Physics of spotless mode of current transfer to cathodes of metal vapor arcs

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A fresh attempt is made to clarify the physics of the diffuse, or spotless, mode of current transfer to cathodes of vacuum arcs. In the case of Cr cathode, the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and a high level of the electron energy in the vicinity of the sheath edge is sustained by electron heat conduction from the bulk plasma. On the contrary, the spotless attachment of vacuum arcs to Gd cathodes may be interpreted as a manifestation of the usual mechanism of current transfer to arc cathodes.

1. Introduction

It is well known that current transfer to cathodes of arc discharges in ambient gases may occur in the spot mode and in the diffuse, or spotless, mode. The diffuse mode is favored by high average temperature of the cathode surface, which can be achieved by reducing the cathode dimensions.

Spots on cathodes of vacuum, or metal vapor, arcs are known equally well. The existence of spotless mode of current transfer to cathodes of vacuum arcs has been firmly established by now [1-7]. Similarly to the case of ambient-gas arcs, the spotless mode on cathodes of vacuum arcs occurs if the average temperature of the cathode surface is high enough, typically around 2000 K. The latter can be achieved by placing the (evaporating) cathode into a thermally insulated crucible. Characteristic features of this discharge are current densities at the cathode of 10^5-10^6 Am^{-2} and a steady highly ionized plasma without microdroplets.

Configuration of spots on both hot (arc) and cold (glow) cathodes of DC discharges in ambient gases can be determined by means of treating the spots as self-organization phenomena; e.g., review [8]. Recently, the same approach was applied to simulation of spots on cathodes of vacuum arcs [9, 10]. However, understanding of the spotless mode on cathodes of vacuum arcs remains elusive: the conclusion [1] that known mechanisms of current transfer to the cathode surface do not explain the above-mentioned current densities still stands. This state of the art is detrimental to potential applications of spotless vacuum arc discharges (e.g., [6, 7]) and to the vacuum arc physics in general.

2. Current transfer from thermal plasmas to emitting and non-emitting cathodes

A characteristic feature of plasma-cathode interaction in arc discharges is a significant electrical power deposited by the arc power supply into the near-cathode space-charge sheath. A part of this power is transported to the cathode by ions produced in the outer section of the sheath or entering the sheath from the quasi-neutral plasma; this power ensures heating of the cathode up to temperatures sufficient for electron emission. The rest of the power is transported by the electron current into the quasi-neutral plasma; this power ensures that the energy of the electron gas is high enough for maintaining a level of ionization which is sufficient for providing the necessary ion current. The ion current usually constitutes a few tenths of the net current; one can assume 30% as a representative value. Thus, about 30% of the power deposited into the sheath goes to ions and is transported to the cathode surface and about 70% goes to electrons and is transported into the quasi-neutral plasma.

If the temperature of the cathode surface is not sufficiently high to produce appreciable electron emission, the only possible mechanism of current transfer to the cathode surface is charge transport by ions entering the sheath from the quasi-neutral plasma. The power is deposited into the electron gas primarily in the bulk plasma and not in the sheath and a high level of the electron energy in the vicinity of the sheath edge is sustained by electron heat conduction from the bulk plasma. This regime is similar to the ion current regime of electrostatic (Langmuir) probes.

The cathode material on which many experiments have been performed is chromium. Thermionic emission current density estimated for the work function A_f = 4.58 eV (a value for polycrystalline chromium surface) and the cathode surface temperature T_w = 2000 K with the use of the Richardson formula is 14 Am^{-2}, which is by orders of magnitude lower than the current densities observed in the experiment. It follows that the spotless attachment of vacuum arcs to chromium cathodes cannot be a manifestation of the above-described usual mechanism of current transfer to arc cathodes; one should rather think of the ion current regime of electrostatic probes.

3. Invoking model of near-cathode plasma layers in vacuum arcs

The above reasoning needs to be supported by more accurate estimates. To this end, a complete model of the near-cathode plasma layer of vacuum arcs is needed, which would describe in a self-consistent way the near-cathode space-charge sheath, balance of the electron energy, and balance of the evaporated metal atoms with their eventual return to the cathode if ionized before the maximum of potential which occurs inside the sheath. Results of calculations performed by means of such model [11] are shown in Fig. 1. One can see that the density j_i of ion current slightly exceeds the electron emission current density. The electric field at the cathode surface is not high enough for the thermo-field electron emission mechanism to come into play and the electron emission is of thermionic nature. Therefore, the electron emission current density j_{em} shown in Fig. 1, which in the framework of the model [11] is evaluated by means of the Murphy and Good formalism, is very well represented by the Richardson-Dushmann formula. On the other hand, j_{em} exceeds the Richardson value j_R, hence the Schottky correction to the work function is significant. The current of fast plasma electrons capable of overcoming the retarding electric field of the sheath and reaching the cathode surface is negligible and not seen on the graph.

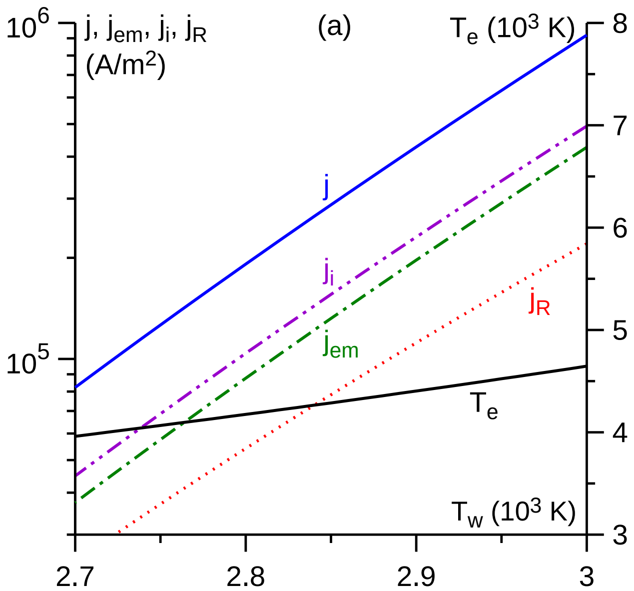

Fig. 1. Computed characteristics of near-cathode layer of vacuum arc. Cr cathode, sheath voltage U = 20 V.

Although the density j of net electric current at the cathode surface exceeds j_R by about a factor of 3, this difference is insufficient to bring the estimates close to the experiment: j attains the value of 10^5 Am^{-2} at $T_w \gtrsim 2700$ K, which is significantly higher than the measured temperatures around 2000 K.

Thus, accurate estimates have confirmed the conclusion that the usual mechanism of current transfer to arc cathodes in the case of chromium cathode cannot sustain current densities of the order of 10^5-10^6 Am^{-2} observed in spotless attachment [1-7]. The root reason is that the power deposited into the electron gas in the sheath is insufficient due to very low electron emission current, as discussed in the preceding section. This manifests itself through very low values of the electron temperature in the near-cathode layer, T_e, and the corresponding ionization degree in the near-cathode layer predicted by this model (cf. curve T_e in Fig. 1): 3960 K and 2.3×10^{-3}, respectively, for T_w = 2700 K and still lower for smaller T_w. Since the plasma is highly ionized under the experimental conditions [1, 5, 7], these values should be deemed unrealistic. It follows that the electrical power is deposited by the external circuit into the electron gas primarily in the bulk plasma and not in the sheath; real values of T_e in the near-cathode layer are much higher than those seen in Fig. 1 and are sustained by electron heat conduction from the bulk plasma, rather than by a local energy input.

4. Estimating ion current from thermal plasma of metal vapor

A question arises if the density of the bulk plasma under the experimental conditions [1, 5, 7] is sufficiently high to ensure the density of ion current to the cathode of the order of 10^5-10^6 Am^{-2}. The plasma in the experiments [1-7] may be considered as a thermal plasma under the pressure equal to the pressure of the saturated vapor of the cathode material evaluated at the cathode surface temperature T_w. Ionization (Saha) equilibrium holds in the bulk of the plasma but is violated in a thin layer adjacent to the near-cathode space-charge sheath; the so-called ionization layer. The scale of thickness of the ionization layer is represented by the ionization length d; e.g., [12]. The maximum ion current that can be extracted from the plasma (ion saturation current) is limited by ambipolar diffusion of the ions across the ionization layer and may be estimated by means of, e.g., [12]. Values found in this way are depicted by the curve $j_i^{(d)}$ in Fig. 2. One can see that the ion current density is of the same order as the experimental current density.

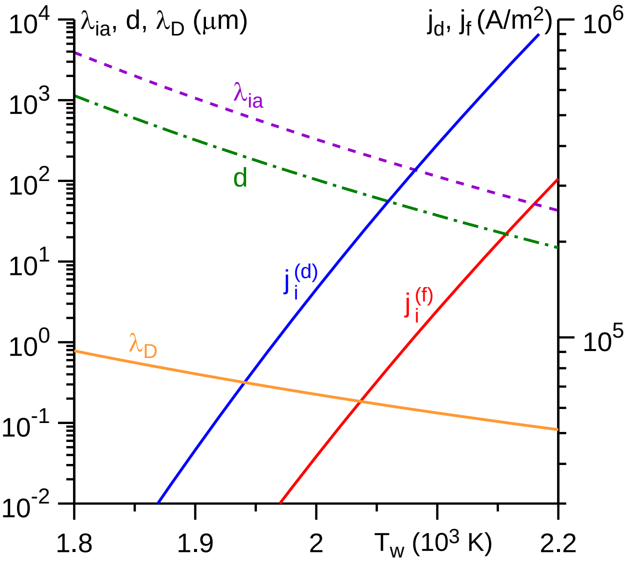

Fig. 2. Ion saturation current. Cr-vapor plasma, T_e = 8000 K.

Also shown in Fig. 2 are the ionization length d, the Debye length λ_D, and λ_{ia} the mean free path for collisions between the ions and neutral atoms. Conditions of the validity of the above evaluation of the ion current read $\lambda_D, \lambda_{ia} \ll d \ll L$, where L is a characteristic dimension of the plasma. Given that $L \sim 1$ cm in the conditions of experiments [1-7], one can see that the inequalities $\lambda_D \ll d \ll L$ are satisfied but the inequality $\lambda_{ia} \ll d$ is not; in fact, λ_{ia} exceeds d by a factor of about 3. An approximate theory for such conditions was developed by means of the so-called multifluid approach [13]. The ion current evaluated by means of this theory is depicted by the curve marked $j_i^{(f)}$ in Fig. 2. Although $j_i^{(f)}$ is smaller than the diffusion value $j_i^{(d)}$, it is still not far away from the experiment: $j_i^{(f)} \geq 10^5$ Am^{-2} for $T_w \geq 2100$ K.

Thus, estimates of the ion saturation current give values consistent with the assumption that the current in the spotless attachment of vacuum arc to chromium cathode is transported by ions diffusing to the sheath edge from the bulk plasma across the ionization layer.

5. Gadolinium cathode

A significant amount of experimental data on spotless vacuum arc attachment has been obtained for cathodes made of gadolinium [2-4, 6, 7]. The value of work function for a polycrystalline surface of gadolinium is 3.1 eV, i.e., quite low. Accordingly, it is well known that thermionic emission current is high enough to ensure the spotless attachment of vacuum arcs to a gadolinium cathode observed in the experiments [2-4, 6, 7].

However, it is of interest to apply to gadolinium cathodes the same approach that was applied above to cathodes made of chromium, in order to once again validate the approach and demonstrate the possibility of self-consistent calculation of some parameters of the spotless vacuum arc on a gadolinium cathode.

Results of calculations for gadolinium cathodes are shown in Figs. 3 and 4. One can see that the current density computed by means of the model of near-cathode layers in vacuum arcs [11] (curve j in Fig. 3) exceeds 10^5 Am^{-2} for $T_w \gtrsim 2000$ K, i.e., is in the right order of magnitude. On the other hand, the ion saturation current from Gd ($j_i^{(f)}$ in Fig. 4) does not exceed approximately 10^4 Am^{-2}. It follows that the spotless attachment of vacuum arcs to gadolinium cathodes is a manifestation of the usual mechanism of current transfer to arc cathodes and cannot be explained by current of ions diffusing from the bulk plasma, in contrast to the case of chromium cathodes.

Let us consider in some detail results given by the model [11] and shown in Fig. 3. T_e in the near-cathode layer is around 3.1×10^4 K, i.e., rather high, and is still higher for higher values of the sheath voltage; e.g., $T_e \approx 6.3\times10^4$ K for U = 20 V. This is a consequence of the significant electrical power supplied to the electron gas in the sheath, which, in turn, originates in the significant electron emission current.

The net current density j is slightly bigger than j_R. An appreciable current is transported by fast plasma electrons attaining the cathode (j_e), while the ion current j_i is very small, about 4% of the electron

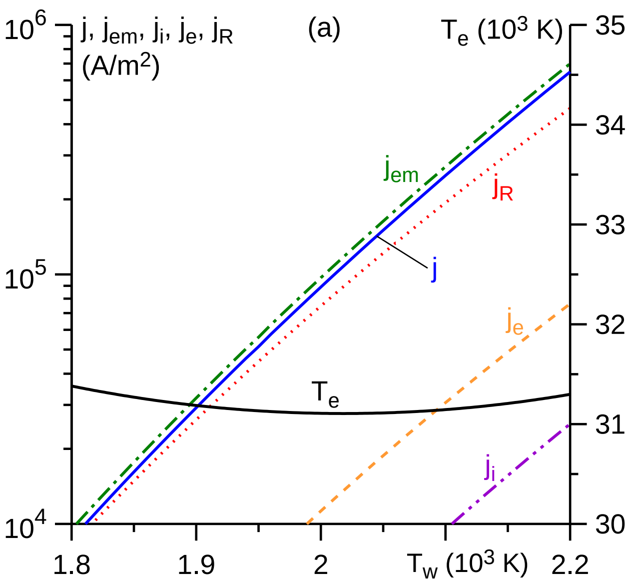

Fig. 3. The same as Fig. 1, Gd cathode, U = 10 V.

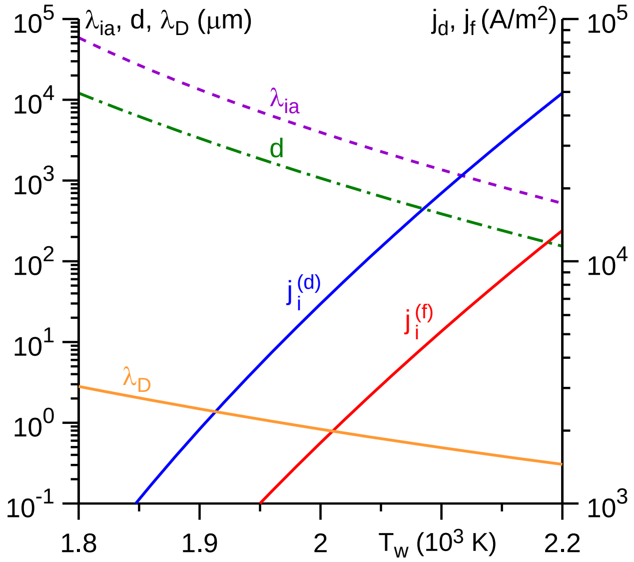

Fig. 4. The same as Fig. 2, Gd-vapor plasma.

emission current. It should be stressed that the latter is not a consequence of the return of most part of evaporated atoms to the cathode in the form of ions; for example, for T_w = 2000 K about 43% of the ions are produced after the potential maximum in the sheath and escape into the plasma. Rather, the smallness of the contribution of the ion current originates in the well-known [2-4, 6, 7] fact that the flux of emitted electrons from a gadolinium surface is significantly higher than the flux of evaporated atoms, which results from the low work function of gadolinium and relatively high evaporation energy.

Values of the ratio j_i/j_{em} that low indicate that the cooling of the cathode by electron emission exceeds heating by the ion current. Therefore, the possible source of heating of gadolinium cathodes in the experiments [2-4, 6, 7] is radiation from the plasma.

The above results conform to experimental information and estimates available in the literature. In particular, the electron temperature measured in Gd is around 3-4 eV for the arc voltage V_a = 10 V and increases to 7-8 eV for V_a = 20 V [6]. The spectral line of doubly charged ions has been observed in Gd and its intensity was found to decrease with an increase of V_a; a possible indication to the presence of triply charged ions [7]. Note that only lines of atoms and singly charged ions have been observed in Cr plasma [7]. The ion current to a gadolinium cathode does not exceed 5% of the electron emission current [4].

6. Conclusions

A fresh attempt is made to clarify the physics of the diffuse, or spotless, mode of current transfer to cathodes of vacuum arcs. In the case of Cr cathode, the usual mechanism of current transfer to arc cathodes cannot sustain current densities of the order of 10^5-10^6 Am^{-2} observed in the experiment, the reason being that the electrical power deposited into electron gas in the near-cathode space-charge sheath is insufficient. It is hypothesized that the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and a high level of the electron energy in the vicinity of the sheath edge is sustained by electron heat conduction from the bulk plasma. Estimates of the current of ions diffusing to the sheath edge from the bulk plasma gave values comparable to the experimental current density, which supports the above hypothesis. On the contrary, the spotless attachment of vacuum arcs to Gd cathodes may be interpreted as a manifestation of the usual mechanism of current transfer to arc cathodes. Results given for gadolinium cathodes by a model of near-cathode layers in vacuum arcs conform to available experimental information.

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