3D numerical simulation of the electric arc motion between bus-bar electrodes

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Thermal plasmas

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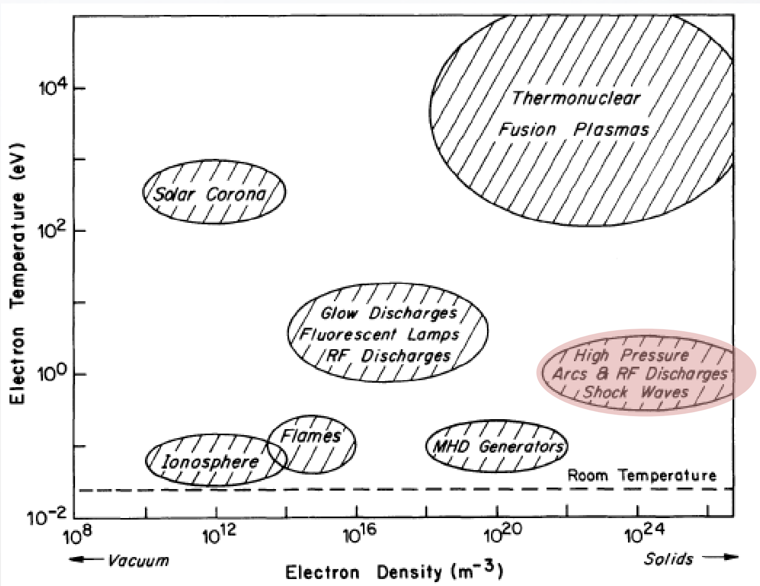
Plasmas classification [1]:

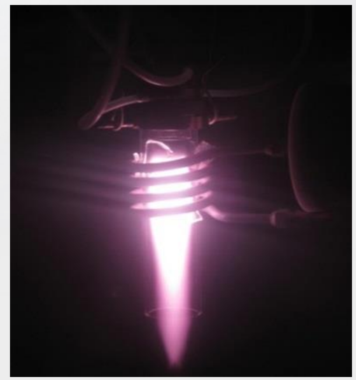


Thermal plasmas characteristics:

$n_e \sim 10^{21} - 10^{26} m^{-3}$ and $T_e \sim 10^4 K$

→ Local Thermodynamic Equilibrium (LTE)

Thermal plasma applications:



Thermal plasma in nature:

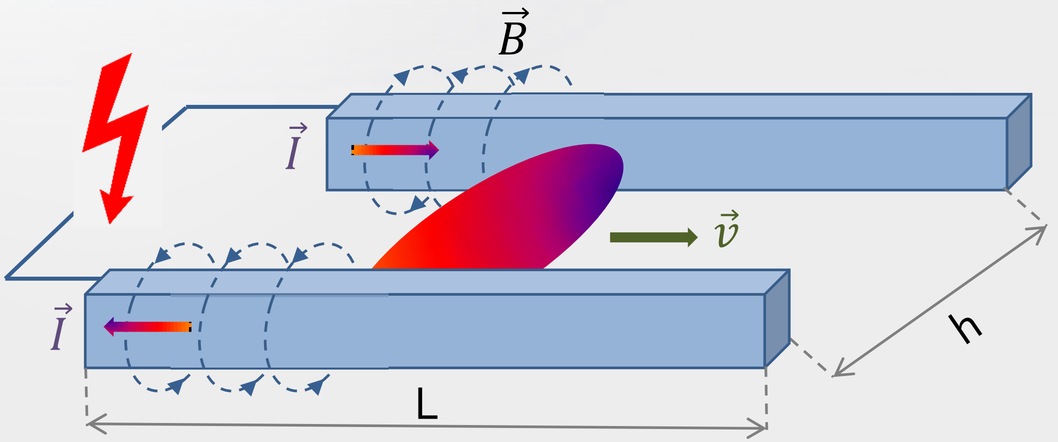
[1] M. I. Boulos, P. Fauchais, and E. Pfender, *Thermal Plasmas Fundamentals and Applications*. Boston, MA: Springer US : Imprint: Springer, 1994.

Objective

Bus-bars electrodes construction, dimensions: L~100 – 200 mm and h ~ 10 mm

Supplied with AC or DC currents in range 100 – 1000 A

Working conditions: 0.1 – 1 atm



In case of fault the **electric arc takes place and propagates along the electrodes.**

Goal: to investigate arc propagation using numerical simulation

Mathematical description

Arc column description and electrodes:

The system of MHD equations in the LTE approximation is solved for arc bulk plasma:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{u} = 0,$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot \rho \boldsymbol{u} \otimes \boldsymbol{u} = -\nabla p + \nabla \cdot \eta \left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\boldsymbol{T}} \right) - \frac{2}{3} \nabla (\eta \nabla \cdot \boldsymbol{u}) + \boldsymbol{j} \times \boldsymbol{B},$$

$$\rho c_p \left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T \right) + \nabla \cdot \boldsymbol{q} = -\boldsymbol{j} \cdot \nabla \varphi - Q_{rad}, \qquad \boldsymbol{q} = -\lambda \nabla T - \frac{5}{2} \frac{kT}{e} \boldsymbol{j},$$

$$\nabla \cdot \boldsymbol{j} = 0, \qquad \boldsymbol{j} = -\sigma \nabla \varphi,$$

$$\nabla \times \frac{1}{\mu_0} \boldsymbol{B} = \boldsymbol{j}, \qquad \boldsymbol{B} = \nabla \times \boldsymbol{A}.$$

In the electrodes:

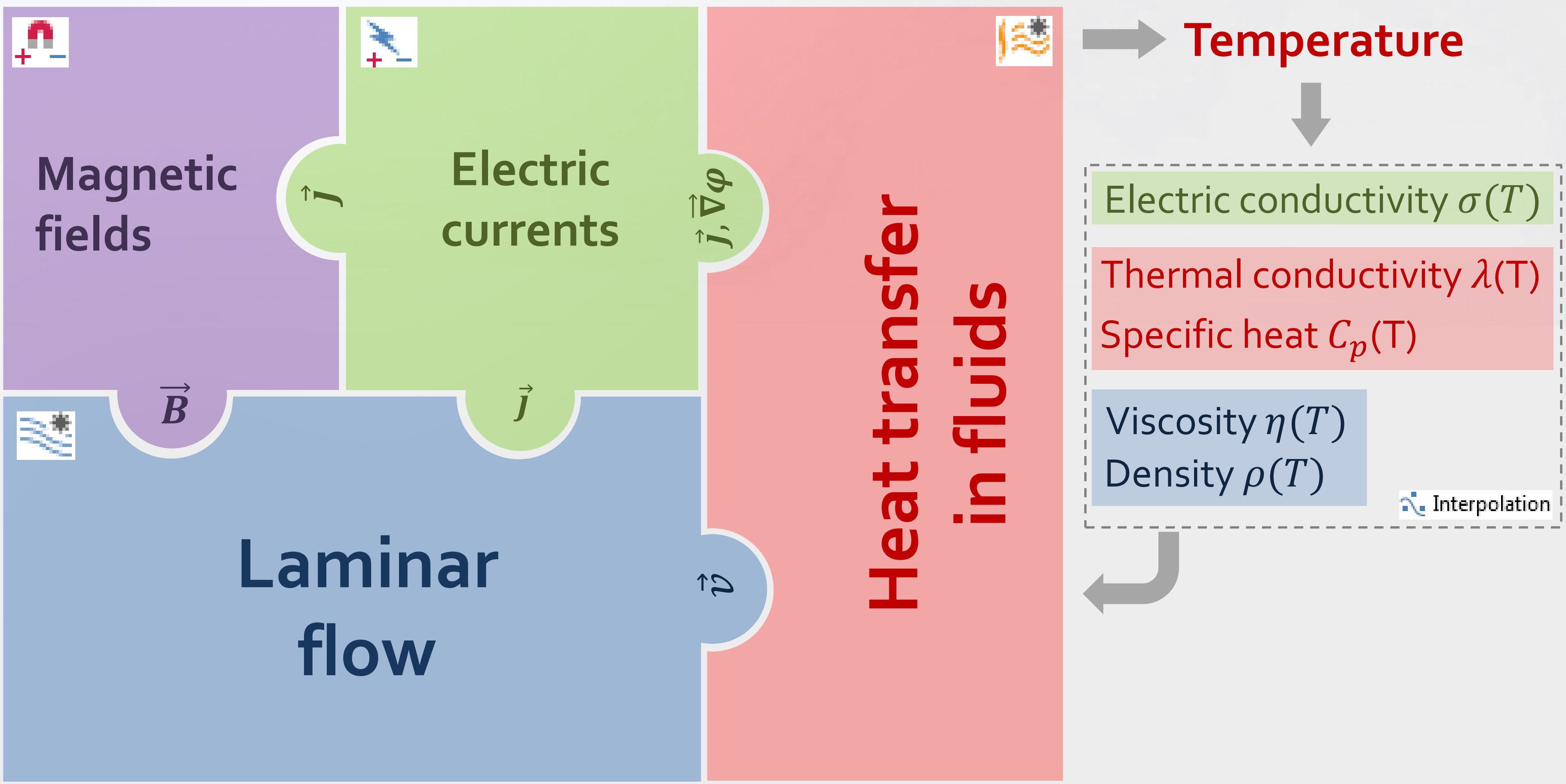
$$\rho_s c_p \nabla \frac{\partial T_s}{\partial t} \cdot (\lambda_s \nabla T_s) + \sigma_s (\nabla \varphi)^2 = 0,$$

$$\nabla \cdot (\sigma_s \nabla \varphi) = 0.$$

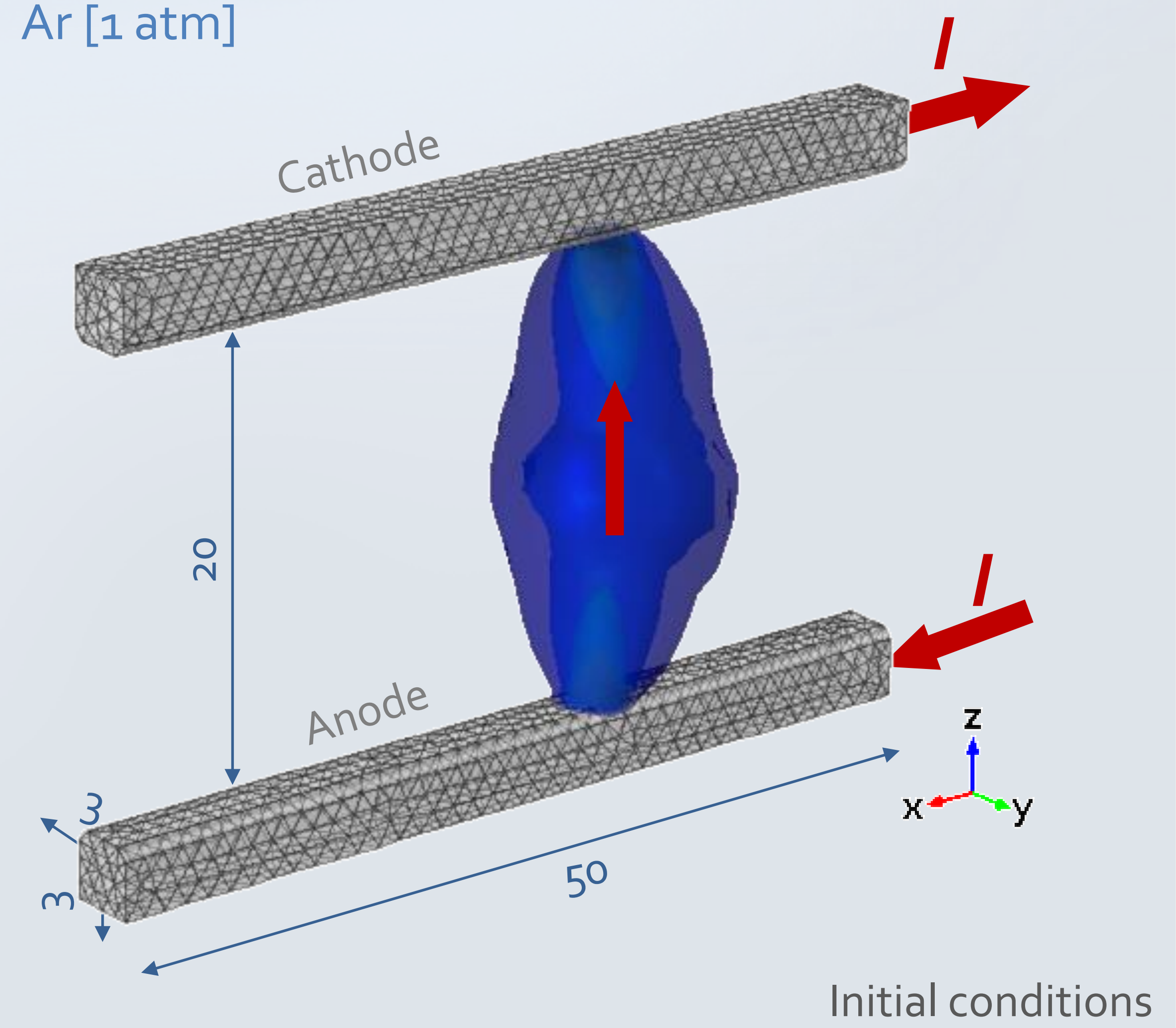
$$\nabla \times \frac{1}{\mu_0} \boldsymbol{B} = \boldsymbol{j}, \qquad \boldsymbol{B} = \nabla \times \boldsymbol{A}.$$

The system is solved with respect to variables: $\boldsymbol{u}, p, T, \varphi, \boldsymbol{A}$ in the arc plasma
and
φ , T_s , $\boldsymbol{A}$ in the electrodes.

Arc model in COMSOL



Calculation conditions



Electrodes:

Plane electrodes
made of copper

Power:

Direct current

I = 200 A

Conditions:

Atmospheric pressure
Gas: argon

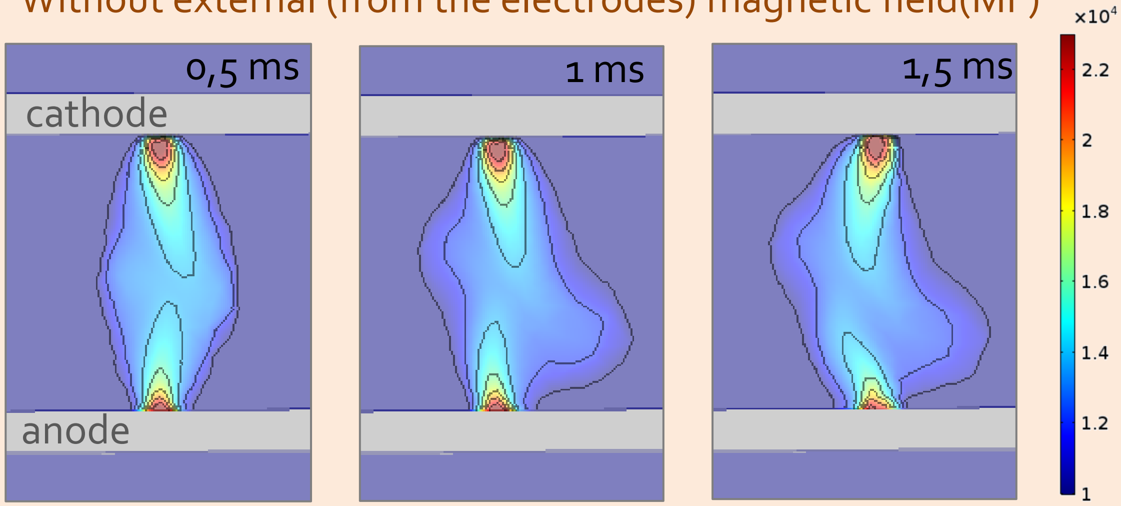
Initial conditions:

Stationary arc with,
fixed spots positions.

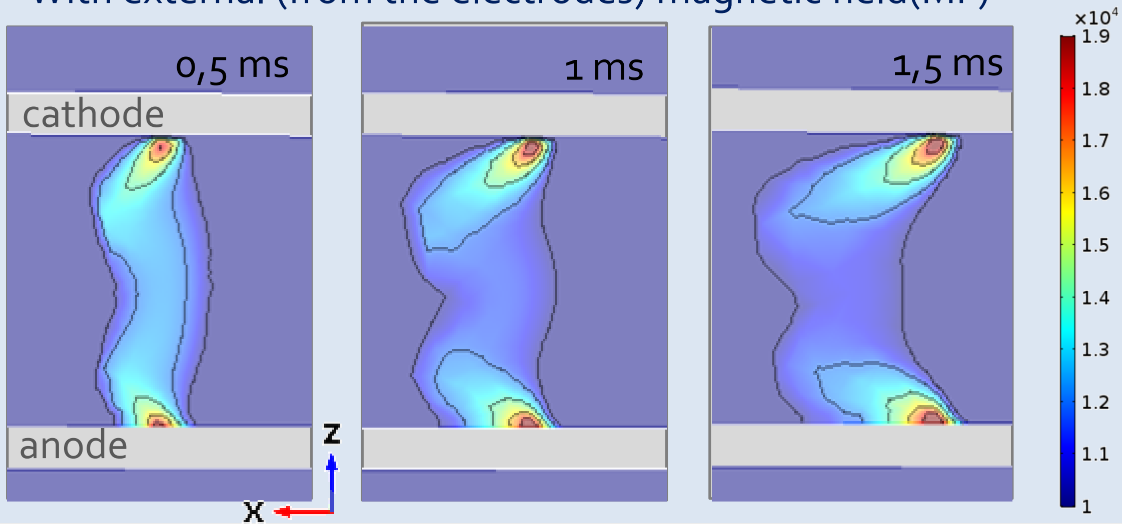
Impact of the magnetic field

Temperature (in K) distributions

Without external (from the electrodes) magnetic field(MF)

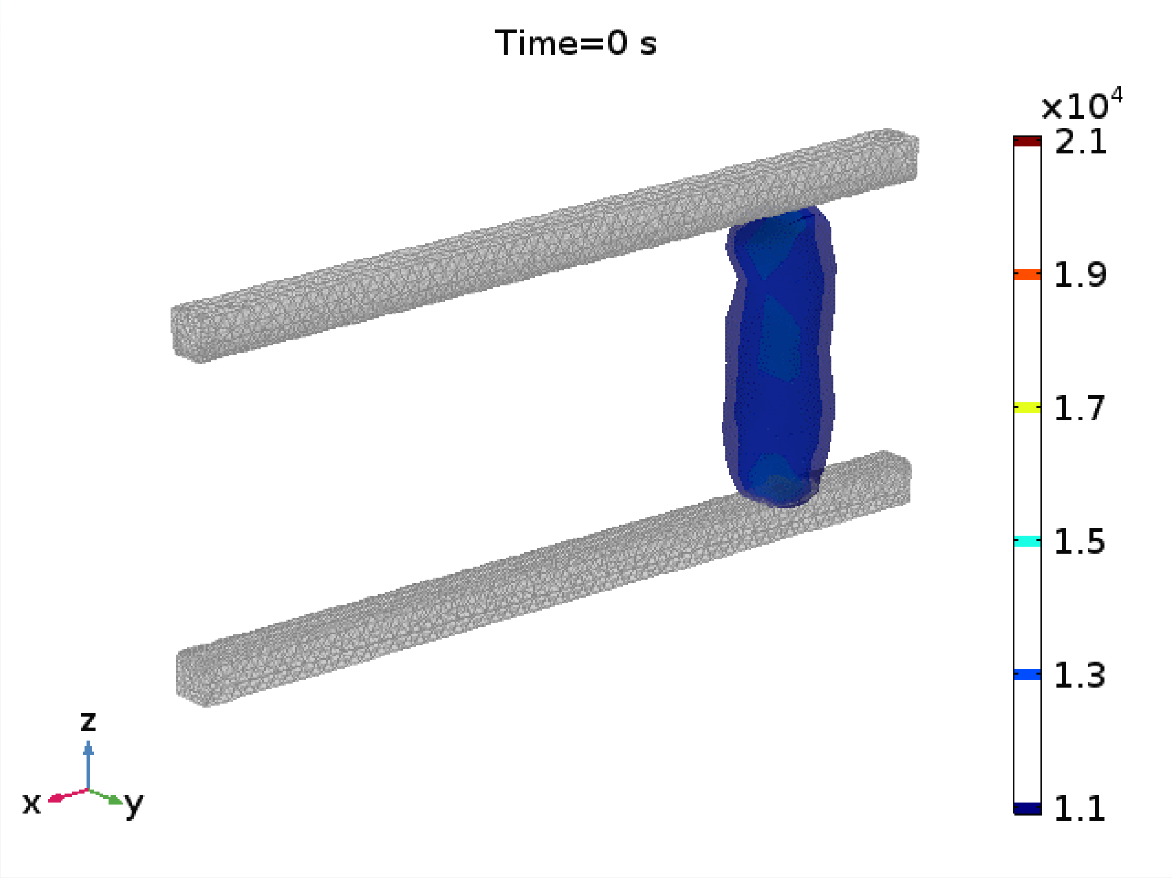


With external (from the electrodes) magnetic field(MF)

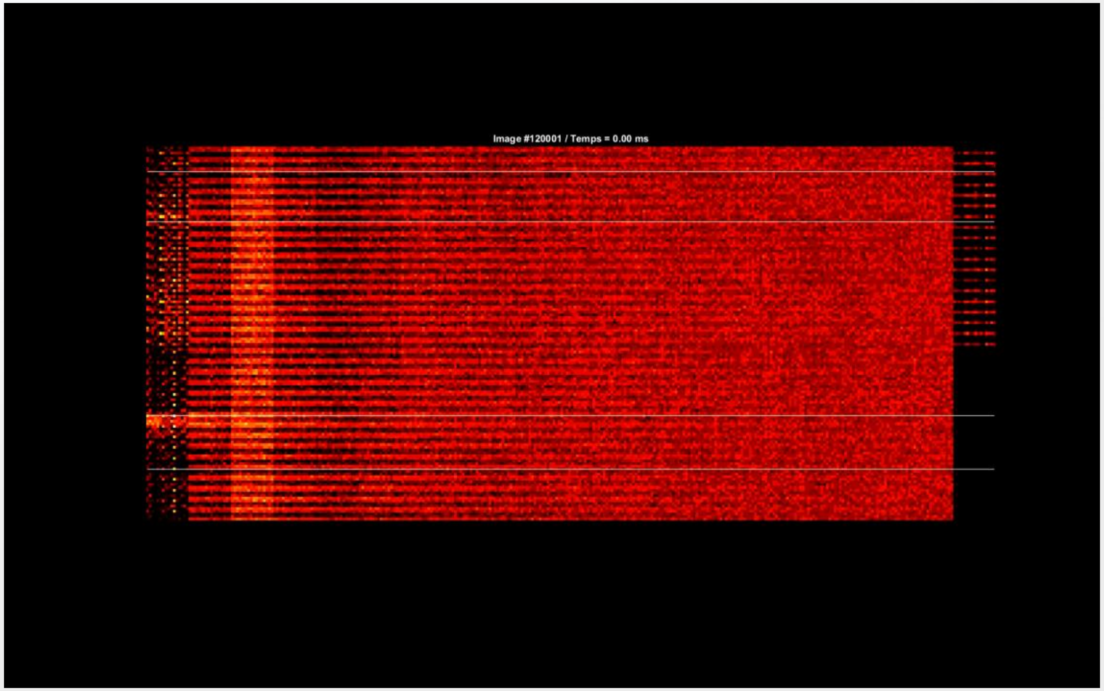


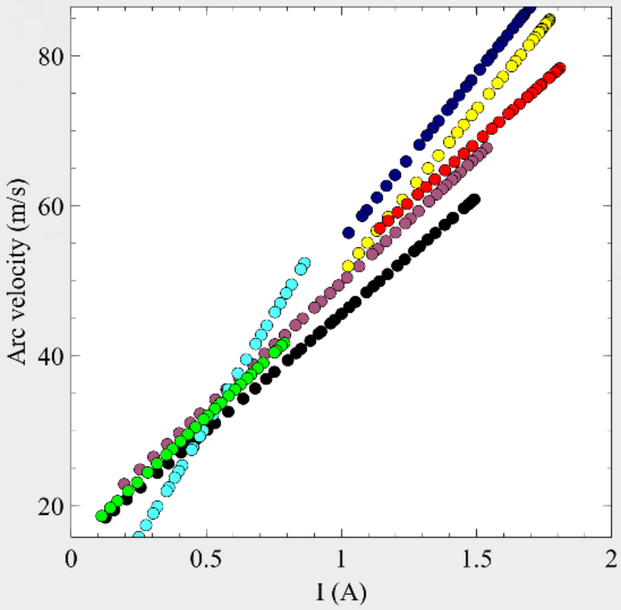
Arc displacement

Arc temperature (in K) evolution with the time



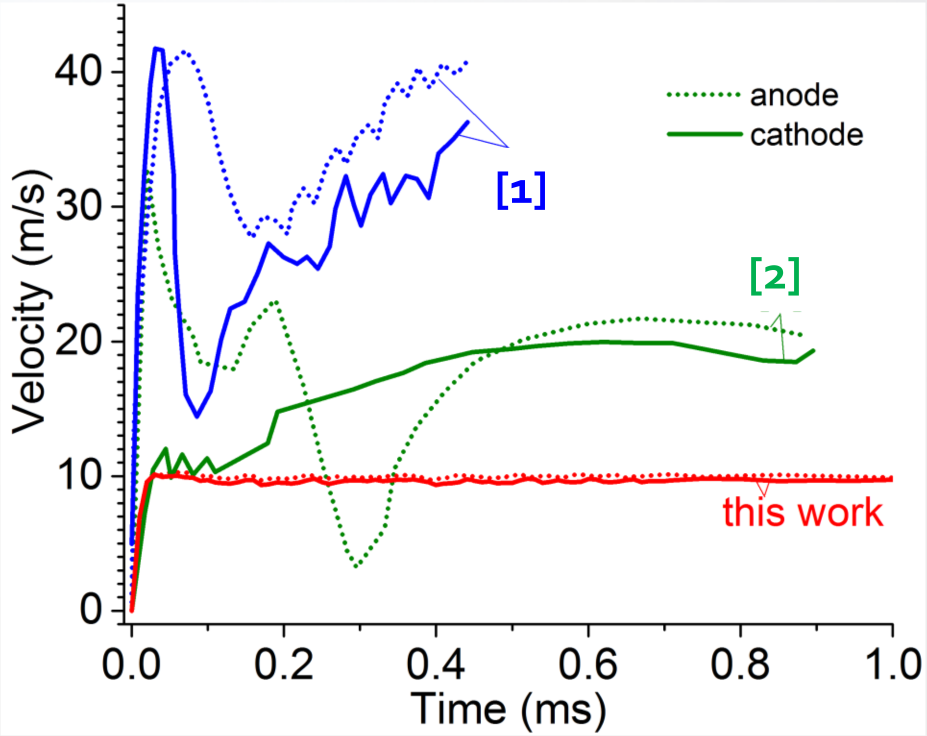
Experiment





I = 1.5 kA peak, h = 20 mm, 60 000 fr/s

Arc displacement velocity



[1] M.Lisnyak, M. Chnani, A. Gautier, J-M. Bauchire, "Behavior of a short electric arc between plane electrodes:numerical and experimental study", contributions to ICPIG congress, July 2017.
[2] B. Swierczynski, J. J. Gonzalez, P. Teulet, P. Freton, and A. Gleizes, "Advances in low-voltage circuit breaker modelling," 2004.

Numerical aspects

- Stabilization
  - Laminar flow
  - Heat transfer in fluids

  → Streamline diffusion
  Crosswind diffusion
- Discretization:
  - Linear or quadratic basic functions.
- Solver :
  - Segregated $(\varphi, \boldsymbol{A}, \boldsymbol{u}, p, T)$ → Direct (MUMPS) and Iterative (GMERS).
- Convergence criteria:
  - Relative tolerance is 0.01.
- Mesh:
  - Number of DOF 10^6, refined near the electrodes with $\Delta x_{max} = 0.6$ mm.
- Calculation time:
  - 7 days with 8 cores, Xeon 3.2 GHz, 32 Gb.

Summary

- COMSOL Multiphysics® allows to perform 3D time-dependent model of the electric arc.
- The good numerical stability for highly nonlinear problems is achieved.
- The calculation time is reasonable, that makes the model interesting for engineering applications.
- The physical aspects of the model corresponds to the experimental observations.

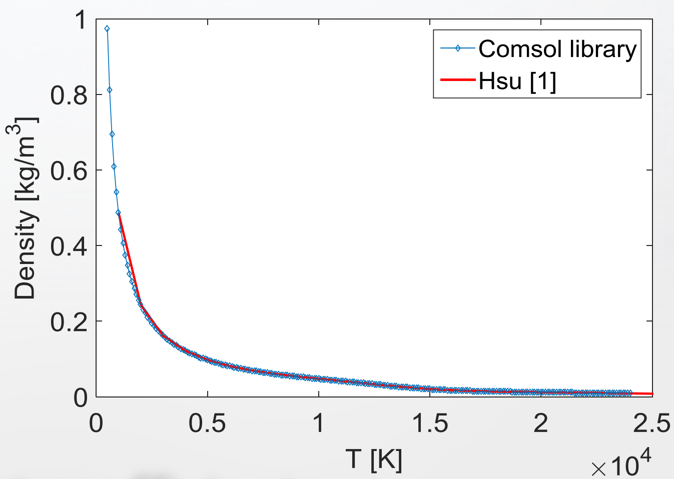
For more details I would like to invite you to the poster 84.

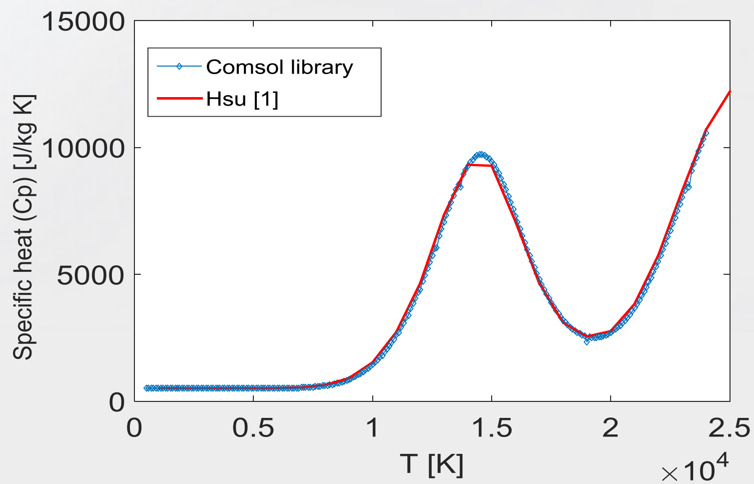
Thank you!

Plasma properties

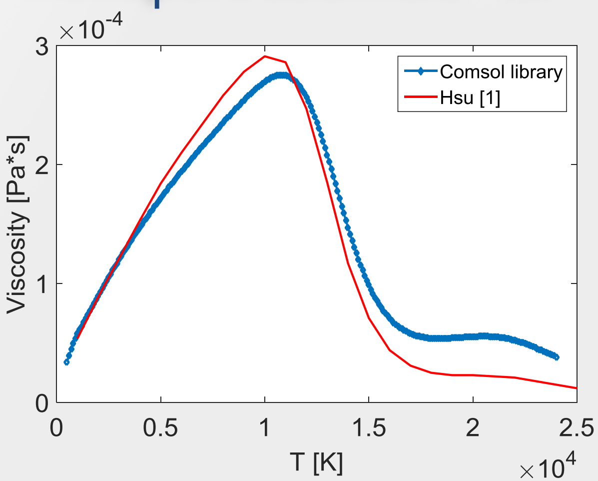
Thermodynamic properties:

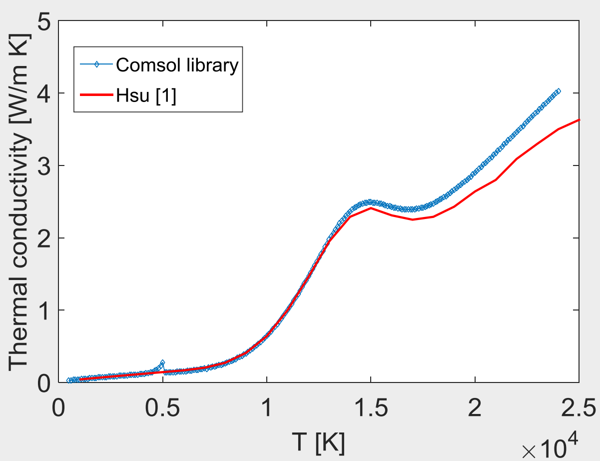
Argon 1 atm

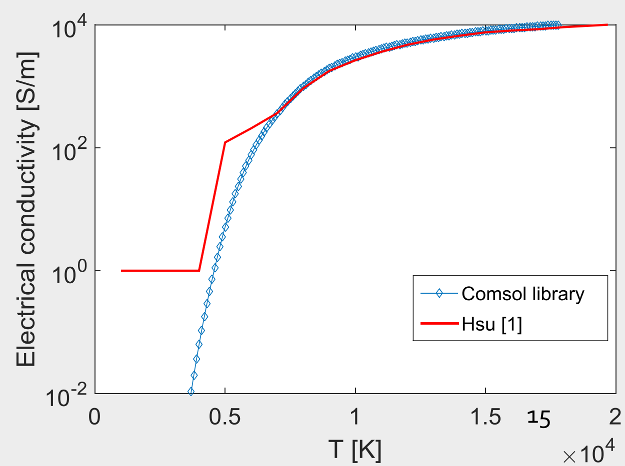




Transport coefficients:







[1] K. C. Hsu, K. Etemadi, and E. Pfender, "Study of the free-burning high-intensity argon arc," *J. Appl. Phys.*, 1983.

Convergence control

Mass conservation

Integration over external surface of the model: $\oint(\rho\vec{v}\cdot\overrightarrow{dS}) \cong 0$

- 2 D case $$\oint(\rho\vec{v}\cdot\overrightarrow{dS}) = 2\pi\rho\int_{o}^{R} v_z\, rdr + \rho R\int_{0}^{h} v_r\, dh = 0$$
- 3 D case $$\oint(\rho\vec{v}\cdot\overrightarrow{dS}) = \oint \rho(v_x n_x + v_y n_y + v_z n_z)\, dS = 0$$

Where n_x, n_y, n_z are normal vectors (directed externally to the surface),
R – model radius, h – model height

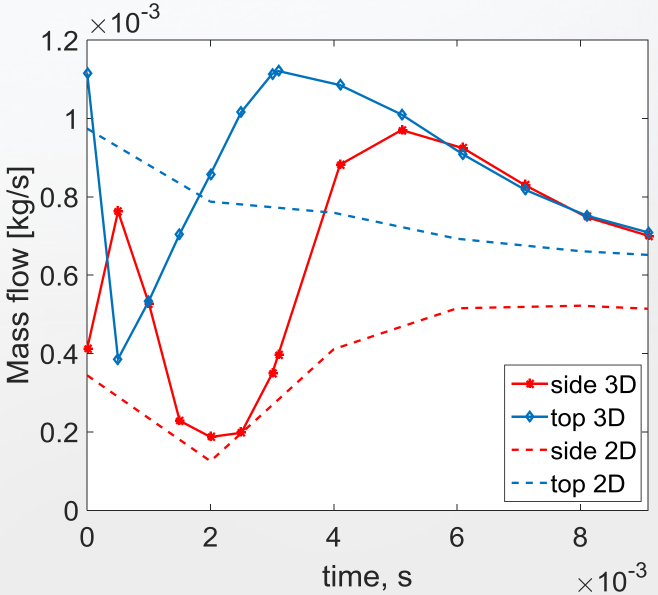
Current conservation

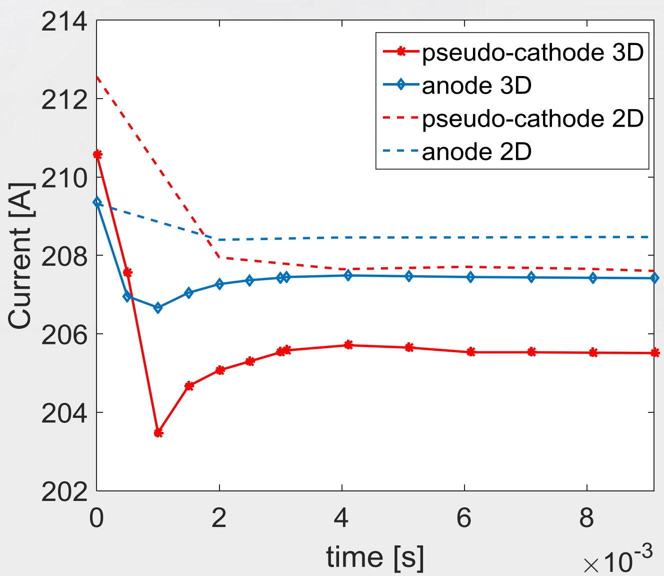
$$\oint(\vec{j}\cdot\overrightarrow{dS})_{cathode} = \oint(\vec{j}\cdot\overrightarrow{dS})_{anode}$$

In COMSOL MF

Results → Derived values → Surface integration

Fluxes calculations





Arc – electrodes interaction

Plasma near the electrodes is not in equilibrium.

Goal: To include plasma-electrodes interaction without implementing non-equilibrium plasma description.

Plasma – anode interaction:

attachment is constricted (spot mode), $R_{as} = 0.8\ mm$.
anode heating is calculated according to:

$$q_a = \left(\frac{5}{2} k T_{\delta_{pl}} + A_f\right)\frac{j}{e}$$

Plasma – cathode interaction:

spot mode on the cathode with the fixed radius [1, 2]: $R_{cs} = 1\ mm$.
temperature in the cathode spot is uniformly distributed [1]: $T_{av} = 3200\ K$.

✓ The current continuity is imposed between plasma and electrodes.

[1] W. L. Bade and J. M. Yos, Theoretical and Experimental Investigation of Arc Plasma-generation Technology, 1963.
[2] M. S. Benilov and A. Marotta, "A model of the cathode region of atmospheric pressure arcs," J. Phys. Appl. Phys., vol. 28, no. 9, p. 1869, Sep. 1995.