Computing DC discharges in a wide range of currents with COMSOL MultiPhysics: time-dependent solvers vs. stationary solvers

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The benefits of the usage of stationary over time-dependent solvers of COMSOL Multiphysics in the modelling of DC discharges are explored and demonstrated using as examples glow and high-pressure arc discharges; in particular, it is investigated whether time-dependent solvers can be used for a systematic computation of different modes of these discharges. It has been found that most modes of both glow and high-pressure arc discharges cannot be computed in the whole range of their existence by a time-dependent solver. Further, time-dependent solvers are unsuitable for a computation of all the states belonging to the retrograde sections of the current-voltage characteristics of the modes, so the discharge manifests hysteresis, which, in principle, can be observed in the experiment.

1. Introduction

The most commonly used for computation DC gas discharges are time-dependent solvers: an initial state of the discharge is specified and its evolution over time is followed until a steady state has been attained. These solvers can be used to compute only steady states which are stable for the specified external circuit against perturbations having the symmetry to which the code is adjusted. It should be stressed that this kind of stability is not equivalent to physical stability, see [1] for a detailed discussion.

On the other hand, iterative processes in stationary solvers need not be equivalent to relaxation in time. In particular, stationary solvers allow one to decouple questions of numerical and physical stability. For example, one can without any difficulty compute states on falling branches of a current voltage characteristic (CVC) treating discharge voltage U as a control parameter, i.e. without a ballast resistance which is generally required by homemade time-dependent solvers. Note that this feature is characteristic not only to the stationary solvers of COMSOL MultiPhysics, which are used in this work, but also to other steady-state solvers based on the Newton linearization with a direct solution of linear equations in finite elements or differences, such as the one used in the online tool simulating plasma–cathode interaction in high-pressure arc discharges [3].

In the last two decades different modes of arc-cathode attachment in high-pressure arc discharges have been computed by means of stationary solvers; see review [2] for a discussion and references. This procedure has now become standard practice and an online tool for simulation is available [3]. Stationary solvers have also revealed the existence of complex behavior of the modes of arc-cathode attachment in high-pressure arc discharges in the form of retrograde sections.

In the last decade, different DC glow discharge modes have been computed by means of stationary solvers, see review [1] and [4] for a discussion and references. Stationary solvers have also revealed complex behavior in the form of retrograde sections in glow discharges, even in apparently simple situations.

This work is aimed at finding whether different modes and complex behavior can be found by means of time-dependent solvers of COMSOL MultiPhysics in both glow and high-pressure arc discharges.

2. The models

A detailed description of the employed models is skipped in this work for brevity. The bulk of the modelling of glow discharges has been done in the framework of the most basic self-consistent model of glow discharge, which takes into account a single ionic species and employs the local-field approximation. Some results obtained in the framework of a model which includes a detailed kinetic scheme, several ionization channels, several ionic species, and non-locality of electron transport and kinetics are also given. Full details of the employed models can be found in [5,6].

As far as high-pressure arc discharges are concerned, 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

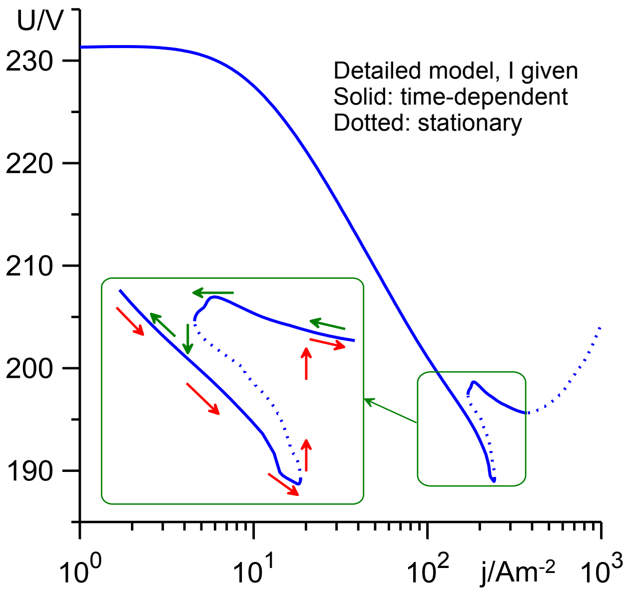


Figure 1: CVC of the 1D mode of glow discharge computed with I as the control parameter and starting from both high and low currents, detailed model. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver.

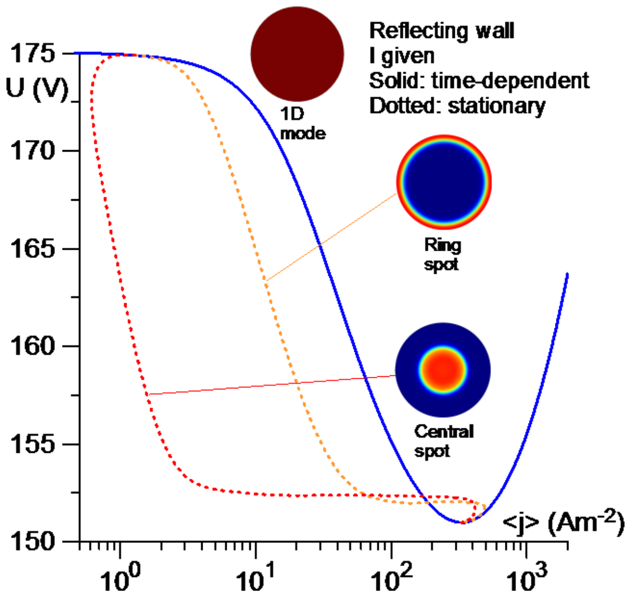


Figure 2: CVC of the 1D mode and a 2D mode of glow discharge associated with a spot at the centre of the cathode or a ring spot at the periphery. I as the control parameter parameter, basic model. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver.

surface heating, which is a widely used tool of simulation of plasma-cathode interaction in high-pressure arc discharges (e.g., [2] 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.

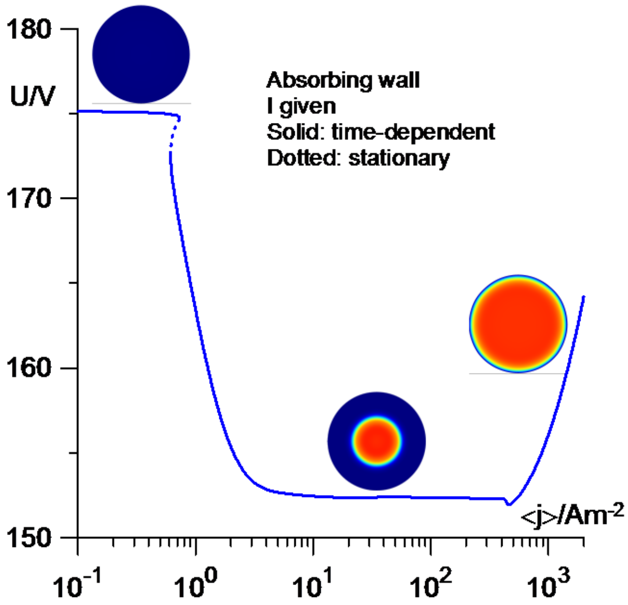


Figure 3. CVC of the 2D fundamental mode of glow discharge. I as the control parameter, basic model. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver.

COMSOL MultiPhysics software is used in this work. This software offers the possibility of representing the anode potential in terms of discharge current without the need to introduce in the model an external circuit, thus allowing for seamless switching between discharge current I and voltage U as the control parameter. It is important to stress that this possibility can be used also with time-dependent solvers. In other words, COMSOL allows the use of a time-dependent solver without a ballast resistance introduced in the models.

In the simulations, the initial condition for the time-dependent solver was an exact solution computed with the stationary solver. The control parameters U and I were then varied with a relative step of roughly 1%.

3 Results

3.1. Glow discharge

The modelling has been performed for a cylindrical discharge vessel with parallel-plane electrodes in xenon under the pressure of 30 Torr. The interelectrode gap is 0.5mm; the radius is 1.5mm in 1D and 2D simulations and 0.5 mm in 3D simulations.

Examples of computed CVC are shown in figures 1-4. In figure 1, the 1D mode computed in the framework of the detailed model with I as the control parameter is shown. This mode possesses an S-shaped section in the CVC which cannot be computed with a time-dependent solver; the discharge manifests hysteresis.

In figure 2, the 1D mode and the 2D mode associated with a spot at the centre of the cathode or a ring-spot at the periphery computed in the framework of the basic model are shown. The time-dependent solver allows computation of the 1D mode in the whole range of its existence. However, this solver does not allow computation of any state belonging to the 2D mode. The stationary solver allows computation of both modes in the whole range of their existence, including retrograde sections.

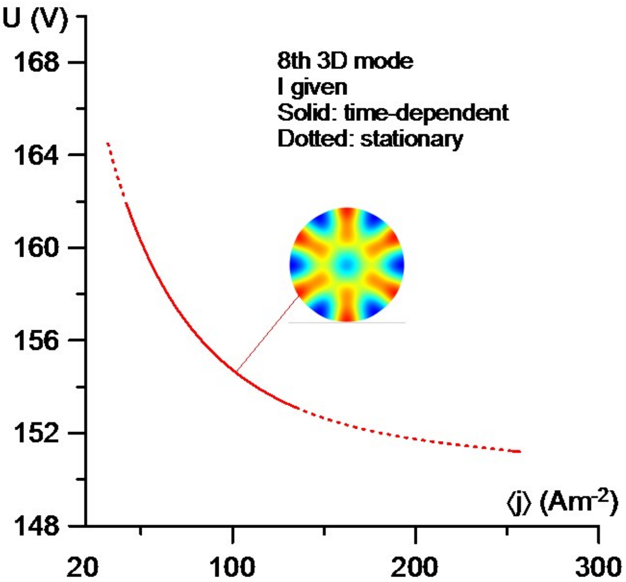
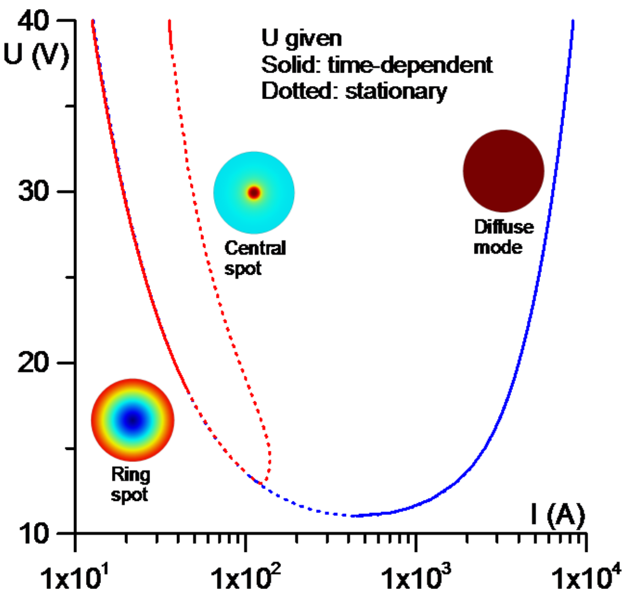
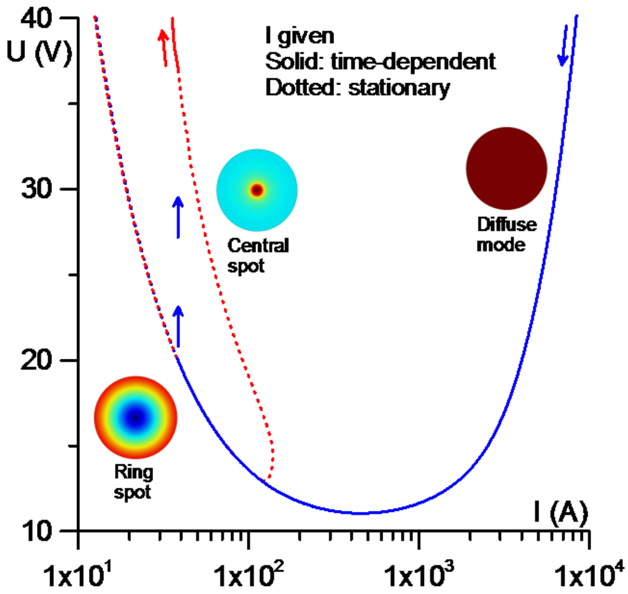


Figure 4. CVC of a 3D mode of glow discharge associated with six spots at the periphery of the cathode. *I* as the control parameter, basic model. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver.



a)



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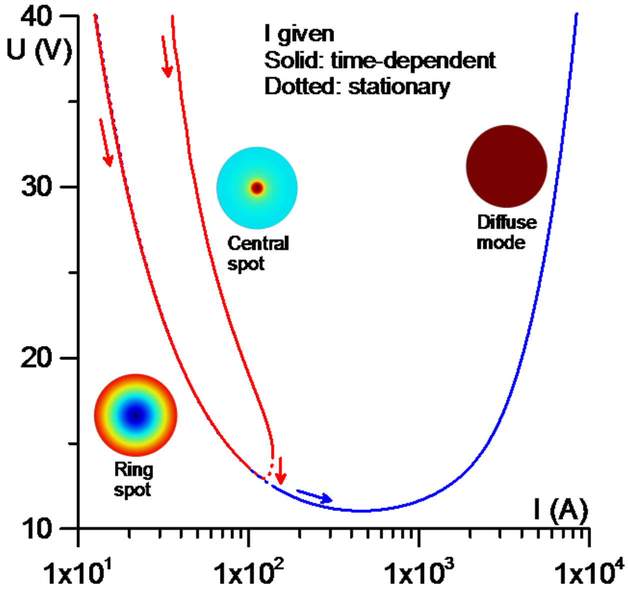

c)

Figure 5. CVC of the diffuse mode and the 2D mode of high-pressure arc discharge associated with a spot at the centre of the cathode or a ring spot at the edge. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver. a): *U* as the control parameter. b): *I* as the control parameter, starting from high currents. c): *I* as the control parameter, starting from low currents.

In figure 3, the 2D fundamental mode (i.e., the mode that exists for all values of discharge current) computed in the framework of the basic model is shown. A small retrograde section of the CVC at low currents cannot be computed with the time-dependent solver; the stationary solver allows computation of the mode in the whole range of its existence.

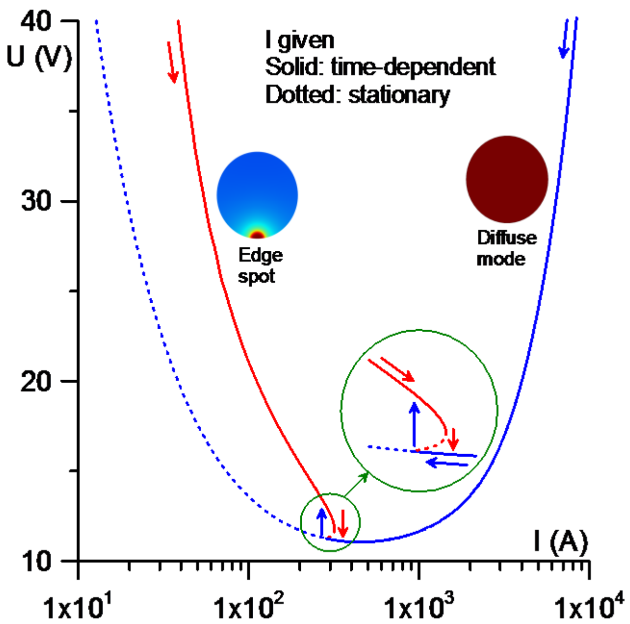

Figure 6. CVC of the diffuse mode and the 3D mode of high-pressure arc discharge associated with a spot at the edge of the cathode; *I* as the control parameter and starting from high currents. Solid line: time-dependent and stationary solvers. Dotted lines: stationary solver.

In figure 4 the 3D mode associated with a pattern of 6 spots on the cathode is shown. The time-dependent solver does not allow computation of this mode in the entire range of its existence, whereas the stationary solver does.

3.2. High-pressure arc discharge

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 [2]: plasma pressure 1bar, cylindrical cathode with a hemispherical tip of radius 1mm and height 12mm.

Examples of computed CVC are shown in figures 5 and 6. In figure 5 the diffuse mode and the 2D mode associated with a central spot or ring spot at the edge of the cathode are shown, computed with input parameter *U* (figure 5a) or *I*, starting from high (figure 5b) or low (figure 5c) currents. Only a few sections of the CVC of the modes can be computed with a time-dependent solver, whereas the whole range of existence of the modes can be computed with a stationary solver. The discharge manifests hysteresis at the transition between the diffuse and 2D central spot modes.

In figure 6, the diffuse mode and the 3D mode associated with a spot at the edge of the cathode is shown computed with *I* as input parameter and starting from both low and high currents. Again, only some sections of the modes can be computed with a time-dependent solver, whereas the whole range of existence of the modes can be computed with a stationary solver. The discharge manifests hysteresis at the transition between the diffuse mode and the 3D mode with a spot at the edge of the cathode.

4. Conclusion

It has been found that most modes of both glow and high-pressure arc discharges cannot be computed in the whole range of their existence by a time-dependent solver. On the other hand, stationary solvers allow one to compute a full pattern of different modes of plasma-cathode attachment in both glow and high-pressure arc discharges, including self-organized modes. It is demonstrated that a key point in the modelling of different modes of DC discharges is the use of stationary solvers.

Further, time-dependent solvers are unsuitable for a computation of all the states belonging to the retrograde sections of the CVC. General speaking, the discharges manifest hysteresis, which, in principle, can be observed in the experiment.

These results allow a better understanding of importance of stationary solvers in the modeling of DC discharges.

Acknowledgments

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