Flashing liquid jets and two-phase droplet dispersion
II. Scaled experiments for derivation of droplet size correlations

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Experimental set-up

- New ‘Dense-spray’ receiving optics used

- Experimental conditions:
  - Droplet measurement size range = 0 – 2132 microns.
  - Ambient (lab.) temperature circa 15 C
  - Rig pressure = 6 - 14 barG
  - Data collected 250 mm downstream on nozzle centerline for flashing sprays and 500 mm for subcooled sprays.
    - 0.75, 1, and 2 mm nozzles characterised.
    - L/d ratios from 0.5 – 4.53.

- PDA collected continuously data through mechanical break-up, transition and fully flashing regimes
Test matrix sub-cooled & super-heated experiments

- Data for the sub-cooled mechanical break-up were recorded:
  - 500 mm down-stream (except for the 0.75 mm cyclohexane data which was recorded 1000 mm down-stream due to large break-up length).
  - 11 radial positions from +10 mm to -10 mm in 2 mm steps.

- Data for the super-heated sprays were recorded:
  - 250 mm downstream (a compromise between the change in break-up length with superheat)
  - On the centerline only so as to record the transient event.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Break-up</th>
<th>Diameter [mm]</th>
<th>L/D [-]</th>
<th>Pressure [barG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Sub-cooled</td>
<td>1, 2</td>
<td>1.01, 0.5</td>
<td>6, 10, 14</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>Sub-cooled</td>
<td>0.75, 1, 2</td>
<td>1.4, 1.01, 0.5</td>
<td>6,8,10,12,14</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Sub-cooled</td>
<td>0.75, 1</td>
<td>4.53, 3.4</td>
<td>6,8,10,12,14</td>
</tr>
<tr>
<td>Water</td>
<td>Super-heated</td>
<td>0.75, 1</td>
<td>3.4, 4.53</td>
<td>10</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>Super-heated</td>
<td>1, 2</td>
<td>1.01, 0.5</td>
<td>7.5, 10</td>
</tr>
<tr>
<td>Butane</td>
<td>Super-heated</td>
<td>0.75, 1, 2</td>
<td>1.4, 1.01, 0.5</td>
<td>9.5, 8, 7.5</td>
</tr>
<tr>
<td>Propane</td>
<td>Super-heated</td>
<td>1, 2</td>
<td>1.01, 0.5</td>
<td>6.5, 7.5</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Super-heated</td>
<td>1</td>
<td>1.01</td>
<td>10</td>
</tr>
</tbody>
</table>
The transient SMD against temperature of a cyclohexane spray is shown.

- $d_0 = 1\, \text{mm}$
- $L/d = 1.01$

Rig temperature, pressure and mass were recorded simultaneously with spray data.

Allows the complete trend of droplet diameter with superheat to be studied.
Flashing Cyclohexane Results (10.5 barg, 2mm, L/D=0.5)
Flashin Cyclohexane Results (10.5barg, 2mm, L/D=0.5)

(1) \(T \approx 16^\circ C, \ T_{sh} \approx -65^\circ C\)
Mechanical break-up

(2) \(T \approx 40^\circ C, \ T_{sh} \approx -41^\circ C\)
Mechanical break-up

(3) \(T \approx 85^\circ C, \ T_{sh} \approx 4^\circ C\)
Transition

(4) \(T \approx 108^\circ C, \ T_{sh} \approx 27^\circ C\)
Fully Flashing
Steps in model development

- Tri-linear approach proposed by Phase II has been verified by transient data.
- Phase III model based on the Phase II model with the following major changes:
  - New correlation for mechanical break-up SMD (including fluid property ratios).
  - Slight modification of regime transition criteria
  - New SMD proposed for fully flashed condition
Steps in model development

1. Mechanical break-up SMD correlation
2. Regime transition criteria
3. Flashing break-up SMD correlation
4. Mechanical droplet size distribution correlation
5. Flashing droplet size distribution correlation
Mechanical break-up SMD correlation

- A three step method was used to derive the mechanical break-up correlation
  - Dimensional form – First the correlation was assumed to take a simple dimensional form where the SMD was only proportional to a pressure and nozzle diameter term.
  - Effect of liquid properties – Next the effect of the fluid properties on the SMD were examined and included in the correlation.
  - Dimensionless form – Finally the correlation was converted into a non-dimensional form and some of the exponents modified to ensure a best fit with the cyclohexane and water data.

- Phase II Correlation:
  \[ \frac{d_{da}}{d_o} = 64.73 \quad We_{Lo}^{-0.533} \quad Re_{Lo}^{-0.014} \left( \frac{L}{d_o} \right)^{0.114} \]

- Phase III Correlation:
  \[ \frac{d_{da}}{d_o} = 74 We_{Lo}^{-0.85} \quad Re_{Lo}^{0.44} \left( \frac{L}{d_o} \right)^{0.114} \left( \frac{\mu_{Lo}}{\mu_{water, stp}} \right)^{0.97} \left( \frac{\sigma_{Lo}}{\sigma_{water, stp}} \right)^{-0.37} \left( \frac{\rho_{Lo}}{\rho_{water, stp}} \right)^{-0.11} \]
Comparison of mechanical break-up correlation with experimental data

Phase III Correlation

Phase II Correlation
Regime Transition Criteria Correlation

- The transition criteria is assumed to take the same form proposed in Phase II:
  - Criteria for Transition A: \[ Ja \phi = 48 \frac{1}{We_v^{\frac{1}{7}}} \text{, with } \phi = 1 - e^{\frac{-2300}{\rho_v / \rho_L}} \]
  - Criteria for Transition B: \[ Ja \phi = 108 \frac{1}{We_v^{\frac{1}{7}}} \]

- For fully flashing conditions, the SMD is assumed to be a constant of 80 microns and decreases at a rate of 1 micron per 10 degrees until a final limit of 10 microns is achieved.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Pressure [barG]</th>
<th>(d_0) [mm]</th>
<th>(L/d_0) [-]</th>
<th>Measured [°C]</th>
<th>Phase II [°C]</th>
<th>Phase III [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Water</td>
<td>10</td>
<td>0.75</td>
<td>4.5</td>
<td>0 - 20</td>
<td>10 – 30</td>
<td>17</td>
</tr>
<tr>
<td>Water</td>
<td>10</td>
<td>1</td>
<td>3.54</td>
<td>-5 - 5</td>
<td>0 - 10</td>
<td>17</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>7.5</td>
<td>1</td>
<td>1.01</td>
<td>10 - 20</td>
<td>30 – 40</td>
<td>15</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>10</td>
<td>1</td>
<td>1.01</td>
<td>0 - 20</td>
<td>30 - 40</td>
<td>15</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>10</td>
<td>2</td>
<td>0.505</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>Gasoline</td>
<td>10</td>
<td>1</td>
<td>1.01</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
</tr>
</tbody>
</table>
Droplet distribution correlation

- The droplet size distribution adopted is the Rosin-Rammler distribution:

\[ \nu (D) = 1 - e^{-a_{RR} \left( \frac{D}{D_{SMD}} \right)^{b_{RR}}} \]

- The exponents used for mechanical break-up and fully flashing are presented in the table below:

<table>
<thead>
<tr>
<th>Correlation</th>
<th>( a_{RR} )</th>
<th>( b_{RR} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elkobt</td>
<td>0.422</td>
<td>5.32</td>
</tr>
<tr>
<td>Phase III (mechanical)</td>
<td>0.4</td>
<td>2.00</td>
</tr>
<tr>
<td>Phase II (fully flashing)</td>
<td>0.79</td>
<td>0.97</td>
</tr>
</tbody>
</table>
Comparison of model with experimental data

Cyclohexane, $d_0 = 1$ mm, $L/d = 1.01$, $P = 7.5$ barG

Cyclohexane, $d_0 = 2$ mm, $L/d = 0.5$, $P = 12$ barG
Comparison of sub-cooled droplet size distribution with experimental data

- Cyclohexane, $d_0 = 0.75 \text{ mm}$, $L/d = 1.4$
Comparison of flashing droplet size distribution with experimental data

- Water, $d_0 = 0.75\text{ mm}$, $L/d = 1.4$, $P = 10\text{ barg}$

![Graph showing comparison of measured and predicted droplet size distribution.](image)
A new model for predicting the SMD and droplet size distributions of a release from a sharp edged orifice from the initial conditions in the nozzle has been developed.

The model covers a wide range of liquids, nozzle diameters, superheat temperature and aspect ratios.

The new mechanical break-up correlation includes the influence of fluid properties and agrees well with the measured data.

The ‘tri-linear’ modeling approach has been verified, across data sets.

Successful simultaneous measurement of rig conditions and droplet data.

New correlations for the regime transition criteria have been developed and verified against experimental data.

New correlations for the droplet size distributions show relatively good agreement with the experimental data.
Some data were clipped due to limitations of the laser diagnostic technique (the technique chosen was still the most appropriate), hence the droplet size distribution correlation may need modifying due to advances in measurement technology.

- Bimodal droplet size distributions under (near-)flashing conditions
- Droplet size correlations for very high superheats
- Additional large-scale experiments and multi-component releases