Modelling arc cathodes covered by an alkali monolayer

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Effects caused by a variation of the work function of the cathode surface due to formation on the surface of a monolayer of alkali metal atoms are studied for particular cases of Na-Hg and Cs-Hg plasmas. It is found that formation of the sodium monolayer affects the diffuse mode of current transfer only moderately and in the same direction that the presence of metal atoms in the gas phase does. Formation of the cesium monolayer produces a dramatic effect: the cathode surface temperature decreases very strongly, the diffuse-mode current-voltage characteristic becomes N-S-shaped.

1. Introduction

The model of nonlinear surface heating has become a widely accepted tool for modelling plasma-cathode interaction in high-pressure arc discharge devices; see works [1–11] and references therein. The model was validated [4, 12] by a detailed comparison with the experiment.

Under conditions characteristic of sodium and metal halide arc lamps, the plasma-producing gas represents a mixture of molecular and atomic species composed of Hg and (some of) the following elements: Hg, Na, Tl, Dy, Sc, Cs, I, and Ar. The presence of alkali metal atoms affects the current transfer in two ways: through variation of properties of the near-cathode plasma layer due to the presence of metal atoms in the gas phase and through variation of the work function of the cathode surface due to formation on the surface of an alkali metal monolayer. The first effect was studied in [13, 14]. The second effect is studied in this work.

2. Work function of a surface covered by a monolayer of alkali atoms

In order to identify effects caused by a variation of the work function of the cathode surface due to formation on the surface of a monolayer of alkali metal atoms, a particular case will be considered where the plasma-producing gas contains mercury and one alkali metal, namely sodium or cesium. As it will be seen later, this selection allows one to illustrate both a situation in which the variation of the work function affects the plasma-cathode interaction only moderately and a situation in which it brings new effects which dramatically change the plasma-cathode interaction. Besides, the Na-Hg plasma is of independent interest in connection with sodium lamps.

The dependence of the work function A_f on the temperature T_w of the cathode surface is as follows. A_f is governed by θ the surface coverage (fraction of the surface which is covered with alkali atoms), which, in turn, is governed by the partial pressure of alkali atoms and the temperature of the cathode surface. At $\theta \ll 1$, when the cathode surface is effectively clean of alkali atoms, A_f takes the value corresponding to tungsten, which is $4.55\,\mathrm{eV}$. At θ close to unity, A_f takes the value corresponding to the alkali metal, which is about $2.6\,\mathrm{eV}$ for Na and about $2.2\,\mathrm{eV}$ for Cs. At θ intermediate between 0 and 1, the dependence $A_f(\theta)$ is non-monotonic and takes a minimum value at a certain $\theta = \theta_m$; note that $\theta_m \approx 0.7$, $A_f(\theta_m) \approx 2.1\,\mathrm{eV}$ for Na [15] and $\theta_m \approx 0.5$, $A_f(\theta_m) \approx 1.6\,\mathrm{eV}$ for Cs [16].

The surface coverage is governed by the condition of equilibrium between the alkali atoms in the gas phase and those bound to the surface, that is, by the condition of equality of adsorption and desorption (evaporation) rates. With increase of the temperature the desorption rate increases exponentially, while the adsorption rate varies much weaker. As a result, the surface coverage monotonously decreases with an increase of T_w at a fixed partial pressure of atoms, from $\theta \approx 1$ at low T_w to $\theta \ll 1$ at high T_w. Given the above-described non-monotony of the dependence $A_f(\theta)$, one concludes that the dependence of the work function on the cathode surface temperature is also non-monotonic.

The dependence of the work function of tungsten covered by a monolayer of Na or Cs on the surface temperature was calculated with the use of semi-empirical formulas given in [15] and [16], respectively, and is shown in figure 1. (Here Z is the molar fraction of alkali metal; the plasma pressure is assumed to be $5\,\mathrm{bar}$ in all calculations given in
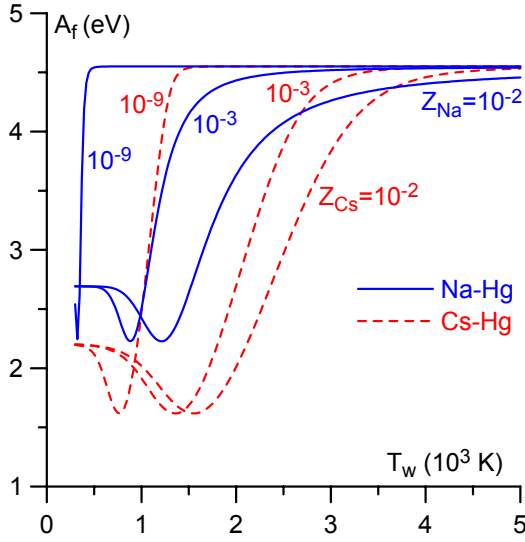
Figure 1: Work function of tungsten covered by a monolayer of Na or Cs in Na-Hg or Cs-Hg plasmas.

this work). One can see that even smalls amounts of the alkali vapor in the plasma, of the order of 1% and less, can produce a significant effect on the work function. It should be emphasized that the decrease of the work function produced by adding Cs to the mercury plasma is stronger than that produced by adding Na and comes into play at higher values of the surface temperature.

3. Modelling diffuse discharge on tungsten cathodes

The density of energy flux from the Na-Hg plasma with $Z_{Na} = 1\%$ and from the Cs-Hg plasma with $Z_{Cs} = 0.3\%$, calculated with account of variation of the work function due to formation on the surface of a monolayer of Na or, respectively, Cs atoms, is shown in figure 2. Also shown are data for the pure Hg plasma. In the range $T \gtrsim 3,000\,\text{K}$, densities of energy flux from the Na-Hg and Cs-Hg plasmas are not very different from that from the Hg plasma. A quantitative difference can be seen at lower temperatures in the case of the Cs-Hg plasma: one or more new maxima appear. A similar but weaker effect appears also in the case of the Na-Hg plasma.

Furthermore, the dashed curve in the figure 2b representing the first growing section of the dependence of q on T_w for the Cs-Hg plasma is S-shaped, although the range of T_w in which the S-shape occurs (i.e., in which the dependence of q on T_w is three-valued) is rather narrow, $1,140\,\text{K} \lesssim T_w \lesssim 1,190\,\text{K}$, and the S-shape is hardly visible. In fact, such S-shape occurs at all values of the near-cathode voltage drop U exceeding approximately $15\,\text{V}$.
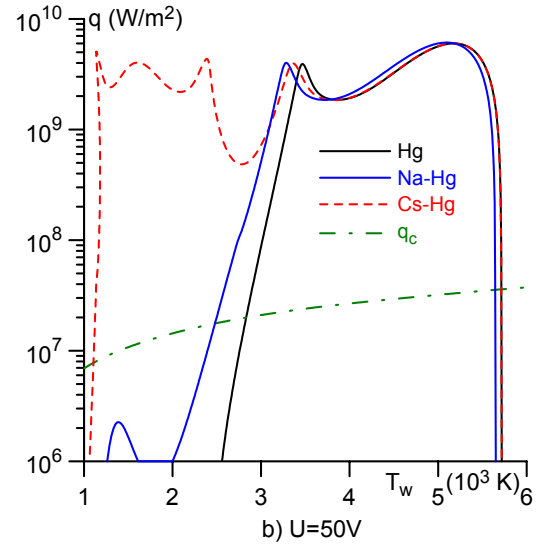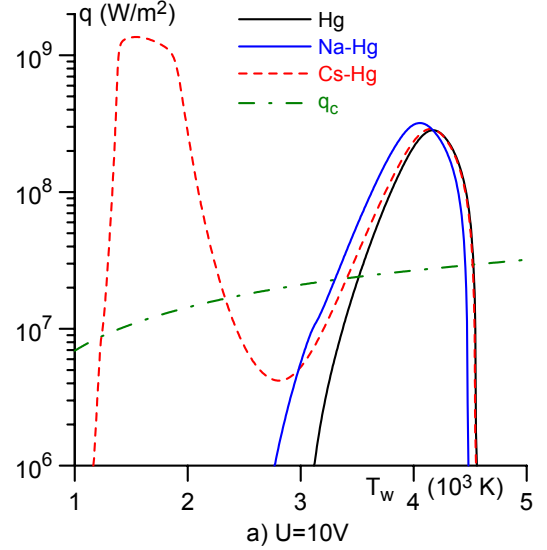

Figure 2: Dependence of the energy flux density from different plasmas to the surface of a tungsten cathode on the surface temperature. Na-Hg plasma: $Z_{Na} = 1\%$. Cs-Hg plasma: $Z_{Cs} = 0.3\%$.

It should be emphasized that the appearance of the new maxima and of the S-shape is entirely due to the variation of the work function, since calculations for the Na-Hg and Cs-Hg plasmas with the fixed value of the work function equal to $4.55\,\text{eV}$, which are not shown on the graph, gave dependences similar to those for the pure mercury plasma.

In order to understand what changes of the diffuse mode of current transfer can be caused by the appearance of the above-mentioned maximum or maxima, it is convenient to resort to the 1D model of the cathode [1]. That is, let us for the mo-

ment consider a rod cathode with a thermally and electrically insulated lateral surface. Thermal balance of such cathode is governed by the equation $q(T_w, U) = q_c(T_w)$, where $q(T_w, U)$ is the density of the energy flux from the plasma to the cathode surface as before and

$$q_c(T_w) = \frac{1}{h} \int_{T_c}^{T_w} \kappa(T)\, dT \qquad (1)$$

is the density of energy flux removed from the cathode top by thermal conduction to the bottom. (Here κ is thermal conductivity of the cathode material and T_c is the temperature of the bottom, which is assumed to be equal to 293 K in this work.) The dependence $q_c(T_w)$ for a tungsten cathode of the height of 14.5 mm is shown in figure 2. One can see that Eq. (1) for the Cs-Hg plasma at $U = 10\,\mathrm{V}$ has four roots. In other words, four different 1D thermal regimes are possible at $U = 10\,\mathrm{V}$. It follows that, while the current-voltage characteristics $U(I)$ of the diffuse mode in the case of Hg and Na-Hg plasmas consists of two branches separated by a minimum [1], the characteristic of diffuse discharge in the Cs-Hg plasma consists of four branches separated by two minima and a maximum.

Since an increase of the work function with an increase of the surface temperature may render non-monotonic the dependence of emission current on the surface temperature, more than one diffuse-mode solution may correspond to the same arc current. In other words, the current-voltage characteristic $U(I)$ of the diffuse mode may become S-shaped.

Thus, one can expect that the variation of the work function caused by a monolayer of alkali atoms does not change qualitatively the diffuse mode of current transfer in the Na-Hg plasma but may affect dramatically the diffuse mode of current transfer in the Cs-Hg plasma.

Results of 2D simulations with account of current and energy collection by the lateral surface are shown in figure 3. (Note that calculations for the same conditions with the fixed value of the work function equal to 4.55 eV, which are not shown on the graph, gave results very close to those for the pure mercury plasma.) In the case of the Na-Hg plasma the variation of the work function causes a decrease of the cathode surface temperature and of the near-cathode voltage drop. In other words, formation of the sodium monolayer on the surface affects current transfer in the same direction that the presence of sodium in the gas phase does but produces a somewhat stronger effect. In general, formation of the sodium monolayer affects interac-
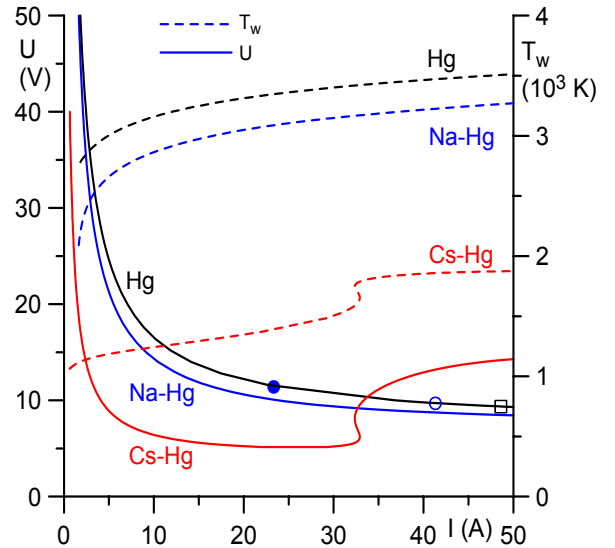

Figure 3: Maximal temperature of the cathode surface and current-voltage characteristics of the diffuse discharge on a tungsten cathode of the radius of 1 mm and of the height of 14.5 mm. Na-Hg plasma: $Z_{Na} = 1\%$, cathode covered by a monolayer of Na. Cs-Hg plasma: $Z_{Cs} = 0.01\%$, cathode covered by a monolayer of Cs. Points: stability limit of the diffuse mode in the Na-Hg plasma with $Z_{Na} = 0.08\%$ on the cathode covered by a monolayer of Na (the full circle); in the Na-Hg plasma with $Z_{Na} = 0.08\%$ on the clean cathode (the open circle); in the Hg plasma (the square).

tion of the Na-Hg plasma with a thermionic cathode only moderately.

On the contrary, there is a striking difference between the dependences $T_w(I)$, $U(I)$ for the Cs-Hg plasma and those for the pure mercury plasma. The temperature of the cathode surface decreases quite significantly. The current-voltage characteristic $U(I)$ is S-shaped (i.e., the dependence of U on I is three-valued) at currents between approximately 32 A and 33 A. A similar S-shape is present also in the dependence $T_w(I)$. In accord to the above discussion, these S-shapes result from the non-monotonic dependence of emission current on the surface temperature (which, in turn, results from the increase of the work function with the surface temperature) and are unrelated to the S-shape present in figure 2b, which occurs at near-cathode voltages and/or cathode surface temperatures higher than those that have been encountered in the calculations represented in the figure 3. Note that the maximum and the second minimum of the current-voltage characteristic, predicted above on the basis of the 1D model, have been revealed also by the 2D

simulation being described, however they are positioned at high currents far beyond the range covered by figure 3.

The complete current-voltage characteristic of the cathodic part of the discharge includes also the branch coinciding with the positive part of the axis of voltages, which describes the situation where no arc is present. Therefore, the complete current-voltage characteristic of the diffuse mode on clean cathodes includes three branches: the branch coinciding with the positive part of the axis of voltages, the falling section of the dependence $U(I)$ describing the diffuse discharge, and the growing section of the dependence $U(I)$ describing the diffuse discharge (which occurs at currents higher than those represented in figure 3). In other words, the complete current-voltage characteristic of the diffuse mode on clean cathodes is N-shaped, which is essential for understanding the spot modes [1]. In such terms, the current-voltage characteristic of the diffuse mode in the Cs-Hg plasma shown in figure 3 should be called N-S-shaped.

Also shown in figure 3 is the limit of stability of the diffuse mode in the Na-Hg plasma against the first mode of 3D perturbations, calculated as described in [1,6] for $Z_{\mathrm{Na}} = 0.08\%$ with and without account of the variation of the work function, and in the pure mercury plasma. In the calculations with account of the variation of the work function at $Z_{\mathrm{Na}} \gtrsim 0.09\%$ the instability disappears, i.e., the diffuse mode becomes stable at all currents against the first mode of 3D perturbations. (Note that the disappearance of the instability against the first mode of 3D perturbations was first detected in calculations with a clean cathode and analyzed in detail in [13], however, on a clean cathode it occurs at higher Z_{Na}.) One can conclude that the presence of sodium in the gas phase results in an expansion of the range of stability of the diffuse mode; the formation of sodium monolayer on the surface produces a similar but somewhat stronger effect.

As far as stability of the diffuse mode in the Cs-Hg plasma is concerned, it is unclear whether the approach [1,6] can be applied directly, given the complex form of the current-voltage characteristic for the Cs-Hg plasma shown in figure 3. Therefore, the question of stability of the diffuse mode in the Cs-Hg plasma requires an additional mathematical treatment and falls beyond the scope of this work.

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