excess ions into the column would explain the progressive decrease in the incremental resistance of the arc Since the plasma temperature decreases with increasing flow rate, the postulated rise in column plasma conductivity cannot be due to thermal ionization This leads to the interesting possibility of a dense plasma medium having an ion fraction in excess of the equilibrium value predicted by the Saha equation, in contrast to the situation in a stationary arc

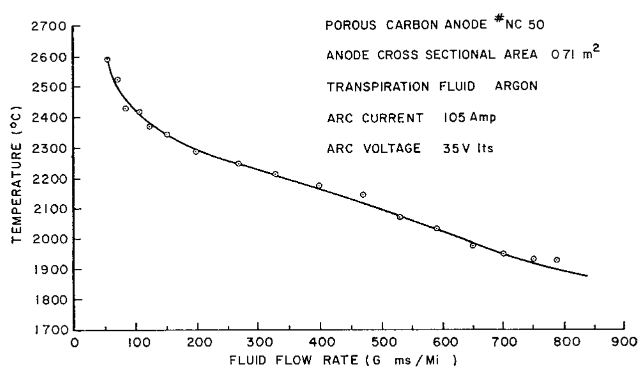

Fig 7 Anode surface temperature vs fluid flow rate

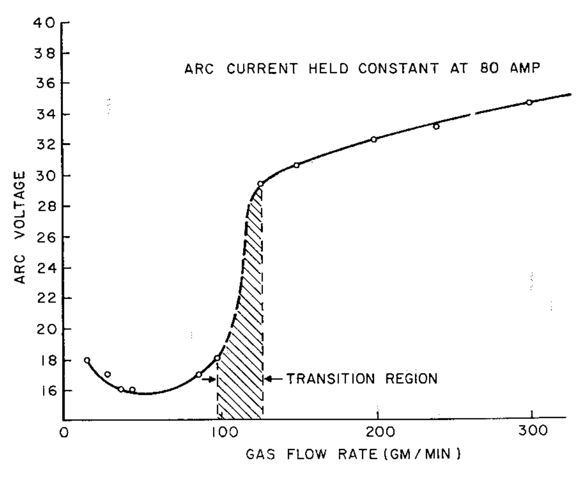

Fig 8 Arc voltage vs flow rate at constant arc current

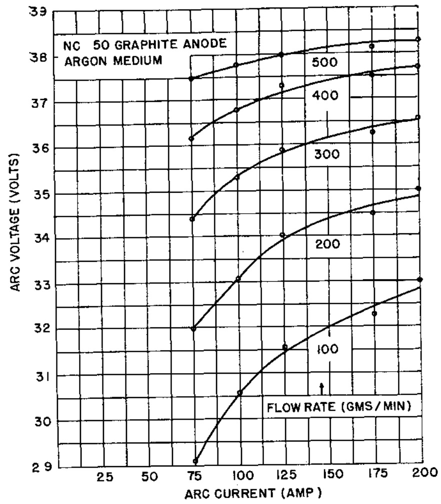

Fig 9 Terminal characteristics for various flow rates

C Transient Probe Experiments

The experiments on the measurement of potential distribution in the vicinity of the anode were carried out to investigate the influence of gas flow on the anode fall voltage In particular, a pronounced change in the drop across the anode sheath induced by increasing the flow rate to a specific value, would support the evidence of Fig 8 to the effect that the gas flow causes a transition in the anode mechanism These experiments were carried out by means of a transient voltage probe that is projected along the axis of the plasma jet until it touches the anode and is then withdrawn The probe consists of a tungsten wire, insulated by a ceramic sleeve except for its very tip, which contacts the hot plasma during the short (~0 1-sec) immersion time of the probe in the arc The probe, which is connected to the anode through a high (1-meg) resistance, draws a minute current from the plasma, approximately proportional to the local plasma potential (referred to the anode) The voltage pulse appearing across the series resistance is fed to an oscilloscope through a coupling circut having a time constant small compared to the residence time of the probe in the flame Thus, by synchronizing the oscilloscope sweep with the probe traverse, an oscillographic record of the plasma potential distribution along the path of the probe tip may be obtained High-speed motion pictures (8000 frames/sec) of the probe traverse showed that the forward motion was quite uniform A

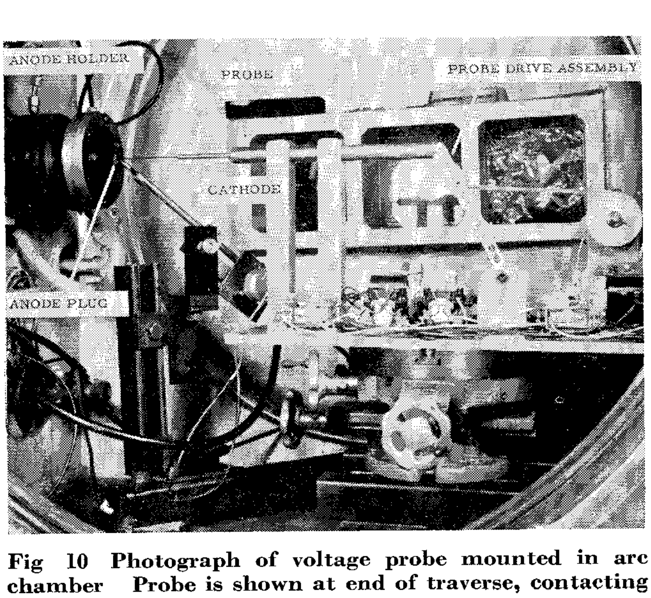

Fig 10 Photograph of voltage probe mounted in arc chamber Probe is shown at end of traverse, contacting porous anode

photograph of the apparatus†† with the probe in the extreme forward position is shown in Fig 10

This transient probe technique was developed by Finkelnburg and Segal,[13] [14] who used it to map the potential distribution of the high-intensity carbon arc They pointed out that the errors introduced into the voltage readings should remain relatively constant if the probe temperature does not change appreciably during the immersion period In this case, a reasonably valid record of the field distribution may be obtained

Oscillograms were taken with this apparatus as the gas flow rate through the anode was varied The traces for a typical run are presented in Fig 11 From a quantitative viewpoint, the traces obtained in successive runs exhibited only a fair degree of reproducibility This may be due in part to voltage surges and also to the fact that successive runs were not all taken with the same anode specimen ‡‡ In any case, the general shape and structure of the traces (for more than 30 runs) were essentially the same as depicted in Fig 11 Therefore, some qualitative observations as to the effect of fluid transpiration on the potential distribution may be made here

A comparison of the no-flow trace with the three flow traces in Fig 11 indicates that the flow of gas through the anode spot is responsible for pronounced changes in the shape of the voltage distribution curve The increased width of the deflected trace under flow conditions obviously signifies the growth of the plasmajet It may also be observed that the no-flow trace and the portions of the flow traces most distant from the anode exhibit large voltage fluctuations In the flow traces, the fluctuations occur in the boundary regions of the flame, where turbulent mixing with the surrounding atmosphere is to be expected Since the probe records the time history of plasma potential at a "point," the large fluctuations are most probably caused by plasma turbulence §§ On this basis, the much smoother traces extending from the anode to the jet boundary for the flow cases indicate a marked smoothing effect on the plasma flow field when the gas is transpired through the anode

The most noticeable effect of gas flow is a decrease in the magnitude of the precipitous voltage drop adjacent to the anode If we assume this to be the anode sheath voltage, then we are forced to conclude that this component of the anode fall voltage is decreased by gas flow through the anode, in contradiction to expectations However, it also will be noticed that the over-all deflection from the horizontal portion of the trace to the base line (anode potential) is increased by gas flow in practically every case If we further assume that the (approximately) horizontal portion of the trace represents the potential of the low-gradient conduction column, then we may view the rising portion of the trace extending 1 cm or so from the anode as an enormously elongated transition region and, therefore, part of a more complex and extensive "anode fall" region It is interesting to note that an early probe measurement of the voltage distribution in the high-intensity carbon arc reported by Bassett[11] has a shape remarkably similar to the flow oscillograms in Fig 11

It is pertinent to mention at this point that the over-all effects of gas flow on the voltage distribution appear to favor transpiration through the anode as an arc-heater technique For example, the decrease in voltage across the sheath portion of the anode fall space caused by gas flow obviously reduces the energy transferred directly to the anode,

†† The authors are indebted to Frank Sileo of Vitro Laboratories for the design of the transient probe mechanism and for his valuable assistance in obtaining the oscillogram traces

‡‡ Differences in local porosity from one specimen to another, which could conceivably influence the voltage curves, were revealed by porosimetry measurements

§§ The type of transient voltage probe described would therefore appear to be an effective method of investigating turbulence in plasma media

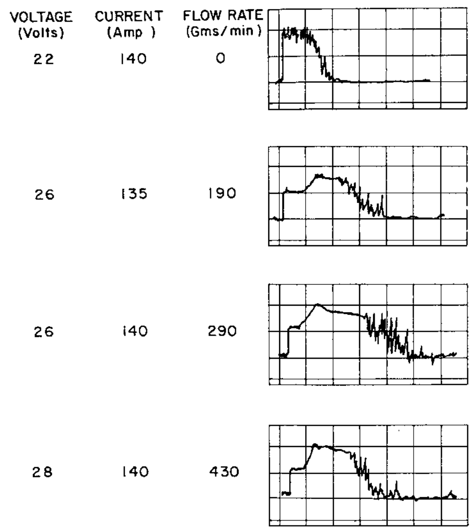

Fig 11 Tracings of oscillograms depicting axial voltage distribution of effluent plasmajet (Tracings should be read from right to left Horizontal scale: 1 div = 1 1 cm of probe traverse; vertical scale: 1 div = 10 v)

whereas the relatively high gradient of the extended transition region signifies appreciable energy dissipation in the flowing gas stream These features, together with the transpiration cooling of the anode itself, offer the possibility of efficient heating of the gas stream with relatively small thermal loading of the anode

IV Discussion

The data gathered thus far are too limited and the phenomena too complex to justify attempts at theoretical interpretation at this time However, from the results of the experiments performed, particularly those involving the transient voltage probe, it is clear that transpiration of fluid through a porous anode may, under suitable conditions, markedly influence the fundamental nature of the gas discharge itself Beyond the introduction of a new technique for heating fluids in the electric arc, the findings presented in this paper suggest that this system may be useful for probing the important discharge mechanisms For example, a variety of arc phenomena associated with the anode fall space, such as column contraction, microspot formation, hissing, etc , have been satisfactorily explained by the theory of Bez and Höcker [15–18] According to this theory, two types of anode sheath are possible, distinguished by the mechanism of generating the ion drift current and designated as the "field ionization" and "thermal ionization" types, respectively Changes in arc behavior have been rationalized by transitions from one type of sheath mechanism to the other, occasioned by high current density, anode vaporization, etc The flow of an external fluid through the anode sheath provides an independent means of controlling such transitions Indeed, the curve of Fig 8 may well represent an example of a transition from the thermal ionization to the field ionization type of anode sheath

The use of this technique to test existing theories of arc mechanisms implies a definitive knowledge of the parameters governing the interaction phenomena between the transpired gas and the arc discharge A comprehensive program to adduce such data is under way at the present time

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