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

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Thermal plasmas

Plasmas classification [1]:

Thermal plasma applications:

Thermal plasma in nature:

Thermal plasmas characteristics:

\[ n_e \sim 10^{21} - 10^{26} \text{m}^{-3} \quad \text{and} \quad T_e \sim 10^4 K \]

Local Thermodynamic Equilibrium (LTE)

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

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0,
\]

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u} \otimes \mathbf{u} = -\nabla \rho + \nabla \cdot \eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \nabla (\eta \nabla \cdot \mathbf{u}) + \mathbf{j} \times \mathbf{B},
\]

\[
\rho c_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \nabla \cdot \mathbf{q} = -\mathbf{j} \cdot \nabla \varphi - Q_{\text{rad}}, \quad \mathbf{q} = -\lambda \nabla T - \frac{5}{2} \frac{kT}{e} \mathbf{j},
\]

\[\nabla \cdot \mathbf{j} = 0, \quad \mathbf{j} = -\sigma \nabla \varphi,\]

\[\nabla \times \frac{1}{\mu_0} \mathbf{B} = \mathbf{j}, \quad \mathbf{B} = \nabla \times \mathbf{A}.\]

In the electrodes:

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

\[\nabla \cdot (\sigma_s \nabla \varphi) = 0.\]

\[\nabla \times \frac{1}{\mu_0} \mathbf{B} = \mathbf{j}, \quad \mathbf{B} = \nabla \times \mathbf{A}.\]

The system is solved with respect to variables: \(\mathbf{u}, p, T, \varphi, \mathbf{A}\) in the arc plasma and \(\varphi, T_s, \mathbf{A}\) in the electrodes.
Arc model in COMSOL

Magnetic fields

Electric currents

Heat transfer in fluids

Laminar flow

Temperature

Electric conductivity \(\sigma(T)\)

Thermal conductivity \(\lambda(T)\)

Specific heat \(C_p(T)\)

Viscosity \(\eta(T)\)

Density \(\rho(T)\)

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Calculation conditions

Ar [1 atm]

Electrodes:
Plane electrodes made of copper

Power:
Direct current

\[ I = 200 \text{ A} \]

Conditions:
Atmospheric pressure
Gas: argon

Initial conditions:
Stationary arc with, fixed spots positions.
Impact of the magnetic field

Temperature (in K) distributions

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

<table>
<thead>
<tr>
<th>Time</th>
<th>Cathode</th>
<th>Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ms</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>1 ms</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>1.5 ms</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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</tr>
<tr>
<td>1 ms</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>1.5 ms</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Arc displacement

Arc temperature (in K) evolution with the time
Experiment

$I = 1.5 \text{ kA peak}, \ h = 20 \text{ mm}, \ 60 \,000 \text{ fr/s}$
Arc displacement velocity


Numerical aspects

- **Stabilization**
  - Laminar flow
  - Heat transfer in fluids
  - Streamline diffusion
  - Crosswind diffusion

- **Discretization:**
  - Linear or quadratic basic functions.

- **Solver:**
  - Segregated ($\varphi, A, u, p, T$) → Direct (MUMPS) and Iterative (GMERS).

- **Convergence criteria:**
  - Relative tolerance is 0.01.

- **Mesh:**
  - Number of DOF $10^6$, refined near the electrodes with $\Delta x_{\text{max}} = 0.6$ mm.

- **Calculation time:**
  - 7 days with 8 cores, Xeon 3.2 GHz, 32 Gb.

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• 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:

Transport coefficients:

Convergence control

Mass conservation

Integration over external surface of the model: \( \oint (\rho \mathbf{v} \cdot d\mathbf{S}) \cong 0 \)

- **2 D case**
  \[ \oint (\rho \mathbf{v} \cdot d\mathbf{S}) = 2\pi \rho \int_0^R v_z r dr + \rho R \int_0^h v_r dh = 0 \]

- **3 D case**
  \[ \oint (\rho \mathbf{v} \cdot d\mathbf{S}) = \oint \rho (v_x n_x + v_y n_y + v_z n_z) dS = 0 \]

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

Current conservation

\[ \oint (\mathbf{j} \cdot d\mathbf{S})_{\text{cathode}} = \oint (\mathbf{j} \cdot d\mathbf{S})_{\text{anode}} \]

In COMSOL MF

Results \( \rightarrow \) Derived values \( \rightarrow \)
Surface integration

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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), $R_{as} = 0.8 \text{ mm}$.  
- 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 \([1, 2]\): $R_{cs} = 1 \text{ mm}$.  
- temperature in the cathode spot is uniformly distributed \([1]\): $T_{av} = 3200 \text{ K}$. 

✔️ The current continuity is imposed between plasma and electrodes.