Extension of the Multiple-Size Group (MUSIG) Model to Phase Change Effects

C. Lifante, T. Frank, A. Burns
ANSYS, PBU
conxita.lifante@ansys.com

D. Lucas, E. Krepper
Forschungszentrum Dresden-Rossendorf

Outline

- **Motivation**
- **Model description**
- **Verification**
- **Validation**
  - TOPFLOW facility & condensation experiment
  - CFD ⇔ Experiment comparison
- **Summary & conclusions**

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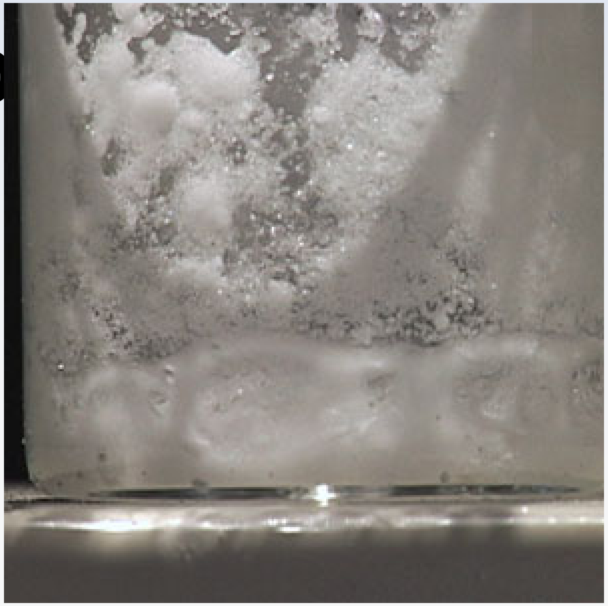
Motivation

- **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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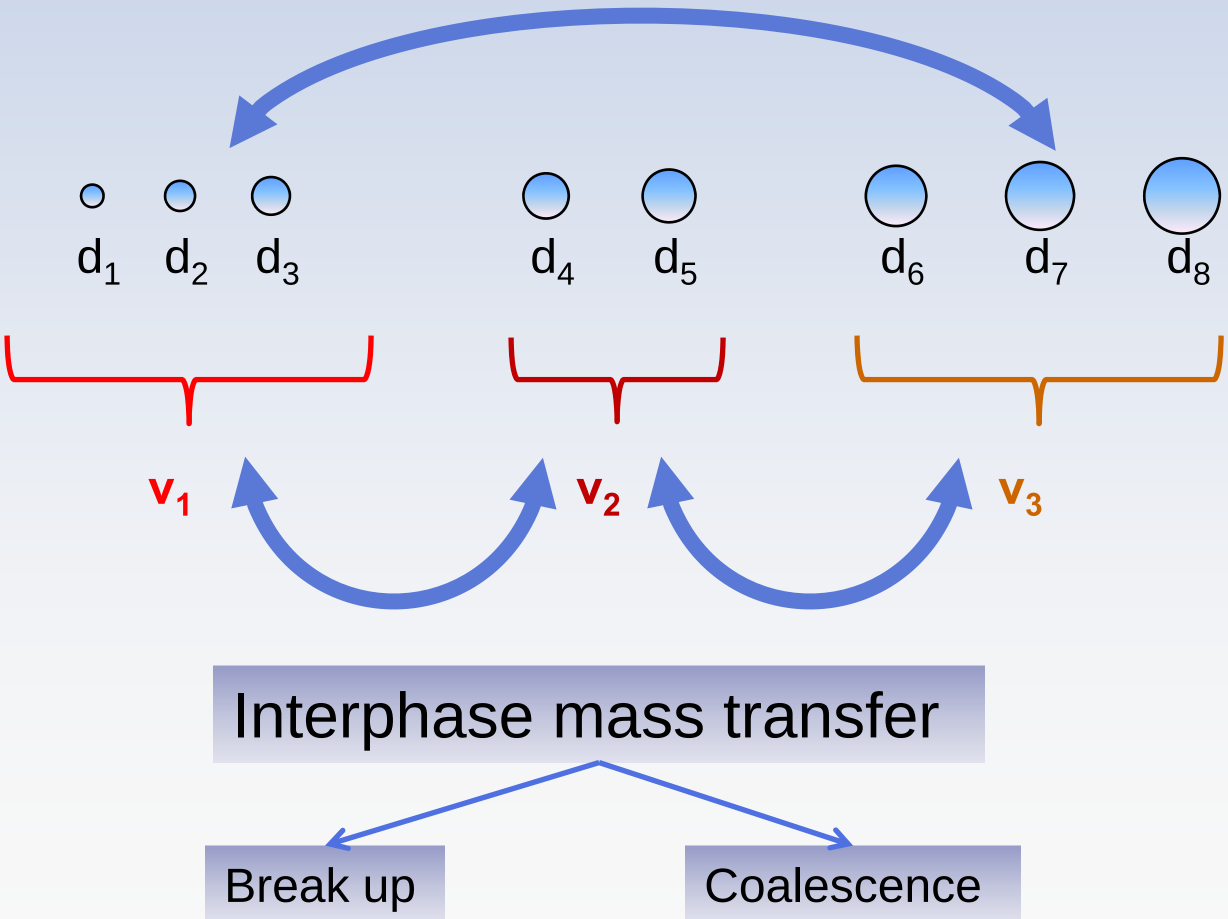
Standard Inhomog. MUSIG Model

- **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 $\sigma(p,T)$

Standard Inhomog. MUSIG Model

- **MUSIG setup:**
  - Definition of 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

Model Extension description

New terms

- **Basic population balance equations**

$$\frac{dn(m,\vec{r},t)}{dt} = \frac{\partial}{\partial t} n(m,\vec{r},t) + \frac{\partial}{\partial \vec{r}}\Big(U(m,\vec{r},t)\,n(m,\vec{r},t)\Big) + \frac{\partial n(m,\vec{r},t)}{\partial m}\frac{\partial m(\vec{r},t)}{\partial t} =$$

$$= B_B - D_B + B_C - B_C$$

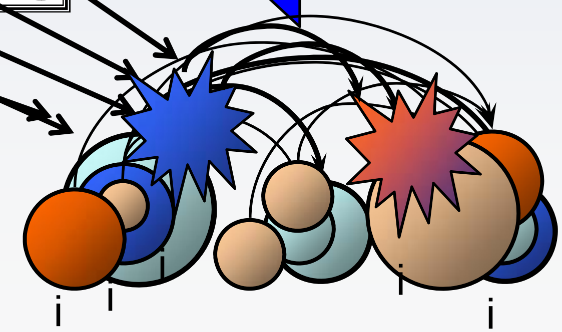
Bubble number density

Breakup/Coalescence terms

- **Size fraction equations**

$$\boxed{\frac{\partial}{\partial t}(\rho_i r_d f_i) + \frac{\partial}{\partial x^j}(\rho_i r_d U_i^j f_i) = S_{B_B} - S_{D_B} + S_{B_C} - S_{D_C} + S_i}$$

$$S_i = \begin{cases} \dfrac{m_i}{m_i - m_{i-1}}\Gamma_i - \dfrac{m_i}{m_{i+1} - m_i}\Gamma_{i+1} & \text{for evaporation} \\[2ex] \dfrac{m_i}{m_i - m_{i-1}}\Gamma_{i-1} - \dfrac{m_i}{m_{i+1} - m_i}\Gamma_i & \text{for condensation} \end{cases}$$



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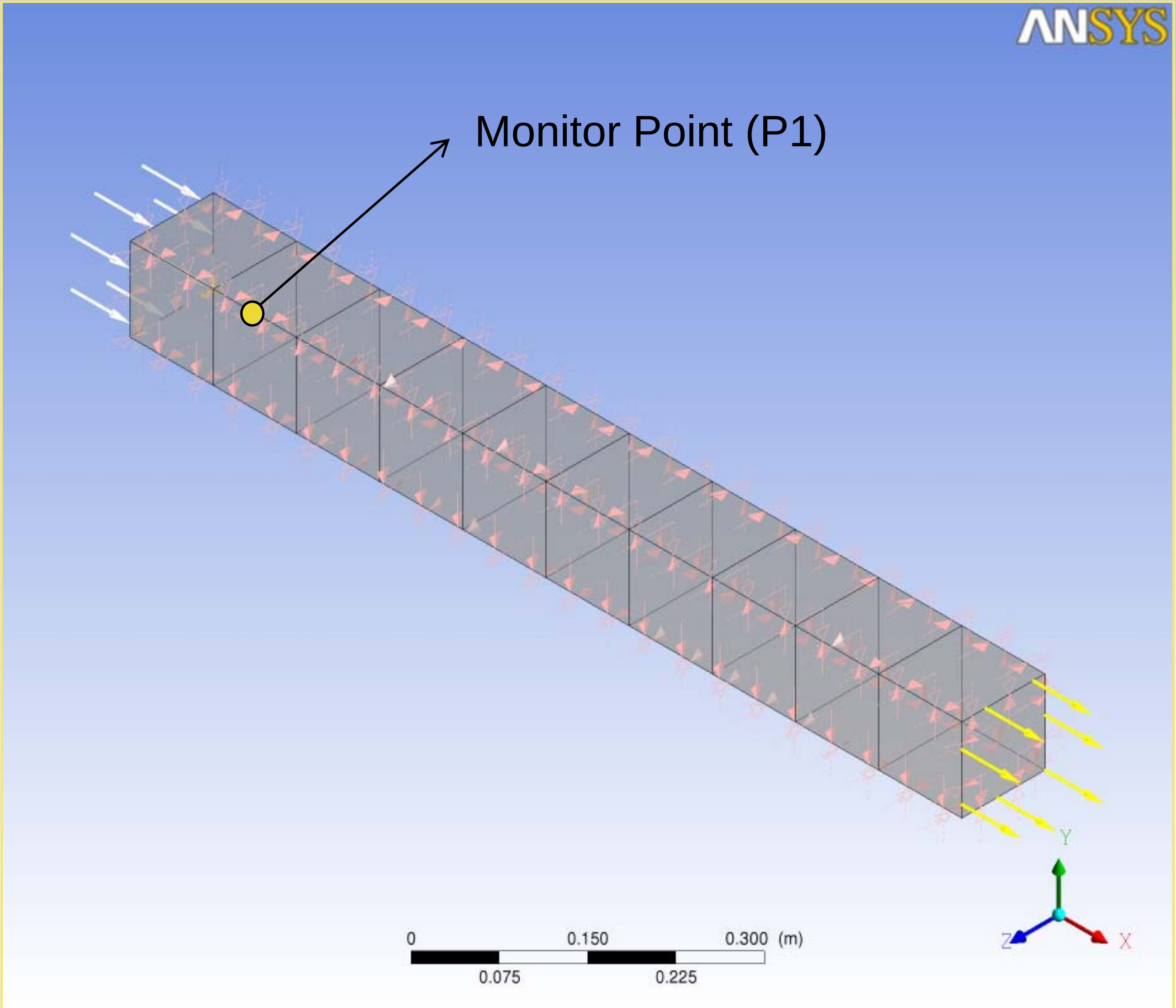
Verification

- **Development steps:**
  - Implementation
  - *Verification* of the implementation
    - Set of test cases
    - Consistency check with other modules
    - Comparison to analytical solutions
  - Validation of the model wrt. experiment

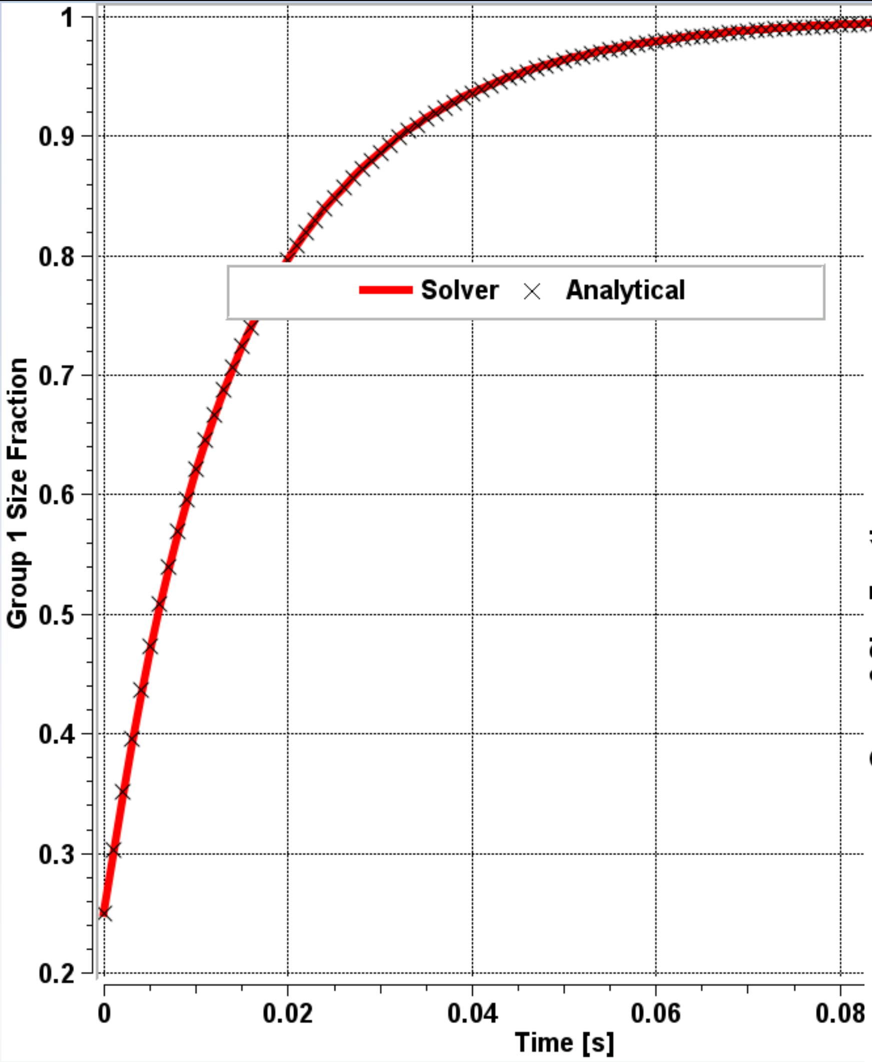
Verification:
Small Condensation Case

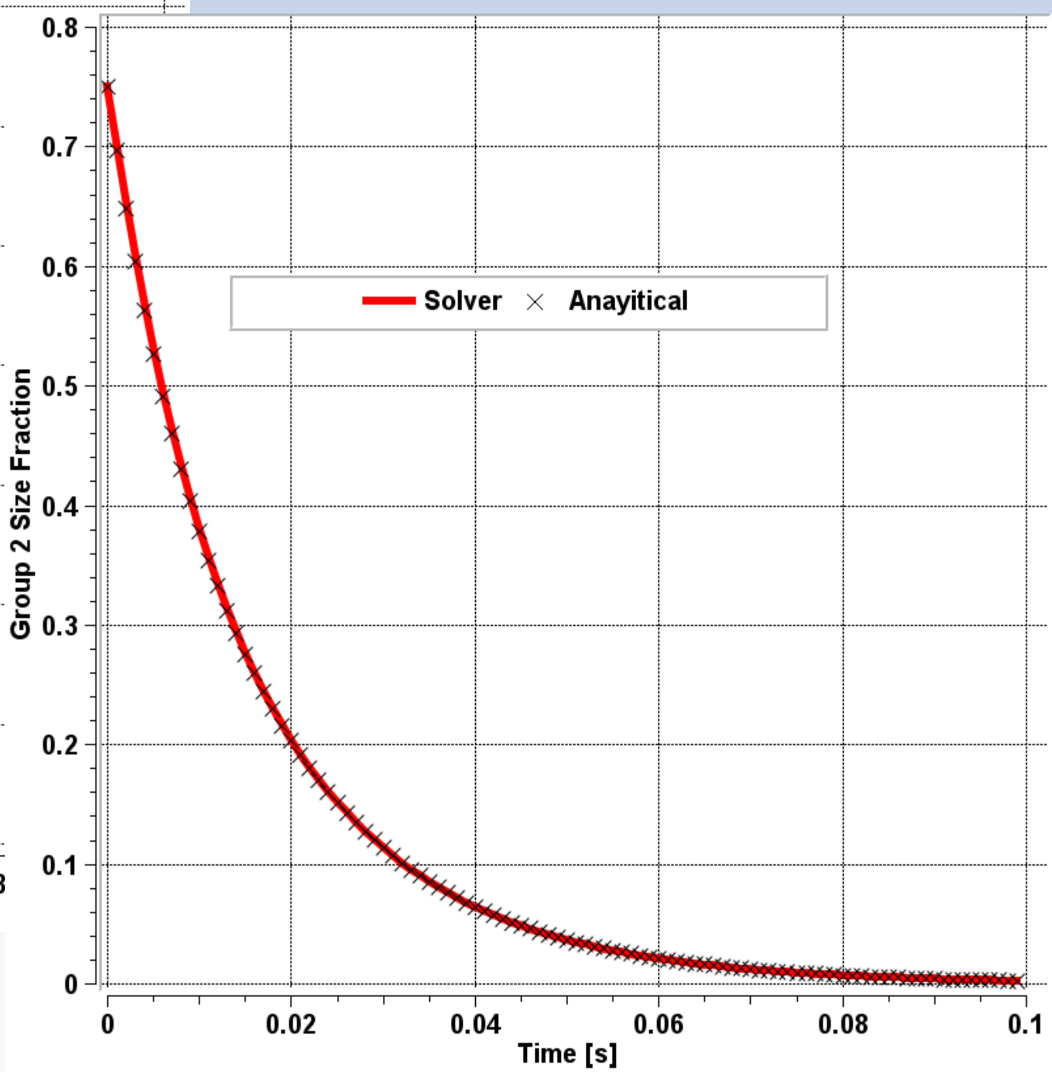


- 10 elements
- Inlet, outlet & sym b.c.
- Water/Vapor
- Main Setup:
  - d_{min}=150 [mm]
  - d_{max}=250 [mm]
  - Equal diameter
  - $\dot{\gamma}$= 5 [kg m^{-2} s^{-1}]
  - f_{10}=0.25,f_{20}=0.75
  - r_{g0}=0.7, r_{l0}=0.3

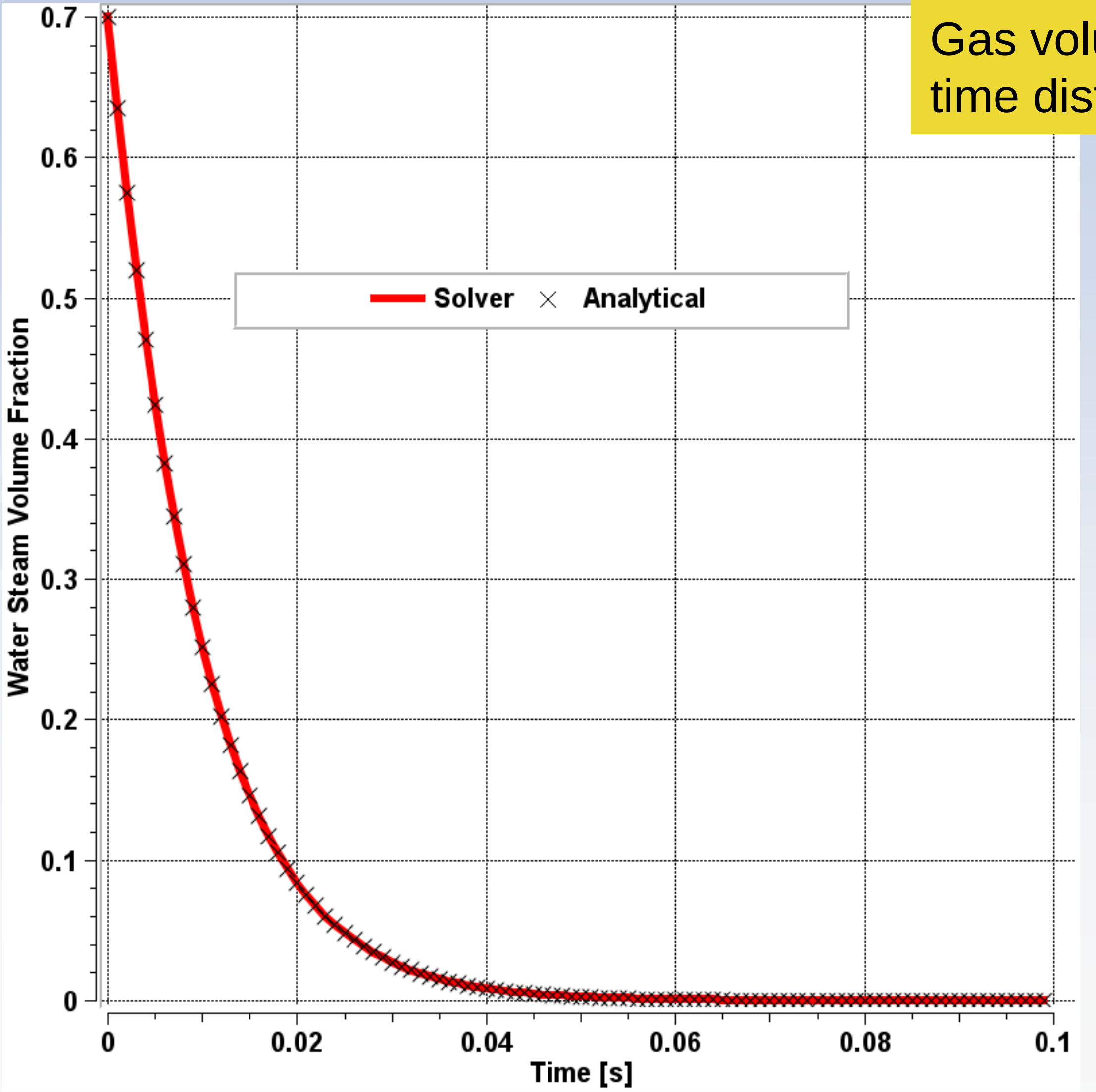
Verification: Small Condensation Case

Size fractions time distribution@P1





Verification: Small Condensation Case



Gas volume fraction time distribution@P1

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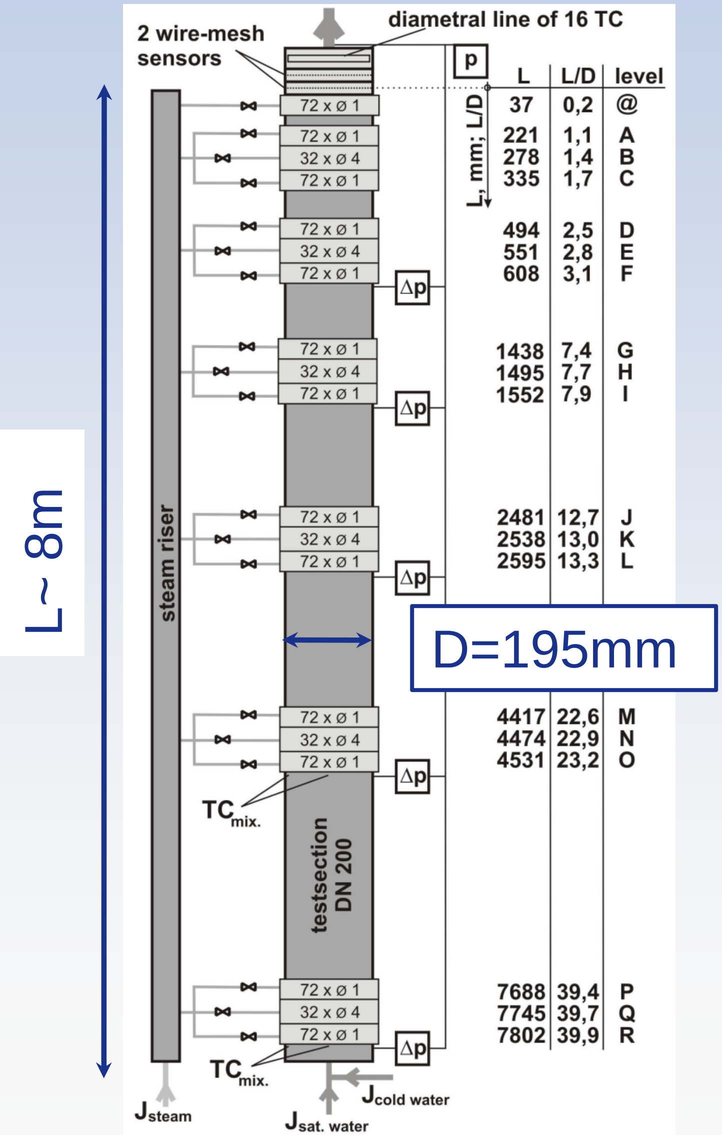
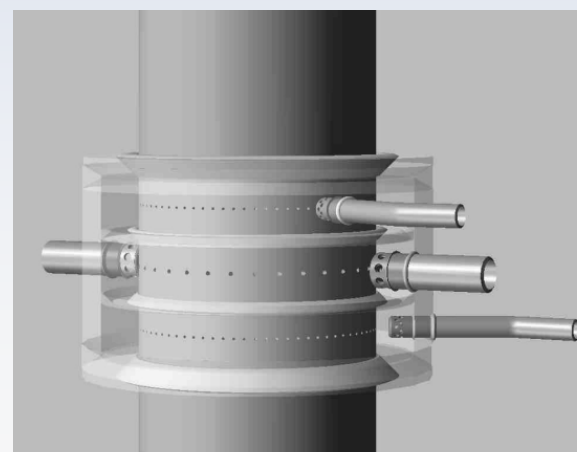
TOPFLOW Test Facility @ FZD

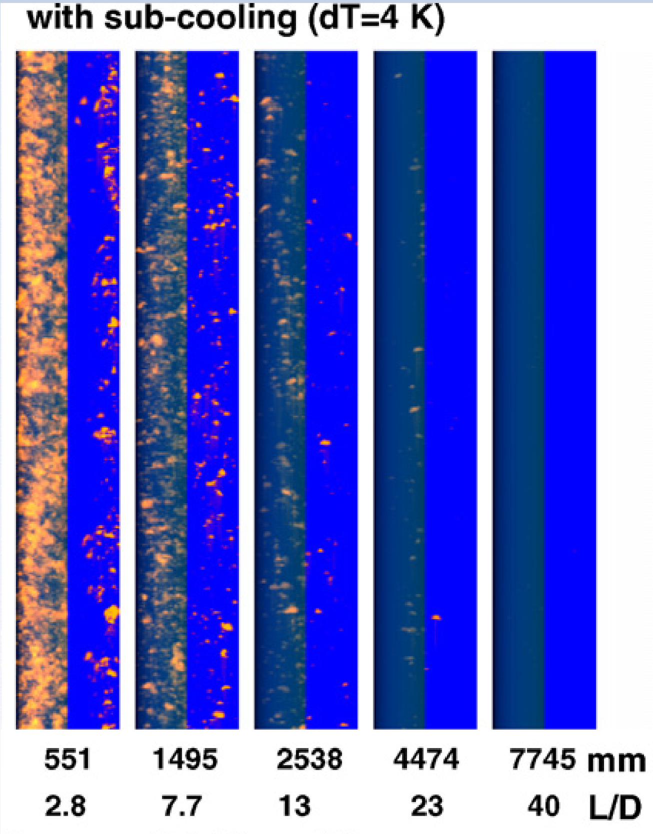




Courtesy of FZD

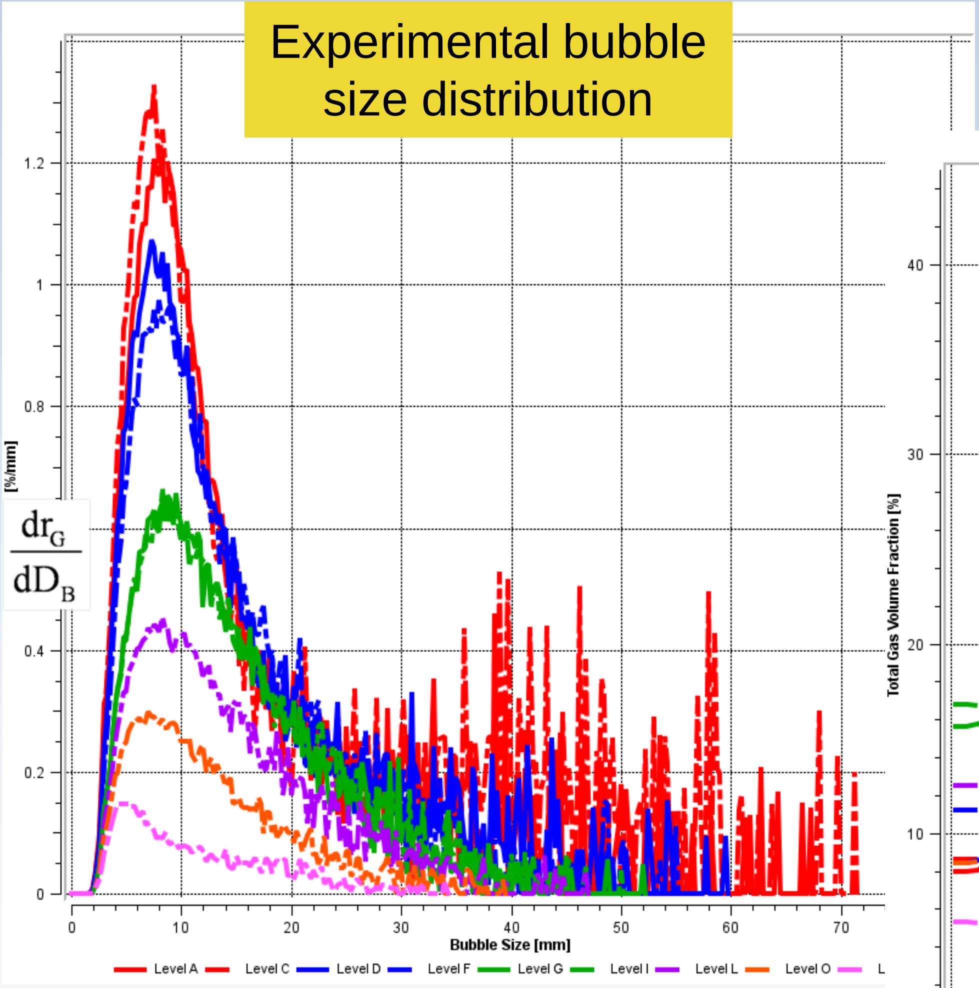
Condensation Test Case

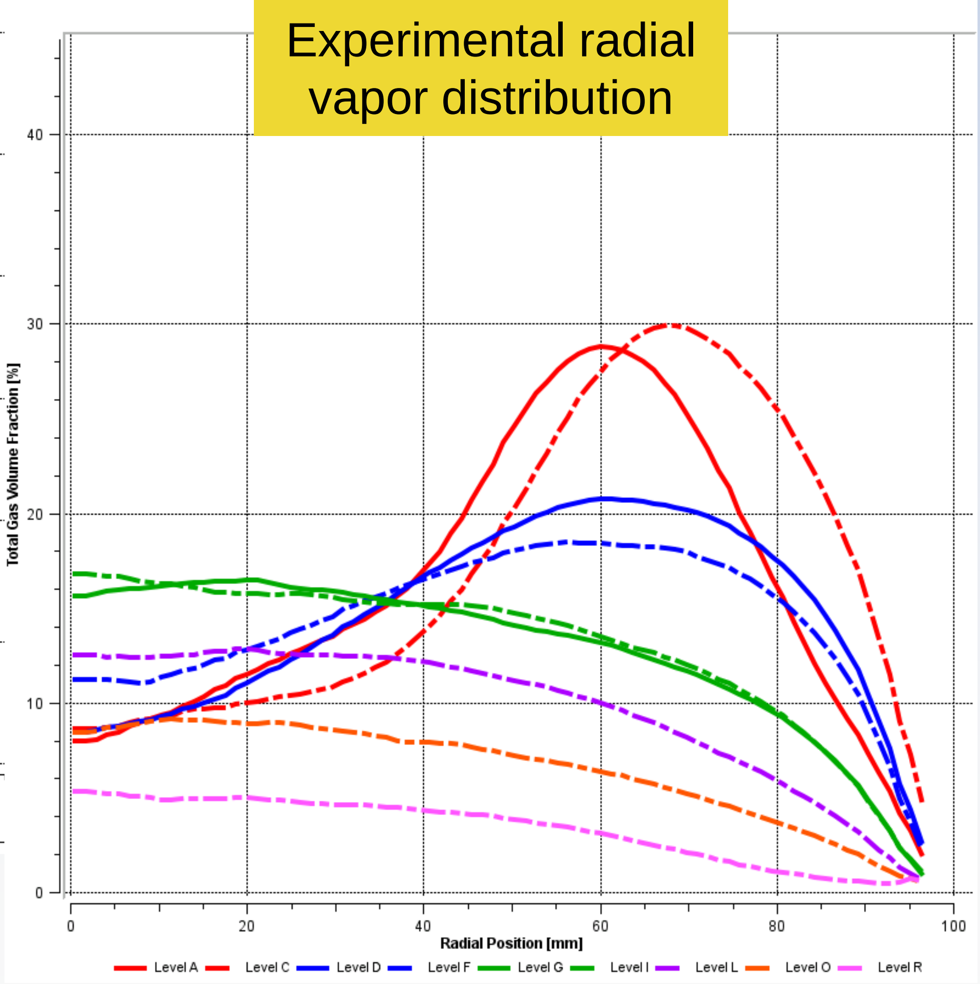
- **P=2 [MPa]**
- **J_w=1.0 [m/s]**
- **J_s=0.54 [m/s]**
- **T_s=214.4 [°C]**
- **T_w=210.5 [°C] → ΔT_w=3.9 [K]**
- **D_{inj} = 1 [mm]**
- **Detailed experimental data:**
  - Bubble size distribution
  - Radial steam volume fraction distribution



Dirk Lucas, Horst-Michael Prasser: "*Steam bubble condensation in sub-cooled water in case of co-current vertical pipe flow*",
Nuclear Engineering and Design, Volume 237, Issue 5, March 2007, Pages 497-508

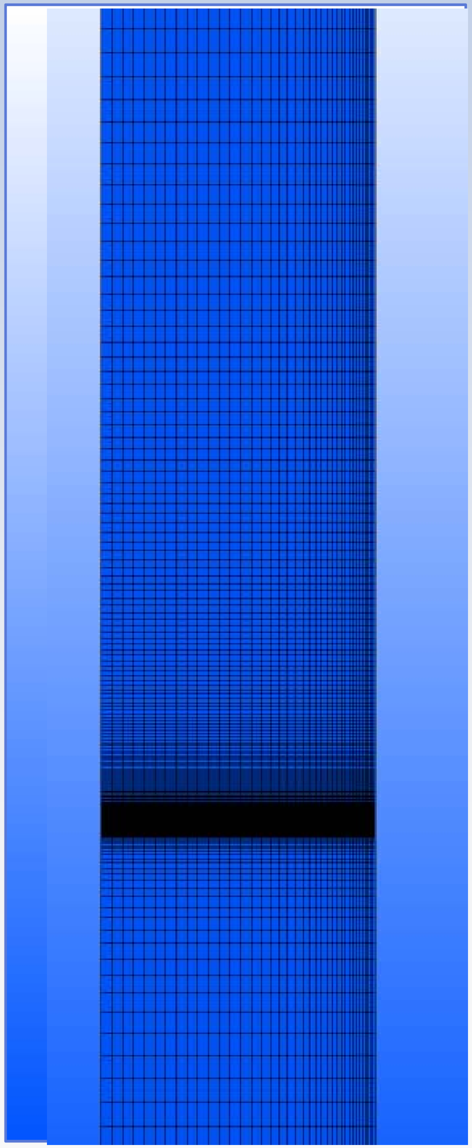
Condensation Test Case





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**



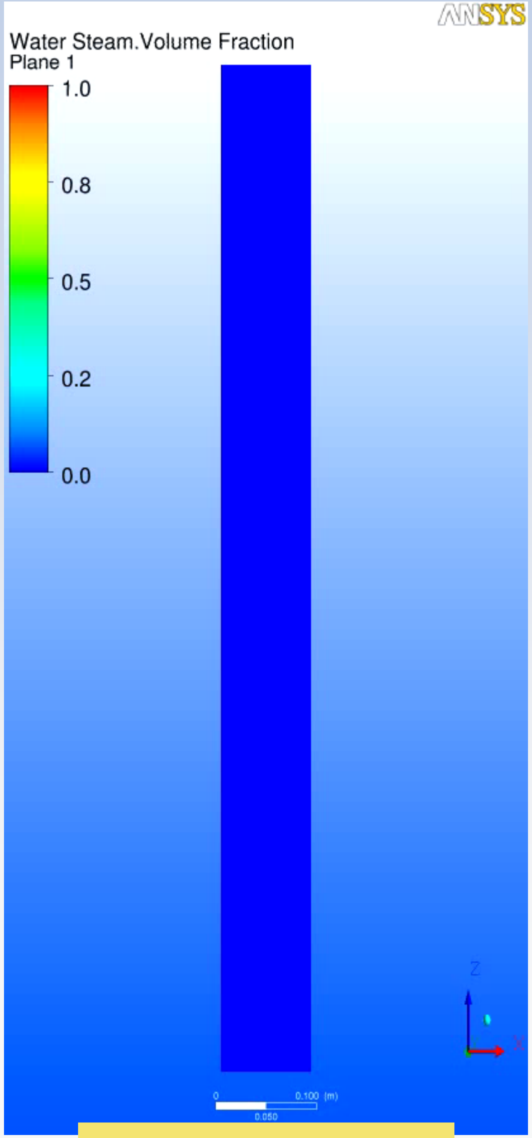
Physical Model Setup

- **Case 1: Locally Monodisperse**
  - Particle diameter: constant number of bubbles

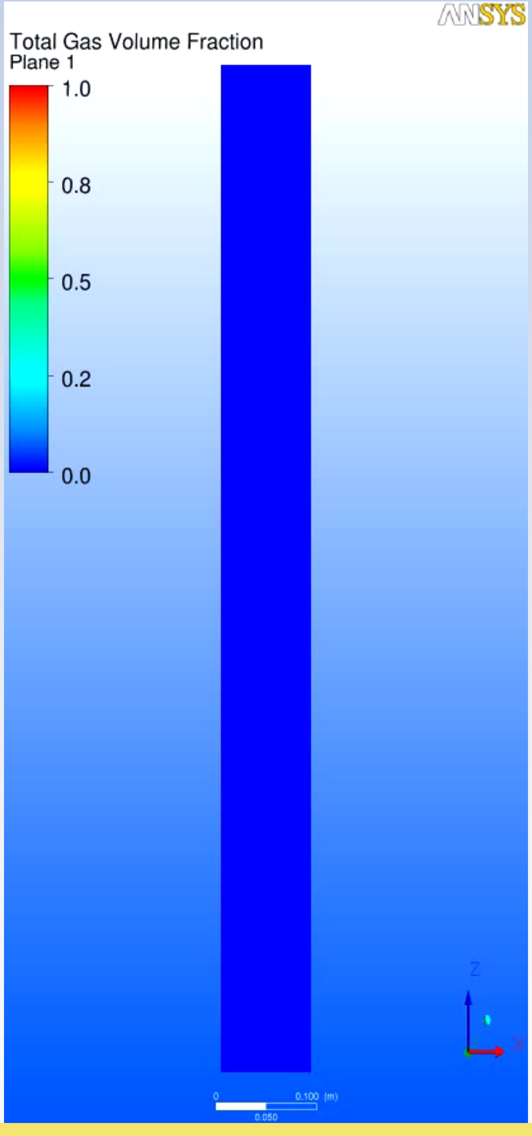
    $d_P = d_P(d_P|_{Inlet}, N_P|_{Inlet})$
- **Case 2-3 : Standard MUSIG & Extended MUSIG**
  - 25 bubble size classes
  - 3 velocity groups:

    0→3 [mm],3→6 [mm], 6→30 [mm]
  - Break up model: Luo & Svendsen (F_B=0.025)
  - Coalescence model: Prince & Blanch (F_C=0.05)

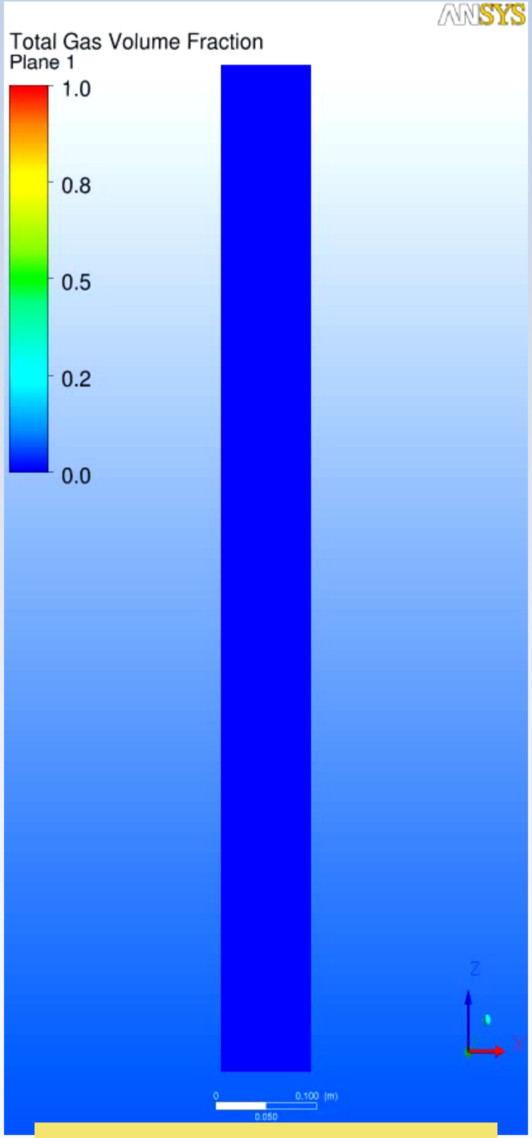
Results: Vapor Volume Fraction



Loc.Monodisp.

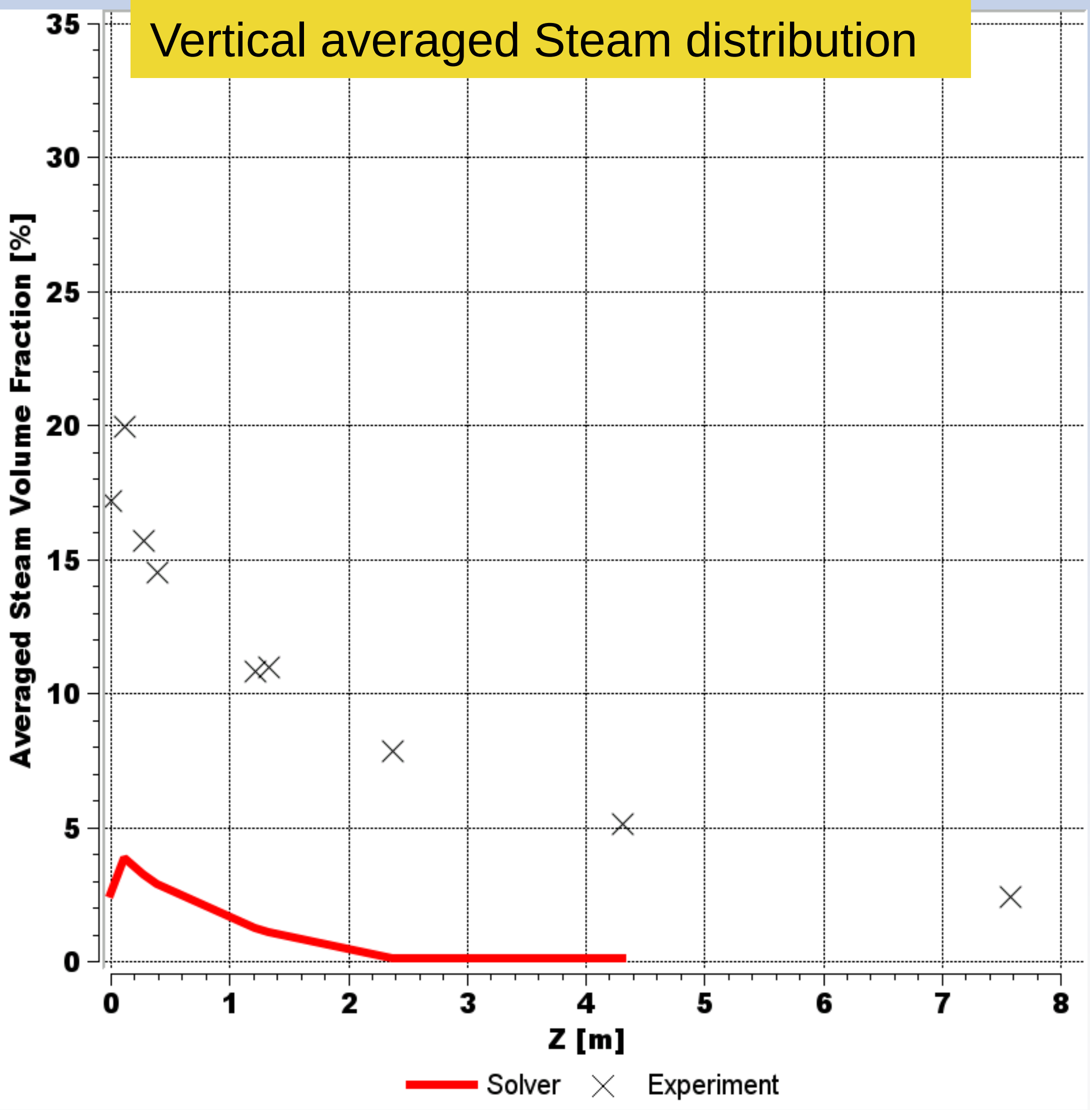


Std. Musig w/o phase change



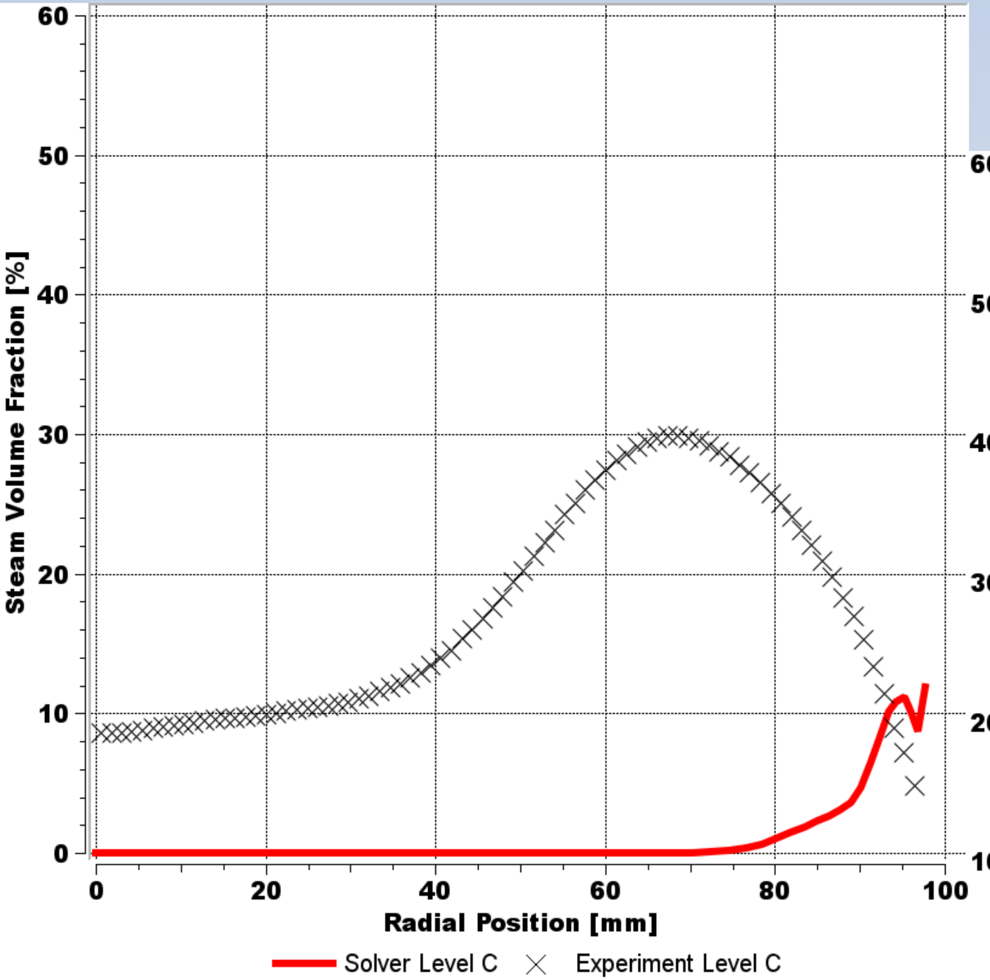
Extended Musig

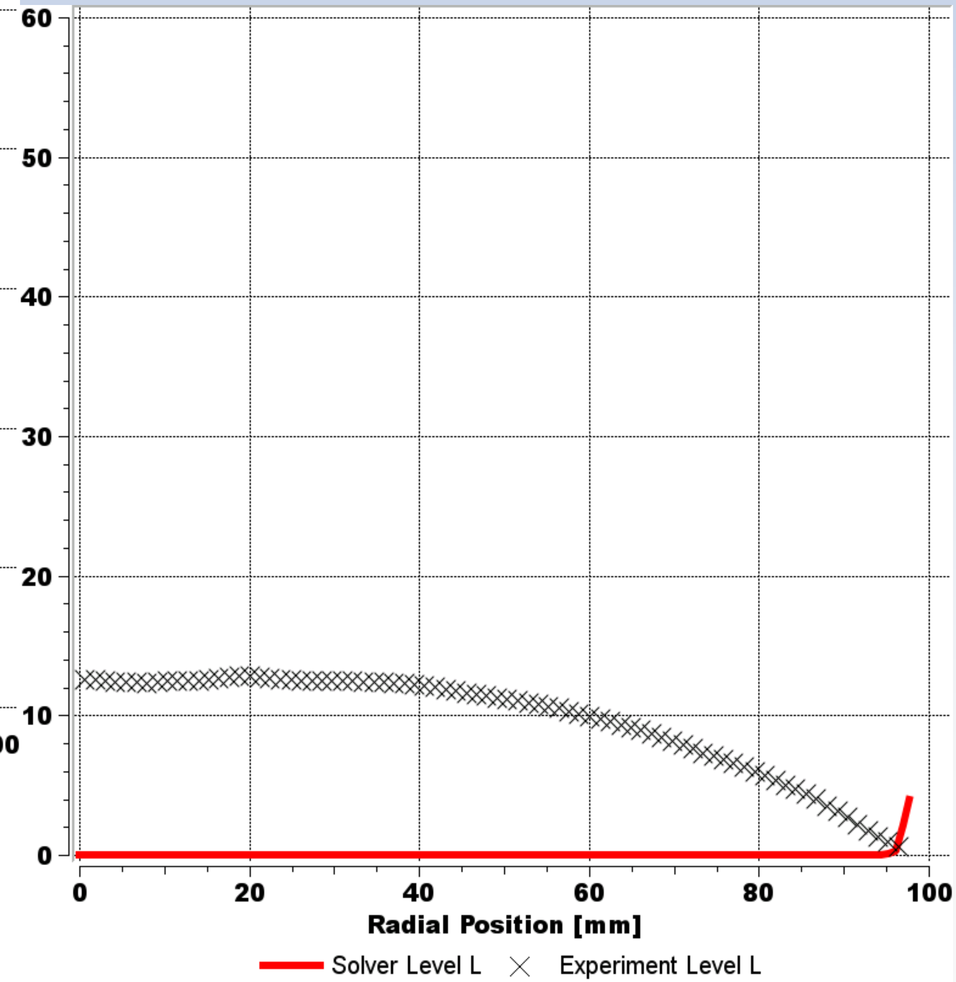
Results: Locally Monodisperse



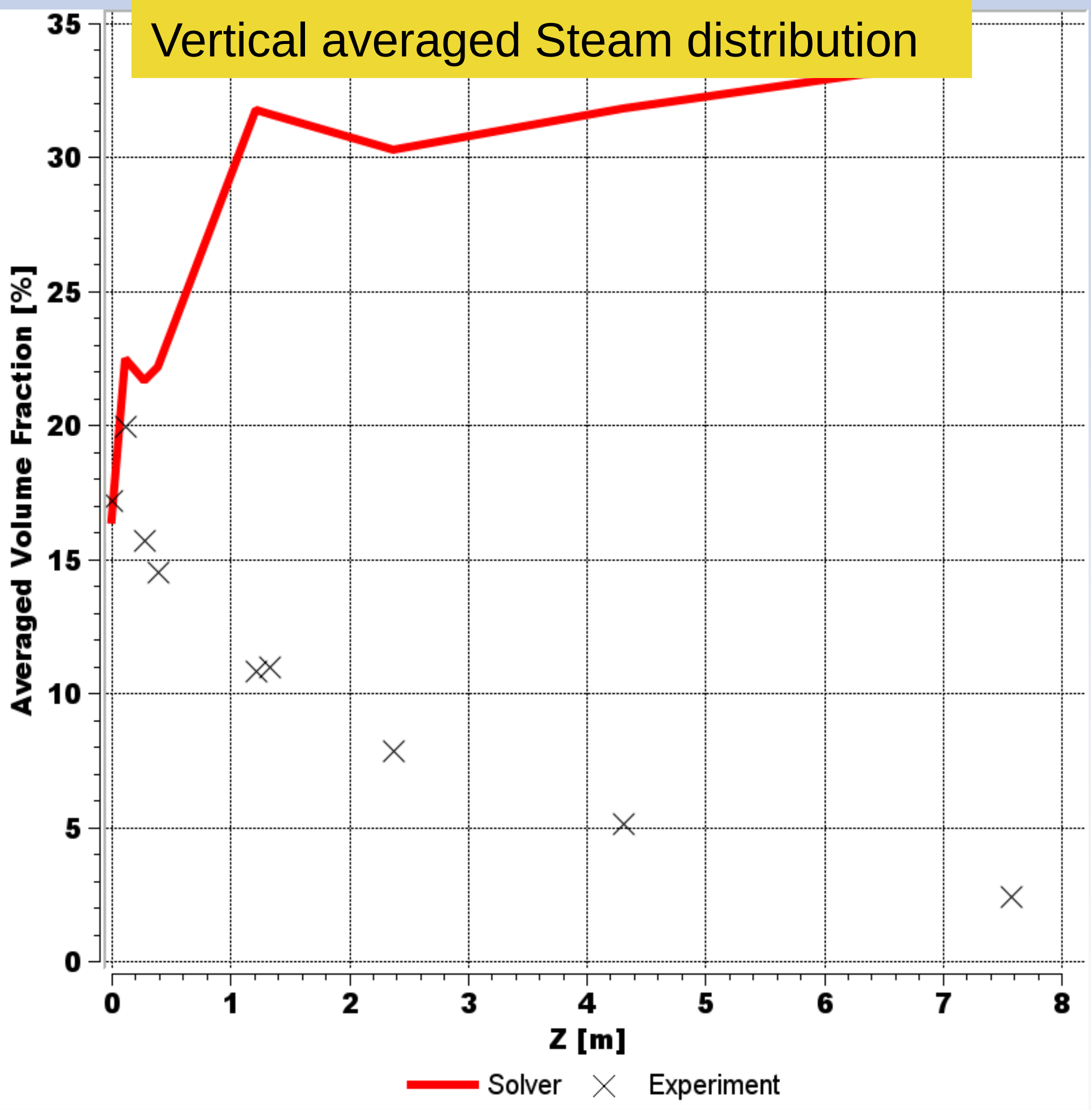
Results: Locally Monodisperse

Radial steam distribution





Results: Standard MUSIG w/o Phase Change



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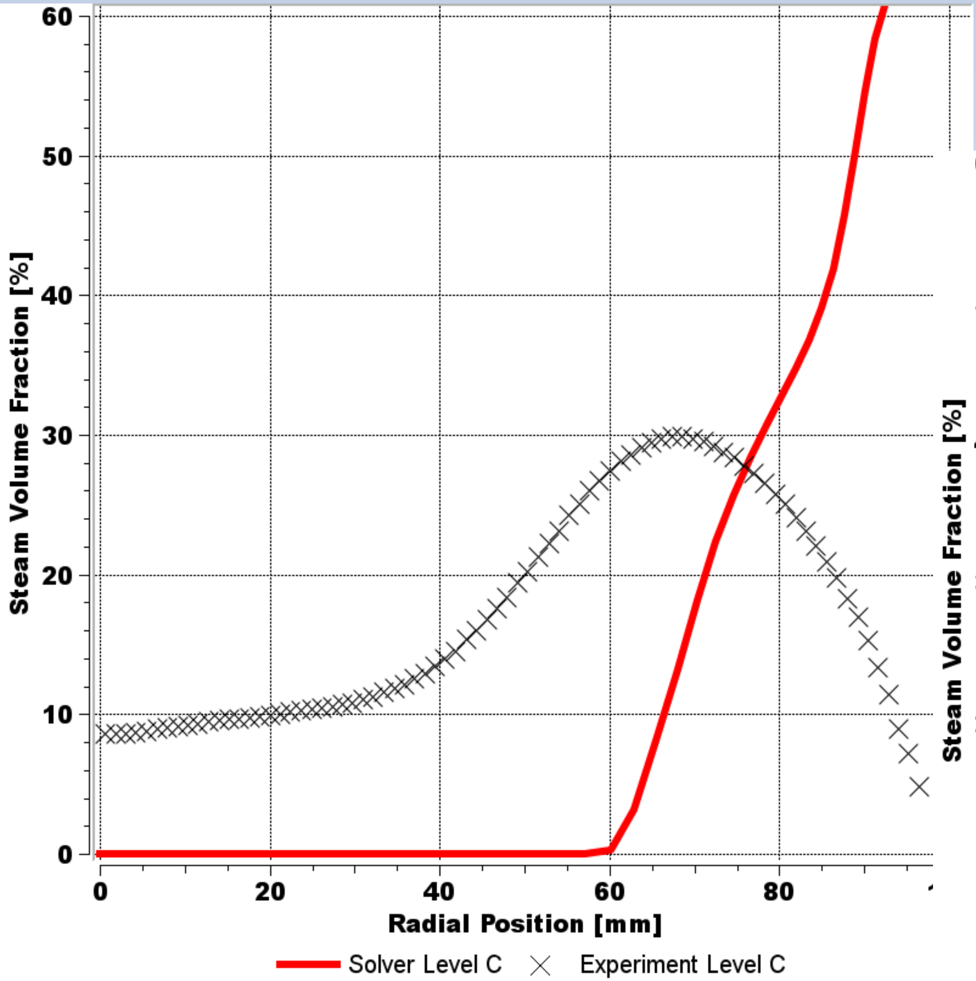
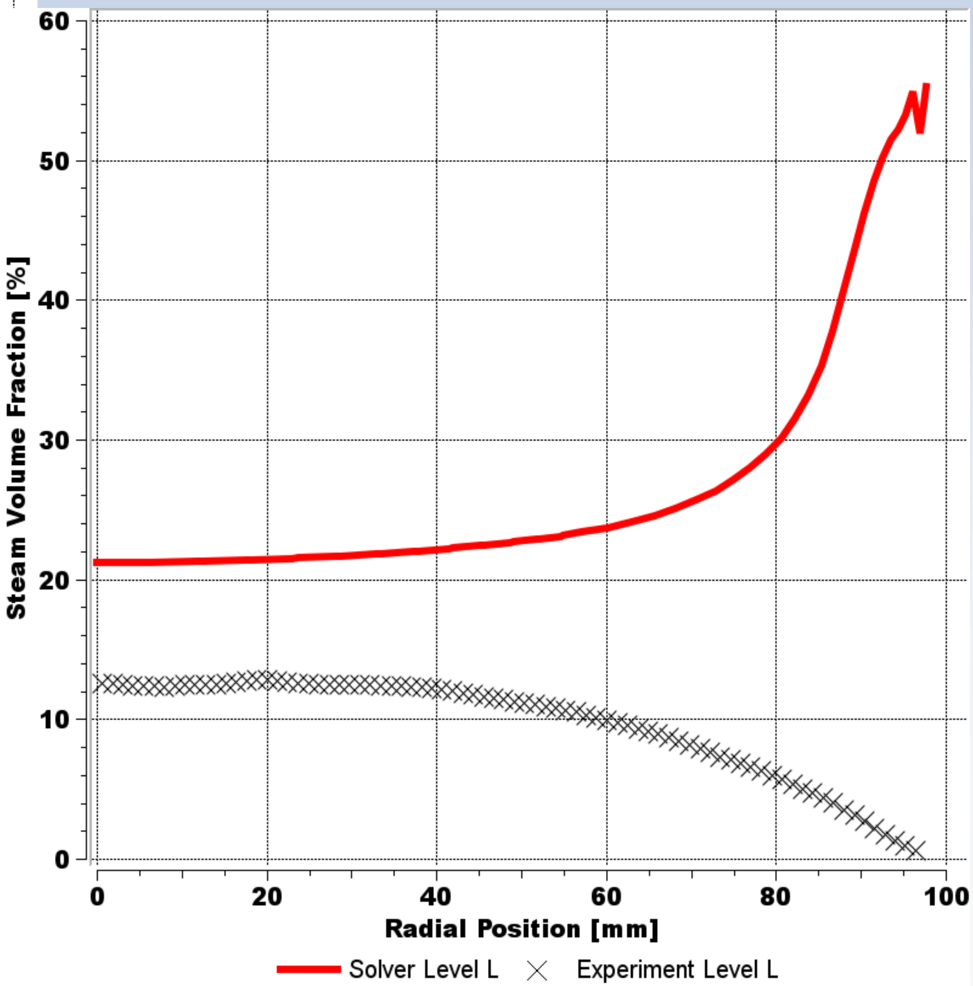
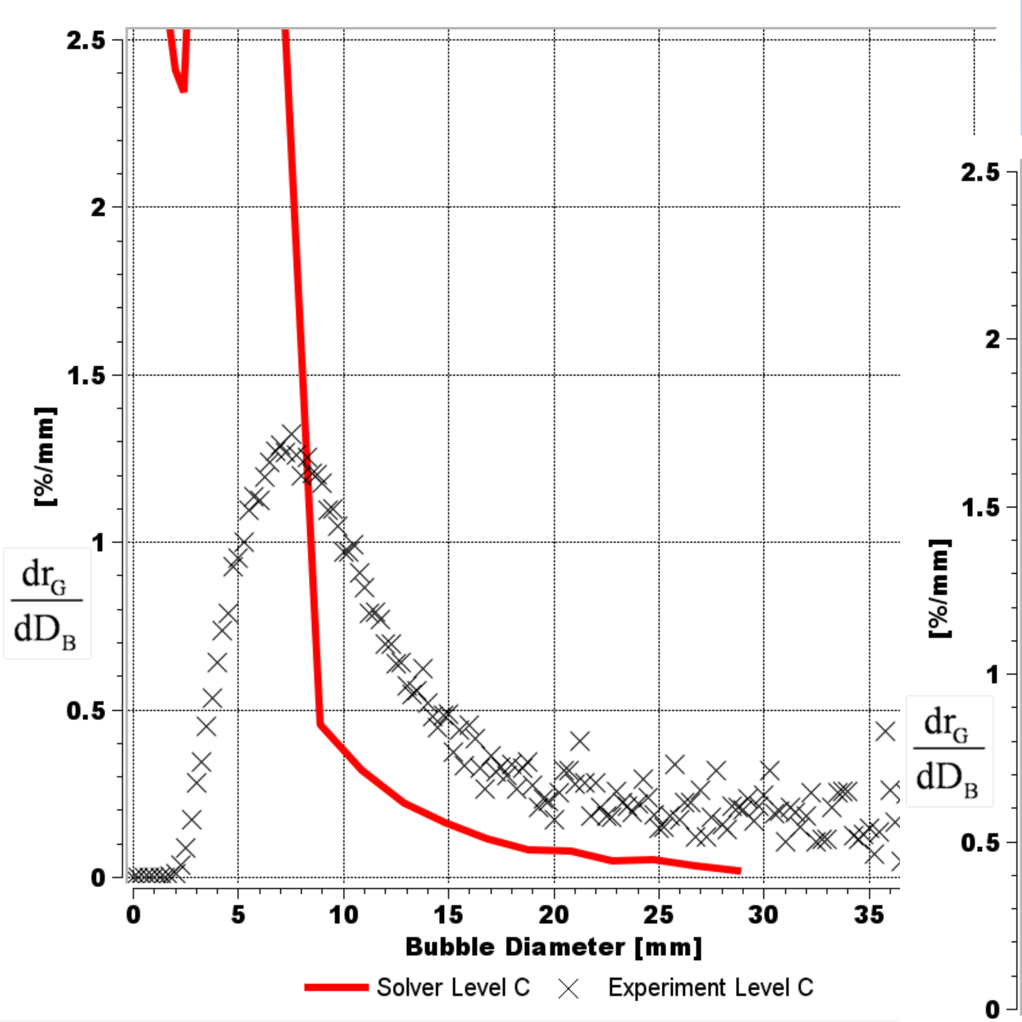


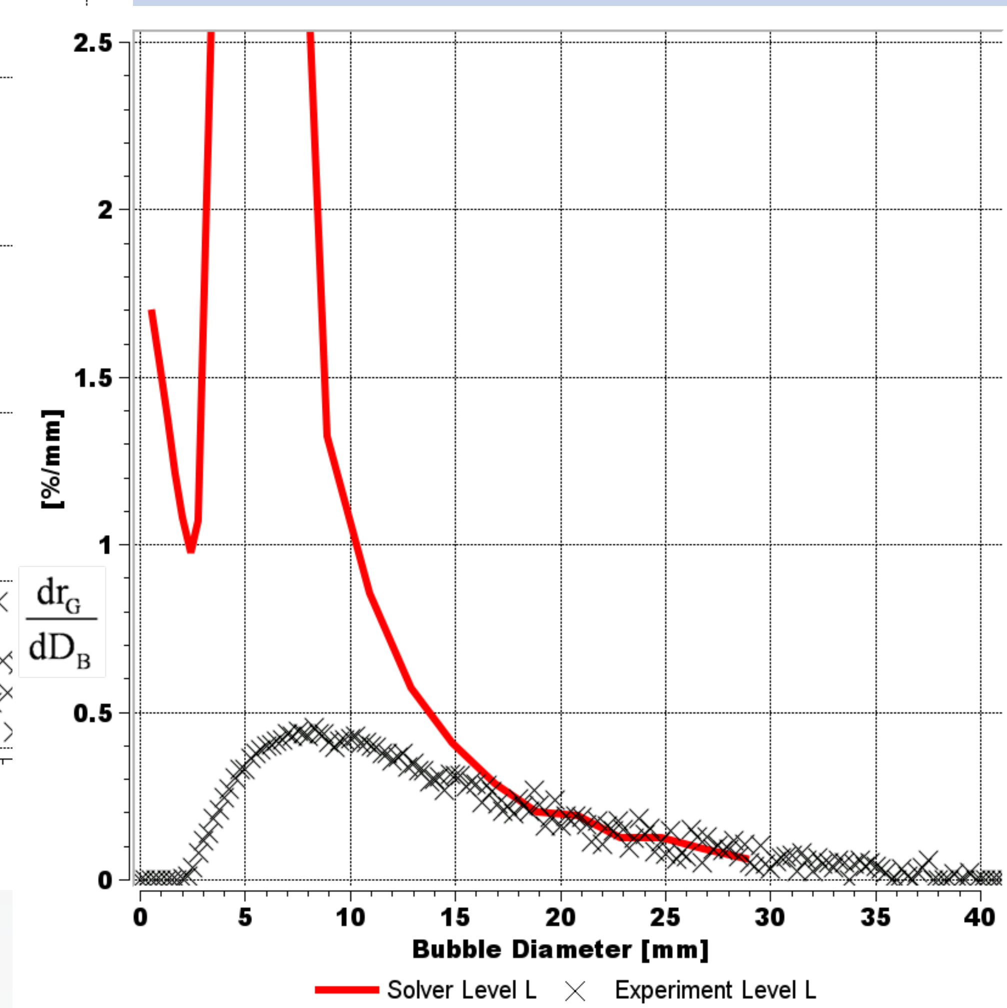
Radial steam distribution



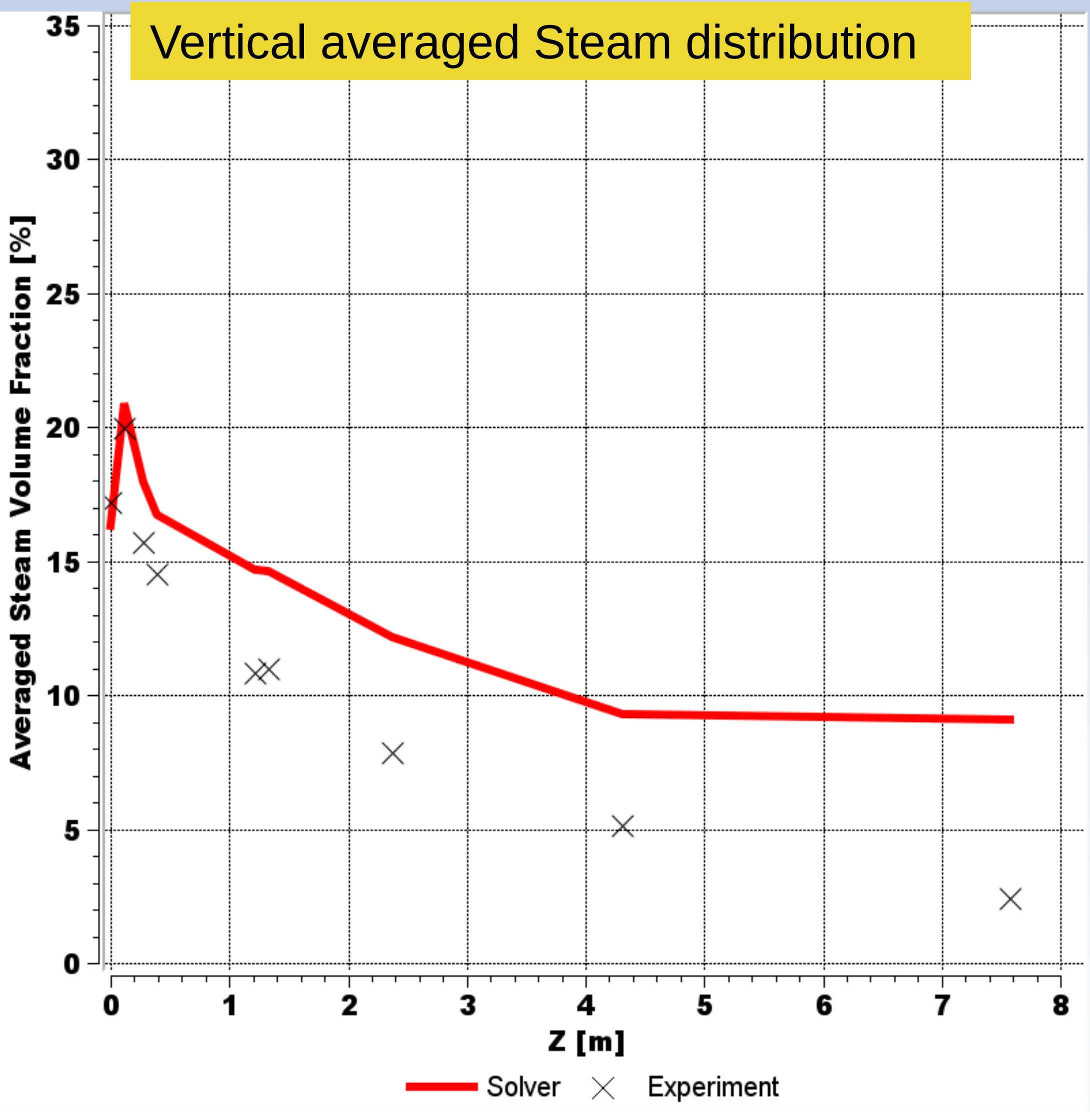
Results: Standard MUSIG w/o Phase Change

Bubble size distribution





Results: Extended MUSIG



Results: Extended MUSIG

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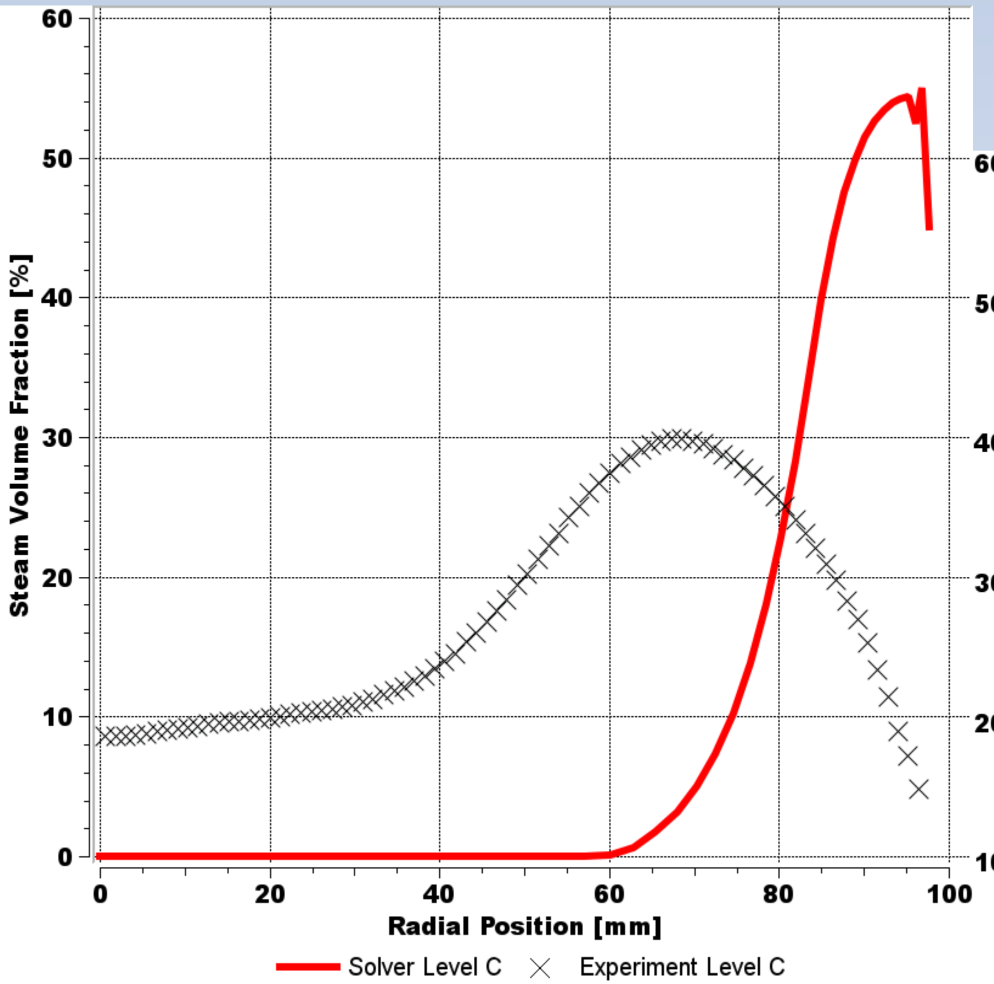

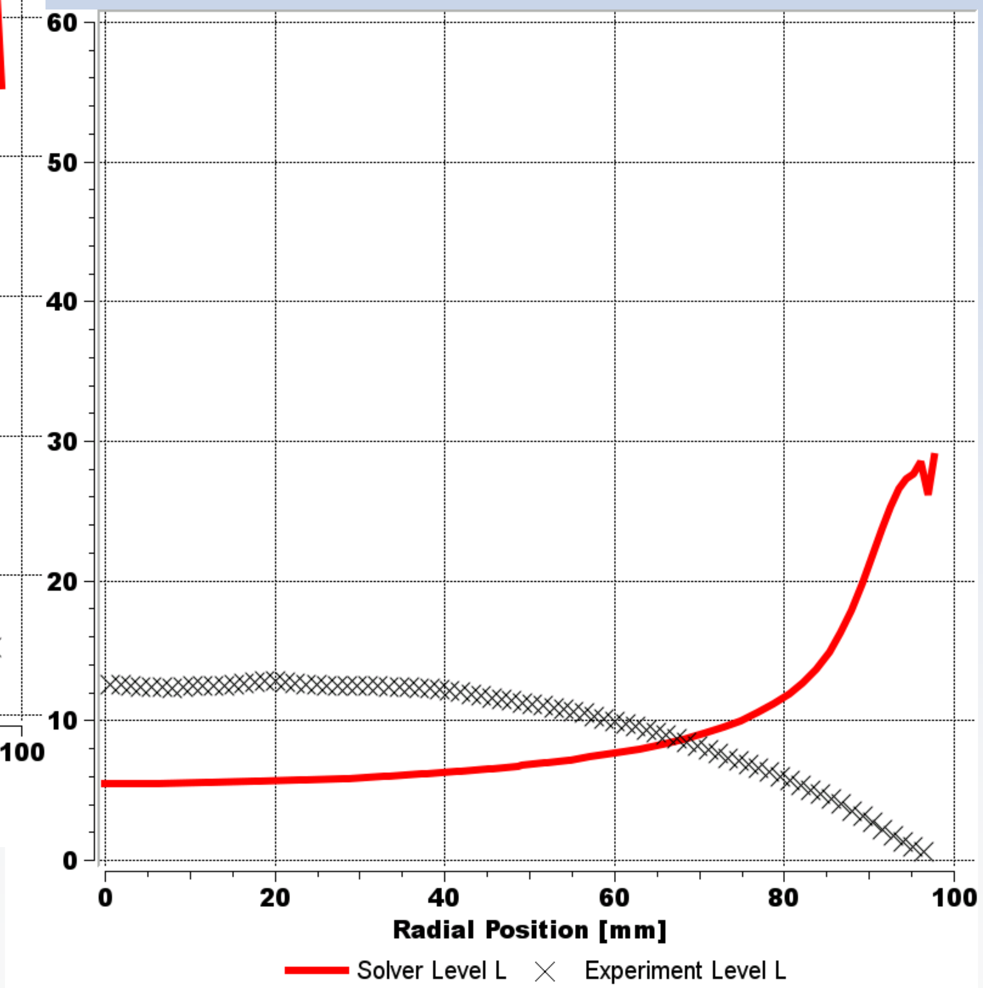

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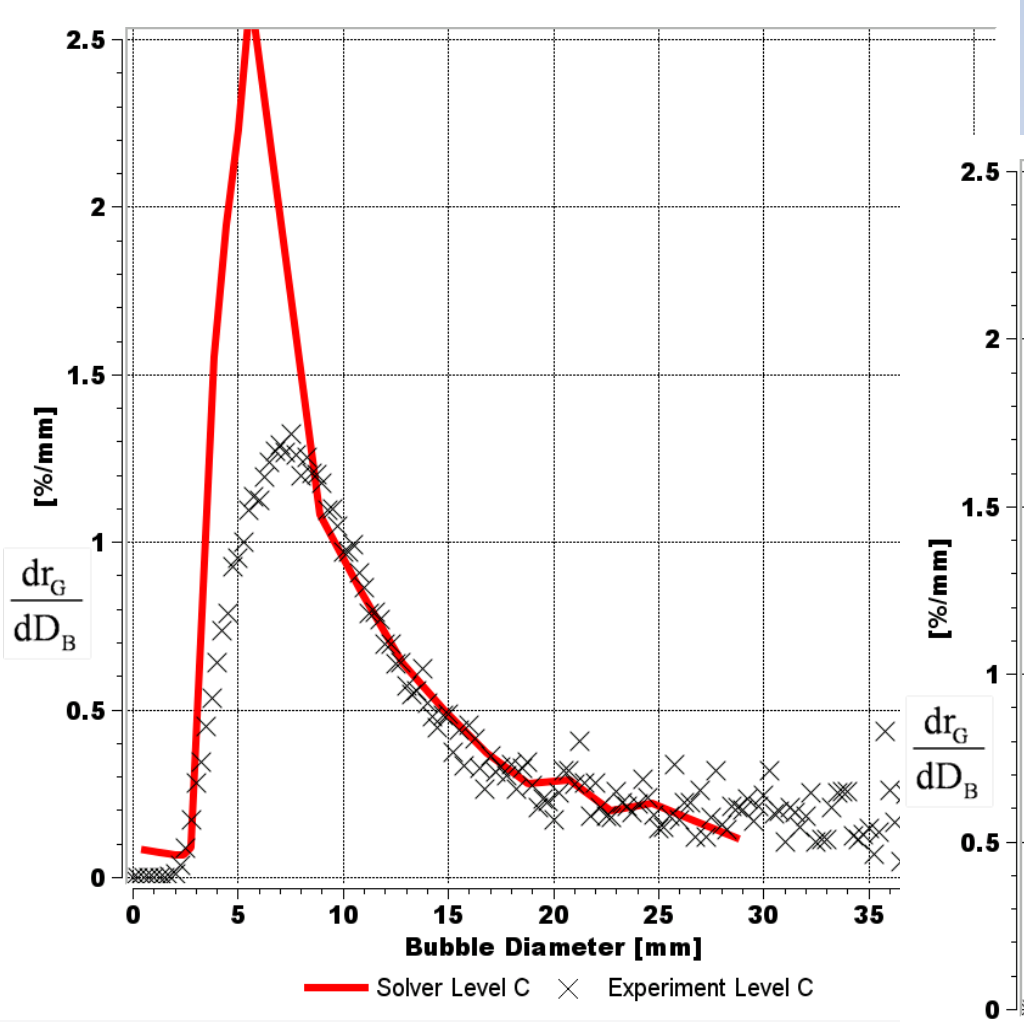

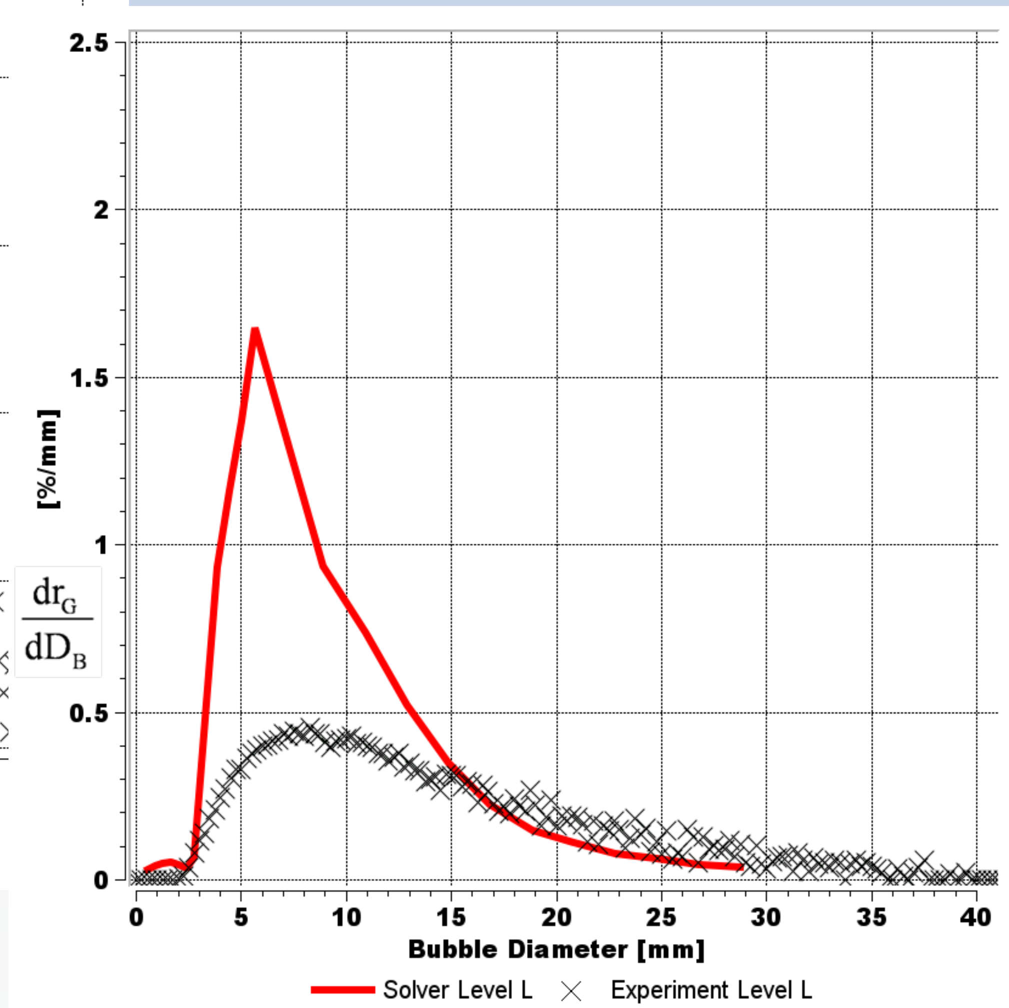

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Summary & Conclusions

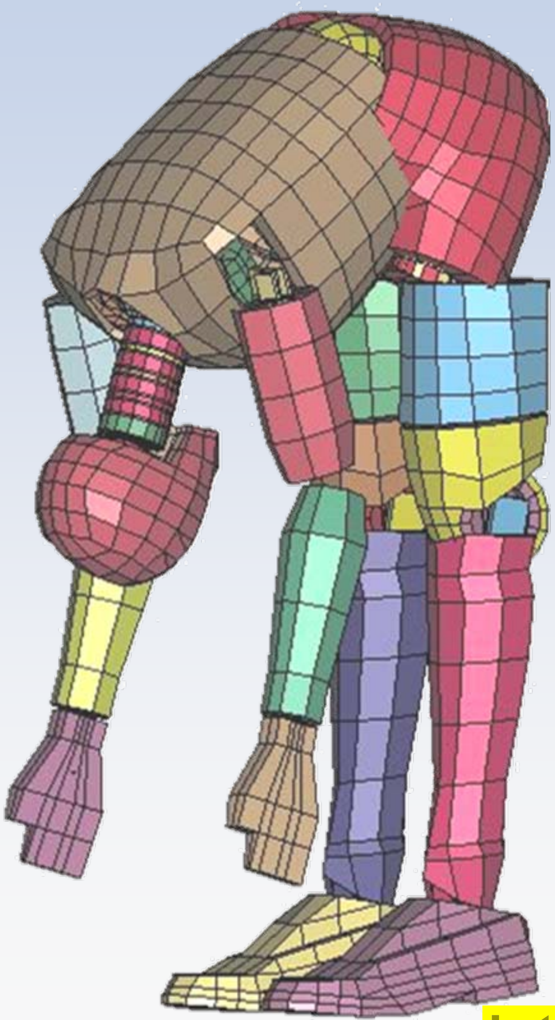
- **An extension of the MUSIG model in ANSYS CFX in order to catch phase change effect was implemented**
- **Successful tests for verification**
- **Condensation case at the TOPFLOW geometry used for validation**
  - Improved bubble size distribution prediction
  - Steam volume fraction prediction displaced to the wall
    - Work in progress:
      - Increase injection velocity
      - Inclusion of WLF

Acknowledgments

- **BMWi Funded Project:**
  - “*Development of CFD Software for the simulation of multi-dimensional flows in the reactor cooling system (Nr. 150-1328)*”

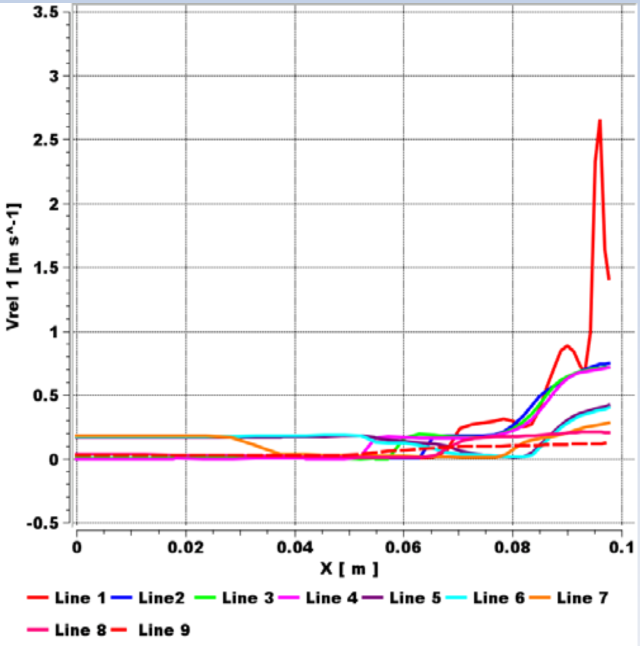
- **All colleagues in FZD & ANSYS involved.** ***Thanks/Danke!***

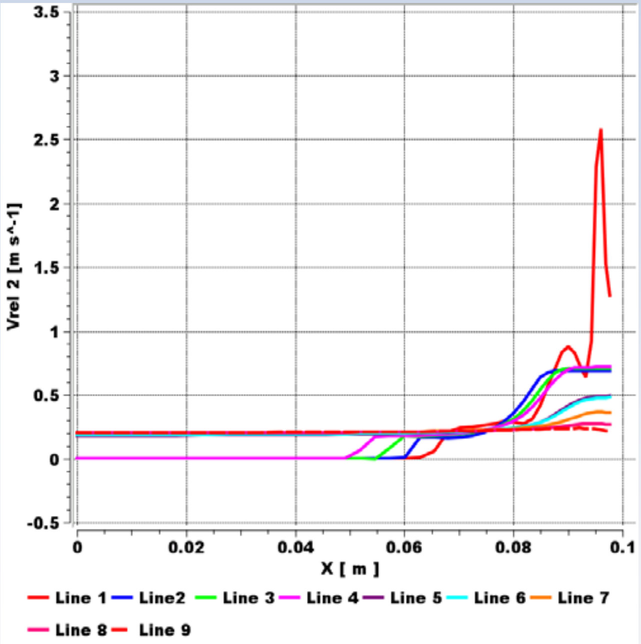
Thank You!

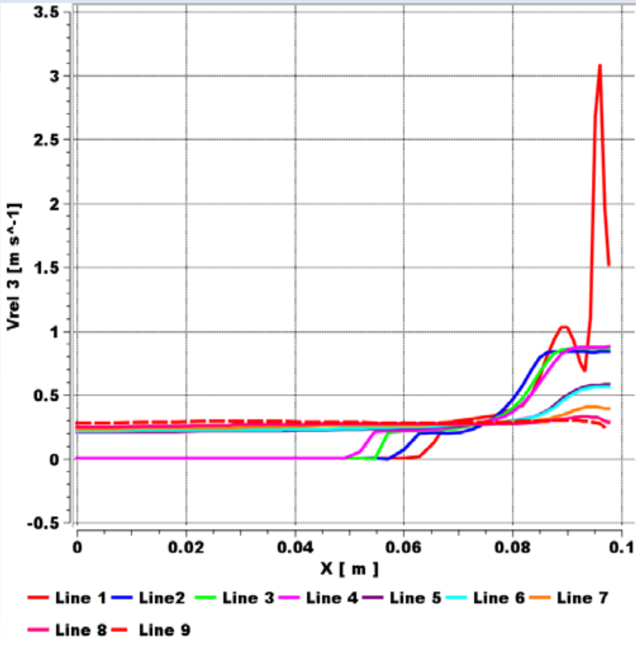


Results: Standard MUSIG w/o Phase Change

Relative Velocities







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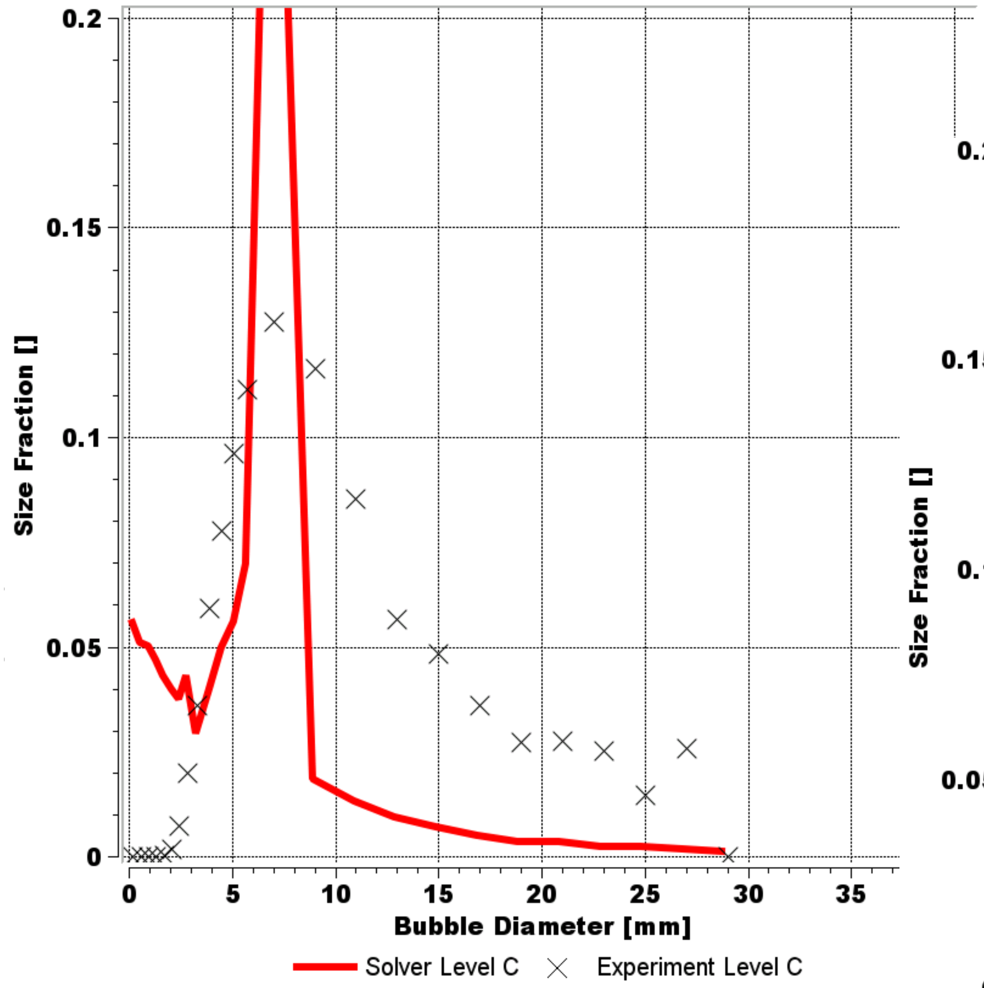
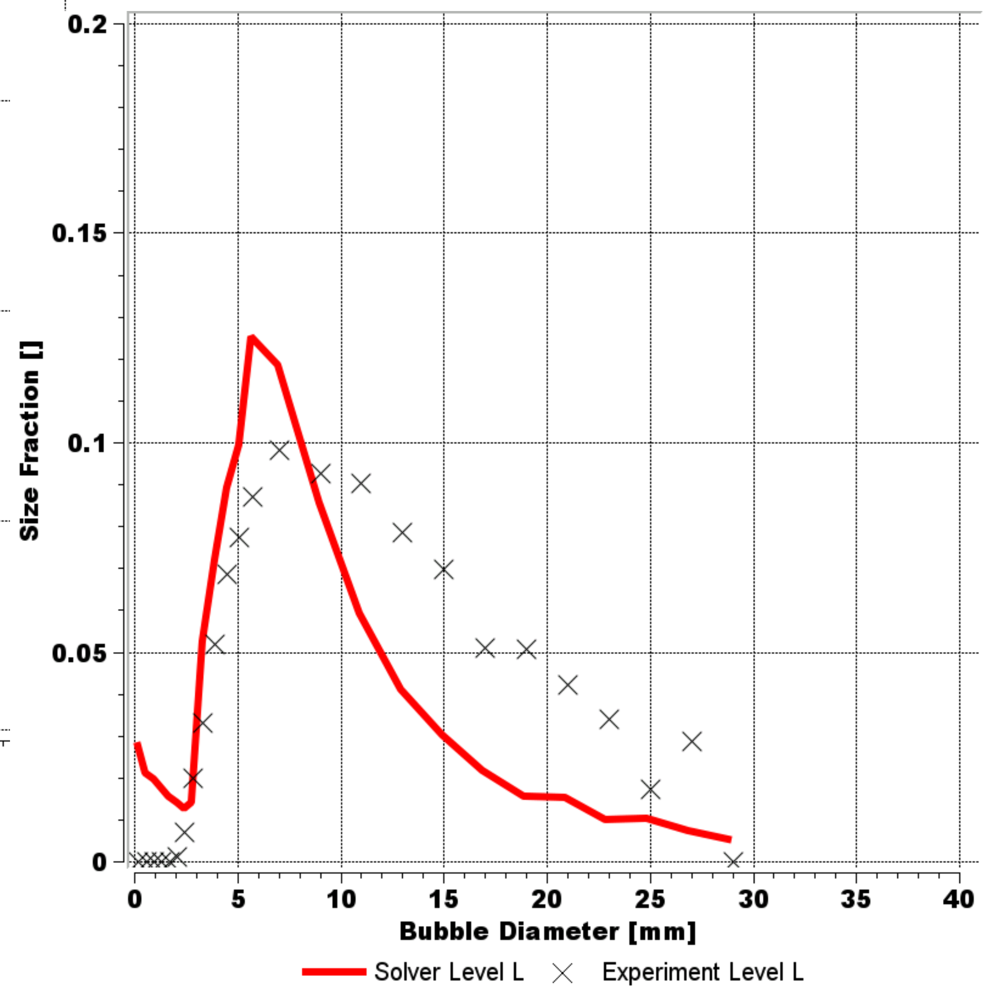
Size fraction distribution





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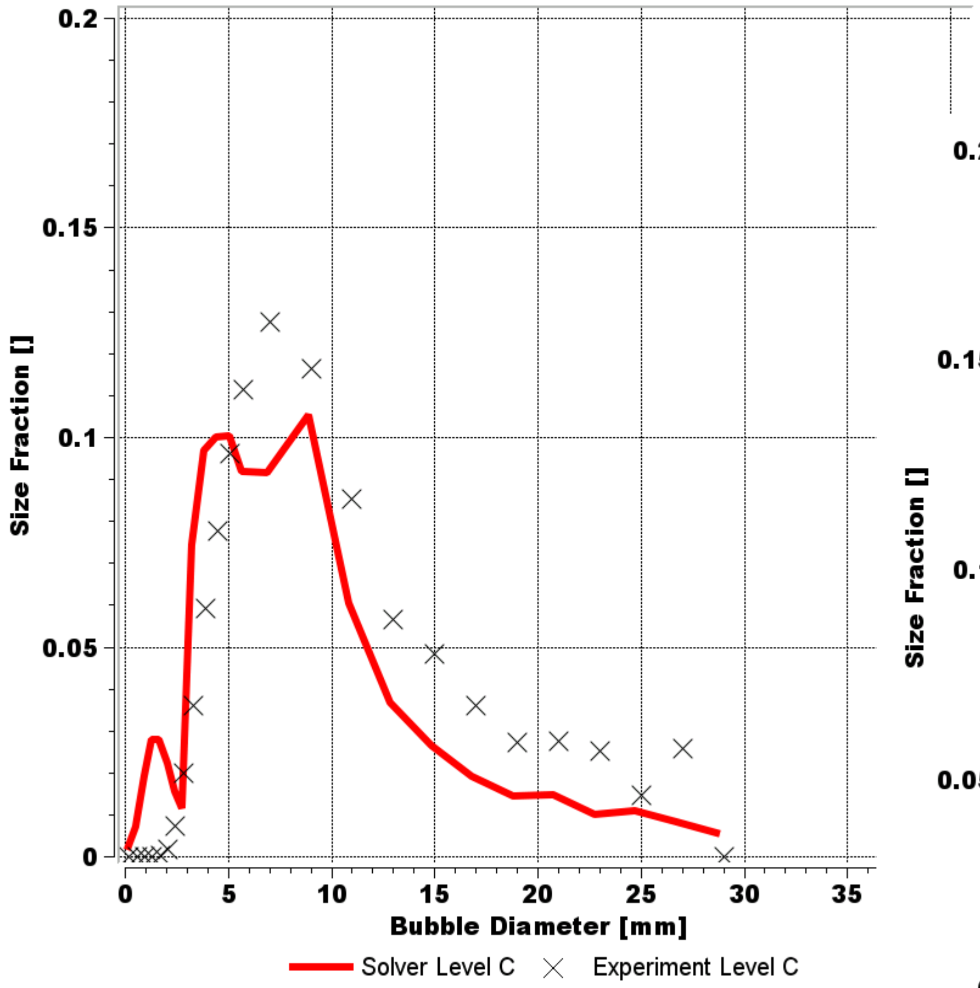

Size fraction distribution