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A 2D Model of a DC Plasma Torch

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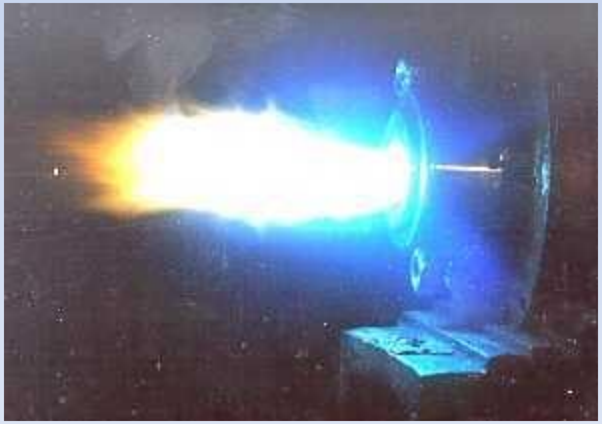
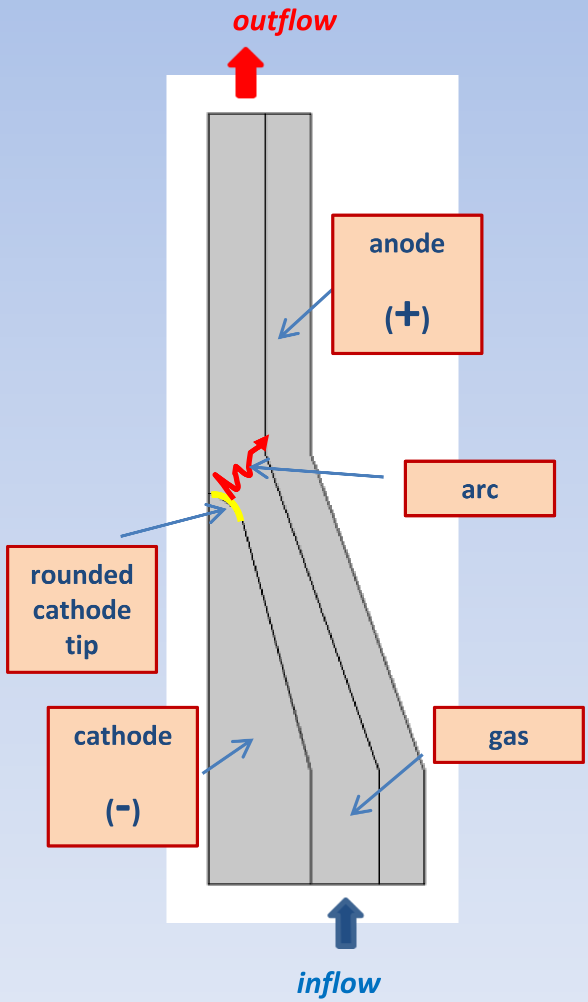
Presentation overview

- DC plasma torch and modeling
- Simplifying assumptions and physical model
- Equations
- Boundary conditions
- Numerical results
- Conclusions



DC plasma torch and modeling

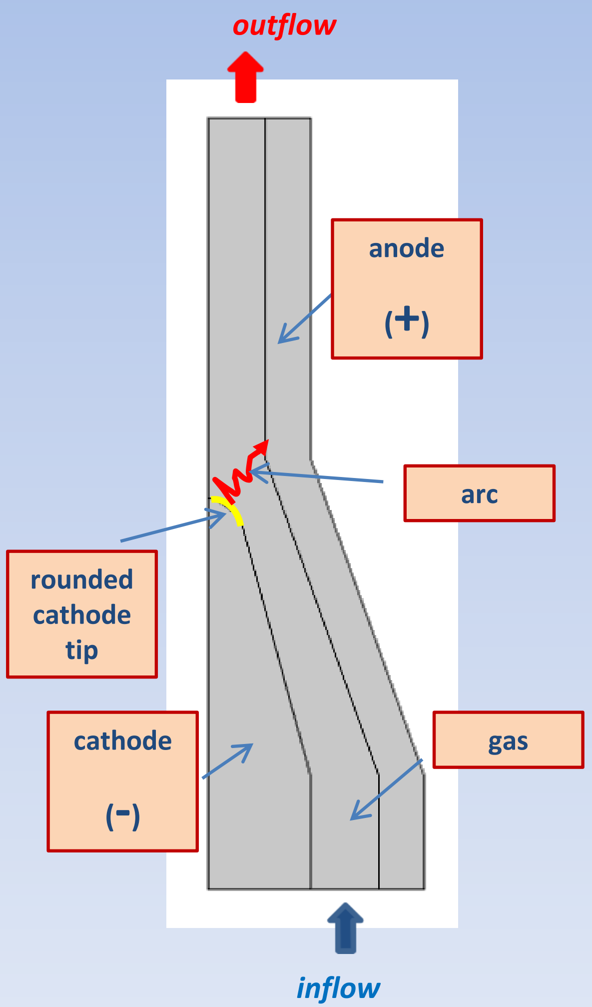


- Direct currents (DC) arc plasma torches represent the primary components of thermal plasma processes (plasma spraying, metal welding and cutting, waste treatment, biogas production, etc.).
- In a non-transferred arc plasma torch, an electric arc can be glowed by applying a direct current (DC) between the cathode and anode, both placed inside the torch.
- Then, the plasma is obtained by heating, ionizing and expanding a working gas, flowing into the torch upstream of the cathode.
- Due to the cooling of the anode, the gas close to the anode surface is cold, electrically no conductive, constricting the plasma.

$\Rightarrow$ ***gas temperature:*** $> 10^4\,\mathrm{K}$

gas velocity: $> 10^2\,\mathrm{m/s}$

DC plasma torch and modeling



The modeling of the DC arc plasma torches is extremely challenging:

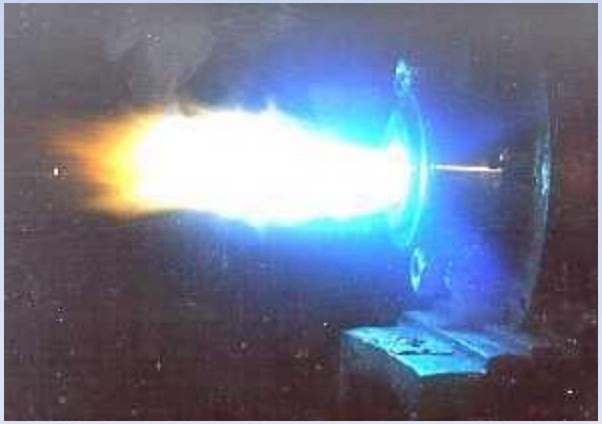
- plasma constituted by ***different species*** (molecules, atoms, ions and electrons)
- several ***coupled phenomena*** due to the interaction between electric, magnetic, thermal and fluid flow fields
- ***highly nonlinear*** plasma flow, presence of ***strong gradients*** and chemical and thermodynamic ***nonequilibrium effects***

Joule heating

$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

Lorentz force

$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$$



Simplifying assumptions and physical model

- The DC plasma torch region is 2D, the plasma flow is assumed axisymmetric and in a steady state.

- We doesn't consider either the formation of the electric spot on the anode surface and the arc reattachment process on the same anode (in 2D the electric spot is annular, while the arc reattachment is strictly a transient phenomenon).

- We assume conditions of local thermodynamic equilibrium (LTE), then the electrons and heavy particles temperatures are equal.

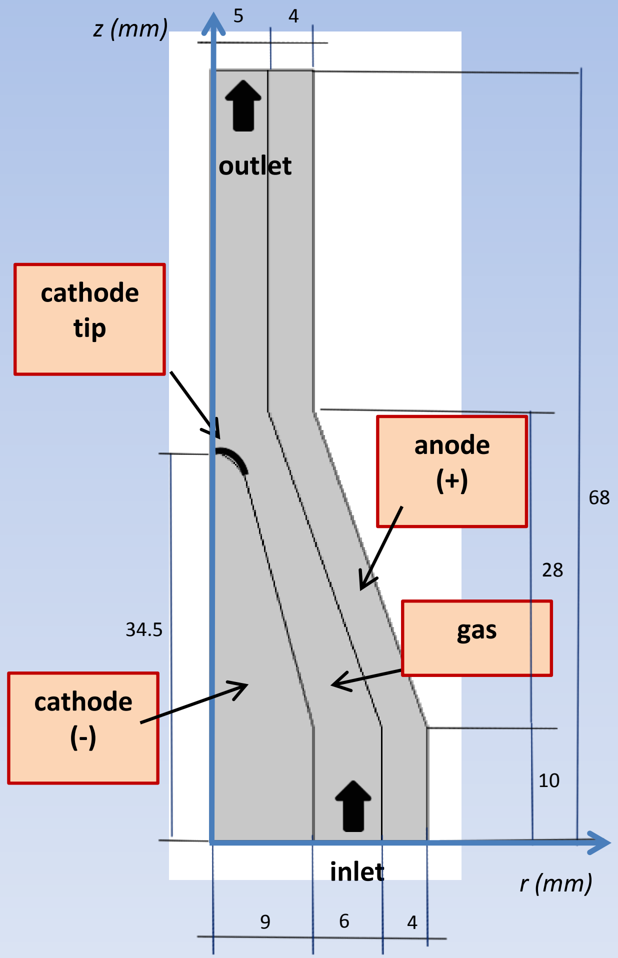
Simplifying assumptions and physical model (cont.)

- The plasma is modeled by using the magnetohydrodynamics equations.
- The plasma is considered optically thin and a net emission coefficient is used for the heat transferred by radiation mechanisms.
- The plasma is considered as a weak compresible gas (Mach number < 0.3).
- Free vortex flow is set at the inlet.
- The working gas is argon, copper is the material both of the anode and the cathode.

Equations: electric currents, magnetic fields, heat transfer and laminar flow

The modeling of the DC arc plasma torch is implemented in Comsol® by using the physics of the following modules:

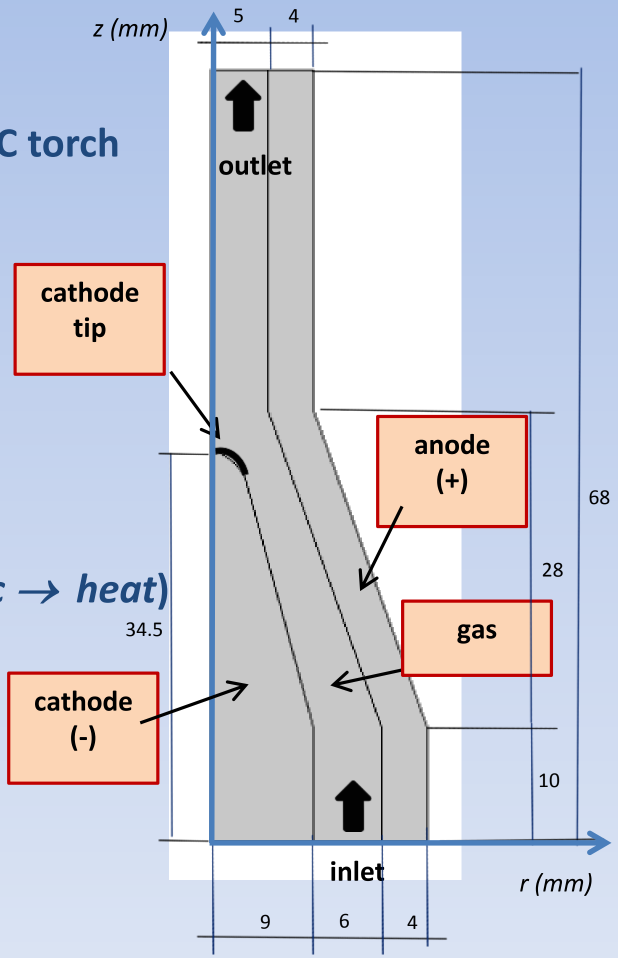
- Plasma module (*Equilibrium Discharges Interface*)
- AC/DC module (*Electric currents, Magnetic fields*)
  rounded cathode tip, argon and anode
  using the vector magnetic potential A : $\nabla \times \mathbf{A} = \mathbf{B}$
  and the electric potential *V* $\mathbf{E} = -\nabla V$
- Heat Transfer module (*Heat transfer in fluids/solids*)
  cathode, argon and anode
- CFD module (*Laminar flow)*
  argon



Equations: multiphysics couplings

Moreover, the coupling phenomena of the plasma flow in the DC torch are represented by setting in Comsol ® :

- plasma heat source (*electric* → *heat*)
- static current density component (*electric* → *magnetic*)
- induction current density (*magnetic* → *electric*)
- Lorentz forces (*magnetic* → *fluid flow*)
- boundary plasma heat source (rounded cathode tip) (*electric* → *heat*)
- boundary plasma heat source (anode) (*electric* → *heat*)
- temperature couplings
  (*heat* → *electric, heat* → *magnetic, heat* → *fluid flow*)



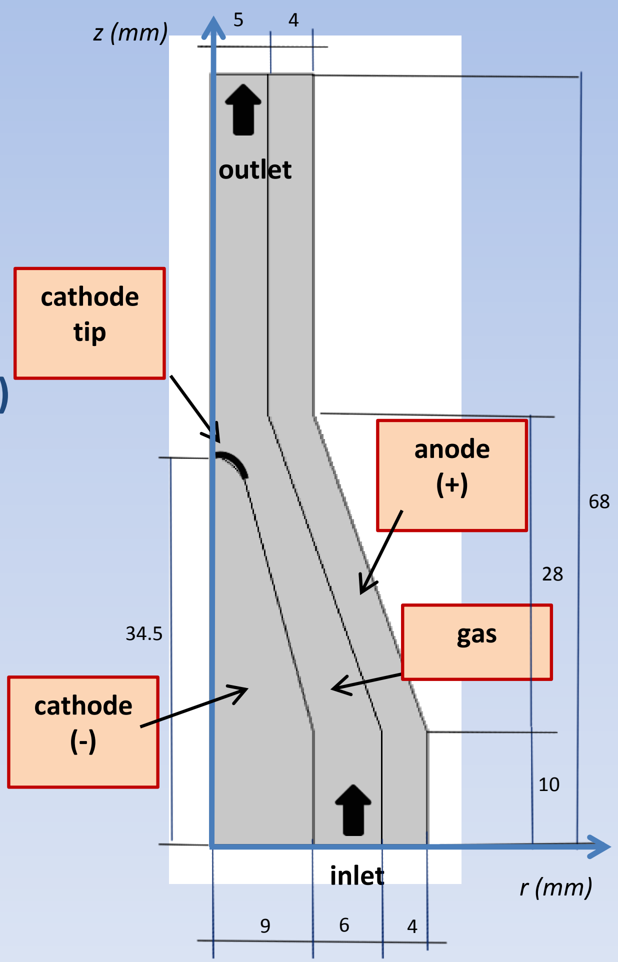
Boundary conditions

Electric currents

- constant current density of -10^7 A/m^2 used on the rounded cathode tip, where the temperature is set to a value of 3500 K (thermionic emission)
- the external anode wall is grounded (electric potential = 0 V)
- axial symmetry on the *z* axis, the other surfaces are electrically insulated $\mathbf{n} \cdot \mathbf{J} = 0$

Magnetic fields

- magnetic potential A fulfills the condition $\mathbf{n} \times \mathbf{A} = 0$ on the boundaries (magnetic insulation) and the axial symmetry on the *z* axis;
- a gauge fixing Ψ_0 = 1 A/m field is used for a A



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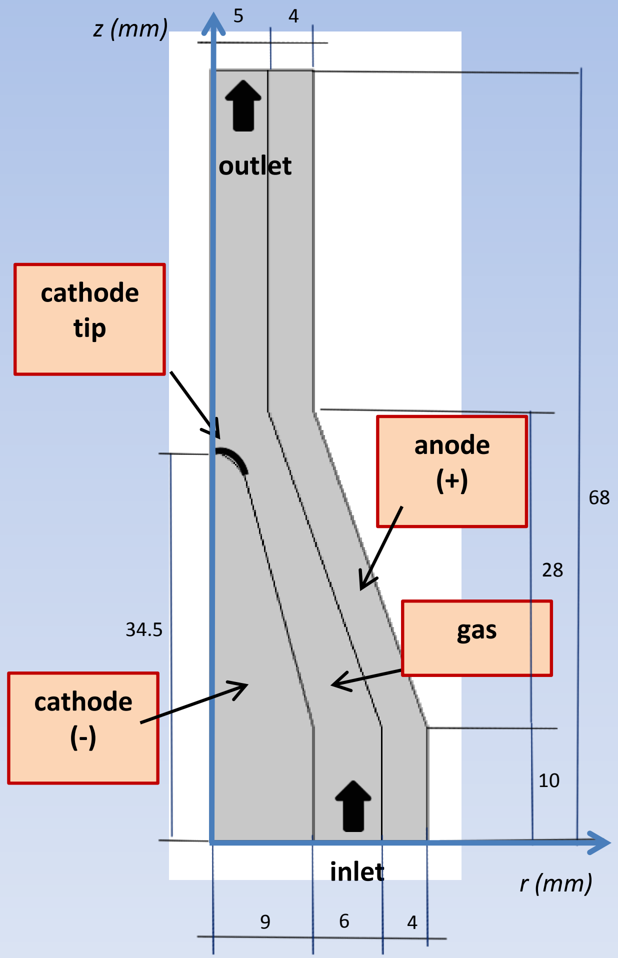
Boundary conditions (cont.)

Heat transfer

- the anode is externally cooled: $h = 10^4$ W/(m² K), $T_{ext} = 500$ K
- axial symmetry on the *z* axis
- the cathode tip has a temperature of 3500 K and the temperature of argon at the inlet is 300 K
- the other surfaces are insulated $-\mathbf{n} \cdot \mathbf{q} = 0$
- prescribed radiosity (gray body) on the internal surfaces

Fluid flow

- free vortex flow at the inlet $v_\theta = k_1 / r$
  k_1 is varied : $81 \times 10^{(-3)}$ m²/s, $67.5 \times 10^{(-3)}$ m²/s, $54 \times 10^{(-3)}$ m²/s
  $v_z = 4$ m/s, $v_r = 0$ ($0.175 \times 10^{(-2)}$ kg/s of argon)
- no slip on the walls
- pressure is set to *0* at the outlet



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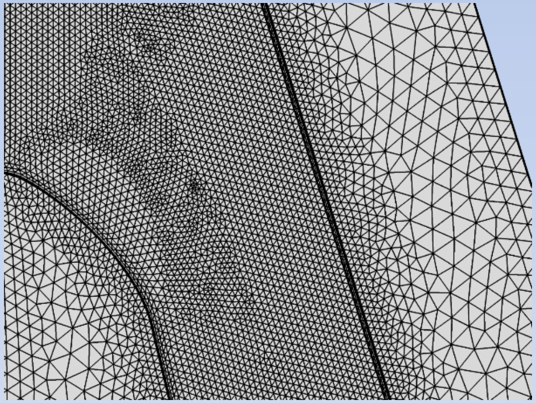
Solution with Comsol Multiphysics ®

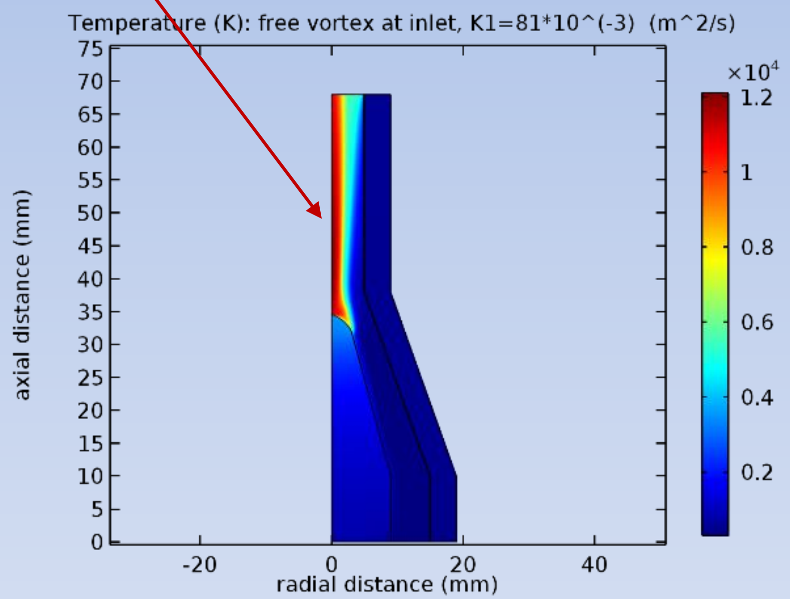
- meshing with nearly 7×10^4 triangle elements, mesh refinement in the plasma region and close to the walls DoFs are 9.2×10^5
- using a fully coupled approach, the MUMPS direct solver is selected
- parametric sweep study of the heat source term is set in order to improve the convergence of the computations
- computational model was run in a workstation with Intel Xenon CPU E5-2687W v2 16 cores, 3.40 GHz (2 processors), 216 GB RAM, 64bit and Windows 7 Operative System
- solution time was approximately of 34600 s



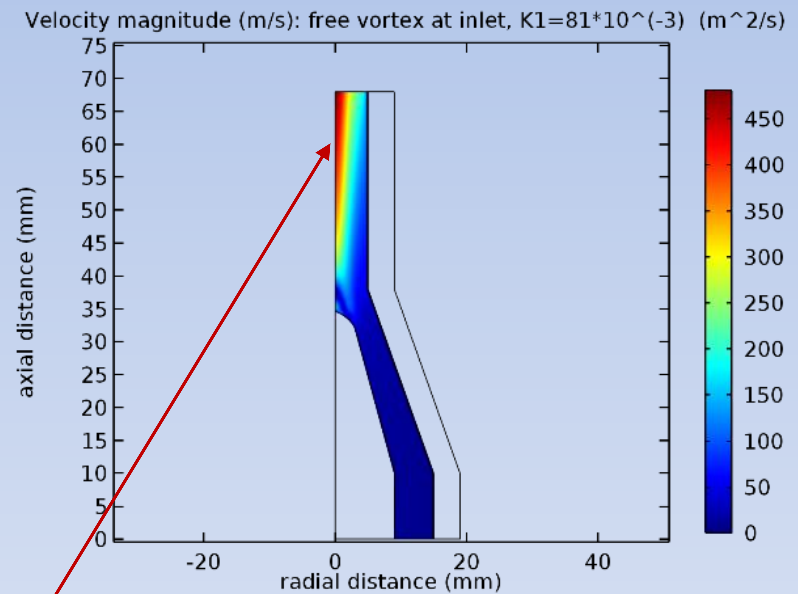
partial view of the mesh

Numerical results: temperature and velocity magnitude

arc column of argon gas, heated, ionized and expanded by the Joule heating



$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$



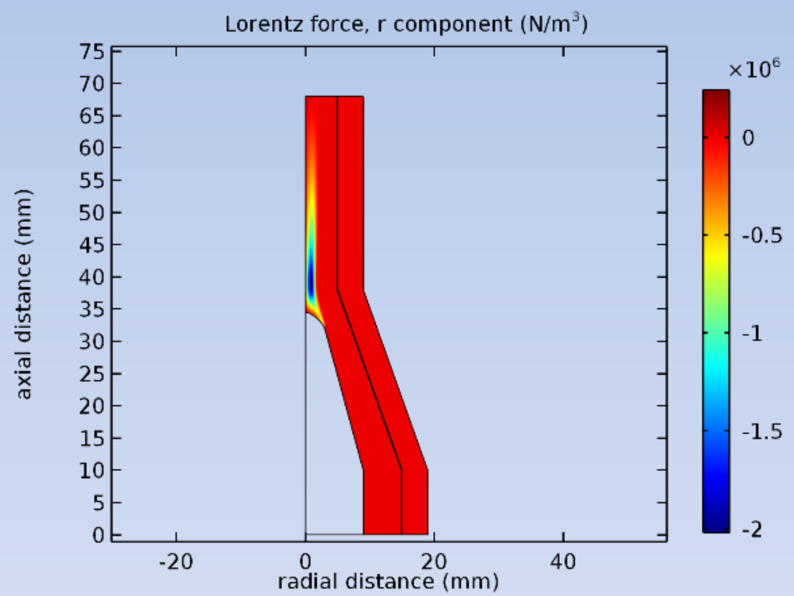
velocity distribution resulting from both the gas expansion and acceleration, the latter one due to the Lorentz force

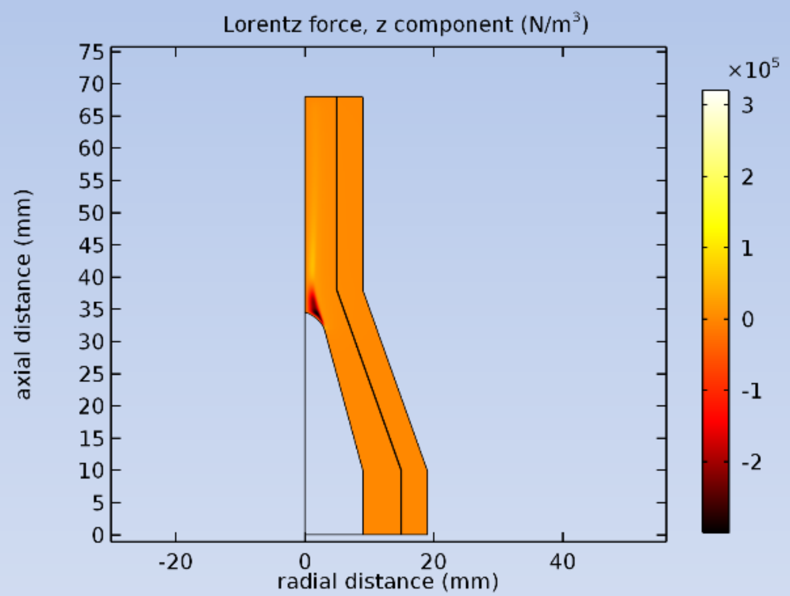
$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$$

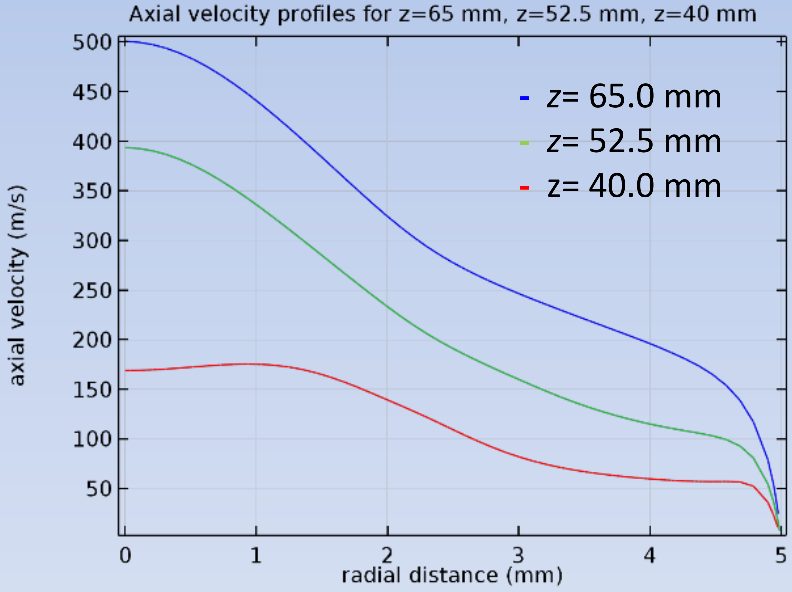
Numerical results: Lorentz forces in the plasma torch

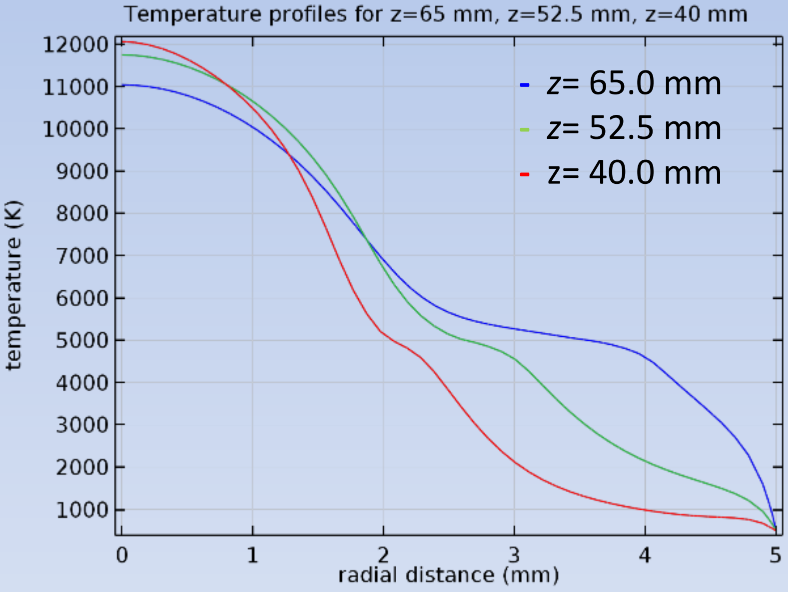
$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$$





Numerical results: radial profiles of axial velocity and temperature

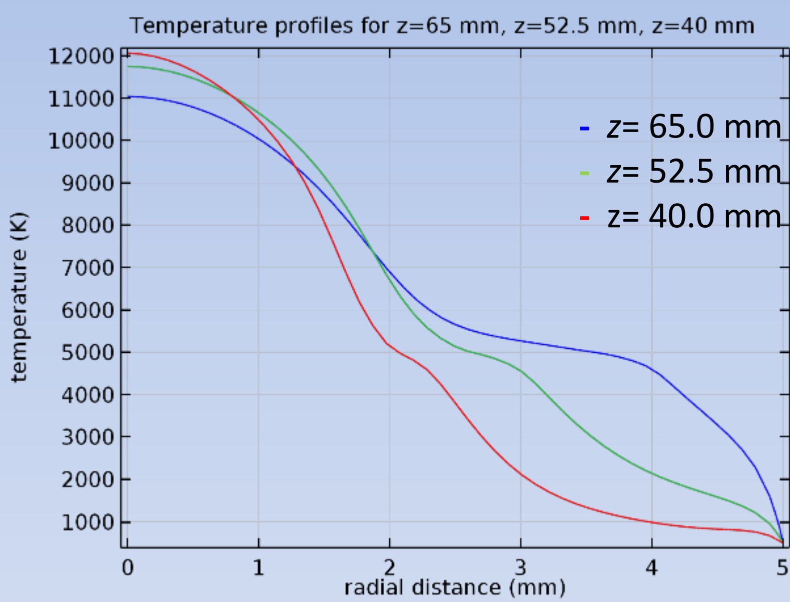


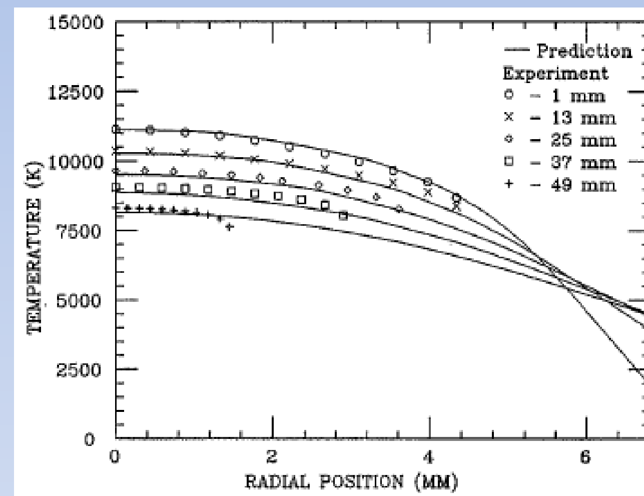


magnitude of the axial velocity increases with increasing distance from the cathode tip

magnitude of the temperature decreases with increasing distance from the cathode tip

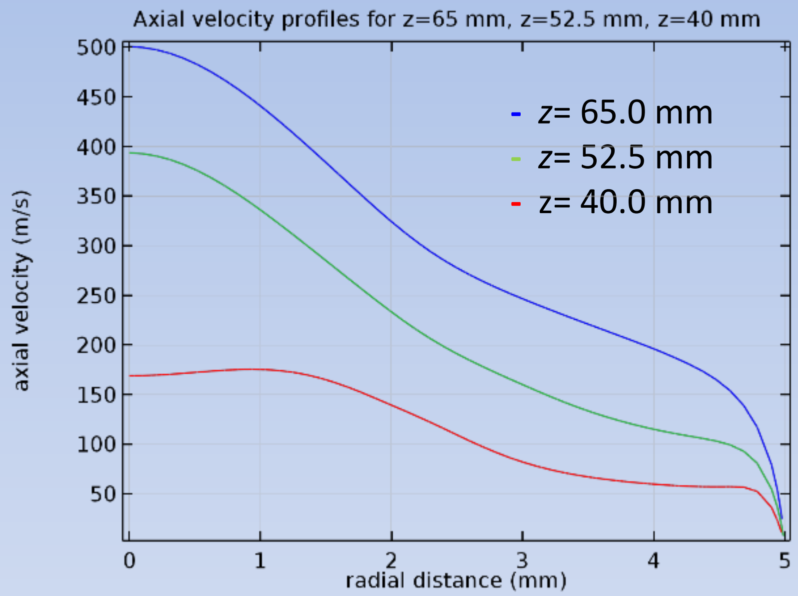
Numerical results: variation of the temperature in the plasma torch

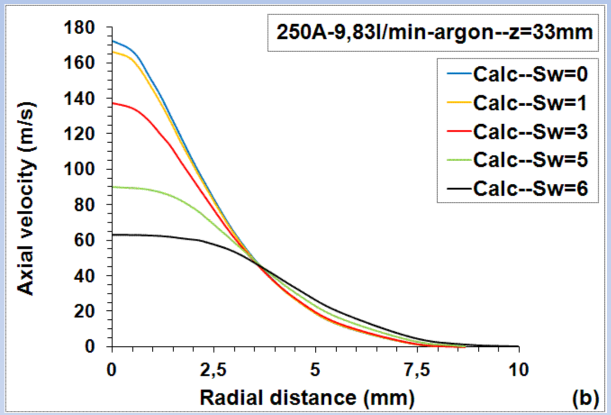




Dilawari et al. [12]

Numerical results: variation of the axial velocity in the plasma torch





Felipini and Pimenta [13]

with variation of the inlet swirl

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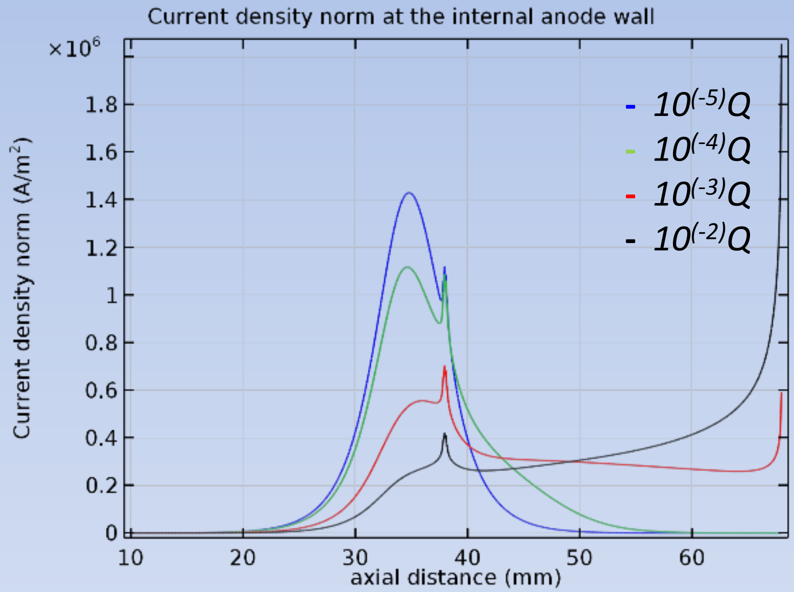
Variation of the current density with *Q*, at the inner anode wall



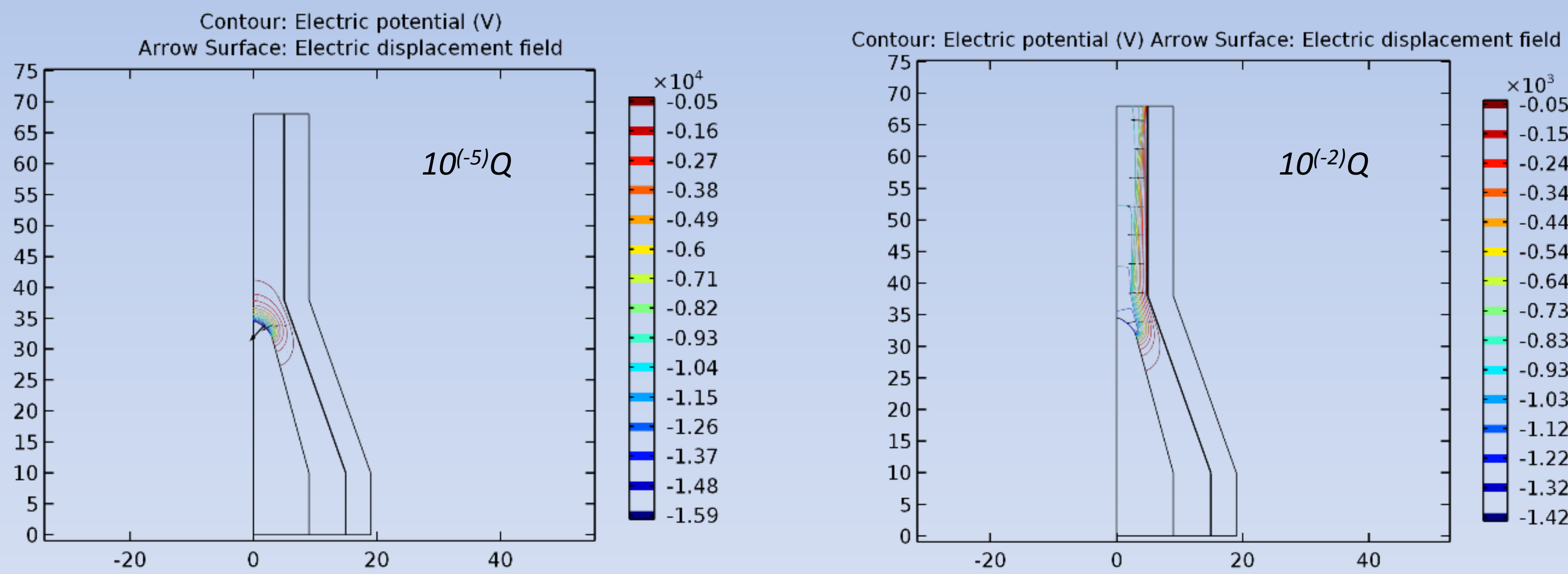
Evolution of the current density normal to the anode wall computed with the parametric study for the heat source term *Q*;

by proportionally reducing the heat source term, which accounts also for the Joule heating effect in the energy conservation equation.

The maximum current density would correspond to the arc root attachment at the inner anode walls (*Deng et al.,* [5]).

With increasing *Q* the electric current moves forward.

Variation of the electric potential and electric displacement field with *Q*



Electric potential and electric displacement field for the reduced heat terms $10^{(-5)}$ *Q* and $10^{(-2)}$ *Q*.

Dependence of fluid-electric phenomena on the parametrized heat source term is evident.

Conclusions

- A DC plasma torch has been modeled and simulated by developing a 2D model of laminar flow, heat transfer and electromagnetic fields.
- To solve the partial differential equations of electric currents and magnetic fields, both in the gas than in the anode region, specific boundary conditions have been used.
- Lorentz forces and Joule heating effects have been modeled, coupled to the physical model and computed.
- The numerical results of the gas temperature and axial velocity result to be quite satisfactory.
- We foresee to develop a more complete reproduction of thermal and fluid phenomena in a 3D model, but computational requirements and computing times should be also taken into account.

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