Antoni Sawicki, Maciej Haltof

Selected Methods Used in Experimental Determination of Near-Electrode Voltage Drops of Electric Arcs.

Part 1: Direct Methods Used in Determination of Near-Electrode Voltage Drops

Abstract: The article discusses the primary difficulties encountered when experimentally determining near-electrode voltage drops of high pressure electric arcs, presents the classification of measurement methods and various variants of direct and indirect measurements (known from reference publications and developed by the authors of the article).

Keywords: electric arc, cathodic voltage drop, anodic voltage drop, arc diagnostics

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Introduction

Most experimental tests of near-electrode voltage drops concern the “fastening” of low-current arc to electrodes (I < 10 A). This results from the necessity of developing improved light discharge sources [1-4]. Significantly fewer reference publications are concerned with higher currents (I > 100 A), which are particularly important in the operation of welding machines, where the amount of heat emitted in a short arc column is commensurable with the amount of heat emitted in near-electrode layers. In addition, the efficiency of heat transfer from these layers to electrodes and elements being cut or joined is higher than from an arc column, where a lot of heat gets dissipated in the environment.

Due to very thin cathodic and anodic layers as well as very high gradients of voltage and temperature, the obtainment of reliable experimental data related to the physical parameters of these layers is very difficult, particularly as regards welding arcs, where melting and boiling electrodes are characterised by very unstable shapes of surfaces, causing permanent movements of anodic and cathodic areas in the space. In such cases, the performance of experimental tests requires undertaking various activities aimed to stabilise arc “fastening” to an electrode and, often, stabilising the position of a plasma column.

There are many methods for the experimental determination of near-electrode electric arc voltage drops. They can include separate determinations of individual drops (anodic or cathodic) or the sum of voltage drops. Usually, determining the sum of near-electrode voltage drops is significantly simpler than determinations of individual components of such a sum. For this reason, the knowledge of at least one component is considered as a great facilitator when determining the value of the other voltage drop components. Methods of the experimental determination of near-electrode voltage

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dr hab. inż. Antoni Sawicki (PhD (DSc) hab. Eng.), Professor at Częstochowa University of Technology;
mgr inż Maciej Haltof (MSc Eng.) – Częstochowa University of Technology, Faculty of Electric Engineering

drops can be divided into various groups. As regards the measurement technique, methods are divided into the following:
- direct methods,
- indirect methods.

In direct methods, measurements of searched voltage drops involve the use of voltmeters, oscilloscopes, voltage transducers etc. In turn, indirect methods are based on meters or transducers of such non-electric quantities as temperature, emission spectrum, cooling agent mass stream etc.

As regards, the effect of a measurement system on arc, methods are divided into the following:
- non-disturbance methods,
- disturbance-introducing methods.

In non-disturbance methods, levels of disturbances introduced to parameters of plasma or electrodes are usually negligible (below the level of natural internal disturbances) and their duration is very short. Non-disturbance methods include spectroscopic and pyrometric methods as well as measurements of arc trace size on electrodes etc. In turn, in disturbance-introducing methods, disturbances are introduced either into an arc column area or in the electrode area. Arc column disturbances primarily include arc column length changes or unintended thermal state disturbances introduced by probes. In turn, disturbances of an electrode state are concerned with the external effect on temperature distribution, chemical composition of materials, number of active arc spots etc.

As regards rates of processes in near-electrode layers and related rates of measurements, methods are divided into the following:
- static methods,
- dynamic methods.

In static methods, theoretical times of observations and introductions of disturbances can be of any duration. However, in practice, arc (and also electrode) parameters change permanently, even in spite of applied stabilisation of a source, which excites current in a circuit with arc. Due to very low values of arc time constants in various gases and at various temperatures of the environment ($10^{-6} \div 10^{-3}$ s), it is possible and desirable to perform quick measurements. Dynamic methods utilise current and voltage waveforms during the initiation and extinction of arcs in circuits with commutation. Similar to tests of processes in the conditions of AC arcs, the recording of electric quantities should be performed with a high sampling frequency of measurement signals.

Direct methods of experimental determination of near-electrode voltage drops

Method of quick arc extension until arc break

This method consists in repeated and very quick pulling apart of electrode contact surfaces with stepped current increasing. After exceeding a certain boundary value, it is possible to observe arc ignitions on the oscilloscope monitor

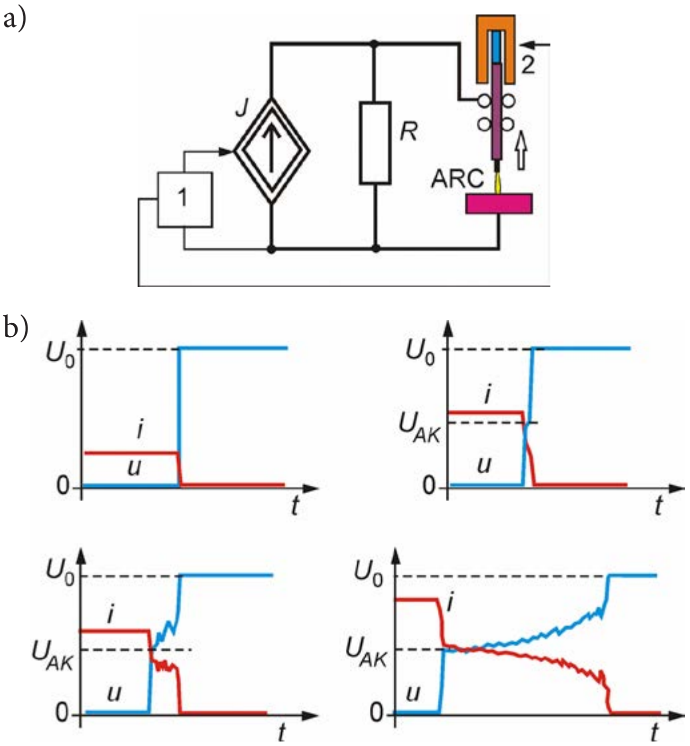

Fig. 1. Implementation of the method of quick arc extension for determining the sum of near-electrode voltage drops: a) schematic diagram of a measurement system (1 – system for controlling a power source J and electromagnetic drive 2); b) examples of electric waveforms in a circuit with stepped current increase and electrodes periodically pulled away

or screen, followed by their extensions and (after exceeding certain lengths) extinctions (Fig. 1). The area of bends of voltage waveforms in time enables the determination of a searched sum of near-electrode voltage drops U_{AK} [5].

Method of arc shortening until the short-circuiting of electrodes

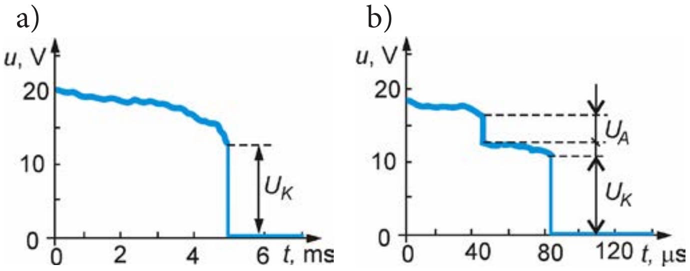

Fig. 2. Voltage waveforms on arc burning between electrodes during their approach until the short circuit: a) determination of cathodic voltage drop U_K during relatively slowly approach of electrodes; b) determination of anodic U_A and cathodic U_K voltage drops during very fast approach of electrodes

The method of determining voltage drops by approaching electrodes until a short circuit is based on the assumption that if the value of current is constant $I = \text{const.}$, changes of arc lengths do not affect the characters of near-electrode processes. However, a small distance between electrodes favours a change of the arc "fastening" point on electrodes (moving to the side surface) and affects the shape of arc.

During relatively slow approach of electrodes until their short circuit, it is possible to record [6] one collapse of diagrams $u(t)$ corresponding to a near-cathode voltage drop (Fig. 2a). In turn, during a very fast approach of electrodes until their short circuit, it is possible to record two collapses of diagrams, corresponding to first, anodic, and next cathode voltage drops (Fig. 2b). An anodic voltage drop is less sensitive to current values that a cathodic voltage drop.

The deliberations below take into consideration electric arcs with DC excitation. They usually correspond to families of voltage-current characteristics presented in Figure 3 and described by the following general dependence:

$$U(I,L)=U_{AK}+U_{col}(I, L) \tag{1}$$

where U_{AK} – sum of near-electrode voltage drops; U_{col} – voltage drop on an arc column. In individual cases, voltage on a column can be approximated using the following formulas:

$$U_{col}(I,L)=\frac{P_M(L)}{I}+U_C(L) \tag{2}$$

$$U_{col}(I,L)=\frac{P_M(L)}{I}+U_C(L)+R_k(L)\cdot I^k \tag{3}$$

where P_M – arc column power in the range of low current values I; R_k, k – approximation factors in high current range.

In the first variant of measurements, arc current values can be selected in such a manner ($I > I_P$ or $I_{P1} < I < I_{P2}$) that the first and the third component in formulas (2) and (3) can be very low and thus negligible. In the second variant, measurements can be conducted maintaining the constant value of current I. In such situations, voltage on arc can be expressed by the following approximated simple formula:

$$U(I,L)\cong U(L)=U_{AK}+EL \tag{4}$$

where E – value of electric field intensity (referred to as voltage gradient in the case of arc deflected from the electrode axis). This dependence can be used to consider several methods of the experimental determination of arc parameters U_{AK} and E.

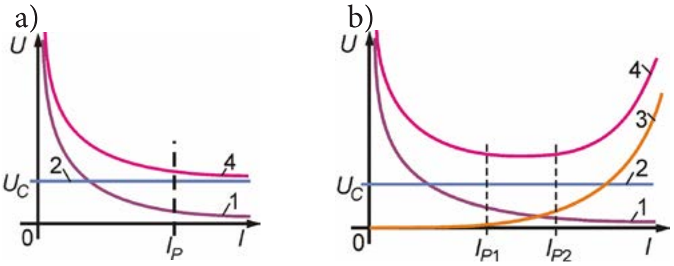

Fig. 3. Approximations of electric arc static voltage-current characteristic: a) hyperbolic-flat characteristic; b) hyperbolic-power characteristic (1-$U=P_M/I$, 2-$U=U_C$, 3-$U=R_kI^k$, 4 – resultant characteristic)

Method of extrapolation of diagram U(L)

The extending and shortening of an arc column is the most common operation used when controlling changes of electric discharge power. Most arc electrotechnological devices are adapted for this purpose. The value of near-electrode voltage drop can be determined without the short-circuiting of electrodes (an undesired phenomenon in some devices). Drop (U'_{AK}) can be calculated using the extrapolation of a line graph in the direction of y-axis (Fig. 4):

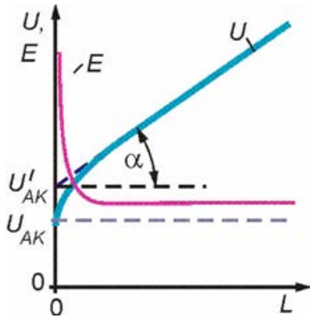

Fig. 4. Changes of voltage on arc triggered by changes of column length while maintaining the constant value of current [6, 7]

$$U(L=0)=U_{AK} \tag{5}$$

In fact, is it possible to observe an additional voltage drop directly before the axis (U'_{AK} -U_{AK}), resulting from energy input for the formation of an arc column shrinkage zone before a cathode. In turn, the intensity of an electric field can be determined on the basis of the tangent of inclination angle of a straight line, approximating the diagram $U(L)$:

$$tg\alpha \propto \frac{dU(L)}{dL} = E \tag{6}$$

Due to possible fluctuations of an arc column length, the approximating straight line should go through points lying at the bottom part of the diagram with experimental data. Such an approach can be justified by the possibility of even significant extension of the column as a result of convective flows of gases, while it is not possible to shorten the column below the distance between electrodes.

Due to the erosion of electrodes and fluctuations of thermal states of plasma and of electrodes, the extending or shortening of an arc column should be performed relatively quickly. For this purpose, special mechanical (spring-based) systems are used. Failure to meet this condition could lead to significant measurement errors.

Two-point method on characteristic U(L)

Not always, due to design-related to technological reasons, the constant change of arc column length is possible. Due to the quasi-linearity of characteristic $U(L)$ (Fig. 5), it is sufficient to determine voltages corresponding to two arc lengths and at the same time to possibly maintain a constant current:

$$U_{a1}=U_{AK}+U_{col1}=U_{AK}+EL_1 \tag{7}$$

$$U_{a2}=U_{AK}+U_{col2}=U_{AK}+EL_2 \tag{8}$$

By solving this system of equations the following parameters are obtained:

$$U_{AK} = \frac{U_{a2}L_1 - U_{a1}L_2}{L_1 - L_2} \tag{9}$$

$$E = \frac{U_{a1} - U_{a2}}{L_1 - L_2} \tag{10}$$

Whilst an advantage of the previous method is the time-space averaging of experimental data, a disadvantage of this method is the possibility of the temporary averaging of data, which could cause greater measurement errors.

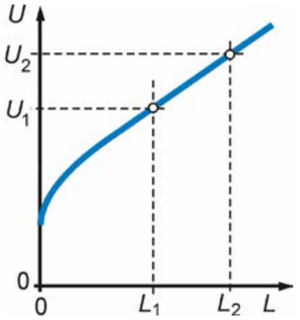

Fig. 5. Selected measurement points on a diagram of changes of voltage on arc caused by changes of column length and maintaining the constant value of current

Method of relative shift of electrode symmetry axes

In in-situ tests of arc of some electrotechnological devices, in comparison with previous solutions, the relative shift of electrode symmetry axes (Fig. 6), while maintaining a constant distance between active planes L_Z and almost the same value of current, could appear easier.

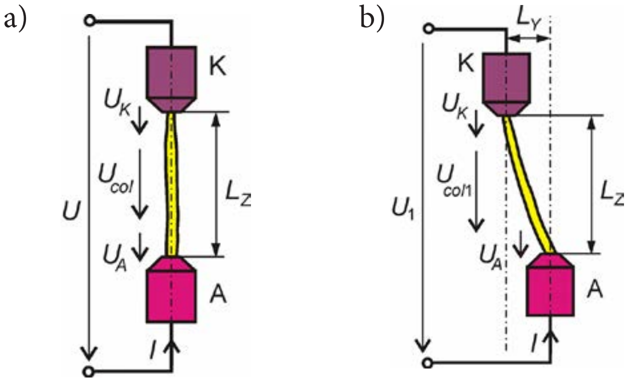

Fig. 6. Arrangement of electrodes and arc column before and after the introduction of column length disturbance by moving an anode

This would result in a change of voltage on arc, according to the dependences:

$$U=U_{AK}+EL_Z \tag{11}$$

$$U_1 = U_{AK} + E\sqrt{L_Y^2 + L_Z^2} \tag{12}$$

Thus, the value of voltage gradient, is expressed by the following formula:

$$E = \frac{U_1 - U}{\sqrt{L_Y^2 + L_Z^2} - L_Z} \tag{13}$$

The sum of near-electrode voltage drops can be calculated using following formula:

$$U_{AK} = U - \frac{L_Z\left(U - U_1\right)}{L_Z - \sqrt{L_Y^2 + L_Z^2}} \tag{14}$$

This method is presented as a variant of the two-point method, yet its variant as a method of diagram $U(L)$ extrapolation with a constant change of L_Y is also possible. Figure 6 presents the movement of an anode, yet it can also refer to the movement of a cathode.

Method of slotting a single non-conducting element into an arc column

The design or operation of some electrotechnological devices preclude movements of electrodes, which significantly hinders the use of the previously described methods (5)-(14). At the same time, it is known that arc column changes made employing a non-conducting ceramic element and a gas blast are often used in the operation of extinguishing chambers of electric devices with contacts maximally pulled apart (separated). A variant of this method used for measurement-related purposes is presented in Figure 7. Inserting (slotting) a ceramic element of theoretically any thickness ($g < L$) at predefined depth s of arc area should be performed as quickly as possible – in order to protect the ceramic element from damage. At the same time, it is necessary to maintain almost the same value of current. The enclosing of a ceramic element by arc can be improved by introducing a nozzle generating a weak transverse gas flow.

Values of arc characteristic parameters can be calculated using the following formulas:

$$U_{AK} = U - \frac{L_Z}{2s}\left(U_1 - U\right) \tag{15}$$

$$E = \frac{1}{2s}\left(U_1 - U\right) \tag{16}$$

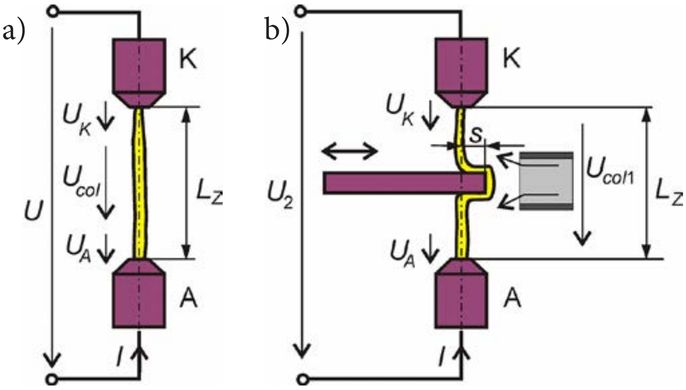

Fig. 7. Arrangement of electrodes and arc column before and after introducing disturbance of column length using a ceramic plate and a gas flow

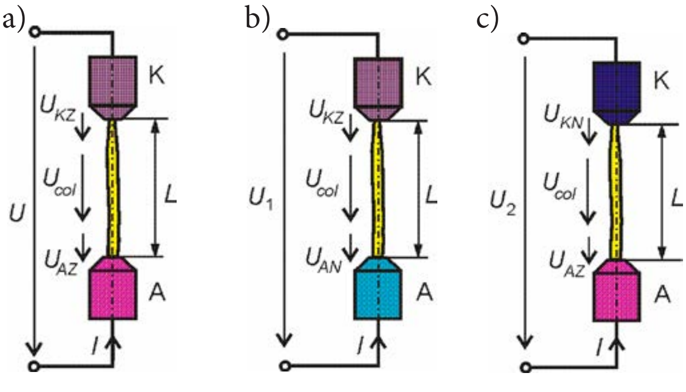

Fig. 8. Arrangement of electrodes made of various materials and of arc column

Method of the successive exchange of electrodes

Having a cathode and an anode of known near-electrode voltage drops U_{KZ} and U_{AZ}, it is possible to experimentally determine near-electrode voltage drops of arc burning between other electrodes of unknown near-electrode voltages U_{KN} and U_{AN}. To this end, below considered are three cases of the burning of arc of the same current I and the same distance between electrodes L. The first case (Fig. 8a) involved the use of electrodes of known near-cathode U_{KZ} and near-anode U_{AZ} voltage drops. The second case (Fig. 8b) involved the use of a cathode of known voltage drop U_{KZ} and an anode of unknown voltage drop U_{AN}. The third case (Fig. 8c) involved the use of a cathode of unknown voltage drop U_{NZ} and an anode of known voltage drop U_{AZ}. The related equations of voltages on arc have the following form:

$$U=(U_{KZ}+U_{AZ})+EL \tag{17}$$

$$U_1=(U_{KZ}+U_{AN})+EL \tag{18}$$

$$U_2=(U_{KN}+U_{AZ})+EL \tag{19}$$

As a result, it is possible to obtain formulas for arc parameters with new electrodes:

$$E=\frac{U-(U_{KZ}+U_{AZ})}{L} \tag{20}$$

$$U_{KN}=U_{KZ}-U+U_2 \tag{21}$$

$$U_{AN}=U_{AZ}-U+U_1 \tag{22}$$

The sum of near-electrode voltage drops of arc burning between ne electrodes amounts to

$$U_{AKN}=U_{KN}+U_{AN}=U_{KZ}+U_{AZ}-2U+U_1+U_2 \tag{23}$$

As can be seen, the determination of the sum of near-electrode voltage drops does not even require the knowledge of a distance between electrodes.

Method of slotting a single conducting element into an arc column

The phenomenon of arc column division into shorter sections is often present in electrical appliances and electrotechnological devices. In the first case, the phenomenon is induced artificially then used for more effective extinction of discharge. In turn, the second case is connected with the presence of disadvantageous double arc deteriorating the efficiency of technological processes and reducing the active life of structural elements (plasma torch nozzles). In the measurement method proposed, the selection of the material of a conducting flat element (metal or graphite) depends on materials used for the electrodes.

In the first case (Fig. 9 a, b), it is assumed that the cathode and anode are made of the same material and that distance L between the primary electrodes is known and constant. An element (plate) of thickness s and made of the same material as that of electrodes is inserted perpendicularly into the arc area. This leads to the formation of so-called double arc. In the second case (Fig. 9 c, d), it is assumed that the cathode and anode are made of different materials having different properties (e.g. emission of electrons). In such case, a bi-metallic

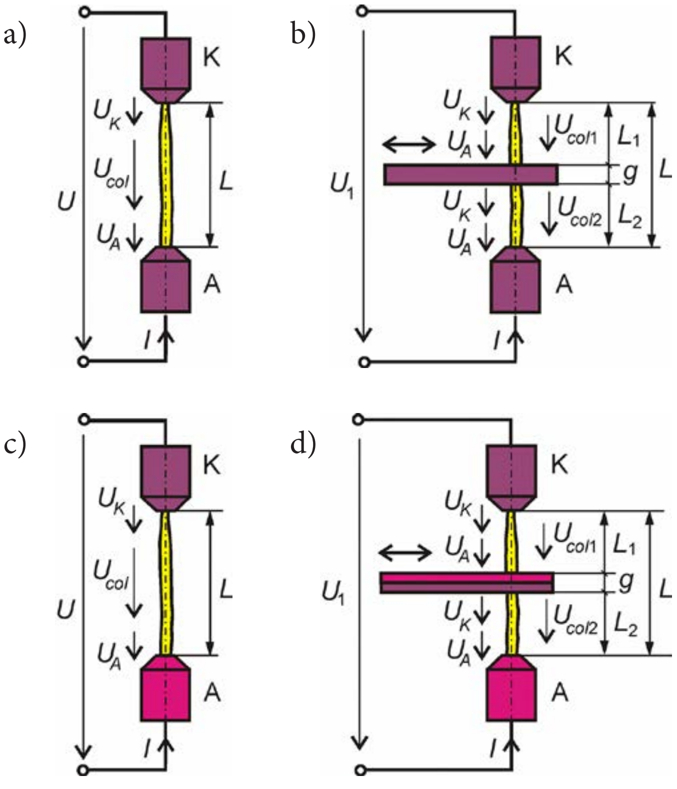

Fig. 9. Arrangement of electrodes, arc column and conducting disturbing element: a), b) electrodes and disturbing element made of the same material; c), d) electrodes and disturbing element made of different materials

element made of the same materials as those of electrodes, of an entire thickness g, is inserted into the arc area. In order to minimise disturbance effects, the moving element should be heated appropriately. Values of arc characteristic parameters can be calculated using the following formulas:

$$U_{AK} = \frac{U_1 L - U(L-g)}{L+g} \qquad (24)$$

$$E = \frac{2U - U_1}{L+g} \qquad (25)$$

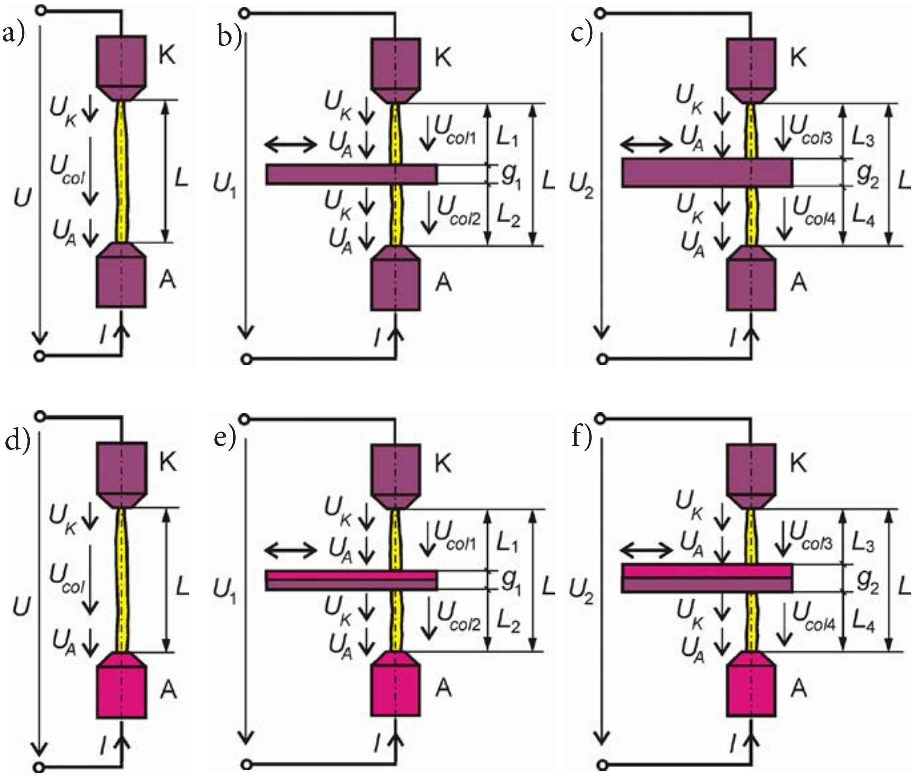

Fig. 10. Arrangement of electrodes, arc column and disturbing elements made of conducting materials having various thicknesses: a), b), c) electrodes and disturbing elements made of the same material; d), e), f) electrodes and disturbing elements made of different materials

Method of slotting two successive conducting elements of different thicknesses into an arc column

If it is difficult to precisely measure distance L between the primary electrodes, it is possible to use the slot method, i.e. consisting in inserting two successive conducting elements of various thickness perpendicularly into the arc column axis. Two cases can be considered, i.e. when electrodes and disturbing elements are made of the same material (Fig. 10a, b and c) and when electrodes and disturbing elements are made of different materials (Fig. 10d, e and f).

Values of arc characteristic parameters can be calculated using the following formula:

$$E = \frac{U_1 - U_2}{g_2 - g_1} \qquad (26)$$

$$U_{AK} = \frac{1}{2}\left[U_1 + U_2 - 2U + (U_1 - U_2)\frac{g_1 + g_2}{g_2 - g_1}\right] \qquad (27)$$

Method of deflecting an arc column using a magnetic field

Controlling the location of welding arc using a quick-changing magnetic field is hindered due to the limited arc extension ability and arc column breaking off from the positive electrode surface due to the weak "fastening" of plasma to an anodic spot [8]. For this reason, welding arc in an alternating transverse magnetic field is less stable than arc in a constant field. In addition, a cathodic spot in a condensed electrode is less active in comparison with an anodic spot. For this reason, it is advisable to prefer the use of a homogenous magnetic field of constant induction B when determining arc parameters.

Assuming that arc burns between an electrode constituting cathode K and a conducting

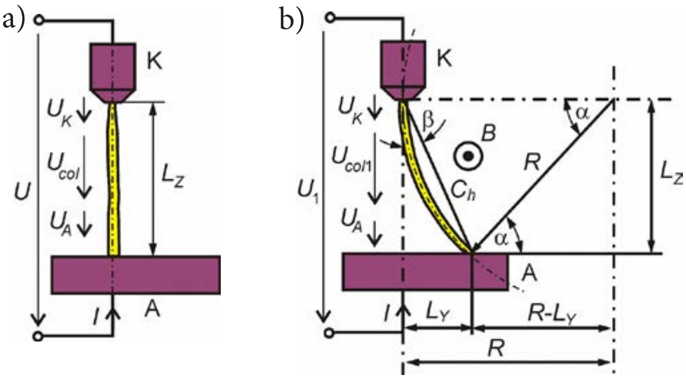

Fig. 11. Arrangement of an electrode (cathode), conducting plate (anode) and arc column in a disturbing homogenous magnetic field: a) $B=0\,\mathrm{T}$, $L=L_Z$; b) $B>0\,\mathrm{T}$, $L>L_Z$, $\beta=\alpha/2$

plate constituting anode A, and that the distance between them is constant and amounts to L_Z, if arc is not affected by any external excitation magnetic field (induction $B=0\,\mathrm{T}$), by appropriately connecting supply leads it is possible to obtain the axial location of the anodic spot centre at a point of coordinates (0, 0, 0) located on the plate (Fig. 11a). The voltage of arc is expressed by the following formula:

$$U=(U_A+U_K)+U_{col}=U_{AK}+EL_Z \tag{28}$$

Affected by a homogenous magnetic field of induction $B\neq0\,\mathrm{T}$, arc moves and is deflected from its axial position (Fig. 11b), and the centre of the anodic spot moves on the plate to point $(0, L_Y, 0)$. Then, the value of the voltage on arc is expressed by the following formula:

$$U_1=(U_A+U_K)+U_{col1}\cong U_{AK}+EL_Z \tag{29}$$

where L is the length of a fragment of a circle having radius R amounting to

$$R^2=(R-L_Y)^2+L_Z{}^2 \tag{30}$$

Therefore,

$$R=\frac{L_Y^2+L_Z^2}{2L_Y} \tag{31}$$

The central angle of the circle, including arc can be determined using the following formula:

$$\sin\alpha=\frac{L_Z}{R}=\frac{2L_YL_Z}{L_Y^2+L_Z^2} \tag{32}$$

whereas the length of arc is expressed by the following formula:

$$L=R\alpha=R\arcsin\frac{L_Z}{R} \tag{33}$$

Solving the system of equations (28) and (29) using equation (33) enables the obtainment of

$$U_{AK}=\frac{1}{2}\left[U+U_1-E\left(L+L_Z\right)\right] \tag{34}$$

$$E=\frac{U_1-U}{L-L_Z} \tag{35}$$

The length of a circle arc can also be determined by replacing the trigonometric function with its approximation using an irrational function:

$$L\cong 2^2R\sqrt{2-\sqrt{2+\sqrt{4-\left(\frac{C_h}{R}\right)^2}}} \tag{36}$$

where C_h – the length of a chord expressed by the following simple formula:

$$C_h^2=L_Y^2+L_Z^2 \tag{37}$$

Arc deflection angle β is related to central angle α by means of the following formula:

$$\sin\alpha=\frac{2L_Y}{\sqrt{L_Y^2+L_Z^2}}\cos\beta \tag{38}$$

The value of angle β is affected by electric quantities ($\beta\propto IB$), which also affects angle α and arc length [9]. If constant arc inclination $L_Y=$ const. is maintained, a change in the value of current changes the induction of the magnetic field in accordance with the following formula:

$$I_1B_1=I_2B_2 \tag{39}$$

Similar deliberations could be made in relation to the effect of a magnetic field on the external stabilised arc of a plasma torch [10]. In addition, the value of arc deflection angle β is affected by mechanical parameters ($\beta\propto IB/(\dot{m}v)$) such as gas mass stream $\dot{m}$ and gas flow rate v. In such case, the obtainment of constant arc inclination $L_Y=$ const. requires the fulfilment of the following condition:

$$\frac{I_1B_1}{\dot{m}_1v_1}=\frac{I_2B_2}{\dot{m}_2v_2} \tag{40}$$

The accuracy of measurements is affected by the deformation of the spot on a flat anode, where the spot takes the shape of an ellipse. It should be mentioned that a magnetic field can deflect the column of arc powered by a source of reverse polarisation. Formulas (28)-(40) are not related to the polarisation of the electrode, and therefore should be treated as universal.

Method of arc column circular bend using a magnetic field

The method presented previously required the use of a plate electrode for moving an arc spot on the plane perpendicular to the bar electrode axis. However, such structure of a measurement system cannot always be used when testing arcs of electrotechnological devices. In the method proposed, bar electrodes are fixed (Fig. 12), similar to the auxiliary electrode EP.

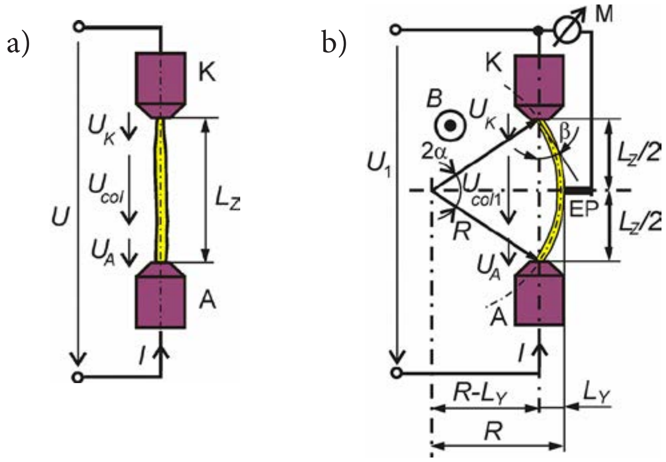

Fig. 12. Arrangement of bar electrodes and arc column in disturbing homogenous magnetic field: a) $B=0$ T, $L=L_Z$; b) $B>0$ T, $L>L_Z$ (*M* – contact indicator – voltmeter), $\beta=\alpha$)

Assuming that arc burns between electrodes constituting cathode K and anode A and that the distance between them is constant and amounts to L_Z, if arc is not affected by any external excitation magnetic field, it is possible to obtain the axial position of a column (Fig. 12a). The voltage of arc is expressed by the following formula:

$$U=(U_A+U_K)+U_{col}=U_{AK}+EL_Z \tag{41}$$

Affected by a homogenous magnetic field of induction $B \neq 0$ T, arc is deflected from its axial position until coming into contact with the additional electrode EP (0, L_Y, $L_Z/2$) and creating double arc (Fig. 12b). The value of voltage on arc directly before its division is expressed by the following formula:

$$U_1=(U_A+U_K)+U_{col1}\cong U_{AK}+EL_Z \tag{42}$$

where *L* is the length of a fragment of a circle having radius *R* amounting to

$$R=\frac{1}{2}\left(L_Y+\frac{1}{4}\frac{L_Z^2}{L_Y}\right) \tag{43}$$

The central angle of the circle, including arc can be determined using the following formula:

$$\sin\alpha=\frac{L_Z}{2R} \tag{44}$$

whereas the length of arc is expressed by the following formula:

$$L=2R\alpha=2R\arcsin\frac{L_Z}{2R} \tag{45}$$

Solving the system of equations (41) and (42) using (45) enables the obtainment of

$$U_{AK}=\frac{1}{2}\left[U+U_1-E\left(L+L_Z\right)\right] \tag{46}$$

$$E=\frac{U_1-U}{L-L_Z} \tag{47}$$

The length of a circle arc can also be determined by replacing the trigonometric function with its approximation using an irrational function:

$$L\cong 2^2 R\sqrt{2-\sqrt{2+\sqrt{4-\left(\frac{L_Z}{R}\right)^2}}} \tag{48}$$

Arc deflection angle *β* is related to central angle *α* by means of the following formula:

$$\sin\alpha=\frac{L_Z}{2\left(R-L_Y\right)}\cos\beta \tag{49}$$

As mentioned before, the value of arc deflection angle *β* is affected by electric quantities ($\beta \propto IB$),which also affects angle *α* and arc length [9].

Similar deliberations could be made in relation to the effect of a magnetic field on the external stabilised arc of a plasma torch [10]. In addition, the value of arc deflection angle *β* is affected by mechanical parameters ($\beta \propto IB/(\dot{m}v)$) such as gas mass stream $\dot{m}$ and gas flow rate *v*.

Modified slot method

The ordinary slot method (24)-(25) contained the assumption that the sum of near-electrode voltage drops U_{AK} of arc is tantamount to the sum of analogous voltage drops U'_{AK} of a slotted plate. However, in some cases such an assumption can be very rough. For this reason, a modification of the slot method is proposed. According to the modified slot method, it is first necessary to determine voltage U'_{AK} of the plate itself, using e.g. the method of successive exchange of electrodes using the arc of known near-electrode voltage drops, and only then it is possible to use the slot method having a plate of already known value U'_{AK}. Thus,

$$U=U_{AK}+EL \tag{50}$$

$$U_1=U_{AK}+ U'_{AK}E\cdot(L-g) \tag{51}$$

As a result,

$$U_{AK}=U-\frac{L}{g}\left(U+U'_{AK}-U_1\right) \tag{52}$$

$$E=\frac{U+U'_{AK}-U_1}{g} \tag{53}$$

Three-point method

It is based on indicating three values of voltage U_1, U_2, U_3 on the arc with three lengths of column L_1, L_2, L_1+L_2. The arc is powered by power source. Accordingly, the arc voltage is:

$$U_1 = U_{AK}+EL_1 \tag{54}$$

$$U_2 = U_{AK}+EL_2 \tag{55}$$

$$U_3 = U_{AK}+E\cdot(L_1+L_2) \tag{56}$$

Then, voltage U_{AK} is equal to:

$$U_{AK}=U_1+U_2-U_3 \tag{57}$$

Main disadvantage of methods using forced changes of arc column length are disturbances caused by its natural fluctuations. Column is being deflected and twisted, especially in arc blowing naturally.

Method of cathode thermal state change

Changes in the temperatures of electrodes in electrotechnological devices affect their operation, particularly as regards cathodes made of refractory materials. Increasing their temperature increases the fraction of thermionic emission and the distribution of a cathodic spot on the surface of a cathode. In turn, decreasing their temperature increases the concentration of a cathodic spot. By maintaining the invariable value of arc current and the distance between electrodes as well as by increasing cathode temperature, it is possible to reduce a cathodic voltage drop and, at the same time, to reduce the entire arc voltage. This method has been used successfully for testing high-pressure arc lamps [11].

Presented below are two states of cathode operation with temperature T_K and T_{Kmax}, ($T_K < T_{Kmax}$). Temperature T_{Kmax} corresponds to the emissive state of a cathode, where a cathodic voltage drop is the smallest $U_K(T_{Kmax}) = U_{Kmin}$. In turn, temperature T_K corresponds to the state of a cathode, where a cathodic voltage drop is greater $U_K(T_K) > U_{Kmin}$. Voltage on arcs with cathodes of these two different temperatures are described by the following equations:

$$U(T_{Kmax})=U_K(T_{Kmax})+U_A+U_{col}=$$

$$=U_{Kmin}+U_A+U_{col} = U_{min} \tag{58}$$

$$U(T_K)=U_K(T_K)+U_A+U_{col} \tag{59}$$

After subtraction, the following formula for a cathodic voltage drop is obtained:

$$U_K(T_K)=U(T_K)-U_{min}+U_{Kmin} \tag{60}$$

It is estimated that the lowest possible value of a cathodic voltage drop is $U_{Kmin} \approx 5$ V [11]. The additional heating of the cathode can be resistant, inductive or by using auxiliary arc.

Conclusions

1. There are numerous methods for determining near-electrode voltage drops of electric arc enabling the selection of the most

effective measurement method in relation to a specific design and specific operating conditions of an electrotechnological device.

2. In spite of many existing methods for determining near-electrode voltage drops, it is difficult to indicate the most universal method which, at the same time, would ensure the highest accuracy of measurements.
3. Comparative analyses (presented in some reference publications) of measurement results related to near-electrode voltage drops, obtained using various methods, can be considered as the most rational measures used in order to increase the reliability of presented test results.
4. Most of the research methods described in this publication (i.e. new developments (11)-(57)) present engineering approaches, not referring to complex analysis of physical phenomena.
5. Using linear approximation (4) neglecting influence of bevel part of column on the arc voltage (Fig. 4) causes overestimation of sought value of the voltage U_{AK}.

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