MODEL FOR A LOW CURRENT VACUUM ARC CATHODE REGION. EFFECT OF THE ELECTRONIC TEMPERATURE

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SUMMARY

Experimental and theoretical studies of arc cathode region have been made during several decades and the task is not yet completed, in spite of many efforts and progress. In this work, a numerical model describing the arc cathode region is developed. The model is then applied to a vacuum arc discharge interacting with a Cu cathode at low current (4-50A). The model yields the temperature and electric field strength at the cathode surface, electrons emitted and total current density, cathode spot radius, different kinds of power densities heating and cooling the cathode, and the plasma electron density. The comparison with experimental results shows good agreements.

Keywords: *vacuum arc, cathode spot, cathode region, current density, power density, spot radius*

1. INDRODUCTION

The arc discharge is a high-current, low-voltage discharge and a high plasma density in the near cathode region. Electrons for the discharge are supplied by the *cathode spot.* The cathode spot, through which current enters the cathode is a highly contracted region (some micrometers) operating under extreme physical conditions (current density 10^{11} A/m^2, power density 10^{11} W/m^2, electric field 10^9 V/m etc.). The cathode voltage drop is only about (*15-20* V for copper cathode [1, 2]. Arc discharges have many important applications: arc welding, high-pressure sodium lamps, fluorescent lamp, etc. Arcs are also involved in power switching. When a circuit carrying current is interrupted, an arc always forms at the switch contacts. The effect of high temperatures produced at the last point on the contacts to open, when the current is confined to a small area. So, a fundamental understanding of the arc-cathode interactions is required.

The experimental study of cathode spot was aimed mainly at determining the following basic spot characteristics: spot radius, the magnitude of the current density at the spot, electrical potential gradient in front of the spot, the rate of the cathode erosion and the morphology of the erosion traces, the electron temperature, the electron density, and the distribution of ion charge states in the vicinity of the spot, etc [1]. Theoretically, the arc consists of three zones: the cathode zone, the positive column, and the anode zone.

The cathode region is considered to be the most active region in electric arcs. Thus, the cathode phenomena have been studied for many years. Unfortunately, this region represents a very difficult subject for experimental investigation owing to its very small dimension, high local pressure, high temperature gradient, intense radiation, etc. [1-3]. Theoretical investigation is hindered by the multiplicity and diversity of process involved. The aim of this work is to present a model of the cathode region in vacuum arc discharge.

2. MODEL

The present model is inspired from the theoretical study of numerous authors (as an example Hantzsche [4], Coulombe [5], Ecker [6], Zhou [7], Bolotov [8], Rethfeld [9], Mitterauer [10] and He[11] who have studied the arc cathode region extensively.

The model assume the evaporation of cathode material from the spot is caused by its elevate surface temperature. The spot high temperature is attributed to Joule heating by the high current density and the deposition of energy by ions and back diffused electrons streaming to the cathode from the ionization region in front of it. The model assumes appearance of a positive sheath in front the spot that produces a high electric field (of the order of 10^9 V/m) which lowers the work function and significantly amplifies electrons emission from the cathode. The postulated mechanism is termed field assisted thermionic (or TF) emission.

According to the generally accepted description for vacuum arcs interacting with their cathodes, the cathode region can be divided into three sub-regions (Fig. 1): cathode spot, space charge zone and ionization zone.

The space charge zone situated in front of the cathode surface is responsible for the acceleration of the emitted electrons from the cathode surface towards the ionization zone and the positive ions formed in the ionization zone towards the cathode. A net positive space charge of local density forms in the space charge zone as a result of the imbalance between the ion and electron density. The electrons extracted from the cathode travel mostly without collision in the space charge zone. When entering in the ionization zone, the emitted electrons have sufficient energy to ionize the copper atoms of vapor released from the cathode material. The resultant positive ions in the ionization zone are also accelerated in the space charge zone towards the cathode surface. The high electric field existing at the cathode surface which is necessary for electron emission from the cathode is created by these positive ions accumulated in front of the cathode surface. The ionization zone is the region in which the ion flux to the cathode surface is formed and the space charge sheath is the region in which ions going to the cathode and electrons emitted from the cathode are accelerated. In the next, we present a model for the vacuum arc cathode region in the case of copper cathode. This model can be applied for other metals.

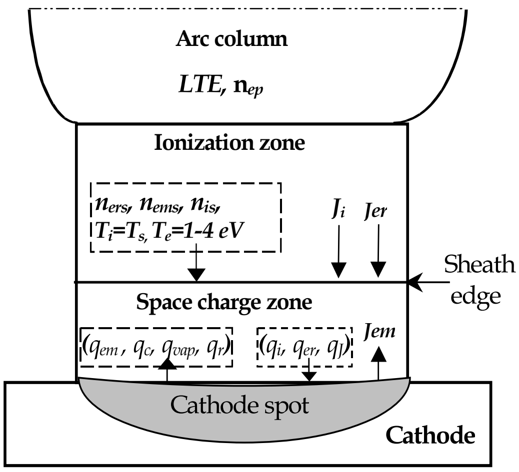

Fig. 1 Model for the vacuum arc cathode region

The electric field strength at the cathode surface is created by the positive ions and it is evaluated using a simplified equation of Mackeown [10].

$$F = \left(\frac{8 \; Z_i \; m_i \; J_i^2 U_c}{e. \; \varepsilon_0^2} \right)^{1/4} \tag{1}$$

Where m_i is the positive ion mass, U_c is the cathode fall, ε_0 is the dielectric constant, Z_i is the mean ion charge, J_i is the positive ions current density and e is the elementary charge.

The high temperature at the cathode surface causes evaporation of Cu atoms and significant local erosion of the cathode material is observed. During the process of arc operation, the flux density of copper (Γ_{ev} in $Kg/m^2.s$) atoms leaving the cathode is described by the Hertz-Knudsen formula [5]:

$$\Gamma_{ev} = \frac{P_{vap}}{4\left(\sqrt{\frac{1}{3} m_{cu} \; k_b \; T_s}\right)} \tag{2}$$

Here, T_s is the local cathode surface temperature, P_{vap} is the equilibrium vapor of the cathode material that correspond to local temperature, m_{cu} is the atom mass of cathode material ($m_{cu} = 63.546 \; uma$ for Cu) and k_B is the Boltzmann constant.

The cathode material vapor pressure (P_{vap}) that correspond to local cathode surface temperature T_s is evaluated with Langmuir formula [5].

$$P_{vap} = 133.32\left(T_s\right)^C \times 10^{-\left(\frac{A}{T_s}+B\right)} \tag{3}$$

Here, $A=17650, B=13.39, C= -1.273$ for Cu.

Particles densities at the sheath edge

n_{ems}, n_{is}, n_{ers} are respectively, the emitted electrons, positive ions and back-diffused electrons densities. n_{es} is the total electron density at the sheath edge.

$$n_{ems} = \frac{J_{em}}{e}\sqrt{\frac{m_e}{2}}\left(\frac{1}{\sqrt{\frac{2 \; k_B \; T_s}{e} + e. \; U_c}}\right) \tag{4}$$

$$n_{is} = \frac{J_i}{e.v_{is}} = \frac{J_i}{e\sqrt{\frac{k_B(T_i + Z_i.T_e)}{m_i}}} \tag{5}$$

$$n_{es} = Z_i.n_{is} \tag{6}$$

$$n_{ers} = n_{es} - n_{ems} = Z_i n_{is} - n_{ems} \tag{7}$$

Positive ions are treated as mono-energetic particles and entering the sheath edge with the Bohm[4] velocity $\left(v_{is} = \sqrt{\frac{k_B(T_i + Z_i.T_e)}{m_i}}\right)$. It is assumed also that all ions recombine at the cathode spot surface [4, 5].

J_{em}, J_i, m_e, v_i, T_e, T_i and Z_i are respectively, the emitted electron current density, the positive ions current density, the electron mass, the velocity of positive ions, the temperature of electrons and positive ions at the sheath edge and the mean ion charge. The electron density at the boundary ionization zone/arc column n_{ep} is [3]:

$$n_{ep} = n_{es}(e^{1/2}) \tag{8}$$

Current densities

The electrons are emitted from the cathode surface under the combined action of the high surface temperatures (T_s) and high surface electric field strengths (F) maintained by the ions present in the sheath. Such electron emission mechanism is called thermo-field (T-F) emission and was described in detail by Murphy and Good [12]. The current density of the emitted electrons from the cathode determined on the basis of the formalism of Murphy and Good reads:

$$j_{em} = e \int_{-W_a}^{+\infty} D\left(F,W\right)\ N\left(T_S,\Phi,W\right)\ dW \tag{9}$$

Where $W_a = \phi + W_f$.

Here, T_S is the cathode spot temperature, F is the electric field at the cathode spot surface, Φ is the work function of cathode material ($\Phi = 4.5\ eV$), W_f is the Fermi level, $D\left(F,W\right)$ is the electron tunneling probability across the barrier and, $N\left(T_s,\ F,\ W\right)$ is the number of Femi-Dirac distributed electrons having energy between W and $W + dW$ and incident on the barrier per unit time and unit surface area. For more details on these expressions and how to calculate the thermo-field emitted electrons see [12].

The current density (J_i) of positive ions which are created in the ionization zone after the metallic vapor have been ionized by electron impact is [4]:

$$J_i = \alpha\, \beta\, Z_i\, e\, \Gamma_{ev} \tag{10}$$

Where, α is the backflow coefficient of vapor towards the cathode and β is the ionization degree of the plasma ($\beta \approx 1$ i.e., all the metal vapor is ionized [4]).

The velocity distribution of electrons at the sheath edge is assumed Maxwellian one, thus some electrons whose velocities are higher than ($\sqrt{\frac{2eU_c}{m_e}}$) can overcome the cathode voltage drop and reach the cathode surface. Thus, the current density of back-diffused electrons from the plasma to the cathode surface $\left(J_{er}\right)$ is given by [4, 11]:

$$J_{er} = \frac{1}{4}\ e\, n_{ers} \sqrt{\frac{8\, k_B\, T_e}{\pi m_e}} \exp\left(-\frac{eU_c}{k_B\, T_e}\right) \tag{11}$$

The quantity $\left(\sqrt{\frac{8\ k_B\, T_e}{\pi\, m_e}}\right)$ represents the average thermal velocity of plasma electrons at the sheath edge.

The total current density $\left(J_t\right)$ is the sum of current densities of emitted electrons, back-diffused electrons and positive ions.

$$J_t = J_{em} + J_i - J_{er} \tag{12}$$

J_t is calculated also by assuming that the cathode spot has a circular shape with radius r_s :

$$J_t = I/A \tag{13}$$

All current densities are assumed to be uniformly distributed over the spot radius. I is the arc current and A is the cathode spot surface $\left(A = \pi\, r_s^{\ 2}\right)$.

Power densities heating the cathode

The cathode is heated by the impinging positive ions and back-diffused electrons and by Joule heating. In the cathode fall potential U_c the ions take the energy (eU_c). Reaching the cathode, the ions give their kinetic energy (eU_c) and the recombination energy $e(V_i - Z_i\Phi_{eff})$ to the cathode surface. Consequently, the power density (q_i) of positive ions is [5]:

$$q_i = \frac{J_i}{Z_i}\left(V_i + Z_i U_c - Z_i \Phi_{eff} + \frac{2.5 k_B T_i}{e} + \frac{Z_i k_B T_e}{2e} + W_{ev}\right) \tag{14}$$

Here, V_i is the ionization potential, $\left(\Phi_{eff} = \Phi - \sqrt{\frac{eF}{4\pi\varepsilon_0}}\right)$ is the effective work function of cathode material and W_{ev} is the condensation energy of copper atom (*3.5 eV* [5]).

The power density of back-diffused electrons q_{er} is:

$$q_{er} = J_{er}\left(\Phi_{eff} + \frac{5 k_B T_e}{2e}\right) \tag{15}$$

q_i and q_{er} are surface power phenomena heating the cathode. Additionally, within the cathode volume and especially below the cathode spot area, power is generated by Joule heating. In order to be comparable with the other components (q_i and q_{er}) this volume source is projected onto the cathode spot surface, resulting in an equivalent power density [4] of:

$$q_J = k_0 \left(J_t\right)^2 r_S \frac{T_s}{\sigma} \tag{16}$$

Where σ is the electric conductivity of copper and can be approximated by the Wiedemann-Franz law as ($\sigma = \frac{\sigma_0}{T_s}$) with σ_0 being the electric conductivity at *300 K*. k_0 is a constant in the range of (*0.5-0.8*) [4].

Power densities cooling the cathode

q_{em}, q_{vap} are respectively, the power density of emitted electron and power density of metal evaporation:

$$q_{em} = J_{em}\left(\Phi_{eff} + \frac{5 k_B T_s}{2e}\right) \tag{17}$$

$$q_{vap} = W_{evap} \cdot \Gamma_{ev} \tag{18}$$

Power loss by spot radiation (q_r) is calculated assuming a blackbody radiation using the Stefan-Boltzmann law [10].

$$q_r = \sigma_{SB} \cdot (T_s)^4 \tag{19}$$

σ_{SB} is the Stefan-Boltzmann constant.

The Power density of heat conduction in the cathode body (q_c) can be estimated as [8]:

$$q_c = \frac{T_s - T_0}{r_s} \lambda \sqrt{\pi} \tag{20}$$

Where, T_s is the cathode spot temperature, $T_0 = 300K$ is the ambient temperature far from the cathode spot, r_S is the cathode spot radius and λ is the thermal conductivity of copper. λ is taken temperature dependent [11, 12].

The total power density heating the cathode is:

$$q_+ = q_i + q_J + q_{er} \tag{21}$$

The total power density cooling the cathode is:

$$q_- = q_{em} + q_{vap} + q_c + q_r \tag{22}$$

In the stationary case, the power balance holds at the cathode surface ($q_+ = q_-$) .

3. RESULTS AND DISCUSSIONS

Computation where performed for a copper cathode with the following parameters:
$(U_c = 15V, U_i = 15V, \alpha = 1)$

For any value of current, the cathode surface is varied until the quantity $\left(\frac{q_+ - q_-}{q_+}\right)$ becomes low than 10^{-5}. In this work the effect of the electronic temperature T_e on the vacuum arc parameters are studied. This model can show the importance of the other parameters: the mean ion charge Z_i and the equivalent ionization potential U_i , the cathode voltage drop U_C , the ionization degree of the metal vapor η , and the back-flow of the metal vapor α .

Figure 2 shows the cathode spot temperature for different arc current and for different values of T_e . These temperatures are high compared with the evaporation temperature (*2868* K) of copper at ambient pressure (10^5 Pa). As arc current increases, the cathode spot temperature increases from *4400 K* to *5000 K*. This order of magnitude is in agreement with the theoretical results of Hantzsche [4], Ecker [6], Mitterauer [10], and He [11]. The value of T_e affects appreciably the values of the cathode spot temperature. As T_e increases the temperature of the cathode spot increases.

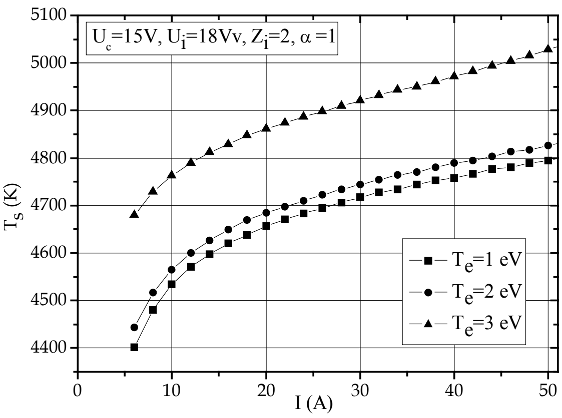

Fig. 2 Cathode spot temperature as function of current and T_e

The electric field strength in front of the cathode spot surface F shows the same tendency as the cathode spot temperature. F presented in Fig. 3 varies in the range $(3-5)\times 10^9 V/m$ and increases as arc current increases. The more important is the electronic temperature T_e , the more important is the electric field strength. The order of magnitude of the electric field agrees well with the results of Hantzsche [4], Ecker [6], Zhou [7], Mitterauer [10], and He [11].

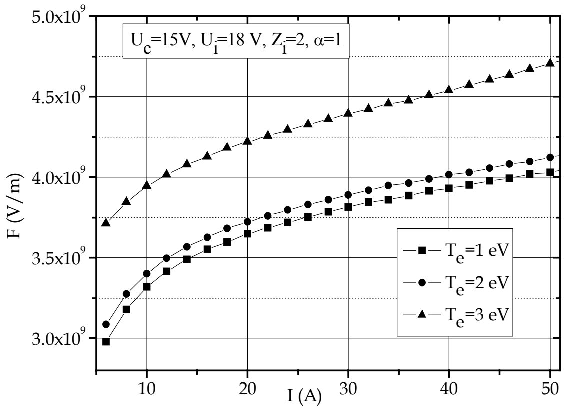

Fig. 3 Electric field at the cathode spot as function of current and T_e

Figure 4 shows that the cathode spot radius doesn't increase many with the current as in Jüttner's [14] and Daalder's [15] results shown in the same figure. At current of *10* A and T_e=*3eV* the spot radius is *5* μm and becomes *7* μm at *50*A. As T_e is increased, the spot radius is decreased and tends to the experimentally obtained values by Jüttner [14] and Daalder [15].

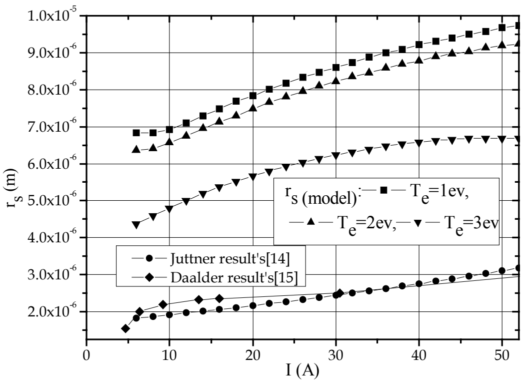

Fig. 4 Spot radius as function of current and T_e

The dependence of the current density in the cathode spot on the arc current and the electronic temperature is shown in Fig. 5. The current density increases in the range (5×10^{10}) to $(4\times10^{11}\,A/m^2)$ as arc current is increased from *4* to *50*A. If T_e is increased from *1eV* to *3eV* the current density is multiplied by a factor two. The most careful measurements of the crater size in function of current were carried out by Daalder [14] and Jüttner [15]. These authors found that at low current (*4-50* A) the crater size is not appreciably affected by the value of the arc current. The current densities have been measured by various authors [2-4, 16]. The results were obtained under different experimental conditions i.e., nature and surface quality of cathode, cathode–anode distance, nature and pressure of gas, method of measurement (spectroscopic or autographic), arc current range, arc duration, etc. Owing to these factors, one can see significant disparities (10^7 -10^{12} A/m^2) [1-4, 16] in the values of current density at the cathode obtained experimentally.

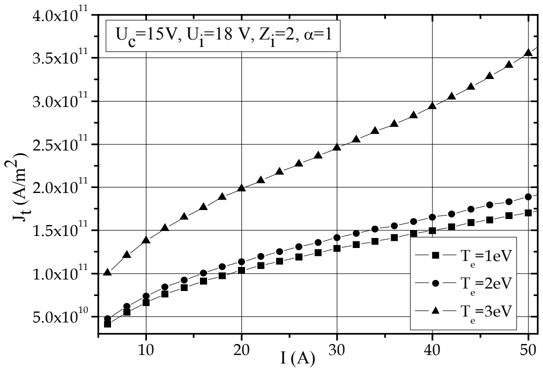

Fig. 5 Current density in the cathode spot as function of current for different values of T_e

The current density of back-diffused electrons J_{er} increases slightly with current as shown in Fig 6. However it is appreciably enhanced when the electronic temperature T_e is increased. For T_e *=1eV* the current density is low than $10^6 A/m^2$ and surpasses $10^{10} A/m^2$ for T_e *=3eV*.

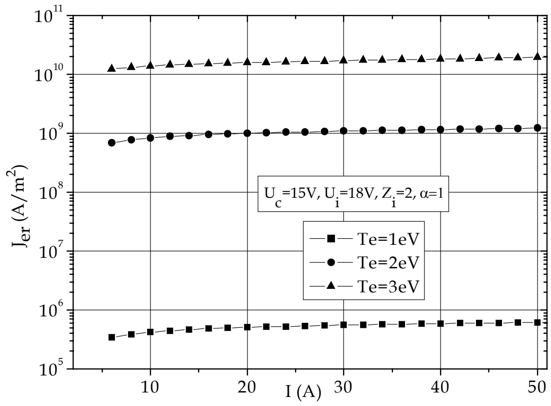

Fig. 6 Current density of back-diffused electrons as function of current for different values of T_e

The power density of back-diffused electrons (q_{er}) heating the cathode as function of current for different values of T_e is shown in Fig. 7. This power density which is proportional to the current density of back-diffused electrons J_{er} shows the same behavior as the later. q_{er} is appreciably enhanced when T_e grows from *1eV* to *3eV*. Indeed, q_{er} is near 10^6 W/m^2 for T_e *=1eV* however for T_e *=3eV* it surpasses 10^{11} W/m^2 which is appreciable.

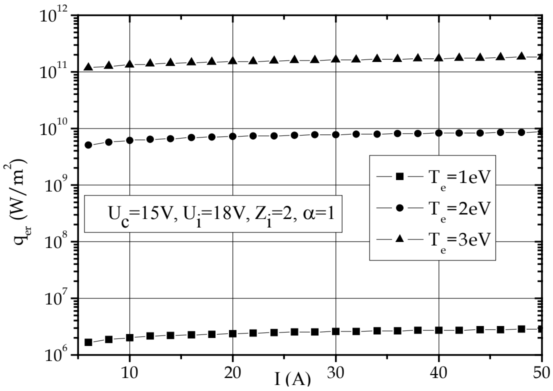

Fig. 7 Power density of back-diffused electrons heating the cathode as function of current for different values of T_e

The power densities of positive ions, retro-diffused electrons and Joule effect heating the cathode are shown in Fig. 8 for (T_e *=1eV*) and Fig. 9 (T_e *=3eV*). It can be seen that the cathode is heated mainly by the positive ions bombardment. Indeed, the density of power provided by the bombardment of the positive ions approaches (10^{12} W/m^2). The Joule effect becomes increasingly significant in heating of cathode as the current increases. The contribution of the retro-diffused electrons in heating the cathode is insignificant for T_e *=1eV*. The situation change for an electronic temperature of T_e *=3eV* and the retro-diffused electrons take part in the contribution of heating the cathode. It exceeds even that of the Joule effect as can be seen in Fig. 9.

It is important to note that the orders of magnitude of power densities of (*10^{11}à 10^{12} W/m^2*) are in good agreement with the results of Hantzsche [4, 16], Jüttner [3] and Ecker[6].

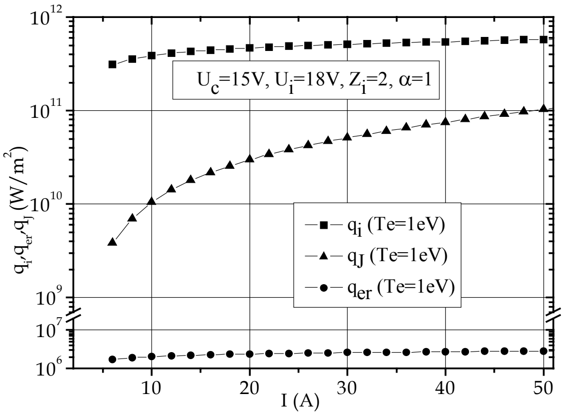

Fig. 8 Power densities heating the cathode as function of current for T_e*=1eV*

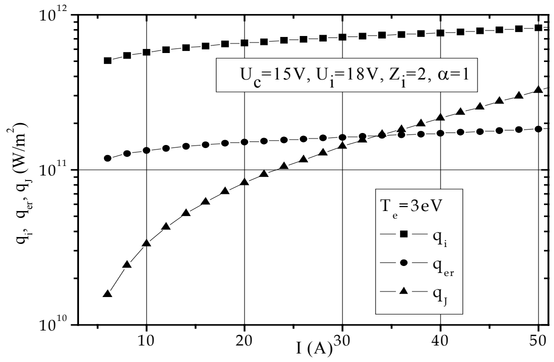

Fig. 9 Power densities heating the cathode as function of current for T_e *=3eV*

The various densities of power cooling the cathode are represented on Fig. 10. It can be seen that the spot radiation can be neglected with respect to other cooling phenomena of the cathode. The cathode is cooled efficiently by the emission of electrons. The cathode vaporization and heat conduction contribute also in the cooling the cathode. This conclusion is also seen in Fig. 11 showing the relative contribution of different power densities cooling the cathode as function of current for T_e*=3eV*.

Figure 12 shows that the density of the electrons in the positive column (n_{ep}) increases with the current from 4×10^{25} to $1\times10^{26}\,m^{-3}$ but decreases when T_e increases. The order of magnitude of this density is in good agreement with the recent experimental results of Popov [17] and those of Jüttner [3].

The erosion rate (Δm) of the metal from the cathode expressed in kg per second increases with the arc current as shown in Fig. 13. The erosion rate decreases when T_e is enhanced from *1* to *3eV*. As an example for a current of *25*A and T_e*=3eV*, Δm is $(1\times10^{-6}\,kg/s)$. This erosion rate corresponds to the value of $(40\,\mu g/C)$ experimentally obtained and generally accepted by many authors (Daalder [15], Jüttner [2]).

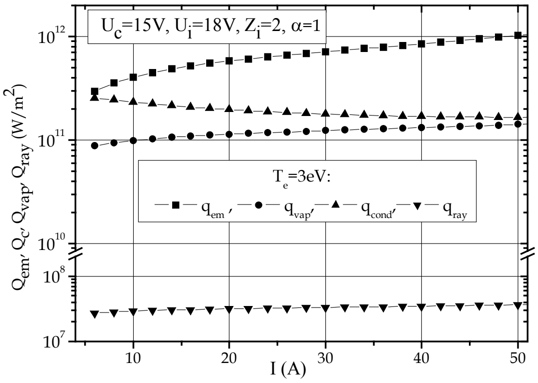

Fig. 10 Power densities cooling the cathode as function of current for T_e *=3eV*

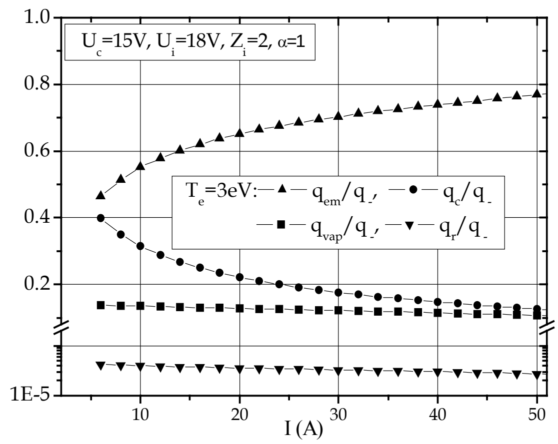

Fig. 11 Relative contribution of different power densities cooling the cathode as function of current for T_e *=3eV*

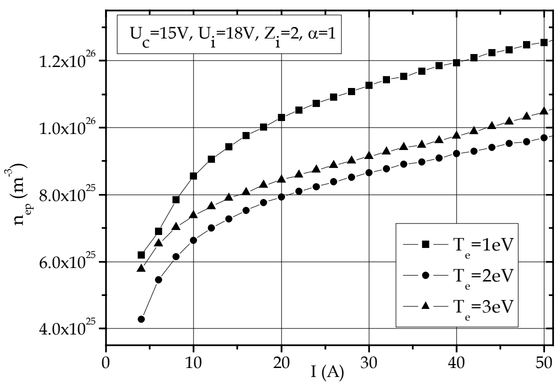

Fig. 12 Plasma electron density as function of current for different values of T_e

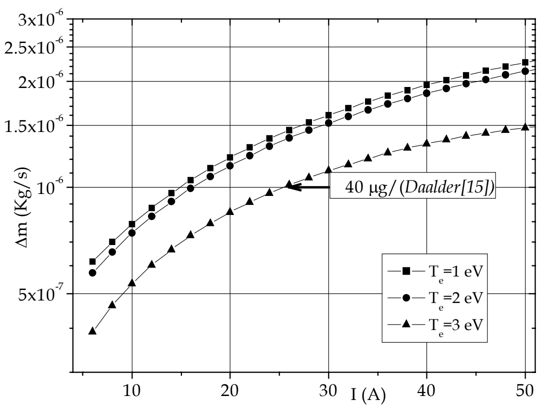

Fig. 13 Cathode erosion rate as function of current for different values of T_e

4. CONCLUSION

In this work we established a model to calculate several parameters of the vacuum arc cathode region at low current (*4* to *50*A). The most important conclusions that can be drawn are:

– The temperature at the cathode spot is larger than the evaporation temperature of copper and lies between *4300* and *4900* K. The cathode temperature is enhanced with increasing the arc current and the electronic temperature.

– The electric field at the cathode surface lies in the range $(3-5)\times10^9 V/m$ and increases with the arc current and the electronic temperature.

– The current density at the cathode is very high (5×10^{10} to $4\times10^{11} A/m^2$) and increases with the arc current. The current density is appreciably enhanced when the electronic temperature grows from *1* to *3eV*.

– The cathode spot radius grows slightly with arc current but decreases when the electronic temperature is increased. The spot radius ranges from *4* to $10\,\mu m$. These values are in good agreements with the experimental results obtained by Jüttner [14] and Daalder [15].

– The influence of the electronic temperature is best seen on the current density of the back-diffused electrons and consequently the power density gained by the cathode from the back-diffused electrons. As an example, for T_e *=1eV* the current density is lower than $10^6 A/m^2$ but surpasses $10^{10} A/m^2$ for T_e *=3eV*. The current density and the power density of the back-diffused electrons increase slightly with the arc current.

– The cathode is heated mainly by the positive ions for low values of the electronic temperature. Heating by Joule effect becomes more and more efficient in the contribution of energy supply to the cathode as the arc current increases. With an electronic temperature of *1eV*, the contribution of back-diffused electrons remains negligible. But, the situation is changed if the electron temperature is raised to *3eV*. The contribution of the back-diffused electrons can surpass the one of the Joule effect.

– The spot radiation can be neglected with respect to the other cooling phenomena of the cathode. The more efficient factor in cooling the cathode is the emission of electrons especially at high current. The cathode vaporization and heat conduction contribute also in cooling the cathode.

– The electron density in the cathode spot plasma is very high (4×10^{25} to $1\times10^{26}\,m^{-3}$) which agrees with the recent measurements of Popov.

– The erosion rate of the cathode material obtained by the model agrees well with experimental and generally accepted value of $40\,\mu g/C$.

Results of the model are in good agreement with results obtained experimentally by different authors. The model can give many other parameters (not represented in this work) of the cathode region.

The values of the parameters (cathode voltage drop U_C, mean ion charge Z_i, equivalent ionization potential U_i and the back-flow coefficient of the metallic vapor towards the cathode α) used by many authors affect considerably the parameters of vacuum arc cathode region. So, experimental and theoretical works must be undertaken to determine with more precision the parameters of the vacuum arc cathode region.

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