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EXPERIMENTAL INVESTIGATION OF A MAGNETICALLY BALANCED ARC IN A TRANSVERSE ARGON FLOW

by

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Experimental Investigation of a Magnetically Balanced Arc in a Transverse Argon Flow[1]

An experimental study of an electric arc in crossed convective and magnetic fields has been made. An electric arc was established across a rectangular test section through which argon gas was flowing at approximately atmospheric pressure and velocities up to 100 m/sec. Magnetic field strengths up to 3 webers/m², oriented so that the Lorentz force opposed the convective force on the arc, were applied perpendicular to both the arc and the direction of the argon gas flow. The test apparatus and the procedure used to obtain the experimental relationship between the velocity of the argon flow and the balancing magnetic field are described. An analysis which assumed the magnetically balanced arc to be a gaseous cylinder positioned between the electrodes and with a diameter varying directly as the arc current satisfactorily explained the observed dependence of the balancing magnetic field on the gas velocity.

Introduction

The interaction of a plasma conductor such as an electric arc and a gas flow in the presence of a magnetic field is currently of considerable technological interest. The arc-type discharge in crossed convective and magnetic fields is common to a number of magnetofluidmechanic devices, e. g., $\mathbf{J} \times \mathbf{B}$ accelerators and magnetically rotated arc heaters. There are many different configurations which may be used to study this three-fold interaction, but basically they reduce to two types; those in which the arc is moved along electrodes through a stationary gas by either an externally applied magnetic field or the magnetic field due to the arc current, and those in which the arc is held stationary with respect to the electrodes in a magnetic field and the gas is caused to flow past the arc. The latter configuration was used in the present experiment.

The motion of the arc along parallel or concentric electrodes (traveling arc) has been studied by many investigators. Some of the more recent studies were made by Angelopoulos [1],[2] Féchant [2], Hesse [3], and Febri [4]. However, several investigators, particularly Winsor and Lee [5] and Guile and Secker [6, 7, 8], pointed out that in certain regimes the motion of the traveling arc was completely controlled by processes within the cathode and anode regions of the arc. Thus this root movement appeared to obscure the fundamental interaction of the arc column plasma with the gas flow and the magnetic field.

Two studies have been reported where a magnetic field has been used to balance the convective force on a stationary electric arc. In these studies, there was no motion of the arc with respect to the electrodes, eliminating the effect of the cathode and anode root motion. Thiene [9] balanced the convective force of velocities up to 2 m/sec on a one-atmosphere argon arc with magnetic fields up to 1.4 gauss. In the analysis, the viscous force, radiation, and the induced field were neglected. A stagnation point was assumed inside the arc column resulting from the balance of forces. It was further assumed that outside the arc column the pressure gradient was balanced principally by the inertial reaction and inside the arc column by some fraction of the Lorentz $\mathbf{J} \times \mathbf{B}$ force. By using these assumptions in the one-dimensional momentum equation and integrating along a streamline going through the stagnation point and the arc center, it was found that

$$B_b = \frac{N\pi D\rho_s V^2}{4I} \qquad (1)$$

where B_b is in gauss, V in cm/sec, D in millimeters, and ρ_s in g/cm³. The constant N was experimentally determined by measuring the other quantities in equation (1) and found to have a value of 4. Experiment verified that B_b was very nearly proportional to V^2 for the range of velocities studied. Thiene's analysis satisfactorily explained the relation between the gas velocity and magnetic field observed in the present experiments.

The electric arc has been balanced in a supersonic airflow of Mach 2.5 by Bond [10, 11, 12] with magnetic fields up to 0.4 weber/m². The arc was drawn between two rods immersed in a supersonic wind tunnel with their long axes parallel to the flow direction. The total pressure was 20 in. Hg, and the arc current was varied from 150 to 700 amps. Bond found that the magnetic field required to balance the arc was independent of the arc current over the range studied.

The present experiments were designed to investigate the balanced electric arc at a range of velocities intermediate to those studied by Thiene and Bond. Argon was used as the test gas. Static test-section pressures were held at about 19 psia, convective velocities up to about 100 m/sec were used, and magnetic fields up to 3 webers/m² were required to balance the arc. The present paper will describe the apparatus and the procedure used to obtain the test data. The experimentally observed dependence of the balancing magnetic field on the gas velocity is presented and compared with equation (1).

Apparatus

A sketch of the test section showing the orientation of the various components is shown in Fig. 1. Argon gas was passed

Nomenclature

$\mathbf{B}$ = magnetic field strength vector
B_b = balancing magnetic field strength
C_d = drag coefficient
D = arc diameter
I = arc current
$\mathbf{J}$ = current density vector
N = experimental constant of Thiene
V = gas velocity
ρ = free stream gas density
ρ_s = stagnation gas density

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[1] This work is a portion of a dissertation submitted to the Graduate Faculty of the University of Missouri in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

[2] Numbers in brackets designate References at end of paper.

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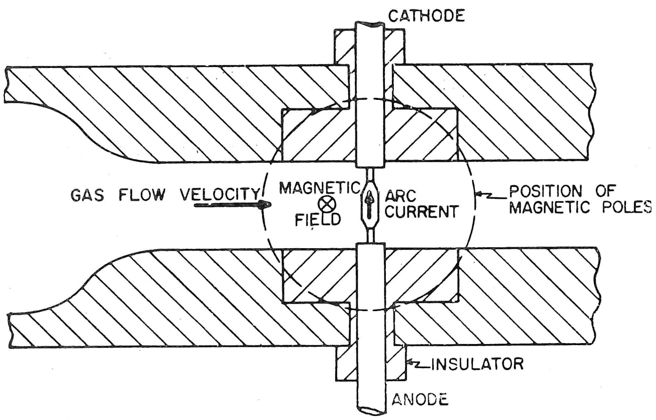

Fig. 1 Sketch of test section showing orientation of arc current, magnetic field, and argon gas velocity

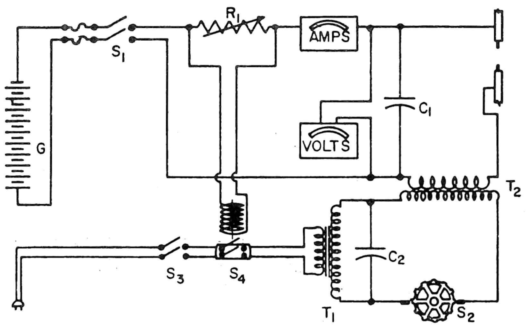

Fig. 2 Arc electrical system

through control valves and a Bailey flow meter to a 0.735-in-wide by 1.250-in-high test section. The test section was located between the pole faces of a Pacific Electric Motor Company model 12A-LI 75 kw electromagnet. The magnet poles tapered from a diameter of 15 in. to a diameter of 3 in. next to the test section. The gap between the pole faces was 1.335 in. A $^1/_2$-in. hole was drilled along the axis of both of the poles through the magnet. Tempered pyrex windows were located in the sides of the test section, which was oriented with respect to the holes in the magnet so as to allow visual observation of the arc. After passing through the test section, the argon was stored and compressed for future reuse.

Electrodes were located in the top and bottom of the test section and were so connected that the top electrode was the cathode. The cathode and the anode were made of $^3/_{32}$-in. thoriated (2 percent) tungsten rods mounted on water-cooled copper supports. The thoriated tungsten rods extended $^5/_{16}$ in. from the ends of the supports. (This distance varied slightly in different runs.) The spacing between the tungsten electrodes was set at $^5/_{32}$, $^5/_{16}$, $^5/_8$, and $^7/_8$ in. in four different series of tests.

The arc electrical system is shown schematically in Fig. 2. The primary power supply was the 250-v battery bank G. The arc was initiated by the high-frequency Tesla spark generator consisting of the rotating spark-gap switch S_2, the 0.00012 microfarad oil-bath capacitor C_2, and the transformers T_1 and T_2. Capacitor C_1 shielded the meters from the high-frequency Tesla discharge, and variable resistor R_1 allowed the arc current to be set at the desired value. When the arc current produced a voltage drop across R_1 of 65 v, the relay S_4 was energized, shutting off the power to the Tesla generator and effectively removing it from the circuit.

Procedure

The procedure during a typical test run will now be described. The magnetic field was first fixed by setting the field resistor in the d-c generator supplying the magnet. The current to the magnet was measured and later could be related to a magnetic field strength value in separate calibration runs. Then the Tesla generator and the arc power supply were connected across the electrodes. Finally, the argon gas flow was started and slowly increased, using a Bailey diaphragm-operated regulating valve, until a stable electric arc was achieved. Readings were taken of the argon flow rate, the argon stagnation temperature in front of the arc, arc current, the arc voltage, and the argon static pressure at the test section wall $1^1/_2$ in. in front of the electrodes and $3^3/_4$ in. behind the electrodes. The gas stagnation temperature at the center of the gas stream was measured with a shielded thermocouple probe $3^3/_4$ in. behind the electrodes in some of the runs.

It was quite easy to determine when the arc was stable. When the gas flow rate was too low to balance the arc, the d-c arc would initiate, the relay would cut out the Tesla generator, the arc would very quickly go out, and the relay would again cut in the Tesla generator. Neither the arc current meter nor the arc voltage meter would give a stable reading. If the argon flow rate was too high, the foregoing phenomena were again observed. By visually observing the direction the arc moved before being blown out, it could be determined whether the flow rate was too high or too low. When the arc was stable, both the arc current and arc voltage were quite stable as was the static pressure in front of and behind the arc. The arc was usually allowed to burn for about two or three seconds in most of the runs while the readings were taken. This time was kept fairly short in order to prevent melting the electrodes. In some of the runs, the arc was allowed to remain for as long as eight seconds with substantial electrode melting. It was easier to obtain a stable arc with shorter electrode separations than with longer ones. In fact, for the $^5/_{32}$-in. electrode spacing, there seemed to be a fairly wide range of flow rates where the arc was stable rather than a single point of stability.

The arc current was varied from 22 to 108 amps in various test runs. The static pressure in front of the arc was held approximately constant during each of the four series of tests with various regulating valves in the argon flow system.

Results

The velocity of the argon gas in the test section was calculated using the continuity equation and values of the gas flow rate and the gas temperature and pressure in the test section. No correction was made for the pressure of the self-magnetic field of the arc because the arc current was sufficiently low that the pressure was less than $^1/_3$ psi even at the highest currents. It was not possible to hold the arc current exactly to the same value in a series of tests; therefore, the data were divided according to the range of value of the arc current. A plot of B_b against V^2 is shown for each of the series of tests. These plots are shown in Figs. 3, 4, 5, and 6 for electrode spacings of $^5/_{32}$, $^5/_{16}$, $^5/_8$, and $^7/_8$ in., respectively. The horizontal and vertical lines on three representative data points in each of the plots give an indication of the maximum uncertainty in the different regions of the graphs. Equation (1) was found to fit the data points to within the experimental uncertainty when the appropriate value of the arc diameter was used.

The total power input to the gas stream was calculated using the measured stagnation temperatures in front of and behind the arc region. This value was found to be nearly equal to the voltage-current product for the arc, indicating little radiation loss or heat loss to the electrode cooling water. In fact, at the higher field strengths and gas flow velocities, the calculated power input to the gas was slightly greater than the voltage-current product. This effect was felt to be due to incomplete mixing of the gas over the short distance between the arc electrodes and the stagnation thermocouple probe.

Discussion

One striking difference between Figs. 3 through 6 and equation (1) is that the data exhibited no dependence on the current. The

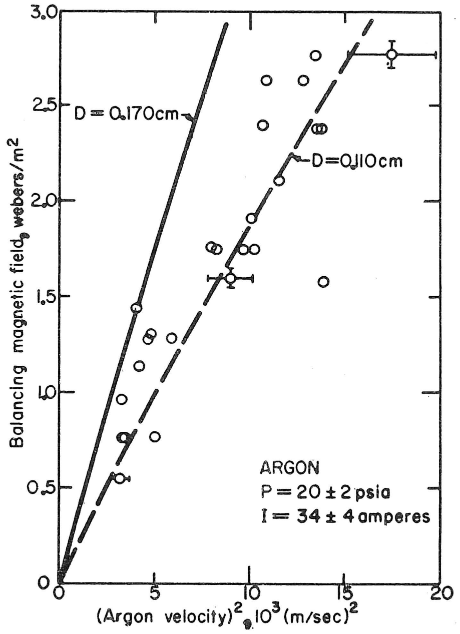

Fig. 3 Dependence of the balancing magnetic field on the square of the argon velocity for a $^5/_{32}$-in. electrode spacing

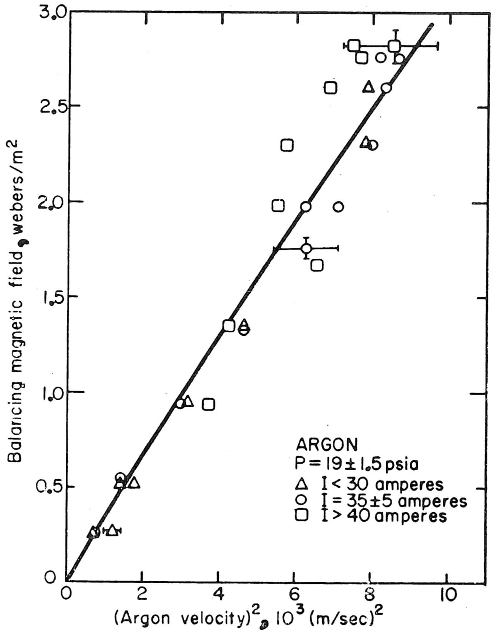

Fig. 4 Dependence of the balancing magnetic field on the square of the argon velocity for a $^5/_{16}$-in. electrode spacing

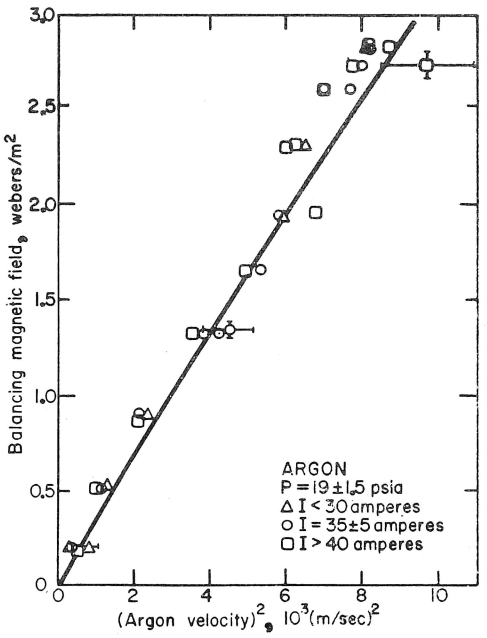

Fig. 5 Dependence of the balancing magnetic field on the square of the argon velocity for a $^5/_8$-in. electrode spacing

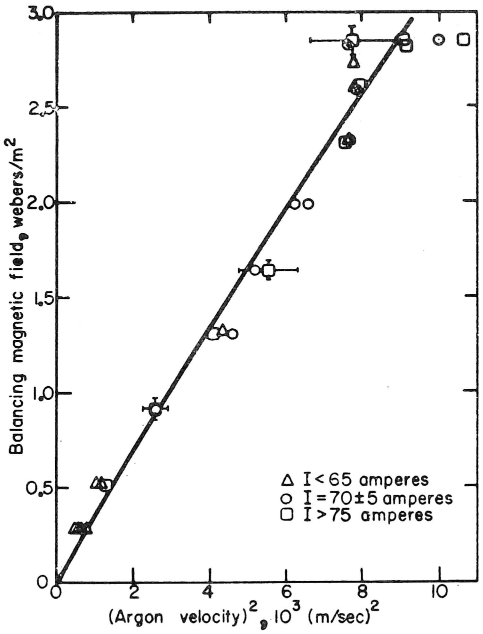

Fig. 6 Dependence of the balancing magnetic field on the square of the argon velocity for a $^7/_8$-in. electrode spacing

magnetic field required to balance a given convective velocity was independent of the arc current. This was also observed by Bond [12] and can be explained by assuming that the arc profile area (or arc diameter) varied in direct proportion to the arc current. This dependence of the arc diameter on the arc current for arc currents from 20 to 100 amps is the same as that reported by Hesse [3].

Using Thiene's value of 4 for N, the arc diameter was calculated to be 0.350 cm for an arc current of 70 amps and 0.175 cm for an arc current of 35 amps. These values were quite similar to those found by other investigators [1, 3, 9, 13], who reported arc diameters in the range of 0.15 to 0.85 cm, increasing with increasing current. It was not possible to directly measure the arc diameter in the present experiment. The solid curves in Figs. 3 through 6 are calculated from equation (1) using the foregoing dependence of the arc diameter on the arc current. There was some scatter in the data but it usually fell quite near these curves for the three longer electrode spacings. This was not true, however, for the smallest electrode spacing, $^5/_{32}$ in. For this small spacing, the arc column was practically nonexistent, the gap between the electrodes being composed primarily of the electrode regions of the arc discharge. The effect of the electric field on stabilizing the arc was much greater at this short spacing, and the arc could thus be balanced over a fairly wide range of gas velocities. A much better fit for these data (the dashed line) in Fig. 3 could be obtained if it were assumed that the $^5/_{32}$-in. arc had a smaller diameter than the other arc lengths at the same arc current. This diameter was calculated to be about 45 percent less than the diameter of the longer arcs at the same current. It is well known that the electrode effects tend to constrict an arc, thus making this a reasonable assumption.

The range of velocities for which it was possible to obtain a stable arc was much narrower at the larger electrode spacings, because as the arc got longer the interaction in the arc column region became relatively more important in comparison to the electrode components of the arc. However, there was still some indication that there may be a small range of velocities over which a stable arc can be achieved. This indicated that an arc slightly curved in either the upstream or the downstream direction may be stabilized due to the electric field effect. In comparison to the fineness of control on the argon flow equipment used, however, the range of velocities over which a stable arc could be obtained was very small.

Balancing Mechanism

On a microscopic scale, the phenomena taking place in a magnetically stabilized electric arc can be described in a general way as follows. The electrons in the arc plasma have a much higher mobility than the positive ions and therefore are the principal receptors of energy from the arc electric field. Because of their low mass, they are also acted upon much more strongly by the applied magnetic field. The electrons transfer the energy that they obtain from the electric field to the ions, primarily by elastic collisions. Because the collision process is relatively inefficient in a monatomic gas, the electrons will be maintained at a Maxwellian temperature above that of the gas atoms and ions. In addition to the energy transfer from the electrons, the positive ions also exchange energy by collisions with the gas atoms. The gas atoms tend to sweep the positive ions downstream from the arc region. At this point, another strong force, the Coulomb force between the positive ions and the electrons, enters the picture. As the ions start to be swept downstream, a slight space charge develops between them and the electrons. Because of the greater mobility of the electrons, an electric field in the direction of the gas stream velocity is also produced by the Hall effect, adding to the electric field created by the convection force on the positive ions. The electrons are held in their cyclotron orbits by the magnetic field and, due to their drift from the cathode to the anode, their $\mathbf{J} \times \mathbf{B}$ interaction with the magnetic field causes a net force to be exerted on them in the upstream direction. When the arc is balanced, the Coulomb force on the electrons due to the convection force exerted on the positive ions by the gas atoms is exactly balanced by the force on the electrons as a result of their $\mathbf{J} \times \mathbf{B}$ interaction with the magnetic field.

On a macroscopic scale, note that equation (1) gives the same relationship between the variables as would be obtained by equating the aerodynamic force on a conducting cylinder with the magnetic retarding force. This balance of force gives

$$IB_b = \frac{1}{2} C_d D \rho V^2, \tag{2}$$

where C_d is the coefficient of drag. For the experimental conditions, the difference between the free-stream density ρ and the stagnation density ρ_s was quite small. By comparing equations (1) and (2), C_d must be equal to $N\pi/2$. Calculating C_d from Thiene's value for N gave a value of 6.28. This is considerably higher than the value of the drag coefficient, which is of the order of 1.2, for a solid cylinder with a laminar boundary layer. (The free-stream Reynolds number based on the arc diameter was between 8,000 and 38,000 in the present experiments, indicating a laminar boundary layer.) This indicated that the arc interaction with the flow was more pronounced than the flow interaction with a solid cylinder of similar size.

Conclusions

It is possible to balance the convective force of a transverse gas flow on an electric arc with an applied magnetic field. For gas velocities up to 100 m/sec, magnetic fields up to 2.92 webers/m^2 are required in a channel with a static pressure of 19 psia. The convective force on the arc was quite similar to the aerodynamic force of a subsonic gas flow on a solid cylinder. An analysis based on the assumption that the electric arc can be replaced by a cylinder with a diameter varying directly as the arc current satisfactorily explained the relation between the gas flow velocity and the balancing magnetic field.

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