Simulation of the Spray Characteristics of Black Liquor

Colloquium on BL Combustion and Gasification
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Agenda

- Project Goals
- Need for Code Development
- Code Development
- Code Validation
- Full Simulation
- Test Cases
- Summary
Long Term Goals

- Create a code which can be used to:
  - Optimise nozzle design
  - Predict droplet size for a particular operation
  - Provide input for CFD modeling
Objective of New Code

- Develop a code (computer program) which can properly simulate the liquid sheet formation and its breakup in a splash plate nozzle
Objective of New Code
Need for Code Development

- Difficulty in testing spray characteristics in-situ
- Difficulty in reproducing firing conditions in the laboratory.
- Equations developed by Dombrowski and co-workers to predict droplet size are not general in nature.
- Improve spreadsheet which is currently used to predict droplet size based on boiler operating conditions.
Code Development

- Work initiated to develop BLSpray in Sept 2000

- Numerical Methods:
  - Basic Assumptions
    - Laminar, Newtonian, incompressible flow
  - 3D Cartesian coordinate system, using a finite volume scheme
  - Full Navier-Stokes equations
Code Capabilities

- Model any shape of solid object
- Handle a wide range of liquid properties
- Handle continuous fluid boundary conditions, inflow and outflow
- Provide liquid film thickness and its velocity distribution at any desired location and cross-section
- Plot results in the form of 3D images
- Include internal and external disturbances
- Simulate, with further development, other types of nozzles
- Can be coupled with CFD modeling software
Steps in Development of BLSpray

- **Step 1:**
  - Develop BLSpray to model normal impact of a liquid jet on a solid plate

- **Step 2:**
  - Develop BLSpray to accurately predict black liquor sheet thickness and velocity at the tip of the splash plate

- **Step 3:**
  - Develop BLSpray to enable the code to determine droplet size and distribution
Initial Code Validation

- Quantitative validation using Ashgriz et al.

<table>
<thead>
<tr>
<th>Jet velocity m/s</th>
<th>Measured Mean Droplet Dia.</th>
<th>Simulation: Droplet Dia range</th>
<th>Simulation: Droplet Dia average</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>~ 160 µm</td>
<td>100-200 µm</td>
<td>150 µm</td>
</tr>
<tr>
<td>26.8</td>
<td>~ 80 µm</td>
<td>50-100 µm</td>
<td>80 µm</td>
</tr>
</tbody>
</table>
Initial Code Validation

- **Numerical simulation**

Azuma and Wakimoto  
Int. Conference on Multiphase Flow, 2001

- **Qualitative validation: liquid film and finger formation at high speed jet impact**
BLSpray: Step 2

- Impingement of black liquor on a plate at an angle
- Progressed from a flat plate to a full nozzle body
Step 2 Validation

- Corn syrup experiments by Obuskovic and Adams
- Validation of sheet thickness and velocity at the tip of the splash plate
Step 2 Validation

- Film Thickness
- BLSpray vs experimental results for two different viscosities
Step 2 Validation

- Film Top Surface Velocity
- BLSpray vs experimental results for two different viscosities

![Graph showing Film Top Surface Velocity vs Angle from Plate Centerline for two viscosities: μ = 175 mPa·s and μ = 325 mPa·s. The graph includes data points for both numerical models and experimental results at angles of 0°, 25°, and 50°.](image)
Full Simulation: Step 3

- Increased computational domain to capture breakup point
- Droplet size distribution obtained from the liquid volume fraction data calculated by the code
Full Simulation: Computational Domain

- The large domain is broken into smaller simulation blocks
- Simulation continues until droplet formation
Images of Full Simulation

$0^\circ < \theta < 10^\circ$

$25^\circ < \theta < 45^\circ$
Test Cases

- One simulation using **BLSpray** gives all flow information in the entire domain of computation.
- Results were analysed at three different cross-sections.
Test Cases: First Set

- Black liquor properties held constant
  - Viscosity 100 mPa·s
  - Surface Tension 60 mN/m
  - Density 1350 kg/m³

- Varied splash plate conditions
  - Nozzle Diameter
  - Jet Velocity
  - Jet Angle

- Looking at effect on sheet characteristics
<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>Jet Velocity (m/s)</th>
<th>Jet Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>22</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>32</td>
<td>10</td>
<td>45</td>
</tr>
</tbody>
</table>
As nozzle diameter increases
- Film thickness increased
- Sheet breaks up further from the plate
- Radial distribution remained fairly constant
Nozzle Diameter

- Top surface velocity increased with increasing nozzle diameter
<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>Jet Velocity (m/s)</th>
<th>Jet Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>22</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>22</td>
<td>10</td>
<td>55</td>
</tr>
</tbody>
</table>
Jet Angle

- As jet angle increases:
  - more atomisation towards side of splash plate, creates more uniform thickness distribution
  - atomisation occurs closer to plate at plane of symmetry
  - little effect on top surface velocity
Jet Velocity

<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>Jet Velocity (m/s)</th>
<th>Jet Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>22</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>22</td>
<td>18</td>
<td>45</td>
</tr>
</tbody>
</table>
Jet Velocity

- As jet velocity increases
  - there is no effect on sheet thickness or radial distribution
  - velocity distribution increases proportionally
Test Cases: Second Set

- Splash plate configuration held constant
  - Nozzle Diameter 32 mm
  - Jet Angle 45 degrees

- Varied key properties affecting droplet size
  - Viscosity
  - Jet Velocity
  - Surface Tension

- Looking at effect on droplet size. Only 0 to 10° from plane of symmetry was analysed.
Test Cases: Second Set

- Breakup length
- Breakup angle
- Breakup point
Low Black Liquor Viscosity: Case 1

- Viscosity: 50 mPa·s
- Jet Velocity: 4 m/s
- Surface Tension: 60 mN/m
- Density: 1350 kg/m³
Low Black Liquor Viscosity: Case 1
Low Black Liquor Viscosity: Case 1

- Average Droplet Diameter: 6.08 mm
- Breakup Length: 270 mm
- Breakup Angle: 8.4 degrees
Typical Splash Plate
Conditions: Case 2

- Viscosity: 200 mPa·s
- Jet Velocity: 4 m/s
- Surface Tension: 60 mN/m
- Density: 1350 kg/m³
Typical Splash Plate Conditions: Case 2
Typical Splash Plate Conditions: Case 2

- Average Droplet Diameter: 6.16 mm
- Breakup Length: 270 mm
- Breakup Angle: 9.5 degrees
Low Jet Velocity:
Case 4

- Viscosity: 200 mPa·s
- Jet Velocity: 1 m/s
- Surface Tension: 60 mN/m
- Density: 1350 kg/m³
Low Jet Velocity: Case 4

Alstom Test Plan Simulation
Case 4
viscosity = 200 mPa·s, velocity = 1.0 m/s

Simulent Inc.
Low Jet Velocity: Case 4

- Average Droplet Diameter: 6.39 mm
- Breakup Length: 120 mm
- Breakup Angle: 36.9 degrees
### Summary of Test Case Results: Second Set

<table>
<thead>
<tr>
<th>Case #</th>
<th>Visc (mPa·s)</th>
<th>Nozzle Velocity (m/s)</th>
<th>Surface Tension (mN/m)</th>
<th>Droplet Size (mm)</th>
<th>Breakup Length (mm)</th>
<th>Breakup Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>4</td>
<td>60</td>
<td>6.08</td>
<td>270</td>
<td>8.4</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>4</td>
<td>60</td>
<td>6.16</td>
<td>270</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>4</td>
<td>60</td>
<td>6.58</td>
<td>320</td>
<td>10.6</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1</td>
<td>60</td>
<td>6.39</td>
<td>120</td>
<td>36.9</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>10</td>
<td>60</td>
<td>4.49</td>
<td>270</td>
<td>3.8</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>4</td>
<td>30</td>
<td>5.48</td>
<td>270</td>
<td>9.5</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>4</td>
<td>90</td>
<td>7.6</td>
<td>280</td>
<td>10.1</td>
</tr>
</tbody>
</table>
Summary

- Preliminary BLSpray has been developed and validated

- Current BLSpray can be used to:
  - optimise current nozzle designs
  - test new nozzle designs
  - understand effects of varying black liquor properties

- Work is continuing to improve the code to include in-situ influences such as vapourisation, vertical velocity
Actual Spray