TEC Tecnológico de Costa Rica

Modeling a DC plasma torch with Comsol Multiphysics

B. Chinè[1], M.F. Mata[2] and I. Vargas[3]

[1] School of Materials Science and Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica;
[2] School of Electromechanics Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica;
[3] School of Physics, Costa Rica Institute of Technology, Cartago, Costa Rica.

bchine@itcr.ac.cr

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Presentation overview

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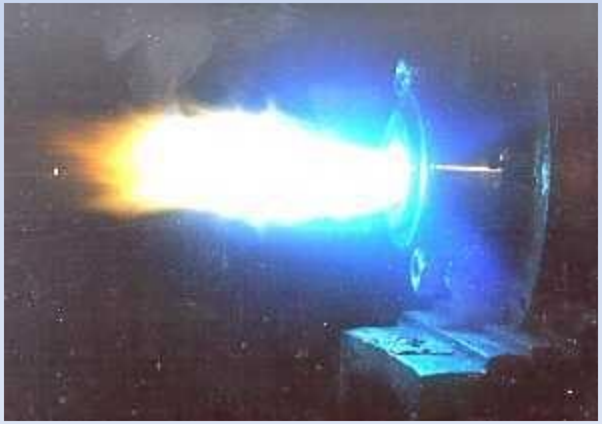
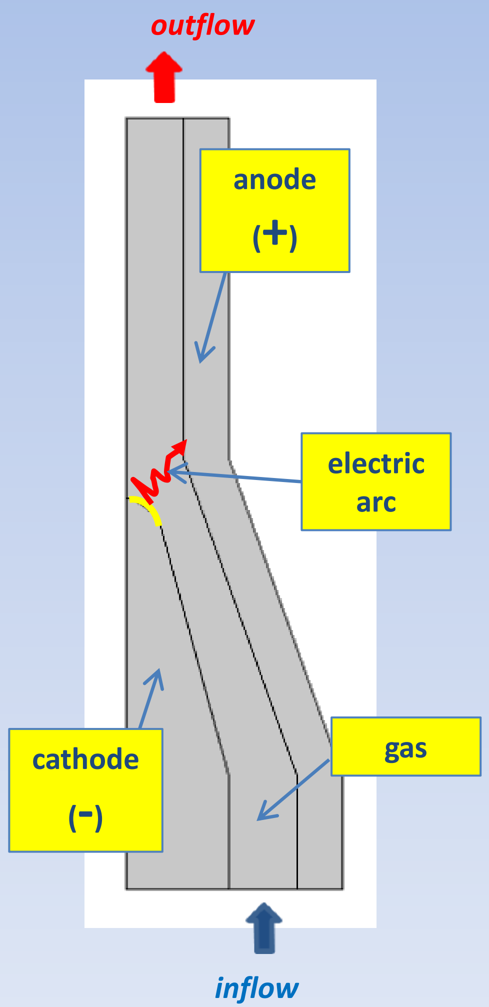


DC plasma torch and modeling [1,2,8,9,10]

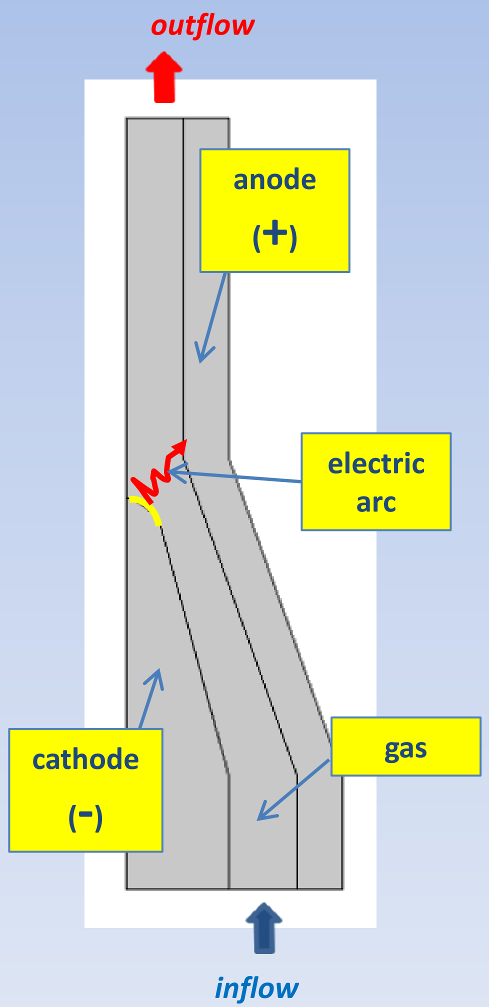


- Direct currents (DC) arc plasma torches represent the primary components of thermal plasma processes (plasma spraying, metal welding and cutting, waste treatment, biogas production, etc.).
- In a non-transferred arc plasma torch, an electric arc can be glowed by applying a direct current (DC) between 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:*** $> 10^4\,\mathrm{K}$

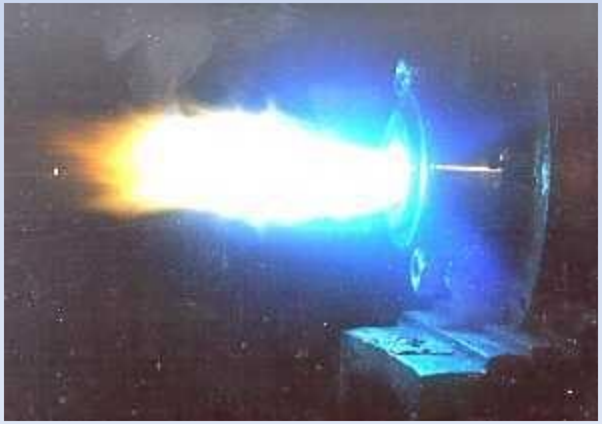
gas velocity: $> 10^2\,\mathrm{m/s}$

DC plasma torch and modeling [1,2,8,9,10]



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***



Simplifying assumptions and physical model

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

- Although the model concerns a non-transferred torch, in this first step:

  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 would be 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).
- Swirling 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

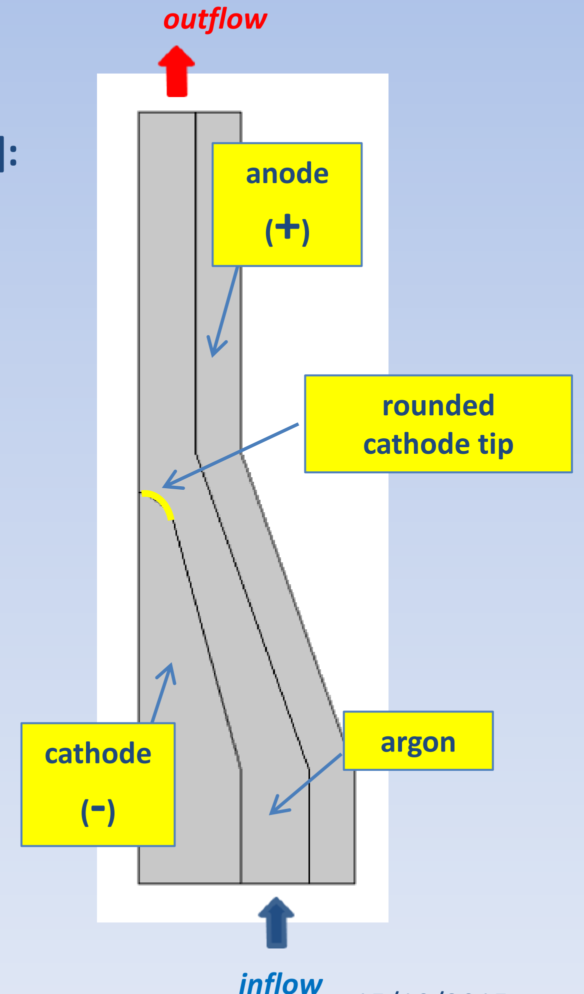
The modeling of the DC arc plasma torch is implemented in Comsol by using the physics of the following modules [4,5,6,7]:

- **Plasma Module (*Equilibrium Discharges Interface*)**

- **AC/DC module (*Electric currents, Magnetic fields*)**
  rounded cathode tip, argon and anode
  using the magnetic vector potential A : $\nabla \times \mathbf{A} = \mathbf{B}$

- **Heat Transfer module (*Heat transfer in fluids/solids*)**
  cathode, argon and anode

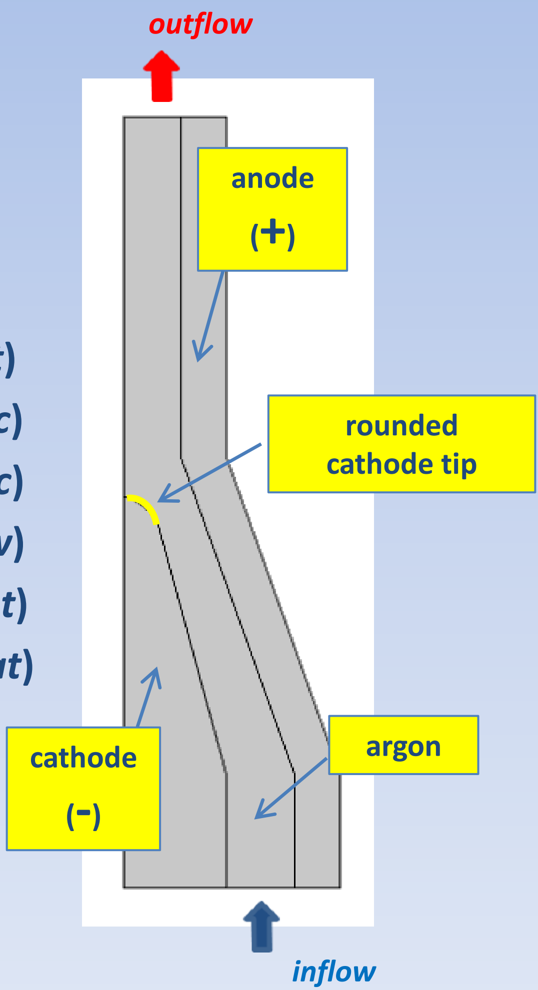
- **CFD modules (*Laminar flow)***
  argon



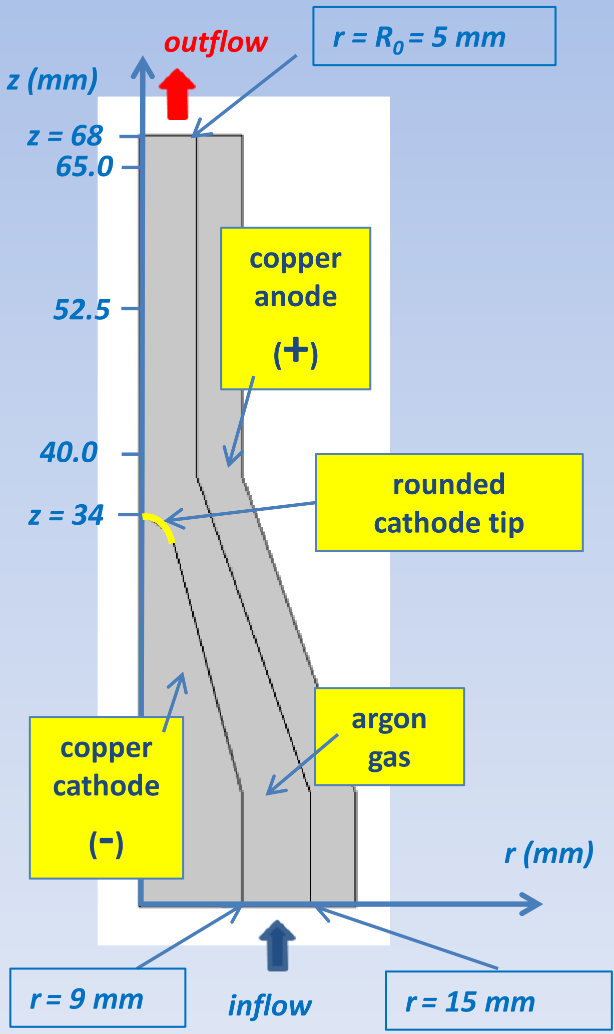
Equations: multiphysics couplings

Also, the coupling phenomena of the plasma flow in the DC torch are represented by setting in Comsol [4]:

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



Boundary conditions



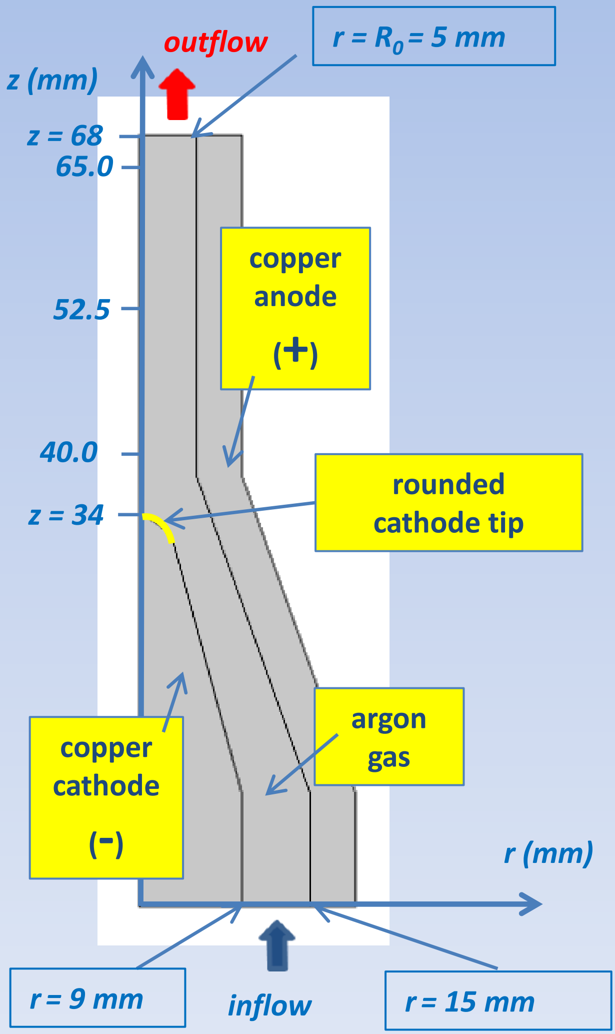
Electric currents

- 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 internal anode wall is grounded (electric potential = 0 V)
- axial symmetry on the *z* axis, the other surfaces are electrically insulated $\mathbf{n} \bullet \mathbf{J} = 0$

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

Boundary conditions (cont.)



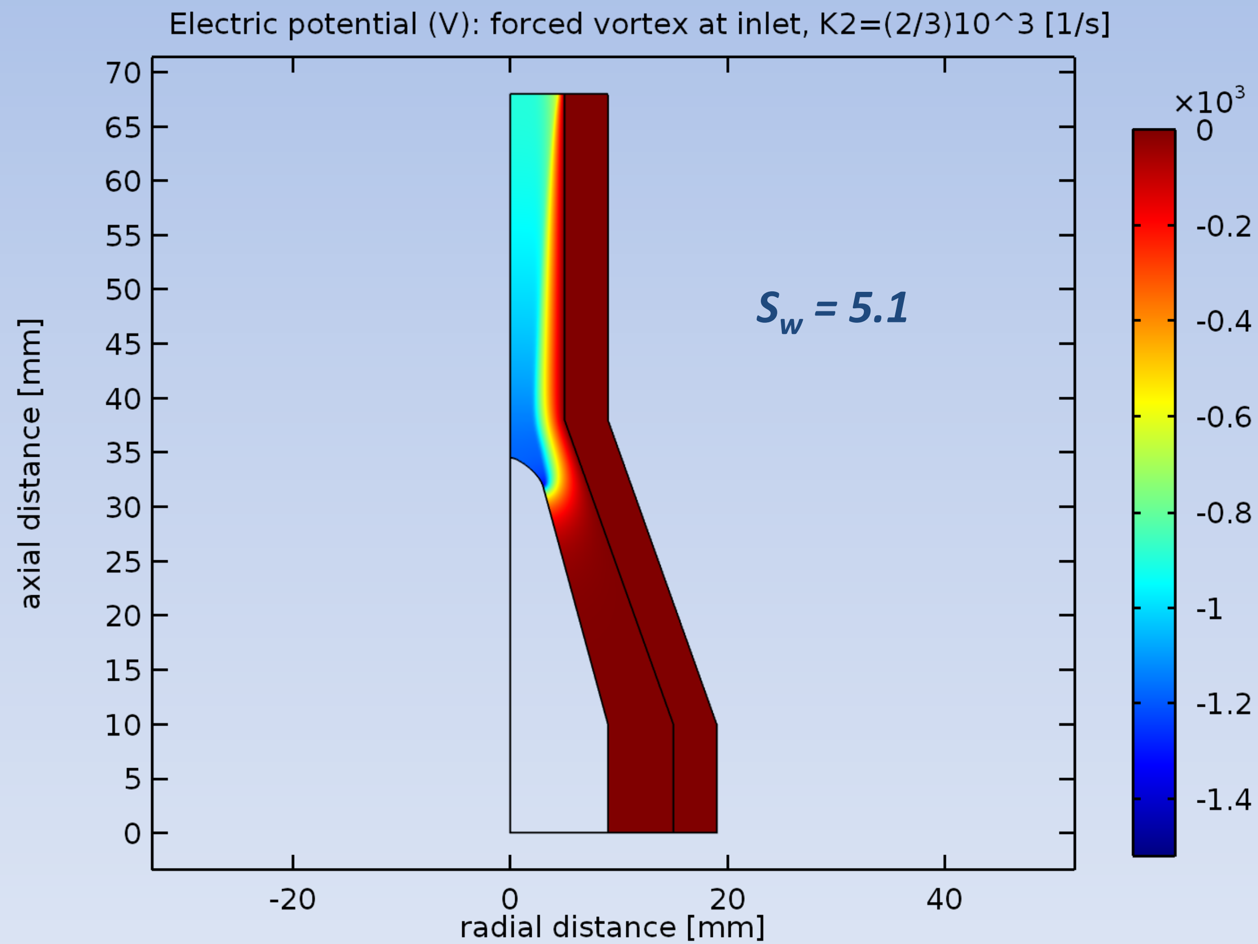
Heat transfer

- the anode is externally cooled: $h = 10^4\ W/(m^2\ K)$, $T_{ext} = 500\ K$
- 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
- prescribed radiosity (gray body) on the internal surfaces $-\mathbf{n}\cdot\mathbf{q}=0$

Fluid flow

- swirling flow at the inlet: *swirl number* $S_w = G_\theta / G_z R_0$
  $v_z = 4 m/s$, $v_r = 0$
  $v_\theta = k_1/r$ free vortex or $v_\theta = k_2 r$ forced vortex, k_1 and k_2 are variables
- no slip on the walls
- pressure is set to *0* at the outlet

Numerical results: electric potential in the plasma torch



$S_w = 5.1$

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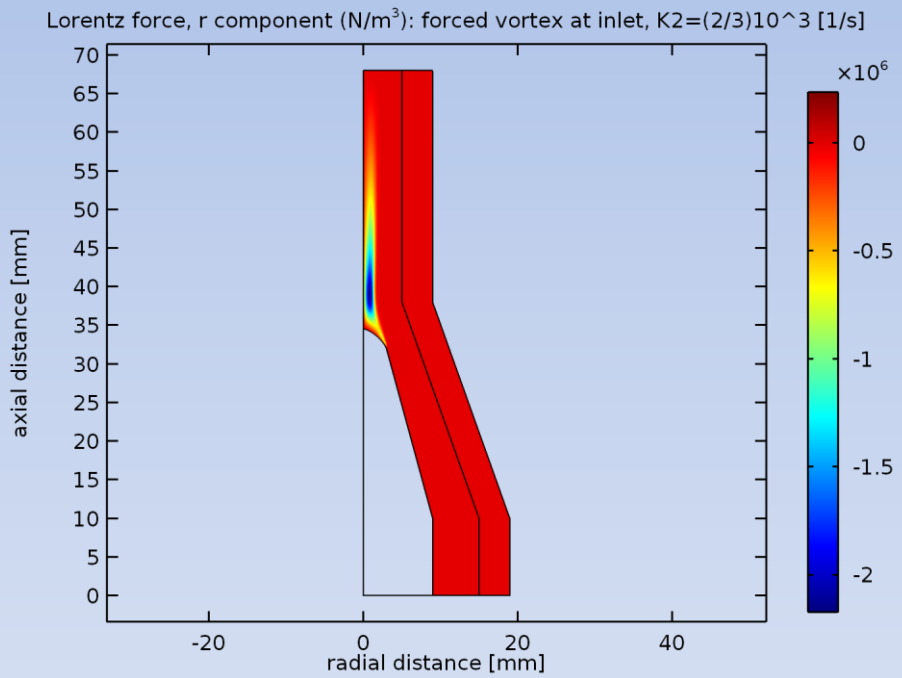
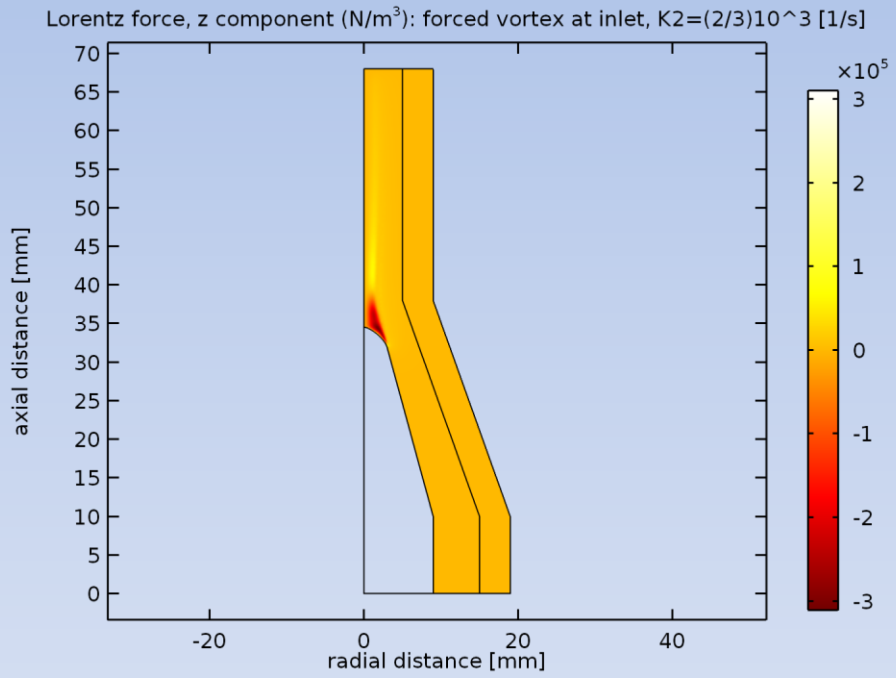
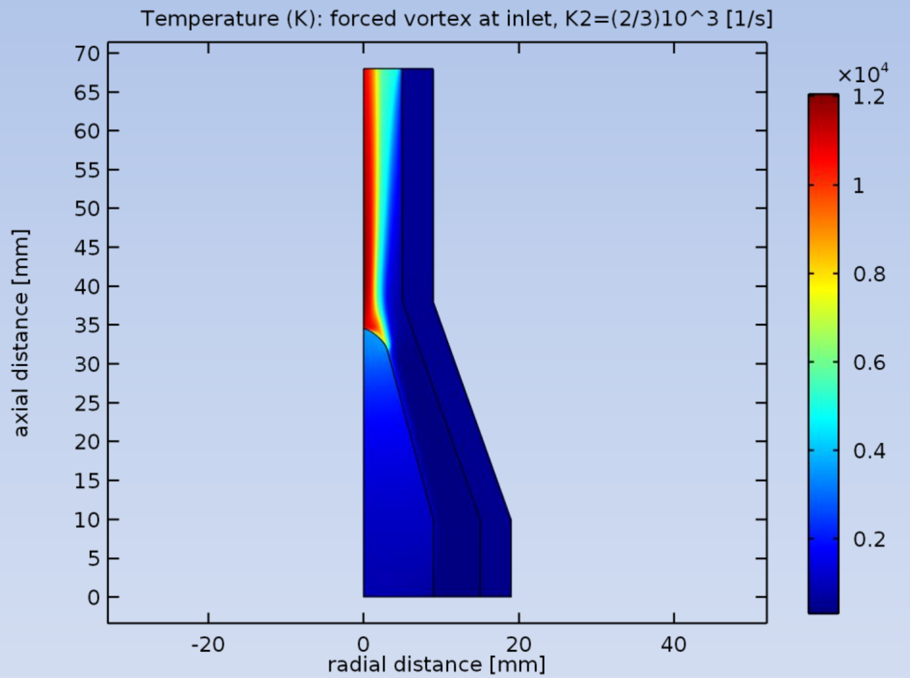
Numerical results: Lorentz forces in the plasma torch

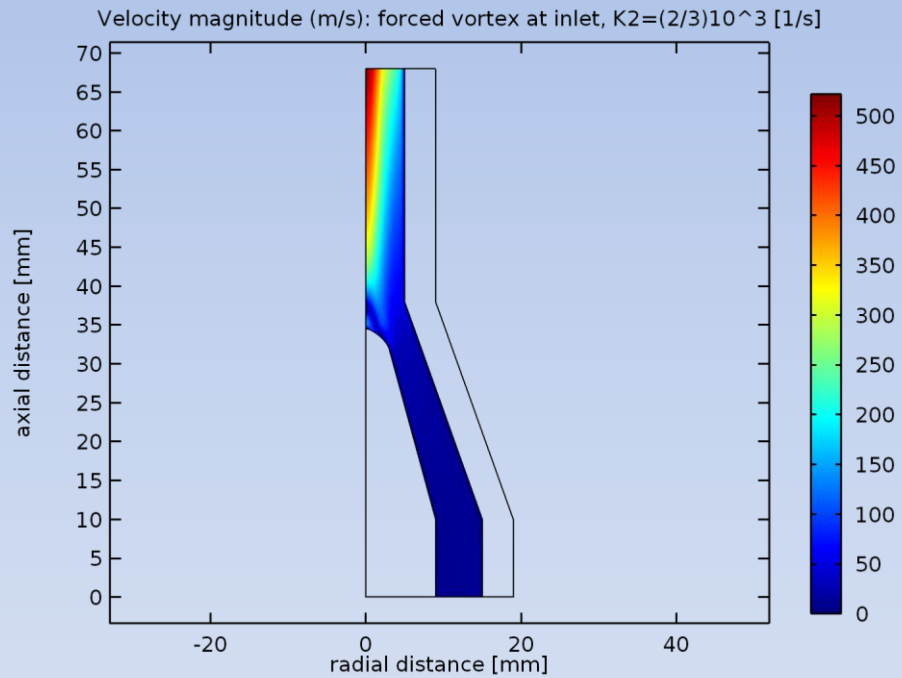




$S_w = 5.1$

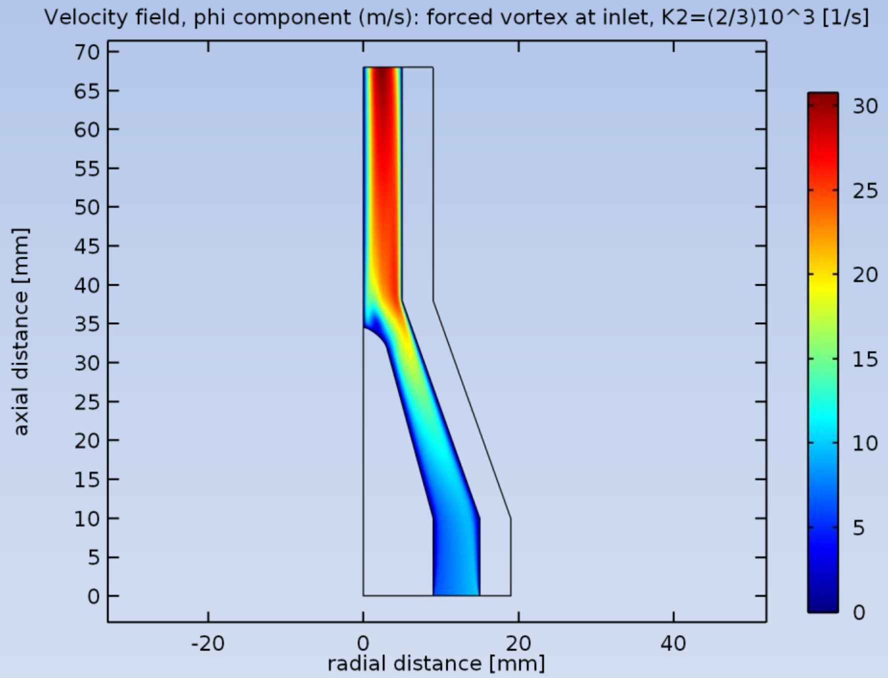
Numerical results: temperature and velocity magnitude

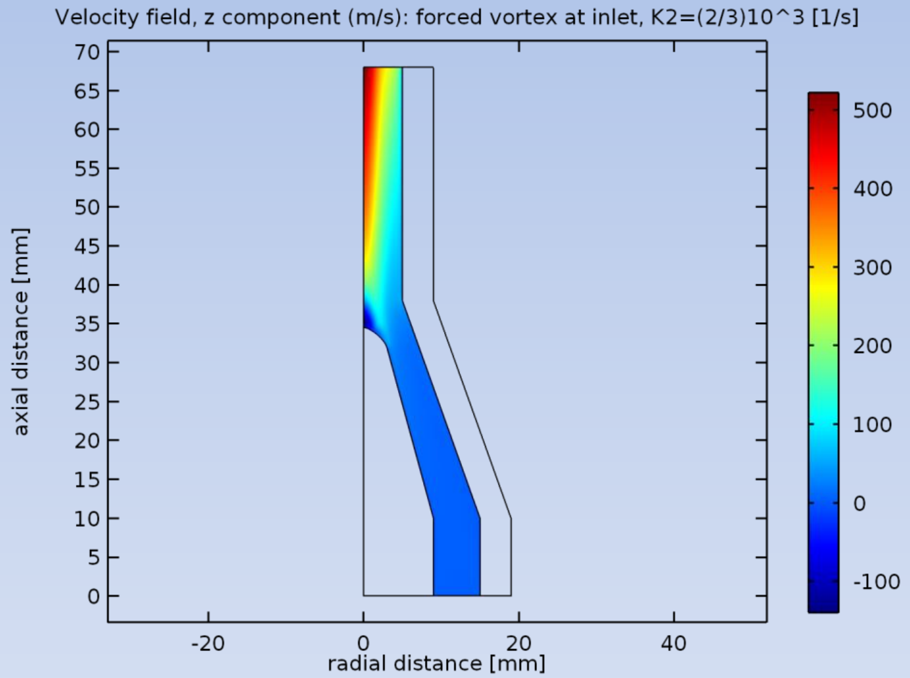




$S_w = 5.1$

Numerical results: velocity components



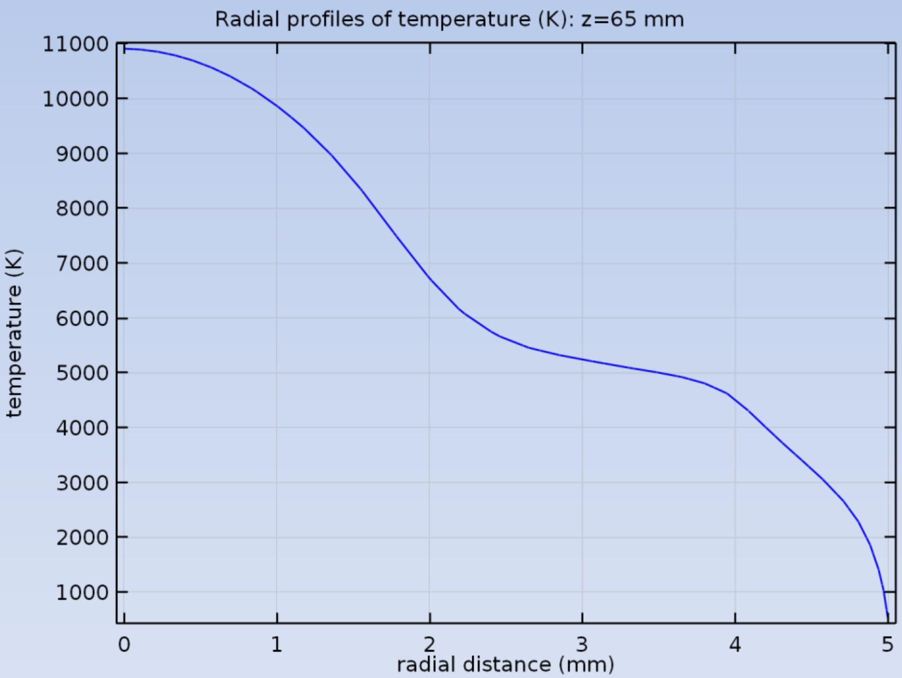


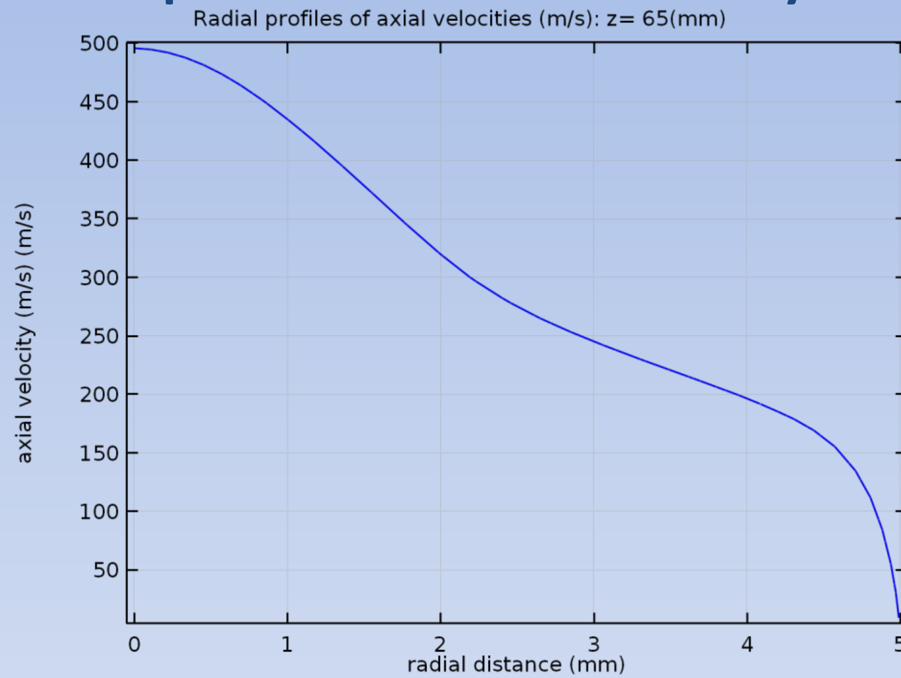
S_w = 5.1

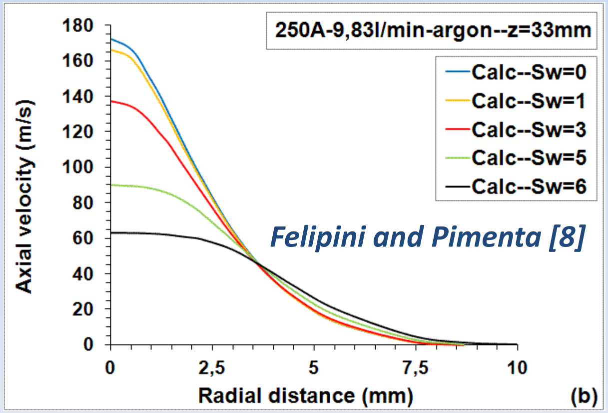
Numerical results: radial profiles of temperature and axial velocity

forced vortex flow

S_w = 5.1



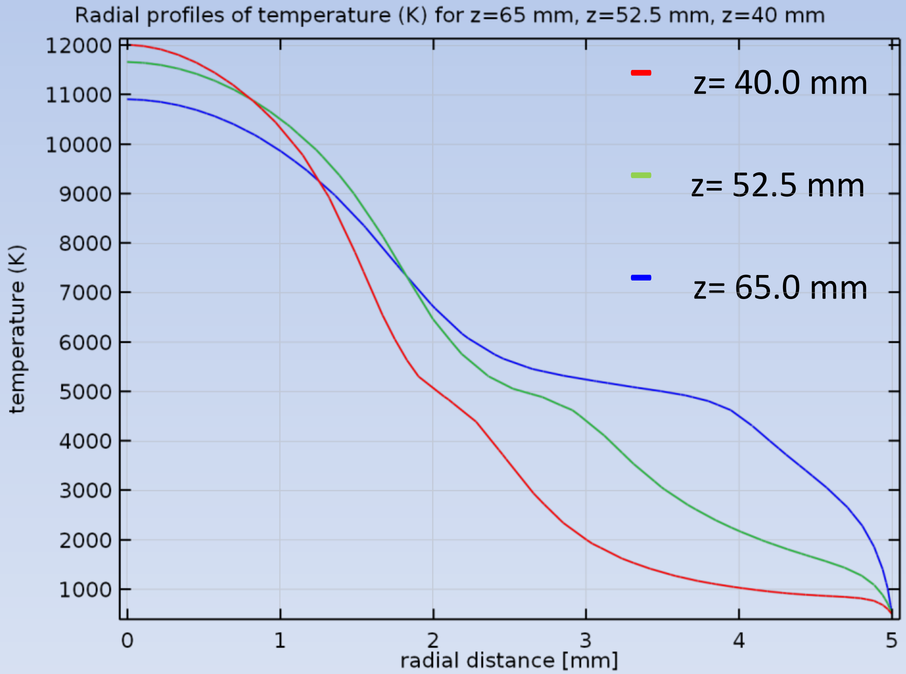


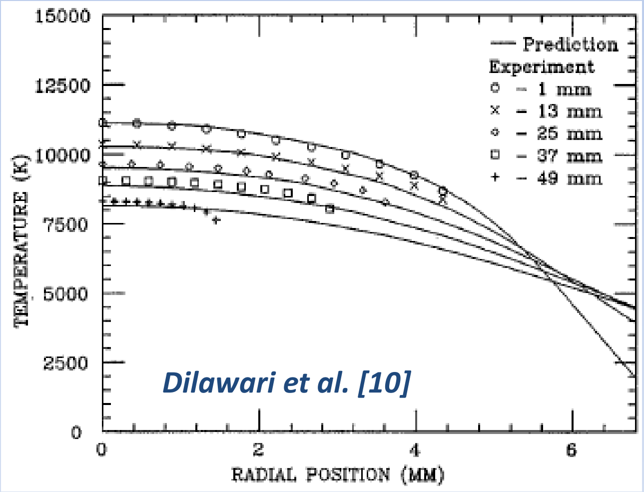


Felipini and Pimenta [8]

Numerical results: variation of the temperature in the plasma torch

forced vortex flow
S_w = 5.1

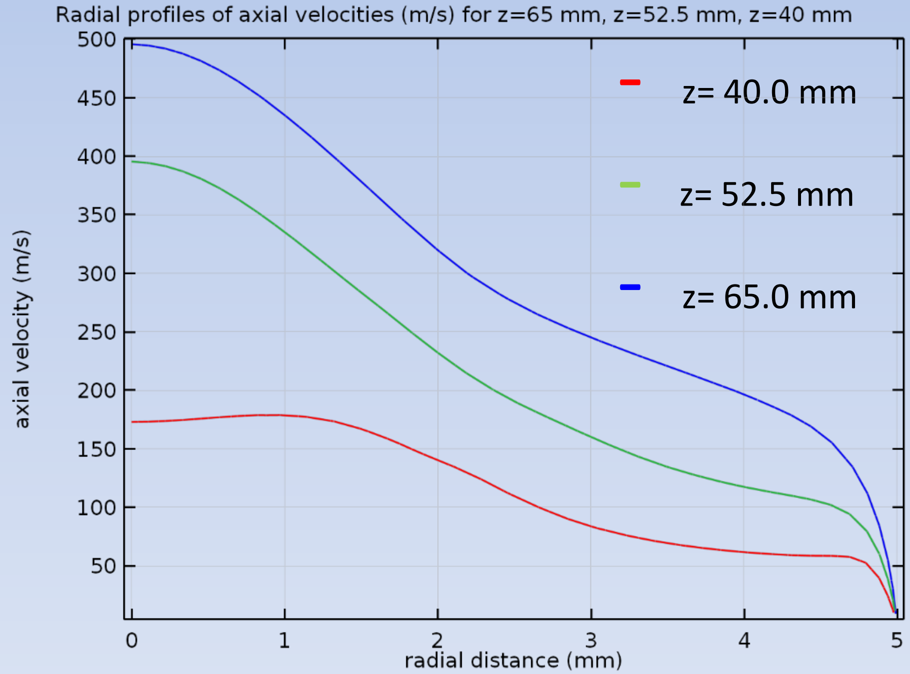




Numerical results: variation of the axial velocity in the plasma torch

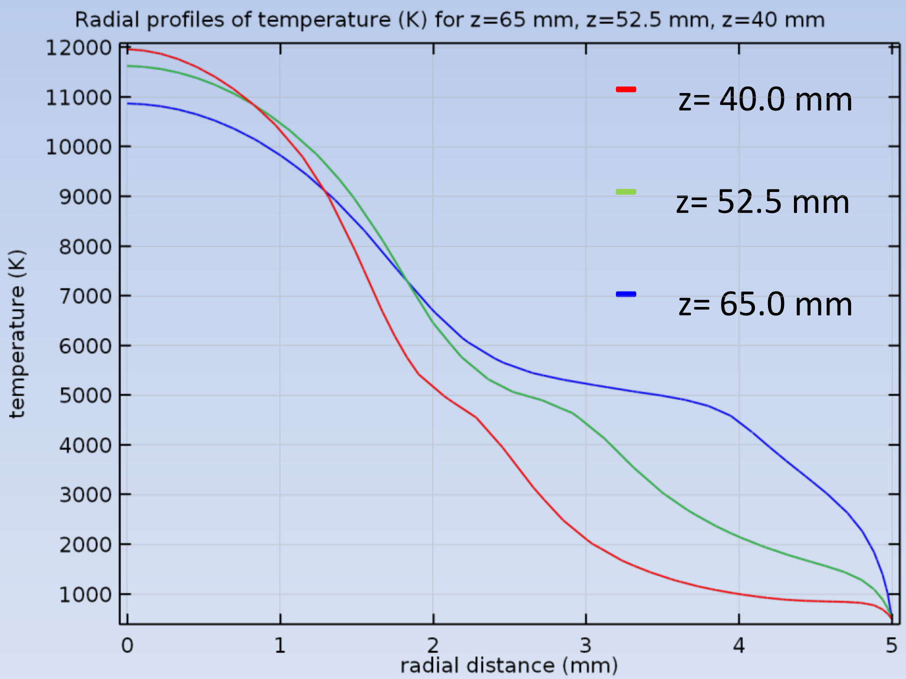
forced vortex flow

S_w = 5.1



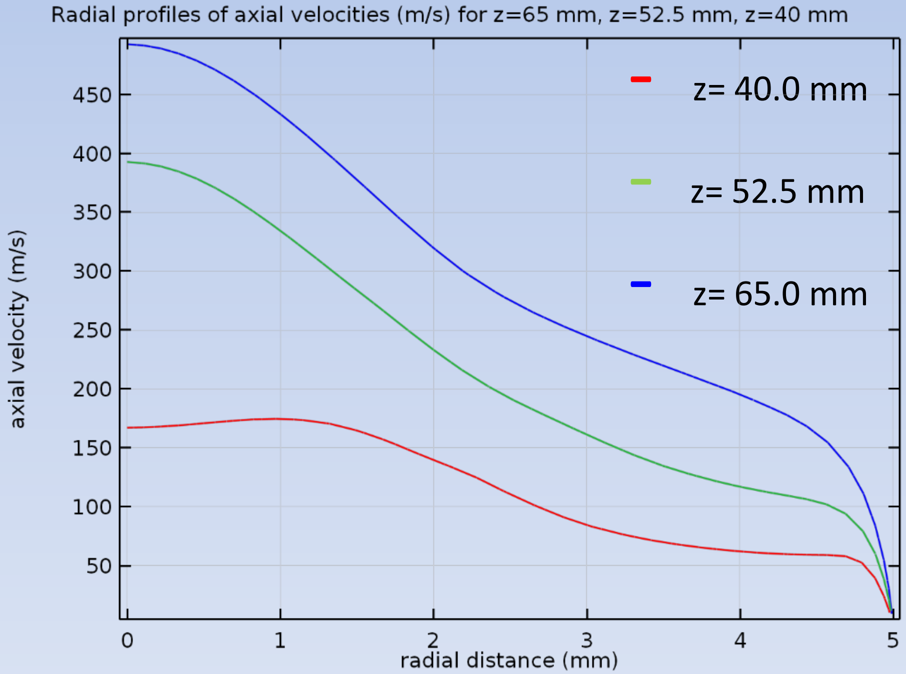
Numerical results: radial profiles of the temperature in the plasma torch

forced vortex flow
S_w = 2.55



Numerical results: radial profiles of the axial velocity in the plasma torch

forced vortex flow
S_w = 2.55



Conclusions

- DC plasma torch has been modeled and simulated by developing a 2D axisymmetric model of the laminar flow and heat transfer.
- The formation of the electric arc in the torch has not been considered in the present modeling work.
- Electric currents and magnetic fields have been incorporated in the model, Lorentz forces and joule heating effects have been computed and coupled to the physical model of the plasma torch.
- The numerical results of temperature and axial velocity of the gas give a quite satisfactory reproduction of the thermal and fluid phenomena in the plasma torch.
- We foresee to develop more complete models, e.g. 3D, including the modeling of the electric arc attachment/reattachment and the turbulence of the flow, although computational requirements and computing times should be considered.

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Acknowledgements

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