Droplet Breakup by a Plasma Jet

Cécile Marchand
Gilles Mariaux

Christophe Chazelas
Armelle Vardelle

Alexandre Douce EDF R&D

Laboratoire Sciences des Procédés Céramiques et de Traitements de Surface, France
Conventional Powder Plasma Spraying

Plasma with high velocity (> 1 000 m.s⁻¹) and high temperature (T > 10 000 K)

Micro-structured coatings
Nano-structured Coatings by Plasma Spraying

Better mechanical properties of nano-structured coatings

**Solid feedstock**: powders

Spraying of agglomerates of nano-size particles

**Liquid feedstock**

Use of stable and homogeneous liquid feedstock with a low viscosity
Liquid Precursor Plasma Spraying

Two main difficulties:

1. Injection and penetration of the liquid into the plasma flow
   Penetration: $\rho_\ell v_\ell^2 \geq \rho v^2$

2. Heterogeneous behavior of the droplets in the core and periphery of the plasma jet

Similar problems in conventional powder plasma spraying

But with liquid feedstock, they are aggravated because of:

- the low specific density of droplets
- the breakup process

Injection of Mo particles in Ar-H₂ plasma jet
Droplet Breakup Processes under Plasma Conditions

- **Aerodynamic Breakup**
  - *Secondary breakup*
  - High relative velocity at the interface of two phases

- **Thermal Breakup**
  - Inner boiling of liquid

- **Liquid droplet: Sphere rupture**
  - Formation of solid shells
  - + pressurization of inner liquid
Aerodynamic Droplet Fragmentation

Breakup results from:
- **Rayleigh-Taylor instabilities**: density difference
- **Kelvin-Helmholtz instabilities**: velocity difference

\[ \rho_{\text{plasma}} (1000 \text{ K}) \sim 0.4 \text{ kg.m}^{-3} / \rho_{\text{water}} \sim 1000 \text{ kg.m}^{-3} \]
\[ v_{\text{plasma}} (1000 \text{ K}) \sim 1000 \text{ m.s}^{-1} / v_{\text{water}} \sim 30 \text{ m.s}^{-1} \]

**Weber dimensionless number**

\[ We = \frac{\rho \Delta U^2 d}{\sigma} \]

- \( \rho \): fluid density
- \( \Delta U \): velocity difference between plasma and droplet
- \( d \): droplet diameter
- \( \sigma \): surface tension

Reference:
Hwang & al., Atomisation & sprays, 6, 1996
Aerodynamic Breakup Regimes

Bag breakup: $\text{We} < 100$

Stripping (shear): $100 \leq \text{We} < 350$

Catastrophic (surface wave) breakup: $\text{We} \geq 350$

$t_b$ : breakup time

Models

TAB Model for low $\text{We}$
O’Rourke, 1987

ETAB Model
Tanner, 1998

Wave Model for $\text{We} > 100$
Reitz, 1982

Pilch & Erdman, Int. Multiphase Flow., 13, 6, 1987
ETAB Model

\[
\frac{dn(t)}{dt} = 3K_{br} n(t) \quad \rightarrow \quad n(t) = e^{3K_{br}t}
\]

\[
\bar{m}(t) = \frac{m_0}{n(t)}
\]

- We ≤ 160: \( K_{br} = k_1 \omega \)
- We > 160: \( K_{br} = k_2 \omega \sqrt{We} \)

### Experimental conditions used for validation of ETAB Model (Schneider, 1995)

<table>
<thead>
<tr>
<th>Liquid feedstock</th>
<th>Fuel</th>
<th>Solution: Dissolved metal salt in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>( P_{injection} = 300 \text{ bars} ) ( d_0 \sim d_{injector} = 150 \mu m ) ( v_0 = 183 \text{ m.s}^{-1} )</td>
<td>( P_{injection} \sim 5 \text{ bars} ) ( d_0 \sim d_{injector} = 300 \mu m ) ( v_0 \sim 30 \text{ m.s}^{-1} )</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>( N_2 ) ( P_{N2} = 15 \text{ bars} ) ( \rho_{N2} = 12.7 \text{ kg.m}^{-3} )</td>
<td>Plasma gas ( T_{plasma} = 300 \text{ K} - 10\ 000 \text{ K} ) ( \rho_{\text{plasma}} &lt; 1 \text{ kg.m}^{-3} )</td>
</tr>
</tbody>
</table>
Modeling the Turbulent Flow outside the Plasma Torch

Main assumptions

- 3-D geometry
- 2 gases: plasma (Ar-H₂) and ambient air (no demixion and chemical reactions)
- Mixing laws to calculate properties (dependant on the temperature)
- Turbulent flow outside the plasma torch: k-ε

Plasma torch operating conditions

- Torch nozzle diameter: 6mm
- Velocity profile (vmax = 1300 m.s⁻¹)
- Temperature profile (Tmax = 13400 K)
Modeling the Liquid Penetration on the Plasma Jet

Main assumptions
- Spherical, punctual and pure liquid droplets (no interactions between droplets)
- Droplets ($\phi = 300$ $\mu$m, $v_0 = 30$ m.s$^{-1}$) subjected to the fluid turbulent dispersion
- Phenomenon: aerodynamic breakup only (no thermal effects or evaporation)

ETAB Model Breakup

We $\geq 12$: breakup possible $\Rightarrow$ calculation of breakup time $t_b$

- $t_b \leq \Delta t$: breakup during current time step
  - $n(t) = e^{3K_{br}t}$
  - Breakup delay = $t_b$

- $t_b > \Delta t$: droplet progress, $t_b$ is calculated again (new$_{t_b}$)
  - new$_{t_b} \leq$ initial$_{t_b}$: Breakup delay = new$_{t_b}$
  - new$_{t_b} >$ initial$_{t_b}$: Breakup delay = initial$_{t_b}$

Created droplets with new characteristics at the current time step:
- diameter, mass, velocity and trajectory
Comparison of the ETAB Model Result and Experimental Observation

Injection of a liquid 300 µm droplet in the plasma jet

\[ k_1 \sim k_2 = 1/4.5 \]

\( \theta \): dispersion angle of the liquid spray jet
\( \alpha \): deviation angle of the liquid spray jet

Trajectory of a 300 µm droplet no breakup
Effect of the $k_1$ Constant on a 300 µm Droplet Breakup

$$n(t) = e^{3K_{br}t}$$ with $K_{br} = k_1\omega$ ($We \leq 160$) and $t_b = 1/K_{br}$

<table>
<thead>
<tr>
<th>$k_1 = 10$</th>
<th>$k_1 = 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image 1]</td>
<td>[Image 2]</td>
</tr>
<tr>
<td>197 breakup $\rightarrow$ 980 droplets</td>
<td>1 breakup $\rightarrow$ 11 droplets</td>
</tr>
<tr>
<td>$t_b \text{ max} = 7.6 \times 10^{-6} \text{ s}$</td>
<td>$t_b \text{ max} = 7.6 \times 10^{-7} \text{ s}$</td>
</tr>
<tr>
<td>$We \text{ max} = 26.9$</td>
<td>$We \text{ max} = 51.8$</td>
</tr>
</tbody>
</table>
Droplets Trajectories

Visualization of 500 droplets maximum
- if number < 500: all droplets display
- if number > 500: maximum different droplets viewed

\[ k_1 = 10 \Rightarrow 980 \text{ droplets} \]
Conclusion

Implementation of ETAB model in Code_Saturne:
- Qualitative study of droplets breakup
- Influence of the k1 constant on the droplet breakup and trajectories of new droplets

➢ Statistic study
➢ Validation of the implementation of the ETAB model in Code_Saturne with simulation of Schneider experiment
➢ Work in progress to determine appropriated constants to plasma conditions
Thanks for your attention