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ENERGY BALANCE OF SHORT FREE-BURNING ARCS AND THEIR ELECTRODES[1]

C. TESAŘ[2], J. PAUKERT[3], Brno

The authors try to find experimentally, the component of heat absorbed by a Cu electrode from a short free-burning arc at alternating current and low voltage. The other electrode is made of graphite. Discussion of results is presented.

ЭНЕРГЕТИЧЕСКИЙ БАЛАНС КОРОТКОЙ СВОБОДНО ГОРЯЩЕЙ ЭЛЕКТРИЧЕСКОЙ ДУГИ И ЕЕ ЭЛЕКТРОДЫ

В работе авторы делают попытку экспериментально определить составляющую тепла, поглощенного медным электродом, которое поступает от короткой свободно горящей электрической дуги переменного тока и произвольного напряжения. Второй электрод сделан из графита. Проведен анализ полученных результатов.

I. INTRODUCTION

The calculation of heat removal from the arc spot to the electrode is an important part of switchgear designing and it has been mentioned in the literature already [1] to [7]. The problem is solved as one-dimensional heat conduction

$$\frac{\partial T}{\partial t}=\frac{\lambda}{c}\frac{\partial^2 T}{\partial v^2}\quad [^\circ\mathrm{C}] \tag{1}$$

with a marginal condition $x=0$, $T=T_K$. Some authors [3], [4], [5] substitute for T_K a value equal or close to the temperature of the melting point of the electrode material, other authors (e.g. Babikov [2] or Tajev [7]), admit that T_K may reach even the temperature of boiling point of the corresponding material. The described method provides a good estimation of heat removal and temperature distribution in

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[2] Katedra fyzikální elektroniky PF UJEP, Kotlářská 2, 611 37 BRNO, Czechoslovakia.

[3] Výzkumný a vývojový ústav elektrických přístrojů (Switchgear Research Institute), Kratochvílova 19, 619 00 BRNO, Czechoslovakia.

an electrode for higher currents, especially for short-circuit currents of the order kA and higher. For low currents (when the arc spot does not cover the whole front surface of the contact) the above-mentioned calculation brings unrealistic high values of the removed thermal power, exceeding even the arc power, as has already been pointed out by Paukert [6].

This study has been worked out with the aim to gather experimental data on temperature distribution and energy balance in electrodes of free-burning arcs. The results can be used to improve switchgear designing.

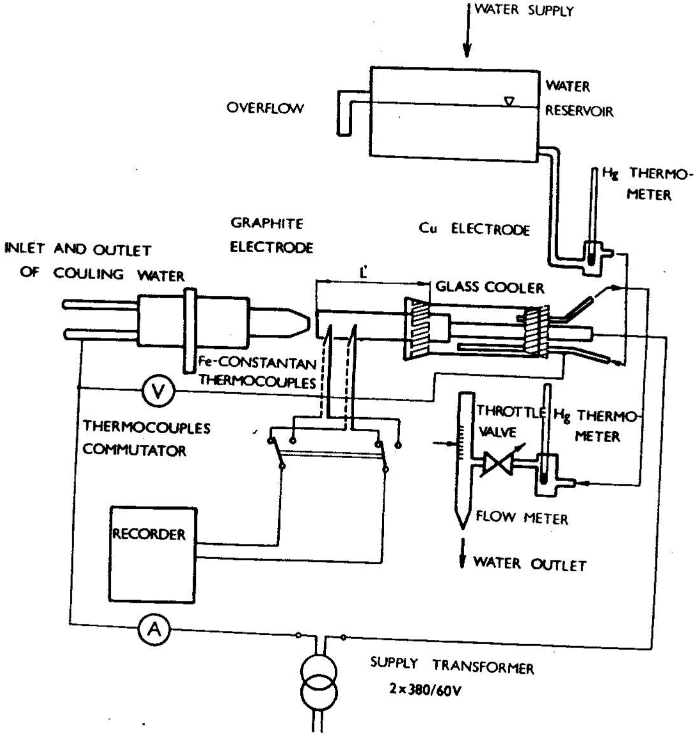

Fig. 1. Experimental setup.

II. EXPERIMENTAL SETUP

The experiments were carried out in the setup in Fig. 1. The arc was supplied from a welding transformer and it was burning at currents from 40 to 70 A with arc voltages from 15 to 35 V. The measured electrode was made of copper and the other of graphite. Both electrodes were provided with coolers, however, the inlet and outlet temperatures and the amount of cooling water were measured on the copper electrode only. The arc was not longer than 1 or 2 mm so that the amount of heat absorbed by air was minimal. The measured Cu electrode was provided with a series of Fe-constantan thermocouples enabling to measure the temperature distribution along the length of the electrode $T=f(x)$. The thermal power transferred from the measured electrode to the cooling water (in the point $x=L'$) was evaluated from the difference of inlet and outlet temperatures and from the amount of cooling water. The measurements were carried out after the steady state of temperature rise had been reached.

III. RESULTS

The distribution of temperature along the length of the electrode, the electrical input of the arc Q_0 and the thermal power transferred by conductance from the electrode to the cooler (in the point $x=L'$) Q_1 were determined directly from experiments.

A further step was to calculate the energy balance in separate sections of the electrode. Temperature distribution was linearized by a broken line. The method of average temperatures was used.

The components of the energy balance were determined from the following equations:

— thermal power transferred by conductance Q_1

$$Q_1 = S\lambda\frac{dT}{dl} = \frac{\pi d^2}{4}(395-0.07\,T_p)\frac{T_1+T_2}{l} \quad [\mathrm{W, m^2, Wm^{-1}K^{-1}, K, m}] \qquad (2)$$

where d, S are diameter and cross-section of the electrode, λ is thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$], T_p average temperature of the rod [°C] $T_p=(T_1+T_2)/2$, T_1, T_2 are temperatures at the end points of the section in question [°C] and l is the length of the section [m].

The thermal conductivity is approximated according to Šorin [10] by the empiric equation

$$\lambda = (395-0.07\,T_p) \quad [\mathrm{Wm^{-1}K^{-1}, °C}] \qquad (3)$$

— thermal power transferred by convection to the surrounding air Q_2

$$Q_2 = \pi d l \alpha (T_p - T_0) \quad [\mathrm{W}] \qquad (4)$$

where α is heat-transfer coefficient [$\mathrm{W\,m^{-2}K^{-1}}$] and T_0 is the temperature of the surrounding air [°C].

In the applied experimental conditions the coefficient α was variable along the electrode length $\alpha=f(x)$. The reason lay in the variable temperature of the rod as well as in the non-uniform speed of the air flow caused by the discharge itself. To calculate the component Q_2 the corresponding value α had to be determined by iteration. In consequence of the limited number of points small deviations appear in temperatures of different points in comparison with the measured ones (see Fig. 2);

— thermal losses caused by radiation Q_3

$$Q_3 = \pi d l \varepsilon \sigma (T_p + 273)^4 \quad [\mathrm{W}] \tag{5}$$

where ε is emissivity of the electrode (according to earlier experiments the value $\varepsilon = 0.45$ was used for heavily oxidized copper) and σ is the Stefan-Boltzman constant ($\sigma = 5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-1}}$).

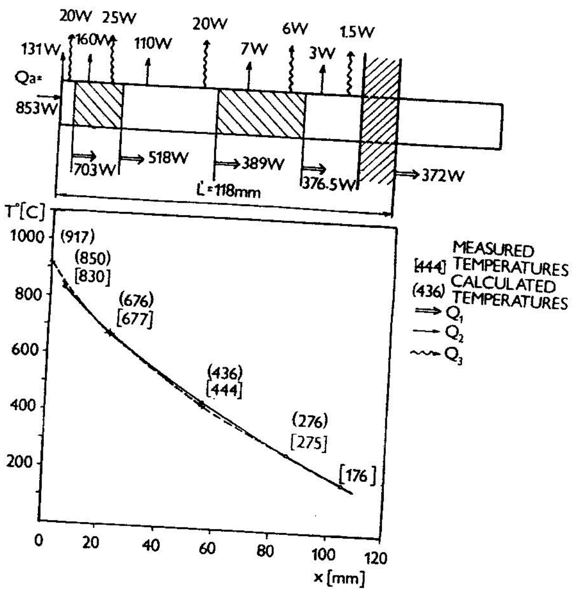

Fig. 2. Graphical representation of temperature and heat flows distribution from the copper rod (diameter 15.9 mm, active length $L' = 118$ mm).

In contrast to the preceding two components Q_1 and Q_2 an error may appear at the component Q_3 when using the method of average temperatures instead of the exact method by integration. As in our measurements the component Q_3 was not dominating and with regard to the accuracy of determining the individual components of energy balance — estimated to about 10% — it was not considered necessary to use the more accurate method of calculation.

One of the measurements, evaluated as described above and serving as an example, may be seen in Fig. 2.

Table 1

Energy balance of a.c. short free-burning arcs in steady state between Cu and C electrodes

Dimensions of Cu electrode	Ø 19.9 mm $L' = 160$ mm	Ø 15.9 mm $L' = 165$ mm	Ø 15.9 mm $L' = 135$ mm	Ø 7.8 mm $L' = 170$ mm	Ø 7.8 mm $L' = 115$ mm	Ø 7.8 mm $L' = 55$ mm
corresponds approx. to current carrying capacity [A]	630	400	400	125	125	125
Q_0 [W] (measured)	1451	1020	1408	1156	1156	1156
q_1 [%] (measured)	31.43	34.60	26.42	4.50	5.97	16.43
q_2 [%] (calculated)	23.02	37.65	29.19	20.50	20.41	11.67
q_3 [%] (calculated)	5.65	10.78	4.97	3.20	2.68	2.25
q_A [%] (calculated)	60.10	83.04	60.58	28.20	29.06	30.36
q_C [%] (estimation according to separate measurements)	12 to 20	12 to 20	12 to 20	12 to 20	12 to 20	12 to 20
$q_p + q_v$ [%] (complement to 100%)	28 to 20	5	27.5 to 19.5	60 to 52	59 to 51	58 to 50
$T_{x=5\,\mathrm{mm}}$ [°C] (measured)	730	948	830	1020	907	($T_{x=10}$) 833
$T_{x=0}$ [°C] (extrapolation)	755	1060	920	1130	1060	1060

The energy balance was compiled from relative components with regard to Q_0, i.e.

$$q_i = \frac{Q_i}{Q_0} 100 \quad [\%, \mathrm{W}]. \tag{6}$$

When compiling the arc energy balance according to Fig. 3, the components Q_2 and Q_3 were taken as the total of the partial components of all the individual sections. The component of heat flowing to the graphite electrode q_C was evaluated from separate series of experiments [8] to about $q_C = 20$ to 12%.

The components q_P (absorption in the surrounding air) and q_V (evaporation of electrodes) were determined as a complement to 100%.

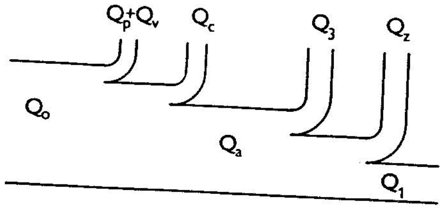

Fig. 3. Diagrammatic representation of energy balance of short a.c. free-burning arc and its electrodes. Q_0 electric input supplied to the arc, Q_P thermal power absorbed in the air, Q_V thermal power for evaporation of Cu electrode, Q_C thermal power transferred to the graphite electrode, Q_a thermal power transferred to the copper electrode, Q_3 thermal losses from the surface of Cu electrode by radiation, Q_2 thermal losses from the surface of Cu electrode by convention to the surrounding air, Q_1 thermal power transferred by conductance from Cu electrode to the cooling water (in the point $x = L'$).

The determined components of energy balance for the used dimensions of electrodes are summed up in Tab. 1. This table is complemented by temperatures measured at the depth $x = 5$ mm under the electrode face and by extrapolated values of temperatures on the electrode face ($x = 0$).

IV. DISCUSSION OF RESULTS AND CONCLUSION

Some conclusions, resulting from the data collected in Tab. 1, may be drawn from the analysis of the general equation for heat conduction through a semi-infinite rod. There is especially the tendency of the component q_a to increase with increasing S and the tendency of the component q_1 to decrease with increasing active length of the rod L'.

Further it may be stated that with the increasing cross-section of the electrode the components q_1 and q_3 show an increasing tendency as well and the components ($q_P + q_V$) show a decreasing tendency. The temperature of the electrode face achieved approximately the temperature of the melting point of copper in case of electrodes with the smallest cross-sections and it decreased in electrodes with larger cross-sections; this is caused by the low thermal resistance of the rods with large cross-sections, enabling to remove higher heat flows Q_a and Q_1, which is also in close connection with the decrease of components ($Q_P + Q_V$) in electrodes with large cross-sections.

The results obtained with the electrode of the diameter 15.9 mm and the length $L' = 165$ mm do not quite fit in the described framework. The reason is that this electrode was the only one the front part of which was melting and dripping during experiments. The most probable reason was a deviation in composition and a consequent change of physical properties in contrast to the other used electrodes.

This contribution helps to gain further insight into thermal processes and energy balance of electric arc and after further mathematical elaboration it may be useful for application to electric switching arcs, from the standpoint of dimensioning their current paths and quenching chambers.

REFERENCES

[1] Keselrung, F.: *Theoretische Grundlagen zur Berechnung der Schaltgeräte.* De Gruyter Co. Berlin 1943.

[2] Babikov, M. A.: *Wichtige Bauteile elektrischer Apparate.* Bd. I. VEB Verlag Technik, Berlin 1954.

[3] Řezníček, J.: *Elektroenergetika.* ČVUT Praha 1951.

[4] Trusca, V.: Electrotechnica (Bucuresti) *21* (1973), 464.

[5] Zaleskij, A. M., Kukelov, G. A.: *Teplovyje rasčety električeskich apparatov.* Energij, Leningrad 1967.

[6] Paukert, J.: Elektrotechnický obzor *58* (1969), 255.

[7] Tajev, I. S.: *Električeskije kontakty i dugogasitelnyje ustrojstva apparatov nizkovo napriaženija.* Energija, Moskva 1973.

[8] Tesař, C., Paukert, J.: Research Report VÚEP 8–0081 (1984).

[9] Tesař, C.: Folia fac. sci. nat. UJEP Brno, Physica, *IX* (1968), 63

[10] Šorin, S. N.: *Sdílení tepla (Heat transfer).* SNTL Praha 1968.

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