with different lithium flow rates. It was found that the electron concentration in the active zone depends weakly on the flow rate of the working substance. With a reduction of the lithium flow rate by a factor of 12 (from 0.018 to 0.0015 g/sec), the quantity n_e changed by a factor of 1.75 (from $1.75 \cdot 10^{15}$ to $1 \cdot 10^{15}$ cm^{-3}). Under these same conditions, the concentration of neutral atoms decreased approximately by a factor of 2.6, which corresponds to an increase of α from ∿88 to ∿92%.

There were no spectral lines of argon ions and atoms on the spectrograms obtained. This means that the argon, fed into the vacuum chamber in order to protect the optical system, made no contribution to the ion component of the plasma. This is confirmed by the fact that an increase of pressure in the vacuum chamber from $\sim 10^{-3}$ to $\sim 5 \cdot 10^{-1}$ mm Hg, due to a change of the argon flow rate, has no effect on the electrical parameters of the discharge. The experimental results obtained can be used for the development of a theoretical model of the operating process in a multichannel cathode.

LITERATURE CITED

1. D. B. Fradkin, A. W. Blackstock, et al., "Experiments using a 25 kW hollow cathode lithium vapor MPD arcjet," AIAA J., 8, No. 5, 886 (1970).
2. L. I. Areev, S. D. Grishin, V. G. Mikhalev, S. N. Ogorodnikov, and V. N. Stepanov, "The characteristics of high-power plasma sources with a hollow cathode," Radiotekh. Elektron., 20, No. 9, 93 (1975).
3. J. L. Delcroix, H. Minoo, and A. R. Trindade, "Gas-fed multichannel hollow cathode arcs," Rev. Sci. Instrum., 40, No. 12, 1555-1562 (1969).
4. A. R. Trindade, "Study of the operating mechanisms of hollow cathodes under arc conditions," State Thesis, Faculty of Sciences, Orsay (1970).
5. J. L. Delcroix, H. Minoo, and A. R. Trindade, "Establishment of a general rule for a hollow cathode arc discharge," J. Physique, 29, No. 6, 605-610 (1968).
6. A. Lorente-Arcas, "Model of the discharge in the hollow cathode," Plasma Phys., 14, No. 6, 651-659 (1972).
7. I. Holtsmark and B. Trumpy, "Broadening of spectral lines," Z. Phys., 31, 803 (1925).
8. N. G. Preobrazhenskii, Spectroscopy of an Optically Dense Plasma [in Russian], Nauka, Novosibirsk (1971).

ELECTRODYNAMIC INTERACTION OF THE ARCS OF PLASMA SMELTING FURNACES

N. I. Bortnichuk, V. Yu. Sandler, and A. V. Khotina

UDC 621.365.2:621.365.95

INTRODUCTION

In plasma smelting furnaces with a ceramic crucible, it is necessary (in contrast from the usual arc furnaces) to deal with long arcs (1 m or more long). In this case, in order to achieve high powers (tens of megawatts or more), several arcs burning in parallel are used.

Under these conditions, it is found that there is a significant electromagnetic interaction of the arcs, leading to their constriction — distortion of the axes and convergence of the anode spots. The force of interaction depends on the distance between the plasmotrons, the length of the arc, and the current strength. Starting from some values of these parameters, the anode spots of the arcs merge into one. It is established by an experimental method that with further increase of constriction of the arcs their burning becomes unstable; pronounced spatial oscillations of the arcs and also voltage fluctuations in them originate, which have a detrimental effect on the operation of the furnace. This circumstance, in the first place, requires careful thought about the design of the current conductors

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 29-34, November-December, 1976. Original article submitted November 18, 1975.

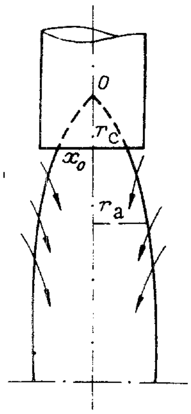

Fig. 1

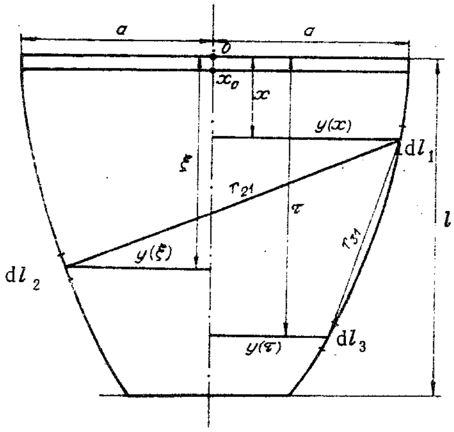

Fig. 2

to the plasmotrons and to the hearth electrode, in order to reduce their effect on the arc columns; secondly, it imposes specific restrictions on the arc parameters and their mutual arrangement, i.e., in the final balance, on the shape and size of the furnace space.

The results of calculations of the interaction of parallel-burning arcs of plasma furnaces, carried out on the basis of a previously developed model of the arc of a smelting plasmotron [1, 2], are given below.

§1. According to the model, a long open arc operates as an electromagnetic pump, sucking gas from the surrounding space into its initial conical section (Fig. 1). This gas, which has already existed in the plasma state, flows along the column in the direction toward the anode, so that the equation $\rho v_x = \text{const}$ is maintained along the cross section of the column (v_x is the axial component of the velocity; ρ is the density of the gas). In the case of extinction of the arcs as a result of distortion of the axis of the column, centrifugal forces and also forces due to the inherent magnetic field of the arc (which straightens the column) originate.

Equality of the electromagnetic and centrifugal forces also determines the shape of the axis of the arc column.

Figures 1 and 2 illustrate the path of the calculation of the electromagnetic forces acting on the column.

The induction of the magnetic field, created at the point (x_1, y_1) by a linear element dl_2 of the second arc, is equal to

$$d\mathbf{B}_{21} = \frac{\mu_0 i\left[d\mathbf{l}_2\mathbf{r}_{21}^0\right]}{4\pi r_{21}^2}.$$

The force acting on an element of the first arc dl_1 is

$$d\mathbf{F}_{21} = \frac{\mu_0 i^2\left[d\mathbf{l}_1\left[dl_2\mathbf{r}_{21}^0\right]\right]}{4\pi r_{21}^2}, \qquad (1)$$

where

$$r_{21}^2 = (\xi - x_1)^2 + [y_1(x_1) - \eta(\xi)]^2;$$
$$\mathbf{r}^0 = \mathbf{r}/|\mathbf{r}|$$

(here and later it will be assumed that the currents of both arcs are identical and equal to i).

The induction of the magnetic field, created at the point (x_1, y_1) by a linear element dl_3 of the same arc, is equal to

$$d\mathbf{B}_{31} = \frac{\mu_0 i}{4\pi}\frac{\left[d\mathbf{l}_3\mathbf{r}_{31}^0\right]}{r_{31}^2};$$

the corresponding force is

$$dF_{31} = \frac{\mu_0 i^2}{4\pi} \frac{[dl_1 [dl_3 r_{31}^0]]}{r_{31}^2}, \tag{2}$$

where

$$r_{31}^2 = (\xi - x_1)^2 + (|y_1(x_1) - \eta(\xi)| + y_0)^2$$

($y_0 = 0.7788$; r_0 is the mean geometrical distance of the cross-sectional area of the arc — in its cylindrical section — from itself [3]). This expression is completely valid only at a constant radius r_0 (absence of a cone in the initial section when $x > x_0$) and with a uniform distribution of the current density over the cross section of the column. However, the error caused by these assumptions is small, since the initial (conical) section of the column amounts to an insignificant part of its total length (less than $10r_0$) and the magnitude of r_0 is small in comparison with the length of the arc.

The total ponderomotive force acting on the element is equal to

$$dF_1 = \int_{x_0}^{l} (dF_{21} - dF_{31}), \tag{3}$$

where x_0 is the distance between the origin of the coordinates 0, located in the body of the cathode at the apex of the arc cone, and the surface of the cathode — the plane of the cathode spot (see Fig. 1); l is the distance between the origin of the coordinates and the plane of the anode — the surface of the liquid bath.

The force $\mathbf{dF}_1$ is balanced by the centrifugal force due to the plasma flow along the axis of the arc column $\mathbf{dF}_a$:

$$dF_C = \left\{ 2\pi \int_0^{r_a} \frac{\rho v_x^2 r}{\sqrt{R_{cr}^2 - r^2}} dr \right\} dl_1,$$

where R_{cr} is the radius of curvature of the axis of the column and ρ is the density of the plasma.

From the accepted assumption ρv_x = const and the fact that $R_{cr} \gg r_0$, it follows that

$$dF_C = \left\{ \frac{2\pi(\rho v_x)^2}{R_{cr}} \int_0^{r_a} \frac{J_0\left(\gamma_1 \frac{r}{r_a}\right)}{\rho_0} r dr \right\} dl_1 = \frac{\mu_0 i^2 \Phi(x) f^2(x)}{8\pi} \frac{\left|\frac{d^2y}{dx^2}\right|}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}} dl_1.$$

In this case, the following relations obtained in [1, 2] are used:

density of the gas,

$$\rho = \frac{\rho_0}{J_0\left(\gamma_1 \frac{r}{r_a}\right)},$$

$$\rho v_x = \left[\frac{\gamma_1}{16 J_1(\gamma_1)} \frac{\mu_0 i^2}{\pi^2 r_0^2} \rho_0 \Phi(x)\right]^{1/2}; \tag{4}$$

radius of the arc,

$$r_a = r_0 f(x),$$

$$f(x) = \left[1 - e^{-2\left(\beta^2 + A_0 \frac{\lambda x}{\rho v_x c_p}\right)}\right]^{1/2}, \tag{5}$$

$$\Phi(x)=\frac{1}{f^2(x)}\left(\frac{1-f^2(x)}{f^2(x)}\right)^t\left\{\ln\left(\frac{r_0 f(x)}{r_C}\right)^2\left[1+\frac{t}{2}\ln\left(\frac{r_C f(x)}{r_0}\right)^2\right]+\frac{\pi t}{3}\left[\arcsin f^2(x)-\arcsin\left(\frac{r_C}{r_0}\right)^2\right]\right\},$$

$$t=\frac{\gamma_1\mu_V c_p}{2\lambda\left(A_0 r_0^2+\gamma_1^2\right)};$$

and x_0 is determined from the equation [2]

$$\frac{x_0\lambda}{\rho v_x c_p}=-\frac{1}{2\,(A_0+\beta^2)}\ln\left(1+\frac{r_C}{r_0}\right).$$

Here γ_1 = 2.405 is the first root of a Bessel function of zero order; ρ_0 is the density of the gas at the axis of the column; r_C and r_0 are the radii of the cathode spot and of the arc column in the cylindrical section, respectively; $\beta = \gamma_1/r_0$; μ_V, λ, and c_p are the coefficients of viscosity and thermal conductivity, and the specific heat of the plasma; μ_0 is the magnetic susceptibility of the vacuum; and A_0 is a coefficient related to the value of the thermal conductivity function in the cylindrical part of the arc column.

The range of variation of c_p/λ at the arc temperature is quite narrow, and this relation is assumed to be constant over the entire arc column. The equation for the axis of the arc column has the form

$$d\mathbf{F}_1-d\mathbf{F}_a=0,$$

Introducing the dimensionless coordinates $x_* = x/a$; $\xi_* = \xi/a$; and $y_* = y/a$ and the dimensionless parameters $x_{0*} = x_0/a$; $y_{0*} = y_0/a$; and $l_* = l/a$ and taking Eqs. (1)-(3) into account, we obtain the equation for the calculation (here the variable of the integration for both terms of the left-hand side is denoted by ξ_*):

$$\int_{x_{0*}}^{l_*}\left\{\frac{\left|\frac{dy_*(\xi_*)}{d\xi_*}\right|(\xi_*-x_*)+[y_*(\xi_*)-y_*(x_*)]}{\{[y_*(\xi_*)-y_*(x_*)]^2+(\xi_*-x_*)^2\}^{3/2}}-\frac{\left|\frac{dy_*(\xi_*)}{d\xi_*}\right|(\xi_*-x_*)+[y_*(\xi_*)-y_*(x_*)]}{\{[|y_*(\xi_*)-y_*(x_*)|+y_{0*}]^2+(\xi_*-x_*)^2\}^{3/2}}\right\}d\xi_*=\frac{\Phi(x_*)f^2(x_*)}{2\left[1+\left(\frac{dy_*}{dx_*}\right)^2\right]^{3/2}}\left|\frac{d^2y_*}{dx_*^2}\right| \quad (6)$$

with the initial conditions $y_*|_{x_*=x_{0*}}=1$; $\left.\frac{dy_*}{dx_*}\right|_{x_*=x_{0*}}=\alpha$.

By conversion to dimensionless coordinates, the index of the exponent on the right-hand side of expression (5) acquires the form

$$-2(\beta^2+A_0\lambda a x_*/\rho v_x c_p).$$

This imposes the additional requirement $a/\rho v_x$ = const or a/i = const [see relation (4)].

In the case of parallel operation of a large number of plasmotrons, the resulting force acting on an element of the arc is the vector sum of the forces due to each arc individually. This is taken into account by the introduction of the coefficient k in the first term below the integral on the right-hand side of Eq. (3), which assumes the form

$$d\mathbf{F}_1=\int_{x_0}^{l}(k\,d\mathbf{F}_{21}-d\mathbf{F}_{31}). \quad (7)$$

Equations (6) and (7) have been solved for current values from 2000 to 12,000 A [a = 1 m, i.e., $0.8\cdot10^{-4} < a/i < 5\cdot10^{-4}$ and $\alpha = 0$ (axes of the plasmotrons are parallel)] for two and three parallel-burning arcs, in which three plasmotrons are located at the apices of an equilateral triangle. For a given value of a/l, its solution corresponds to each value of a/i. Figure 3 shows the results of a calculation for arcs with a current strength of 12,000 A.† Here 1 is the axis of the arc column, and 2 is the curve passing through the center of the anode spots of arcs of different length. Calculations for other values of current strengths gave results in the arc which differ only very slightly (a change of current from 2000 to 12,000 A gave a difference of approximately 1%). Therefore, for practical purposes, the calculations carried out for a single value of the current strength can be used.

†Calculation on the computer was carried out by I. V. Chikhladze.

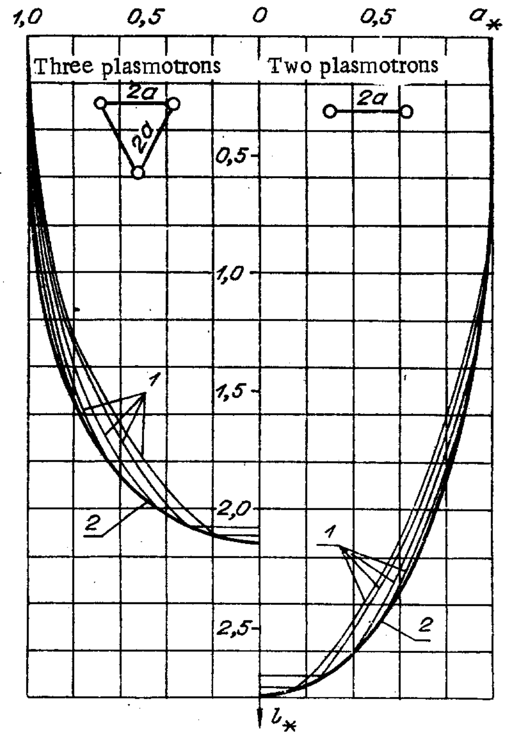

Fig. 3

§2. It follows from the calculations carried out that:

1) in the case of two or more plasmotrons of constant current, the shape of the arc column burning in the furnace space depends on the length, number of parallel-burning arcs, and on their mutual arrangements; it is almost independent of the current strength and flow rate of the plasma-forming gas;

2) in the case of plasmotrons with parallel axes, the length of the arc (distance from the nozzle section to the metal), in order to ensure stable burning, must be not more than 1.3 to 1.35 times the distance between the plasmotron axes;

3) for three plasmotrons with parallel axes, located at the apices of an equilateral triangle, the length of the arc must not exceed the distance between the plasmotrons;

4) the interaction of the arcs is weakened considerably by tilting the axes of the plasmotrons. With an angle of tilt to the vertical equal to 30° ($\alpha = 0.58$), interaction can be neglected.

LITERATURE CITED

1. Industrial Facilities for Electric-Arc Heating and Their Parameters [in Russian], Énergiya, Moscow (1971).
2. R. S. Bobrovskaya, N. I. Bortnichuk, A. A. Voropaev, A. V. Donskoi, S. V. Dresvin, and M. M. Krutyanskii, "Parameters of an open arc, stabilized by a longitudinal argon flow," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1973).
3. P. L. Kalantarov and L. A. Tseitlin, Calculation of Inductivities [in Russian], Énergiya, Leningrad (1970).