Initial droplet size distributions for subsea blowouts with and without injection of chemicals - experimental study and model predictions*)

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*) Based on results from American Petroleum Institute project API JITF D3 conducted by SINTEF. Project manager Per Johan Brandvik
Major issues

- What can be learned from lab studies?
  - The scaling issue
- Basic theory for droplet breakup
  - Breakup regimes
  - Scaling laws
  - Bubbly flow
  - Buoyant jets
- Results from lab studies
  - Experimental design
  - Correlations for Volume Median Diameter (VMD) from lab data
  - Droplet size distributions
- Practical examples
  - Up-scaling from lab to field
What can be learned from lab studies? (1)

- Our main issue is deepwater blowouts with outlet diameters up to 0.5 m and oil flow rates up to 400 m$^3$ per hour.
- Nozzle diameters and oil flow rates corresponding to such cases are not achievable in lab experiments:
  - Lab-scale nozzle sizes will be limited to the millimeter range
  - Lab-scale flow rates will be limited to a few liters per minute
- Moreover, lab-scale tests will be momentum dominated jets, while full scale blowouts tend to be buoyancy dominated
- Upscaling from lab to field must rely on scaling laws involving certain non-dimensional numbers
  
  - Weber number: \( We = \rho U^2 D / \sigma \)
  - Reynolds number: \( Re = \rho U D / \mu \)
  - Froude number: \( Fr = U / \sqrt{g'D} \)
What can be learned from lab studies? (2)

Lab vs field scale*)

*) Lab: Oil only. Field and full scale: 50% gas by volume
What can be learned from lab studies? (3)

- Jet-like vs. plume-like behavior

![Graphs showing relative plume rise and distance downstream for different conditions.]
Breakup regimes (1)
Tang and Masutani 2003

(a) Rayleigh instability
(b) Sinuous mode
(c) Intermediate
(d) Atomization
Breakup regimes (2)

Breakup modes (Tang and Masutani 2003)
Breakup regimes (2)

Breakup modes (Tang and Masutani 2003)

- Silicone oil
- Mineral oil
- Liquid CO$_2$

We = 324
Scaling laws (1)
Modified Weber number scaling

- Wang and Calabrese (1986)*:
  
  \[ \frac{d_{50}}{D} = A \text{We}^{-3/5} [1 + B \text{Vi} (\frac{d_{50}}{D})^{1/3}]^{3/5} \]

  where A and B are empirical coefficients,
  and \( \text{Vi} = \frac{\text{We}}{\text{Re}} = \mu \frac{U}{\sigma} \) is the Viscosity number

- \( \text{Vi} \ll 1 \):
  
  \[ \frac{d_{50}}{D} = A \text{We}^{-3/5} \] (Weber number scaling)

- \( \text{Vi} \gg 1 \):
  
  \[ \frac{d_{50}}{D} = C \text{Re}^{-3/4} \] (Reynolds number scaling)
  
  - This condition may result from injection of a chemical dispersant into the oil, which may reduce IFT by a factor of 100 or more.

Scaling laws (2)

Bubbly flow

- The effect of gas released together with oil may be accounted for in terms of an efficient exit velocity

\[ U_n = \frac{U_{oil}}{(1 - n)^{1/2}} \] (Void fraction adjustment)

where \( U_{oil} \) is the oil only exit velocity,
\( n \) is the gas void fraction in the exit flow.

Buoyant jets

- The effect of buoyancy may be accounted for by a velocity adjustment

\[ U' = U_n (1 + 1/Fr) \] (Buoyancy adjustment)

where \( Fr = \frac{U_n}{(g' D)^{1/2}} \) is the Froude number

This adjusted velocity is used in the Weber and Reynolds numbers:

\[ We' = \rho U'^2 D /\sigma, \quad Re' = \rho U' D /\mu \]
Experimental design (1)

- SINTEF’s Tower Tank facility

- Tower tank dimensions:
  - Height 6 m, diameter 3 m
  - Water volume 40 m³

- Nozzle diameter 0.5 – 3 mm.
- Flow rates 0.1 – 3 L/min
- Different arrangements for injection of dispersants

Droplet size measurements.
- Primary tool:
  LISST with range from 2.5 to 500 microns
  Mounted 3 m above nozzle
Experimental design (2)

- Oil only tests
  - All tests in the atomization regime
  - Peak droplet diameter within LISST range
  - Nozzle diameter 0.5 mm, oil flow 0.1 – 0.5 L/min
  - Nozzle diameter 1.5 mm, oil flow 0.5 – 3 L/min

- Tests with injection of dispersants
  - Nozzle diameter 1.5 mm, oil flow 1.2 – 1.5 L/min
  - Dispersant to Oil Ratio (DOR): 1:1000 – 1:25
    - Upstream injection (injected into the oil line),
    - Simulated injection tool (into the oil line close to nozzle)
    - injection above nozzle
Experimental design (3)
Example: Test series with variable DOR

Samples taken from plume for IFT measurements etc.

Droplet size distributions from LISST (time averaged)

Peak values correspond to VMD for log-normal distributions
Droplet size distributions

Cumulative distributions 17.04 2012 experiments

- Oil alone 1.5 L/min
- DOR 1:1000
- DOR 1:500
- DOR 1:250
- DOR 1:100
- DOR 1:50
- DOR 1:25

Cumulative volume fraction

Lognormal (1)
Log normal (2)

Droplet size, microns
Correlations with lab data (1)
Correlations with lab data (2)

\[ \text{We}^* = \frac{\text{We}}{[1 + B Vi (d_{50}/D)^{1/3}]} \]
Up-scaling from lab to field (1)

- Up-scaled droplet distributions based on equal oil-only Weber numbers, \( \text{We} = \rho \frac{U_{oil}^2}{\sigma} \frac{D}{\text{d}} \)
- We’ and Re’ based on effective oil velocity \( U' \), adjusted for void fraction and buoyancy

<table>
<thead>
<tr>
<th>Case</th>
<th>D, mm</th>
<th>Q oil</th>
<th>Void</th>
<th>U m/s</th>
<th>U’ m/s</th>
<th>We’</th>
<th>Re’</th>
<th>d50 oil</th>
<th>d50 disp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab</td>
<td>1.5</td>
<td>1.5 L/min</td>
<td>0</td>
<td>14.1</td>
<td>14.1</td>
<td>15 283</td>
<td>1783</td>
<td>133 um</td>
<td>46 um</td>
</tr>
<tr>
<td>Field</td>
<td>120</td>
<td>64 m³/h</td>
<td>50%</td>
<td>1.6</td>
<td>3.1</td>
<td>57 593</td>
<td>30 950</td>
<td>4.2 mm</td>
<td>0.49 mm</td>
</tr>
<tr>
<td>Full scale</td>
<td>400</td>
<td>392 m³/h</td>
<td>50%</td>
<td>0.9</td>
<td>2.7</td>
<td>153 670</td>
<td>92 300</td>
<td>7.7 mm</td>
<td>0.76 mm</td>
</tr>
</tbody>
</table>

~ 60 kbbl/day
Up-scaling from lab to field (2)

- Relative MVD
Up-scaling from lab to field (3)
Droplet size distributions: lab scale

Lab. exp. D = 1.5 mmØ
Up-scaling from lab to field (4)
Droplet size distributions: field experiment scale

Field exp. D = 120 mmØ

- Oil
- Disp

Volume fraction

Droplet size, mm
Up-scaling from lab to field (5)
Droplet size distributions: full scale

Full scale $D = 400 \text{ mm}\phi$

<table>
<thead>
<tr>
<th>Droplet size, mm</th>
<th>Volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>0.25</td>
<td>0.30</td>
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<tr>
<td>0.35</td>
<td>0.42</td>
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<tr>
<td>0.49</td>
<td>0.58</td>
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<tr>
<td>0.69</td>
<td>0.81</td>
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<tr>
<td>0.96</td>
<td>1.13</td>
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<tr>
<td>1.33</td>
<td>1.57</td>
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<td>2.59</td>
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<td>3.60</td>
<td>4.25</td>
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<tr>
<td>5.01</td>
<td>5.92</td>
</tr>
<tr>
<td>6.98</td>
<td>8.24</td>
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<tr>
<td>9.72</td>
<td>11.47</td>
</tr>
<tr>
<td>13.53</td>
<td>15.97</td>
</tr>
<tr>
<td>18.85</td>
<td>21</td>
</tr>
</tbody>
</table>

- Oil
- Disp
Up-scaling from lab to field (summary)

Main assumptions

- IFT presumed to be reduced by a factor of 200 with dispersant injection
- Lab scale:
  - Lognormal distributions with stdev = 0.7
- Field scale and full scale:
  - Rosin Rammler distribution with $\alpha = 1.8$ for untreated oil,
  - Lognormal distribution with stdev = 0.7 with dispersant injection

Results

- Larger gap between treated and untreated oil for field scale and full scale than for lab scale
- Explanation:
  - Droplet size for treated oil governed by Reynolds number scaling
  - Large volume flows has large Reynolds numbers (see table above)
Conclusions

- Extensive Lab studies conducted in Sintef 6 m tank to simulate blow-out with subsurface dispersant injection
- Experiments show Corexit substantially reduces droplet size even at high DOR (1:100)
- Wang and Calabrese algorithm with calibrated coefficients found to fit lab and DeepSpill results very well
- Algorithm suggests subsea dispersants made major difference in surfaced volume for Macondo
- See Johansen et al. and Brandvik et al. (2013, Marine Pollution Bulletin – in press)
- Further studies underway to better understand:
  - Dispersant type, oil type, oil temperature
  - Gas, large water depth (pressure), hydrate formation
  - Droplet coalescence /breakup post-momentum jet