Ionization layer with collision-free atoms at the edge of partially to fully ionized plasmas

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Ionization (Saha) equilibrium, which holds in strongly ionized high-pressure plasmas, e.g., those generated in high-current arc discharges, is violated in thin layers near solid surfaces contacting the plasma. Of particular importance is the non-equilibrium layer near the cathode, since it is in this layer that the ion current to the cathode surface is formed, which heats the surface to the high temperatures necessary for electron emission. More precisely, the ion current is formed in the outer - quasi-neutral - section of the near-cathode non-equilibrium layer; the so-called ionization layer. An understanding and adequate theoretical description of the ionization layer are needed for evaluation of the ion current to the cathode.

The physics of the ionization layer may be briefly described as follows. Ions generated in the ionization layer move to the cathode surface where they recombine. (On their way to the cathode, the ions cross the space-charge sheath, where they are accelerated by the sheath electric field, but this is not directly relevant to this context.) Neutral atoms thus formed are desorbed from the surface and move into the plasma, with some or all of them being ionized while crossing the ionization layer. A theoretical description of the relative motion of the ions and the atoms in the ionization layer depends on the relationship between the scale of thickness of the ionization layer, l, and the mean free path for collisions between the atoms and the ions, λ_{ia}.

An example is shown in Fig. 1. Here l_{cf} and l_{dif} are scales of thickness of the ionization layer, evaluated in the limiting cases where a neutral atom, while moving across the ionization layer, suffers virtually no or many collisions, respectively. Also shown are characteristic mean free paths for collisions between the ions, λ_{ii}, and between the neutral atoms, λ_{aa}, the Debye length λ_D, the ionization degree ω, and the parameter α, which characterizes the ratio l/λ_{ia}. All these quantities refer to conditions at the "edge" of the ionization layer, where the plasma is in ionization equilibrium, and the partial composition of the plasma was evaluated by means of the Saha equation in terms of the electron temperature in the ionization layer, T_e, the heavy-particle temperature, T_h, which is set equal to 3000 K, and the plasma pressure.

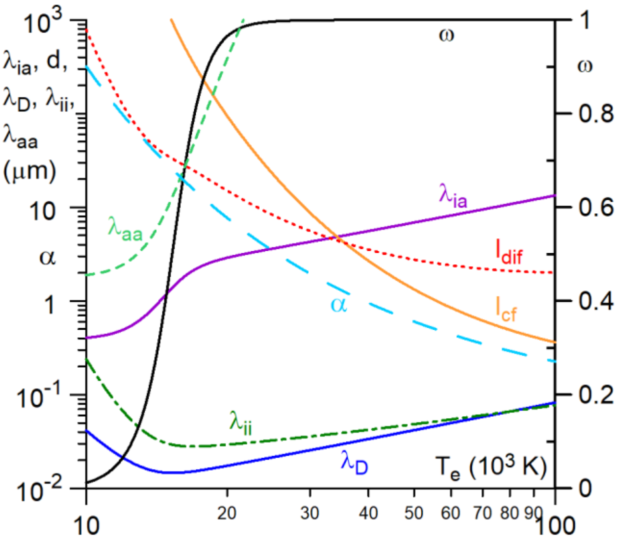
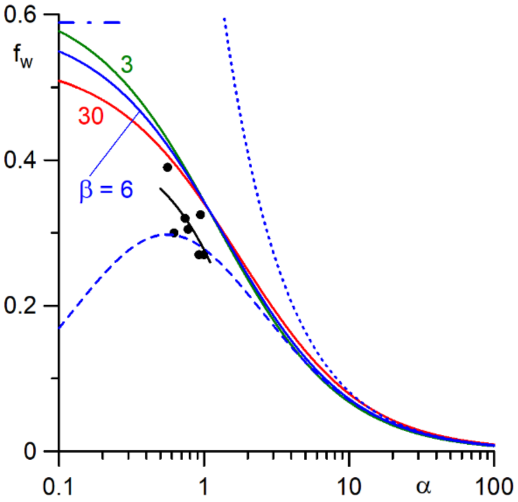


Fig. 1: Characteristic length scales in the ionization layer in atmospheric-pressure argon arc.

In the fully developed arc-cathode regime, the current-collecting part of the cathode surface is hot and the near-cathode voltage drop is low. As a consequence, T_e is relatively low as well and $l > \lambda_{ia}$. The ionization layer may be described in the diffusion approximation in this regime. The contrary situation occurs during glow-to-arc transitions: when a hot arc spot has just formed on the cathode surface, a significant part of current still flows to the cold surface outside the spot in the glow-discharge regime, and therefore the near-cathode voltage continues to be high at all points of the cathode surface including in the spot. T_e is high in this case and $l < \lambda_{ia}$. The coupling between the ion and atom species in the ionization layer is not strong and the diffusion description of the ion-atom relative motion in the layer is not valid. Since $\lambda_{ii} < l$ and $\lambda_{aa} > l$, a fluid description of the ion motion should be combined with a kinetic description of the motion of the atoms. The resulting problem admits a simple analytical solution, which is used to derive formulas for evaluation of the ion current to the cathode surface for a wide range of conditions, including for arbitrary values of the ratio l/λ_{ia} and the ionization degree.

An example is shown in Fig. 2. Here f_w is the normalized ion current, coming to the cathode from the ionization layer across the space-charge sheath, and $\beta = T_e/T_h$. Also shown are the ion current evaluated in the diffusion approximation, in the approximation of collision-free atoms, and by means of the multifluid theory [1]. Also shown are experimental data taken from figure 5 of [2], which were transformed as described in [3] and refer to conditions with $\beta \approx 6$.



Normalized ion current to the cathode. Solid: this work, β = 3, 6, 30. Dotted: diffusion approximation, β = 6. Dash-dotted: approximation of collision-free atoms, β = 6. Dashed: multifluid theory [1], β = 6. Circles and short solid line: experimental data from [2] and their linear fit.

As expected, values of the normalized ion current given by the theory of this work, by the multifluid theory, and the diffusion theory are all close to each other for large α. For α of order unity and smaller, the diffusion values substantially exceed values given by the theory of this work. The multifluid theory gives lower values than the theory of this work and the difference increases as α decreases; a consequence of the difference in asymptotic behaviour of the function $f_w(\alpha)$ for small α.

Given that the theory of this work is better justified theoretically than both the diffusion and multifluid theories, one would expect that the theory of this work conforms to experiment better than both the diffusion and multifluid theories. This is clearly the case as far as the diffusion theory is concerned. This appears to be the case also for the multifluid theory, although the scatter of experimental data is too great to make an unambiguous conclusion.

The possibilities of using the obtained results to improve existing methods for modeling high-pressure arc discharges and their interaction with electrodes (e.g., review [4] and references therein) in order to increase their accuracy in relation to glow-to-arc transitions on cold cathodes will be discussed at the conference.

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