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Formation of stationary and transient spots on thermionic cathodes and its prevention

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Abstract
Spots on cathodes of high-pressure arc discharges induced by a rapid increase in the arc current are studied numerically and experimentally. Appearance of stationary and transient spots is analysed in the context of the general pattern of steady-state modes of current transfer to thermionic cathodes and their stability. Transient spots are studied in experiments with COST-529 standard lamps. Modelling and experimental results are in reasonable agreement. A method to prevent formation of transient spots on cathodes of high-pressure arc discharges by means of short negative rectangular current pulses is proposed and validated both numerically and experimentally. Experimental indications are found that the main mechanism of blackening of burners of HID lamps that accompanies appearance of transient cathode spots is evaporation of the cathode material and not sputtering.

(Some figures in this article are in colour only in the electronic version)

M Supplementary animations are available in the online edition at http://stacks.iop.org/JPhysD/41/144004

1. Introduction

The appearance of spots on cathodes of HID lamps represents a major problem for designers, in the first place, due to the blackening of burner's walls which accompanies the appearance of spots. At present, the physics of spots on thermionic arc cathodes is understood relatively well. They appear as a result of a thermal instability for which the role of positive feedback is played by the growing dependence $q(T_w)$, where q is the density of the energy flux from the plasma to the cathode surface and T_w is the local temperature of the surface. This positive feedback is opposed by thermal conduction in the cathode body, which tends to smooth out perturbations, i.e. produces a stabilizing effect. A competition of these two mechanisms results in the appearance, or not, of spots on thermionic arc cathodes.

The stabilizing effect of thermal conduction is enhanced by a reduction of cathode dimensions. Therefore, dc cathodes may be forced into the spotless, or diffuse, mode by reducing their dimensions. (The same idea may be expressed in other words which are very familiar to designers of arc devices: if a cathode is small, it is easier to heat it up to temperatures necessary for the diffuse operation.) Besides, prevention of spots on dc cathodes may be facilitated by an intelligent choice of the cathode shape.

The situation is more complex as far as ac arcs are concerned: transient spots may be provoked even on small cathodes by rapid variations of the arc current. Typically, spots appear on electrodes of ac HID lamps at the beginning of the cathodic phase immediately after current zero, when the cathode on the whole is not yet hot enough to efficiently transfer current from the arc. After operating in the spot mode for some time, the cathode on the whole usually gets hot enough, the arc attachment switches into the diffuse mode and remains diffuse during the rest of the cathode phase.

It seems natural to try to prevent formation of transient spots on cathodes of ac HID lamps by means of an intelligent choice of the current waveform. Such a choice can be guided by numerical modelling, which has at present attained an advanced stage and is capable of providing a reasonably accurate description of most aspects of operation of thermionic arc cathodes.

This topic is dealt with in this work. Formation of spots and factors favouring and hindering their appearance are studied by means of numerical modelling and experimentally. The obtained results also shed light on the mechanism of blackening of the walls of burners of HID lamps which accompanies the appearance of transient spots: the cathode material gets into the gas phase most probably due to evaporation from the spot rather than due to sputtering that could occur during the voltage spikes after current zero.

Modelling results given in this paper refer to argon and mercury arcs and to spots induced by a current step (after a few seconds at a constant current, the arc current is instantly increased to a higher value which is maintained constant until the transition process terminates). This way of inducing transient cathodic spots has already been described in the literature [1, 2]; it is convenient for methodical purposes while being an adequate way of reproducing the scenario of spot formation on cathodes of ac HID lamps after current zero. The experiments have been performed on COST-529 standard HID lamps.

The outline of the paper is as follows. The numerical model and the experimental setup are described in sections 2 and 3, respectively. In section 4, results are given on a general pattern of appearance of stationary and transient spots on thermionic cathodes and on the effect of the cathode shape and material, as well as a comparison between the simulation and experimental results. Results on prevention of transient spots are given in section 5. Conclusions of the work are summarized in section 6.

2. Numerics

The modelling has been performed by means of the model of nonlinear surface heating, which has become by now a more or less standard tool for simulation of plasma–cathode interaction in high-pressure arc discharges (see, e.g., review [3]). A detailed description of the model can be found elsewhere (e.g. [3] and references therein; one may also find useful the Internet site [4] where some theoretical material is posted and also an online tool for simulation of the diffuse mode of current transfer developed on the basis of this model). In brief, this model may be described as follows.

Let us consider a thermionic cathode of a high-pressure arc discharge, which receives current and heat flux from the plasma. Joule heat generation inside the cathode is negligible. The procedure of finding a solution describing the plasma–cathode interaction in the framework of the model of nonlinear surface heating consists of two steps. First, one solves equations describing current transfer through the near-cathode plasma layer, thus calculating all parameters of the near-cathode layer as functions of the local temperature T_w of the cathode surface and of the near-cathode voltage drop U. In particular, densities of the energy flux and of the electric current to the cathode surface are determined: $q = q(T_w, U)$ and $j = j(T_w, U)$, respectively.

At the second step, the temporal evolution of the temperature distribution inside the cathode body and at the surface is calculated by means of solving the thermal-conduction equation in the cathode:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T), \qquad (1)$$

where ρ, c_p and κ are, respectively, mass density, specific heat and thermal conductivity of the cathode material. This equation is solved with the following boundary conditions:

$$T = T_c \qquad (2)$$

at the base of the cathode; and

$$\kappa \frac{\partial T}{\partial n} = q(T_w, U) \qquad (3)$$

at the rest of the cathode surface, where n is a direction locally orthogonal to the cathode surface and directed outside the cathode and $q(T_w, U)$ is the dependence found at the first step.

Equation (1) takes no account of heat sources inside the cathode and therefore applies at temperatures below the melting point T_m of the cathode material. In order to render this equation applicable also at $T \geqslant T_m$, an approach is used which is in the spirit of the effective specific heat method employed in simulation of metal casting [5]: the specific heat c_p in the thermal-conduction equation (1) is supplemented with the term $g(T)H_f$, where H_f is the latent heat of melting of the cathode material and $g(T)$ is a Gaussian function:

$$g(T) = \frac{1}{\sqrt{\pi}\Delta T} \exp\left(-\frac{T - T_m}{\Delta T}\right)^2. \qquad (4)$$

Here ΔT is a parameter characterizing the width of the assumed phase change interval; it should be chosen sufficiently small so that its value does not affect simulation results.

The arc current I is treated as a known function of time, the near-cathode voltage drop U is treated as a function of time to be determined jointly with the function $T(x, y, z, t)$. I is related to T and U by the equation

$$I(t) = \int j[T_w(t), U(t)]\, dS, \qquad (5)$$

where $j(T_w, U)$ is the dependence found at the first step and the integral is extended to the entire surface of the cathode except its base.

The numerical realization of the model employed in this work is similar to the one described in [6]. In particular, the near-cathode plasma layer is calculated as described in [7–9] and summarized in [10], the thermal-conduction problem in the cathode body (1)–(3) is solved jointly with equation (5) for the functions $T(x, y, z, t)$ and $U(t)$ with the use of the commercial finite element software COMSOL Multiphysics.

Although cathodes considered in this work are axially symmetric, temperature distributions corresponding to modes with a spot are three-dimensional in space (3D). Therefore all simulations described in this work have been performed in 3D. We assume that 3D temperature distributions $T(x, y, z, t)$ corresponding to modes with a spot possess planar symmetry and, furthermore, that the plane of symmetry of a function $T(x, y, z, t)$ is the same for all t, thus excluding from consideration situations in which a spot changes its azimuthal position with time. The calculation domain is restricted to half of the cathode, say $\varphi \geqslant 0$, where (r, φ, z) are cylindrical coordinates with the axis z coinciding with the

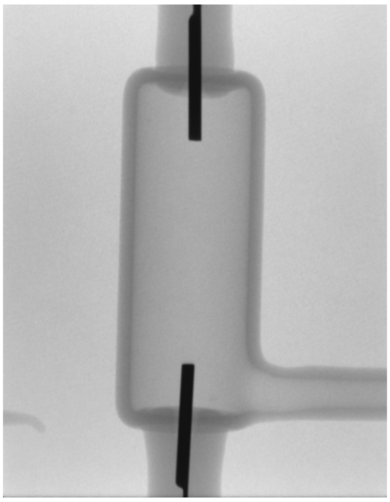

Figure 1. X-ray photograph of the burner of a type 2 lamp.

axis of symmetry of the cathode. In principle, a spot in such geometry can appear with equal probability either at $\varphi = 0$ or at $\varphi = \pi$. However, this ambiguity does not pose a problem in practice: a local refinement of the finite element mesh 'attracts' a spot as pointed out in [1], and the mesh in the vicinity of a probable localization of a spot anyway must be refined in order to ensure good numerical accuracy.

Numerical results given in this work refer to cathodes made of tungsten. Data on thermal conductivity and emissivity of tungsten have been taken from [11, 12], respectively. Data on the specific heat of tungsten have been taken from [13]; a constant value of 291 J kg^{-1} K^{-1} was assumed according to [14] at temperatures above the melting point of tungsten $T_m = 3683$ K. The value of 192.5 kJ kg^{-1} was assumed for latent heat of melting of tungsten. ΔT was set equal to 10 K in most of the calculations reported in this work.

3. Experimental

Experiments were performed on COST-529 standard lamps, which are HID lamps with quartz walls and a quartz envelope [15], operated in vertical position. The lamps used were filled with 5 mg of mercury, apart from about 300 mbar argon filling (at room temperature) as the starter gas, which resulted in an operating pressure of about 4 bar.

The lamps were equipped with pure tungsten rod electrodes shown in figure 1. Some of the lamps had electrodes of radius $R = 250\,\mu$m and of height (the total length of the rod from one tip to another) $h = 9$ mm and the others had electrodes with $R = 350\,\mu$m and $h = 11$ mm. In the following, these lamps will be referred to as lamps of type 1 or 2, respectively. X-ray photographs show that the part of the electrode which is inside the burner varies slightly from one lamp to another. For lamps of type 1 the average length of the electrodes inside the burner is 1.9 mm with an average dispersion of 0.1 mm, while for lamps of type 2 the average length of the electrodes inside the burner is 3.7 mm with an average dispersion of 0.29 mm. The x-ray photographs also show a rounded edge at the front surface of the electrodes with 25 μm radius on average. Note that in the modelling the boundary condition (3), which applies at the current-collecting part of the cathode surface, is employed only at the part of the cathode which is inside the burner. The rest of the lateral surface of the cathode is considered thermally and electrically insulated. The length of the part of the cathode which is inside the burner was set equal to the above-mentioned average values, variations of these lengths from one lamp to another were neglected. The front surface of the cathode was assumed flat with a rounding of radius of 25 μm at the edge. The temperature at the base of the cathode T_c was set equal to 1000 K.

The power supply to the lamps was provided by a voltage-driven power amplifier FM 1295 DCU/I 750 made by MedTech Engineering, which functioned as a current source controlled by an arbitrary waveform generator Agilent 33220A. During warm up, the lamps were operated for about 5 min at a 100 Hz square wave, at the power level of 70 W. Current jumps necessary to induce the spots were generated by superimposing a square wave of 0.1 Hz over a dc current. In other words, the cathode operated for 5 s at a (constant) current $I = I_1$ and then for 5 s at a higher current $I = I_2$, after which the current was again reduced to I_1 and the cycle was repeated. The transition time between the two current values was within 5 μs.

The electrode at the bottom of the burner was operated as the cathode. The image of the cathode and the near-cathode region was magnified 10 times and focused on a screen. The mode of arc attachment to the cathode was diagnosed by photodiodes placed on the screen in front of the cathode's image. Measurements were registered by a digital oscilloscope Yokogawa DL 1640 with a sampling rate of 200 MS s^{-1}.

4. Results

4.1. General pattern of appearance of transient spots

Formation of transient spots on thermionic arc cathodes induced by current steps was studied numerically in [1, 2]. An important question which has not been dealt with in these works is a relation between transient spots and steady-state modes of current transfer and their stability. This question is studied in this section.

Let us consider the following conditions which are convenient for the purposes of illustration and not very different from those treated in [1]: a rod cathode of radius $R = 0.5$ mm and a height of $h = 12$ mm, with a flat front surface, with the entire lateral surface active (i.e. without electrically and/or thermally insulated sections), the temperature at the base of the cathode T_c is 1000 K, the arc is operated in argon under the pressure of 2 bar.

According to results of the linear stability theory [16, 17], the only steady-state modes of current transfer that can be stable are the diffuse mode and the first spot mode (the mode with a spot at the edge of the front surface of the cathode). The diffuse mode is associated with axially symmetric temperature distributions in the cathode, the first spot mode is associated with 3D distributions. Current–voltage characteristics of these modes for the above conditions are shown in figure 2. In

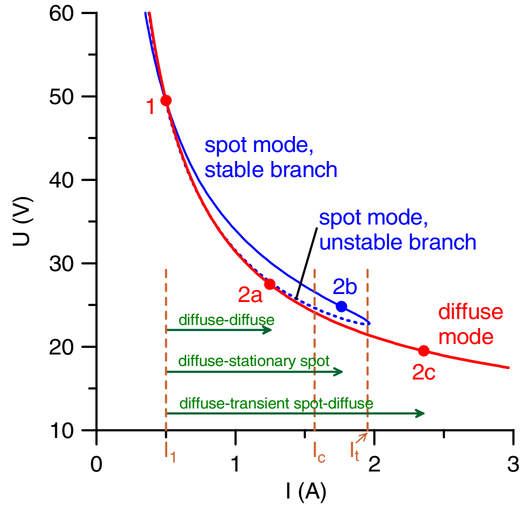

Figure 2. Calculated current–voltage characteristics of steady-state modes of current transfer and scenarios of non-stationary transitions. Cathode with a flat front surface in Ar plasma.

agreement with the general pattern established in [6], the steady-state spot mode is composed of two branches separated by a turning point and exists in a limited current range $I \leqslant I_t$, where I_t is the arc current corresponding to the turning point; $I_t \approx 1.95$ A in this case. According to results [16, 17], the diffuse mode is stable under the considered conditions, the branch of the spot mode which manifests higher values of U in the vicinity of the turning point (and is represented in figure 2 by the solid line) is also stable, and the branch of the spot mode which manifests lower values of U in the vicinity of the turning point (and is represented by the dotted line) is unstable.

Let us assume that the cathode initially operates in the steady-state diffuse mode at a certain current $I = I_1$. The corresponding initial state is represented in figure 2 by a circle marked 1. At a certain moment the current starts growing rapidly and swiftly attains a target value $I = I_2$, after which it remains constant. (It was assumed that the arc current grows from I_1 to I_2 in 1 μs linearly with time in the modelling reported in this section.) The temperature distribution in the cathode body and the near-cathode voltage drop will undergo a transition process and finally a new steady state will be reached. One could think of three scenarios of such a transition.

According to results of the linear stability theory [16, 17], the diffuse mode of current transfer is stable against small perturbations. It should also be stable against finite perturbations unless their amplitude exceeds a certain threshold. Therefore, one can expect that the diffuse mode is maintained during the whole transition process if the target current I_2 does not exceed a certain threshold value I_c; if $I_2 > I_c$, the diffuse mode gives way to the spot mode. This threshold value depends on conditions and also on the initial current I_1.

Thus, the first possible scenario occurs in the case $I_2 < I_c$: the diffuse mode is maintained during the whole transition process and the final steady state is diffuse as well. In other words, this is a transition between two stable diffuse states with intermediate states being diffuse as well. This scenario is schematically shown in figure 2 by the horizontal arrow marked 'diffuse–diffuse' and the final steady state is depicted by the circle marked 2a.

Now let us consider the case $I_2 > I_c$. If the target current is within the range of existence of the steady-state spot mode, i.e. $I_c < I_2 < I_t$, then the final steady state may belong either to the diffuse mode or to one of the two branches of the spot mode. The first possibility does not look very probable: a spot, once having started to form, will tend to persist whenever possible. The branch of the spot mode that is shown in figure 2 by the dotted line is unstable. Hence, one should expect that the final steady state will belong to the branch of the spot mode which is depicted in figure 2 by the solid line. This state is represented by the circle marked 2b. Thus, the second possible scenario occurs in the target current range $I_c < I_2 < I_t$: the diffuse mode during the transition process gives way to the spot mode and the latter is maintained indefinitely. In other words, this is a transition from a stable diffuse state to a stable state with a stationary spot. This scenario is schematically shown in figure 2 by the horizontal arrow marked 'diffuse-stationary spot'. Obviously, this scenario is possible provided that $I_c < I_t$.

If the target current is beyond the range of existence of the steady-state mode, $I_2 > I_t$, then the final state can only belong to the diffuse mode as represented by the circle marked 2c since no other stationary states are possible at $I = I_2$. One can say that a transient spot, which has appeared at the initial stage of the transition process, is destroyed by thermal conduction at a later stage. This is the third possible scenario: in the target current range $I_2 > I_t$, the diffuse mode during the transition process gives way to the spot mode, which later gives way to the diffuse mode again. In other words, this is a transition between two stable diffuse states which occurs through intermediate states with a transient spot. This scenario is schematically shown in figure 2 by the horizontal arrow marked 'diffuse–transient spot–diffuse'.

The above scenarios are confirmed by the numerical modelling. Let us consider, as an example, results for the initial current $I_1 = 0.5$ A. The temperature distribution in the cathode is axially symmetric in the initial state. If the target current is below approximately 1.57 A, then the temperature distribution in the cathode remains axially symmetric during the transition process and the electric current distribution along the front surface of the cathode remains more or or less uniform. If the target current exceeds approximately 1.57 A, the axial symmetry breaks down during the transition process and a current distribution with a narrow maximum at the edge of the front surface of the cathode occurs: a hot cathode spot appears. This non-stationary spot either evolves into a stationary spot belonging to the branch of the spot mode which is depicted in figure 2 by the solid line, or disappears giving way to a diffuse steady state, depending on whether the target current is in the range 1.57 A $\lesssim I_2 \lesssim$ 1.95 A or above this range.

Numerically calculated temporal variation of the maximum temperature of the cathode surface and near-cathode voltage drop for the initial current $I_1 = 0.5$ A and three values of the target current is shown in figure 3. (It is assumed that the current starts growing at the moment $t = 100\,\mu$s.) In the case $I_2 = 1.5$ A, the temperature distribution during the whole

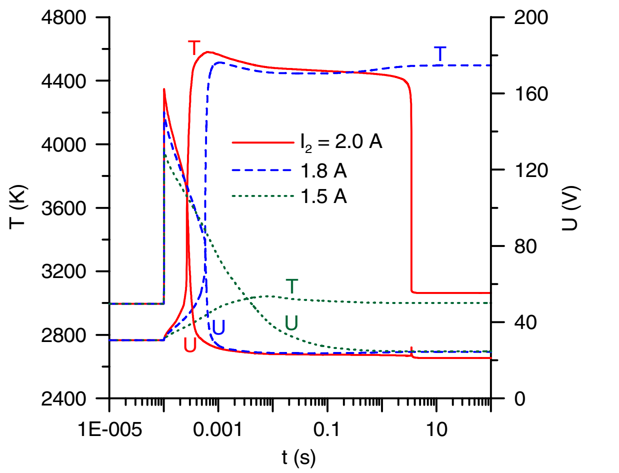

Figure 3. Calculated maximum temperature of the cathode surface and near-cathode voltage drop for different current jumps. Cathode with a flat front surface in Ar plasma. $I_1 = 0.5$ A.

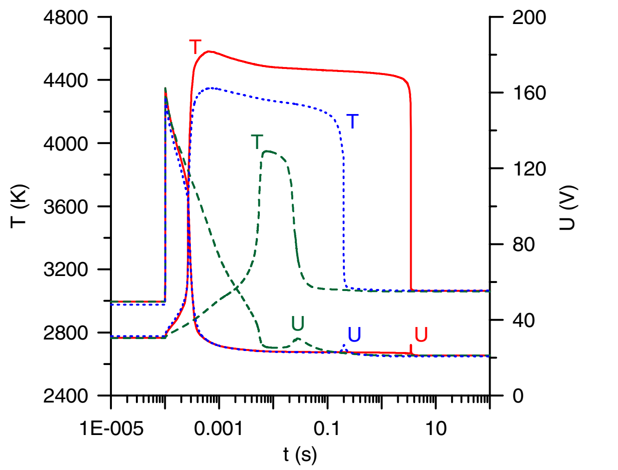

Figure 4. Calculated maximum temperature of the cathode surface and near-cathode voltage drop. Ar plasma, $I_1 = 0.5$ A, $I_2 = 2.0$ A. Solid: cathode with a flat front surface. Dashed: cathode with a rounded edge at the front surface. Dotted: cathode with a flat front surface, thermal conductivity of tungsten from [18].

transition process remains axially symmetric, the maximum temperature of the cathode surface remains around 3000 K. The near-cathode voltage drop gradually decreases after the initial spike. One can say that the transition process in this case occurs in the diffuse mode.

In the case $I_2 = 1.8$ A, the axial symmetry breaks down during the transition process and a hot spot is formed, with a maximum temperature of the cathode surface being around 4500 K. The formation of the spot is accompanied by a sharp fall of the near-cathode voltage. Once having been formed, the spot continues to exist indefinitely. In other words, the final steady state belongs to a spot mode. A more detailed investigation shows that this state belongs to the branch of the first spot mode which is depicted in figure 2 by the solid line, thus confirming conclusions on stability obtained in [16, 17] by means of a linear stability analysis.

A spot is also formed in the case $I_2 = 2.0$ A; however, in this case it does not exist at all times but rather disappears around $t = 3$ s, its disappearance being accompanied by a small voltage peak. In other words, the spot is transient in this case and the final steady state in this case belongs to the diffuse mode.

Obviously, these numerical results fully conform to the above qualitative considerations and $I_c \approx 1.57$ A for this case. These results also qualitatively conform to numerical results reported in [1], however, with an important exception: the second above-described scenario, a transition from a stable diffuse state to a stable state with a stationary spot, was not detected in [1].

An essential question is how sensitive is the appearance of transient spots with respect to variations of the cathode shape and material properties. This point is illustrated by figure 4. Solid lines in this figure represent the calculated maximum temperature of the cathode surface and near-cathode voltage drop for the same conditions as above at $I_1 = 0.5$ A, $I_2 = 2.0$ A. (These lines are the same as corresponding lines in figure 3.) The dashed lines represent simulation results for the same conditions but for a cathode with a rounded edge of the front surface, with a rounding of the radius of 100 μm. One can see that the spot on a rounded cathode is formed considerably later, is considerably less hot and lives much less than the spot on a cathode with the flat front surface. This difference can be interpreted as a consequence of better cooling conditions on a rounded edge.

The dotted lines in figure 4 represent results of simulations performed for a cathode with a flat front surface for the same conditions as above but with the use of data on thermal conductivity of tungsten given in [18]. The latter data seem to refer to thoriated tungsten but have also been used for modelling cathodes made of pure tungsten [1, 2, 19, 20]. At moderate temperatures these data are nearly the same as the data given in [11] and used in this work; however, at higher temperatures the thermal conductivity from [18] appreciably exceeds that from [11]. One can see from figure 4 that the replacement of the data [11] by those from [18] results in an appreciable decrease in both the temperature and the lifetime of the spot, while the time of formation of the spot remains virtually unchanged. Again, this effect can be interpreted as a consequence of better cooling conditions for a spot due to higher thermal conductivity at high temperatures.

Calculations performed neglecting the latent heat of melting reveal that the latent heat has only a marginal effect on the results, with the formation and decay times of the spot being virtually unchanged, in agreement with what was reported in [20].

4.2. Comparison of simulations and experiment

Let us apply the above-established pattern to conditions of the experiments with COST-529 standard lamps. Current–voltage characteristics of the diffuse mode of current transfer calculated for cathodes of types 1 and 2 are shown in figure 5. Stationary spots for these conditions exist at very low currents and very high voltages and the corresponding current–voltage characteristics cannot be shown on the graph. In terms of the preceding section, the value I_t is very low, hence the

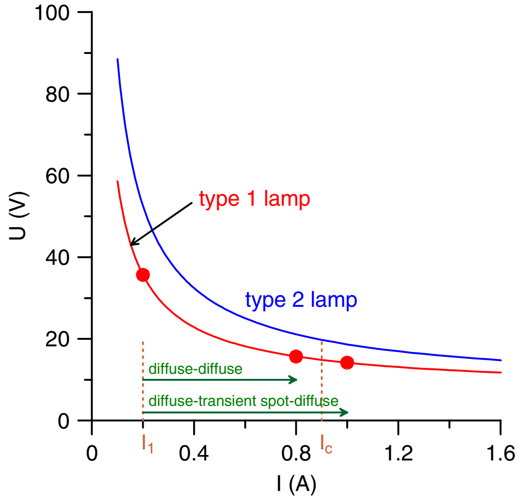

Figure 5. Calculated current–voltage characteristics of the steady-state diffuse mode and scenarios of non-stationary transitions. Cathodes of COST-529 standard lamps.

second above-described scenario does not take place in these conditions and only diffuse–diffuse and diffuse–transient spot–diffuse transitions are possible, as is schematically shown in figure 5 for the lamps of type 1.

This conclusion is confirmed by the numerical modelling. (It was assumed that the arc current grows from I_1 to I_2 linearly with time in 5 μs in the modelling of COST-529 lamps.) For a cathode of type 1 and $I_1 = 0.2$ A, a diffuse–diffuse transition occurs for $I_2 < 0.96$ A and a diffuse–transient spot–diffuse transition occurs for $I_2 \geqslant 0.96$ A; in other words, $I_c \approx 0.96$ A in this case. For a cathode of type 2 and $I_1 = 0.3$ A, a diffuse–diffuse transition occurs for $I_2 < 1.27$ A and a diffuse–transient spot–diffuse transition occurs for $I_2 \geqslant 1.27$ A; $I_c \approx 1.27$ A. Typical calculation results on evolution of the maximum temperature of the cathode surface and near-cathode voltage drop for conditions of COST-529 standard lamps are shown in figure 6(*a*) and are similar to those discussed in the preceding section.

An essential point in the experiment is an appropriate choice of the initial current I_1 of the current jump. This current must be not too small in order to minimize sputtering that occurs at low currents where the near-cathode voltage drop is high, while at the same time it must be not too high in order that the limit I_c of the appearance of transient spots corresponds to the lamp power not much more than 100 W. It is seen from figure 5 that the difference in the near-cathode voltage drop between type 1 and type 2 cathodes at $I = 0.2$ A is about 17 V. One can therefore expect that sputtering for a type 2 lamp at 0.2 A should be significantly increased as compared with a type 1 lamp operating at the same current and this indeed was observed in the experiment: operation of a type 2 lamp with an initial current of 0.2 A resulted in a very fast blackening of the burner. Therefore, the initial current I_1 of the current jump was set equal to 0.2 A for type 1 lamps and to 0.3 A for type 2 lamps.

Typical experimental results can be seen in figure 6(*b*), where the lamp voltage and the intensity of light emitted by the near-cathode region are shown under the same conditions

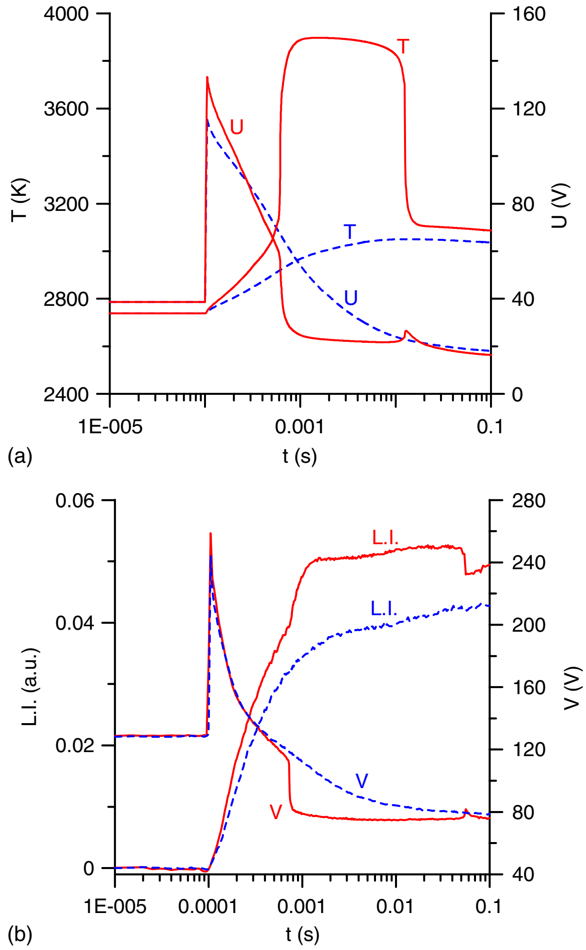

Figure 6. Diffuse transition and transient spots on cathodes of type 1 lamps. $I_1 = 0.2$ A. Solid: $I_2 = 1.0$ A. Dashed: $I_2 = 0.8$ A. (*a*) Calculated maximum temperature of the cathode surface and near-cathode voltage drop. (*b*) Measured intensity of light emitted by the near-cathode region and lamp voltage.

as those of the modelling shown in figure 6(*a*). For $I_2 = 0.8$ A, the light intensity increases before it stabilizes about 0.1 s after the jump. This is expected behaviour: the cathode and arc temperatures are higher at higher currents. There is a sharp peak in the lamp voltage just after the jump, which afterwards undergoes a smooth decrease down to a constant voltage of about 80 V. For $I_2 = 1.0$ A, there is a steep increase of the intensity in light emitted by the near-cathode region at about 0.7 ms which is accompanied by a steep decrease in the lamp voltage at the same instant; a hot cathode spot is being formed. After about 50 ms, the light intensity steeply decreases and then remains constant, this decrease being accompanied by a small peak in the lamp voltage; the spot has decayed.

The experimental results on the lamp voltage conform to trends observed in [1]; however, the measured light intensity does not. A spot formation in the experiments [1] was indicated by triangle-shaped peaks in the intensity of light emitted by the near-cathode region, which are accompanied by a steep decrease in the lamp voltage drop at the same instant. In the experiments of this work such peaks have not been observed and what indicates a spot formation is a change in slope of the temporal dependence in the light intensity accompanied by a

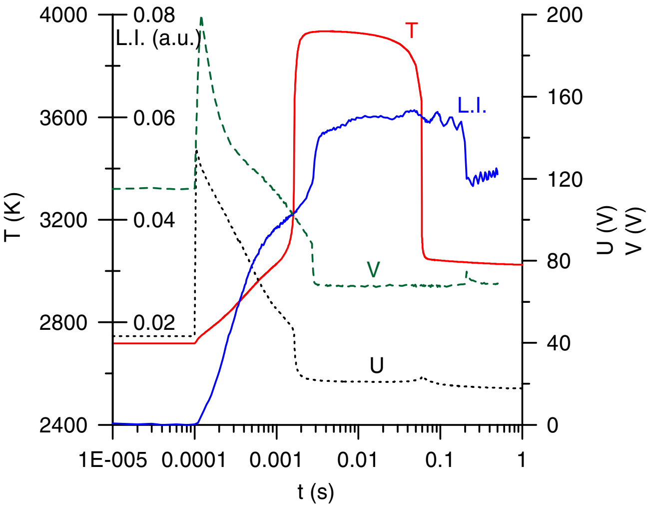

Figure 7. Calculated maximum temperature of the cathode surface and near-cathode voltage drop and measured intensity of light emitted by the near-cathode region and lamp voltage. Type 2 lamps, $I_1 = 0.3$ A, $I_2 = 1.3$ A.

steep decrease in the lamp voltage drop at the same instant. Furthermore, the light intensity signal observed in this work is rectangular and not triangular as in [1].

Comparing figures 6(*a*) and 6(*b*), one can see that, although computed quantities are not the same as those measured (the near-cathode voltage drop U and the maximum temperature T of the cathode surface versus the lamp voltage V and the intensity $L.I.$ of light emitted by the near-cathode plasma), a good qualitative agreement exists between the simulations and the experiments. In particular, the diffuse–diffuse transition occurs in the case $I_2 = 0.8$ A and a diffuse–transient spot–diffuse transition occurs in the case $I_2 = 1.0$ A both in the modelling and in the experiment, a rectangular peak in the light intensity observed in the case $I_2 = 1.0$ A conforms to numerical results for the maximum cathode temperature for this case. The spot formation time in the modelling for the case $I_2 = 1.0$ A was 0.52 ms, while the average spot formation time for type 1 lamps and $I_2 = 1.0$ A in the experiment was 0.55 ms with an average dispersion of 0.15 ms. Note that the spot formation time was defined in the modelling and in the experiment as the time interval between the current jump and the rapid decrease in the near-cathode or, respectively, lamp voltage; since the latter decrease occurs very rapidly (within 10 μs both in the modelling and in the experiment), such a definition is unambiguous.

However, there is a significant difference in the lifetime of transient spots: for example, the lifetime for type 1 lamps and $I_2 = 1.0$ A in the modelling was 12 ms, while the average lifetime in the experiment was 58 ms with an average dispersion of 3 ms. In other words, the model predicts a much earlier decay of transient spots than observed in the experiment.

A good qualitative agreement between the modelling and the experiment occurs also for type 2 lamps, as is shown by an example depicted in figure 7. The spot formation time in the modelling for the case $I_2 = 1.3$ A was 1.64 ms, while the average spot formation time in the experiment for this case was 3.27 ms with an average dispersion of 0.37 ms; agreement not so good as for type 1 lamps, but still within the factor of 2. Again, there is a significant difference in the lifetime of transient spots: the lifetime for type 2 lamps and $I_2 = 1.3$ A in the modelling was 57 ms, while the average lifetime in the experiment was 245 ms with an average dispersion of 15 ms.

It is unclear what is the reason for the latter discrepancy. It can hardly be attributed to the effect of parameters such as cathode radius, portion of the cathode inside the burner, rounding of the cathode edge and temperature of the base of the cathode: this effect has been numerically investigated and found to be not strong enough. For example, an increase in the calculated spot lifetime by a factor of 3.3 is attained by an increase of 20% in the cathode radius; however, the latter increase is far above the accuracy of characterization of the electrodes.

5. Prevention of transient spots

The formation of a spot induced by a current jump can be interpreted as a result of the cathode failure to undergo uniform heating, as a response to the increase in current. Educated guesswork would lead one to expect that a brief reduction of the current shortly after the current jump could aid the cathode to be heated up uniformly, thus preventing the appearance of a spot. This applies to both stationary and transient spots; however, only prevention of transient spots is considered in this work since no stationary spots exist under the conditions of the present experiment.

The modelling has confirmed the above idea: transient spots indeed do not appear provided that the timing, duration and magnitude of the current reduction are right. An example is shown in figure 8(*a*), which refers to a 0.2–1.0 A current jump on a type 1 cathode. 0.4 ms after the jump, the current was for 0.3 ms reduced to 0.3 A. The maximum temperature of the cathode surface is below 3200 K: appearance of a spot is indeed prevented. The corresponding experimental results are shown in figure 8(*b*) and are in excellent agreement with the modelling results: the shapes of temporal variations of the light intensity and of the lamp voltage indicate that the transient spot is indeed prevented. Note that the intensity of light emitted by the near-cathode region decreases sharply when the current is lowered to 0.3 A and again increases as soon as the current grows back to 1.0 A; however, variations in the light intensity on such a short time scale are not perceivable by the human eye.

An example of modelling and experimental results on spot prevention on type 2 cathodes is given in figure 9, which refers to the 0.3–1.3 A current jump. Here, spots are prevented with a reduction of the current to 0.4 A which starts 0.3 ms after the current jump and lasts for 0.5 ms.

It is well known that transient spots appearing at the beginning of the cathodic phase on electrodes of ac HID lamps cause a rapid blackening of walls of the burner. One could think of two principal mechanisms leading to this blackening: sputtering of the cathode material, which can accompany near-cathode voltage spikes occurring after the current zero, and evaporation of cathode material from the spot. In the conditions being considered in this work, the current reduction aimed at preventing spots occurs some time after

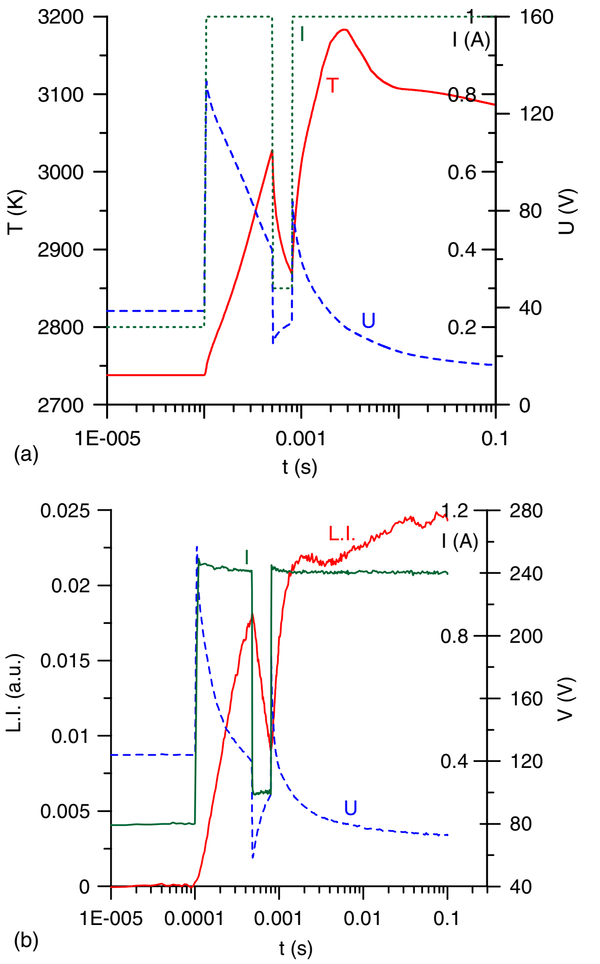

Figure 8. Prevention of transient spots on cathodes of type 1 lamps, 0.2–1.0 A current jump. (*a*) Calculated maximum temperature of the cathode surface and near-cathode voltage drop. (*b*) Measured intensity of light emitted by the near-cathode region and lamp voltage.

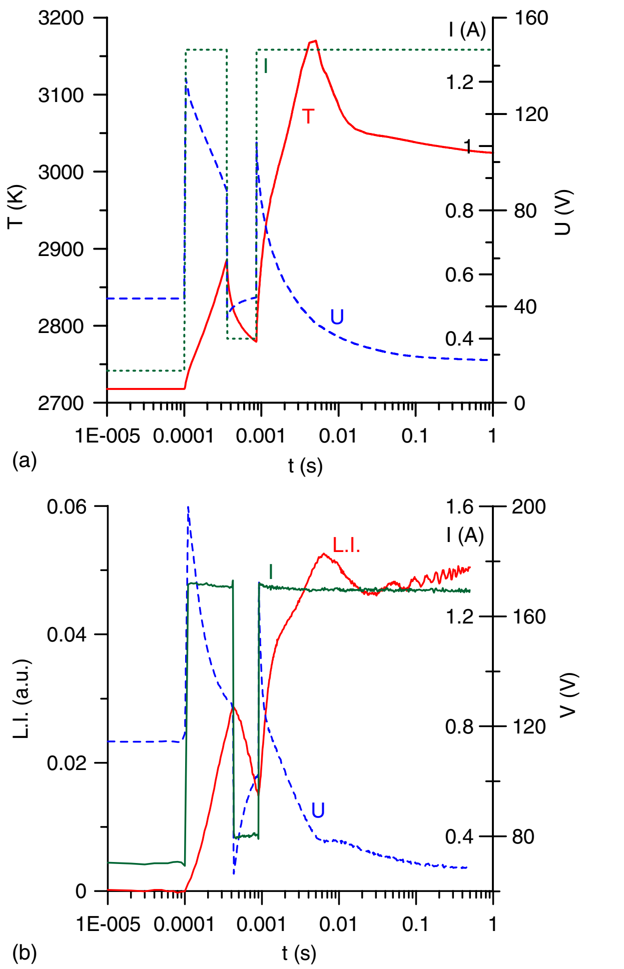

Figure 9. Prevention of transient spots on cathodes of type 2 lamps, 0.3–1.3 A current jump. (*a*) Calculated maximum temperature of the cathode surface and near-cathode voltage drop. (*b*) Measured intensity of light emitted by the near-cathode region and lamp voltage.

the current jump, thus the near-cathode voltage spike that occurs immediately after the jump is not affected by the current reduction. This allows one to separate effects caused by the two above-mentioned mechanisms.

In this connection, the following experiment was performed. Two lamps of type 1 were operated for one hour with a square-wave arc current between 0.2 and 1.0 A with a frequency of 0.1 Hz. Transient spots were prevented in one of the lamps by means of the above-described current reduction, while no measures were taken to control the arc attachment to the cathode of the second lamp. Blackening of the burner around the cathode turned out to be much more pronounced in the second lamp. Since the voltage spike immediately after the jump was the same in both lamps and, consequently, the sputtering also is likely to be the same, one can conclude that the increased blackening of the burner occurring in the second lamp is a result of evaporation of tungsten from the cathode rather than sputtering. Of course, this experiment also demonstrates that the prevention of transient spots may considerably increase the lifetime of a lamp.

Obviously, a brief reduction of current proposed in this work does not represent the only way to prevent appearance of transient spots: modelling has revealed that this could be achieved, e.g., by controlling the portion of the cathode inside the burner of the lamp. However, this can require a considerable change in the design: for example, for a 0.2–1.0 A current jump on a type 1 cathode the transient spot may be prevented by a reduction in the length of the portion of the cathode inside the burner of the lamp of about 50%.

It is interesting to note that short rectangular current pulses have already been used for controlling the spot mode of arc attachment in UHP lamps [21, 22]. However, the pulses employed in [21, 22] were used to add current to the electrode and took place at the end of the anodic phase, i.e., were substantially different from those employed in this work, and served a different objective, namely, to facilitate appearance of a protrusion on the electrode surface. On the other hand, this attests to the technical viability of the spot prevention method proposed in this work.

6. Conclusions

Analysis based on the general pattern of steady-state modes of current transfer to thermionic cathodes of high-pressure arc discharges and their stability and supported by numerical modelling reveals that temporal evolution of a stable diffuse mode perturbed by a rapid increase in the arc current follows one of three scenarios: (a) a transition between two stable diffuse states via intermediate diffuse states, (b) a transition from a stable diffuse state to a stable state with a stationary spot and (c) a transition between two stable diffuse states via intermediate states with a transient spot.

Near-cathode voltage drop and maximum temperature of the cathode surface computed for conditions of model HID lamps are in good qualitative agreement with the measured lamp voltage and intensity of light emitted by the near-cathode plasma. There is good agreement also on the threshold current and time of formation of transient spots, although not on their lifetime.

A possibility of prevention of appearance of transient spots by means of a brief reduction of the arc current shortly after the initial current increase is proposed and justified both numerically and experimentally. Experiments on identical HID lamps performed with and without prevention of transient spots allow one to separate effects produced by sputtering and evaporation of the cathode material on blackening of burners of HID lamps that accompanies appearance of transient cathode spots. The conclusion is that the main mechanism is evaporation and not sputtering.

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