The Inhomogeneous MUSIG Model: Validation and Comparison with TOPFLOW experiments

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• The testcase TOPFLOW-074
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Multiphase Flow Models

Free Surface Flows
- Homogeneous VOF \( (U_i=U_k) \)
- Inhomogeneous VOF \( (U_i \neq U_k) \)

Heterogeneous Mixtures
- Particle Model
  - Monodisperse (length scale \( d_p \))
  - Polydisperse (Population balance)
- Mixture Model
Polydispersed bubbly flow caused by breakup & coalescence

Transition from disperse bubbly flow to slug flow:

• **coalescence** of bubbles
• turbulent bubble **breakup**

bubble size distribution; polydisperse bubbly flow
counter-current radial motion of small and large bubbles;
more than one velocity field

new population balance model (inhomogeneous MUSIG)
The inhomogeneous MUSIG model

- momentum equations are solved for $N$ gas phases (vel. groups)
- size fraction equations for $M$ bubble size classes in each vel. group
- bubble coalescence and break-up over all $NxM$ MUSIG groups

\[ \frac{dV_1}{dP_1} \quad \frac{dV_2}{dP_{a+1}} \quad \frac{dV_{N}}{dP_{M}} \]

\[ \frac{dP_{a}}{dP_{a+1}} \quad \frac{dP_{b}}{dP_{b+1}} \quad \ldots \quad \frac{dP_{x+1}}{dP_{x+2}} \]

\( N(d_P) \)

break up

coalescence

\( d_{P,krit} \)
Inhomogeneous MUSIG model solves for:

- **N** volume fraction equations
- **N+1** momentum equations
- **(>) 2** turbulence model equations
- **NxM** size fraction equations

\[
\frac{\partial}{\partial t} (\rho_d r_{dg}) + \frac{\partial}{\partial x} \left( \rho_d r_{dg} u_{g,j}^i \right) = S_g
\]

\[
g = 1, \ldots, N \cdot M
\]

\[
j = 1, \ldots, N
\]

\[
r_d = \sum_{g=1}^{N \cdot M} r_{dg}
\]

\[
f_{dg} = \frac{r_{dg}}{r_d}
\]

\[
\sum_{g=1}^{N \cdot M} f_{dg} = 1
\]

\[
\sum_{g=1}^{N \cdot M} S_g = 0
\]
The inhomogeneous MUSIG model

\[ S_g = \rho_d \sum_{h=g+1}^{N \cdot M} B_{gh} r_{dh} \]  
\[ - \rho_d r_{dg} \sum_{h=1}^{g-1} B_{gh} \]  
\[ + \frac{1}{2} \rho_d \sum_{h=1}^{g} \sum_{i=1}^{g} C_{hi} r_{dh} r_{di} X \]  
\[ - \rho_d r_{dg} \sum_{h=1}^{N \cdot M} C_{gh} \frac{r_{dh}}{m_h} \]  
breakup birth
breakup death
coalescence birth
coalescence death
The TOPFLOW test facility at FZR

- FZR TOPFLOW test facility with DN200
- Gas injection through 72 x 1mm Ø wall injection holes
- $J_W = 1.017 \text{ m/s}$
- $J_G = 0.0368 \text{ m/s}$
- $r_G = 3.49\%$
  (mean gas volume fraction)
• **3x7 MUSIG model** applied to TOPFLOW-074 testcase with:
  - \( N=3 \) velocity groups and \( M=21 \) size classes (7 in each group)
  - overall bubble diameter range \( d_p=0,\ldots,13\text{mm} \)
  - equal diameter discretization (\( \Delta d_p=0.619\text{mm} \))

- Air1 vel. group : \( d_{p,\text{min}}=0.31\text{ mm} \); \( d_{p,\text{max}}=4.02\text{mm} \)
- Air2 vel. group : \( d_{p,\text{min}}=4.64\text{ mm} \); \( d_{p,\text{max}}=8.36\text{mm} \)
- Air3 vel. group : \( d_{p,\text{min}}=8.98\text{ mm} \); \( d_{p,\text{max}}=12.69\text{mm} \)
5 different simulations with 3x7 MUSIG model:

<table>
<thead>
<tr>
<th>No.</th>
<th>Grid level</th>
<th>No. of elements</th>
<th>$C_{TD}$</th>
<th>comment</th>
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<tr>
<td>1</td>
<td>2</td>
<td>32.000</td>
<td>1.0</td>
<td>reference case</td>
</tr>
<tr>
<td>2</td>
<td>4 (mod.)</td>
<td>260.442</td>
<td>1.0</td>
<td>grid refinement above the point of gas injection ($z=0.0$; expanding mesh)</td>
</tr>
<tr>
<td>3</td>
<td>4 (mod.)</td>
<td>260.442</td>
<td>1.0</td>
<td>inlet BC initialization with $u$, $v$, $w$, $k$, $\omega$ from fully developed single-phase flow</td>
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<td>4</td>
<td>4 (mod.)</td>
<td>260.442</td>
<td>1.0</td>
<td>changed gas inlet bubble size distribution</td>
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<tr>
<td>5</td>
<td>4 (mod.)</td>
<td>260.442</td>
<td>0.5</td>
<td>reduced turbulent dispersion</td>
</tr>
</tbody>
</table>
Gas Inlet Bubble Size Distribution

Cases 1-3 and 5:
- inlet nozzle injection
  - 80% of VF in class 7 (Air1)
  - 20% VF in Air1, Air2, Air3
  
  equally distributed over all remaining size classes

Case 4:
- inlet nozzle injection
  - Air1 VF = 0.844% of VF
  - Air2 VF = 88.72% of VF
  - Air3 VF = 10.93% of VF
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

- TOPFLOW-074 best results obtained in Case 4
- near wall gas injection at z=0.0m
- level R results show core peak in air VF profiles
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

- good agreement at levels L through R
- too fast spreading of the bubble plume from inlet
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

level C (z=0.335m) to level L (z=2.595m)

turbulent dispersion

coalessence
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

- Air VF at level L (z=2.595m), level O (z=4.531m) and level R (z=7.802m)
- agreement with experiments improves with increasing height
- good prediction of radial demixing processes for different bubble size classes
Overall Comparison of different Validation Tests

C and R level results for Cases 1-5

- Exp. FZR-074, level C
- CFX, level C, grid 2, TD=1.0
- CFX, level C, grid 4, TD=1.0
- CFX, level C, grid 4, TD=1.0, init.
- CFX, level C, grid 4, TD=1.0, init., BC
- CFX, level C, grid 4, TD=0.5
- Exp. FZR-074, level R
- CFX, level R, grid 2, TD=1.0
- CFX, level R, grid 4, TD=1.0
- CFX, level R, grid 4, TD=1.0, init.
- CFX, level R, grid 4, TD=1.0, init., BC
- CFX, level R, grid 4, TD=0.5
Overall Comparison of different Validation Tests

- C and R level results for Cases 1, 3 and 4

![Graph showing comparison of air volume fraction between experimental data and CFD simulations for different cases and grid resolutions.](image-url)
Case 4: Velocity Profiles

I. R Level Comparison with Exp.

0.0 25.0 50.0 75.0 100.0
x [mm]

Air velocity [m/s]

Exp. FZR-074, level I
CFX, level I, Air1
CFX, level I, Air2
CFX, level I, Air3

Exp. FZR-074, level L
CFX, level L, Air1
CFX, level L, Air2
CFX, level L, Air3

Exp. FZR-074, level O
CFX, level O, Air1
CFX, level O, Air2
CFX, level O, Air3

Exp. FZR-074, level R
CFX, level R, Air1
CFX, level R, Air2
CFX, level R, Air3
Case 4: Evolution of Bubble Size Distribution – Level R

- **Air volume fraction [\%]**
  - MUSIG Air1 VF, level R
  - MUSIG-Group 1 VF
  - MUSIG-Group 2 VF
  - MUSIG-Group 3 VF
  - MUSIG-Group 4 VF
  - MUSIG-Group 5VF
  - MUSIG-Group 6VF
  - MUSIG-Group 7VF

- **Bubble diameter**

- **Number Density [\%]**
  - TOPFLOW-074, Level A
  - TOPFLOW-074, Level R

- **Air volume fraction [\%]**
  - MUSIG Air2 VF, level R
  - MUSIG-Group 8 VF
  - MUSIG-Group 9 VF
  - MUSIG-Group 10 VF
  - MUSIG-Group 11 VF
  - MUSIG-Group 12 VF
  - MUSIG-Group 13 VF
  - MUSIG-Group 14 VF

- **Air volume fraction [\%]**
  - MUSIG Air3 VF, level R
  - MUSIG-Group 15 VF
  - MUSIG-Group 16 VF
  - MUSIG-Group 17 VF
  - MUSIG-Group 18 VF
  - MUSIG-Group 19 VF
  - MUSIG-Group 20 VF
  - MUSIG-Group 21 VF

- **Too strong coalescence**
Summary & Conclusions

- New population balance model in CFX-5: inhomogeneous NxM MUSIG model
- Validation on TOPFLOW-074:
  - radial demixing of differently sized bubbles
  - good agreement for air void fraction and velocity profiles at higher pipe elevations
  - too fast spreading of near wall bubble plume
  - too strong coalescence (imbalance with breakup)
- Validation for broader range of flow conditions necessary: TOPFLOW test matrix
- Revision of breakup & coalescence models
- Future extension of inhomogeneous MUSIG model to condensation & boiling