Simulating plasma-cathode interaction in high-pressure arc discharges by means of time-dependent and stationary solvers of COMSOL Multiphysics

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Peculiarities of the usage of stationary and nonstationary solvers in the calculation of modes of current transfer to cathodes of high-pressure arc discharges are illustrated on the example of an axially symmetric tungsten cathode operating in the atmospheric-pressure argon plasma. Simulations are performed by means of stationary and time-dependent solvers of COMSOL Multiphysics. A given mode of current transfer in the whole range of its existence can be calculated by means of a stationary solver, while the use of a nonstationary solver only allows calculating stationary states which are stable for given loading conditions against axially symmetric perturbations. Nonstationary simulations revealed that states belonging to the retrograde section of the current-voltage characteristic are unstable and states outside the retrograde section are stable, so the discharge manifests hysteresis which, in principle, can be observed in the experiment.

1. Introduction

In the last 15 years multiple modes of current transfer to cathodes of high-pressure arc discharges have been computed by means of stationary solvers, see review [1]. The use of stationary solvers has now become a more or less standard practice; a free online tool for simulation of different modes of current transfer to cathodes of high-pressure arc discharges which employs a stationary solver can be found at http://www.arc_cathode.uma.pt/tool/. Apart from computing multiple modes of current transfer, stationary solvers have revealed the existence of complex behavior of the modes of arc-cathode attachment in high-pressure arc discharges in the form of loops and S-shaped sections.

An important feature of the code used to calculate modes of current transfer to cathodes of high-pressure arc discharges is the possibility of using the discharge voltage U or discharge current I as a control parameter while calculating a steady-state mode. In particular, the possibility of switching the control parameter is of extreme importance in the vicinity of an extreme point of the current-voltage characteristic or a turning point, otherwise, calculations stop. The commercial finite element software COMSOL Multiphysics offers a possibility to easily switch between I and U as input parameter, and the pattern of multiple modes of current transfer to cathodes of high-pressure arc discharges [1] was calculated in this way. This procedure will be used also in this work.

An interesting question which will be addressed in this work is to find whether modes of current transfer and complex behavior can be found by means of time-dependent solvers in arc discharges.

This article attempts to illustrate the peculiarities of stationary and nonstationary solvers in the calculation of modes of current transfer to cathodes in high-pressure arc discharges. Time-dependent simulations have been performed in order to investigate the stability of different modes of current transfer to cathodes of high-pressure arc discharges. These nonstationary simulations also allow calculating the pattern of hysteresis of a particular mode.

2. Model and numerics

The model used in this work is obtained by introducing an account of Joule heat production in the cathode body into the model of nonlinear surface heating, which is a widely used tool of simulation of plasma-cathode interaction in high-pressure arc discharges (e.g., [1] and references therein). To this end, the electric current continuity equation supplemented with Ohm's law is solved jointly with the equation of heat conduction in the cathode body. COMSOL Multiphysics software is used. A detailed description of the model can be found in [2].

3. Results and discussion

Calculation results reported in this work refer to a tungsten cathode and an argon arc under the following conditions, which are typical for experiments with high-pressure arc discharges [3]: plasma pressure 1bar, cylindrical cathode with a hemispherical tip of radius 1mm and height 12mm. The current transfer occurs in a mode which embraces states with a hot spot at low currents and states with a diffuse temperature distribution at high currents; a complete description of this mode can be found in [2]. Here, we only mention that the mode of current transfer being considered possesses two turning points, one at $I = 7.698$A and the other at $I = 12.448$A, and a retrograde section between these turning points. It follows that three different steady-state thermal regimes are possible for any current from the range $7.698\text{A} \leq I \leq 12.448\text{A}$. In figure 1 it is represented the part of the current-voltage characteristic and of the dependence of the maximum temperature of the cathode on the arc current for this mode, which is relevant for the present work. (In this figure it is convenient to represent turning point on the dependence of the maximum temperature of the cathode on the arc current rather than on the current-voltage characteristic.) A variation of the thermal regime of the cathode occurs on the retrograde section, as shown by figure 2. (In this figure, d is the distance from the center of the front surface of the cathode measured along the generatrix; the range $0 \leq d \leq 1.57$mm corresponds to the front surface of the cathode while the range $d \geq 1.57$mm corresponds to the lateral surface.) While in the state *a* there is a hot spot at the center of the front surface, there is a diffuse temperature distribution in the state *c*. At state *b*, the thermal regime of the cathode is intermediate.

Data on figure 1 were calculated by means of a stationary solver. Starting from low currents with a suitable initial approximation and using I as a control parameter, the current-voltage characteristic is calculated by means of the use of a stationary solver with increasing the discharge current and calculating the correspondent discharge voltage. At the current corresponding to the turning point 1 the computed steady-state mode break off. This break-off represents a failure of the numerical method rather than a physical effect. In fact, if at this point we change the control parameter from I to U and decrease voltage one can pursuit the calculation of the current-voltage characteristic. Beyond this point, one can again use I as a control parameter, and decreasing the current one can reach the turning point 2. Here, we have to change again from I to U and decreasing U one can pursuit the calculation of the current-voltage characteristic. Beyond this point, a change from U to I is necessary and increasing the current one can go in direction to high currents. It is to mention that one also can calculate the current-voltage characteristic showed in figure 1 using a stationary solver and starting calculations at higher currents.

A question which arises now is whether it is possible to obtain the data shown in figure 1 with a nonstationary solver. In order to answer to this question, calculations have been performed using a nonstationary solver.

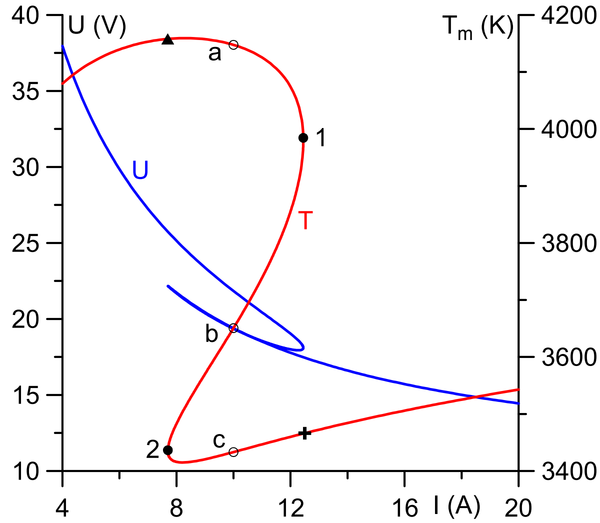

Figure 1. Current-voltage characteristic and maximum temperature of the cathode. Circles: turning points. Open circles: states at the same current $I = 10$ A.

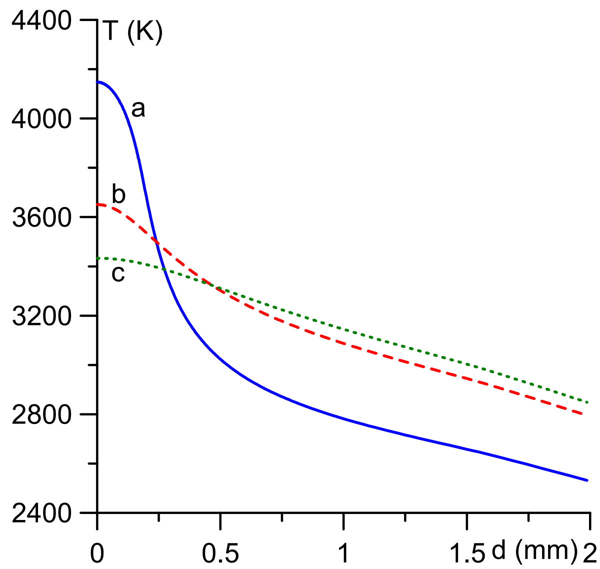

Figure 2. Distributions of the temperature along the cathode surface. $I = 10$A, states a, b, and c are indicated in Fig. 1.

Starting at low currents from an initial condition equal to the initial approximation used for stationary calculations, iterations converge for the same solution obtained with the stationary solver. Using this converged solution as initial condition and a current slight higher than the previous one, iterations converge for this new value of current. Repeating this procedure for increasing current, the current-voltage characteristic can be calculated by means of a stationary solver until the current corresponding to the turning point 1. In order to pursuit the calculation of the current-voltage characteristic beyond the turning point 1, the control parameter was changed from I to U, and the solution corresponding to this turning point was used as initial condition to calculate a solution for a voltage slight lower than the one corresponding to the turning point. Iterations converge for a state corresponding to a situation of no discharge; the temperature of the cathode is the same of the cooling fluid. This calculation indicates that the use of a nonstationary solver does not allow the calculation of the retrograde section of the current-voltage characteristic. Below we will see that this result has a clear physical meaning.

An interesting question that one can pose now is to know what happens if solutions corresponding to turning points 1 and 2 are used as initial conditions for nonstationary calculations with the current fixed, respectively, at slight higher and lower than the current corresponding to the turning points. Results of nonstationary calculations performed in these conditions are presented in figure 3. From this figure, one can see that if the solution corresponding to the turning point 1 is used as initial condition for a nonstationary calculation with a current slight higher than the current corresponding to the turning point, iterations converge to a state with a maximum temperature much lower than the one of the state corresponding to the turning point 1. The final state is represented in figure 1 by a cross. From figure 3, one also can see that if the solution corresponding to the turning point 2 is used as initial condition for a nonstationary calculation with a current slight lower than the current corresponding to the turning point, iterations converge to a state with a maximum temperature much higher than the one of the state corresponding to the turning point 2. The final state is represented in figure 1 by a triangle. Since the turning points of the mode of current transfer are neutrally stable [4], one can expect, in accordance with the evolution of the maximum temperature and voltage shown in figure 3, that values of the inverse of growth increment of the perturbation in the vicinity of these points are quite high.

The above mentioned nonstationay calculations show that the mode of current transfer under investigation manifests hysteresis which, in principle, can be observed in the experiment. The complete dependence of the maximum temperature of the cathode on the arc current calculated by means of a nonstationary solver is shown in figure 4. It comprises two separated branches (a high-temperature branch and a low-temperature branch)

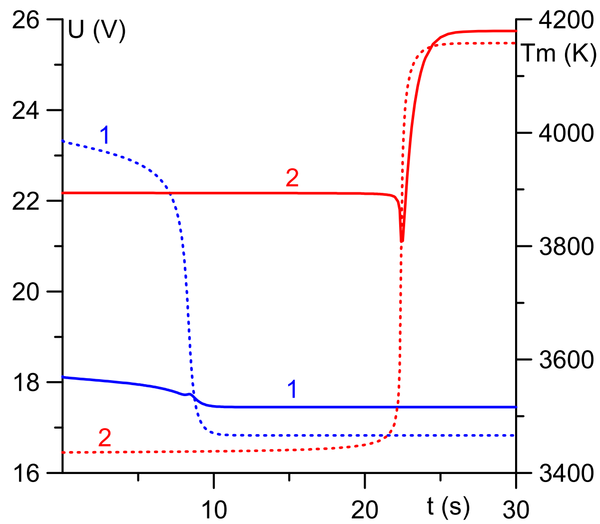

Figure 3. Evolution of the near-cathode voltage drop (solid) and of the maximum temperature of the cathode (dotted) starting from turning point 1 (lines 1) and from turning point 2 (lines 2).

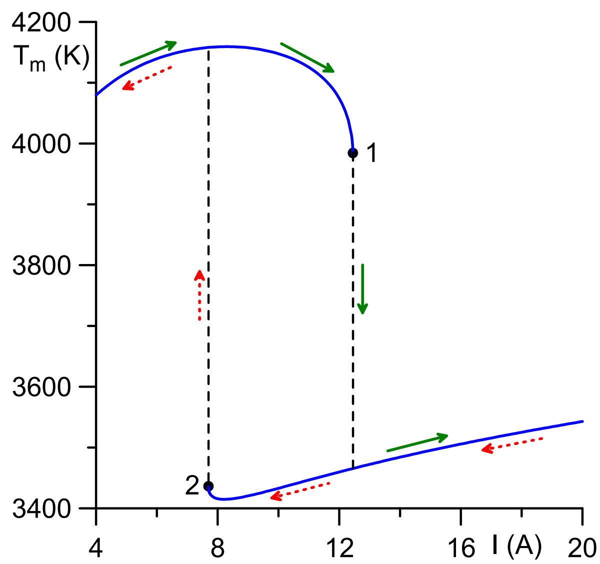

Figure 4. Hysteresis on the dependence of the maximum temperature of the cathode on the arc current. Circles: turning points.

and possesses hysteresis.

An important question is which of the three steady-state solutions that exist in the current range $7.698\text{A} \leq I \leq 12.448\text{A}$ are stable and can be observed in the experiment. Nonstationary calculations have been performed in order to answer this question. In these calculations, perturbed solutions belonging to different parts of current-voltage characteristic have been used as initial conditions for calculations performed with fixed current. Results of these calculations are shown in figure 5. In this figure, one

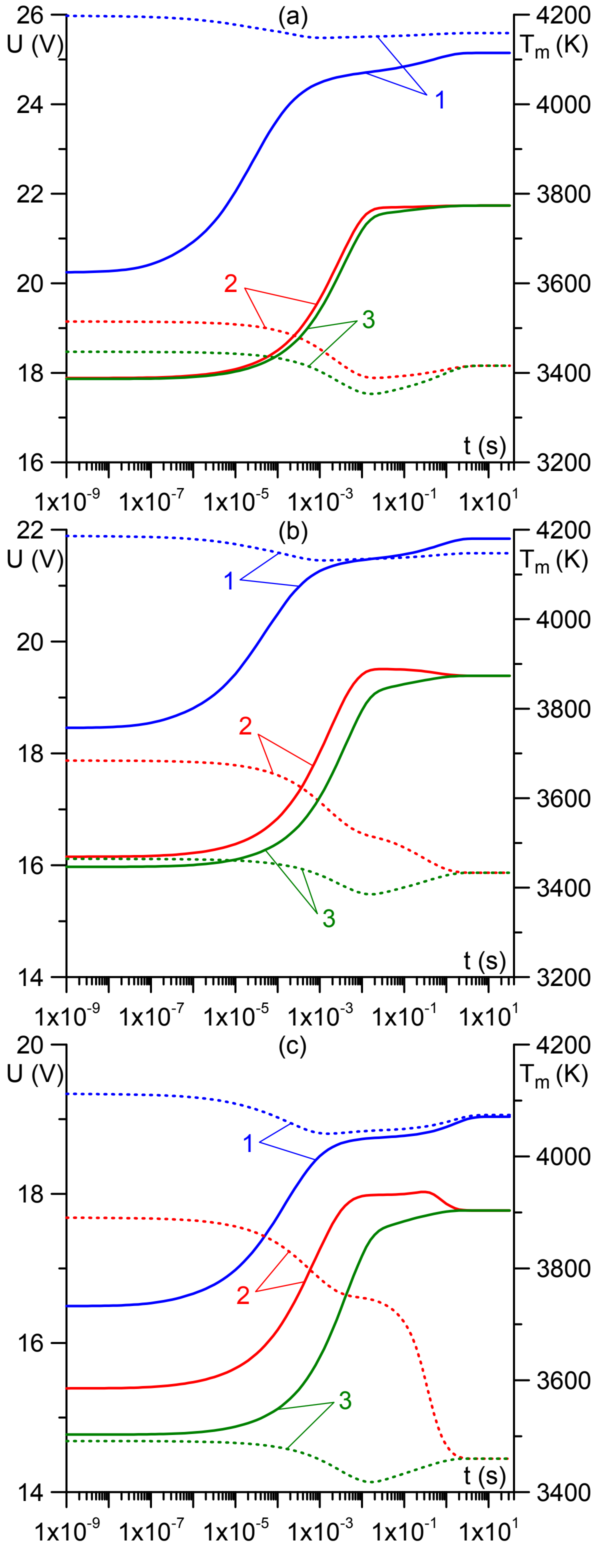

Figure 5. Evolution of the near-cathode voltage drop (solid) and of the maximum temperature of the cathode (dotted). (a): 8A. (b): 10A. (c): 12A. 1: starting from high-temperature branch. 2: starting from retrograde section. 3: Starting from low-temperature branch.

can see that iterations never converge to stationary solutions belonging to the retrograde section. (Iterations of calculations starting from perturbed solutions belonging to the retrograde section converge to solutions belonging to the low-temperature branch.) On the other hand, calculations starting from perturbed solutions belonging to high- and low-temperature branches converge to these solutions itself. The same result is obtained when nonstationary calculations start from perturbed states outside the current range corresponding to the retrograde section. Therefore, one can conclude that states belonging to the retrograde section are unstable and states outside the retrograde section are stable if they operate at a fixed current, which is a usual situation. It is to mention that similar calculations to those represented in figure 5 have been performed with fixed voltage. Results of these calculations reveal that states belonging to the retrograde section and states outside the retrograde section are unstable if they operate at a fixed voltage, which is a usual situation, since the mode of current transfer exhibits negative resistance.

4. Conclusion

In this work we have shown that the complete current-voltage characteristic of a mode of current transfer to a cathode of high-pressure discharge can be calculated by means of a stationary solver. On the other hand, the use of a nonstationary solver only allows calculating stationary states which are stable. Nonstationary simulations revealed that states belonging to the retrograde section of the current-voltage characteristic are unstable and states outside the retrograde section are stable, so the mode manifests hysteresis which, in principle, can be observed in the experiment.

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4. References

[1] M. S. Benilov, J. Phys. D: Appl. Phys. **41** (2008) 144001.

[2] M. S. Benilov and M. D. Cunha, J. Appl. Phys. **113** (2013) 063301.

[3] N. K. Mitrofanov and S. M. Shkol'nik, Tech. Phys. **52** (2007) 711.

[4] M. S. Benilov and M. J. Faria, J. Phys. D: Appl. Phys. **40** (2007) 5083.