Modelling of an argon gliding “arc” discharge

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Abstract: In this work we have analysed the properties of a gliding DC discharge in argon. Despite the usual designation of these discharges as “gliding arc discharges”, it was found previously that they operate in two different regimes – glow and arc. Here we analyse the differences in both regimes by means of two dimensional fluid modelling. In order to address different aspects of the discharge operation, we use two models – Cartesian and axisymmetric in cylindrical coordinate system. The obtained results show that the two types of discharges produce a similar plasma column for a similar discharge current. However, the different mechanisms of plasma channel attachment to the cathode could produce certain differences in the overall discharge effect on the treated gas.

Keywords: gliding arc discharge, 2D fluid model, atmospheric pressure glow discharge, atmospheric pressure arc discharge

1. Introduction

Gliding arc discharges (GAD) are DC or low frequency AC discharges produced usually between two diverging electrodes. The plasma channel moves along the electrodes due to a forced gas flow and when its length becomes very long, the discharge diminishes and it reignites at the closest electrode distance. The GAD attracted considerable interest [1] because of its ability to produce a non-equilibrium plasma at atmospheric pressure. At the same time, a considerable power can be applied while keeping the gas temperature relatively low and avoiding the appearance of a classical thermal arc discharge. It also provides a good selectivity and efficiency in many different plasma chemistry applications for gas reforming and treatment [1-3]. The simple design, the affordable set-up and the operation under atmospheric pressure makes it even more attractive for industrial applications.

Despite the simplicity of building GADs, they are rather difficult for experimental diagnostics and theoretical studies. This is mainly due to the non-stationary nature of the discharge and often, due to the luck of good repeatability between the discharge cycles. Moreover, fast photographs of the discharge [4] show the existence of two different regimes of operation – arc and glow. In the case of an arc discharge, the discharge is sustained by thermo-field electron emission from the cathode and it is accompanied with the formation of a tiny cathode spot. In the case of a glow discharge, the discharge is sustained by secondary electron emission due to ion bombardment. Experimental studies [4] even show that both regimes could be present in a single cycle of the plasma channel evolution.

In this work we present a theoretical study of both gliding arc and gliding glow discharges based on two dimensional fluid plasma models. The work aims at describing the mechanisms governing the gliding of the plasma channel and at pointing out the similarities and the differences between both regimes.

In section 2 we will describe shortly the numerical models used for the derivation of the included results. In section 3 we will discuss the discharge properties based on an axisymmetric 2D model, while in section 4 we discuss the discharge gliding mechanisms based on results from a 2D model in a Cartesian coordinate system.

2. Description of the models

Here we use two models in argon – a 2D model in Cartesian coordinate system and a 2D model in cylindrical coordinate system assuming axial symmetry.

The Cartesian model considers the geometry presented in Fig. 1b and it describes the behaviour of a plasma channel that is infinite in the “z” direction, under the impact of a forced gas flow causing the plasma displacement along the electrodes. The model is described in more detail in [5] and it includes the balance equations for all species, the Poisson equation, the electron energy balance, the gas thermal balance and the Navier-Stokes equations neglecting the inertial term. The electrode profile and size in Fig. 1b is based on the geometry of the electrodes used in the experiments described in [6, 7]. In many of our simulations we will use similar conditions as in the above mentioned experiments since they were carried out in argon gas and provide a good starting point for our study. Moreover, they provide data for experimentally measured discharge parameters.

The axisymmetric model considers an axially symmetric discharge between two cylindrical electrodes (Fig. 1a). Obviously, this model cannot describe the discharge gliding due to the limited dimensionality. However, the model accounts approximately for the convective process by introducing a loss term in all conservation equations equal to $-\alpha\nu_{\mathrm{elong}}$, where α is the conserved variable (species densities and energy density) and ν_{elong} is a constant frequency proportional to the intensity of the convection process, i.e., it is related to the gas velocity. The above approach relies on the assumption that the convection causes stretching of the plasma channel, which effectively reduces the densities of the conserved variables.

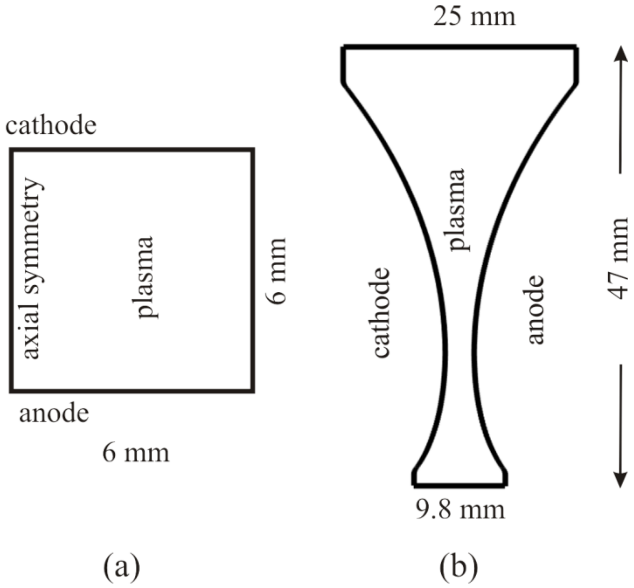

Fig. 1. Geometries considered in the models. (a) axisymmetric and (b) Cartesian model.

Both models are described in more detail in [5] and there are only two differences within the used axisymmetric model compared to [5]: a) the cathode heating is neglected and therefore we do not solve equations (12) and (13) in [5]; and b) we include the above mentioned loss terms accounting for the convection process.

The Ar plasma chemistry is the same as in [5] and the following species are considered: electrons, Ar atoms, Ar^{+}, Ar_2^{+}, the lumped states of 4s and 4p groups Ar(4s) and Ar(4p) and the lumped Ar_2^{*} which includes $Ar_2(^1\Sigma_u^+)$ and $Ar_2(^3\Sigma_u^+)$ excited molecules.

The models are solved with the commercial software Comsol Multiphysics® using the Plasma module [8].

3. Results and discussion.

3.1. Comparison between arc and glow discharge within a 2D axisymmetric geometry

We will start the presentation of our results by comparing the two regimes within the axisymmetric geometry. This ensures that the created plasma in both cases is subject to the same convective process and it has the same length. All results from that model are at a time $t = 100\ \mu$s, which corresponds approximately to the initial stages of discharge gliding. The value of ν_{elong} is fixed at 5 kHz. This value is based on a rough estimation of the extension rate of the plasma channel calculated from the photographs available in [6, 7]. The discharge current is limited by an external resistor. A voltage source provides a constant voltage of U_{s} = 3700 V. The particular values of the simulation parameters are noted in the figure captions.

In Fig. 2 we present results for the electron density n_e for both regimes. The ballast resistor (R_b) is slightly different in both cases in order to provide the same discharge current of 31 mA, which is similar to the typical experimental value [6, 7]. Visually both discharges differ mainly in the cathode region and they are very similar in the rest of the domain. The difference in the cathode region is expected because of the different electron emission process which modifies the cathode fall region. In the case of arc with field emission (Fig. 2a) the current near the cathode is concentrated in a tiny channel and a small cathode spot is formed in order to provide the strong electric field needed for efficient field emission. In the case of glow discharge (Fig. 2b), the cathode spot is wide in order to provide a large enough surface for the electron current emission.

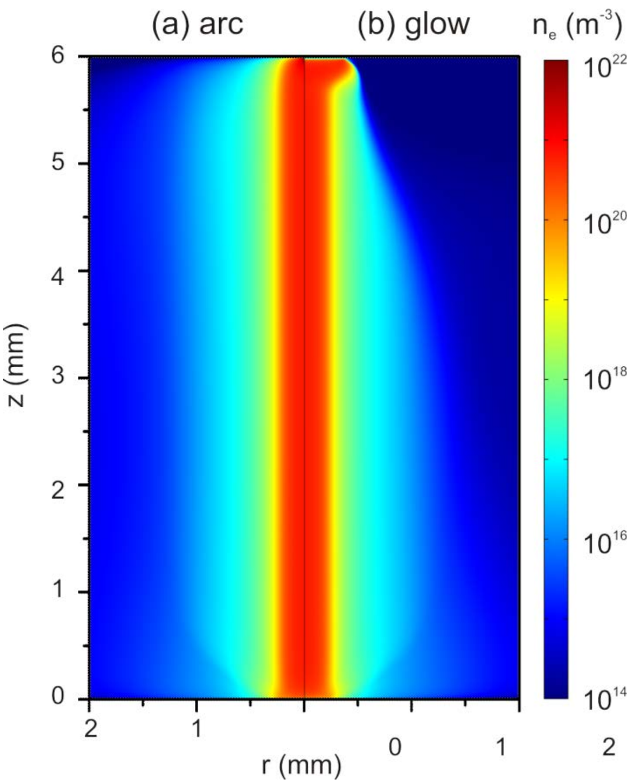

Fig. 2. Electron density distribution, calculated with the axisymmetric model in the case of arc (a) and glow (b) discharges at t = 0.1 ms. The following simulation parameters are used: a) FEF = 400, $\gamma_s = 0$, $R_b = 115$ kΩ, b) FEF = 0, $\gamma_s = 0.01$, $R_b = 110$ kΩ

The similarities and the differences between both regimes could be better seen in a 1D plot of the plasma parameters. The electric potential along the symmetry axis (z) is plotted in Fig. 3. The small plots inside the figure provide a zooming on the electrode regions. The profiles are practically identical in the anode and the central regions and they differ in the cathode region only. The cathode fall in the arc is in the order of 15 V while for the glow discharge it is around 190 V.

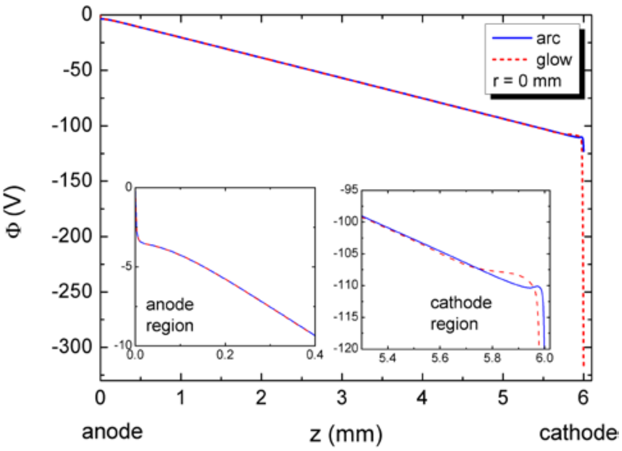

Fig. 3. Electric potential distribution along the symmetry axis. The simulation conditions are the same as in Fig. 2.

A thorough analysis of the obtained results shows that for the two regimes the plasma channels are completely identical outside the cathode region, i.e., 0.3 mm away from the cathode surface.

3.2. *Comparison between arc and glow gliding discharge within a 2D Cartesian geometry*

The above results show that if the plasma channels in both regimes have identical shapes and they are subject to the same convective effects, we observe very similar properties outside the cathode regions. Are there any circumstances under which the above assumptions are violated for the two different regimes of operation? Our study shows that the answer is yes and for certain conditions the different mechanisms of attachment of the plasma channel may introduce differences in the plasma channel length and stretching rate.

In [5] we have commented that in the arc regime, the cathode spot is firmly attached to the emission centre. The attachment point is expected to be a surface protrusion or some kind of contamination, causing a local increase of the electric field and thus providing conditions for field electron emission. Without such a field amplification centre, our axisymmetric model shows that the discharge tends to operate in a glow regime. However, the different mechanisms of the plasma column attachment to the cathode may change the convective elongation of the plasma column. For example in the case of a glow regime, the 2D Cartesian model shows that the cathode contact point (root) tends to follow the anode contact point (Fig. 4). This motion is self-consistently calculated within the model and it is determined by the bending of the plasma channel and the resulting increase of the electric field between the cathode and the plasma channel downstream.

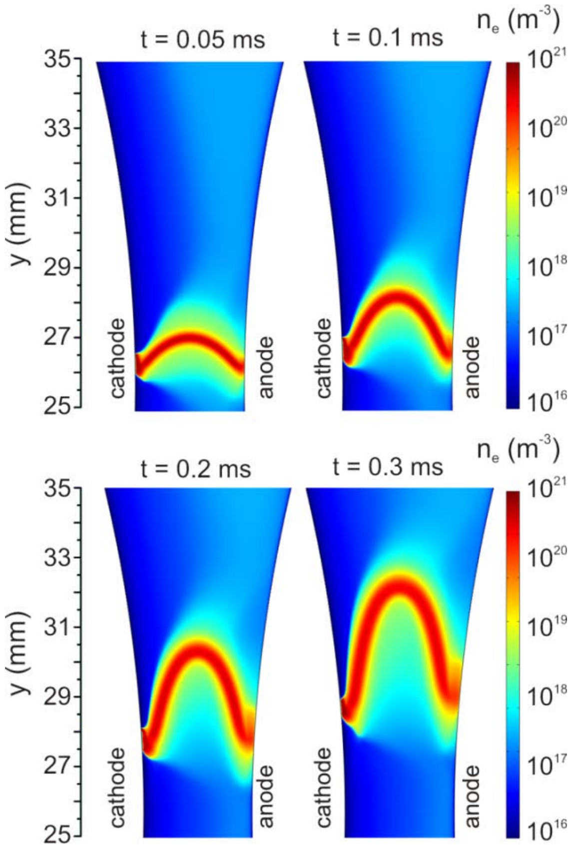

Fig. 4. Electron density distribution, calculated with the 2D Cartesian model in the case of a glow discharge, at different moments in time, as noted in the figure. The following simulation parameters are used: FEF = 1, $\gamma_s = 0.01$, $R_b = 25\ \Omega$, U_s = 1000 V.

On the other hand, in the case of an arc operation (Fig. 5), the plasma channel is firmly attached to the electron emission position for a long time and the cathode root of the arc moves downstream by a new breakdown downstream [5]. This jumping motion of the arc cathode root is accompanied with jumps (drops) in the discharge voltage due to the fast reduction of the discharge length. In [5] we have modelled this kind of movement by artificially initiating new breakdowns between the cathode and the plasma channel, following the movement of the anode root. In this case the resulting displacement of the arc is similar to the glow discharge. However, we should stress that depending on the conditions of the surface (presence of emission centres), the appearance of a new breakdown could be hindered by the lack of such centres and the discharge may remain attached to the same point at the cathode for a long time (Fig. 5, t = 0.3 ms). This causes a more intensive stretching of the arc on the left hand side (the side of the cathode) and it could modify slightly the plasma column there. Moreover, the longer length of the discharge might have a different effect in the case of gas treatment for example.

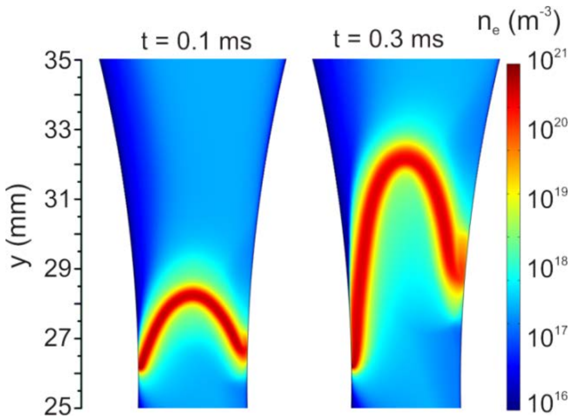

Fig. 5. Electron density distribution, calculated with the 2D Cartesian model in the case of an arc discharge, at different moments in time, as noted in the figure. The following simulation parameters are used: FEF = 500, $\gamma_s = 0.05$, $R_b = 25\ \Omega$, U_s = 1000 V.

4. Conclusions

The gliding arc discharge is analysed by means of 2D fluid models. The use of different models (Cartesian and axisymmetric) allows us to address different aspects of the discharge operation while preserving the computational time and the required resources to reasonable values.

The obtained results show that the two regimes of discharge operation produce to a large extent a very similar plasma channel. Substantial differences are observed only in proximity to the cathode. The differences are caused by the different electron emission mechanisms in both cases.

The different properties of the plasma channel attachment to the cathode, however, can cause some differences between the two regimes. In the case of a glow discharge, the cathode root tends to follow the anode root. In the case of arc operation, the cathode root still follows the anode root but with certain delay, compensated with fast jumps. The duration of that delay is probably determined by the surface properties of the cathode. If the delay is substantial, the length of the plasma channel is effectively longer compared to the glow regime and this can have different effect in gas treatment applications.

5. Acknowledgments

This research was carried out in the framework of the network on Physical Chemistry of Plasma-Surface Interactions - Interuniversity Attraction Poles, phase VII (http://psi-iap7.ulb.ac.be/), and supported by the Belgian Science Policy Office (BELSPO).

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