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Selfconsistent Simulation of Development of Anode Spot in High Current Vacuum Arc

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Abstract — A self-consistent simulation of anode heating by 6.5 kA vacuum arc during the half-wave of 50 Hz current with 1 m/s contact opening was carried out. The calculations were done in the framework of hybrid high current vacuum arc model, which treats ions and atoms as macroparticles with the help of particle-in-cell methods, but electron subsystem is treated as massless fluid with quasineutrality assumed. The occurrence of an anode plasma plume (like that found in experiments) was obtained in the result of modeling. It is shown that the energy flux of line radiation from the interelectrode plasma to the anode is a critical reason of the appearance and maintenance of the anode plume.

Introduction

High-current vacuum arc (HCVA) is an arc with current in the order of several kiloamperes. Such kind of arcs is typical for vacuum interrupters or circuit breaker [1]. At the moderate current, the main source of plasma in HCVA is multiple cathode spots [2, 3]. However, when the current increases to a certain threshold value, the anode becomes an additional plasma source. The bright, well defined spot appears at the anode surface. This phenomenon is known as the anode spot [4, 5]. It was reported also that anode spot appearance sometimes accompanied by anode plasma plume in bright shell [6, 7, 8].

The appearance of the anode spot significantly reduces the ability of vacuum interrupters to switch off the current. Therefore, there is considerable interest in the study of this phenomenon from the industry of the production of interrupters. Despite the interest, the theoretical models for the emergence and development of the anode spot are relatively weakly developed.

Schematically, the processes at the anode of the HCVA are as follows. At the beginning of contact opening due to the Hall effect, the current narrows near the anode [9]. As a result, somewhere in the center of the anode, the density of the heat flux from the plasma to the anode increases significantly. Anode surface is heated up to a temperature at which the saturated vapor pressure becomes higher than the total pressure of near-anode plasma. After that, the anode vapor starts to flow into the interelectrode gap, where the vapor is ionized. Some difficulty in modeling this sequence is that for self-consistent determination of the anode surface temperature it is necessary to perform calculations along the half-wave of power frequency current (~10 ms). However, the characteristic times of plasma processes in the interelectrode gap are about of several microseconds. Such calculations were carried out in [10] based on MHD model [9]. It was shown that after the onset of intense evaporation of the anode, the current-constricting mechanism gradually ceases to work. As a result, the initially small hot spot on the surface of the anode increases in size with increasing current, while the maximum temperature of the surface of the anode remains approximately constant. In the model [10], no mechanism was found that would ensure the existence of a well-defined overheated area on the anode that is necessary for the formation of an anode spot or plasma plume. The constriction of heat flux due to Hall and pinch effects are too weak to provide this in the case of HCVA with evaporating anode. The anode plasma plume was modeled in [11, 12], but this was not a self-consistent simulation since the anode temperature was set arbitrarily. Thus, up to now, a self-consistent simulation of the appearance of the anode plasma plume in HCVA has not been performed. In this article, we tried to perform such a simulation.

Description of the model

The processes of plasma creation, plasma anode interaction, and anode evaporation were self-consistently modeled using a previously developed two-dimensional axisymmetric hybrid model [13]. The hybrid model allows to direct simulate the evaporation (including Knudsen layer), ionization and charge exchange. In the hybrid model, ions and electrons are described using different approaches. Ions and neutrals are described with the help of particle-in-cell (PIC) approach, but electron subsystem is treated as massless fluid with quasineutrality assumed.

Calculations were carried out for copper electrodes with a radius of 1 cm, a contact opening velocity of 1 m/s, and a half-wave current of 50 Hz with the current maximum of 6.5 kA (Fig. 1). Like in [10], the simulation along the half-wave of the current was carried out as follows. We found a stationary solution for plasma in the interelectrode gap for a specific current and the interelectrode gap size, considering the evaporation from the anode. Then the heat flux to the anode (like in Fig. 2) was calculated. Further, using the previous distribution of the anode temperature as the initial condition, we, by interpolating the heat flux to the anode, solved the non-stationary two-dimensional problem for the anode temperature development. After the anode surface temperature was updated, the solution for the plasma in the gap was recalculated, and so on. Thus, a series of stationary solutions for the plasma in the opening gap were found together with a non-stationary solution for the anode temperature development (Fig. 1).

In model [10], only the electron, ion and atom components of the heat flux to the anode were taken into account. The radiation flux from the plasma was not considered. In this model, the radiation flux from the plasma to the anode is additionally considered. This is the energy flux of line radiation from the plasma volume. Plasma is assumed to be optically thin. To estimate the effect of line radiation, we use a very rough (in this case) approximation — the approximation of truncated hydrogen atom [14]. It is assumed that all atoms or ions excited by the electron impact decay via radiation.

An open question is an incident radiation absorption coefficient (AC) of the anode surface. In the general case, AC depends on many parameters, including the frequency of the incident radiation, the state, composition and temperature of the surface, etc. In the paper, we consider solutions only for two values of the AC: 0 and 1. In the first case, the radiation does not affect the heating of the anode; in the second case, the radiation gives the maximum possible effect.

Results of calculations

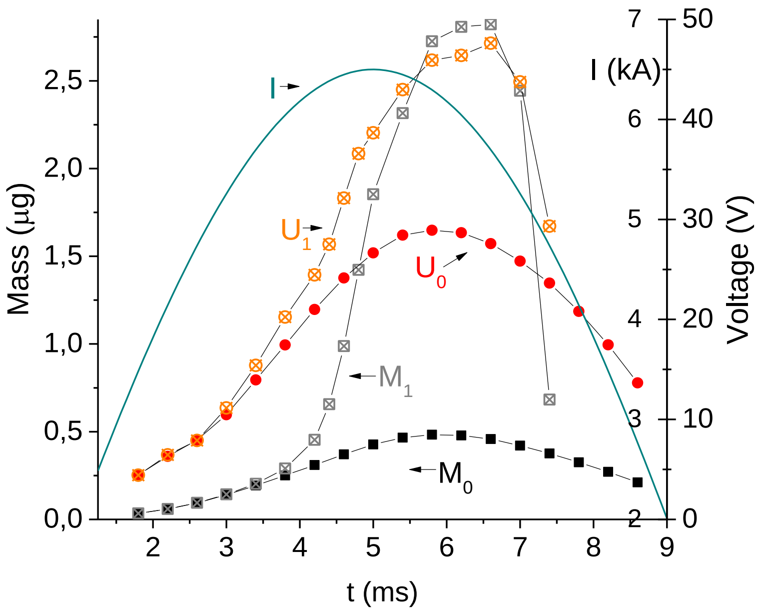

Fig. 1. Evolution of total interelectrode plasma mass (M) and plasma voltage drop (U) during half-wave of sinusoidal current (I). Substring 0 means calculation with AC=0. Substring 1 means calculation with AC=1.

The calculations showed that in the case of AC = 1, after 4 ms, intense evaporation of the anode begins and, as a result, a dense plasma torch appears near the anode. Up to this point, the contribution of the radiation flux to the heating of the anode is relatively small. In the case of AC=0 the plasma torch does not appear, despite of the anode evaporation.

At low currents, the anode remains cold and the plasma enters the gap only from the cathode spots. The cathode erosion in the model is considered constant, therefore, the plasma mass curve in the gap approximately repeats (in the case of AC = 0) the current curve with a slight time shift. The voltage drop curve in the gap plasma behaves in a similar manner. The voltage drop across the arc plasma (Fig. 1) does not contain a cathode drop but contains an anode drop. The anode drop in our calculations always remains negative.

Results of calculations (2)

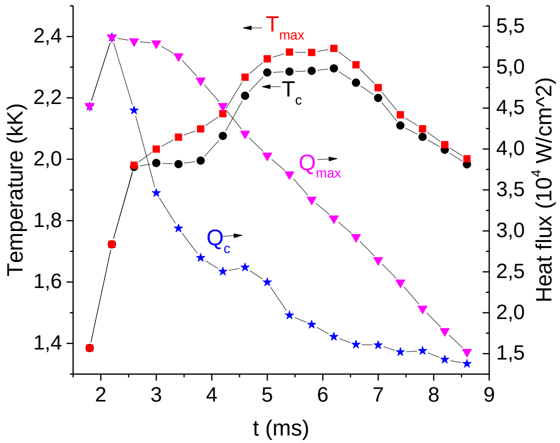

Fig. 2. Maximal anode surface temperature (T_{max}), surface temperature in the anode center (T_c), maximal anode heat flux (Q_{max}), anode heat flux in the center (Q_c). Calculation with AC=0.

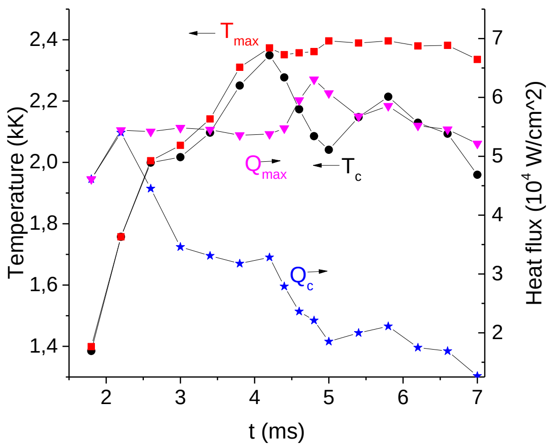

Fig. 3. Maximal anode surface temperature (T_{max}), surface temperature in the anode center (T_c), maximal anode heat flux (Q_{max}), anode heat flux in the center (Q_c). Calculation with AC=1.

Initially, the anode is passive, and the current at the anode is greatly narrowed due to the Hall effect. Because of this, a relatively small hot region arises in the center of the anode. After the surface temperature of the anode reaches 2000 K, intense evaporation begins. The area of the hot spot on the anode increases (Fig. 4). And the density of heat flow to the anode decreases, even despite the increase in current (Fig. 2, 3). This is due to the fact that after the onset of strong evaporation from the anode, the injection of a cold, weakly ionized plasma into the gap leads to a general cooling of the plasma and weakening of the current constriction. As a result, the maximum density of the heat flux to the anode decreases and shifts in the direction of the electrode edge (Fig. 5). However, in the case of AC = 1, the radiation flux to the anode partially compensates for the decrease in the heat flux due to the current shift. Thus, heat flux drops not so fast as in the case of AC=0 (compare Fig. 2 and 3).

Results of calculations (3)

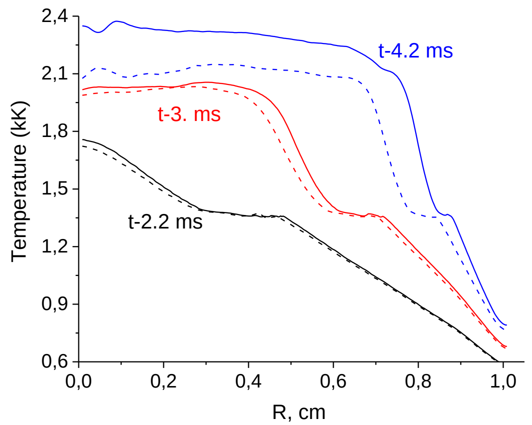

Fig. 4. Anode temperatures at different instants. Solid lines mean the case with AC=1; dashed lines – AC=0.

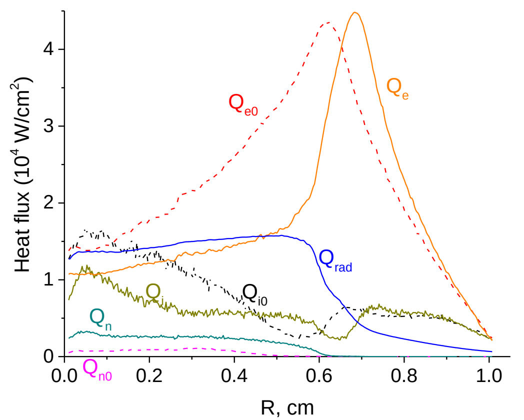

Fig. 5. Anode heat flux components as function of radius at instant 3.8 ms. It is denoted heat fluxes of: Q_e- electron; Q_i- ion; Q_n- neutrals; Q_{rad} – radiation. Solid lines mean the case with AC=1; dashed lines – AC=0.

After the start of intense evaporation, in case of AC=1, a cloud of weakly ionized plasma appears at the anode. The power of linear radiation increases dramatically. The resulting heat flow to the anode also increases sharply. In this case, the system has positive feedback. As shown in Fig. 3, the anode surface temperature reaches approximately 2.4 kK, and remains at the same level during ~ 3 ms. In our calculations the plasma plume appeared at t~4 ms (Fig. 6). Further, with increasing current, the size of the anode plasma plume increases. As follows from Fig. 1 (curve M), the plasma mass in anode plume is higher than the plasma mass in the rest of interelectrode gap approximately by factor of 6.

Results of calculations (4)

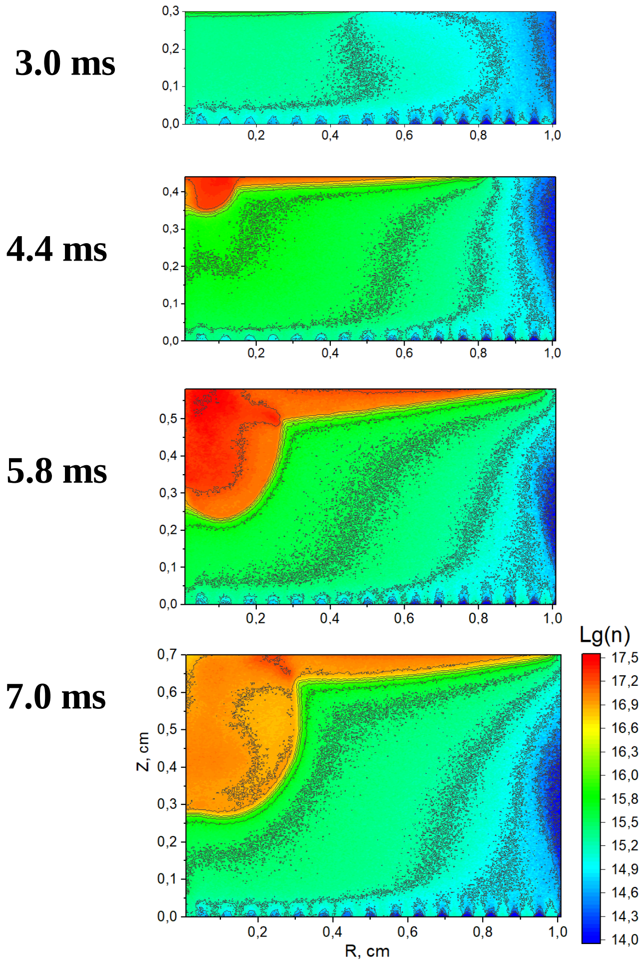

Fig. 6. Distributions of total (ions + atoms) plasma density in interelectrode gap at different instants. Anode is at the top; AC=1.

Appearance of the anode plasma plume is accompanied by the increase in the voltage drop across the gap (Fig.1, curve U). The reason for this is the penetration of cold weakly ionized plasma into the gap, which significantly reduces the conductivity of the interelectrode plasma. As is known from experiments [6–8], the appearance of an anode spot of type 2 is accompanied by a sharp change in the arc voltage. In our simulation, the voltage change is not as sharp as in the experiments. However, we believe that the main cause of the voltage jump in the experiment is the appearance of a dense plasma formation with reduced conductivity near the anode.

Results of calculations (5)

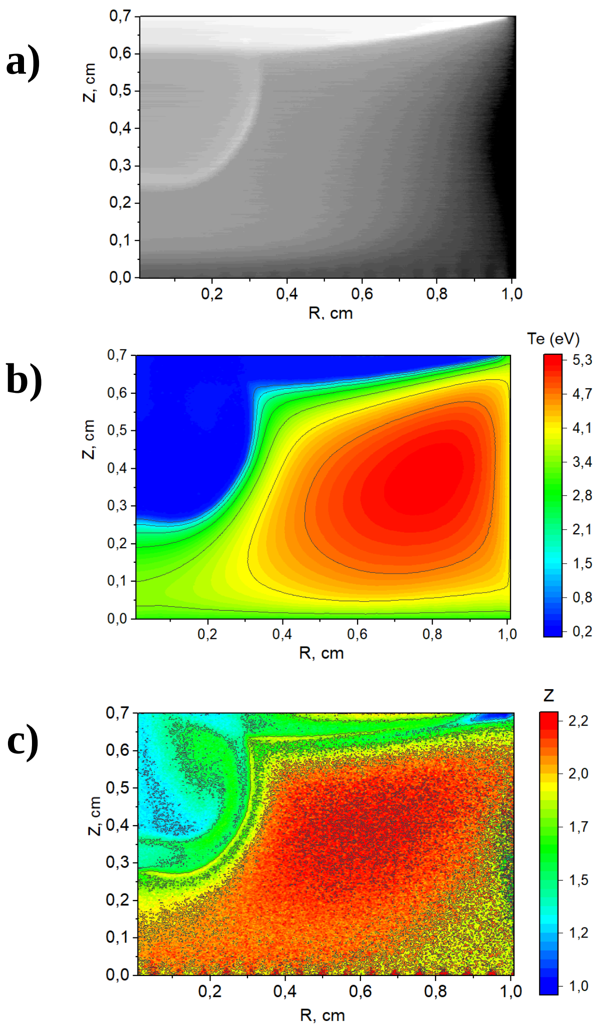

Fig. 7. a) Plasma appearance at 7 ms. ; b) Electron temperature at 7 ms.; c) Ion mean charge state at 7 ms. Anode is at the top; AC=1.

After reconstruction of the plasma appearance using Abel transformation the near anode plasma formation looks like a pale bubble with a bright shell on a bright near anode podium (Fig. 7a). The plasma plume temperature is considerably smaller than the interelectrode plasma temperature (Fig 7b). The density in plasma plume is much higher than the interelectrode plasma density (Fig. 6). Ion mean charge state in the plume is about unity, while ion mean charge state around the plume is about two (Fig. 7c). Ion density in the plume is much less than atom density. The ion density has a maximum along the plume boundary. Thus, the plasma ionization degree in the plume is much less than unity. Electrical conductivity of the plasma in the plume is low. Thus, the arc current tends to flow around the plume. All this leads to the fact that the electron and ion flows to the anode at the base of the plume are negligible. The high temperature there is maintained solely by the flow of radiation energy from the plasma. Thus, the radiation flux from the interelectrode plasma to the anode is very important cause of the appearance of the anode plume.

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