High spatial and temporal resolution planar capacitive sensing in oil-water pipe flow

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NOVEMBER 29, 2013
OUTLINE

• Holdup Estimation in Core Flow Using Image Processing
• Film thickness measurement using infrared images
• Planar sensor simulation
• Next steps
Holdup estimation in core flow using image processing
Algorithm

Pre-processing
- Cutting
- Noise Reduction
- Contrast enhancement
Algorithm

Segmentation

• Active contours
• Mathematical morphology
Algorithm

Volume Calculation

- Radius measurement
- Polynomial fit
- Integration
- Oil Holdup

\[ r(x) = x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0 \]

\[ V_o = \int_0^L \pi r^2(x) \, dx \]

\[ \tilde{h}_o = \frac{V_o}{\pi R^2 L} \]
Evaluation

Holdup correlation

\[ U_{os} (1 - \tilde{h}_o) - s_0 U_{ws} \tilde{h}_o - c V_{ref} \tilde{h}_o^q (1 - \tilde{h}_o)^m = 0 \]

\[ V_{ref} = a_i^{n_i - 2} \sqrt{gD} \left( \frac{\rho_2 - \rho_1}{\rho_2} \right)^{1/2 - n_i} \left( \frac{\rho_2 \sqrt{gDD}}{\mu_2} \right)^{n_i/2 - n_i} \]

\[ q = \frac{7 - 3n_i}{4 - 2n_i} \]

c, m, a, g, D, \mu, \rho, n are constants

From Rodriguez et al, 2006

Parameters
Fractional difference between areas (DFA)
Sensitivity (S)
Mean square error (MSE)
Number of sites of disagreement (NSD)
Holdup results

<table>
<thead>
<tr>
<th>Test</th>
<th>Holdup by correlation</th>
<th>Holdup using Active Contours</th>
<th>Holdup using Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.521</td>
<td>0.462</td>
<td>0.498</td>
</tr>
<tr>
<td>2</td>
<td>0.812</td>
<td>0.625</td>
<td>0.634</td>
</tr>
<tr>
<td>3</td>
<td>0.709</td>
<td>0.584</td>
<td>0.597</td>
</tr>
<tr>
<td>4</td>
<td>0.814</td>
<td>0.693</td>
<td>0.701</td>
</tr>
</tbody>
</table>

Relative error %

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.32</td>
<td>4.22</td>
<td>2.98</td>
</tr>
<tr>
<td>2</td>
<td>23.03</td>
<td>0.98</td>
<td>4.65</td>
</tr>
<tr>
<td>3</td>
<td>17.63</td>
<td>4.65</td>
<td>2.09</td>
</tr>
<tr>
<td>4</td>
<td>14.86</td>
<td>2.09</td>
<td>2.09</td>
</tr>
</tbody>
</table>

Average

<table>
<thead>
<tr>
<th>Holdup by correlation</th>
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<th>Holdup using Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.71</td>
<td>2.98</td>
<td>2.98</td>
</tr>
</tbody>
</table>
Film thickness measurement using infrared images

- Rectangular channel with adjustable space between the sensor and the wall in front of it.
- Micrometer screws from 0 to 700 microns in steps of 100 microns.
- Oil was added to the water and then introduced as a flow on the top of the channel.
- The average measured values (using conductance planar sensor) were compared with the film thickness calculated by the infrared images.
Experiments

<table>
<thead>
<tr>
<th>Test</th>
<th>Vo (mL)</th>
<th>Vw (mL)</th>
<th>Average Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1 to Test 7</td>
<td>5</td>
<td>400</td>
<td>16.53</td>
</tr>
<tr>
<td>Test 8 to Test 14</td>
<td>10</td>
<td>400</td>
<td>20.68</td>
</tr>
<tr>
<td>Test 15 to Test 21</td>
<td>100</td>
<td>100</td>
<td>28.42</td>
</tr>
</tbody>
</table>

\[
ARE = \frac{1}{N} \sum_{N} \text{abs}(\frac{F_{Im} - F_{S}}{F_{Im}}) \times 100\%
\]
Algorithm

Pre-processing:
Cutting

Segmentation:
Mathematical morphology

Film thickness Calculation

\[ F_{lm} = \left( \frac{1}{NP} \sum N_w \right) \times MP \]

\[ F_{lm} = 378.19 \]

<table>
<thead>
<tr>
<th>Vo (mL)</th>
<th>Vw (mL)</th>
<th>NP</th>
<th>MP</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>400</td>
<td>11935</td>
<td>400</td>
</tr>
</tbody>
</table>
Results

Test 4. Micrometers position 400µm and average film thickness by image 383.04µm and by sensor 373.28µm.

Test 14. Micrometers position 700µm and average film thickness by image 613.7243µm and by sensor 611.295µm.

Test 20. Micrometers position 600µm and average film thickness by image 531.53µm and by sensor 504.04µm.
Results

Water Film Thickness

Micrometers Position [$\mu$m]
Planar sensor simulations

• Objective: Find the best capacitive planar sensor geometry
  • 5 geometries were tested
• Comparative features:
  • maximum measurable thickness of the film,
  • quasi-linear sensor characteristics
  • spatial resolution.
• Calculation of the sensor characteristic is done by solving the three-dimensional potential equation within the liquid film on top of the sensor electrode system using Comsol.
Planar sensor geometries

Geometry 1

Geometry 2

Geometry 3

Geometry 4

Geometry 5
Simulation results

![Graph showing simulation results]

- **Film Thickness [µm]**
- **Dimensionless Capacitance [-]**

- **Geometries:**
  - Geometry 1
  - Geometry 2
  - Geometry 3
  - Geometry 4
  - Geometry 5

The graph illustrates the relationship between film thickness and dimensionless capacitance across different geometries.
NEXT STEPS

- Calibration of capacitive planar sensor
• Sensor characterization:
  System frequency response

• Sensor and camera setting - setup in vertical 2" pipe

• Oil-Water tests (dispersed flow) in vertical pipe

• Water film thickness estimation by:
  • Capacitive sensor
  • High speed images
Acknowledgments