Numerical Modelling and Experimental Characterisation of Cascaded Arc Discharges in Argon and Hydrogen

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Introduction

A cascaded arc [1, 2] is used as the primary plasma source in Magnum-psi, a new device for plasma surface interaction studies that recently became operational in our institute.

The objective of this work is related to the generation and study of plasmas expected in the divertor region of future Tokamaks. It has also wide applications in the industry.

The arc is operated in argon and hydrogen and is placed inside a coil capable of generating a magnetic field of up to 1.8 Tesla. Apart from the cathode housing, the arc initially consisted of four plates with a central bore of 4 mm in diameter and a nozzle-shaped anode ring mounted on a 40 cm diameter low-pressure chamber, in which the plasma expands. The voltage-current characteristics of this arc have been measured in the absence and presence of a magnetic field of 0.4 Tesla. We have modified the arc geometry, starting with a narrower channel of 2mm diameter near the cathodes and a wider opening of 4mm diameter in the last plates and the anode ring. The arc is started in argon and hydrogen is added halfway along the arc. Such an arc is more stable in the presence of a magnetic field and the erosion of the cathode points by the hydrogen plasma is reduced. Characteristics of the modified arc will also be presented.

We report on modelling of the arc using the PLASIMO library developed at the Eindhoven University of Technology [3, 4], using a two-dimensional Non Local Thermal Equilibrium model.

Experimental data

The results, presented in Fig. 1, show that, as expected from earlier measurements, the addition of hydrogen to the argon flow significantly increases the voltage needed to sustain the arc. The potential variation along the arc for argon-hydrogen mixtures further indicates

that for low argon flows all argon ions are transferred into hydrogen ions by charge exchange. The electric field in all cases is nearly constant inside the arc, showing considerable changes only in the sheath regions of the cathodes and the anode ring. Applying a magnetic field enhances the power dissipation in hydrogen significantly, probably due to a constriction of the current conducting channel. In argon, however, this effect is almost absent.
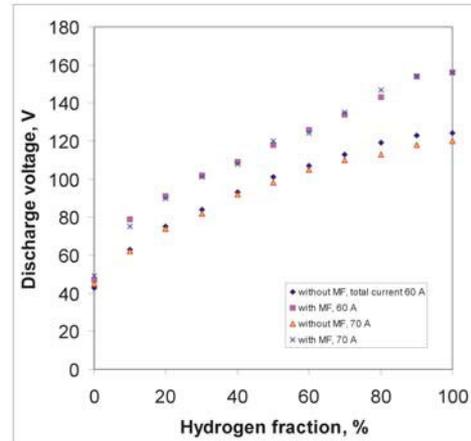
Fig.1: Potential vs hydrogen fraction

Description of the model

With the use of a two-dimensional hydrodynamical model, plasma processes in the arc are simulated. The governing equations in the model are:

- Particle balance equations: $\vec{\nabla} \cdot \left[n_h \vec{u} \right] - \vec{\nabla} \cdot \left[D_h \vec{\nabla} n_h \right] = S_h$

D_h and $\vec{u}$ are the diffusion coefficient of species h and the plasma bulk velocity, respectively, while S_h denotes the net production of species h due to the collisional-radiative processes

- Total mass conservation: $\nabla \cdot \left[\rho \vec{u} \right] = 0$

- Momentum balance (bulk plasma): $\left[\nabla \cdot \left(\rho \vec{u} \vec{u} \right) \right]_i = -\left(\vec{\nabla} p \right)_i + \left(\vec{\nabla} \cdot \tau \right)_i + \left(\vec{j} \times \vec{B} \right)_i$

where i denotes the axial or radial component.

- Energy balance for heavy particles (h): $\vec{\nabla} \cdot \left(\rho_h \varepsilon_h \vec{u} \right) + p_h \vec{\nabla} \cdot \vec{u} + \vec{\nabla} \cdot \vec{q}_h = \tau_h : \vec{\nabla} \vec{u} + Q_h$

where ε_h is the internal energy per unit mass of the heavy particle. The heat flux is $\vec{q}_h = -\lambda \vec{\nabla} T_h$ and Q_h denotes the energy gain or loss through elastic/inelastic reactions.

- Energy balance for electrons (e): $\vec{\nabla} \cdot \left(\rho_e \varepsilon_e \vec{u} \right) + p_e \vec{\nabla} \cdot \vec{u} + \vec{\nabla} \cdot \vec{q}_e = Q_{Ohm} + Q_e$

Q_{Ohm} is the energy gain through Ohmic heating.

- Equation of state: $p = \sum_{\alpha} p_{\alpha}$ with $p_{\alpha} = n_{\alpha} k_b T_{\alpha}$

where k_b is the Boltzmann constant. All other parameters have their usual meanings.

Plasma Source Geometry:

The gas is fed from the cathode side into the Cascaded Arc where it is ionized by the applied current. The plasma flows through the channel of diameter 2mm and then it enters in the 4mm diameter region, is accelerated and expands internally as shown in Fig. 2, where the pressure and ion density inside the arc are plotted. Finally the plasma leaves the arc and expands at the anode side into the vacuum chamber at low pressure. The length of the channel is 45 mm. For the simulation we took a specific part of the arc in such a way that the west boundary is located at the first cascade plate. The east boundary is located at the outlet of the arc. The north boundary is formed by channel wall and the south boundary is the symmetry axis. Note that the individual character of the plates is not considered. A grid of 16 radial × 64 axial points is used. It is also assumed that the electric field is zero in the radial direction and that the axial field has no radial dependence.
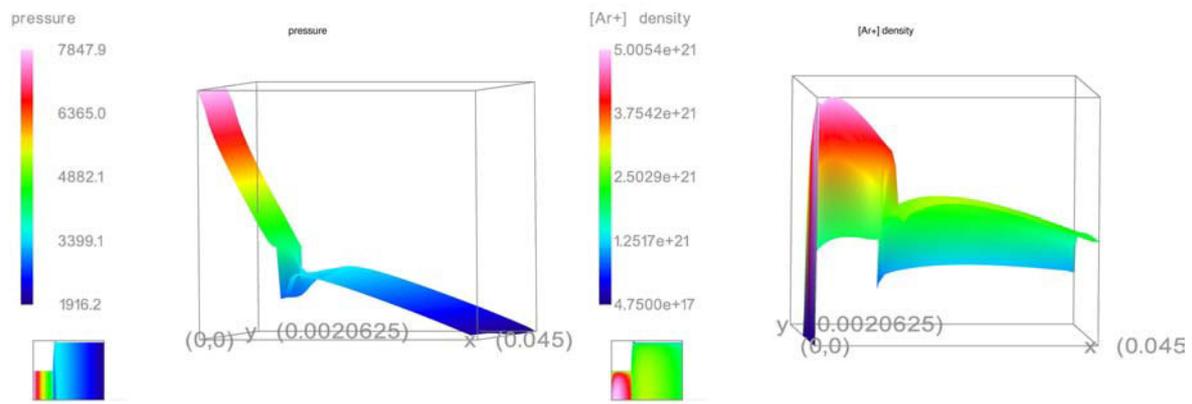

Fig.2: Pressure and ion density profile for Ar with 60 A current and 0.5 SLM.

Results and Discussion

In Fig. 2 the pressure and ion density inside the arc are plotted for Ar gas. The pressure decreases abruptly due to internal expansion and re-establishes itself when entering the 4 mm region from the 2 mm channel. The density of the Ar^+ ions is also higher in the 2 mm diameter region but is reasonably high at the outlet (10^4 times the inlet). Fig 3 shows the
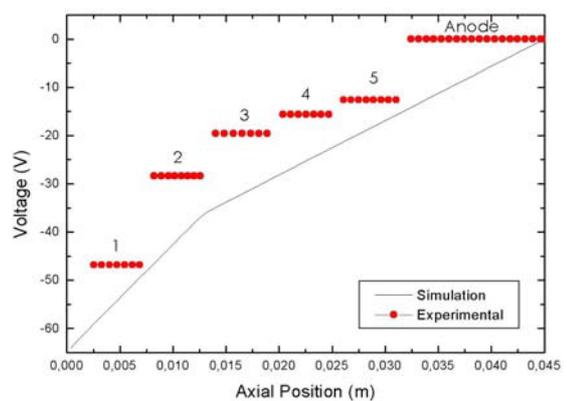

Fig.3: Comparison of experimental and simulation values of voltage vs axial position for 0.5 SLM and 60 A.

measured electric potential at different plates and results from the simulation. The circles indicate the width of each plate and the anode. The experimental and simulation values are reasonably in agreement.

Fig 4. shows the E-field for the straight Arc (4 mm diameter and 41 mm length) for 60 A current, for Argon and Hydrogen. From the figure we can see that experimental values are higher than

Fig. 4: Comparison of experimental and simulation values of E-field for argon and hydrogen.

the simulation values for hydrogen. One of the reasons is that in simulation we use 2.5 SLM flow and in the experiment we use 3.5 SLM flow.
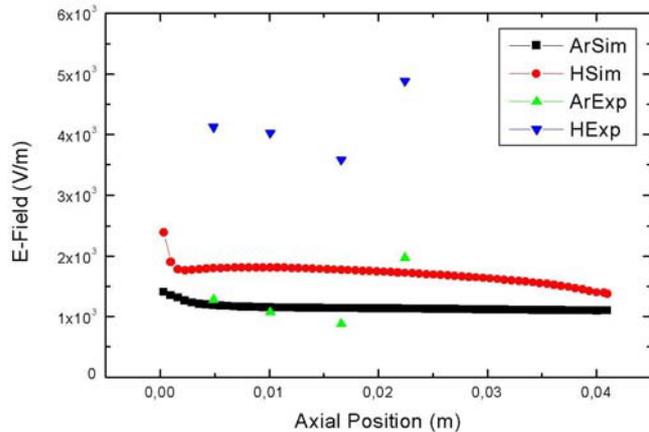
Conclusions and Future research

Our first results show good agreement with experiments in argon without a magnetic field. The next steps will be inclusion of hydrogen, the influence of the magnetic field, and further modifications of the Arc geometry. An extensive comparison with the experiments will be made to validate the model.

In the near future we will also include the pinching effect due to current as well as the axial magnetic field applied on Magnum-psi.

Acknowledgements

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