A Reduction of Wall Friction in Bubbly Flow with Micro Bubbles in a Vertical Pipe

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Air-Water Test Loop

separator

air sampling tank

storage tank

Local parameters
measurement

Temperature control unit

Test section transparent acrylic tube 4000mm long, 20mm ID

milky flow

after separation string-like air flow

before separation

2000 1000 500

pressure gauge

pressure drop measurement

micro-bubble generator

pump

Main flow line
Frictional Pressure Drop - Results

Single-phase flow:
Laminar flow: \( f_m = \frac{64}{Re} \)
Turbulent flow: \( f_m = 0.3164 \times Re^{-0.25} \)

Laminar-turbulent transition:
\( \alpha = 0.2\% \)  \( Re \sim 4,000 \)
\( \alpha = 0.3\% \)  \( Re \sim 5,500 \)
\( \alpha = 0.5\% \)  \( Re \sim 7,000 \)

Milky bubbly flow:
Significant reduction in wall friction (provisionally called as pseudo-laminarization)

Possible applications:
- low drag fluid transport in pipeline without chemical additives
  - No pollution
- towards smart fluids

**WHY** such significant reduction occurs?
Liquid Velocity Profiles - Results

Flow conditions (friction factor):

<table>
<thead>
<tr>
<th>α</th>
<th>Re=4,900</th>
<th>Re=12,000</th>
<th>Re=22,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>turbulence</td>
<td>turbulence</td>
<td>turbulence</td>
</tr>
<tr>
<td>0.3%</td>
<td>pseudo-laminar</td>
<td>transition</td>
<td>turbulence</td>
</tr>
<tr>
<td>0.5%</td>
<td>pseudo-laminar</td>
<td>transition</td>
<td>turbulence</td>
</tr>
</tbody>
</table>

Why still pseudo-laminarization?
A Change of Laminar Sublayer Structure?
(Comparison with Universal Velocity Profile)

Single-phase water flow: well correlated by the von Karman's universal velocity profile
Milky bubbly flow: turbulent flows follow the universal velocity profile
Psuedo-laminar flows are far from the universal velocity profile.
not on the extension of the velocity in the laminar sublayer
Transition flows are intermediate between the two

\[ u^+ = y^+ \]
\[ u^+ = 2.5 \ln y^+ + 5.5 \]