Low-current electric arc in the open air between the end of the cathode and long vertical anode

Kh K Tazmeev\textsuperscript{1} and B Kh Tazmeev\textsuperscript{2}

\textsuperscript{1}Branch of Kazan Federal University in Naberezhnye Chelny, 10A Sujumbike av., Naberezhnye Chelny, 423812, Russia
\textsuperscript{2}Naberezhnye Chelny Branch of Kazan National Research Technical University named after A.N. Tupolev, 1 Academician Korolyov str., Naberezhnye Chelny, 423814, Russia

E-mail: tazmeevh@mail.ru

Abstract. The electrical discharge was investigated experimentally in the open atmosphere at currents less than 1 A. The cylindrical rods and flat plates were used as anode. They were installed in front of the cathode rod vertically or obliquely. The modes in which the discharge makes regular self-oscillations were detected. Electric field intensity in the discharge column and the electron temperature were calculated.

1. Introduction

The first experiments were carried out with an electric arc in a high combustion mode (Petrov, Davy and Ritter) \cite{1, 2}. However, despite a long history, the study of open high-current arc is not complete. A more detailed study opens its new properties. In particular, high-speed imaging methods for recording shows that the geometrical form continuously changes, including in the case of horizontally oriented electrodes \cite{3}. The low-current modes of combustion are studied in less detail. Currently, they are virtually ignored. Some characteristics of the low-current modes of combustion are given in the research \cite{4}. This work can be attributed to the attempt to fill this gap in the study of low-current electric arc.

2. Experiment

Copper rods of different diameters (4-12 mm) and a copper plate with dimensions of 150x150 mm were used as anode. They were installed either vertically or inclined at a certain angle. The cathode was a hafnium rod with a diameter of 6 mm. It was mounted in a copper frame and located horizontally at a predetermined distance \( l \) from the anode. In the case of the inclined anode \( l \) was calculated along the horizontal line from the upper extremity of the cathode as shown in Figure 1.

![Electrodes assembly](image)

Figure 1. Electrodes assembly: 1 – anode; 2 – cathode; 3 – barrel.
A full-wave rectifier which was connected to the secondary windings of a three-phase step-up transformer was the power source. Pulsations of the rectified voltage were smoothed with C-L-C filter. The output voltage amounted to 1760 V. The discharge current is changed by varying the ballast resistor in the range of 1 to 11 kΩ. Oscillograms of current and voltage were recorded with a digital oscilloscope AKIP-15/1. The voltage drop across the shunt with a resistance of 0.5 ohms was current signal, and the signal of voltage was by ohmic divider 6kΩ/12MΩ.

Snapshots of discharges were taken by using high-speed video camera Videoscan-401. The emission spectra were recorded by high-speed fiber-optic spectrometer AvaSpec-3648 in the wavelength range of 484-708 nm with a resolution of 0.15 nm (diffraction grating 1200 lines/mm, the input optical gap of 10 microns).

3. The results of experiments, their processing and discussion

The feature of the electric arc in the present configuration of the discharge was anode spot, which makes a forced move to a considerable distance in the vertical direction when l exceeds a certain threshold value $l_{\text{threshold}}$. In the current ranges of 0.1-0.9 A numeric values $l_{\text{threshold}}$ were in the range of 3-4 mm.

![Figure 2. Oscillograms of voltage and current. Anode - copper plate. Exposure of snapshots 2 ms.](image)

When anode spot moves up, the length of the discharge channel $l_{\text{arc}}$ was increasing, voltage arc $U$ was increasing and the discharge current $I$ was decreasing (figure 2). The higher was the initial current, the higher was rise the anode spot. This behavior of the arc is explained by increasing buoyancy force, defined as

$$F_{\text{Arch}} = \rho_{\text{air}} g V_{\text{arc}},$$

where $\rho_{\text{air}}$ – air density, $V_{\text{arc}}$ – volume of the discharge channel of the arc. With an increase current discharge channel expands, the volume of the arc increases and, consequently, according to (1) increases the buoyancy force.

The movement of the anode spot broke off by shunting. After shunting anode spot again moved up, and thus appeared the pulsating combustion. The pulsations frequency was varying, and the amplitude of the voltage (and current, respectively) was not constant too (figure 3a). With increasing $l$ pulsations became ordered and discharge switched in a mode of regular self-oscillations at practically constant frequency and almost unchanged values of voltage and current amplitudes (figure 3b). A further increase of $l$ resulted to a violation of the regularity of oscillations (figure 3c). Pulsations occurred less frequently. There were long periods of stable combustion, which was amounted to tens of seconds. Stable regimes were established with different voltages and, respectively, the currents.
(figure 3d). To do this, the rise of the discharge column upward was limited by foreign refractory object which was placed on top of the discharge area.

**Figure 3.** Oscillograms of voltages and currents in oscillatory (a, b, c) and stable (d) combustion modes. Anode - copper rod Ø4.5 mm. (a) – \( l = 5.0 \) mm; (b) – 6.0; (c) – 7.5; (d) – 8.0.

Continuous stretching of the discharge channel without shunting was terminated after reaching some maximum \( l \) value of \( l_{\text{max}} \). It amounted 12-13 mm in the interval of currents of 0.8-0.9 A. \( l_{\text{max}} \) reduced when current decreased.

**Figure 4.** Electric field intensity in the arc column.

Registration of voltage waveforms in the mode of stable combustion which was performed simultaneously with the photographing, allowed to calculate the intensity \( E \) of the electric field in the arc column by the formula

\[
E = \frac{\Delta U}{\Delta l_{\text{arc}}},
\]  

(2)
where $\Delta U$ – the voltage difference determined from the oscillograms, $\Delta l_{\text{arc}}$ - change the length of the discharge channel, as measured by the corresponding photographs. Results of calculation of $E$ in graph form are shown in figure 4.

This dependence of $E$ on $I$ allows us to give an explanation of a sharp increasing $U$, arising out of the discharge pulsations (figure 2). Discharge channel elongates and the current decreases in the final phase of pulsations. Both of these factors contributed to an increase of voltage and if they were acting together they accelerated its growth.

The high intensity $E$ of the electric field in the discharge column can be noted as one of the features of the low-current mode of combustion. For example, in a open carbon arc at $I = 200$ A, they are in the range of 10-20 V/cm [2].

Anode region was painted in greenish color on the instant photos of discharge. The copper vapor had this characteristic. Spectral studies confirmed the receipt of the vapors of copper in the discharge region. In the visible range, the spectral lines of copper was the most intense.

Radiation spectra of copper atoms are used to determine the electronic temperature $T_e$ of the relative intensities of the lines in the approximation of LTE [5]. In this study, $T_e$ was calculated using three pairs of lines: CuI 515.32 and CuI 578.21; CuI 521.82 and CuI 578.21; CuI 510.55 and CuI 521.82. These modes in which the spatial position of the anode spot can be considered stationary (anode spot was moving insignificantly and the current was changing slightly) were chosen. The values of $T_e$ which was obtained by the three pairs of lines of copper atoms at currents of more than 0.3 A, were comparable within the error of calculations. Thus, the acceptability of this method of calculation of $T_e$ were determined by the condition $I \geq 0.3$ A. The average value $T_e$ was accepted as the final result. In the current range of 0.3-0.8 A was a slight increase of $T_e$ with increasing current $I$. The average value of $T_e$ was within in the range of 5100-5500 K.

4. Conclusions
In the low-current combustion mode, open horizontally oriented electrical discharge had a number of features. The most notable of these were: 1) the length of the discharge channel can many times exceed electrode spacing; 2) the current range of 0.2-0.5 A and the interval of 5-7 mm inter-electrode distance was a favorable factor for the emergence of regular self-oscillations; 3) the strength of the electric field in the discharge column was much higher than in high-current open arc; 4) anode material is heated to high temperatures and erodes in the root spot at currents 0.3 A or more. As a side note it should be mentioned that in this research the electrical discharge was investigated in the transition from arc to the glow discharge and the name “low-current arc” in relation to him was conditional. This was also stipulated in paper [4].

In practice, the combustion mode with regular self-oscillations can be used in processes of surface modification of metals and other solid conductors, in particular graphite.

References
[1] Raizer Y P 2001 Gas Discharge Physics (Berlin: Springer)
[2] Drummond J E 2013 Plasma Physics (New York: Dover Publications)
[3] German O V, Glinov A P, Golovin A P, Kozlov P V and Lyubimov G A 2013 Plasma Physics Reports 39 1142
[4] Korolev Y D, Frants O B, Landl N V, Bolotov A V and Nekhoroshev V O 2014 Plasma Sources Science and Technology 23 (5) 054016
[5] Fujimoto T 2004 Plasma spectroscopy (Oxford: Clarendon Press)