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ON HEAT TRANSFER EFFECT ON ELECTRIC ARC MOTION IN A TRANSVERSE MAGNETIC FIELD

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К ВОПРОСУ О ВЛИЯНИИ ПРОЦЕССОВ ТЕПЛООБМЕНА НА ДВИЖЕНИЕ ЭЛЕКТРИЧЕСКОЙ ДУГИ В ПОПЕРЕЧНОМ МАГНИТНОМ ПОЛЕ

Аннотация—Проводится обобщение экспериментальных данных по скорости движения дуги в поперечном магнитном поле методами теории подобия. Рассматривается возможность учета процессов теплообмена внутри дурового столба и на его поверхности для снижения разброса экспериментальных точек.

NOMENCLATURE

V, arc velocity [m/s];
I, current [A];
B, magnetic induction [Wb/m^2];
$\rho_0 \lambda_0 \sigma_0 C_{p_0} T_0$, values of density, thermal conductivity, electric conductivity, heat capacity and temperature, respectively;
p, pressure [bar];
L, typical dimension (distance between electrodes) [m];
μ_0, magnetic permeability.

THE BEHAVIOUR of an electric arc in a transverse magnetic field is attracting the attention of many investigators. This interest is brought about by the possibility of plasmoid acceleration up to considerable velocities and the heating up of gases to high temperatures. Nowadays a great deal of experimental data on electric arc velocity in a transverse magnetic field is available. There are some attempts to correlate these data by the methods of similarity theory [1–3] with due allowance for inertia and electromagnetic forces. However, the scatter of experimental points in a generalized coordinate system appears to be rather large. This may be partly explained by difference in experimental conditions namely, non-uniformity of electrode material and shape, geometric non-similarity of the electric arc installation, a change of medium composition, etc. But even for correlation of experimental data obtained under the same conditions the scatter of points is still rather considerable.

The nature of the scatter indicates that in addition to casual processes which give rise to a random point scatter, there are some processes that exert an influence on arc velocity, an allowance for which could give a better correlation of experimental data.

An analogous situation exists in theoretical consideration of the motion of an electric arc in a transverse magnetic field. In a theoretical model the electromotive force is usually assumed to be balanced by that of aerodynamic drag. The most difficult point in such a model is the determination of the drag coefficient C_f which depends on many factors practically not amenable to a theoretical analysis. Experimental estimates of C_f differ by more than on order of magnitude [4]. This is an additional indication that, for an increase of calculation accuracy, some processes not taken into account should be allowed for.

Since the cross-section of the arc column depends to a considerable extent on the removal to the surrounding gas of the Joule heat generated in the arc, and the resistance to arc motion is determined by the cross-sectional dimensions, it is natural to suppose that this omission of heat transfer processes is partly responsible for the low accuracy of the correlating empirical equations.

In the present paper an attempt is made to allow for the heat transfer processes while correlating experimental data on arc velocity in a transverse magnetic field.

The arc velocity dependence on current is complicated. As current increases, there is first observed a velocity increase, then a sharp fall, again followed by a rise. In paper [5] the supposition is made that the velocity decrease at currents of 80–100 A is caused by a transition of the arc column from the cored into the non-cored state.

Following King's concepts [6] contraction of a free burning arc occurs on transition through the maximum of heat conduction on temperature rise with increasing current. If in a transverse-blown arc heat from the arc column is also transferred by conduction, then the contraction mechanism is to be determined [7] by the number

$$\Pi_T = \lambda_0 T_0 \sigma_0 L^2/I^2$$

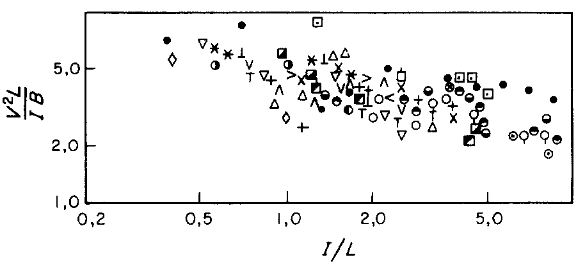

FIG. 1. Relationship $V^2L/IB = f(I/L)$ for an arc moving in a transverse magnetic field between parallel copper electrodes in air

V, m/s; I, A; B, Wb/m^2; L, m.

Symbols denote L and B

0·0127 m: ● −0·0120 Wb/m^2; ⊙ −0·025; ⊖ −0·535; ♀ −0·081; ⊕ −0·108

0·0191 m: □ −0·0125 Wb/m^2; ◩ −0·026; ◩ −0·535; ◪ −0·108

0·254 m: + −0·0125 Wb/m^2; × −0·027; * −0·081; ◇ −0·108

0·0320 m: ○ −0·125 Wb/m^2; T −0·024; ⊥ −0·520; < −0·081; ⌽ −0·108

0·0380 m: △ −0·0120 Wb/m^2; ▽ −0·0245; v −0·0245; > −0·0805; ∧ −0·108.

and the criterial equation will take the form

$$\Pi_V = f(\Pi_T)$$

wherein

$$\Pi_V = \rho V^2 L/IB.$$

To consider this relationship, let us plot $\Pi_V = f[\ln(1/\Pi_T)]$ using the experimental data from [8] (Fig. 1). To avoid the effect of such factors as electrode material and the arc's self magnetic field, only the data of experiments with copper electrodes connected to current supply at both ends were used. The range of values tested was as follows: I = 190–1000 A; B = 0·012–0·108 Wb/m^2; L = 0·0127–0·038 m. Since the ambient medium in the experiments considered was not varied (discharge occurs all the time in air), then instead of dimensionless numbers the dimensional groups may be employed

$$\Pi_V \sim V^2L/IB; \qquad \Pi_T \sim L^2/I^2.$$

As is seen from Fig. 1, there is a distinct relation between Π_V and Π_T. The vast majority of points forms with some scatter a line, the equation of which is

$$\frac{V^2L}{IB} = 140\left(\frac{I}{L}\right)^{-0\cdot373} \qquad (1)$$

The root-mean-square deviation is 23 per cent.

Some points, however, show a rather considerable deviation from the approximating line. No presupposed inflexions of the function $\Pi_V = f(\Pi_T)$ are observed. There are "zigzags" but only for separate aggregates of points and these are not correlated in the considered coordinate system. Therefore, some other processes rather than maximum heat conduction are responsible for the sharp drops and rises of the arc velocity.

For the explanation of the "zigzags" in the arc velocity vs. current relation, it may be assumed that at a certain moment there occurs a change of the relative role of different heat transfer mechanisms simultaneously proceeding in the arc. If energy transfer by radiation is ignored, and this is negligible in the experiments under consideration, then attention should be focussed on three such processes: conductive heat transfer within an arc column characterized by Π_T, convective heat transfer at the arc surface defined by the Péclét number and convective heat transfer due to "blowing-through" of the arc by a gas current in cross-flow. The latter mechanism is characterised by the number

$$\Pi = \rho_0 h_0^2 \sigma_0^2 L^5 B_0 / I^3.$$

Since the experimental data applied refer to arc motion between parallel electrodes in cold air, gas density inside the arc column appears to be almost two orders of magnitude lower than that in the surrounding air. In this case the arc is practically non-porous. The estimates made in [9] show that heat transfer due to blowing-through is of no importance for the arc velocities observed. Therefore, it can be assumed that the conductive heat transfer inside the arc column and convective transfer at its surface need only be taken into account.

The convective heat transfer effect may be tested in the same manner as in the case of conductive one. The Péclét number for the case under consideration (when arc velocity sets in with interaction between electromagnetic and inductive forces) transforms to

$$Pe = \frac{\rho_0 C_{p_0}^2 IBL}{\lambda_0^2} \backsim IBL\rho_0$$

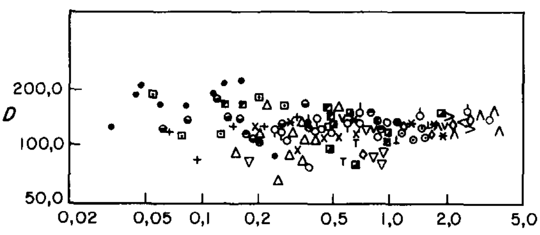

FIG. 2. Effect of the Péclét number on the generalized air arc velocity between parallel copper electrodes in a transverse magnetic field.

$$D = \left(\frac{V^2 L}{IB}\right)\left(\frac{I}{L}\right)^{0.361}; \quad C = IBL.$$

Legends as in Fig. 1.

With ρ_0 = const., $Pe \backsim IBL$, if it is assumed that $\rho_0 \backsim P$, then $Pe \backsim PIBL$.

In Fig. 2 experimental data are represented as

$$\lg \frac{V^2 L}{IB} + 0.361 \lg \frac{I}{L} = f(IBL).$$

The graph shows that at small Pe numbers experimental points are characterized by considerable scatter which, however, decreases with increase in the Péclét number. At $IBL > 1$ the scatter stabilizes but the curve within this interval becomes parallel to the abscissa axis indicating the absence of any dependence on IBL.

The Péclét number "degeneration" observed is similar to that of the Reynolds number at its larger values. Since the Prandtl number appears to change little here, the Reynolds and Péclét numbers turn out to be interchangeable. If physical properties of the gas at the arc column boundary are taken in accordance with the enthalpy value from [10]: ($\lambda_0 = 1.53$ W/mK; $\rho_0 = 1.97 \cdot 10^{-2}$ kg/m^3; $C_{p_0} = 4.53 \cdot 10^3$ J/kgK), then Pe at $IBL = 1$ is $1.7 \cdot 10^5$.

For gases the Prandtl number is close to unity, therefore the Reynolds number will have the same value and thus indicate the presence of fully developed turbulent flow. Hence both the Péclét number degeneration and estimates of the Reynolds number make us suppose that at $IBL > 1$ turbulent flow is established at least at the arc column periphery (i.e. in the zone of processes described by Pe).

Inside the arc column the Joulean heat removal is controlled by the temperature gradient, since radiation and heat transfer due to the arc porosity may be ignored. In such a case, at large Pe, the heat transfer processes, which determine the dimensions of the arc cross-section and consequently the arc velocity, must depend mainly on Π_T. As Pe decreases, its effect must grow and the role of Π_T will relatively decrease.

For checking of the suppositions made, the experimental data were divided into two groups by the value $IBL = 10^{-1}$ J/m. By power approximation the following equations were obtained:

$$\frac{V^2L}{IB} = 42{\cdot}4\left(\frac{I}{L}\right)^{-0{\cdot}269} (IBL^{-0{\cdot}195} \quad (\text{at } IBL < 10^{-1}) \qquad (2)$$

$$\frac{V^2L}{IB} = 280\left(\frac{I}{L}\right)^{-0{\cdot}442} (IBL)^{0{\cdot}03} \quad (\text{at } IBL > 10^{-1}). \qquad (3)$$

For the whole range the equation becomes

$$\frac{V^2L}{IB} = 121\left(\frac{I}{L}\right)^{-0{\cdot}361} (IBL)^{0{\cdot}043}. \qquad (4)$$

The root-mean-square scatter of experimental points with respect to values described by equations (2)–(4) is 24 per cent, 14 per cent and 24 per cent, respectively.

These data prove the suppositions made above. But they cannot answer the question whether turbulence spreads into the arc column or not, since Π_T takes into account all the heat transfer processes dependent on the temperature gradient, including turbulent heat conduction as well.

Thus, depending on the arcing regime, a change in the relative role of heat transfer processes does take place. But "zigzags" in Fig. 1, evidenced by separate aggregates of experimental points are not eliminated in the generalized correlation considered above. They appear to depend on some other processes as, for example, the processes at the electrode.

At small Péclét numbers the scatter of experimental point increases and large scatters of the drag coefficient are likely to occur in this region. Therefore it is reasonable to reconsider any experimental data referring to small Péclét numbers. There are such data in [11] where an arc was investigated in air when moving between annular brass electrodes at gaps $L = 2$ mm, pressures ranged from 0·0018 to 14·6 atm and currents from 4 to 360 A. The value of $IBLP$ changed from $1{\cdot}5 \cdot 10^{-6}$ to 1. In this case there occurs not only sharp retardation of the arc but at low pressures even a reversal of its direction of motion.

It follows from the foregoing that in this range of the Péclét numbers the main role is played by the convective heat transfer, hence $\pi_V = f(\text{Pe})$ will be considered. In a dimensional form it appears more convenient to take the number inverse to Π_V, since it is proportional to the drag coefficient.

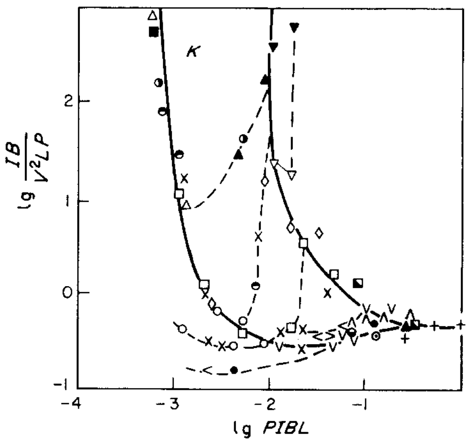

FIG. 3. Drag of arc moving between annular brass electrodes in air $L = 2$ mm.

Symbols denote B and P.

$B = 0{\cdot}106$ Wb/m²; + 14·6 atm; ○ 7·8; ∧ 3·72; ∨ 2·36; □ 1·0; ◇ 0·53; ▽ 0·26.
$B = 0{\cdot}054$ Wb/m²; ● 7·8 atm; > 4·68; < 3·72; ⊻ 2·36; ⊼ 0·79; △ 0·53; □ 0·26.
$B = 0{\cdot}034$ Wb/m²; ⊖ 6·44 atm; ◑ 4·40; ⊣ 2·36; ⊖ 0·79; ◑ 0·53; ⋉ 0·26.

Figure 3 presents the graph

$$\lg IB/V^2LP = f \lg (PIBL)$$

from which it is seen that at $PIBL = 10^{-3}$–10^{-2} the drag coefficient is subject to considerable scatter. The graph is restricted at the upper limit by $IB/V^2PL = 10^3$. Within this range infinite values of the drag coefficient are also noticed and these correspond to zero arc velocity. It may be seen, however, that the main part of the experimental points fall into two descending curves (solid lines) with separate points in between them forming several ascending branches (dotted lines).

If we follow any group of points (for example, upwards pointing triangles or open squares), it will be seen that the drag coefficient (with increase in *IBLP*) at first sharply falls along the left-hand solid curve, then in some part of it an ascending branch separates and runs up to the right-hand solid curve where a sharp fall follows again. Some cases of sharp arc retardation are also observed near the right-hand solid curve but these do not develop. With increase in *IBLP*, two solid curves run together passing along the abscissa axis which is the lower boundary of the drag coefficient. For this boundary curve the following approximating equation may be written

$$\frac{IB}{V^2LP} = 0{\cdot}535\,(PILB)^{0\cdot187}. \tag{5}$$

By analogy with low temperature processes it may be assumed that the descending branches correspond to laminar gas flow around the arc, followed by the transition zone and then by the fully developed turbulent region. A considerable difference, however, lies in the fact that there are two ascending branches instead of one. Besides, the lower left-hand points show a tendency to the formation of some additional ascending branches on the left-hand side.

It is still difficult to explain the presence of two descending branches. Perhaps it is attributive to the influence of electrode processes, for example, such as jets from arc spots. But nevertheless these two descending branches somehow throw light on changes in arc motion observed with current growth. In [12] it is stated that at small currents an arc, while moving, draws a continuous trace. Then, within some current range, the arc spot begins to jump along electrodes leaving a broken trace. With a further increase, however, the trace from the spot is again continuous. The solid descending curves apparently reflect two possible regimes of the laminar arc motion. Within the interval between them the arc motion is highly unsteady: velocity drops and even arc stoppage are observed. This is just the region which the arc overcomes by jumping. If we assume the values of physical properties used above, it appears that the unsteady motion lies with $Pe = 100$–3000.

The considerations given here show that the use of similarity methods makes it possible to clear up the relative role of some processes in an electric arc and even to obtain fairly accurate empirical equations in spite of scatter of the experimental data. Of course, the results obtained must be treated with some caution because of drawbacks of the method and difficulty of its application to an electric arc, in which strict similarity cannot exist. Nevertheless, the results present material for consideration and should lead to further investigations.

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Abstract—A correlation is presented of experimental data on arc velocity in a transverse magnetic field using the similarity methods. The possibility is considered of allowance for heat transfer processes within an arc column and at its surface with the purpose of decreasing experimental scatter.

EFFET DU TRANSFERT THERMIQUE SUR LE MOUVEMENT DE L'ARC ÉLECTRIQUE DANS UN CHAMP MAGNÉTIQUE TRANSVERSAL

Résumé—On présente des résultats expérimentaux sur la vitesse d'un arc dans un champ magnétique transversal coordonnés par des méthodes de similitude. On considère la possibilité d'existence de processus de transfert thermique dans une colonne d'arc et sur sa surface avec l'idée de diminuer la dispersion expérimentale.

DER EINFLUSS DES WÄRMEÜBERGANGS AUF DIE BEWEGUNG DES LICHTBOGENS IM MAGNETISCHEN QUERFELD

Zusammenfassung—Es wird die Korrelation von Versuchsergebnissen über die Bogengeschwindigkeit in einem magnetischen Querfeld nach der Ähnlichkeitsmethode gegeben. Um die experimentelle Streuung zu verringern, wurde die Möglichkeit erwogen, den Wärmeübergang in einem Bogen und an seiner Oberfläche zu berücksichtigen.