The stationary vacuum arc on non-thermionic hot cathode

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Abstract. Experimental study of vacuum arc with distributed spot on plumbum cathode at temperatures 1.25–1.45 kK has been presented. At these conditions current density of thermionic emission from cathode was less than $1 \mu A/cm^2$, while the mean current density on the cathode was about 10 A/cm$^2$. Plumbum was placed in heat-insulated crucible (cathode) with external diameter 25 mm. Electron-beam heater was situated under the crucible. Arc current was changed in the range 20–70 A, arc voltage was about 15 V. The studied arc is characterized by the absence of the random voltage fluctuations; the micro particles of cathode erosion products were observed only in transition regimes. Spectral data of plasma radiation and values of the heat flow from plasma to cathode were obtained. It has been experimentally established that the evaporation rate in arc approximately two times less than without discharge. The average charge of plumbum particles in the cathode jet was in range 0.2–0.3e. Comparison of the characteristics of studied discharge on thermionic gadolinium cathode and non-thermionic cathodes was fulfilled. One can assume that ions provide the charge transfer on the cathode in the studied discharge.

1. Introduction
Cathodes of vacuum arcs were characterized by flows ratio of thermal evaporated atoms to electrons $S_{ae}$ [1]. This ratio may be used for estimation of relative contribution of ions and electrons in charge transfer on the cathode. For some elements (mercury, copper, alkali metals and others) ratio $S_{ae}$ is much greater than unit. Therefore for these metals thermionic contribution in charge transfer on cathode has to be small. In papers [2, 3] vacuum arc with cathode distributed spot (CDS) on chromium (Cr) cathode ($S_{ae} \approx 10^4$) was studied. This discharge is distinguished by low current density on cathode, less than $10^2$ A/cm$^2$. In this paper the results of experimental study of similar discharge on plumbum (Pb) cathode ($S_{ae} \approx 10^8$) is presented.

2. Experimental facility and data
The discharge was initiated in vacuum chamber with residual gas pressures less than 10 mPa. Plumbum with mass about 15 g was placed in molybdenum heat-insulated crucible (cathode) with external diameter 25 mm. Outlet of the crucible was 14 mm in diameter. Main part of experiments was carried out with crucible covered by molybdenum cap with mass 12 g that
has 6 mm hole. By estimations, it allowed us to decrease Pb evaporation rate approximately in five times. Electron-beam heater (EBH) was situated under the crucible. The water-cooled steel disc with central hole of 15 mm in diameter was used as the anode. The distance between electrodes was about 30 mm.

The crucible temperature $T_c$ was measured by brightness-temperature pyrometer. By estimations the difference between measured temperature and mean temperature of Pb surface due to temperature drop in crucible wall was less than 3%. Heat flow from plasma to cathode surface was measured by method described in [1]. Spectral diagnostics and probe diagnostics above the anode were carried. In particular above the anode ion collector was situated which was used to determine average plasma charge by condensation method.

The experiments were carried out by following scheme. With the help of EBH crucible was heated to the temperature $T_c \approx 1.15$ kK where plumbum saturated vapor pressure $p_s \approx 30$ Pa [4]. Above the crucible a weak purple glow was observed at this temperature. Its intensity and shape were changing over time. Apparently this glow appears as a result of vapor ionization by electrons leaking from EBH. Isolated anode was charged by leakage current to potential about 10 V. At crucible temperature $T_c \approx 1.25$ kK ($p_s \approx 0.13$ kPa) voltage (380 V) from power supply was applied to discharge gap. Then either low-current discharge (figure 1a) with current about 10 mA and voltage $U \approx 340$ V was initiated or arc (figure 1b) with voltage $U \approx 15$ V. Low-current discharge could exist tens of seconds and then transformed to arc.

![Figure 1. Discharges on plumbum cathode: (a) $I \approx 10$ mA, $U \approx 340$ V, $T_c = 1.24$ kK; (b) $I = 20$ A, $U = 13.8$ V, $T_c = 1.33$ kK.](image)

Vacuum arc with CDS on Pb as a similar discharge on Cr [2,3] are characterized in steady state by absence of micro particles in erosion products and irregular voltage and plasma luminosity pulsations.

The crucible thermogram of one of the experiments is shown in figure 2. Discharge with the current 29 A initiated at $t = 56$ s and crucible temperature was $T_c \approx 1.26$ kK. EBH with power $N = 80$ W was switched off at $t = 77$ s, when crucible temperature was about 1.38 kK. After 7 seconds arc current was reduced to 20 A and was hold constant by the time $t = 270$ s, arc voltage was about 15 V. At the time $t = 195$ s EBH was switched on and its power equaled $N = 45$ W. As a result cathode temperature increased from 1.33 to 1.38 kK. At the time $t = 270$ s arc current was increased to 29 A, immediately after that cap flied from the crucible. At that moment $T_c \approx 1.38$ kK, hence $p_s \approx 0.68$ kPa [4]. Estimations show that in order to drop the cap plasma pressure had to be about 0.87 kPa. Without cap, discharge existed during about 35 s and faded due to total Pb evaporation. Presented data shows that crucible temperature reacts on arc current and EBH power changing. Value of arc voltage 15 V almost stayed constant when
current changed from 20 to 70 A. Surface area of liquid Pb taking into account the meniscus was 3–5 cm$^2$ and typical cathode current density was about 10 A/cm$^2$.

It is experimentally shown that Pb evaporation rate in arc conditions approximately two times less than at the same crucible temperature without arc. Estimations of Pb evaporation rate without arc based on the model [5] show that in used crucible geometry about 80% of evaporated atoms returns back to surface. It means that in arc conditions about 90% of evaporated atoms returns back to crucible surface as atoms or ions. Typical value of specific cathode erosion, which is ratio of evaporated atoms during experiment to total charge transferred through discharge gap, was about 0.7 atoms per electron.

Electron temperature in plasma above the anode laid in range 0.4–0.6 eV while arc current equaled 25 A and voltage was about 15 V. Average charge of Pb particles in cathode plasma jet measured by condensation probe dropped from 0.25 e to 0.17e with increasing arc current from 18 to 37 A. Plasma radiation spectra contained lines of Pb atoms and singly charged ions.

Studied discharge by current density, saturated vapor pressure and voltage is quite similar to discharge on Cr cathode [2, 3]. As it was showed in paper [3] no one mechanism of electron emission can’t provide the charge transfer on Cr cathode. This conclusion is also valid to discharge on Pb cathode. Work function of Pb equals 4 eV [4] then at temperature $T_c = 1.33$ kK (figure 2) thermionic current density is $J_e \cong 0.15$ mA/cm$^2$, that is eight orders less than cathode current density $J_c$.

In papers [1, 3] characteristics of discharge with CDS on thermionic gadolinium (Gd) cathode ($S_{ac} \cong 0.05$) were presented. Comparison of discharges properties on thermionic cathode and cathodes on Cr and Pb had shown their qualitative difference. For self-sustained discharge (EBH power $N = 0$) the voltage on Cr and Pb with the same discharge gap geometry and arc current is much less (almost in 10 times) than on Gd cathode. At great values of EBH power the opposite relation takes place—voltage on thermionic cathode falls down to 3 V and on Cr cathode to 7 V. These differences could indicate that charge transfer mechanisms on thermionic cathode and Cr or Pb cathodes are quite different. Further hypothesis of ion charge transfer on Pb and Cr cathodes is discussed.

Figure 2. Crucible thermogram.
3. Hypothesis of ion charge transfer

Maximum ion current density $J_{im}$ on the cathode can be calculated in assumption that all evaporated atoms return to cathode as ions:

$$J_{im} = e\frac{p_s}{\sqrt{2\pi m_a k_B T_c}},$$

(1)

where $e$—the electron charge, $m_a$—the atom mass, $k_B$—the Boltzmann constant. Estimations from equation (1) show that value of ion current is enough to provide charge transfer on cathode of studied arc. For example, arc steady state with current $I = 20$ A and $T_c = 1.33$ kK (figure 1b), at these conditions saturated Pb vapor pressure $p_s \cong 0.38$ kPa and equilibrium density of Pb atoms equals $n_s = 2 \times 10^{16}$ cm$^{-3}$ [4]. From (1) it follows that $J_{im} \cong 30$ A/cm$^2$. Thus if 30% of evaporated atoms return to cathode as ions it will be enough to provide charge transfer ($J_c \cong 10$ A/cm$^2$). The same estimations for Cr cathode show provision of charge transfer.

If one assumes that all charge on cathode is transferred by ions, then their energy on the cathode may be estimated from energy balance. From plasma-cathode heat flow measurements it follows that for discussed regime ($I = 20$ A, $T_c = 1.33$ kK) energy transmitted to the cathode by every ion is enclosed in range 4.7–6.2 eV. This energy consists of energy released due to ion neutralization (ionization potential minus work function, for Pb—3.4 eV) and kinetic energy. Thus ion kinetic energy in this regime is in range 1.3–2.8 eV. In vacuum arc on Cr cathode with current increase from 50 to 200 A ion kinetic energy decreased from 5 to 1.5 eV [3]. For Pb discharge with ion kinetic energy 2 eV (ion velocity—0.95 $\times$ 10$^5$ cm/s) and current density $J_c \cong 10$ A/cm$^2$ ion concentration on cathode surface equals $7 \times 10^{14}$ cm$^{-3}$.

Obtained results are in accord with qualitative model of cathode layer of arc discharge with ion charge transfer described in [6]. In accordance with this model the electron diffusion plays significant role in the processes in cathode layer. Near the cathode the diffusion and drift electron flows are approximately equal in value and are opposite directed, and the resulting density of electron current on cathode is much less than arc current density. For ions diffusion and drift fluxes are co-directed. As a result of electron diffusion there is an alignment of charged particles density; and the space charge near cathode is practically absent. Estimated from energy balance relatively low ion energies support this assumption. Distributions of electrical potential and electron temperature are non-monotonic. Maximums of potential ($\approx 10$ V) and electron temperature ($\approx 2$ eV) are situated from the cathode at the distance of ionization length. Energy balance in ionization layer is provided by electron thermal conductivity. High rates of concentration and electron temperature in cathode layer provides great efficiency of step ionization.

4. Conclusion

Presented results demonstrate that in vacuum arc on plumbum and chromium cathodes charge could almost completely be transferred by ions. This charge transfer mechanism can be expected on other cathodes with atom-electron ratio $S_{ae} \gg 1$: mercury, copper, bismuth, alkali metals and others. We should note that this statement is only correct for steady state of arc. For example, autoelectronic emission can provide notable charge transfer on these cathodes at the moment of arc ignition due to vacuum breakdown. However the discharge on this stage cant be regarded as arc due to values of its current and applied voltage.

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