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ELECTRIC CHARACTERISTICS OF THE ROTATING ARC WITH GRAPHITE ELECTRODES IN THE MAGNETIC FIELD

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Abstract: The electric characteristics of a d. c. arc burning under influence of applied magnetic field were observed. The effect of the magnetic field on the changes of the electric field in the arc column and electrode regions is described, as well as the effect on the arc power per unit length of the plasma column, the arc power dissipated in the vicinity of the electrodes and the total arc power. An attempt was made to connect the electrical parameters with the arc plasma rotation frequency.

1. Introduction

An electrical arc burning in an external inhomogeneous magnetic field is a very convenient spectrochemical source for analysis of elements in traces[1,2]

The application of an inhomogeneous magnetic field to the arc enables a considerable increase of the spectral line intensities to be achieved[1,2]. The spectral line intensity amplification may be considered as a consequence of the increased residence time of the particles of elements in the plasma due to the enlarged integral volume of the plasma under the conditions in which its rotation frequencies are higher than the rate of transport processes of the particles outside the plasma.

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It has been found that the rotation frequency of the plasma column brought about by the Lorentz force is one of the very important parameters in the spectral line intensity. amplification study of the elements in traces[3-5].

At higher intensities of the arc current and in stronger magnetic fields a splitting of the arc plasma occurs, the integral plasma volume diminishes and the amplification of the spectral line intensity decreases[6].

The presence of the magnetic field affects the change of the electric characteristics of the free-burning arc. In the present paper these changes, caused by the influence of the magnetic field, will be studied.

2. *Experimental arrangement*

In Fig. 1 the position of the electrode system with respect to a spectrograph and an electromagnet is shown schematically. The horizontal position of the magnet is determined by its axis corresponding to the axis of the electrode system, and

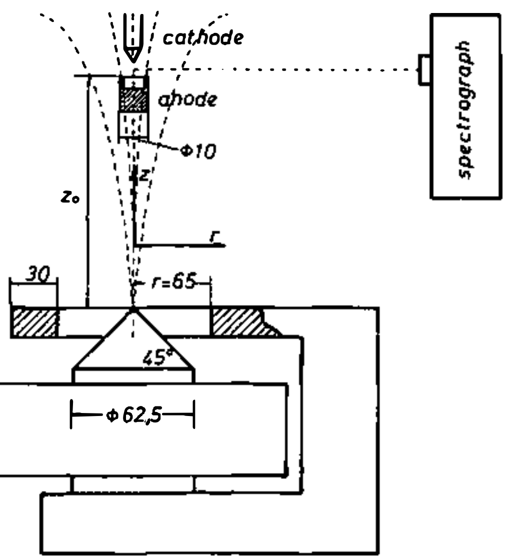

Fig. 1.

this vertical axis lies in the same plane as the axis of the optical bench. The latter is perpendicular to the plane of the spectrograph slit. The electromagnet is fixed in the horizontal plane by a mechanical system, while in the vertical direction it may be moved so that the distance z between the magnet and the electrode system may be varied over the range of 30—130 mm. The same figure shows the geometry of the magnetic field i. e. the lines of the magnetic field in the position of the electrode system.

The vertical and horizontal components of the magnetic field were measured by setting up the Hall probes respectively. The frequency of the plasma rotation was measured with a photomultiplier probe system[3].

3. *The measurement of the magnetic field*

The basic data on the vertical component of the magnetic field B_z, obtained from the measurement are shown in Fig. 2. The axial component of the magnetic field was measured as a function of the magnet supply current at different distances z above the magnetic pole. As the supply current increases, the magnetic field increases more rapidly at smaller distances than at larger ones.

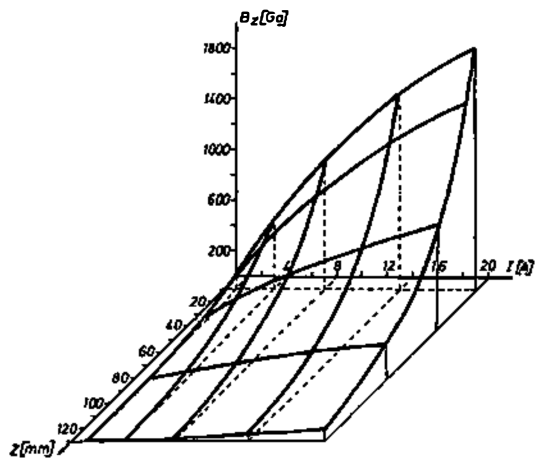

Fig. 2.

The measurement of the radial component was performed at different axial distances and at a radial distance of 2.5 mm from the axial axis, i. e. in the middle of the radius of the lower electrode (Fig. 1) which is most frequently used in experiments. The dependence of the radial component on the electromagnet current was measured at the given space points. The results of measurements are given in Fig. 3.

From these measurements it is possible to derive the gradients of the vertical and horizontal components in the direction of z axis. These gradients can be presented as a function of distance z from the top of the magnetic pole. By means of these measurements and those of the vertical and horizontal components depending on the radial distance, the geometry of magnetic field is determined.

In order to show the inhomogeneity of the axial component, the curve of the axial component versus the distance z with the magnet supply current I_m, as a parameter, was first drawn and there from the gradient of the axial component

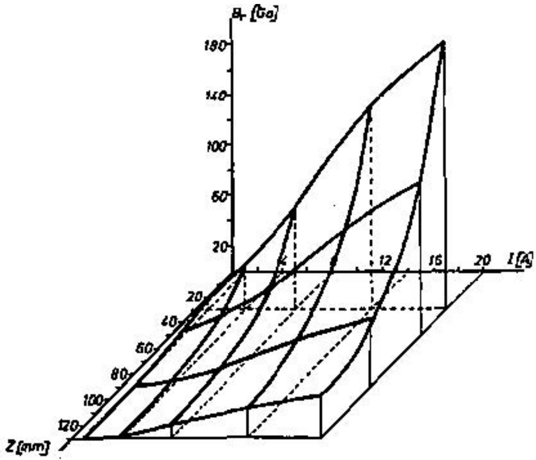

Fig. 3.

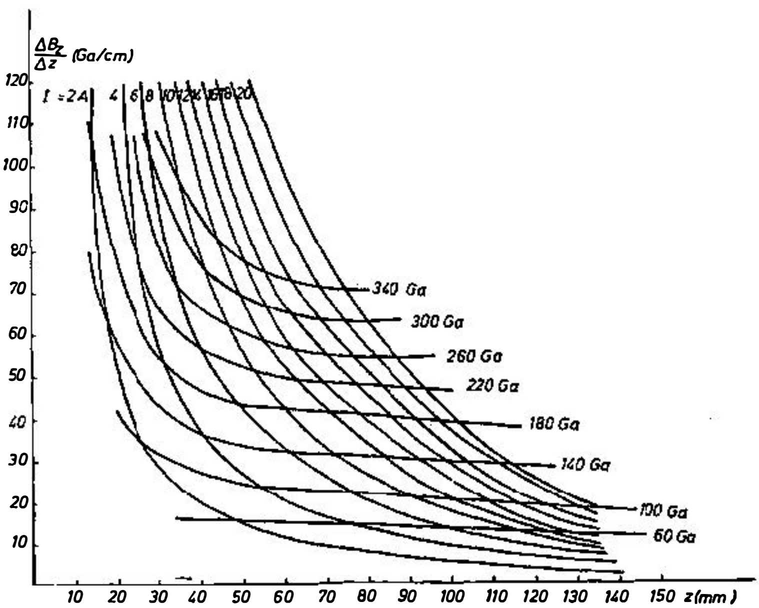

Fig. 4.

$\partial B_z/\partial z$ in the axial direction was determined and plotted as a function of the axial distance. This dependence is given in Fig. 4. In the plots of $\partial B_z/\partial z$

as a function of z, curves corresponding to each value of the axial component are given. From the curves B_z = const. the change of this gradient at the same values of the axial component may be seen.

4. *The measurement of the electric field and electric power*

We shall first consider the $U - I$ characteristics of the free-burning arc between graphite electrode[7]

$$U = a + b\,l + \frac{c + d\,l}{I} \tag{1}$$

where $a, b, c,$ and d are constants, l is the length of the arc column, U is the voltage drop in the arc and I is the arc current. Rearranging the terms of the above equation, one obtains

$$U = \left(b + \frac{d}{I}\right) l + a + \frac{c}{I}. \tag{2}$$

On the other hand, it may be written

$$U = E\,l + U_a + U_c, \tag{3}$$

where E is the electric field, and $U_a + U_c$ is the sum of the anode and cathode voltage drops.

Comparing Equs. (2) and (3), for the modulus of the electric field in the arc column one obtains the expression

$$E = b + \frac{d}{I}, \tag{4}$$

and it follows that the value of the electrode voltage drops is given by the relation

$$U_a + U_c = a + \frac{c}{I}. \tag{5}$$

From Equ. (1) the total electric power of the arc is obtained

$$P = (a + b\,l)\,I + c + d\,l, \tag{6}$$

from (4) the power per unit length of the arc column (P'/l)

$$\frac{P'}{l} = b\,I + d, \tag{7}$$

while from Equ. (5) the power dissipated for the processes in the electrode regions

$$P'' = a\,I + c. \tag{8}$$

The coefficients a, b, c, and d are determined from experimental results on $U = f(I)_l$ by the method of least squares for the case of a free-burning arc in the absence and in the presence of the magnetic field.

Taking into account that the anode is broader than the cathode, and that the plasma is formed between the narrower cathode and the edge of the anode, we took this distance to be the length of the arc column l. This is only an approximation, because in the case where the magnetic field is used, a deformation of the plasma column occurs, and therefore the length l should be corrected to some larger value. Nevertheless, our earlier photographs of the rotating plasma taken by a high-speed camera justify the acceptance of such a model in a first approximation.

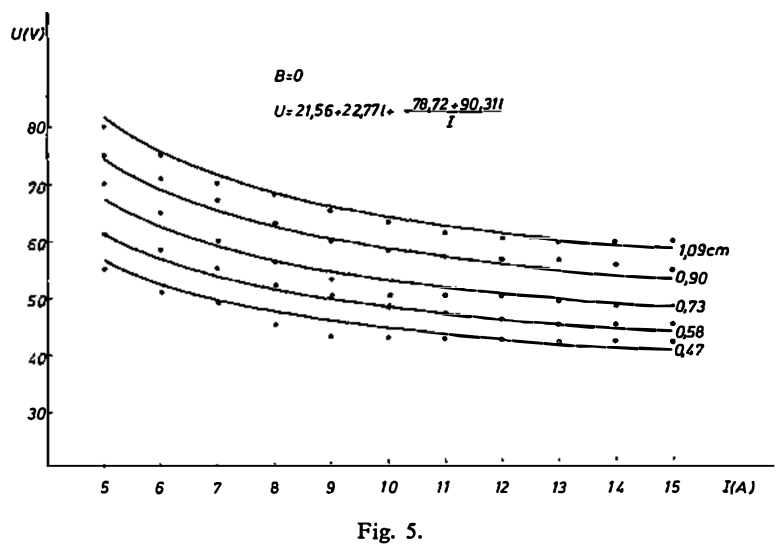

Fig. 5.

Fig. 5 shows the $U - I$ characteristics of the free-burning arc in the absence of the magnetic field. The arc current values were varied from 5 to 15 A and the distance from 0.5 to 11 mm. Calculation of the coefficients a, b, c and d for this case yields

$$U = 21.56 + 22.77\,l + \frac{78.72 + 90.31\,l}{I}. \tag{9}$$

When inhomogeneous magnetic field is applied to the arc, the $U - I$ characteristics of the arc change. The measurements were performed at the value of the vertical component of $B_z = 60$ Ga in the axis of the magnetic system and

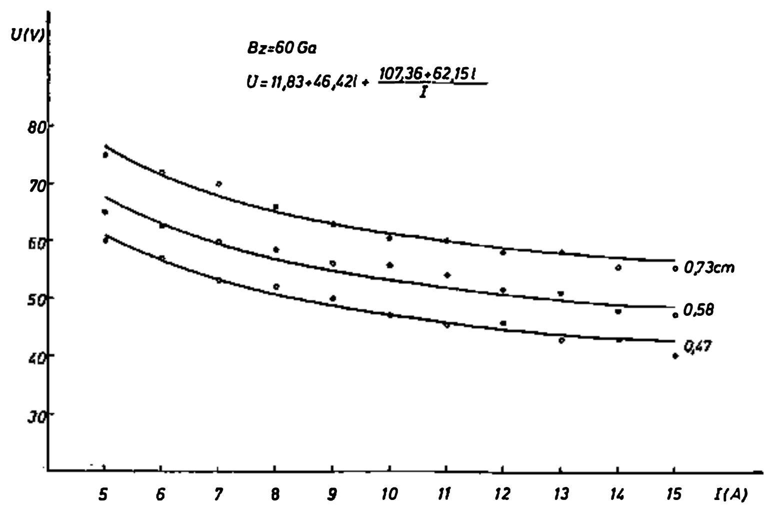

Fig. 6.

$B_r = 13$ Ga taken at the radial distance of $r = 2.5$ mm. The choice of these parameters of the magnetic field is justified by the fact that in the earlier investigations the greatest increase of the spectral line intensities has been achieved with such a configuration of the field.

The following expression is obtained for the $U - I$ characteristics in the presence of magnetic field

$$U = 11.83 + 46.42\,l + \frac{107.72 + 62.15\,l}{I}, \tag{10}$$

presented in Fig. 6.

From Equ. (1), evaluating in the usual way the maximal absolute errors in the variables, the maximum relative error $\Delta U/U$ is found to be 9.3%. The deviations from the curves represented by Equs. (9) and (10) are within the limits of this error.

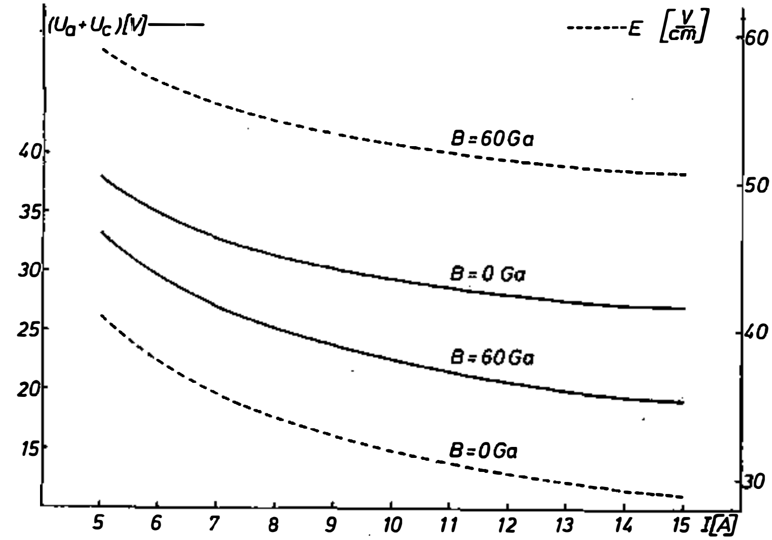

Fig. 7.

For the electric field in the column of a free-burning arc we have

$$E = 22.77 + \frac{90.31}{I}, \tag{11}$$

while in the case of the applied magnetic field

$$E = 46.42 + \frac{62.15}{I}. \tag{12}$$

The diagrams in Fig. 7 represent the dependences E (I) defined by Equs. (11) and (12).

The dependence of the electrode voltage drops on the arc current as shown in Fig. 7 is given for the case of a free-burning arc by the relation

$$U_a + U_c = 21.56 + \frac{78.72}{I}, \tag{13}$$

and in the presence of the magnetic field by the expression

$$U_a + U_c = 11.83 + \frac{107.36}{I}. \qquad (14)$$

For the power dissipated per unit length of the arc column in the absence and in the presence of the magnetic field the following expressions are obtained

$$\frac{P'}{l} = EI = 22.77\, I + 90.31, \qquad (15)$$

$$\frac{P'}{l} = 46.42\, I + 62.15, \qquad (16)$$

respectively presented in Fig. 8.

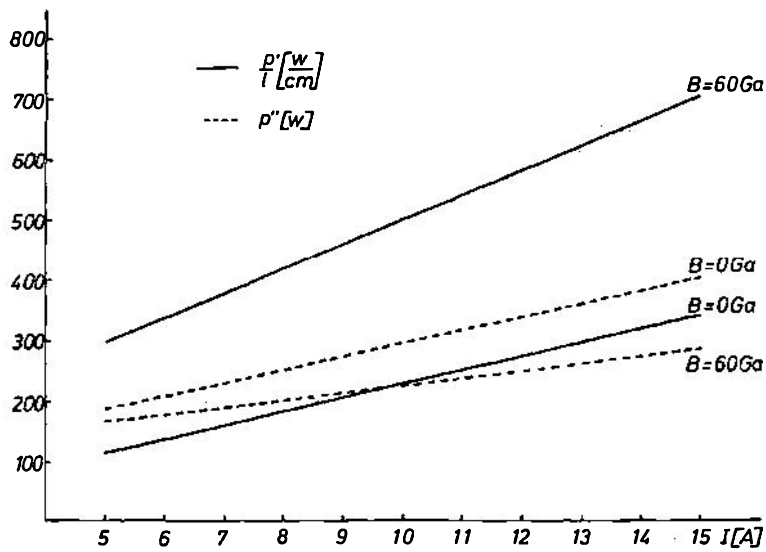

Fig. 8.

The dependence of the power dissipated in the region of the electrode voltage drops on the arc current in the absence and in the presence of the magnetic field is given by the following expressions

$$P'' = 21.56\, I + 78.72, \qquad (17)$$

$$P'' = 11.83\, I + 107.36, \qquad (18)$$

presented in Fig. 8 as well.

In order to gain a better insight into the influence of the magnetic field on total power, the measurements of the power were performed in the range of the axial component of the magnetic field from 20 to 160 Ga, and in the arc current range 6 — 16 A. In Fig. 9 the total arc power is given as a function of the axial component of the magnetic field, the arc current being taken as a parameter. Fig. 10 shows dependence on the arc current with the magnetic field as a parameter.

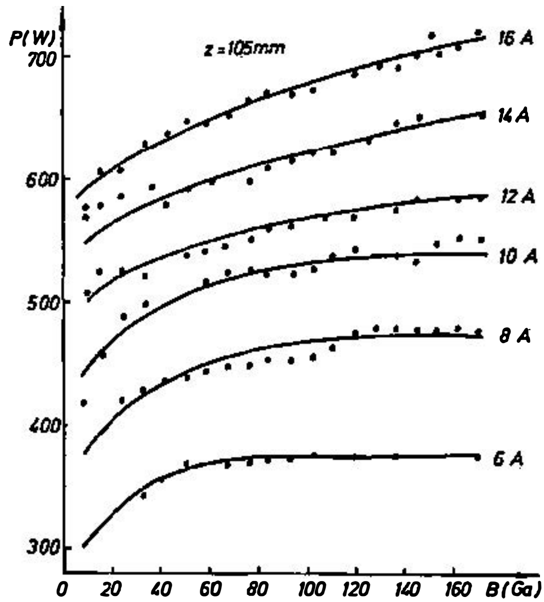

Fig. 9.

The effect of the geometry of the magnetic field on the total arc power has been investigated by measuring the power as a function of the axial component at different distances z of the arc from the magnetic pole, at a constant arc current of 12 A. The purpose of the study was to investigate the influence of the inhomogeneity of the axial component in the axial direction, and that of the ratio of the axial and radial components, on the total power of the arc. The results of these measurements are shown in Fig. 11, where from it may be seen that the points corresponding to the total arc power at different gradients and B_z/B_r ratios, i. e. at different distances z above the magnet pole, but at the same axial components are grouped around some mean value. It may be concluded that the influence of geometry of the magnetic field on the total arc power is not considerable.

Fig. 12 shows the total arc power as a function of rotation plasma column frequency. This diagram corresponds to that shown in Fig. 9. The frequency was measured in the arc current range 6—16 A and the magnetic field B_z range 20—140Ga.

5. *Discussion*

An arc rotating in an inhomogeneous magnetic field was observed under optimum conditions with respect to the rotation frequencies of the plasma column for spectrochemical determination.

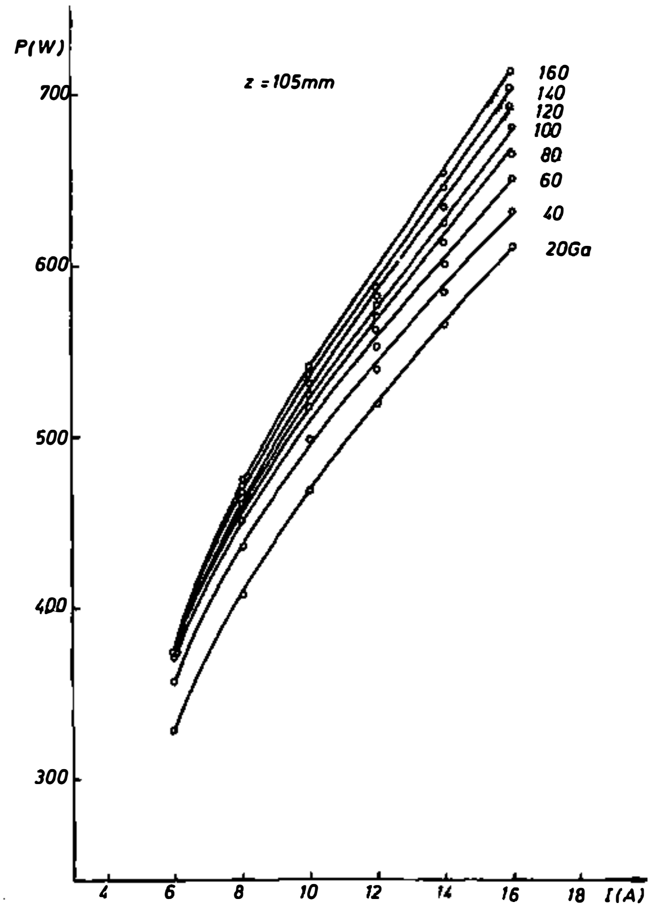

Fig. 10.

The obtained results show that the electric field in the plasma column is increased by applying an external magnetic field in the case of a rotating plasma, with respect to a non-rotating arc in the absence of the magnetic field. External magnetic field disturbs the motion of charged particles between electrodes, hence a stronger electric field is necessary to maintain a constant current. The ranges of electrode voltage drops in the magnetic field in the case of the rotating arc plasma are even smaller. The changes of the power dissipated per unit length of the plasma column and the changes of the power dissipated in the electrode region are found to behave in the same way (Figs. 7 and 8).

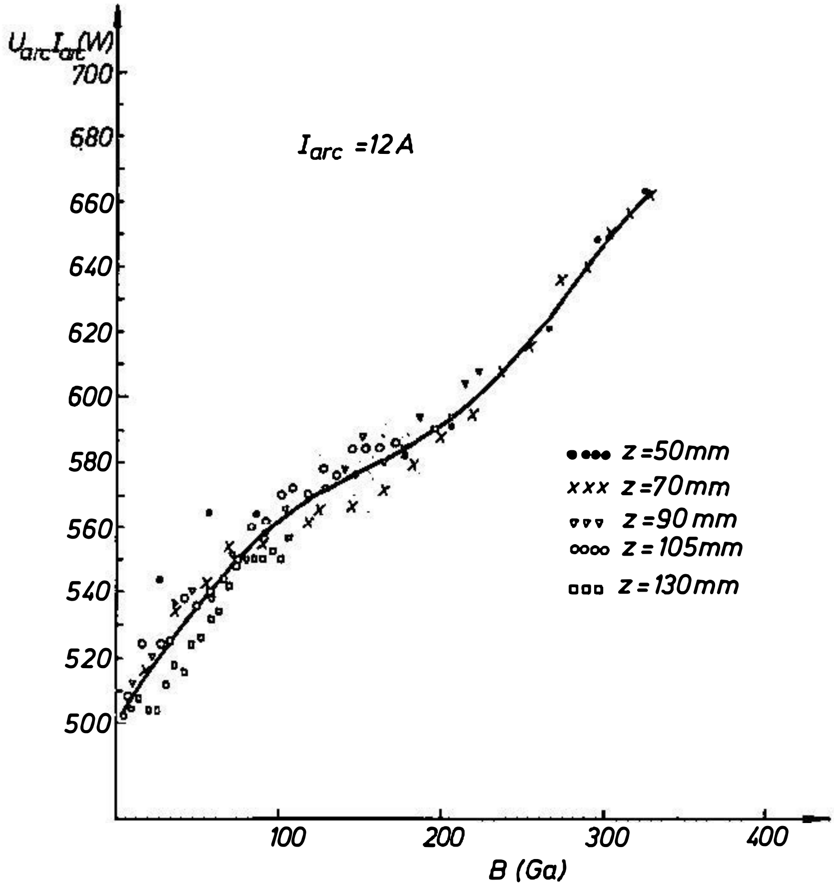

Fig. 11.

It can be seen that the total power depends on the arc current and on the magnetic field strength. The dependence of rotating frequency on the arc current and on the magnetic field[3-5], is given by the equation

$$f = \frac{I\,B}{k}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{19}$$

where k is a function depending on the properties of the plasma column. Some of these are: gas species, concentration of ions and neutrals, plasma temperature, electrode region processes, etc. Under steady working conditions, k can be taken as a constant. τ is a time constant, t is the time measured from the moment when the arc starts burning and plasma rotating. The exponential part describes the transition state. For the stationary state we have the frequency

$$f = \frac{IB}{k}. \tag{20}$$

The diagram in Fig. 12, relating the arc power either to frequency or to magnetic field and the arc current, enables us to obtain, by measuring only electrical parameters, the values of rotating plasma frequency. The dependence presented in Fig. 12 assumes k to be constant (Equ. 20). The parameter changes de-

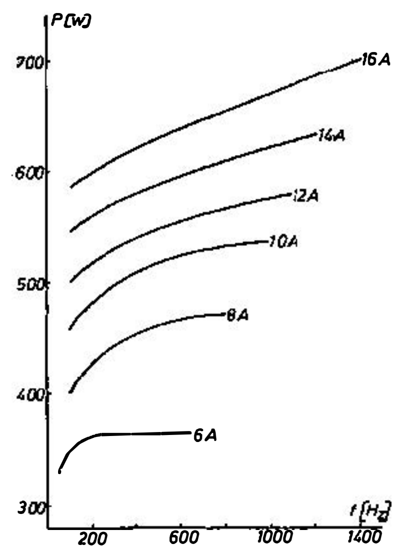

Fig. 12.

termining k (arc atmosphere, pressure, etc.) can change the value of k. That leads to the rotation frequency change, and to different effect of the magnetic field on the total arc power.

References

1) V. Vukanović, V. Georgijević, D. Vukanović and M. S. Todorović, Spectrochimica Acta, **24B** (1969) 535;
2) M. S. Todorović, V. Vukanović and V. Georgijević, Spectrochimica Acta **24B** (1969) 571;
3) M. S. Todorović, V. J. Georgijević and M. Zlatanović, Proc. Phenom. in Ioniz. Gases, Oxford, (1971) 214;
4) M. Zlatanović and M. S. Todorović, Proc. VI Yug. Symp. on Phys. of Ion Gases, (1972) 193;
5) M. S. Todorović and M. Zlatanović, Proc. VI Yug. Symp. on Phys. of Ion Gases, (1972) 189;
6) M. S. Todorović, M. V. Vukanović, V. M. Georgijević, T. A. Mihailidi and P. S. Torodović, Proc. IX Inter. Conf. on Phenom. in Ioniz. Gases, (1969) 321;
7) V. L. Granovski, Električeskii tok v gaze, Moskva, (1971) 218.

ELEKTRIČKE KARAKTERISTIKE ROTIRAJUĆEG LUKA S ELEKTRODAMA OD GRAFITA U MAGNETSKOM POLJU

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Sadržaj

Ispitivane su električke karakteristike luka koji gori pod uticajem' spoljašnjeg magnetskog polja čija je geometrija tačno određena. Određeni su parametri volt-amperske karakteristike. Ova karakteristika se daje uporedo i za slučaj kada nije primenjeno magnetsko polje te nema rotacije plazme. Ispitivan je uticaj magnetskog polja na prielektrodne padove napona, na električno polje u plazmi, na snagu po jedinici dužine luka, na snagu u prielektrodnim oblastima i na ukupnu snagu. Učinjen je pokušaj uspostavljanja veze između električnih parametara i frekvencije kojom rotira luk pod uticajem primenjenog magnetskog polja.