VELOCITY OF AN ELECTRIC ARC IN AN ANNULAR GAP

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We investigate the influence of the current, magnetic-field induction, air flow, and interelectrode gap on the arc velocity in an annular gap between concentric electrodes. Generalized equations in critical (dimensionless) form are presented for the experimental data.

Electric arcs moving in a magnetic field have attracted the interest of scientists and engineers for many years. The motion of arcs over electrodes have been the subject of many papers (cf. [1]). There are generalized expressions for the motion velocity, which pertain mainly to an arc moving over parallel electrodes [2-6]. There are fewer data on the velocity of an arc moving in a gap between concentric electrodes. In this case, however, the arc column is under more complicated conditions, especially when it is located in a stream of cold gas.

In many devices, an arc placed in a transverse stream is used to heat gas to high temperature. The gas flow can be varied in a wide range, thereby significantly altering the conditions under which the arc burns. At small gas flows, the arc column moves in practice in a heated medium, whereas in the case of good ventilation of the gap the motion is in a cold gas. In installations with concentric electrodes, the circumferences of the anode and of the cathode are not equal, so that when the arc moves the velocities of the cathode and anode regions are not uniform, and this leads to a lengthening and periodic shunting of the arc column.

The lengthening of the column is due to the additional energy loss, and affects the characteristics of the arc. On the other hand, the shunting has a random character, and this causes random oscillations of the current, of the voltage, and of the arc velocity. A considerable scatter of the experimental data is therefore observed in the measurements. Nonetheless, the use of statistical methods makes it possible to reveal the main laws, and the use of the theory of approximate scaling makes it possible to obtain generalized formulas.

The present investigations of the electric-arc velocity were performed in a setup with concentric copper electrodes. The diameter of the outside electrode was 40 mm, and the data of the inside electrode was 28 or 34 mm [7]. An axial magnetic field was produced by solenoids with adjustable independent supply, which made it possible to vary the induction from 0 to 0.29 T. To ensure a certain minimal arc velocity so as to prevent burning up of the electrodes, the magnetic induction was never lower than 0.085 T. The arc current ranged from 100 to 800 A. Air was blown through the gap between the electrodes at a flow rate that varied from 0 to 14 g/sec. The air was fed into the interelectrode gap tangentially in the same direction of motion as the arc.

In the experiments we measured the current, air flow, magnetic field induction, and arc velocity. The velocity was measured by recording the current pulses in the slotted half-section of the other electrode, using a procedure described in [7]. Thus, what was actually measured was the average velocity of the arc spot over the surface of the electrode.

The experiments have demonstrated a considerable scatter of the average velocity of the arc spot. The largest deviation, ±60%, was observed at zero gas flow, but when this flow increased it dropped to ±(40-20)%. With increasing air flow, the average arc velocity decreased. The decrease of the velocity

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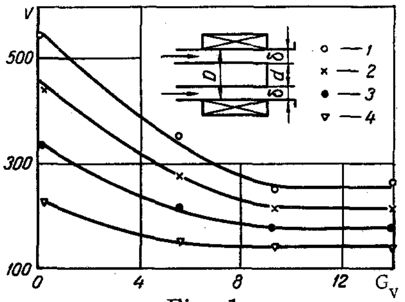

Fig. 1

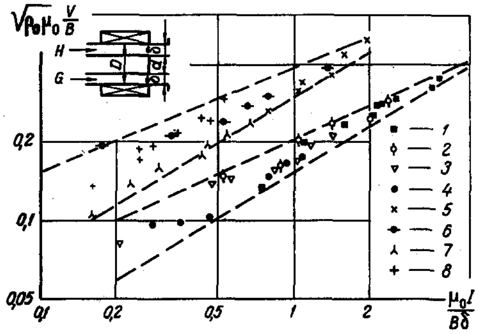

Fig. 2

Fig. 1. Average arc velocity versus flow of ventilating gas (δ = 6 mm; B = 0.29 T): 1) I = 800; 2) 600; 3) 400; 4) 200.

Fig. 2. Generalized arc velocity in a ventilated annular gap: at δ = 3 mm: 1) B = 0.085; 2) 0.12; 3) 0.23; 4) 0.29 T; at δ = 6 mm: 5) B = 0.085; 6) 0.12; 7) 0.23; 8) 0.29 T; I = 100-800 A; G = 0. Cooled copper electrodes.

with increasing air flow was at first quite rapid, but the arc velocity assumes a practically constant value starting with a certain air flow (Fig. 1).

With increasing current and intensity of the external magnetic field, the arc velocity increases. In a certain range, the dependence of the velocity on the current and on the induction of the magnetic field can be represented by a linear function [7]. Such approximations, however, are limited in character and it is more convenient to use a similarity-theory (scaling) method to generalize the experimental data.

There have been a number of papers devoted to derivation of criteria for the generalization of the characteristics of electric arcs and to the generalization of the experimental data [8]. To obtain general relations for the velocity of an arc in a magnetic field it is customary to use the dimensionless numbers $\Pi_1 = \sqrt{(\rho_0/\mu_0)}(\delta V/I)$, $\Pi_2 = \sqrt{\rho_0\mu_0}(V/B)$ or their product $\Pi_3 = \rho_0 V^2\delta/IB$ [10]. The dimensionless argument for the case when there is no flow of external gas around the arc one uses the dimensionless number $\Pi_4 = \mu_0 I/B\delta$.

In a ventilated annular gap it is necessary to take into account the influence of the gas flow and the curvature of the electrode surfaces. The influence of the curvature is clearly seen in Fig. 2, which shows the generalized relations

$$\sqrt{\rho_0\mu_0}\,\frac{V}{B} = f\left(\frac{\mu_0 I}{B\delta}\right) \tag{1}$$

at zero air flow for gaps of 3 and 6 mm. As seen from Fig. 2, the arc velocity is larger in the gap with δ = 6 mm.

It is not very likely that this difference is due to the size of the gap. Similar generalizations given in [5] for parallel electrodes have shown that the size of the gap exerts no influence in the range 12-38 mm. At smaller gaps, the velocity usually decreases somewhat with increasing interelectrode gap, rather than increasing [1]. Consequently, this velocity difference is apparently due to the curvature of the gap, which can be taken into account by means of the parametric dimensionless number $\Pi_5 = \delta/D$. In this case the data given in Fig. 2 can be approximated with an root mean square error of 10% by the expression

$$\sqrt{\rho_0\mu_0}\,\frac{V}{B} = 1.746\left(\frac{\mu_0 I}{B\delta}\right)^{0.506}\left(\frac{\delta}{D}\right)^{0.877}. \tag{2}$$

The data of [4, 5] show that besides the electromagnetic forces taken into account by the dimensionless number Π_4, it is necessary to take into account the pressure forces. In the presence of flow of external gas around the arc, the ratio of the pressure forces to the inertia forces is given by the dimensionless number $\Pi_6 = W\sqrt{\rho_0/P}$. When this number is increased, the generalized velocity of the arc decreases, but the scatter of the experimental points remains at its previous level.

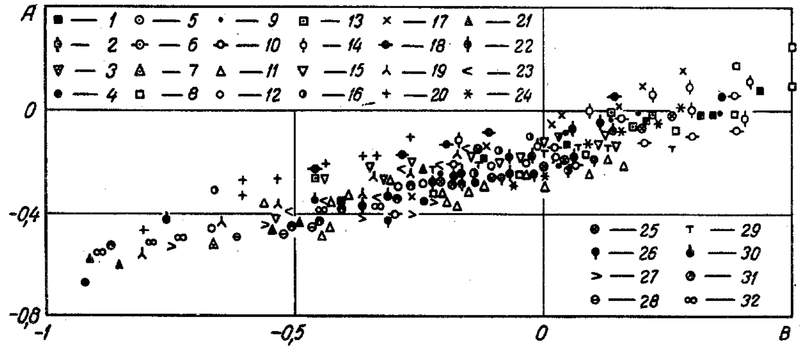

Fig. 3. Generalized arc velocity in a ventilated annular gap (I = 100-800 A; D = 40 mm; $A = \log\left[\sqrt{\rho_0\mu_0}\,\frac{V}{B} \Big/ \left(\frac{\delta}{D}\right)^{0.516} e^{-41.2W\sqrt{\rho_0/P}}\right]$; $B = \log\left(\frac{\mu_0 I}{B\delta}\right)$: at δ = 3 mm, G = 0: 1) B = 0.085; 2) 0.12; 3) 0.23; 4) 0.29 T; G = 5.5 g/sec: 5) B = 0.29; 6) 0.12; 7) 0.23; 8) 0.085; T; G = 9.2 g/sec: 9) 0.085; 10) 0.12; 11) 0.23; 12) 0.29 T; G = 14 g/sec: 13) 0.085; 14) 0.12; 15) 0.23; 16) 0.29 T; at δ = 6 mm, G = 0: 17) 0.085; 18) 0.12; 19) 0.23; 20) 0.29 T; G = 5.5 g/sec: 21) 0.29; 22) 0.12; 23) 0.23; 24) 0.085 T; G = 9.2 g/sec: 25) 0.085; 26) 0.12; 27) 0.23; 28) 0.29 T; G = 14 g/sec; 29) 0.085; 30) 0.12; 31) 31) 0.23; 32) 0.29 T.

A generalization of the experimental data with allowance for the dimensionless number Π_6 is shown in Fig. 3. We see that the scatter does not exceed 50%. The data in Fig. 3 are approximated in the entire range indicated above for the variation of the current, air flow, magnetic-field induction, and gap geometry, with a root mean square error 16%, by the formula

$$\sqrt{\rho_0\mu_0}\,\frac{V}{B} = 0.691\left(\frac{\mu_0 I}{B\delta}\right)^{0.484}\left(\frac{\delta}{D}\right)^{0.516} e^{-41.2W\sqrt{\frac{\rho_0}{P}}}. \tag{3}$$

In formulas (2) and (3) we used dimensionless complexes containing scale values of the density and pressure of the ambient medium. In the experiments, the pressure was equal to atmospheric, and the density ρ_0, in accord with [9], was assumed equal to $1.97 \cdot 10^{-2}$ kg/m^3. In calculating the velocity of the flow around the arc we used the value of the air density at atmospheric pressure and at 15°C.

The exponents in the dimensionless numbers Π_4 and Π_5 of expression (3) represent certain average values of these quantities for the entire range or variation of the gas flow.

A comparison of formulas (2) and (3) shows that the change of the flow of cold gas in the gap has little effect on the dependence of Π_2 on Π_4, whereas the exponent of Π_6 decreases to almost one-half its value. A change takes place also in the numerical coefficient of the formula. An explanation of this fact is apparently that the gap curvature affects the characteristics of the arc by altering the shape of the arc.

With increasing gap curvature, the angle of inclination of the arc to the outer electrode, over the surface of which the velocity is measured, decreases, and the velocity of the electric arc is increased by the breakdown of the cold gas layer next to the electrode. It is also possible that in the investigated case, at a gap δ = 3 mm, the predominant influence is exerted by processes near the electrodes, in which the arc velocity increases rather than decreases with increasing gap. Blowing cold gas over the arc causes in turn periodic lengthening of the arc column in the axial direction. The angle between the arc column and the magnetic-field line then decreases, and with it also the force acting on a unit length of the arc column. The exponent of the dimensionless number Π_5 is accordingly decreased.

The exponent of Π_4 fluctuates insignificantly and its mean value is 0.5. This means that the arc's own magnetic field has little influence on the arc motion in the annular gap with the investigated configuration. In fact, if we divide equations (2) and (3) by $(\Pi_4)^{0.5}$, we obtain the respective formulas

$$\sqrt{\frac{\rho_0\delta}{IB}}\,V = 1.746\left(\frac{\mu_0 I}{B\delta}\right)^{0.006}\left(\frac{\delta}{D}\right)^{0.877},$$

$$\sqrt{\frac{\rho_0\delta}{IB}}\,V = 0.691\left(\frac{\mu_0 I}{B\delta}\right)^{-0.016}\left(\frac{\delta}{D}\right)^{0.516} e^{-41.2W\sqrt{\frac{\rho_0}{P}}}, \tag{3a}$$

in which the influence of the dimensionless number Π_4 is negligible and fluctuates about zero. The number $\Pi_7 = \sqrt{(\rho_0\delta/IB)}V$ is equal to the square root of Π_3, which is obtained directly from the equation of motion without taking into account the magnetic field of the arc itself [6].

Thus, we can use in place of (2a) and (3a) the simpler expressions

$$\sqrt{\frac{\rho_0\delta}{IB}}\,V = 1.74\left(\frac{\delta}{D}\right)^{0.837}, \tag{2b}$$

$$\sqrt{\frac{\rho_0\delta}{IB}}\,V = 0.69\left(\frac{\delta}{D}\right)^{0.516} e^{-41.2W\sqrt{\frac{\rho_0}{P}}}. \tag{3b}$$

These expressions show that the motion of the electric arc is controlled by processes of interaction of the arc column with the gas. The regions next to the electrodes exert practically no influence on the arc motion in the investigated range of parameters.

Thus, our investigation has shown that arc motion in a ventilated gap obeys the same laws as in an interelectrode gap with forced draft. The formulas become somewhat more complicated because of the need for taking into account the curvature of the arc path. By referring the pressure forces to the inertial forces instead of the electromagnetic forces as in the absence of gas flow around the arc it becomes possible to avoid the introduction of an additional dimensionless number and to generalize the velocity of an arc moving in a magnetic field and in a gas stream. An interesting fact is that formulas (3) and (3a) do not include dimensionless numbers that reflect the heat-exchange processes, although allowance for these processes is quite desirable, since the ventilation of the gap changes the gas temperature in the path of the arc. At the same time, the heat-exchange conditions, on which the dimensions of the arc and its aerodynamic resistance depend, are also altered. Attempts were made to generalize the experimental data obtained in the present study with account taken of heat exchange, and corresponding expressions, which are not presented here, were not derived. However, even if we generalize separately the sections with strong and weak dependence on the gas-flow velocity, the resultant accuracy is worse than when the dimensionless number Π_6 is used. An additional introduction of a "convective" energy-dependent dimensionless number $\Pi_8 = \rho_0 W \sigma_0 \eta_0 \delta^3 / J^2$ in formulas (3) and (3a) affect their accuracy little.

This fact could be used to justify analytic methods for calculating characteristics, with separation of the equations of motion and energy. But since all the air was used to ventilate the gap in the present study, the dimensionless number Π_6 coincides with $\Pi_9 = W_\infty/\sqrt{h_0}$, which reflects the energy lost to acceleration of the gas [14]. Numerical estimates show, however, that the energy lost to acceleration of the gas was very small compared with the energy used for its heating under the experimental conditions. The principle role is played by heating of the gas. In addition, strengthening the ventilation of the gas lowers the temperature and the viscosity of the air, and these exert opposite effects on the sign of the exponent of W, whereas blowing off the arc presupposes a minus sign here. This indicates that at low velocities of the axial flow the principle role is played by the lengthening of the arc in the axial direction and not by heat exchange. With further increase of the axial velocity, however, the length of the arc becomes stabilized and the heat-exchange processes come into play. The exponent of W should then become positive. In the investigated range of parameters, this effect can be neglected, so as not to complicate it any further.

Besides, with the already physical phenomena, the arc column is influenced also by other factors, allowance of which can yield a more detailed picture of the behavior of the arc. To this end, however, it is desirable to generalize the experimental data pertaining to different pressures and to different flowing gases.

NOTATION

I is the intensity of arc current;
G is the gas-flow rate;
V is the velocity of arc;
W is the velocity of the gas around the arc;
B is the magnetic field induction;
D is the diameter of external electrode;

δ is the gap between electrodes;

μ_0 is the magnetic permeability;

ρ_0, η_0, σ_0 are the scale values of density of gas, electric conductivity, and enthalpy;

P is the ambient pressure.

LITERATURE CITED

1. T. W. Myers and W. C. Roman, Aerospace Research Laboratories Report, ARL 66-0184, USA (1966).
2. G. Yu. Dautov and M. F. Zhukov, Prikl. Mat. Tekh. Fiz., No. 2 (1965).
3. V. W. Adams, A. E. Guile, W. T. Lord, and K. A. Naylor, Proc. IEE, 114, No. 10 (1967) (G.B.).
4. V. W. Adams, RAE T.R. 67077 (1967) (G. B.).
5. O. I. Yasko, Proc. IEE, 116, No. 3 (1969).
6. O. I. Yasko, Brit. I. Appl. Phys. (J. Phys. D.), Ser. 2, 2 (1969).
7. A. S. Shaboltas, Inzh.-Fiz. Zh., 17, No. 3 (1969).
8. O. I. Yas'ko, Inzh.-Fiz. Zh., 15, No. 3 (1968).
9. A. S. Koroteev and O. I. Yas'ko, Inzh.-Fiz. Zh., 10, No. 1 (1966).
10. A. I. Zhidovich and O. I. Yas'ko, Inzh.-Fiz. Zh., 16, No. 3 (1969).