On the validity of the two-fluid model for simulations of bubbly flow in nuclear reactors

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Background

• Two-phase simulations for a full core

• Coupling with heat transfer

• 3D

• Transient

• Use of “new and innovative modelling strategies” to contribute to the development of high-fidelity simulations on a longer run

DREAM4SAFER
Development of Revolutionary and Accurate Methods for Safety Analyses of Future and Existing Reactors
Challenges

• The grid is too coarse

• Meso-scale structures cannot be resolved

• The governing equations must account for this

• In this project, the closures to the governing equations are to be derived from highly resolved numerical solutions to the “microscopically correct” governing equations
Scale terminology

- Two-fluid model with coarse resolution, *macroscale*
- Two-fluid model with fine resolution, *microscale*
- Bubbles in a continuous liquid
- Gas-liquid interface
The two-fluid model

- Continuity equation for the dispersed (bubbly) phase:
  \[
  \frac{\partial}{\partial t} (\alpha_b \rho_b) + \nabla \cdot (\alpha_b \rho_b \mathbf{u}_b) = 0
  \]

- Volume fraction field of the continuous (liquid) phase:
  \[
  \alpha_l = 1 - \alpha_b
  \]

- Momentum balance equations:
  \[
  \frac{\partial}{\partial t} (\alpha_k \rho_k \mathbf{u}_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k) = -\alpha_k \nabla p + \nabla \left[ \alpha_k \mu_k \left( \nabla \mathbf{u}_k + \nabla \mathbf{u}_k^T \right) \right] + \alpha_k \rho_k \mathbf{g} + K (\mathbf{u}_q - \mathbf{u}_k)
  \]

\[
K = \alpha_l \alpha_b \frac{18 \mu_l}{d_b^2} \frac{C_D Re_p}{24}
\]
Computational setup

- Fully periodic 2D domain
- Aspect ratio = 4
- Domain size: 0.1 x 0.4 (m)
- Mesh: 64 x 256
- Gravity acts in the negative vertical direction
- A pressure drop is applied in the opposite direction of gravity to drive the flow at a relevant velocity
- Total simulation time is set to 4 s (corresponds to >40 flow-through times)
Gas-solid flow

- The setup is used to simulate an established gas-solids case from Benyahia & Sundaresan (2012)
- Good agreement is found
- A time-resolved uniformity index is defined:

\[
\Phi(t) = \frac{\alpha_{q,\text{max}} - \alpha_{q,\text{min}}}{\alpha_{q,\text{avg}}}
\]

Snapshots of discrete phase volume fraction at \( t = 2.5 \) s (left) and 3.5 s (right). Blue and red indicate dilute and dense (volume fraction of 0.2 and higher) flow regions.

Benyahia & Sundaresan, Powder Technology (2012)
• When the same case is rerun with only material properties changed (to a typical liquid-gas flow), no meso-scale structures appear.

• However: if the bubble size is changed to obtain the same terminal velocity as in the gas-solids case (bubble diameter increases from 75 to 680 \( \mu \text{m} \)), meso-scale structures appear (but seem to be of different character).
Mesh resolution

- Mesh resolution has a significant influence on the appearance of meso-scale structures
Influence of $\alpha_{\text{avg}}$

- Meso-scale structures seem to appear only at high enough average bubble loading ($\alpha_{\text{avg}} = 0.05$ or higher)

- These results are consistent with literature investigations on the stability of uniformly bubbling suspensions (e.g. LBM w/ lift force by Sankaranarayanan & Sundaresan, CES 2002) where stability was lost at $\alpha_{\text{avg}} = 0.0257 - 0.0334$
Influence of walls

- Bounding the geometry with free-slip walls in the horizontal directions has a significant influence on the appearance of meso-scale structures.
Inconsistencies with RANS

- Employing k-\(\varepsilon\) together with the two-fluid model suppresses the appearance of meso-scale structures

- In such a setup, there is an inconsistent mixing of scales over which averaging is performed
Conclusions

- Meso-scale structures can appear under conditions relevant to nuclear reactors if:
  - The mesh resolution is fine enough
  - The temporal resolution is fine enough
  - The bubble size is large enough
  - The steam void fraction is large enough

- Meso-scale structures are dampened/suppressed by:
  - The presence of walls
  - The modelling of turbulence via an eddy viscosity

- These results have been corroborated by comparisons with a different computational technique (MP-PIC) and with two different CFD codes
Thank you for your attention!

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The computations in this work were partially performed on C3SE computing resources.
The interphase momentum exchange is significantly affected by the sub-grid homogeneity of the dispersed phase distribution.

The presence of meso-scale structures mean that:

- The sub-grid distribution of the dispersed phase is inhomogeneous
- There are significant fluctuations in the local slip velocity
- The effective interphase momentum transfer is lower than in the uniform state

The combined presence of meso-scale structures and unresolved geometry mean that:

- Phase segregation may be enhanced
- Effective interphase transfer terms are affected
The two-fluid model

- Continuity equation for the dispersed (bubbly) phase:
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  - \alpha_k \nabla p + \nabla \cdot \left[ \alpha_k \mu_k \left( \nabla \mathbf{u}_k + \nabla \mathbf{u}_k^T \right) \right] + \alpha_k \rho_k \mathbf{g} + K (\mathbf{u}_q - \mathbf{u}_k)
  \]
  \[
  K = \alpha_l \alpha_b \frac{18 \mu_l}{d_b^2} \frac{C_D \text{Re}_p}{24}
  \]

- No discrete phase pressure – to avoid sensitivity to such model parameters
- The isotropic contribution to the discrete phase stresses comes from the shared pressure field
- The deviatoric contribution comes from the product of the discrete phase velocity gradients with the continuous phase viscosity
Mesh resolution

- Mesh resolution has a significant influence on the appearance of meso-scale structures

<table>
<thead>
<tr>
<th>Mesh</th>
<th>$d_p/\Delta x$</th>
<th>$\Delta x/d_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x32</td>
<td>0.0544</td>
<td>18.4</td>
</tr>
<tr>
<td>16x64</td>
<td>0.1088</td>
<td>9.2</td>
</tr>
<tr>
<td>32x128</td>
<td>0.2176</td>
<td>4.6</td>
</tr>
<tr>
<td>64x256</td>
<td>0.4352</td>
<td>2.3</td>
</tr>
<tr>
<td>128x512</td>
<td>0.8704</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The Kolmogorov length scale is approximately $5d_p$
Temporal resolution

- Approximate magnitude and overall qualitative behavior of $\Phi$ converged at a time step of $10^{-4}$ s
Influence of walls

- Bounding the geometry with free-slip walls in the horizontal directions has a significant influence on the appearance of meso-scale structures.

<table>
<thead>
<tr>
<th>Domain</th>
<th>$d_p/\Delta x$</th>
<th>$\Delta x/d_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>0.4352</td>
<td>2.3</td>
</tr>
<tr>
<td>5 cm</td>
<td>0.8704</td>
<td>1.1</td>
</tr>
<tr>
<td>1 cm</td>
<td>4.352</td>
<td>0.23</td>
</tr>
</tbody>
</table>

![Graph](image)
Influence of walls

- No-slip walls create steep gradients and cause (somewhat) different behavior

<table>
<thead>
<tr>
<th>Domain</th>
<th>Liquid</th>
<th>Bubbles</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>Free slip</td>
<td>Free slip</td>
<td>64x256</td>
</tr>
<tr>
<td>1 cm</td>
<td>No slip</td>
<td>Free slip</td>
<td>128x512</td>
</tr>
</tbody>
</table>

- Lift forces on bubbles in the near-wall region (currently not taken into account) are also known to affect phase separation
**Scale terminology**

Two-fluid model with coarse resolution

*macroscale*

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**The mesoscale structures:**

- Arise due to local instabilities
- Characteristic sizes $O(10-100d_p)$
- Can be captured by a transient two-fluid model

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*Figure 1. Instantaneous greyscale plots of solids volume fraction.*


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Two-fluid model with fine resolution

*microscale*