Modelling a reverse-vortex flow gliding arc plasma reactor in 3D

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Abstract: A reverse-vortex flow gliding arc plasma reactor is modelled by means of the COMSOL Multiphysics Software. The plasma is operating in argon, at atmospheric pressure, and the power input ranges from 300 W to 1 kW. The arc movement in the reactor is observed, and results for the plasma density, electron temperature, and gas temperature are obtained.

Keywords: plasma, modelling, gliding, arc, atmospheric, 3D, Comsol, CFD, fluid, MHD

1. Introduction

Gliding arc (GA) plasma reactors are interesting atmospheric plasma sources because of their simplicity and reliability. A major field of their application is the CO_2 conversion into value-added chemicals and new fuels. While conventional GAs can already operate efficiently in gas conversion, a newly envisaged method for efficiency improvement has been studied recently. The innovative technique of reverse vortex-flow stabilization (RVF) allows to lower the heat losses at the walls of the reactor [2].

As shown in Fig. 1, the pressurized gas enters the tube through a tangential inlet, forming an upward vortex flow. At the same time, the gas expands, cooling down the walls. A pressure gradient is formed from the centre of the tube to the walls. Thus, a secondary (downward) vortex flow is formed, exiting the tube in the opposite direction. The plasma itself is confined within the inner flow, providing nearly perfect heat insulation from the walls, which leads to a higher degree of ionization and a higher energy efficiency. The remarkably high energy efficiency is attributed to the flow characteristics in the RVF plasma reactor. The vortex gas flow is associated with the Ranque effect of temperature separation, which is still under investigation [2, 3].

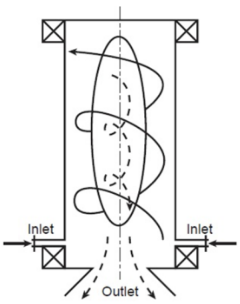

Fig. 1. Schematic diagram of RVF stabilized GA configuration [1].

2. Model description

2.1. Plasma model

Atmospheric pressure plasma modelling in 3D comes with a very high computational cost. The model described here is a quasi-neutral fluid plasma model. Two temperatures are evaluated – electron temperature $\boldsymbol{T_e}$ and gas temperature $\boldsymbol{T_g}$. A reduced number of plasma species is considered – Ar atoms, electrons, Ar^+ ions and excited Ar atoms (4s). We assume a drift-diffusion approximation.

In this way, the plasma model is constructed using several coupled partial differential equations (PDEs). The electron balance equation reads as follows:

$$\frac{\partial n_e}{\partial t} + \nabla.\left(-\mu_e n_e \vec{E} - D_e \nabla n_e\right) + \left(\vec{U}_g.\nabla\right)n_e = R_e \quad (1)$$

$$-\mu_e n_e \vec{E} - D_e \nabla n_e = \vec{G}_e \quad (1.1)$$

where n_e is the electron density, μ_e is the electron mobility, D_e is the electron diffusion coefficient, $\vec{E}$ is the electric field, $\vec{U}_g$ stands for the gas velocity and R_e for electron production reaction rates. In analogy, the equation for ion balance reads:

$$\frac{\partial n_i}{\partial t} + \nabla.\left(-\mu_i n_i \vec{E} - D_i \nabla n_i\right) + \left(\vec{U}_g.\nabla\right)n_i = R_i \quad (2)$$

$$-\mu_i n_i \vec{E} - D_i \nabla n_i = \vec{G}_i \quad (2.1)$$

The electron energy balance equation is:

$$\frac{\partial n_e \bar{\varepsilon}_e}{\partial t} + \nabla.\left(-\mu_{\varepsilon,e} n_e \vec{E} - D_{\varepsilon,e} \nabla(n_e \bar{\varepsilon}_e)\right) + \left(\vec{U}_g.\nabla\right)n_e \bar{\varepsilon}_e$$

$$= q_e \vec{E}.\vec{G}_e + n_e \Delta\bar{\varepsilon}_e + Q \quad (3)$$

where $\bar{\varepsilon}_e$ is the averaged electron energy, Q is the background heating and:

$$\mu_{\varepsilon,e} = \frac{5}{3}\mu_e \quad (3.1) \qquad D_{\varepsilon,e} = \frac{2}{3}\mu_{\varepsilon,e}\bar{\varepsilon}_e \quad (3.2)$$

Instead of solving the Poisson equation, the electric field is derived from the current conservation law. We subtract eq. (1) from eq. (2) into:

$$\frac{\partial(n_i - n_e)}{\partial t} + \nabla.\left(\vec{G}_i - \vec{G}_e\right) + \left(\vec{U}_g.\nabla\right)(n_i - n_e) = R_i - R_e \quad (4)$$

Multiplying by the elementary charge $|q_e|$ and defining $|q_e|\left(\vec{G}_i - \vec{G}_e\right) = \vec{\vartheta}$, we obtain:

$$|q_e|\frac{\partial}{\partial t}(n_i - n_e) + \nabla.\vec{\vartheta} + |q_e|\left(\vec{U}_g.\nabla\right)(n_i - n_e) = 0 \quad (5)$$

$$\vec{\vartheta} = |q_e|\left[\left(\mu_i n_i \vec{E} - D_i \nabla n_i\right) - \left(-\mu_e n_e \vec{E} - D_e \nabla n_e\right)\right] \quad (6)$$

Furthermore, the plasma conductivity is:

$$\sigma_{pl} = |q_e|(\mu_e n_e + \mu_i n_i) \quad (7)$$

Taking into account $\vec{E} = -\nabla\varphi$, we can rewrite Eq. (5) into:

$$|q_e|\frac{\partial}{\partial t}(n_i - n_e) + \nabla.\left(\sigma_{pl}\vec{E} + |q_e|(D_e \nabla n_e - D_i \nabla n_i)\right) + $$
$$+|q_e|\left(\vec{U}_g.\nabla\right)(n_i - n_e) = 0 \quad (8)$$

For the quasi-neutral $(n_e - n_i = 0)$ case, we obtain the following equation for the current conservation:

$$\nabla.\left[\sigma_{pl}(-\nabla\varphi) + |q_e|(D_i \nabla n_i - D_e \nabla n_e)\right] = 0 \quad (9)$$

A further assumption is made as follows [4]. The thermal diffusion of the electrons and the ions is neglected, i.e.,

$$\nabla D_e \nabla n_e = D_e \nabla n_e \quad (10)$$

$$\nabla D_i \nabla n_i = D_i \nabla n_i \quad (11)$$

Denoting $n_e = n_i = n$, we obtain:

$$\frac{\partial n}{\partial t} + \nabla.\left(\mu_i n \vec{E} - D_i \nabla n\right) + \left(\vec{U}_g.\nabla\right)n = R_i \quad (12)$$

$$\frac{\partial n}{\partial t} + \nabla.\left(-\mu_e n \vec{E} - D_e \nabla n\right) + \left(\vec{U}_g.\nabla\right)n = R_e \quad (13)$$

Combining the two equations above, yields:

$$\nabla.\left(\mu_i n \vec{E} - D_i n\right) + \left(\vec{U}_g.\nabla\right)n - R_i = \nabla.\left(-\mu_e n \vec{E} - D_e \nabla n\right) + \left(\vec{U}_g.\nabla\right) - R_e \quad (14)$$

Or, with $R_i = R_e$, we obtain:

$$\nabla.\vec{G}_i = \nabla.\vec{G}_e \quad (15)$$

Therefore:

$$\mu_i n \vec{E} - D_i \nabla n = -\mu_e n \vec{E} - D_e \nabla n \quad (16)$$

The ambipolar electric field is:

$$\overrightarrow{E_{amb}} = \frac{\nabla n(-D_e + D_i)}{n(\mu_i + \mu_e)} \quad (17)$$

and the ambipolar diffusion:

$$D_{amb} = \frac{\nabla n(D_i - D_e)}{n(\mu_i + \mu_e)} \quad (18)$$

This leads to:

$$\overrightarrow{E_{amb}} = \nabla n D_{ai} \quad (19.1) \qquad D_{ai} = \frac{D_i - D_e}{(\mu_1 + \mu_e) n_i} \quad (19.2)$$

Now we can finally replace in the ion balance equation:

$$\frac{\partial n_i}{\partial t} - \nabla.\left(D_i \nabla n_i - \mu_i n_i \overrightarrow{E_{amb}}\right) + \left(\vec{U}_g.\nabla\right)n_i = R_i \quad (20)$$

In this way we derived the balance equations for the case of a single type of ions (Ar^+).

The considered electron collision reactions are mentioned in Table 1, where BS means that the rate coefficient is calculated from the cross-section, by means of the Boltzmann solver.

Table 1. Electron collisions.

Reaction	Rate coefficient	Ref.
$e + Ar \rightarrow e + Ar$	BS	[5]
$e + Ar \rightarrow e + Ar(4s)$	BS	[5]
$e + Ar(4s) \rightarrow 2e + Ar^+$	BS	[5]
$Ar^+ + e + Ar \rightarrow Ar + Ar$	$1.5 \times 10^{-40}\left(\frac{T_g}{300}\right)^{-2.5}$	[6]

Note that this chemistry is very simple, even too simple for an atmospheric pressure plasma, but we focus here in first instance mainly on the physical behavior of the RVF gliding arc.

The streamer stage of the arc is omitted. Instead, an artificial plasma channel is created at the initial position of the arc.

2.2. Gas flow model

Typically, the gas flow in the RVF reactor is highly turbulent . For this reason, the gas flow is calculated by the Reynolds-averaged Navier-Stokes equations (RANS) for turbulence modelling.

3. Results and Discussion

Fig. 2 shows the calculated movement (at early stage) of the arc inside the RVF plasma reactor with 4 tangential gas inlets. The plasma density is in the order of 10^{20} m^{-3}, and the electron temperature is about 2 eV. We can see the arc convection due to the gas flow and temperature. The arc moves along with the gas flow.

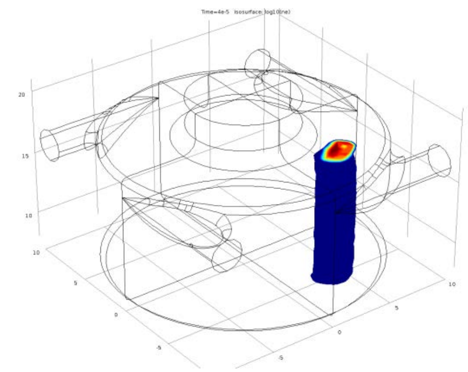

Fig. 2. Modelled gliding arc moving in RVF reactor.

In Fig. 3 the calculated reverse-vortex flow pattern is presented. Two vortices, inner and outer, are visible.

Fig. 4 shows the flow velocity magnitude inside the reactor, with a maximum value of 100 m/s. These results meet the expected properties of the RVF stabilized gliding arc reactor and are within good agreement with previous experimental and numerical studies [1, 2].

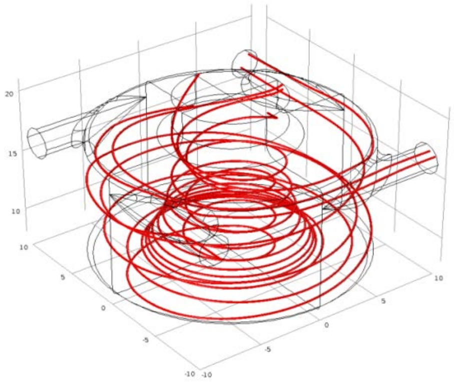

Fig. 3. Reverse-vortex flow pattern with 4 tangential inlets.

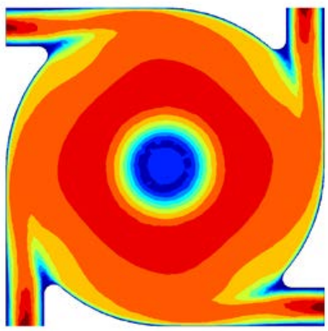

Fig. 4. Flow velocity plot in RVF reactor.

4. Conclusion

The model described in this work is an early attempt to study numerically the plasma behavior in a RVF plasma reactor. Modelling the plasma in 3D is certainly a challenge, as the computational cost is very high. Thus, certain approximations have been made, but with a reasonable assumptions. Future steps will be towards CO_2 plasma chemistry and experimental validation of the reactor within the PLASMANT group.

5. Acknowledgements

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