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## FAST TRACK COMMUNICATION

# Quenching thermal instability in the body of a thermionic arc cathode

**P G C Almeida, M S Benilov, M D Cunha and J G L Gomes**

Departamento de Física, CCCEE, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal

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**Abstract**
The possibility of quenching the instability causing the appearance of spots on thermionic cathodes of high-pressure arc discharges is demonstrated by means of numerical simulations and experimentally. This possibility stems from the fact that the instability is of a thermal nature and therefore slow. While of significant interest by itself, this possibility may be exploited to prevent in real time the formation of cathode spots in arc devices.

(Some figures may appear in colour only in the online journal)

The formation of spots on cathodes of arc discharges is a phenomenon of high interest from the point of view of both fundamental science and applications. Considerable advances in understanding cathode spots in high-pressure arc discharges were achieved during the last decade due to effort invested by several research groups in different countries. In particular, it has been proved that the formation of spots is a result of development of thermal instability in the body of the cathode, caused by the growing dependence of the energy flux from the plasma on the temperature of the cathode surface; e.g. [1] and references therein. Being of a thermal nature, this process is relatively slow: the time scale is of the order of tens of microseconds. This time is much longer than the response time of modern electronic devices. Therefore, one can think of quenching the instability at the initial stage of its development by adjusting the supply of electrical power to the arc, thus preventing the formation of cathode spots. An experimental implementation of such a quenching is in principle rather simple: one can use a microcontroller in order to monitor the arc–cathode interaction and, if the beginning of the development of the instability has been detected, change the settings of the arc power supply in such a way that the instability is rapidly quenched.

The possibility of real-time quenching an instability under complex experimental conditions is of significant interest by itself. Moreover, this possibility may be exploited to prevent in real time the formation of cathode spots in arc devices, which may be beneficial for their performance and lifetime. The aim of this work is to demonstrate by means of numerical simulations, and experimentally, that such real-time quenching is achievable.

The experimental setup was similar to that in [2] and in brief can be described as follows. Experiments were performed on COST-529 standard arc lamps, which are arc lamps with quartz walls and a quartz envelope [3], operated in the vertical position. The lamps used contained 5 mg of mercury, apart from about 300 mbar (at room temperature) argon filling as the starter gas, which resulted in an operating pressure of about 4 bar. The lamps had pure tungsten rod electrodes of radius 250 $\mu$m and height 9 mm. The lamp was powered by a voltage-driven power amplifier FM 1295 DCU/I 750 supplied by MedTech Engineering, which functioned as a current source controlled by an arbitrary waveform generator Agilent 33220A. The arc voltage and current were registered by a digital oscilloscope Yokogawa DL 1640 operated at a sampling rate of 200 kHz. The image of the cathode and the near-cathode region was magnified ten 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.

A reproducible appearance of cathode spots is not easy to achieve in the experiment. For the purposes of investigation, a convenient way of provoking the appearance of a cathode spot is to rapidly increase the discharge current [2, 4, 5]. Current jumps necessary to induce the spots were generated by means of a square signal of 0.1 Hz with a dc offset. 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

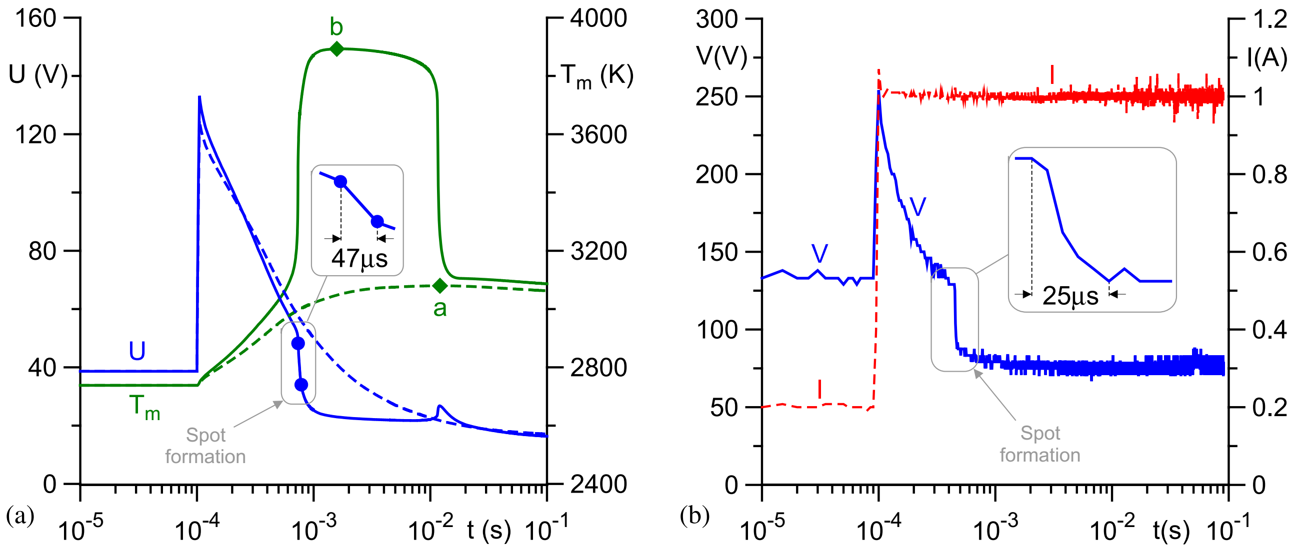


**Figure 1.** Formation of transient spots. $I_1 = 0.2$ A. (*a*) Modelling $I_2 = 1.0$ A (solid; the spot is formed), $I_2 = 0.9$ A (dashed; the spot is not formed). (*b*) Experiment. $I_2 = 1.0$ A (the spot is formed).

reduced back to $I_1$ and the cycle was repeated. The transition time between the two current values was shorter than 5 $\mu$s. Each series of experiments was preceded by a warm-up: the lamp was operated for about 5 min at a 100 Hz square signal at a power level of 70 W.

The numerical modeling was performed in the framework of the model of nonlinear surface heating (e.g. [1] and references therein), which is a standard tool of modeling of plasma–cathode interaction in low-current arc discharges. Note that the characteristic times of processes in the near-cathode plasma layer (the region where the energy flux from the plasma to the cathode is generated) are much shorter than the characteristic time of heat propagation in the cathode body; see, e.g., the estimates in [1]. Therefore, the modelling of evolution of the temperature distribution inside the cathode in the framework of the model of nonlinear surface heating is performed under the assumption that processes on the plasma side are quasi-stationary. Joule heat generation in the cathode body is taken into account for generality, although under the considered conditions this is a minor effect. The modelling reported in this work refers to an Hg plasma under a pressure of 4 bar.

Representative numerical and experimental results are shown in figure 1. Here $U$ is the computed near-cathode voltage, $V$ is the measured arc voltage, and $T_m$ is the computed maximum temperature of the cathode (which occurs on the cathode surface). The current was switched from $I_1$ to $I_2$ at $t = 100\,\mu$s. The sudden increase in the maximum cathode surface temperature $T_m$ and decrease in the near-cathode voltage $U$ seen in figure 1(*a*) in the case $I_2 = 1$ A at $t = 720\,\mu$s mark a formation of a cathode spot. The spot is associated with a plateau in the dependence $T_m(t)$, exists for approximately 11 ms, and then disappears. In the case $I_2 = 0.9$ A, the spot does not form. The same trends are observed in the experiment (the data for $I = 0.9$ A are not shown in figure 1(*b*) for reasons of clarity). In the experiment shown in figure 1(*b*), the instant of beginning of formation of the spot was 445 $\mu$s. This instant varied from one cycle to the other, as well as from one lamp to the other, and reached 735 $\mu$s. Note that the computed function $T_m(t)$ attains the maximum value $T_m = 3080$ K at $t = 12.1$ ms for $I_2 = 0.9$ A and $T_m = 3893$ K at $t = 1.59$ ms for $I_2 = 1$ A. These maxima are marked in figure 1(*a*) by diamonds *a* and *b*, respectively. The corresponding values of the near-cathode voltage drop are close to 23 V.

The above trends have been established by previous investigations [2, 4, 5]. Note that the relation between the visual development of an arc spot and the decrease in the near-cathode voltage was demonstrated with the use of high-speed photography in [6], e.g. figure 17 in that paper. Of particular interest for this work is the time of formation of spots. In the experiment, this time was estimated as shown in figure 1(*b*) and in this case was 25 $\mu$s. Once again, this time was observed to vary between cycles and lamps. In the modelling, the end of spot formation was defined as the instant at which $\mathrm{d}U/\mathrm{d}t$ assumes the same value that it had the moment immediately before the beginning of spot formation. The corresponding spot formation time was 47 $\mu$s.

It is of interest to compare this time with the time of propagation of heat in the cathode body over a distance of the order of the spot radius. Assuming $2.5 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$ as a representative thermal diffusivity and 50 $\mu$m for a representative spot radius, one finds that the time of propagation of heat is 100 $\mu$s. This time is of the same order as the above-mentioned spot formation times given by the experiment and the modelling; another confirmation of the thermal nature of the instability leading to the appearance of the spot.

The instability is due to the growing section of dependence $q(T_w)$, where $q$ is the density of energy flux from the plasma to the cathode surface and $T_w$ is the temperature of the cathode surface. As an example, this dependence is shown in figure 2 for two values of the near-cathode voltage drop $U$. Diamonds *a* and *b* have the same meaning as in figure 1(*a*), i.e. they mark maximum values attained by the cathode surface temperature

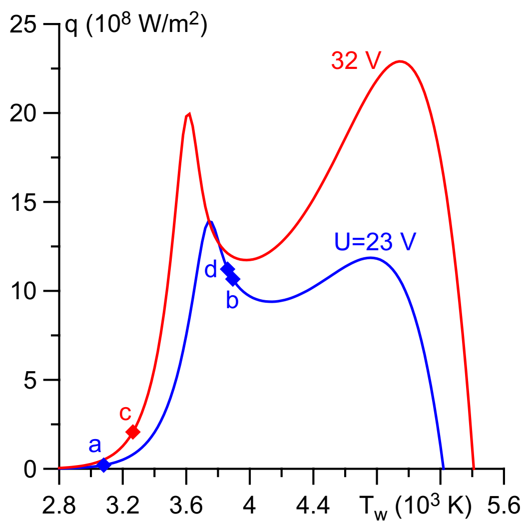


**Figure 2.** Computed dependence of the density of energy flux from the plasma on the temperature of the cathode surface.

after the switching in the cases without and with formation of a spot, respectively. It is known that well-developed stationary spots operate on the falling (and, consequently, stable) section of the dependence $q(T_w)$. It follows from figure 2 that the same is true also for transient spots: the state $b$, which corresponds to a well-developed spot, is positioned on the first falling section of $q(T_w)$. It is interesting to note that stationary spots operate on the second falling section of $q(T_w)$ rather than on the first one [7].

The time of spot formation found above is much longer than the response time of modern electronic devices. Hence, there is enough time for the power supply circuit to quench the thermal instability by briefly reducing the arc current as soon as the beginning of development of the instability has been detected. In this work, this is detected through the sudden decrease in the near-cathode or arc voltage seen in figure 1: the derivative $\mathrm{d}U/\mathrm{d}t$ or $\mathrm{d}V/\mathrm{d}t$ is monitored and the current is reduced when $-\mathrm{d}U/\mathrm{d}t$ or $-\mathrm{d}V/\mathrm{d}t$ has reached a certain (high enough) value.

The modelling confirms the possibility of real-time quenching of thermal instability. An example in figure 3(*a*) shows the effect of a current reduction $\Delta I = 0.5$ A. In the modelling, the current was reduced from $I = 1$ A to $I = 0.5$ A at the moment $t = 737\,\mu$s, which is when the criterion $\mathrm{d}U/\mathrm{d}t < -0.53\,\mathrm{V}\,\mu\mathrm{s}^{-1}$ becomes satisfied. The current value 1 A was restored after a time interval $\tau = 0.7$ ms, i.e., at $t = 1.437$ ms.

As the current has been reduced, the buildup of the cathode temperature is interrupted and reversed: the maximum temperature of the cathode, which equals 3518 K at $t = 736\,\mu$s, decreases to 2935 K at $t = 1.437$ ms. The cathode temperature starts increasing again at $t > 1.437$ ms, i.e. after the arc current value $I = 1$ A has been restored. However, the maximum value attained by the temperature (marked by the diamond $c$) is significantly lower than that in the case without quenching and is positioned on the first growing section of the dependence $q(T_w)$, as seen in figure 2. Moreover, the dependence $T_\mathrm{m}(t)$ in figure 3(*a*) does not exhibit the characteristic plateau seen in the dependence $T_\mathrm{m}(t)$ for $I_2 = 1$ A in figure 1(*a*), and rapidly decreases down to values of the order of 3100 K, characteristic of the diffuse discharge. Furthermore, the dependence $U(t)$ does not exhibit the characteristic spot extinction pulse seen in figure 1(*a*) at $t \approx 12$ ms. One can conclude that the thermal instability has been quenched.

The possibility of real-time quenching of thermal instability has also been confirmed by the experiment. Three main components have been added to the power supply circuit before the amplifier: a differentiator circuit, a microcontroller, and a summing circuit. The microcontroller detected the beginning of development of thermal instability by analyzing the signal received from the differentiator and generated a negative rectangular signal which was added to the square wave produced by the signal generator. An example of quenching is shown in figure 3(*b*). The current was reduced when the criterion $\mathrm{d}V/\mathrm{d}t < -1.6\,\mathrm{V}\,\mu\mathrm{s}^{-1}$ was satisfied. The photodiodes indicated successful quenching, although the duration of the reduced-current period in the experiment, $\tau = 1.1$ ms, is longer than that in the modelling.

Given a certain depth of current reduction, it is possible to quench the spot mode with current reductions of different durations. However, there is a minimum duration, $\tau_\mathrm{min}$, required for quenching. Figure 4 shows the effect of current reductions of durations smaller by 0.1 ms than those in figure 3. When the reduced-current period is over and the arc current value $I = 1$ A has been restored, the instability reappears and a spot is formed. The maximum of the computed spot temperature is marked by the diamond $d$. The state $d$ is positioned on the first falling section of $q(T_w)$ close to the state $b$ as seen in figure 2, an unsurprising result since both states $b$ and $d$ correspond to a well-developed spot. Note that the formation of the spot in the experiment has been indicated by the photodiodes and the sharp decrease in the arc voltage (the latter was detected by the differentiator circuit; however, the microcontroller was programmed not to react).

The minimum duration of the reduced-current period required for quenching, $\tau_\mathrm{min}$, depends on the depth of current reduction $\Delta I$. For example, if $\Delta I$ in the experiment with the lamp used in the experiments shown in figures 1, 3, and 4 increases from 0.5 to 0.6 A, then $\tau_\mathrm{min}$ decreases from 1.1 to 0.7 ms. However, a further increase in $\Delta I$ has no effect on $\tau_\mathrm{min}$. The dependence $\tau_\mathrm{min}(\Delta I)$ was reproducible for the same lamp up to the moment where the transient spots could no longer be induced. There is a scatter of about of factor of 2 between different lamps. It is interesting, however, that the minimum value of $\tau_\mathrm{min}$ which can be attained by increasing $\Delta I$ (and which was equal to 0.7 ms for the lamp used in the experiments shown in figures 1, 3 and 4), was found to be around 0.7 ms also for other lamps.

Short rectangular current pulses have been used for controlling the cathode arc attachment in [2, 8, 9]. The pulses employed in [8, 9] were used to add current to the electrode at the end of the anodic phase. Since the electrode temperature in the anodic phase for the current range of interest is lower than that in the cathodic phase and rapidly increases with the

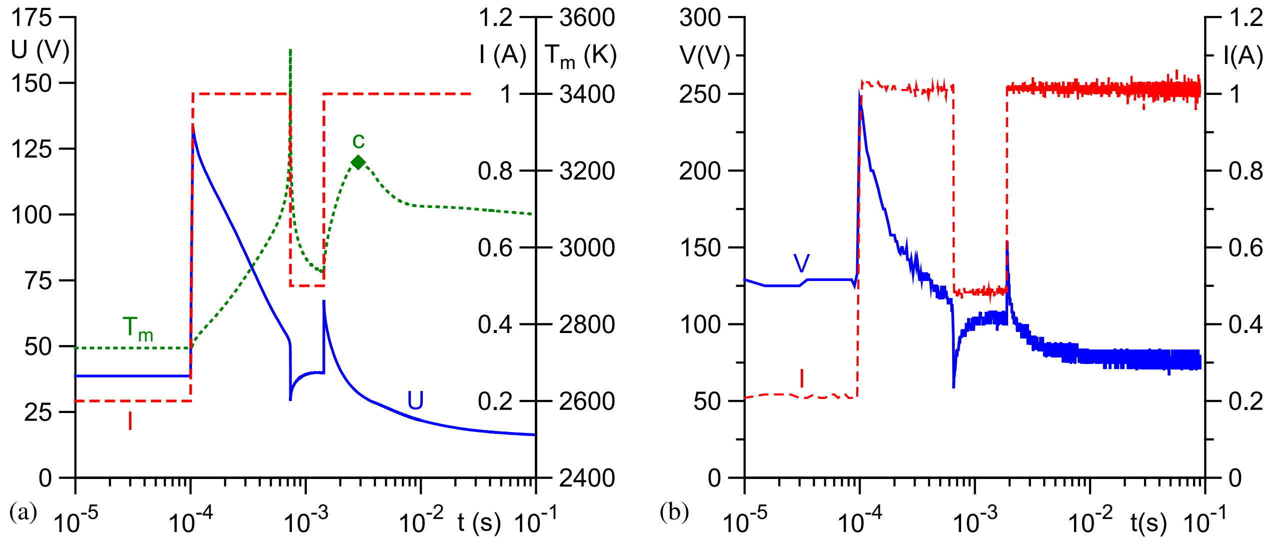


**Figure 3.** Successful quenching of thermal instability. $I_1 = 0.2$ A, $I_2 = 1.0$ A, $\Delta I = 0.5$ A. (*a*) Modeling. $\tau = 0.7$ ms. (*b*) Experiment. $\tau = 1.1$ ms.

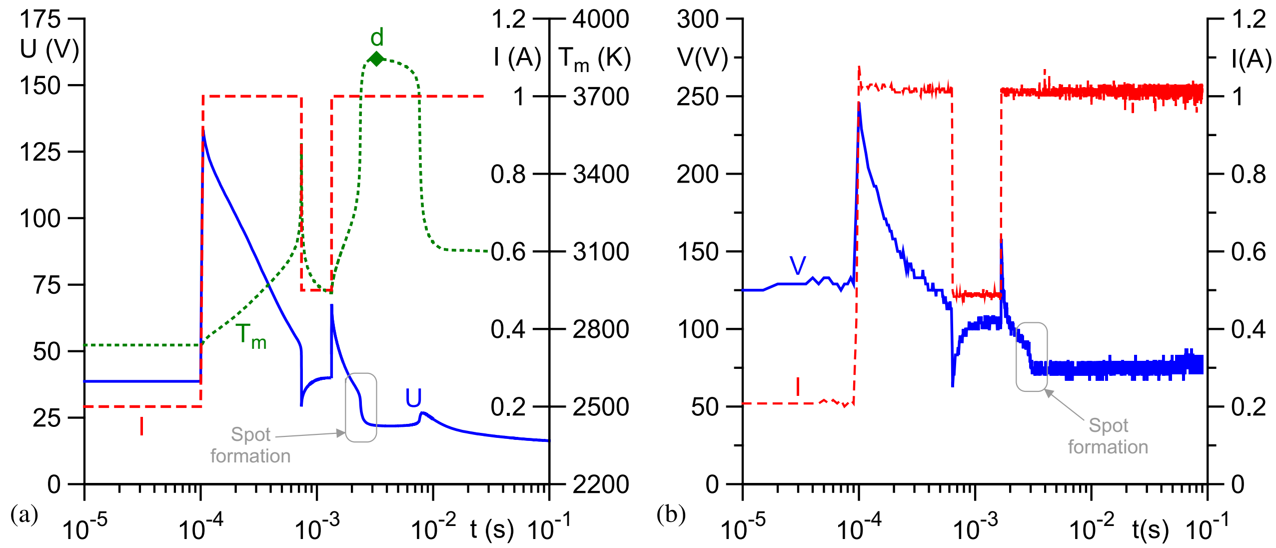


**Figure 4.** Unsuccessful quenching of thermal instability (the instability reappears and the spot is formed). $I_1 = 0.2$ A, $I_2 = 1.0$ A, $\Delta I = 0.5$ A. (*a*) Modeling. $\tau = 0.6$ ms; (*b*) experiment $\tau = 1.0$ ms.

arc current [10], such pulses result in an additional heating of the electrode at the end of the anodic phase and may, at least in principle, produce an effect similar to that of current reduction at the beginning of the cathodic phase. However, the conditions of the works [8, 9] are specific (the operating pressure of the arc is 200 bar) and the effect produced by the pulses is different from that in this work: the pulses favor growth of a tip on the electrode which occurs during the cathodic phase [8]. In [2], negative pulses were applied in the cathodic mode 0.4 ms after each current switching from $I_1$ to $I_2$, which allowed one to prevent the appearance of cathode spots. The arc power supply in [2] was pre-programmed; in other words, current pulses were applied in a pre-emptive way. The approach used in this work is different: the current is reduced only when needed, so the instability is quenched in real time rather than prevented pre-emptively.

In summary, in this study we showed, by means of numerical simulations and experimentally, the possibility of real-time quenching of the thermal instability in the body of thermionic cathodes leading to the formation of cathode spots. This was achieved by briefly reducing the arc current when a specific pattern characteristic of spot formation occurs in near-cathode or arc voltage. In addition to being of physical interest, this approach may be useful in settings where the appearance of cathode spots is unprovoked, such as in low-current gliding discharges [11], and which therefore cannot be prevented by means of a pre-programmed power supply pattern and rather should be quenched in real time.

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