Journal of Engineering Physics and Thermophysics, Vol. 73, No. 6, 2000

VELOCITY OF ELECTRIC-ARC MOTION BETWEEN COAXIAL ELECTRODES IN A MAGNETIC FIELD

A. M. Esipchuk,[a] **L. I. Sharakhovskii,**[b] **and A. Marotta**[a]

UDC 537.523

Experimental results are generalized and a formula for the velocity of arc motion in a variable-density medium in the annular gap between the coaxial electrodes of an electric-arc gas heater is refined based on consideration of the balance of the Ampere motive force and the force of aerodynamic resistance that affect the arc column.

Introduction. Displacement of an electric arc along electrodes with the aid of a magnetic field is widely used in technology for reducing erosion of contacts of electric switches and electrodes of electric-arc heaters of gas. Development of a reliable method for calculating the arc velocity in the magnetic field is very important for electric-arc heaters, since this velocity, along with the current strength and temperature of the electrodes, primarily determines their service life [1-3]. Very high velocities of the arc (hundreds or even thousands of meters per second instead of tens of meters per second in its displacement by means of a vortex gas flow) are easily reached in electric-arc heaters through the use of a magnetic field [4].

In contactors, switches, and some other devices (for example, in electromagnetic guns or so-called "railtrons"), the arc moves rectilinearly under the action of the Ampere force. Experiments on these devices and special aerodynamic benches with the electric arc balanced in a gas flow and also on electric-arc heaters have shown that at atmospheric pressure the arc moving at a constant velocity relative to the gas can be considered as an impermeable body under the action of counterbalanced electromagnetic and aerodynamic forces [5-7]. The equation of balance of electromagnetic and aerodynamic forces for this arc can be written in the following form (for unit length of the arc column):

$$I \times B = \frac{1}{2} C_x d \rho_0 v_0^2 \,. \tag{1}$$

G. A. Kukekov suggested an empirical relation for the coefficient of aerodynamic resistance of an electric arc in a magnetic field [6]:

$$C_x = 1 + 6.36 B^{0.3} \,. \tag{2}$$

To eliminate the unknown diameter of the arc column d from the balance relation (1), Kukekov used an empirical relation relating the current density in the arc column to the arc velocity:

$$j = 2 \cdot 10^6 v_0 \,, \tag{3}$$

or for a cylindrical column, assuming $j = 4I/\pi d^2$:

---

[a]Gleb Wataghin Institute of Physics at Campinas State University, Campinas, Brazil (Instituto de Fisica "Gleb Wataghin," Universidade Estatual de Campinas, Unicamp, 13083-970, Campinas, Sã Paulo, Brasil); [b]Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 6, pp. 1255-1260, November–December, 2000. Original article submitted April 5, 2000.

$$d \approx 8 \cdot 10^{-4}\sqrt{\left(\frac{I}{v_0}\right)}. \quad (4)$$

Having substituted (4) into (1), Kukekov obtained a formula for the velocity of arc motion in a magnetic field:

$$v_0 = 185\,(IB^2/C_x^2\,\rho_0^2)^{1/3}\,. \quad (5)$$

The formula is used successfully for calculation of the velocity of rectilinear motion of an electric arc in a magnetic field in electric switches.

However, in electric-arc heaters, the motion of the arc differs fundamentally from its displacement in electric switches. The major difference is that, in electric-arc heaters, the arc rotates around the electrodes along a closed trajectory instead of the rectilinear displacement (translation) in switches and railtrons. Here, the circumferential velocity of the arc in electric-arc heaters is always much higher than the linear axial velocity of the flow of a venting gas in the cavity of the electrodes. As a result, the arc, as a rule, reaches its own thermal wake which has an elevated temperature and a reduced density compared to their values in the undisturbed flow. Depending on the ratio of the circumferential velocity of the arc and the axial velocity of the gas, this can lead to severalfold acceleration of the arc motion compared to the velocity calculated by formula (5).

In [4] and then in [8], a hypothesis was suggested according to which in the motion of an arc in a magnetic field in a variable-density medium the product ρv^2 remains constant, i.e.,

$$\rho v^2 = \rho_0 v_0^2\,. \quad (6)$$

Here the subscript 0 refers to any initial conditions, including the conditions in the undisturbed flow. Using the indicated hypothesis for processing experiments in [4], the author obtained a semiempirical relation for the dimensionless gas density in front of the arc as a function of the ratio of the circumferential velocity of the arc to the axial velocity of the gas:

$$\rho/\rho_0 = \sqrt{\left(\frac{k\varphi}{v}\right)}, \quad (7)$$

where $K \approx 10$. From a simultaneous solution of (1), (4), (6), and (7) the author [4] obtained a formula for the velocity of arc motion around the circumference of the electrodes of electric-arc heaters:

$$v = K\left(\frac{IB^2}{C_x^2\rho_0^2}\right)^{4/9}\varphi^{-1/3}, \quad (8)$$

where $K \approx 485$. This formula was checked in processing extensive experimental data (about one thousand experiments) within a wide range of parameters. However, it has a serious drawback that lies in application of a physically incorrect empirical relation (2) to the coefficient of aerodynamic resistance of the arc. Indeed, $C_x \approx 10$ for B = 3 T, which is physically meaningless for the coefficient of aerodynamic resistance, since the highest values of this coefficient known in aerodynamics for similar flow modes do not exceed 2 (see, e.g., [5]).

The results of modern studies disclose the reason for this disagreement. Now it is found [5] that an arc column in motion in a gas does not have the shape of a regular circular cylinder, as was adopted by Kukekov, but is "flattened" across the direction of motion. Kukekov also obtained expressions (2) and (3) in photographing the arc from the side and not toward the direction of motion, so he obtained an underestimated value of the middle cross section of the arc column. Precisely this led Kukekov to overestimated values of the coefficient of aerodynamic resistance C_x that are physically meaningless.

The present work is aimed at obtaining a physically correct and more exact, compared to (5) and (8), formula for the velocity of arc motion along a closed trajectory in a magnetic field.

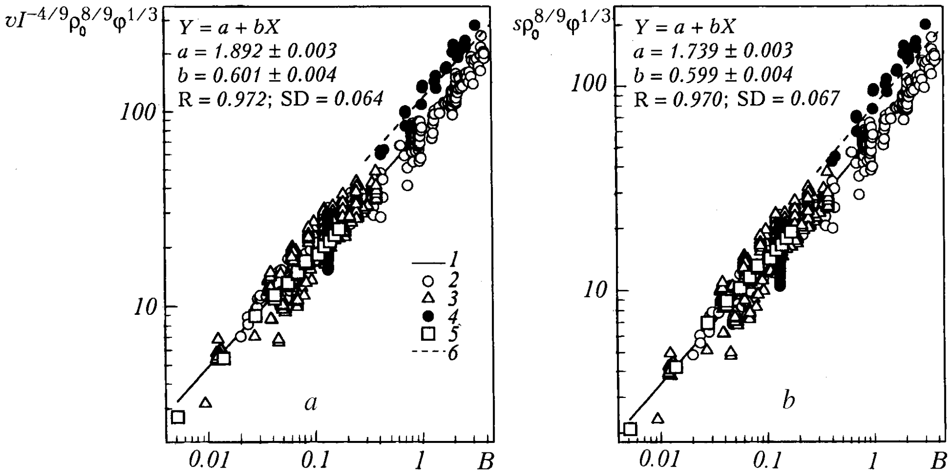

Fig. 1. Generalization of experimental values of the combinations $vI^{-4/9}\rho_0^{8/9}\varphi^{1/3}$ and $s\rho_0^{8/9}\varphi^{1/3}$ with respect to the magnetic field (the correlation parameters are given for logarithmic coordinates): 1) linear approximation of the experimental data of HMTI and GWIP; 2) HMTI data for 0.5–5-mm interelectrode gaps; 3) data of GWIP for a 3-mm gap; 4) HMTI data for a 7-mm gap; 5) data of McGill University for a 4-mm gap; 6) theoretical line corresponding to arc splitting into two channels.

Experimental Setup. In this study, we used experimental results obtained on setups of the A. V. Luikov Heat and Mass Transfer Institute (HMTI) of the National Academy of Sciences of Belarus (Minsk, Belaris), the Gleb Wataghin Institute of Physics (GWIP) of Campinas University (Campinas, Brazil), and McGill University (Montreal, Canada) [7]. All these setups are similar in design. They have a coaxial arrangement of the electrodes, axial, without swirling, gas supply to the interelectrode space, and displacement of the arc around the circumference of the electrodes using an external magnetic field produced by special solenoids. Schematic diagrams of the setups are not given here because all of them are described in previous works [4, 9, 10].

The velocity of the arc was determined from its rotational velocity in the annular gap between the coaxial electrodes, which was measured by a photoelectric or magnetic pickup that recorded each turn of the arc. The velocity of the arc on the mean radius of the interelectrode gap was taken as its linear velocity.

Results of the Investigations. To eliminate the unknown value of the coefficient of aerodynamic resistance C_x, we processed the results of about 1400 experiments conducted on the three setups, using the formula $v\varphi^{1/3}\rho_0^{8/9}I^{-4/9} = f(B)$, which corresponds to relation (8), if C_x is eliminated from it.

The range of the studied parameters on all the setups was 0.01–3.9 T for the magnetic field, 100–1760 A for the current strength, and 0.23–33 m/sec for the axial velocity of the gas in the interelectrode gap. The diameter of the outer electrode ranged from 32 to 90 mm. In the experiments, the interelectrode gap was varied from 0.5 to 7 mm. The experiments were conducted with air (the setups of HMTI and GWIP) and with nitrogen (the McGill setup) [7].

Moreover, in accordance with the theoretical concepts of erosion of cold electrodes of electric-arc heaters described in [2, 12], the same experiments were processed in a somewhat different form convenient for calculation of the erosion and service life of these electrodes: $s\rho^{8/9}\varphi^{1/3} = f(B)$. Here $s = v/\sqrt{I}$ is the "reduced" velocity, which simplifies calculations of erosion in a thermophysical model of it [2, 12].

As a result we obtained that the combinations $(vI^{-4/9}\rho_0^{8/9}\varphi^{1/3})$ and $(s\rho^{8/9}\varphi^{1/3})$ can be represented as proportional to $B^{0.6}$ (see Fig. 1). This coincides with the data of [7], where the same value of the exponent was proposed for a dependence of the velocity of the arc v on the magnetic field obtained on a coaxial electric-arc setup.

As a result of the indicated processing of the results of all the experiments mentioned (about 1400 points), we obtained simple relations for the linear and reduced velocity, v and s, respectively:

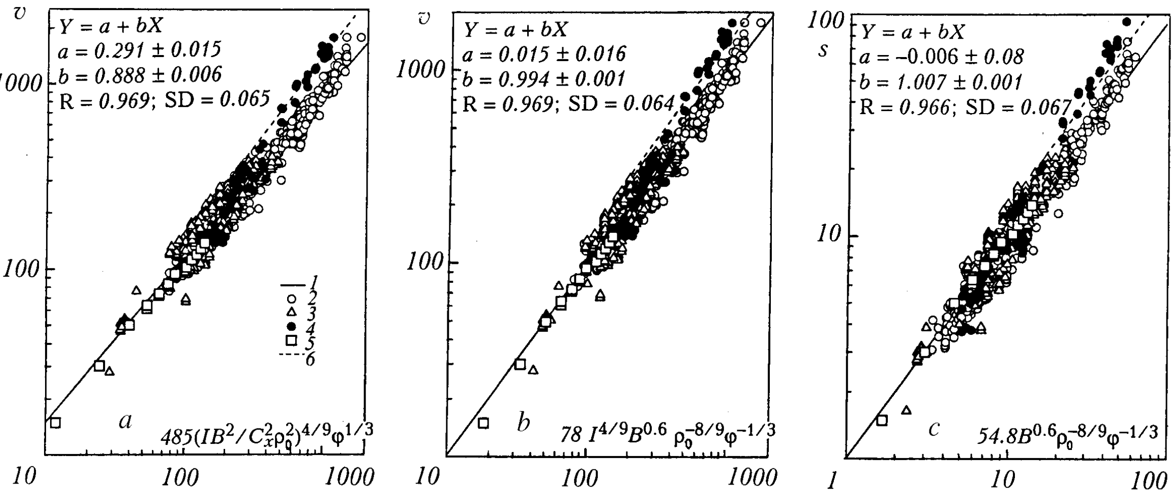

Fig. 2. Comparison of experimental values of the absolute (v) and reduced (s) velocities of the arc with calculations by formulas (8) (a), (9) (b), and (10) (c). For notation 1-6 see Fig. 1. The correlation parameters are given for logarithmic coordinates. s, msec^{-1}·A$^{-0.5}$.

$$v = 78 I^{4/9} B^{0.6} \rho_0^{-8/9} \varphi^{-1/3}, \tag{9}$$

$$s = 54.8 B^{0.6} \rho_0^{-8/9} \varphi^{-1/3}. \tag{10}$$

A comparison of calculations by the previous formula (8) and the new formulas (9) and (10) with results of the experiments is shown in Fig. 2a, b, and c, respectively (in logarithmic coordinates). It is seen that the coefficients of linear regression a and b for the representation of the velocity in the form of relations (9) and (10) (see Fig. 2b and c) are close to ideal: $a \approx 0$, $b \approx 1$, whereas for relation (8) (see Fig. 2a) they significantly differ from these: a = 0.29, b = 0.89. This indicates a much larger systematic error in relation (8) compared to (9) and (10). The coefficients of correlation for the representation of the velocity in the form of (8), (9) or (10), as is seen from a comparison of Fig. 2a, b, and c, differ slightly: from 0.966 for (10) to 0.969 for (9) and (8). This indicates that the exponent of I in (8) and (9), which is equal to 4/9, is somewhat better than 0.5 in s (the reduced velocity) entering (10). However, to model the erosion, with allowance for the very small difference in the results of generalization with respect to v and s, it is preferable to use relation (10), which greatly simplifies the corresponding calculations (see [12]). For more accurate calculations of the velocity of arc motion, we can recommend formula (9).

Figures 1 and 2 present for comparison the points obtained by Szente on the McGill setup with nitrogen [7]. The density of the nitrogen and the air was taken equal to 1.25 and 1.29 kg/m^3, respectively. It is seen that the data of [7] are in good agreement with both (9) and (10).

In our experiments we used interelectrode gaps of 0.5 to 7 mm, which practically did not affect the arc velocity. Some special features could be observed only for the maximum gap of 7 mm. In Figs. 1 and 2, the points referring to this gap are filled in dark. It is seen that they deflect upward from the remaining points more and more with displacement to the right along the abscissa, to the region of strong magnetic fields. However, this anomaly becomes substantial only at velocities of the arc higher than 500 m/sec and magnetic fields stronger than 0.4 T. Such strong magnetic fields virtually are not used in electric-arc heaters. We can assume that this occurs due to the lowered stability of a long arc column in intense transverse blowing, which leads to its dynamic splitting from time to time into several parallel flow channels.

The arc velocity was measured by the frequency of an optical signal picked off a phototransducer. Splitting of the arc column under these conditions must lead to an increase in the frequency of the recorded signal.

This instability and arc splitting were revealed, for example, in [13] by spectroscopic studies on an analogous electric-arc setup, with this splitting increasing as the anode was approached. In a 5.15-mm gap and a 0.1-T magnetic field, the statistical-mean number of arc channels was 1.1–1.3.

It is obvious that stationary splitting of the arc column into two parallel channels should lead to doubling of the rotational velocity registered by the phototransducer, with a constant linear velocity of the arc. However, this splitting must cause a twofold decrease in the current in each arc channel. As a result, the registered increase in the rotational velocity for two parallel flows must be only $2^{5/9}$ times according to formula (9) and $\sqrt{2}$ times by formula (10). This apparent increase of $2^{5/9}$ or $\sqrt{2}$ times in the velocity is shown by dashed lines in Figs. 1a and 2a and b for (9) and in Figs. 1b and 2c for (10), respectively. It is seen that the dark points gradually reach these lines. This can be treated as follows – as the velocity increases, the statistical-mean number of parallel flow channels increases, and for magnetic fields stronger that 0.4 T and a velocity higher than 500 m/sec it becomes close to 2. Thus, splitting of the arc column leads to an increase in the frequency of the recorded signal with an actual decrease in the linear velocity of the arc due to the decrease in the current.

Splitting of the arc channel and a decrease in the linear velocity of the arc with an increase in the distance between the parallel electrodes of more than 1–2 mm is described for the case of rectilinear motion of the arc (see, e.g., [14, 15] and references there).

Conclusion. As a result of generalization of a large number of experiments (about 1400), we obtained new formulas (9) and (10), more exact compared to previously published ones, for calculation of the velocity of electric-arc motion around the circumference of the electrodes in electric-arc heaters under the action of a magnetic field. The new formulas can be used in designing plasmatrons and for theoretical analysis of optimum modes of their operation with minimum erosion of the electrodes [12].

The authors are grateful to A. A. do Prado and J. B. Pineiro for their technical assistance in the work. We express our gratitude to Scientific Funds of Brazil (CNPq, FAPESP, and FINEP) for financial support of this work.

NOTATION

I, current strength, A; B, magnetic induction, T; C_x, coefficient of aerodynamic resistance; d, diameter of the arc column, m; ρ_0, gas density in the undisturbed flow, kg/m^3; v, arc velocity, m/sec; v_0, arc velocity in the undisturbed flow, m/sec; j, current density in the arc column, A/m^2; w, axial velocity of the gas in the electrode, m/sec; $\varphi = (1 + w)^{-1} + w$, empirical function of the axial velocity of the gas; R, coefficient of correlation; SD, root-mean-square deviation.

REFERENCES

1. A. V. Luikov, E. A. Borovchenko, V. I. Krylovich, V. V. Toropov, L. I. Sharakhovskii (Sharakhovsky), and A. S. Shaboltas, in: *Proc. Japan Soc. Mech. Eng. (Semi-Int. Symp. ISME-1967)*, September 4-8, 1967, Tokyo (1967), pp. 113-119.
2. A. Marotta and L. I. Sharakhovskii (Sharakhovsky), *J. Phys. D: Appl. Phys.*, **29**, 2395-2403 (1996).
3. A. Marotta, L. I. Sharakhovskii (Sharakhovsky), and A. M. Esipchuk (Essiptchouk), *Annals New York Acad. Sci.*, **891**, 36-42 (1999).
4. L. I. Sharakhovskii, *Inzh.-Fiz. Zh.*, **20**, No. 2, 306-313 (1971).
5. W. C. Roman and T. W. Myers, *AIAA J.*, **5**, No. 11, 2011-2017 (1967).
6. G. A. Kukekov, *Zh. Tekh. Fiz.*, **11**, No. 3, 229-234; No. 10, 972-978 (1941).
7. R. N. Szente, R. J. Munz, and M. G. Drouet, *J. Phys. D: Appl. Phys.*, **21**, 909-913 (1988).
8. J. Kopainsky and E. Shade, *J. Appl. Phys.*, **20**, 147-153 (1979).
9. R. N. Szente, R. J. Munz, and M. G. Drouet, *J. Phys. D: Appl. Phys.*, **20**, 754-756 (1987).
10. A. M. Esipchuk, A. Marotta, and L. I. Sharakhovskii, *Inzh.-Fiz. Zh.*, **73**, No. 6, 1235-1244 (2000).

11. L. I. Sharakhovskii (Sharakhovsky), A. Marotta, and V. N. Borisyuk, *J. Phys. D: Appl. Phys.*, **30**, 2018-2025 (1997).
12. L. I. Sharakhovskii (Sharakhovsky), A. Marotta, and V. N. Borisyuk, *J. Phys. D: Appl. Phys.*, **30**, 2421-2430 (1997).
13. N. Desaulnier-Sourcy and J. L. Meunier, *J. Phys. D: Appl. Phys.*, **28**, 2505-2513 (1995).
14. A. B. Koroteev, V. M. Mironov, and Yu. S. Svirchuk, *Plasmatrons – Design, Characteristics, and Calculation* [in Russian], Moscow (1993).
15. O. I. Yas'ko, *Electric Arc in a Plasmatron* [in Russian], Minsk (1977).