Multi-physics simulation of microwave capillary discharge in Argon: towards comprehensive power balance

R. Brunovský[1], A. Obrusník[1,2], Z. Bonaventura[1], G. D. Stancu[3]

[1] *Department of Plasma Physics & Technologies, Masaryk University, Brno, Czech Republic*
[2] *PlasmaSolve s.r.o., Brno, Czech Republic*
[3] *Laboratoire EM2C, Centrale Supélec, L'Université Paris-Saclay, France*
rbrunovsky@mail.muni.cz

With growing environmental concerns, modern science increasingly focuses on processes that offer high efficiency in power conversion and usage. Microwave capillary plasma is notable for its high power densities (up to 10^5 W cm^{-3}) achieved with relatively low input powers [1]. In this work, we simulate Argon plasma generated in a surfatron, i.e., an electromagnetic wave-heated capillary discharge. One of the advantages of surfatron discharge is in its electrodeless configuration, which offers a great flexibility in operation conditions [1].

The microwave capillary discharge is simulated using the *COMSOL Multiphysics*. The multi-physics model comprises:

1. the microwave electromagnetic field,
2. an ambipolar plasma model for Argon including plasma chemistry processes,
3. the neutral Argon gas flow simulated by using fluid module.

The model is solved in 2D axisymmetric geometry. In fluid flow module, Navier-Stokes equations together with continuity equation are solved for velocity vector and density of the fluid [2]

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho\left(\boldsymbol{u}\cdot\nabla\right)\boldsymbol{u} = \nabla\cdot\left(-p\boldsymbol{I} + \boldsymbol{K}\right), \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\left(\rho\boldsymbol{u}\right) = 0, \tag{2}$$

where $\boldsymbol{u}$ is the flow velocity, ρ is the density of the liquid, p is pressure, $\boldsymbol{I}$ is the unit matrix and $\boldsymbol{K}$ is the stress tensor defined as

$$\boldsymbol{K} = \mu\left(\nabla\boldsymbol{u} + \left(\nabla\boldsymbol{u}\right)^{\mathrm{T}}\right) - \frac{2}{3}\mu\left(\nabla\cdot\boldsymbol{u}\right)\boldsymbol{I}, \tag{3}$$

where μ is the fluid viscosity. The pressure and velocity obtained from these equations serve as input parameters for the plasma module. In solving of the capillary flow, the flow is considered to be weakly compressible.

The electric field is solved by microwave module of *COMSOL Multiphysics* using the equation [2]

$$\nabla\times\mu^{-1}\nabla\times\boldsymbol{E} = \left(\omega^2\varepsilon_0\varepsilon_{\mathrm{r}} - j\omega\sigma\right)\boldsymbol{E}, \tag{4}$$

where ω is the angular frequency, ε_0 is permittivity of vacuum, ε_{r} is the relative permittivity and σ is conductivity. Within this context, it is also assumed that the ion motion can be neglected relative to the electron motion, due to the short timescale of microwave oscillations.

The evolution of electron density n_{e} is described by continuity equation [2]

$$\frac{\partial n_{\mathrm{e}}}{\partial t} + \nabla\cdot\boldsymbol{\Gamma}_{\mathrm{e}} = R_{\mathrm{e}}, \tag{5}$$

where $\boldsymbol{\Gamma}_{\mathbf{e}}$ represents electron flux and R_{e} denotes the electron source term accounting for electron gain and loss processes considered. Moreover, equation for energy density is solved [2]

$$\frac{\partial n_{\epsilon}}{\partial t} + \nabla\cdot\boldsymbol{\Gamma}_{\epsilon} + \boldsymbol{E}_{\mathrm{a}}\cdot\boldsymbol{\Gamma}_{\mathrm{e}} = S_{\epsilon} + Q_{\mathrm{rh}}/e, \tag{6}$$

where $\mathbf{\Gamma}_\epsilon$ represents energy flux density, $\boldsymbol{E}_\mathbf{a}$ is ambipolar electric field, S_ϵ is energy source term due to electron collision processes and [2]

$$Q_{\mathrm{rh}} = \frac{1}{2}\mathrm{Re}\left(\boldsymbol{J} \cdot \boldsymbol{E}^*\right), \tag{7}$$

is the electron heating by the microwave field with $\boldsymbol{J}$ representing the density of the electron current and * denotes the complex conjugate.

The geometry used in the simulation is shown in Fig. 1. Note that the geometry is similar to the one specified in [3]. The electron density distribution in the capillary for the pressure of 2000 Pa, and the absorbed microwave power of 61 W is shown in Fig. 2. Experiment results from [1] show that that only a low fraction of power, ranging between 4% to 20% is actually absorbed in the discharge itself. While the majority of the input power is, in fact, dissipated by other means. In this contribution we will study in detail the power balance in the microwave capillary discharge in various physical conditions. The ultimate goal is to compare the simulation results with experimental power balance determined by precise measurements that were published in [1].

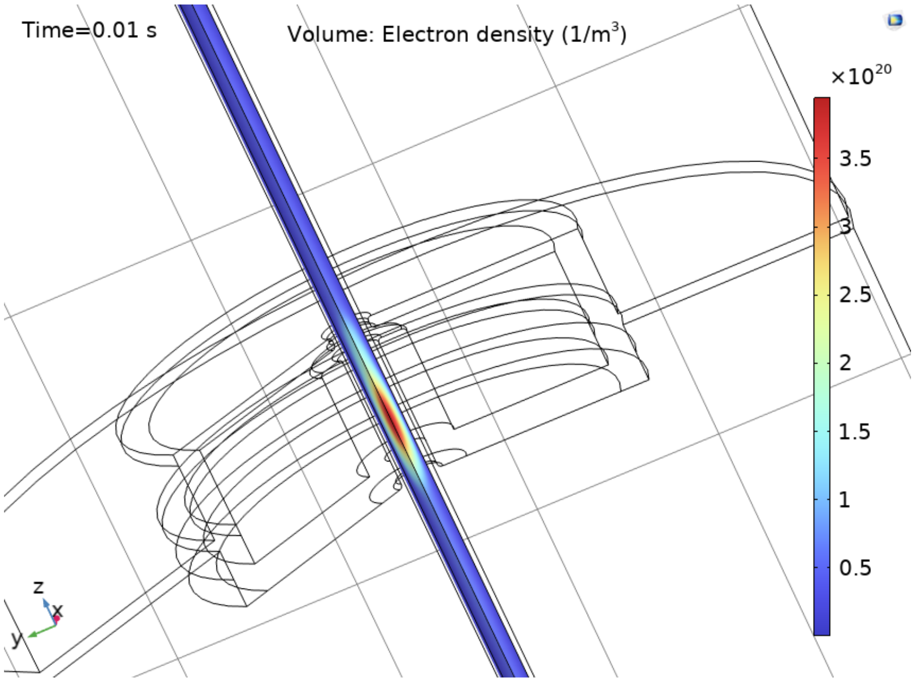

Fig. 1: Electron density in capillary at $p = 2000$ Pa and absorbed power $P_{\mathrm{abs}} \approx 61$ W visualised in 3D with entire surfatron geometry.

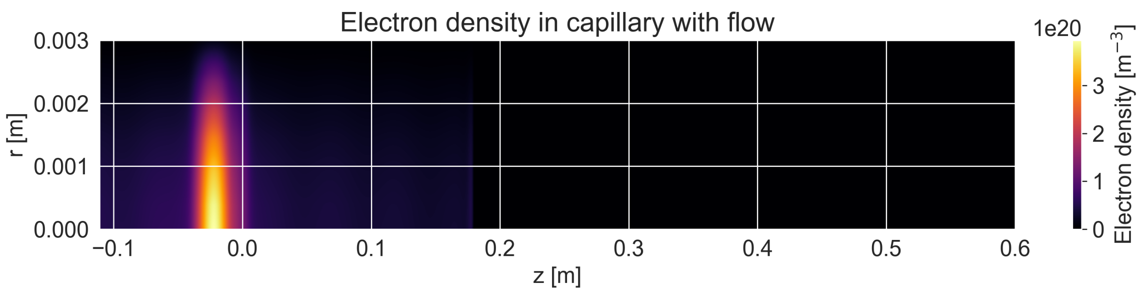

Fig. 2: Electron density in capillary at $p = 2000$ Pa and absorbed power $P_{\mathrm{abs}} \approx 61$ W.

[1] F Coquery et al, *Plasma Sources Sci. Technol.* **31** 055003 (2022).
[2] COMSOL Inc. Plasma module user's guide, version 6.1., www.comsol.com, (2022).
[3] M Jimenez-Diaz et al, *J. Phys. D: Appl. Phys.* **45** 335204 (2012) .