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ENERGY BALANCE OF AN AC ARC BURNING ON VERTICAL HORN—SHAPED ELECTRODES AT HIGH CURRENTS[1])

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The paper deals theoretically and experimentally with the energy balance of an AC arc electrode at high currents. The cooling of horn-shaped electrodes is experimentally studied. On this basis the time constants for evaluation algorithms for initial temperature, heat-transfer coefficient α and thermal absorption in the electrodes are calculated.

I. INTRODUCTION

The heat absorbed in arc electrodes is mainly generated in arc roots by converting a part of the electrical energy in the region of the electrode-fall potentials into heat [1]. The lesser part of the transmitted heat originates in the arc column. The transfer to the electrodes is due to the enormous heat conductivity of the plasma and due to its heat radiation [2].

The most used method for evaluating the absorption in the electrodes is the calorimetrical method. It is suitable especially for removable electrodes at lower currents or for water-cooled electrodes [3]. In case of horn-shaped electrodes (Fig. 1.) at high currents it is possible to use the method of extrapolating the maximal average temperature in all the volume of the horns $T(r, t)$ immediately after the extinction of the pulse arc.

The appropriate calculations and extrapolation can be carried out only on the basis of the knowledge of the course and the mathematical description of the cooling of the studied electrode, i.e. from the course of temperature in the given place of the surface and in the given time. In our case, the arc-burning time did not exceed 20 ms.

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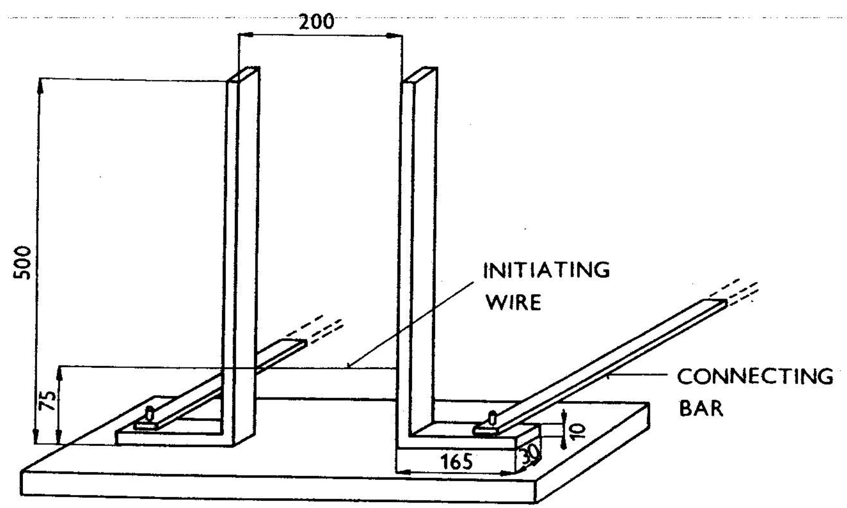

Fig. 1. The experimental arrangement of the horn-shaped electrodes.

II. THEORETICAL ANALYSIS

The problem of cooling vertical horn-shaped electrodes and of determining the quantity of the originally absorbed heat can be most appropriately modelled as the cooling of an infinitely long cylinder, which theory is well elaborated [4]. If we take the cylinder cross-section equal to the prismatic horn-shaped electrode one, the model will be almost perfect with one difference only, namely that the cylinder has a minimum surface.

Fourier's solution of the differential equation of heat conduction in cylindrical coordinates

$$\frac{\partial \Theta}{\partial t} = a\left(\frac{\partial \Theta}{\partial r} + \frac{1}{r}\cdot\frac{\partial \Theta}{\partial r}\right) \qquad (1)$$

leads to the solution of a time equation and Bessel's differential equation. In eq. (1) there is $a = \lambda / c\varrho$ "the temperature conductivity", where $\lambda_{Cu} = 393\ \mathrm{W\,m^{-1}\,K^{-1}}$ is the thermal conductivity, $c_{Cu} = 390\ \mathrm{J\,kg^{-1}\,K^{-1}}$ is the specific heat, $\varrho_{Cu} = 8.9 \times 10^3\ \mathrm{kg\,m^{-3}}$ is the density.

The boundary conditions of eq. (1) are: a) the initial temperature distribution in the electrode — we assume the same temperature in the whole volume of the electrode for $t = 0$ there is $T(r, t) = T(r) = \text{const.}$, b) the boundary condition for the thermal effect on the electrode — we assume that the electrode surface is surrounded by quiet air with temperature $T(ok)$ and with a heat-transfer coefficient $\alpha\ [\mathrm{W\,m^{-2}\,K^{-1}}]$.

The particular solution of eq. (1) is

$$\Theta(r, t) = \Theta_a \sum_{i=1}^{\infty} \frac{2 J_1(m_i) J_0\left(\frac{m_i}{R} r\right)}{m_i [J_0^2 m_i + J_1^2 m_i]} \mathrm{e}^{-m_i^2 F_0} \qquad (2)$$

By substitution $r = R$ we obtain equation for a surface temperature.

In eqs. (1) and (2) $\Theta(r, t) = T(r, t) - T(ok)$ denotes the difference of temperatre in the given place in the cylinder $T(r, t)$ and the temperature of the surroundings $T(ok)$ and $\Theta_a = \Theta(r) = \Theta(R)$ for $t = 0$. Θ_a, $\Theta(r)$, $\Theta(R)$ are temperature differences relating to the cylinder axis, an arbitrary point of the cylinder, and the cylinder surface at the starting moment.

Further, m_i is the solution of the transcendental equation

$$m \frac{J_1(m)}{J_0(m)} = Bi, \qquad (3)$$

where Bi the Biot number for the cylinder, is $Bi = \frac{\alpha r}{\lambda} \ll 1$, ($r = 10^{-2}$ m, $\alpha = (4 - 11)\ \mathrm{W\,m^{-2}\,K^{-1}}$, $\lambda_{Cu} = 393\ \mathrm{W\,m^{-1}\,K^{-1}}$), J_0 and J_1 are Bessel functions of the first kind, zero and first order, is a heat-transfer coefficient for quiet air. For very small Bi the eq. (3) has usually one solution m_1 only. F_0 denotes the Fourrier number for the cylinder

$$F_0 = \frac{\lambda}{c\varrho} \cdot \frac{t}{r^2} \qquad (4)$$

At small $Bi \ll 1$ the constant in eq. (2):

$$\frac{2 J_1(m_1) J_0(m_1)}{m_1 [J_0^2 m_1 + J_1^2 m_1]},$$

where $r = R$ is approximately equal to 1 [4]. For the Cu bar $R^2 = R_{eq}^2 = \frac{P}{\pi}$ is in eq. (4). P is the cross-section of the Cu bar, the horn-shaped electrode.

For a measured temperature difference $\Theta(R, t)$ the searched maximal temperature $T(R)$ in the time $t = 0$ can be expressed as

$$T(R) = T(ok) + \Theta(R, t)\,\mathrm{e}^{t/t_c}, \qquad (5)$$

where $1/t_c = m_1^2 \frac{\lambda}{c\varrho} \cdot \frac{1}{R^2}$ [s^{-1}], t_c is the time constant which is derived from the material properties λ, c, ϱ, the dimensions of the electrode and the heat-transfer coefficient α.

The approximative value of the time constant t_c can be obtained from the relation for convective heat transfer:

$$Q_a = \alpha S \Theta(R) t_c$$

and from the thermal capacity:

$$Q_c = M c \Theta(R),$$

where M denotes the electrode mass and S is the surface. For $Q_a = Q_c$ when $T(R, t_c) = T(ok)$ there is:

$$t_c = Mc/\alpha S. \tag{6}$$

The comparison of the results obtained from eqs. (5) and (6) shows that the calculation according to eq. (6) is sufficiently accurate.

From the formal point of view the time constant t_c in eq. (5) represents the time during which the temperature difference of the electrode change e-times. Physically in eq. (6) t_c represents the time which is needed for the total cooling of the electrode at a constant temperature difference $\Theta(R) = T(R) - T(ok) =$ = const.

We suppose also that for the course of the cooling the eq. (5) is valid. For two measurements of surface temperature in two instants, $t_1 < t_2$, there applies

$$\frac{\Theta(R, t_1) e^{t_1/t_c}}{\Theta(R, t_2) e^{t_2/t_c}} = 1. \tag{7}$$

By taking the logarithm of (7) and after arrangements we get

$$t_c = \frac{t_2 - t_1}{\ln \Theta(R, t_1) - \ln \Theta(R, t_2)}. \tag{8}$$

The cooling of the whole electrode is caused both by convectional heat transfer and by heat radiation $Q_\varepsilon \sim f(T^4)$. When the temperature differences are small, i.e. $\Theta(R, t)$ is only several units of K, it is true that the heat losses by radiation are smaller, but within the same order as the losses caused by convection into the surroundings (decribed by the heat-transfer coefficient α). When interpreting the experimentally obtained cooling curves, both types of losses are included into the one-time constant t_c, together with the heat conduction within the material.

III. RESULTS AND DISCUSION

From the theory it follows that when we know the cooling curve of a given electrode and when we measure its surface temperature $T(R, t)$ at a certain time instant and supposing a homogeneous heating of the electrode, it is possible to calculate the original temperature immediately after heating up. In the case when the electrode has been heated locally on one of its ends, it is necessary to measure the temperature aproximatelly in the half of its length where the average temperature was supposed, which has been experimentally verified [5].

In Fig. 2. the cooling curves of a horn-shaped electrode are shown. It has been uniformly heated in its whole volume and during the cooling it was suspended in air. For the model the cylindrical electrode $R = R_{eq}$ is in agreement with the calculated value $\alpha = 8\,W\,m^{-2}K^{-1}$. From the measured curve there follows $t_c = 44.8$ min and $\alpha = 4.7\,W\,m^{-2}K^{-1}$.

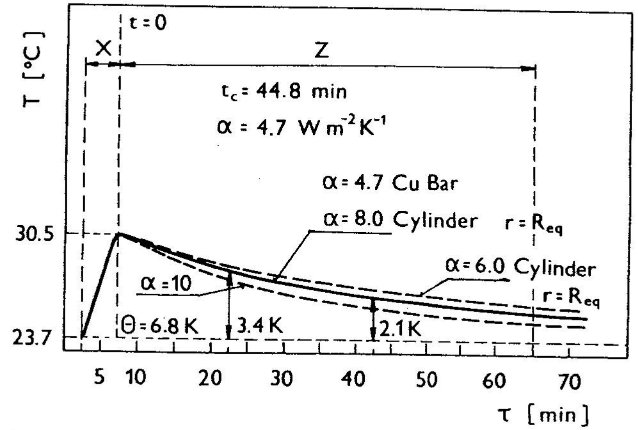

Fig. 2. The cooling curves of the horn-shaped electrode. The electrode was uniformely heated in the whole volume. The measured cooling curve for the Cu-bar: $t_c = 44.8$ min $\Rightarrow \alpha =$ $= 4.7\,W\,m^{-2}K^{-1}$. For the model of the cylindrical electrode $r = R_{eq}$ the calculated value for $\alpha = 10;\ 8;\ 6\,W\,m^{-2}K^{-1}$.
x ... the time of the heat on,
z ... the time tested according to eq. (8) for $t_c = 44.8$ min.

In Fig. 3. there is an experimental cooling curve of the electrode, mounted on an insulator base plate with a connecting Cu bar with a cross-section of $124\,mm^2$. The temperature was measured in the place where the wire begins, approximatelly in the half of the electrode length. The evaluated values are $t_c = 27.7$ min and $\alpha = 7.7\,W\,m^{-2}K^{-1}$. The higher value of α against $\alpha = 4.7$ for the case without connecting bar (Fig. 2.) is caused by the transformation of the thermal conductivity λ into α.

The results of the above mentioned analysis of the electrode response to the thermal impulse, in the case when the electrode has been heated locally at one of its ends, $t_c = 27.7$ min according to Fig. 3., were used for a critical evaluation of an earlier energy balance of horn-shaped electrodes in the high-current range [6]. The experiments were performed in the arrangement shown in Fig. 1. on Cu horn-shaped electrodes with a cross section of 10 × 30 mm, a total length of 650 mm, spaced 200 mm. The ignition of the arc has been carried out by means of melting the Cu wire with a varying cross-section. The arc currents ranged from 10 to 120 kA at 550 V, 50 Hz. The arc-burning time did not exceed 20 ms.

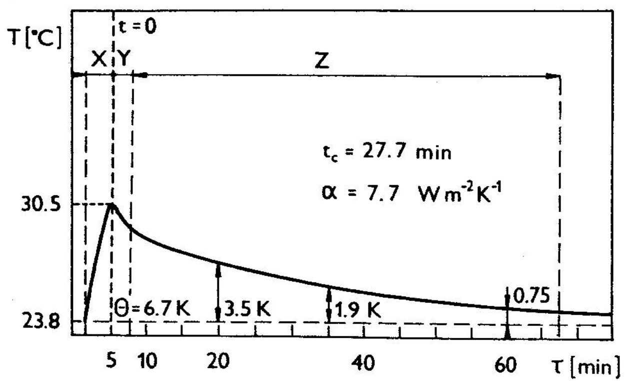

Fig. 3. The measured cooling curve for Cu-bar electrode mounted on an insulator base. The electrode was connected with a power source by a Cu-bar (cross section 124 mm^2). The time constant was: $t_c = 27.7$ min ⇒ $\alpha = 7.7\,\mathrm{W\,m^{-2}\,K^{-1}}$.

x ... the time of the heat on,
y ... the real time for establishing the temperature equilibrium,
z ... the time tested according to eq. (8) for $t_c = 27.7$ min.

The energy balance contained the following components: A_{el} supplied arc energy, evaluated from oscillograms, taken over from [6], A_E energy absorbed in electrodes, calculated from excessive temperatures in both electrodes by means of the analysis suggested in this paper. The original values in [6] were overestimated, A_{zar} irradiated energy, avaluated from average values of 3 bolometers. Original values from [6] has been taken over without a correction A_{tl} is the energy of the pressure wave, evaluated by means of a pressure detector. The values from [6] were reduced to 90 %, taking into account the space angle shielded by the electrodes, A_{vzd} energy absorbed in the surrounding air. In the original publication [6] was not taken into account. This component was evaluated from the formula.

$$A_{el} = A_E + A_{zar} + A_{tl} + A_{vzd}.$$

The relative components of the energy balance: $a_E = A_E/A_{el}$, $a_{zar} = A_{zar}/A_{el}$, $a_{tl} = A_{tl}/A_{el}$, $a_{vzd} = A_{vzd}/A_{el}$, [%] are shown in Figs. 4. to 7. Experimentally evaluated values show a considerable scatter. Therefore the zone of the measured values is represented by the lower and the upper envelope in Figs. 4. to 7. The authors believe that this kind of representation contains more useful information for practical applications than a single curve obtained by regression.

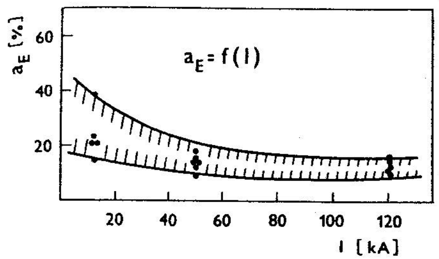

Fig. 4. The relative component of the energy balance $a_E = A_E/A_{el}$ [%], where A_E is the energy absorbed in the electrodes, A_{el} is the supplied arc energy.

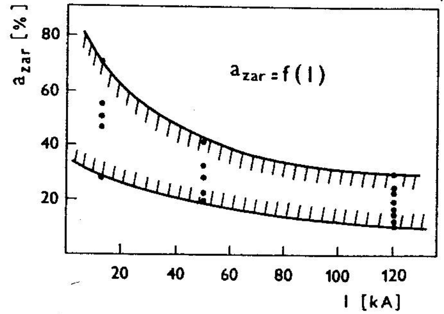

Fig. 5. The relative component of the energy balance $a_{zar} = A_{zar}/A_{el}$ [%], where A_{zar} is the irradiated energy of the arc, A_{el} is the supplied arc energy

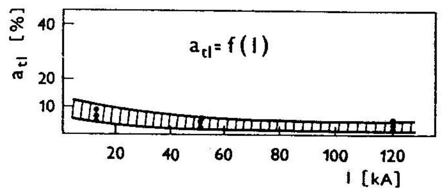

Fig. 6. The relative component of the energy balance $a_{tl} = A_{tl}/A_{el}$ [%], where A_{tl} is the energy of the pressure wave, A_{el} is the supplied arc energy.

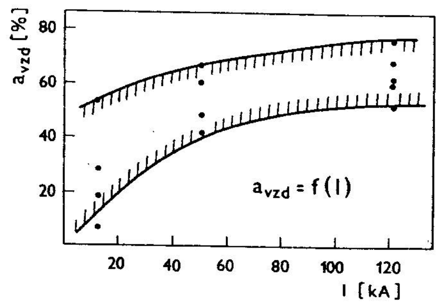

Fig. 7. The relative component of the energy balance $a_{vzd} = A_{vzd}/A_{el}$ [%], where A_{vzd} is the energy absorbed in the surrounding air, A_{el} is the supplied arc energy.

The components a_E, a_{zar}, a_{tl} have with increasing current a decreasing tendency. The component a_{vzd} increases with increasing current. This behaviour of the individual components is in agreement with a previously published energy balance measured on the circuit breaker, the contactor and on the electrodes [7, 8, 9].

The component of the energy absorbed in the electrodes A_E is directly proportional to the product of the arc current and the electrode voltage drop, which can be regarded as constant. The component A_E is therefore linearly dependent on the current, meanwhile in the arc the supplied energy A_{el} increases faster than linearly because the experiments were carried out in the current range where the arc-VA characteristic is increasing [10]. The relative component a_E therefore decreases with increasing current.

The components of the irradiated energy A_{zar} and of the pressure wave energy A_{tl} are increasing only little with the current, thus the corresponding relative components a_{zar} and a_{tl} have a decreasing tendency. The component a_{tl} had even a very low value.

The component of the energy absorbed in air A_{vzd} includes not only the convective transfer from the arc column, but the recombination energy and other components united with microprocesses in the arc column as well. The optical observation [6] showed that in the current range between 10^3 and 10^5 A the volume of the arc plasma rapidly increases, especially in connection with the rapid fluctuations of the arc shape and with its high mobility. The ascertained increasing tendency of the component a_{vzd} is therefore not surprising.

The measured values of the components a_{zar} and especially a_{vzd} show a considerable scatter. The assessed accuracy of the individual components A_E, A_{zar}, A_{tl}, A_{vzd} is about 20 %.

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