Plasma jets are used as directed sources of energy, momentum and excited species in diverse technologies, such as spray coating, chemical synthesis, waste treatment and pyrolysis. The fluid, thermal and electromagnetic dynamics from the jet produced by a direct-current non-transferred arc plasma torch are explored using time-dependent three-dimensional simulations encompassing the dynamics of the arc inside the torch, the development of the jet through the outside environment, and the later impingement of the jet over a substrate. The plasma flow is described mathematically by a chemical equilibrium and thermodynamic nonequilibrium (two-temperature) model and numerically by a coupled fluid-electromagnetic transport model and a Variational Multiscale Finite Element Method. Simulation results uncover various aspects of the flow dynamics, including the jet forcing due to the movement of the arc; the prevalence of deviations between flow-species and electron temperatures in the plasma fringes, the development of shear flow instabilities around the jet; the occurrence of localized regions with high electric fields far from the arc; the fluctuating expansion of the gas ejected from the torch, and the formation and evolution of coherent flow structures.

### 1. Introduction

- **DC Arc Plasma Torches:** Essential components of diverse industrial technologies, e.g., plasma spraying, material processing, gasification.
- **Flow in plasma torches controlled by diverse & complex phenomena...**

### 2. Mathematical Model

- **Thermodynamic nonequilibrium (NLTE) diatomic distribution functions for electrons and heavy-species (T_e \neq T_R).**
- **Optically thin radiation transport.**
- **Fully-coupled:** Compressible, reactive, electromagnetic fluid.

#### Mathematical Formulation

\[
\begin{align*}
\text{Continuity:} & \quad \nabla \cdot \mathbf{U} = 0 \\
\text{Momentum:} & \quad \nabla \cdot \mathbf{F} = \mathbf{S} \\
\text{Species:} & \quad \nabla \cdot \mathbf{Y} = \mathbf{R} \\
\text{Energy:} & \quad \nabla \cdot \mathbf{H} = \mathbf{Q} \\
\end{align*}
\]

#### Equations Table

<table>
<thead>
<tr>
<th>Equation</th>
<th>Transport</th>
<th>Advection</th>
<th>Diffusion</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservation of mass</td>
<td>( \rho ) \nabla \cdot \mathbf{U} = 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Conservation of electron momentum</td>
<td>( \rho \mathbf{U} \cdot \nabla \mathbf{U} = \mathbf{F} - \nabla \mathbf{P} - \mathbf{S} )</td>
<td>0</td>
<td>0</td>
<td>( \mathbf{S} )</td>
</tr>
<tr>
<td>Conservation of species</td>
<td>( \rho \nabla \cdot \mathbf{Y} = \mathbf{R} )</td>
<td>0</td>
<td>0</td>
<td>( \mathbf{R} )</td>
</tr>
<tr>
<td>Conservation of energy</td>
<td>( \nabla \cdot \mathbf{H} = \mathbf{Q} )</td>
<td>0</td>
<td>0</td>
<td>( \mathbf{Q} )</td>
</tr>
<tr>
<td>Magnetic induction</td>
<td>( \nabla \times \mathbf{B} = 0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3. Numerical Model

#### Variational Multiscale Finite Element Method

- **Variational form:**
  \[
  \int \mathbf{W} \cdot (\mathbf{Y} + \text{Diff}) \, dV = 0
  \]
- **Scale decomposition:**
  \[
  \mathbf{Y} = \mathbf{Y} + \mathbf{Y}_v^\text{vortex} + \mathbf{Y}_v^\text{perturbation}
  \]
- **Large scales resolved**: \( \mathbf{Y} \)
- **Small scales modeled**: \( \mathbf{Y}_v^\text{vortex} \)
- **Approximate inverse of transport operator**
  \[
  \mathbf{T} = \mathbf{I} - \alpha \mathbf{A}
  \]

#### Solution Approach

- **Time stepping:** Predictor multi-corrector alpha method – fully implicit, second order, control of resolved frequencies.
- **Nonlinear solver:** Globalized Implicit Newton-Krylov – robust & efficient.
- **Linear solver:** Preconditioned GMRES.

### 4. Model Set-Up

#### 4.1 Computational Domain

- **Domain:** Torch inside (arc dynamics), torch outside (jet dynamics), substrate region (impingement), sponge zone (nonreflecting outflow).
- **Discretization:** Hexahedral Finite Elements (second order accurate), refined solid boundaries to capture sharp gradients.

### 5. Flow Dynamics From a DC Plasma Jet

#### 5.1. Arc Reattachment and Flow Dynamics

- **Jet forcing:** Movement of the arc.
- **Flow instabilities:** Development of shear flow instabilities around the jet.
- **Localization of regions:** High electric fields far from the arc.
- **Jet expansion:** Fluctuating expansion of the gas ejected from the torch.
- **Coherent flow structures:** Formation and evolution.

#### 5.2. Thermodynamic, electrical & fluid relaxation

- **Flow structure:** Large-scale flow features that can be unambiguously identified.
- **Q-criterion:** Symmetric \( \mathbf{Q} \) & anti-symmetric \( \mathbf{Q} \) parts of \( \nabla \mathbf{u} \).
- **\( \mathbf{Q} \) reference value**
- **Q criterion:**
  \[
  Q = \frac{1}{2} (\mathbf{D} : \mathbf{D} - \mathbf{S} : \mathbf{S})
  \]
  \( \mathbf{Q} \): reference value

#### 5.3. Thermodynamic Nonequilibrium

- **Model:**
  \[
  
  \]
  \( \mathbf{S} \): source term

#### 5.4. Instabilities Development

- **Kelvin-Helmholtz instability**

#### 5.5. Fluid Dynamics and Coherent Structures

- **Flow dynamics:**
  \[
  \frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F} = \mathbf{S} + \mathbf{Q}
  \]
  \( \mathbf{S} \): source term

### 6. Conclusions

- **Flow dynamics from an arc discharge plasma jet:** Fully-coupled nonequilibrium simulations – capture from optical emission to instabilities.
- **Comprehensive (consistent & complete) turbulence model not yet included.**

### References


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**Abstract**

Plasma jets are used as directed sources of energy, momentum and excited species in diverse technologies, such as spray coating, chemical synthesis, waste treatment and pyrolysis. The fluid, thermal and electromagnetic dynamics from the jet produced by a direct-current non-transferred arc plasma torch are explored using time-dependent three-dimensional simulations encompassing the dynamics of the arc inside the torch, the development of the jet through the outside environment, and the later impingement of the jet over a substrate. The plasma flow is described mathematically by a chemical equilibrium and thermodynamic nonequilibrium (two-temperature) model and numerically by a coupled fluid-electromagnetic transport model and a Variational Multiscale Finite Element Method. Simulation results uncover various aspects of the flow dynamics, including the jet forcing due to the movement of the arc; the prevalence of deviations between flow-species and electron temperatures in the plasma fringes, the development of shear flow instabilities around the jet; the occurrence of localized regions with high electric fields far from the arc; the fluctuating expansion of the gas ejected from the torch, and the formation and evolution of coherent flow structures.

**Optical emission between \( T_e \) and \( T_R \) fields**

**Reconstructed figure from Optical emission.** (center) electron temperature \( T_e \) and (right) heavy-species temperature \( T_R \)

**Flow dynamics in an arc reattachment event:** Sequence of snapshots of \( T_e \) distribution. The arrows indicate the location of the initial (left) and formed (now) arc anode attachments. The total voltage drop is: (A) 32.6, (B) 32.2, (C) 35.6, (D) 32.5, (E) 31.5, (F) 29.8, (G) 31.2, and (H) 32.3 V.