Mechanistic Modeling for Size-Selective Removal and Separation of Fines or Paraffin Crystals from Thin Beds

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Outline:

1. Objectives
2. Practical Significance
3. Roots
4. Experimental & Modeling
5. Results & Conclusions

...2 min discussions...
1. Objectives

1. To expose the power of the near-wall turbulent activity for size-selective removal of particles from interface beds,

2. To introduce the 0.1-100 µm scale to multiphase particle transport and separation studies,

3. To use a mechanistic modeling approach to assess the aging of crystalized paraffin and the fine sand grading,

4. To create interest and curiosity for developing on-line novel industrial separation technologies,

…. to read the paper and ask questions.
The Problem:

Dancing on The Breezy Beaches of Sestri Levante

...and listen to small sand grains storries...
Grain “1”
Let’s Dance – It’s Such a Nice Breeze!

Grain 2 (to “1”):
You go play with kids, the wind will blow you away!

Grain 3:
I eat too much!
I am too heavy!

Grain 1: 0.1-30 μm
Grain 2: 31-50 μm
Grain 3: 61-150 μm
Grain 2 (the strong one!)

Sorry kids, I was wrong -
I have been just blown away!

Why Me?
By-By!
What's Wax?

- Here is what “a PIG” can do ... and see ...
- The PIG Operator would add:

  "A "high-velocity" line is harder to pig and you should call me more often ... if you want more oil."

Picture: Courtesy: STATOIL - Snorre B to Statfjord B (Sept. 2001)
2. Practical Significance

“Aging” (or “hardening”) of deposited wax during turbulent flow of waxy crude(*) indicates increasing of high Cn Concentration in the deposited jelly layer ... WHY?

(*)Experimental work: 
(*) Hsu, J., Santamaria, M. & Brubaker, J. SPE 28480, 1994

Validated first with THIS MODEL

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“Aging” ... WHY?

FACTS:
1. Turbulent bulk flow,
2. Liquid (not solid!) jelly layer (JL)
3. Floating Cn wax crystals
4. Size-dependent entrainment
5. Size ↔ component correlation

JL = Jelly Layer

JL a soup w. paraffin crystals (warm crude core flow)

2. Practical Significance to LAB & MODEL

More Laboratory

Physical Model

Turbulent Bulk Flow

FACTS:
1. Turbulent bulk flow,
2. Liquid (not solid!) jelly layer (JL)
3. Floating Cn wax crystals
4. Size-dependent entrainment
5. Size ↔ component correlation

... so what ???!!!
Observations

1. Turbulent bulk flow,
2. Liquid (not solid!) jelly layer (JL)
3. Floating Cn wax crystals
4. Size-dependent entrainment
5. Size (n) correlation

Mechanistic Modeling

1. Burst-Sweep Jetting Removal,
   Experimental (“Petronas”) Rig
2. Heterogeneous Nucleation
3. Size-Specific Removal Forces
4. Crystal Size
5. Subcooling

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The Detachment – A Critical Moment!

4 Forces on the sandy beach

“Small” \((F_b=F_a)\)

“Intermediate” \((F_g=F_b)\)

“Large” \((F_g=F_d)\)

Net Wt. \((F_g)\)

Adhesion \((F_a)\)

Hydr. Drag \((F_d)\)

Burst Updraft \((F_b)\)

3. Roots

Turbulent Flow

Sweep

1-2 w.u.

(R. Adrian, Harpin vortex 2007 Phys.of Fluids)


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4. Modeling – Particle Entrainment

Pipe Flow 0.31 m/s
D=95mm
Water 20°C
\( \tau_w = 0.3 \text{Pa} \)

4 Forces
3 Pairs

**Critical Detachment Shear** (\( \tau \)) (Pa)

<table>
<thead>
<tr>
<th>Bead/Cristal Size ( d_p ) (μm)</th>
<th>“Small” ((F_b = F_a))</th>
<th>“Interm.” ((F_g = F_b))</th>
<th>“Large” ((F_g = F_d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>100</td>
<td>No</td>
<td>Entrained</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>Entrained</td>
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<td>0.01</td>
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<td>0.00</td>
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</table>

- Glass Beads-Water
- Waxy Crude Paraffin (API 40, 60°C WAT=15°C)

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4. Modeling – Particle Entrainment Rate

Number of Particles of Seize “$d_p$”

$[d_{p1} < d_p < d_{p2}]$

removed from the “Observation Area” ($A_o$) during 1 sec

$N(d_p)/s/A_o$
4. Experimental & Modeling

A Physical (Mechanistic) Model Explains Aging of Paraffin Deposited Layer Exposed to Turbulent Bulk Flow - Explained Without the Use of Empirical Dispersion Coefficients (as done) Bringing Direct Experimental Evidence is Tricky – Let’s Use Silica Fine Sand or Glass Beads!

Laboratory Work Performed at University of Alberta

Glass Beads
Leica – Particle Scanning Microscope

A Similar Size Scale & Range

<table>
<thead>
<tr>
<th>Glass bead avg. dia. (dp) (μm)</th>
<th>0.00</th>
<th>0.15</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
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</tr>
</tbody>
</table>

100μm
5. Laboratory versus Modeling
Glass Beads in a LOOP: 95mm ID /L=12 m, Water 0.3 m/s
5. Laboratory versus Modeling
Aging of Deposited Paraffin(*)

[Graphs and data plots showing aging of deposited paraffin]
5. Conclusions

- Now we know why the PIG Operator was right! …:
  - *A “high-velocity” (high Re etc) line is harder to pig*

- Now we may design on-line size-selective separators for fine particles & crystals,

- Now we may handle better the near-wall turbulent transport activity ($$$),

- Now we may trust the mechanistic modeling approach more than before…
Acknowledgments

Thank you!
Coherent flow structures in a depth-limited flow over a gravel surface: The role of near-bed turbulence and influence of Reynolds number - R. J. Hardy, James L. B., S. N. Lane, and P.E. Carbonneau, J. GEOPHYS. RES., V. 114, 2009
Figure 7. Limiting operation conditions - upper and lower fluid transport velocity limits versus particle diameter (glass beads and water).
Tables 1. (a) Forces potentially involved in the entrainment of a particle laying/rolling at fluid-solid interface, (b) Force balances specific to three major groups of particles [17].

(a)

<table>
<thead>
<tr>
<th>#</th>
<th>Force</th>
<th>New/Old</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Net Weight</td>
<td>F_g</td>
<td>$F_g = \left(\pi / 6\right) d_p^3 \rho g \Delta \rho$</td>
</tr>
<tr>
<td>2</td>
<td>Adhesion</td>
<td>F_a</td>
<td>$F_a = c_1 d_p$</td>
</tr>
<tr>
<td>3</td>
<td>Drag</td>
<td>F_d</td>
<td>$F_d = c_d \rho_f \left( \frac{U^2}{2} / \lambda \right) \cdot A_p$ for: $Re_{(dp, u)} \geq 1$</td>
</tr>
<tr>
<td>4</td>
<td>Lift</td>
<td>F_L</td>
<td>Replaced by $F_b$</td>
</tr>
<tr>
<td>5</td>
<td>Burst Updraft</td>
<td>F_b</td>
<td>$F_b = c_2 \rho_f \frac{U^2}{V} \cdot (Re_{\lambda})^2$ for: $Re_{(dp, u)} \leq 1$</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>#</th>
<th>Zone</th>
<th>Force Balance</th>
<th>Critical Removal Sh. Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small Particles</td>
<td>$F_a = F_b$</td>
<td>$\tau_{wc} = k_1 \cdot (d_p)^{-4/3}$</td>
</tr>
<tr>
<td>2</td>
<td>Intermediate</td>
<td>$F_g = F_b$</td>
<td>$\tau_{wc} = k_2 \cdot (d_p)^0$</td>
</tr>
<tr>
<td>3</td>
<td>Large Particles</td>
<td>$F_g = F_d$</td>
<td>$\tau_{wc} = k_3 \cdot d_p^{1/1}$</td>
</tr>
</tbody>
</table>


...A rate selective extraction CALCULATION MODEL is available (P.Toma)