Near Field Behavior of Oil & Gas Plumes

Effects of bubble/droplet sizes

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A. Chow
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Phase Separation

- Bubbles & droplets can separate from plume (and fractionate) due to stratification or crossflow
- DWH was stratification dominated
- DeepSpill was crossflow dominated

Socolofsky & Adams (2002)
Gas bubbles create plume, but currents “blow” oil and entrained seawater downstream, leaving gas to rise separately.

Socolofsky & Adams (2002)
Density stratification is caused when lighter (warmer) water overlies heavier (colder) water.

Light gas and heavy seawater rise to a level of neutral buoyancy causing oil and seawater to separate from the gas and intrude laterally.

Gas bubbles continue to rise, causing plume to restart, with lesser quantities of oil

Correlations

Principal independent variables: B, N, \( u_s \), z, \( U_a \)

\[
\frac{h_T}{(B/N^3)^{1/4}} = 2.8 - 0.27\left(\frac{u_s}{BN}\right)^{1/4}
\]  
(300-400 m)

\[
f = 1.0 - 0.048\left[\frac{u_s}{BN}\right]^{1/4} \]  
(0.9-0.95)

\[
\frac{Q_i}{(B^3/N^5)^{1/4}} = 0.9 - 0.38\left[\frac{u_s}{BN}\right]^{0.24}
\]  
(~1500-2000 m\(^3/s\))

\[
h_i = 1.2U_a/N
\]  
(30-100 m)

\[
b_i = 0.65QN/\left(U_a\right)^2
\]  
(100-500 m)

Socolofsky & Adams (2003, 2005),
Akar and Jirka (1995)
Peak CDOM measurements vs Predicted trap height
\[ D_{\text{max}} \sim (s/r)^{3/5} e^{-2/5}; \ e \sim U^3/D; \ D_{\text{max}}/D \sim rQ_o/sD^3)^{-0.6} \]

High jet velocity (high \( e \)), and chemical dispersants (low \( s \)) produce small droplets (right)
Large drops

Atomization

Reynolds Number, $Re = \rho UD\mu$

Ohnesorge Number, $Z = \frac{\mu}{\rho D^{3/2}}$

Rayleigh varicose breakup
Sinuous wave breakup
Filament core breakup
Wave Atomization
Fully atomization
Boundary 1: $Z = 5.5/Re_D$
Boundary 2: $Z = 10/Re_D$

Large drops

\[ W' = \frac{rQ_o^2}{sD_o^3} \]

Atomization

Ohnesorge Number, \( Z = \frac{\mu}{\rho g D^3} \)

Reynolds Number, \( Re = \frac{\rho UD}{\mu} \)

Large drops

Atomization

\[ W' = \frac{rQ_o^2}{sD_o^3} \]

\[ D/D_o \sim W'^{-3/5} \]

Simulated & Observed Cumulative Gas BSD from DeepSpill Field Experiment
(cm; Data from SINTEF: average of near and far measurements Fig 7.1.12; Model 2: $D_o = 6$ cm, n = 3)
Simulated & Observed Cumulative Oil DSD from DeepSpill Field Experiment

(cm; data from SINTEF: ave of close and far measurements Fig 7.1.14; (Model 2; $D_o = 6$ cm, $n = 3$)
Applying Chemical Dispersants to Sub-Surface Oil Spills

Chevron-MIT study also involving TAMU and U. Hawaii

- Dispersants produce smaller droplets which
- Acting individually:
  - Rise more slowly
  - Dissolve/degrade more rapidly
- Within a plume:
  - Separate from bubbles and larger droplets
  - Avoid rapid plume transport to surface
How small droplets do you need for effective dispersal?

- Plume behavior depends on $B$, $N$, $u_s$, $z$
  - $U \sim (B/z)^{1/3}$
  - $h_p, h_t \sim (B/N^3)^{1/4}$
  - $U_c \sim (BN)^{1/4}$

- Expect droplets to detrain/intrude as function of
  - $U_N = w_s/(BN)^{1/4}$
Plume Classification

Socolofsky and Adams (2005)

$h_T > H$

$h_T < H$

Type 1

Type 1*

Type 2

Type 3

$U_N < 1.4$

$1.4 < U_N < 2.4$

$2.4 < U_N$

Socolofsky & Adams (2005): $U_N > 0.6$ no intrusion (bubbles)

Chow (2004): $U_N < \sim 0.1$ significant intrusion (glass beads & brine motivated by CO$_2$ storage)
## Ballotini glass beads

*(Potters Industries – Dawson-MacDonald Co.)*

<table>
<thead>
<tr>
<th>Bead</th>
<th>Median Diameter (cm)</th>
<th>$U_s$ (cm/s)*</th>
<th>$U_N$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.072</td>
<td>11.0</td>
<td>2.0</td>
</tr>
<tr>
<td>B (GC)</td>
<td>0.051</td>
<td>7.5</td>
<td>1.4</td>
</tr>
<tr>
<td>C</td>
<td>0.032</td>
<td>4.3</td>
<td>0.78</td>
</tr>
<tr>
<td>D (GC)</td>
<td>0.025</td>
<td>3.1</td>
<td>0.56</td>
</tr>
<tr>
<td>AD</td>
<td>0.015</td>
<td>1.4</td>
<td>0.25</td>
</tr>
<tr>
<td>AE (AC)</td>
<td>0.012</td>
<td>1.0</td>
<td>0.18</td>
</tr>
<tr>
<td>AG (GC)</td>
<td>0.0081</td>
<td>0.52</td>
<td>0.095</td>
</tr>
<tr>
<td>AH (AC, GC)</td>
<td>0.0064</td>
<td>0.38</td>
<td>0.070</td>
</tr>
</tbody>
</table>

*SG = 2.5; $B = 3 \times 10^{-5}$ m$^4$/s$^3$; $N = 0.3$ s$^{-1}$
Experimental water tank

- High-carbon steel frame
- 38 mm thick, two-ply, fully-tempered, laminated glass
- High-carbon steel base

Dimensions:
- Width: 1.22 m
- Height: 2.44 m
- Length: 2.12 m (by 1.6 m wide)
Two-tank stratification method
Release mechanism

Mariotte siphon

1L Bottle
Funnel
Sponge
D=2.5cm PVC Pipe system

12V Vibrator

Water surface
Collection trays

- Each cell measures 4cm by 5cm
- Longer piece: 35 cells (total length: 140 cm)
- Shorter piece: 14 cells (each measures: 56cm)
- Two measurements per location
Experiments with beads AH, AG, D, B
1000g per release, water depth = 190cm

<table>
<thead>
<tr>
<th></th>
<th>AH</th>
<th>AG</th>
<th>D</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_s$ (cm/s)</td>
<td>0.38</td>
<td>0.52</td>
<td>3.1</td>
<td>7.5</td>
</tr>
<tr>
<td>$Q_b$ (m$^3$/s)</td>
<td>1.94E-6</td>
<td>2.09E-6</td>
<td>3.1E-6</td>
<td>2.9E-6</td>
</tr>
<tr>
<td>B (m$^4$/s$^3$)</td>
<td>2.77E-5</td>
<td>2.98E-5</td>
<td>4.42E-5</td>
<td>4.13E-5</td>
</tr>
<tr>
<td>N (1/s)</td>
<td>0.254</td>
<td>0.258</td>
<td>0.251</td>
<td>0.263</td>
</tr>
<tr>
<td>$U_N$</td>
<td>0.0738</td>
<td>0.0987</td>
<td>0.537</td>
<td>1.306</td>
</tr>
<tr>
<td>Type</td>
<td>$1^*$ (intrusion)</td>
<td>$1^*$ (intrusion)</td>
<td>$1^*$ (detrainment)</td>
<td>$1^*/2$ (borderline)</td>
</tr>
</tbody>
</table>
\[ U_N = \frac{u_s}{(BN)^{1/4}} \]

- \( U_N \) = Non-dimensional slip velocity
- \( u_s \) = Slip velocity of particles
- \( B \) = Buoyancy flux
- \( N \) = Stratification frequency
- \( (BN)^{1/4} \) = Characteristic plume fluid velocity

\[ y = -0.06\ln(x) + 0.0533 \]
\[ R^2 = 0.99482 \]
### Deepwater Horizon*

<table>
<thead>
<tr>
<th>Diameter (um)</th>
<th>$U_s$ (cm/s)</th>
<th>$U_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>3.5</td>
<td>0.16 to 0.30</td>
</tr>
<tr>
<td>300</td>
<td>0.69</td>
<td>0.03 to 0.06</td>
</tr>
<tr>
<td>100</td>
<td>0.094</td>
<td>0.004 to 0.008</td>
</tr>
<tr>
<td>30</td>
<td>0.0086</td>
<td>0.0004 to 0.0008</td>
</tr>
<tr>
<td>10</td>
<td>0.00095</td>
<td>0.00004 to 0.00008</td>
</tr>
</tbody>
</table>

Preliminary conclusion: Droplets smaller than at least 300 mm should intrude

Spherical oil droplets with density = 0.85 g/cm$^3$; $B = 0.5$ to 1.0 m$^4$/s$^3$; $N = 0.0004$ to 0.0027 s$^{-1}$
Droplet rise through non-entraining intrusion layer

\[ t_i = \frac{h_i}{u_s} \]
\[ V_i = Q_i t_i = \pi r_i^2 h_i \]
\[ r_i = \left( \frac{Q_i}{\pi u_s} \right)^{1/2} \]
\[ Q_i = 0.9B^{3/4}/N^{5/4} \]
\[ r_i = 0.5B^{3/8}/(N^{5/8}u_s^{1/2}) \sim D^{-1} \]
Correlations

Principal independent variables: B, N, \( u_s \), z, \( U_a \)

\[
h_T / (B / N^3)^{1/4} = 2.8 - 0.27(u_s / (BN)^{1/4})
\]

(300-400 m)

\[f = 1.0 - 0.048[u_s / (BN)^{1/4}]^{0.86}\]

(0.9-0.95)

\[
Q_i / (B^3 / N^5)^{1/4} = 0.9 - 0.38[u_s / (BN)^{1/4}]^{0.24}
\]

(~1500-2000 m\(^3\)/s)

\[h_i = 1.2U_a / N\]

(30-100 m)

\[b_i = 0.65QN / U_a^2\]

(100-500 m)

Socolofsky & Adams (2003, 2005),
Akar and Jirka (1995)
Data from Chow (2004)
Deepwater Horizon

- 300 mm drop: $180 < s_r < 800$ m
- 30 mm drop: $5.5$ km $< s_r < 24$ km

Much of the oil was found on surface within 1 km of source (must have been large droplets; dispersants not totally effective)

Data from Chow (2004)
Ongoing and future work

- Add’l exp’ts being conducted
  - low & intermediate $U_N$
  - poly-dispersed buoyancy source (oil/gas, large/small oil)
- Stratification & current (towing release)
- Transport & fate within intermediate field (intrusion layer & open ocean above layer)
- Interfacing particles with Lagrangian transport models
Near Field oil distribution can be used in simple 1-D models of advection, diffusion, dissolution/degradation
SABGOM: data-assimilating 3D ocean circulation model

LTRANS: 3D particle-tracking with advection, diffusion, and oil transformations

LTRANS transports/transforms droplets. Droplets with different size, DOB, decay properties transported independently; concentration distributions can be computed during post-processing

Multi-phase oil plume model
Questions?