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A Plasma Torch Model

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Presentation overview

- DC plasma torch and modeling
- Physical model
- Equations
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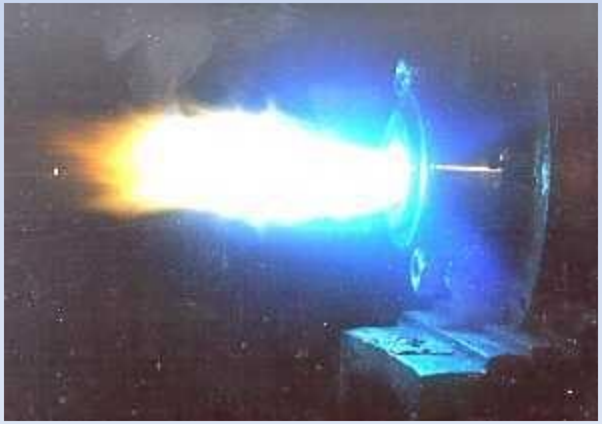
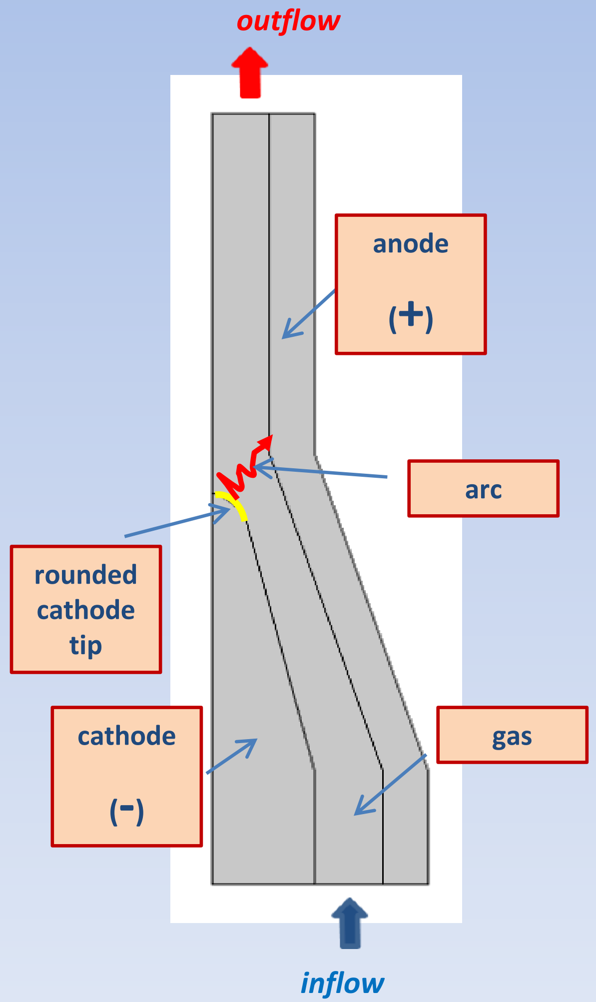
- Numerical results
- Conclusions



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

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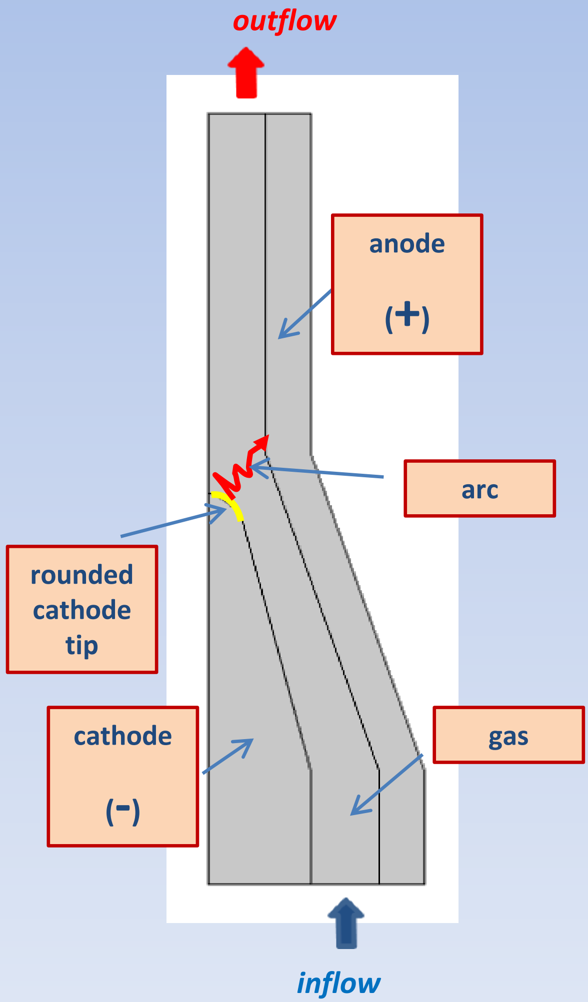
DC plasma torch and modeling



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

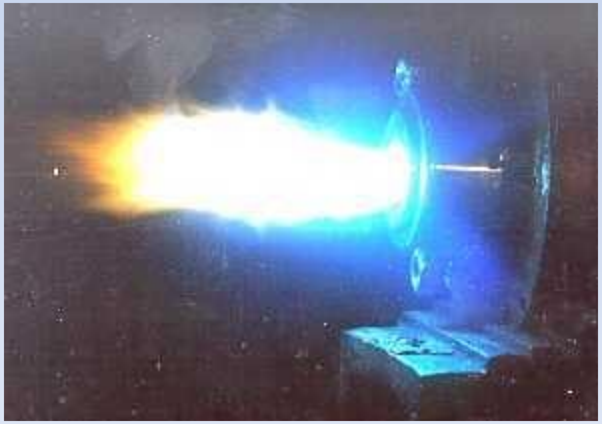
- plasma constituted by *different species* (molecules, atoms, ions and electrons)
- several *coupled phenomena* due to the interaction between electric, magnetic, thermal and fluid flow fields
- *highly nonlinear* plasma flow, presence of *strong gradients* and chemical and thermodynamic *nonequilibrium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

Joule heating

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

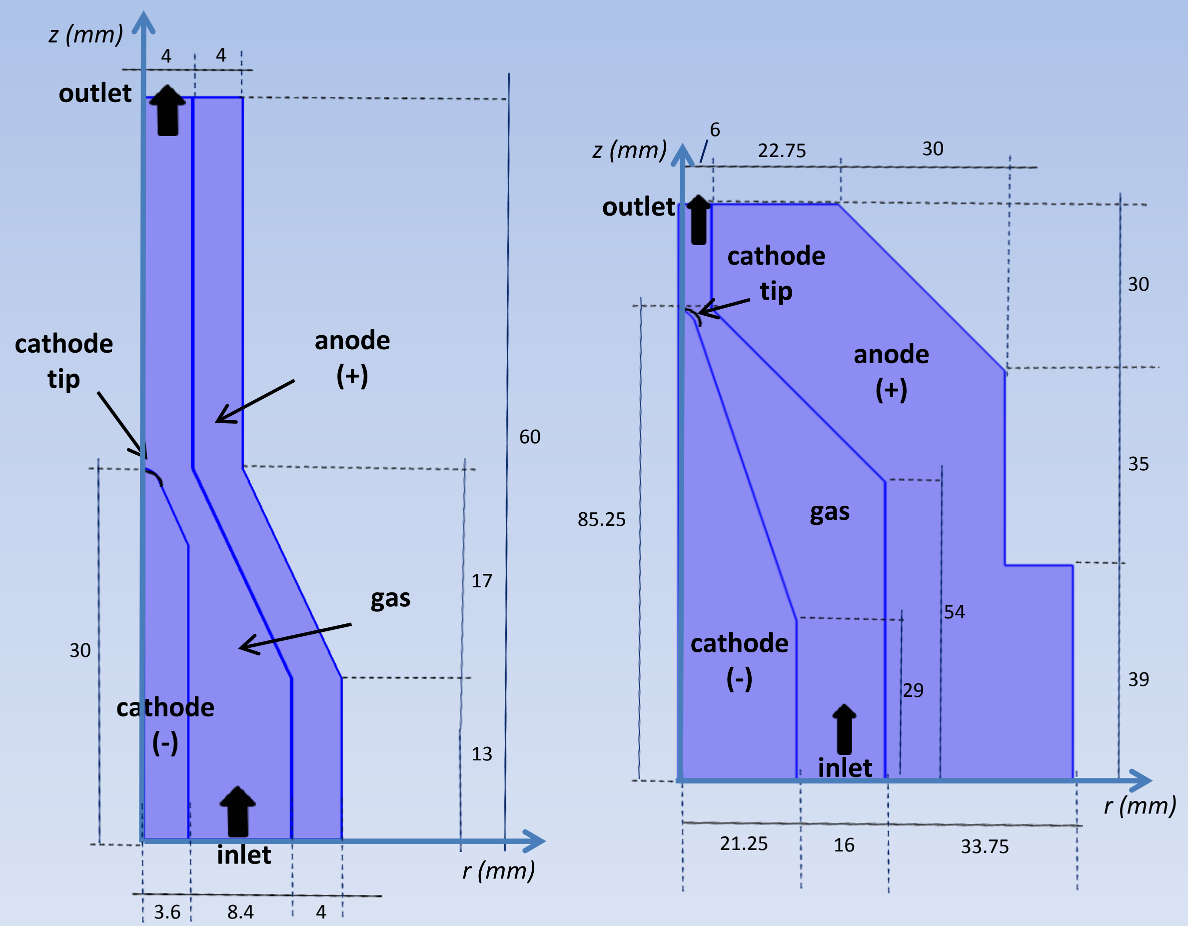
Lorentz force

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



Physical model

- **Two different DC plasma torches are modeled as 2D regions; the plasma flow is assumed axisymmetric and in steady state.**
- **The working gas is argon for *torch 1* and nitrogen for *torch 2*; copper is the material both of the anode and the cathode.**
- **A free vortex flow is set at the inlet.**



torch 1 **(He-Ping Li (He-Ping Li *et al.* [3], He-Ping and Xi Chen [8])**

torch 2 **(Mozingo [9])**

Physical model: simplifying assumptions

- The plasma is modeled by using the magnetohydrodynamics equations and considered as a weak compresible gas (Mach number < 0.3).
- We assume conditions of local thermodynamic equilibrium (LTE), then the electrons and heavy particles temperatures are equal. The plasma electric conductivity σ is very low for temperatures T below a critical value (e.g. near the cooled anode wall of the torch), hence the electric current might be not guaranteed.
- To ensure the electric flow in the gas region, an artificial minimum value of electrical conductivity is set up:

  a) σ_{min} = 8000 S/m in the whole fluid region

  b) σ_{min} = 8000 S/m in a thin region between the cathode and anode

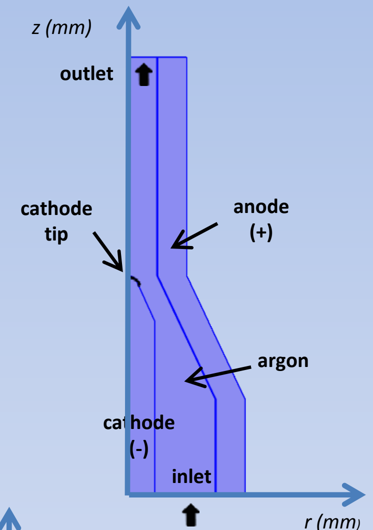
Physical model: simplifying assumptions (cont.)

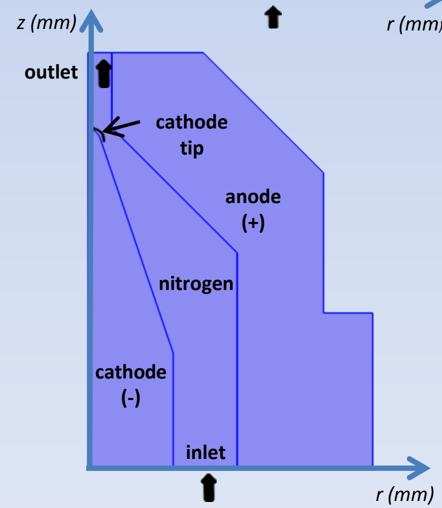
- We do not consider either the formation of the electric spot on the anode surface and the arc reattachment process on the same anode (in 2D the electric spot is annular, while the arc reattachment is strictly a transient phenomenon).
- The plasma is considered optically thin and a net emission coefficient is used for the heat transferred by radiation mechanisms.

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

The modeling of the DC arc plasma torches 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, gas and anode
  using the vector magnetic potential A : $\boxed{\nabla \times \mathbf{A} = \mathbf{B}}$
  and the electric potential *V* $\boxed{\mathbf{E} = -\nabla V}$
- Heat Transfer module (*Heat transfer in fluids/solids*)
  cathode, gas and anode
- CFD module (*Laminar flow)*
  argon or nitrogen



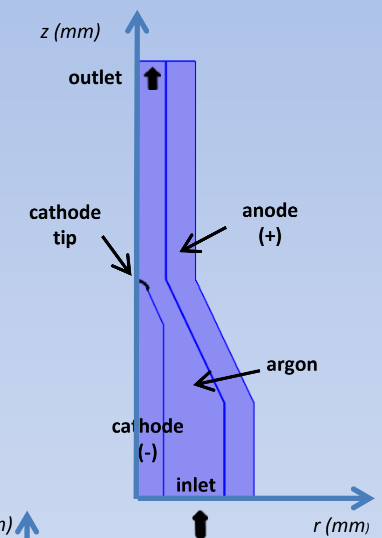


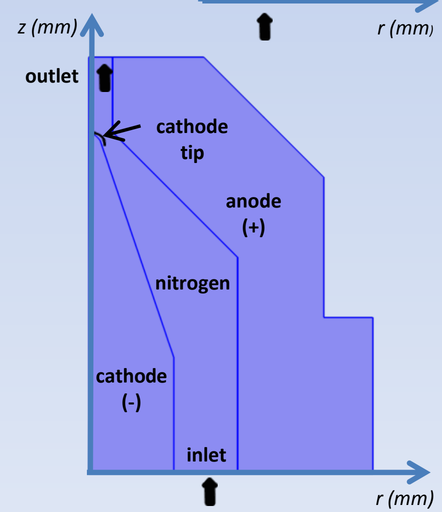
z (mm)

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*)





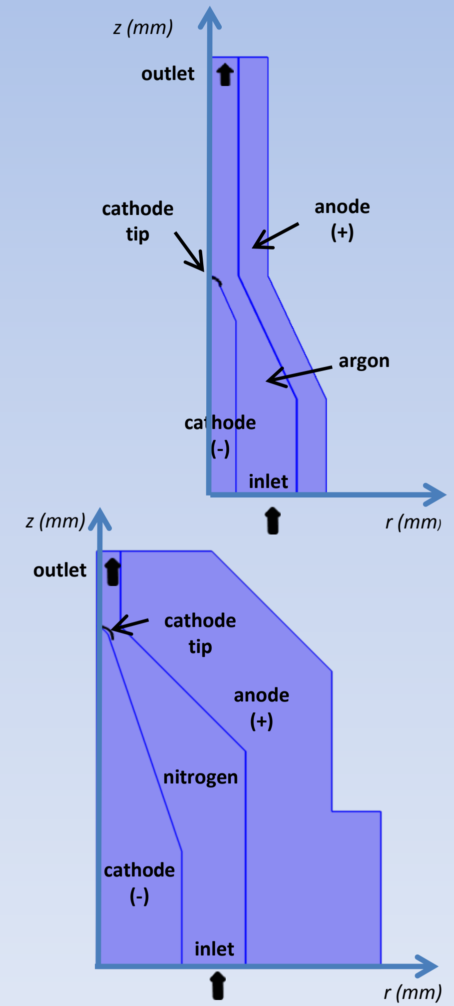
Boundary conditions

Electric currents

- current density in the range of $10^7 \div 10^8$ A/m^2 *(torch 1)* and of $10^6 \div 10^7$ A/m^2 *(torch 2)* 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 $\mathbf{n} \bullet \mathbf{J} = 0$

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



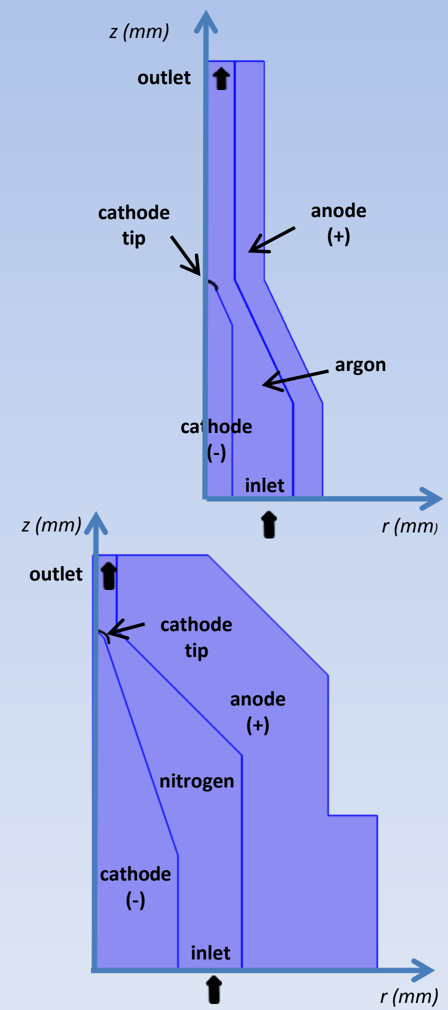
Boundary conditions (cont.)

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 while the temperature of the gas at inlet is 300 K
- the other surfaces are insulated $-\mathbf{n} \bullet \mathbf{q} = 0$
- prescribed radiosity (gray body) on the internal surfaces

Fluid flow

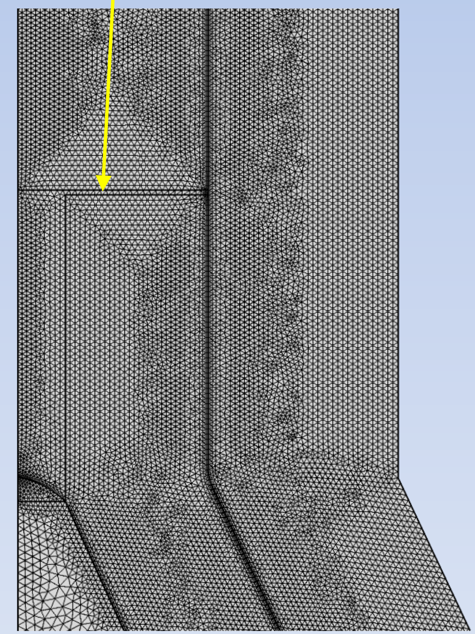
- *Torch1 inlet :* 2.0 STP m^3/h of argon (v_z = 1.35 *m/s), v_r* = 0 and three free vortex flows $v_\theta = k_1/r$ (k_1 equal to 4.86x$10^{(-3)}$ m^2/s, 9.72x$10^{(-3)}$ m^2/s and 14.58x$10^{(-3)}$ m^2/s)
- *Torch2 inlet :* 6.35 STP m^3/h of nitrogen (v_z = 1.37 *m/s), v_r* = 0 and three free vortex flows $v_\theta = k_1/r$ (k_1 equal to 0.291 x$10^{(-1)}$ m^2/s, 0.582x$10^{(-1)}$ m^2/s and 0.873x$10^{(-1)}$ m^2/s)
- no slip on the walls
- pressure is set to 0 at the outlet



Solution with Comsol Multiphysics ®

- meshing *torch1* and *torch2* with nearly 1.1×10^5 (1.4×10^6 DOFs) and 1.3×10^5 (1.7×10^6 DOFs) triangle elements, respectively; mesh refinement close to the walls
- using a fully coupled approach, the MUMPS direct solver is selected
- 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

thin region between the cathode and anode with σ_{min} = 8000 S/m



torch1: partial view of the mesh between the cathode and anode

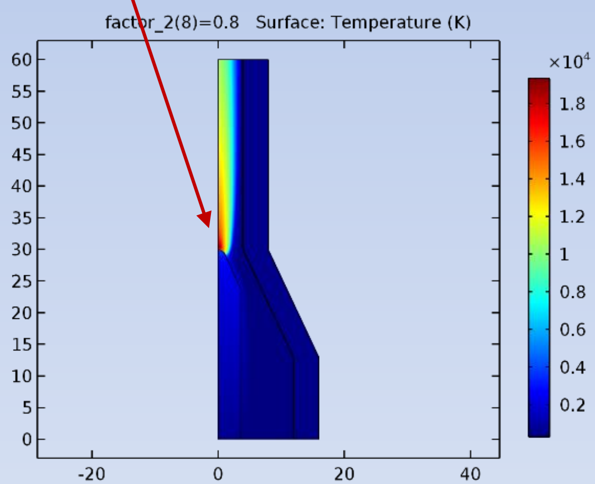
Numerical results: temperature and velocity magnitude for *torch1*

σ_{min} = 8000 S/m in the whole fluid region

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

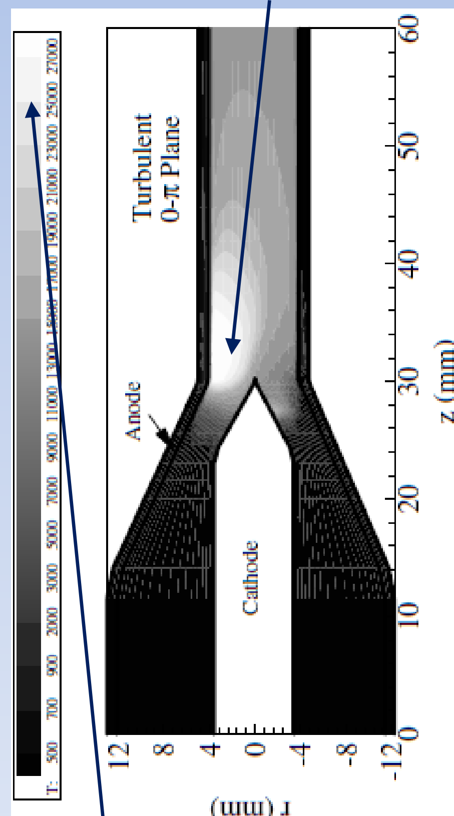
$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

2D, T is axisymmetrical



Temperature field of the *torch 1* (2.0 STP m^3/h, k_1 = 4.86x$10^{(-3)}$ m^2/s, J_n= 0.8x10^8 A/m^2).

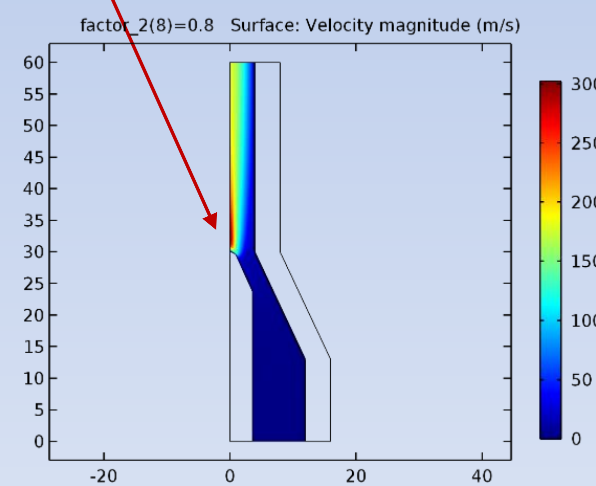
He-Ping and Xi Chen [8]:
3D, T is non-axisymmetrical



the maximum temperature and axial velocity for *torch1*, computed by He-Ping and Xi-Chen [8], are higher

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

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



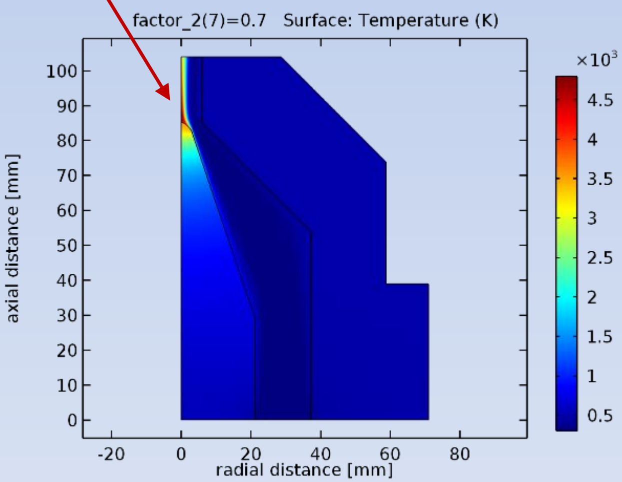
Velocity field of the *torch 1* (2.0 STP m^3/h, k_1 = 4.86x$10^{(-3)}$ m^2/s, J_n= 0.8x10^8 A/m^2).

Numerical results: temperature and velocity magnitude for *torch2*

σ_{min} = 8000 S/m in the whole fluid region

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

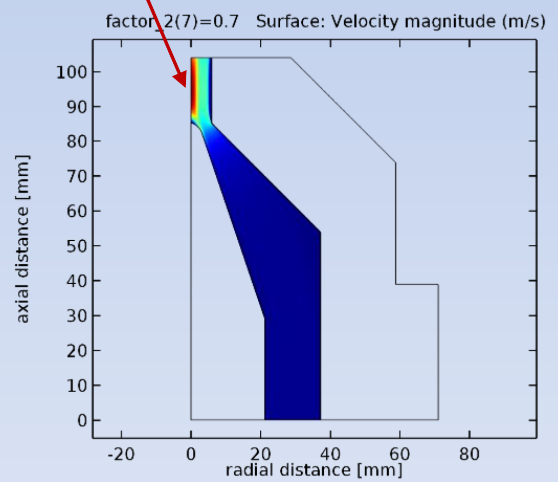
$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$



Temperature field of the *torch 2* (6.35 STP m^3/h, k_1 = 0.291x10$^{(-1)}$ m^2/s, J_n= 0.7x10^7 A/m^2).

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

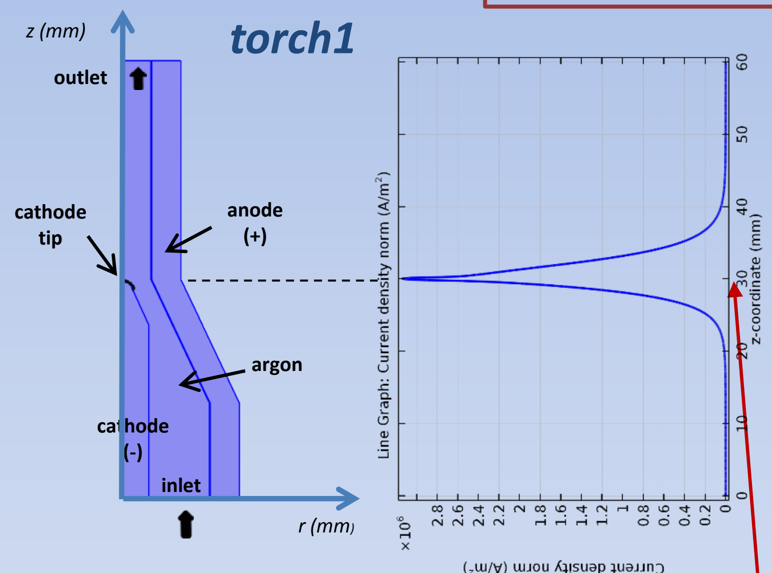
$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \qquad \mathbf{F}_L = \mathbf{J} \times \mathbf{B}$$



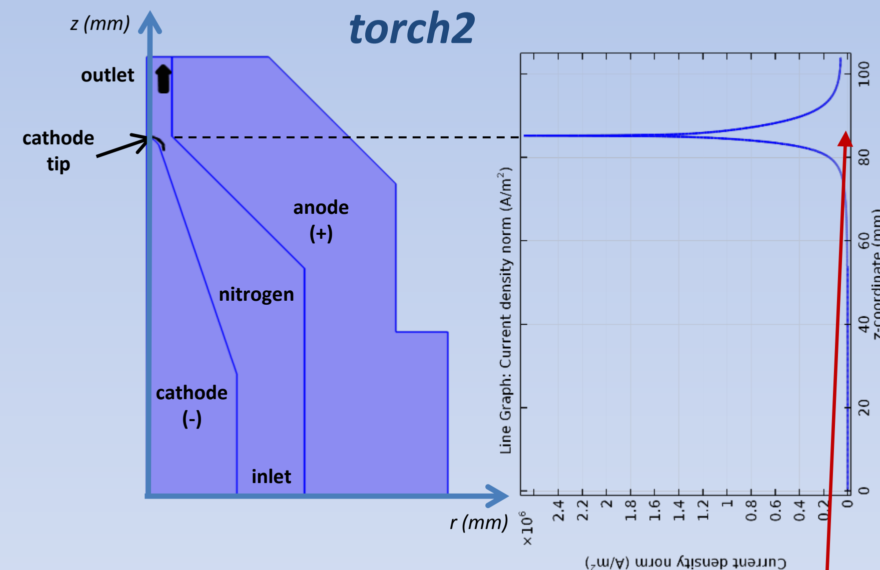
Velocity field of the *torch 2* (6.35 STP m^3/h, k_1 = 0.291x10$^{(-1)}$ m^2/s, J_n= 0.7x10^7 A/m^2).

Numerical results: arc attachment

σ_{min} = 8000 S/m in the whole fluid region



Current density norm at the internal anode wall of *torch 1* (2.0 STP m^3/h, k_1 = 4.86x10$^{(-3)}$ m^2/s, J_n= 0.8x10^8 A/m^2).



Current density norm at the internal anode wall of *torch 2* (6.35 STP m^3/h, k_1 = 0.291x10$^{(-1)}$ m^2/s, J_n= 0.7x10^7 A/m^2).

the same position of *z*=30 mm is given by our computational results

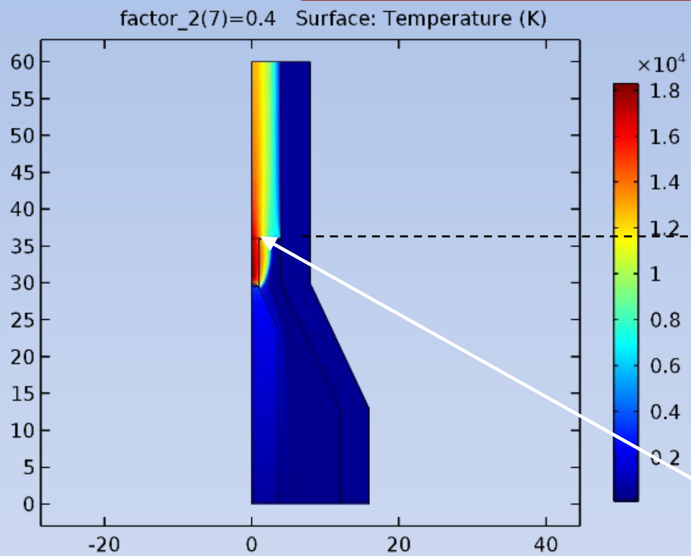
at *z*=85.25 mm, intersection between the convergent and the cylindrical section of the anode

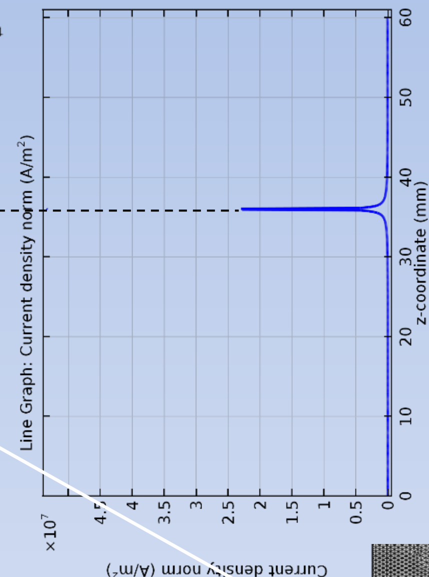
He-Ping and Xi Chen [8]:

the position of the arc attachment is near the intersection between the convergent part and the cylindrical part of the anode (*z*=30 mm) and it is not uniform in the circumferential direction.

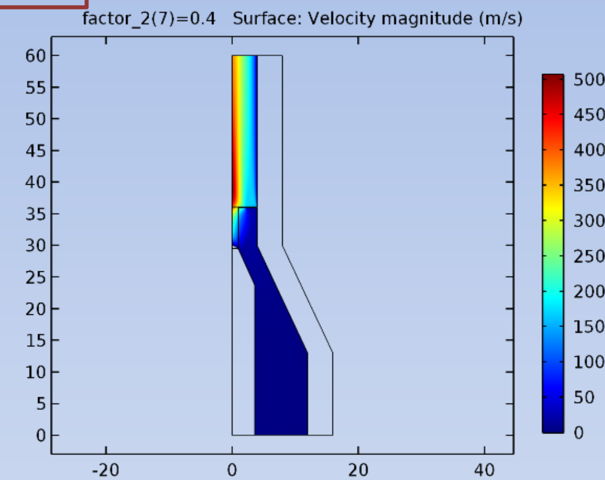
Numerical results: temperature and velocity magnitude for *torch1*

σ_{min} = 8000 S/m in a thin region between cathode and anode





Temperature field of the *torch 1* (Q = 2.0 STP m^3/h, k_1 = 4.86x10$^{(-3)}$ m^2/s, J_n= 0.4x10^8 A/m^2).

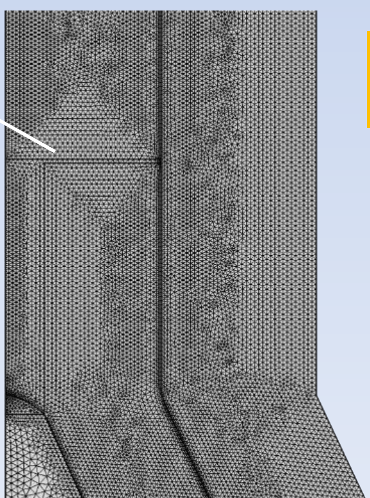


Velocity field of the *torch 1* (Q = 2.0 STP m^3/h, k_1 = 4.86x10$^{(-3)}$ m^2/s, 0.4x10^8 A/m^2).

Whereas the axial velocity is nearly doubled.

Having halved the normal current density in the cathode tip, the maximum temperature reaches the same values of the previous case with σ=8000 S/m in the whole fluid region.

thin region between the cathode and anode with σ_{min} = 8000 S/m



Conclusions

- **Two DC plasma torches have been modeled and simulated by developing 2D models of laminar flow, heat transfer and electromagnetic fields.**
- **Lorentz forces and Joule heating effects have been represented, coupled to the physical model and finally computed.**
- **In order to ensure the electric flow, we have used an artificial minimum value of 8000 S/m (σ_{min}) for the electrical conductivity of the gas: a) in the whole fluid region; b) in a thin channel between cathode and anode.**
- **The numerical computations of the gas temperature and axial velocity, which depend on where we set the artificial electrical conductivity, 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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Acknowledgements

Many thanks for your attention !

We would like to also acknowledge:

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