Prediction of Polydisperse Steam Bubble Condensation in Subcooled Water using the Inhomogeneous MUSIG Model

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Outline

• Motivation
• Model description
• Validation
  – TOPFLOW facility & condensation experiment
  – CFD ↔ Experiment comparison
    • Previous approaches vs. extended MUSIG
    • Improvements in the extended MUSIG simulations

• Summary & conclusions
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Motivation

- **NRS applications:**
  - Subcooled boiling in nucl. react fuel assemblies
  - Steam injection into pools
  - Steam bubble entrainment in subcooled liquids by impinging jets

- **Cond./evap. rates depend on IAD**
  - bubble size distribution

- **Need of polydispersed inhomogeneous simulations**

- **Need to deal with phase change effects**
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Standard Inhomog. MUSIG Model

- Polydisperse fluids

  - Small bubbles move with the fluid phase
  - Large bubbles are more influenced by buoyancy
  - Lift coefficient changes its sign at a critical size; depends on $\sigma(p,T)$

Velocity group mass transfer

- Break up
- Coalescence
• **MUSIG setup:**
  - Definition of the initial *diameter classes* \( (d_i) \)
    - Mass classes used
  - Definition of *velocity groups* \( (v_j) \)
    - Homogeneous/Inhomogeneous
    - Which \( d_i \) belong to each \( v_j \)
  - 1 *size fraction equation* for each bubble diameter
  - 1 *momentum equation* for each velocity group
• **Basic population balance equations**

\[
\frac{dn(m, \bar{r}, t)}{dt} = \frac{\partial}{\partial t} n(m, \bar{r}, t) + \frac{\partial}{\partial \bar{r}} \left( U(m, \bar{r}, t)n(m, \bar{r}, t) \right) + \frac{\partial n(m, \bar{r}, t)}{\partial m} \frac{\partial m(\bar{r}, t)}{\partial t} = B_B - D_B + B_C - D_C
\]

Bubble number density

• **Size fraction equations**

\[
\frac{\partial}{\partial t} \left( \rho_i r_d f_i \right) + \frac{\partial}{\partial x_j} \left( \rho_i r_d U_i^j f_i \right) = S_{B_i} - S_{D_i} + S_{B_{C_i}} - S_{D_{C_i}} - S_i
\]

\[
S_i = \begin{cases} 
\frac{m_i}{m_i - m_{i-1}} \Gamma_i - \frac{m_i}{m_{i+1} - m_i} \Gamma_{i+1} & \text{for evaporation} \\
\frac{m_i}{m_i - m_{i-1}} \Gamma_{i-1} - \frac{m_i}{m_{i+1} - m_i} \Gamma_i & \text{for condensation}
\end{cases}
\]
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### TOPFLOW Test Facility @ FZD

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<td>D</td>
<td>E</td>
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<tr>
<td>7802</td>
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</tbody>
</table>

**D = 195mm**

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**Courtesy of FZD**
Condensation Test Case

- $P = 2$ [MPa]
- $J_w = 1.0$ [m/s]
- $J_s = 0.54$ [m/s]
- $T_s = 214.4$ [°C]
- $T_w = 210.5$ [°C] $\rightarrow \Delta T_w = 3.9$ [K]
- $D_{inj} = 1$ [mm]
- Detailed experimental data:
  - Bubble size distribution
  - Radial steam volume fraction distribution

Condensation Test Case

Experimental bubble size distribution

Experimental radial vapor distribution
Numerical Setup

- 1/6 of geometry simulated, 60°
- Symmetry b.c.
- 260.442 elements*
- 12 x Injection nozzles modeled by SOURCE POINTS
  - $D_{inj}$ modified (4mm) for $v_{inj}$
- SST turbulence model
- $F_{drag}$, $F_{lift}$, $F_{TD}$ considered
Physical Model Setup

• Locally Monodisperse
  – Particle diameter: constant number of bubbles
    \[ d_P = d_P(d_{P|\text{Inlet}}, N_{P|\text{Inlet}}) \]

• Standard MUSIG & Extended MUSIG
  – 25 bubble size classes
  – 3 velocity groups:
    \[ 0 \rightarrow 3 \text{ [mm]}, 3 \rightarrow 6 \text{ [mm]}, 6 \rightarrow 30 \text{ [mm]} \]
  – Break up model: Luo & Svendsen (\( F_B = 0.025 \))
  – Coalescence model: Prince & Blanch (\( F_C = 0.05 \))
Results: Vertical averaged steam distribution

![Graph showing steam volume fraction over distance with different lines for Monod, Standard MUSIG, Extended MUSIG, and Experiment data points.]

- Injection nozzles
- Pipe end

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Results: Radial steam distribution

![Graph showing radial steam distribution with various curves for different conditions and experimental levels.](image)
Results: Radial steam distribution
Results: Bubble size distribution

\[
\frac{d\rho_G}{dD_B} \quad [\%/mm]
\]

- Stand. MUSIG
- Erweit. MUSIG
- Experiment Level A
- Experiment Level C

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Results: Bubble size distribution

- Graph showing distribution of bubble diameters with different markers for Standard MUSIG, Erweit. MUSIG, and Experiment Level I.

- Graph showing distribution of bubble diameters with different markers for Standard MUSIG, Erweit. MUSIG, and Experiment Level L.

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Results: Tests Comparison

Steam Volume Fraction [%]

Radial Position [mm]

Config 1

Config 2

Config 3

Erweit. MUSIG

Erweit. MUSIG + SP@75 mm

Erweit. MUSIG + SP@75 mm + WLF

Erweit. MUSIG + SP@75 mm + WLF + CTD=1.5

Erweit. MUSIG + SP@75 mm + WLF + CTD=1.5 + Nu (Tomiyama)

Erweit. MUSIG + SP@75 mm + WLF + CTD=1.5 + Nu (Tomiyama) + D=1 mm

Experiment Level C
### TOPFLOW Condensation case

<table>
<thead>
<tr>
<th>Config 1</th>
<th>$D_{inj} = 4\text{mm}$</th>
<th>Source point @ Wall</th>
<th>-</th>
<th>-</th>
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<tbody>
<tr>
<td>Config 2</td>
<td>$D_{inj} = 4\text{mm}$</td>
<td>Source point @ 75 mm</td>
<td>$F_{WLF}$</td>
<td>CTD=1.5</td>
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<tr>
<td>Config 3</td>
<td>$D_{inj} = 1\text{mm}$</td>
<td>Source point @ 75 mm</td>
<td>$F_{WLF}$</td>
<td>CTD=1.5</td>
</tr>
</tbody>
</table>
Results: Vapor Volume Fraction

Config 1

Config 2

Config 3
Results: Vertical averaged steam distribution
Results: Radial steam distribution
Results: Radial steam distribution
Results: Bubble size distribution

\[ \frac{dr_g}{dD_B} \]

[Graph showing bubble size distribution with different configurations and experiment levels]
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Summary & Conclusions

• An extension of the MUSIG model in ANSYS CFX in order to catch phase change effect was implemented.
• Condensation case at the TOPFLOW geometry used for validation
  • The comparison with previous approaches proved the necessity of the extension
  • Qualitatively better results, however improvements in the Setup were required
  • A parameter study led to also quantitative satisfactory results
• Implementation performed in a customized solver based on ANSYS CFX 12
Thank You!