THREE-DIMENSIONAL TIME-DEPENDENT NON-EQUILIBRIUM MODELING OF ARC AND JET DYNAMICS IN DC PLASMA TORCHES

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Industrial applications require the description of (highly-coupled) arc-jet dynamics.
Mathematical Model

- **Thermodynamic non-equilibrium** \((T_e \neq T_h) \Rightarrow 2\) energy equations:

<table>
<thead>
<tr>
<th>(i)</th>
<th>(Y_i)</th>
<th>transient</th>
<th>advective</th>
<th>diffusive</th>
<th>reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(p)</td>
<td>(\frac{\partial p}{\partial t})</td>
<td>(\bar{u} \cdot \nabla p + p \nabla \cdot \bar{u})</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>(\bar{u})</td>
<td>(\rho \frac{\partial \bar{u}}{\partial t})</td>
<td>(\rho \bar{u} \cdot \nabla \bar{u} - \nabla p)</td>
<td>(-\nabla \cdot \varphi)</td>
<td>(\bar{J}_q \times \bar{B})</td>
</tr>
<tr>
<td>3</td>
<td>(T_h)</td>
<td>(\rho \frac{\partial h_h}{\partial t})</td>
<td>(\rho \bar{u} \cdot \nabla h_h)</td>
<td>(-\nabla \cdot \bar{q}_h)</td>
<td>(\frac{Dp_h}{Dt} + \dot{Q}_{eh})</td>
</tr>
<tr>
<td>4</td>
<td>(T_e)</td>
<td>(\rho \frac{\partial h_e}{\partial t})</td>
<td>(\rho \bar{u} \cdot \nabla h_e)</td>
<td>(-\nabla \cdot \bar{q}_e)</td>
<td>(\frac{Dp_e}{Dt} + \dot{Q}_J - \dot{Q}<em>r - \dot{Q}</em>{eh})</td>
</tr>
<tr>
<td>5</td>
<td>(\phi_p)</td>
<td>0</td>
<td>0</td>
<td>(-\nabla \cdot \bar{J}_q)</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>(\bar{A})</td>
<td>(\frac{\partial \bar{A}}{\partial t})</td>
<td>(\nabla \phi_p - \bar{u} \times \nabla \times \bar{A})</td>
<td>(\eta \nabla^2 \bar{A})</td>
<td>(\bar{0})</td>
</tr>
</tbody>
</table>

➢ **If** \(T_e = T_h\) ➢ **Thermodynamic Equilibrium**
Numerical Approach

• **System of transient – advective – diffusive – reactive equations:**

\[
A_0 \frac{\partial Y}{\partial t} + (A \cdot \nabla)Y - \nabla \cdot (K \nabla Y) - (S_1 Y + S_0) = \mathcal{R}(Y) = 0
\]

• **Multi-scale Variational Finite Element Method:** \( Y = \overline{Y} + Y' \)

\[
\int_{\Omega} \mathbf{W} \cdot \mathcal{R}(\overline{Y})d\Omega + \int_{\Omega'} \mathcal{P}(\overline{W})\tau \cdot \mathcal{R}(\overline{Y})d\Omega' = 0
\]

\( \text{total} = \text{large} + \text{small} \)

• **Solver:** \( \alpha \)-method, Globalized Inexact-Newton, Pre-Cond. GMRES
Computational Domain

Commercial DC Arc Plasma Torch

torch inside

cathode anode

cathode arc

jet

Finite element mesh ➤
Inside the Torch: Arc Dynamics

Arc reattachment result of simulations - no additional model -

Heavy parts. temp.  Electron temp.

Conds: Ar, 400 A, 60 slpm
Anode Attachment

@ attachment:

$T_h$: 300 to 800 [K]

$T_e$: 4000 to 12000 [K]

Significant electron temperature increase

Heavy parts. temp.  Electron temp.
Arc and Jet Dynamics

Simulations reveal complex (large) structures of fluctuating jet

Conds: Ar, 400 A, 60 slpm

Schlieren image plasma jet turbulence*
Thermodynamic Non-Equilibrium in Plasma Jet

\[ \theta = \frac{T_e}{T_h}, \text{ horizontal plane} \]

\[ \theta = \frac{T_e}{T_h}, \text{ vertical plane} \]

Significant thermodynamic non-equilibrium remains down the jet
Arc Movement as Jet Forcing

time

simulation | experiment

1 | 1
2 | 2
3 | 3
4 | 4

torch | jet
jet |
Conclusions

1) Thermodynamic non-equilibrium model applied to arc and jet dynamics in commercial plasma torch
2) Arc dynamics force the jet, cause large scale fluctuations
3) Non-equilibrium significant around the arc and jet periphery
4) Non-equilibrium description essential for realistic arc plasma modeling

Thank You