



The Inhomogeneous MUSIG Model: Validation and Comparison with TOPFLOW experiments

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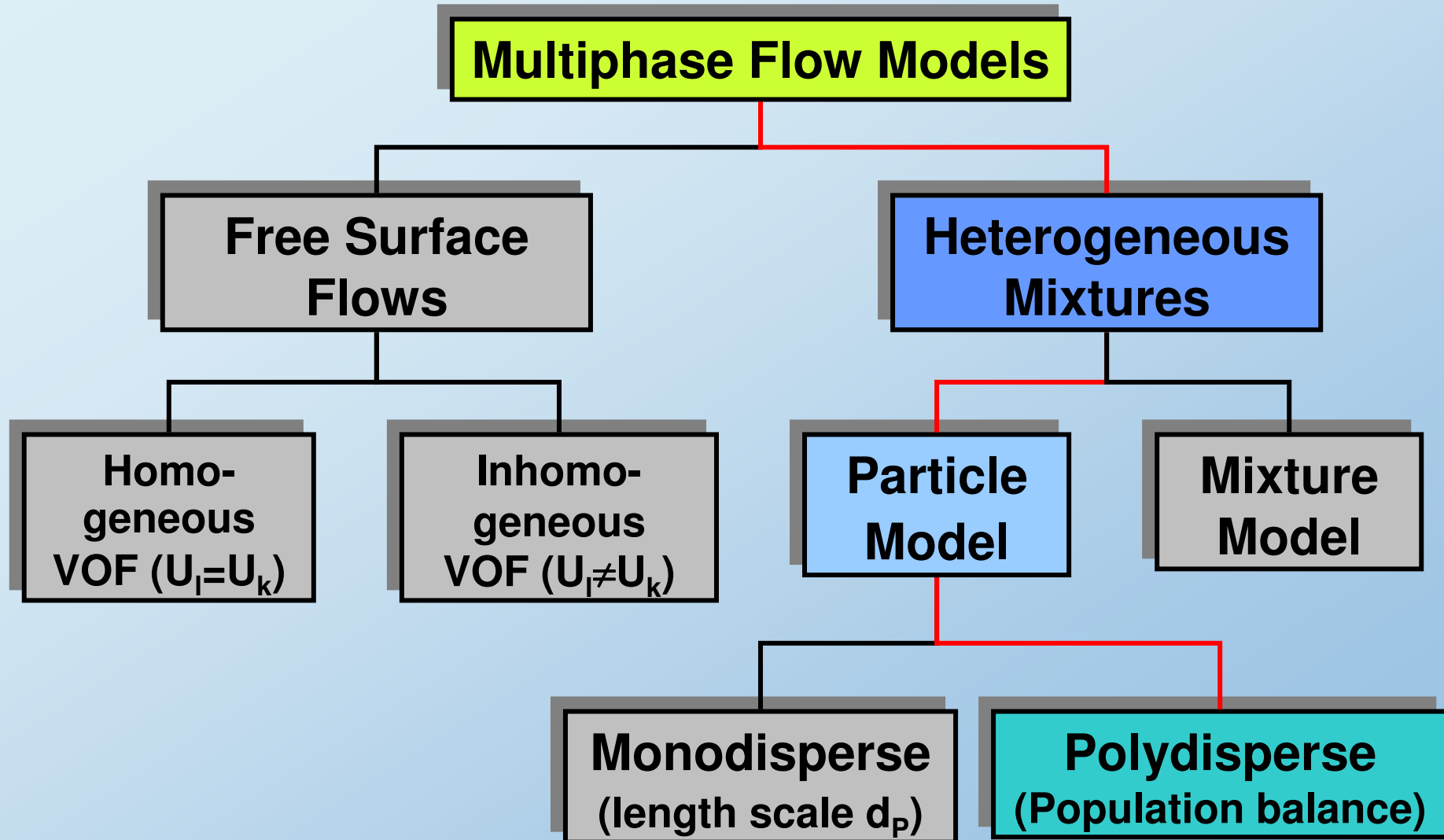
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- **Introduction**
- **The testcase TOPFLOW-074**
- **Validation tests and comparison with experimental results**
- **Summary & Conclusions**



Polydispersed bubbly flow caused by breakup & coalescence

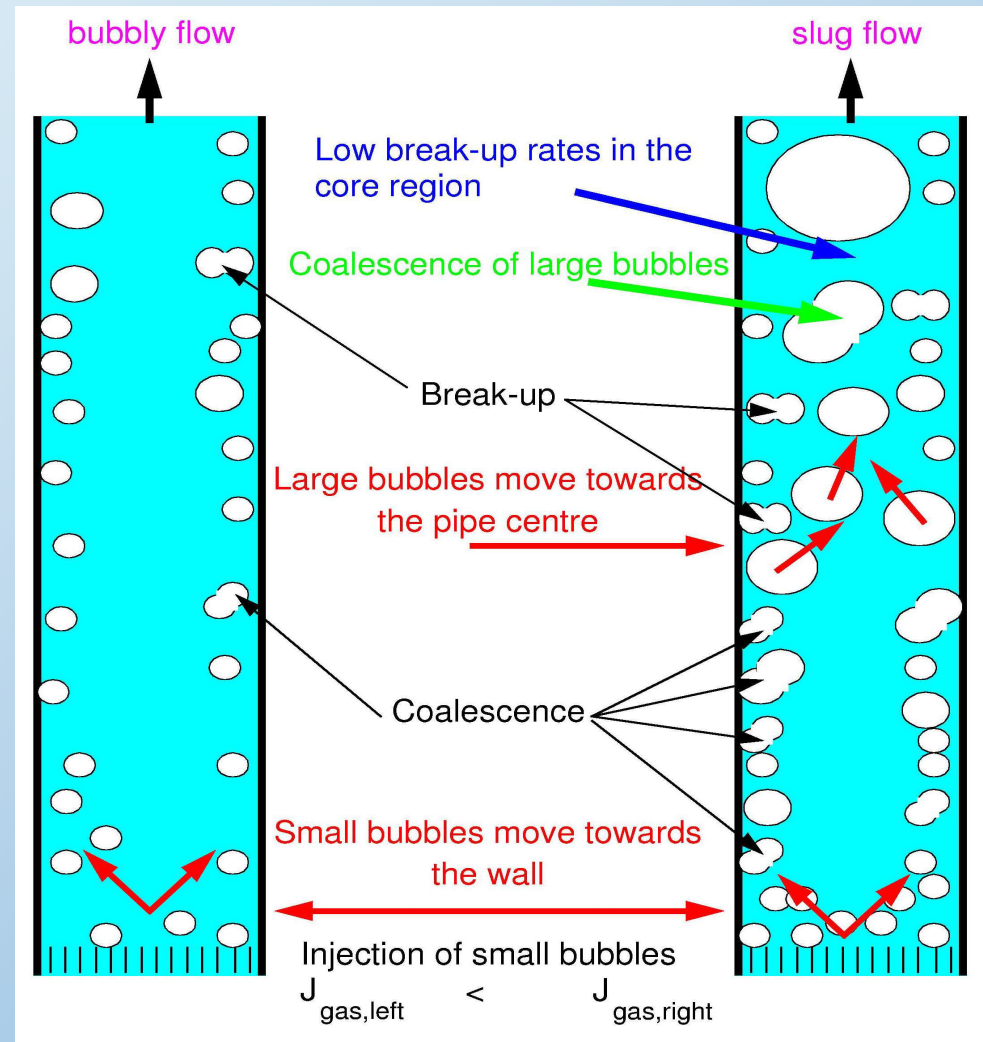


Transition from disperse bubbly flow to slug flow:

- **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

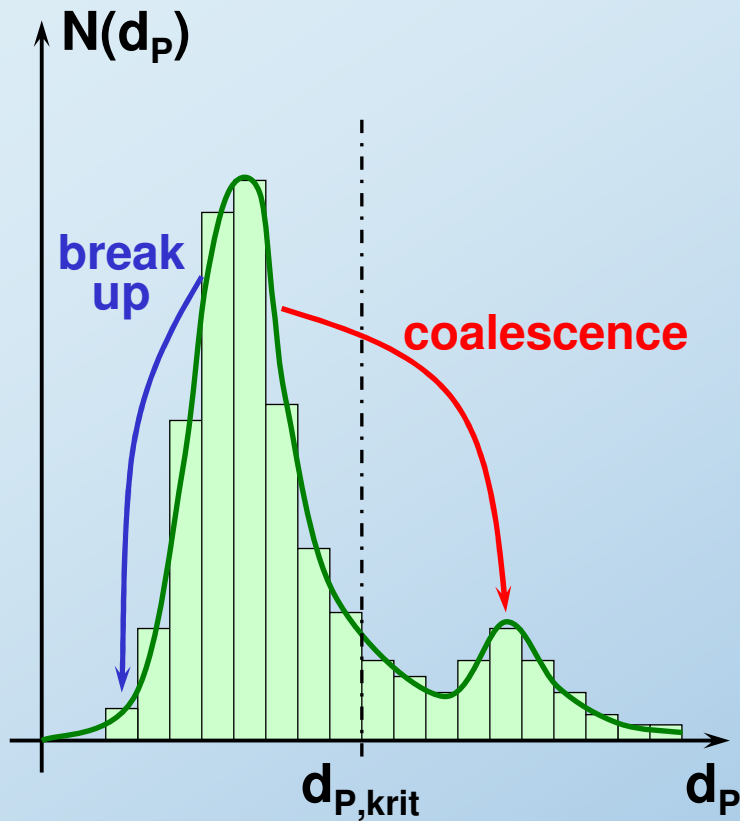
new population balance
model (inhomogeneous
MUSIG)



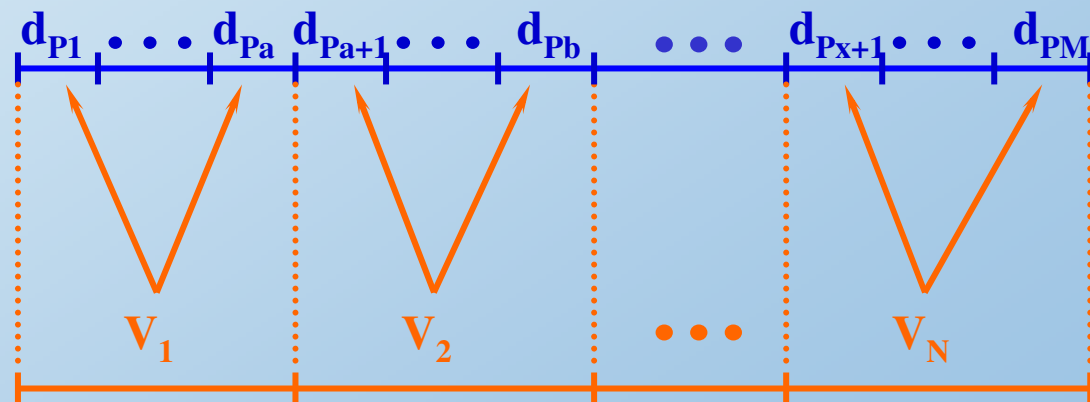
The inhomogeneous MUSIG model



- 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**



size classes (M)



velocity groups (N)

Inhomogeneous MUSIG model solves for:

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

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

$$g = 1, \dots, N \cdot M$$
$$j = 1, \dots, N$$

$$r_d = \sum_{g=1}^{N \cdot M} r_{dg} \quad , \quad f_{dg} = \frac{r_{dg}}{r_d} \quad , \quad \sum_{g=1}^{N \cdot M} f_{dg} = 1 \quad , \quad \sum_{g=1}^{N \cdot M} S_g = 0$$

The inhomogeneous MUSIG model

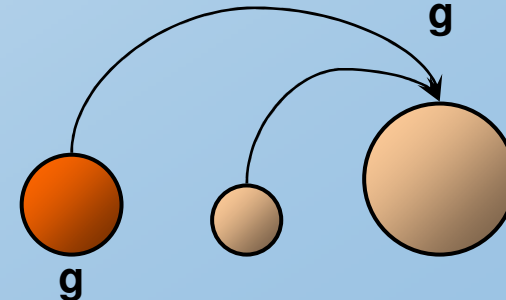
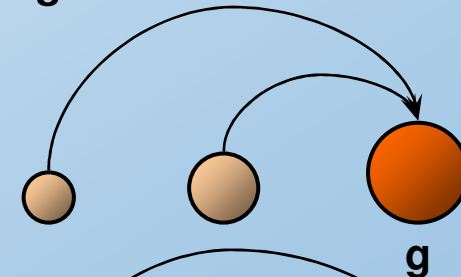
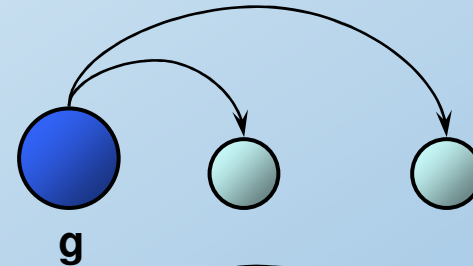
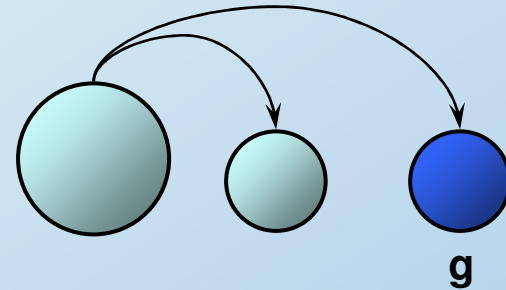


$$S_g = \underbrace{\rho_d \sum_{h=g+1}^{N \cdot M} B_{gh} r_{dh}}_{\text{breakup birth}}$$

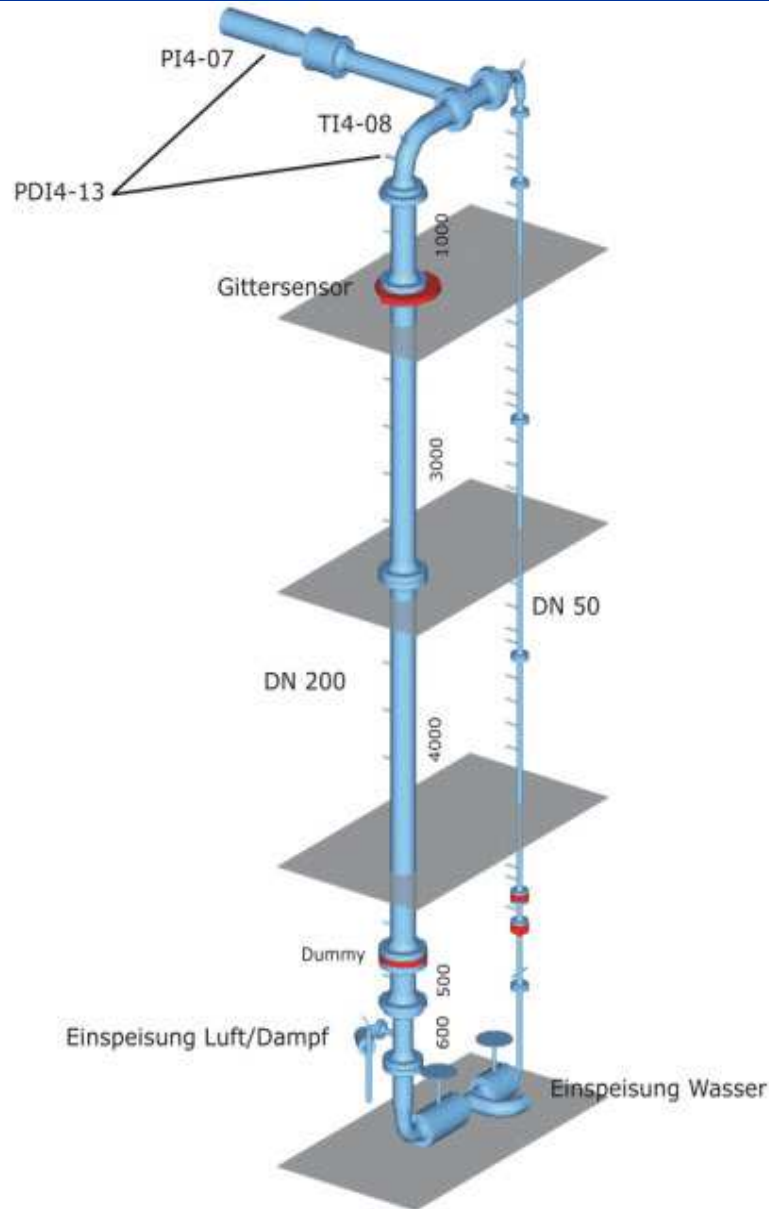
$$- \underbrace{\rho_d r_{dg} \sum_{h=1}^{g-1} B_{gh}}_{\text{breakup death}}$$

$$+ \underbrace{\frac{1}{2} \rho_d \sum_{h=1}^g \sum_{i=1}^g C_{hi} r_{dh} r_{di} X_{g \leftarrow hi} \frac{m_h + m_i}{m_h m_i}}_{\text{coalescence birth}}$$

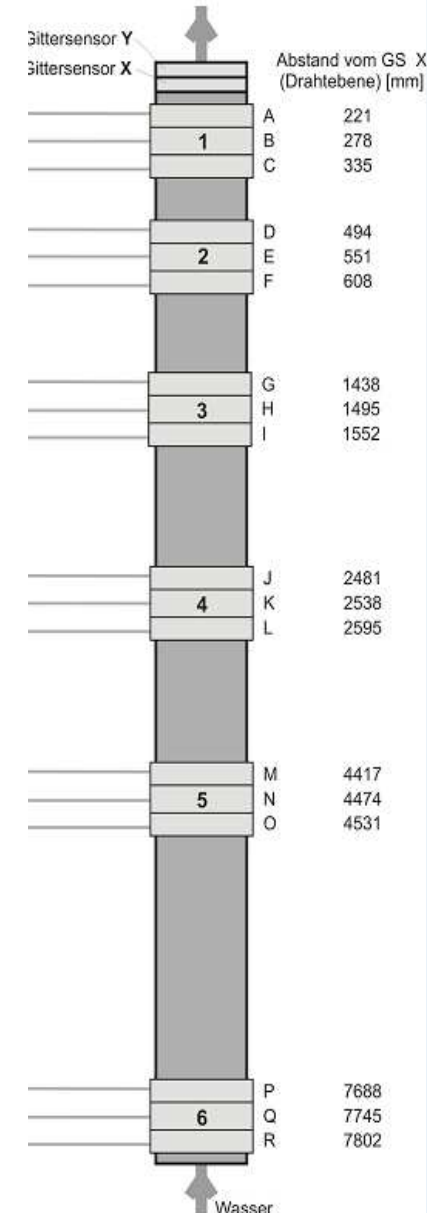
$$- \underbrace{\rho_d r_{dg} \sum_{h=1}^{N \cdot M} C_{gh} \frac{r_{dh}}{m_h}}_{\text{coalescence death}}$$



The TOPFLOW test facility at FZR



- FZR TOPFLOW test facility with DN200
- gas injection through 72 x 1mm Ø wall injection holes
- $J_W=1.017$ m/s
 $J_G=0.0368$ m/s
- $r_G=3.49\%$
(mean gas volume fraction)



3x7 inhomogeneous MUSIG simulations for TOPFLOW-074



- **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 $d_p=0, \dots, 13\text{mm}$
 - equal diameter discretization ($\Delta d_p=0.619\text{mm}$)
 - **Air1 vel. group :** $d_{p,\min}=0.31 \text{ mm}$; $d_{p,\max}=4.02\text{mm}$
 - **Air2 vel. group :** $d_{p,\min}=4.64 \text{ mm}$; $d_{p,\max}=8.36\text{mm}$
 - **Air3 vel. group :** $d_{p,\min}=8.98 \text{ mm}$; $d_{p,\max}=12.69\text{mm}$

3x7 inhomogeneous MUSIG simulations for TOPFLOW-074



5 different simulations with 3x7 MUSIG model:

No.	Grid level	No. of elements	C_{TD}	comment
1	2	32.000	1.0	reference case
2	4 (mod.)	260.442	1.0	grid refinement above the point of gas injection (z=0.0 z=8.0m; expanding mesh)
3	4 (mod.)	260.442	1.0	inlet BC initialization with u, v, w, k, ω from fully developed single-phase flow
4	4 (mod.)	260.442	1.0	changed gas inlet bubble size distribution
5	4 (mod.)	260.442	0.5	reduced turbulent dispersion

Gas Inlet Bubble Size Distribution



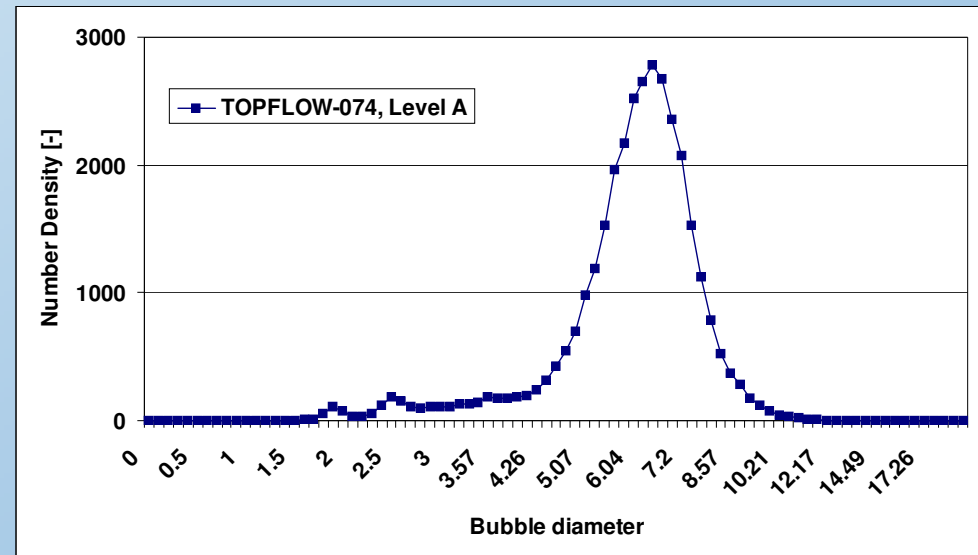
Cases 1-3 and 5:

- 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



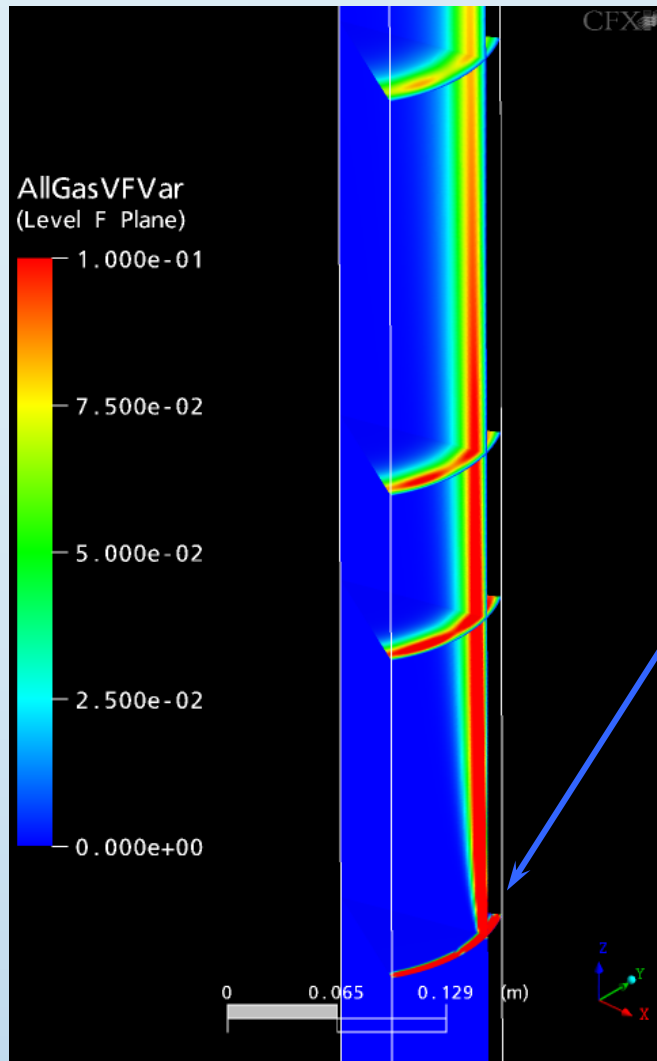
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074



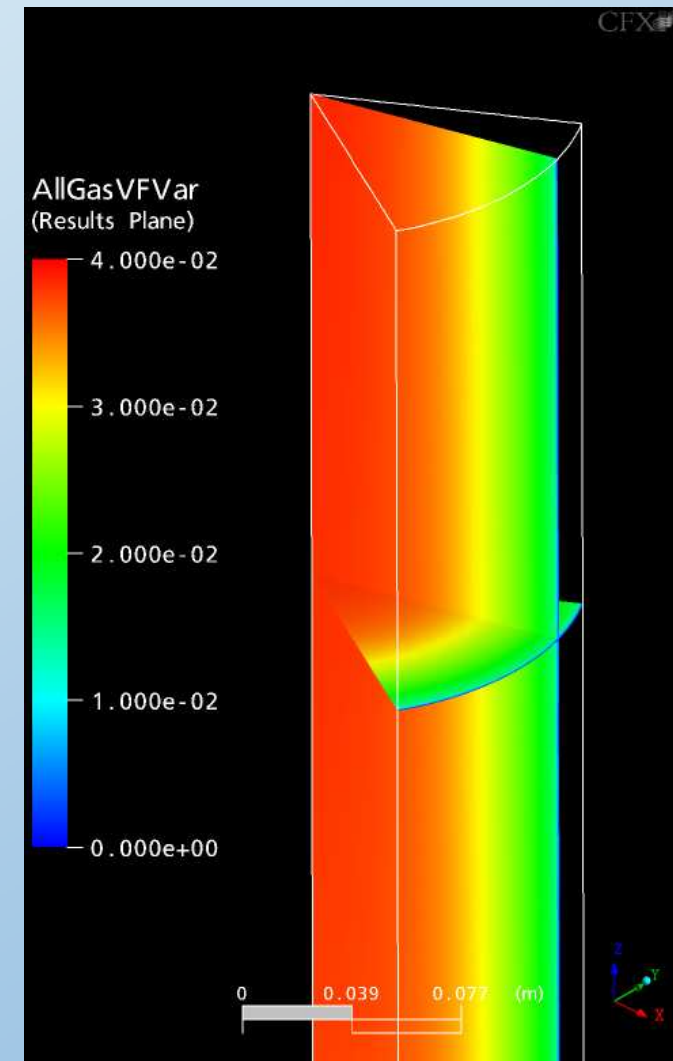
Inlet level

level F

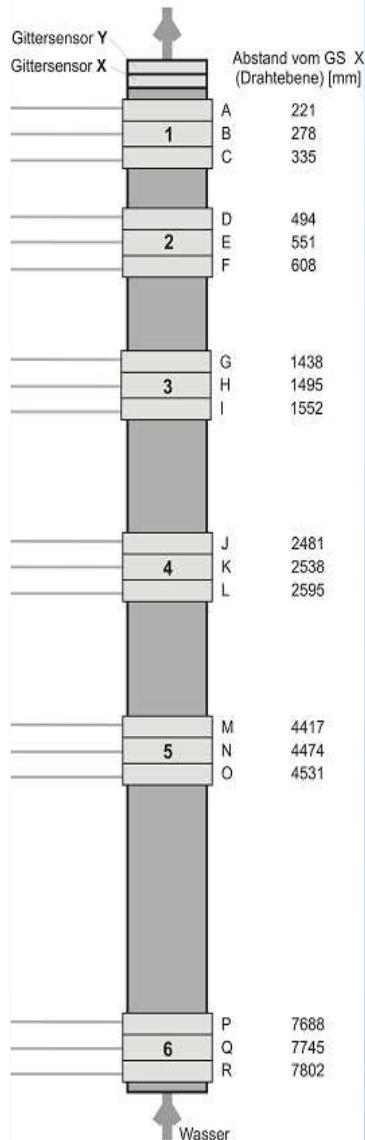
level R



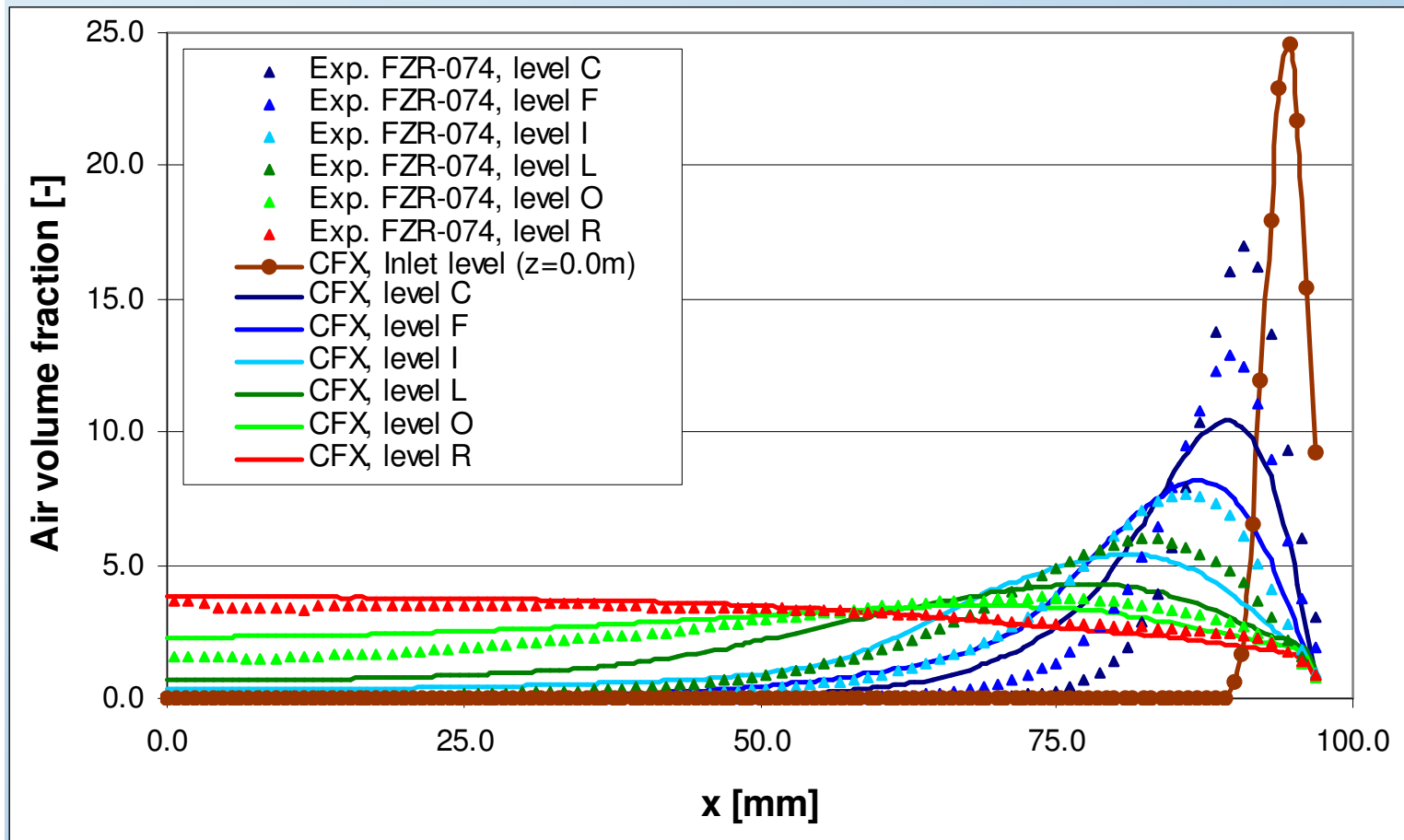
- TOPFLOW-074 best results obtained in **Case 4**
- near wall gas injection at $z=0.0\text{m}$
- level R results show core peak in air VF profiles



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



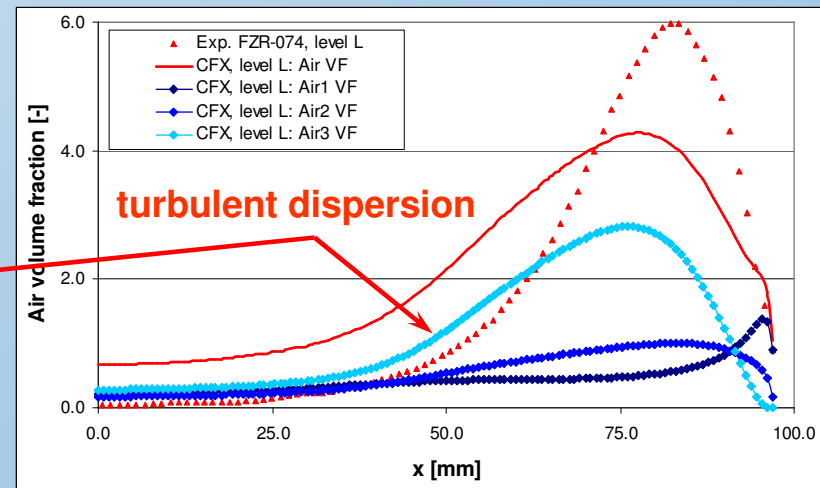
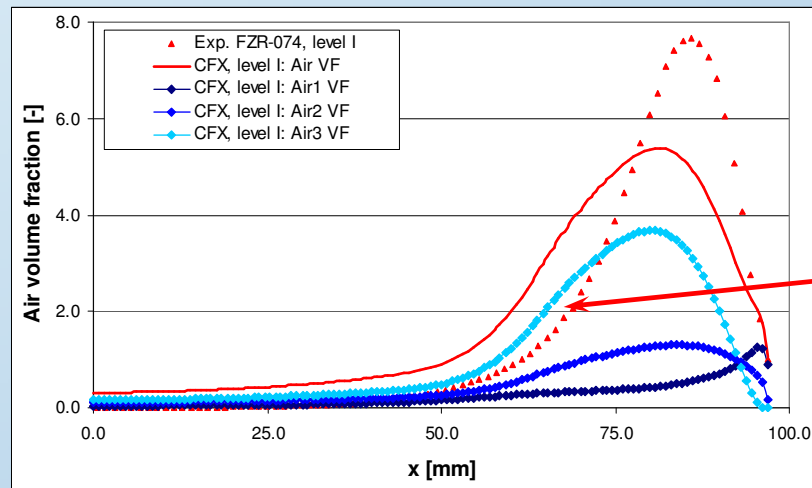
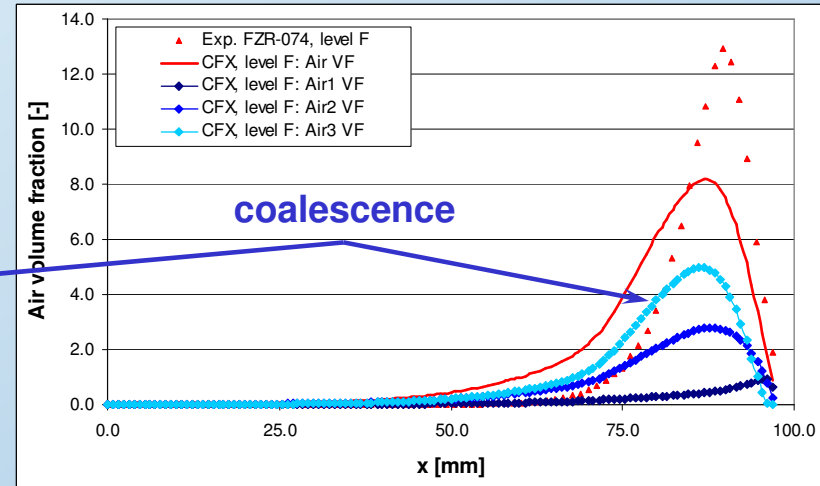
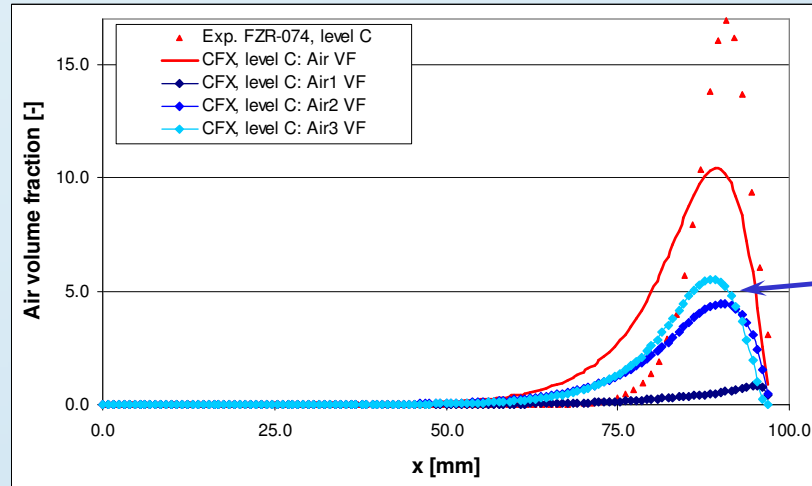
- good agreement at levels L through R
- too fast spreading of the bubble plume from inlet



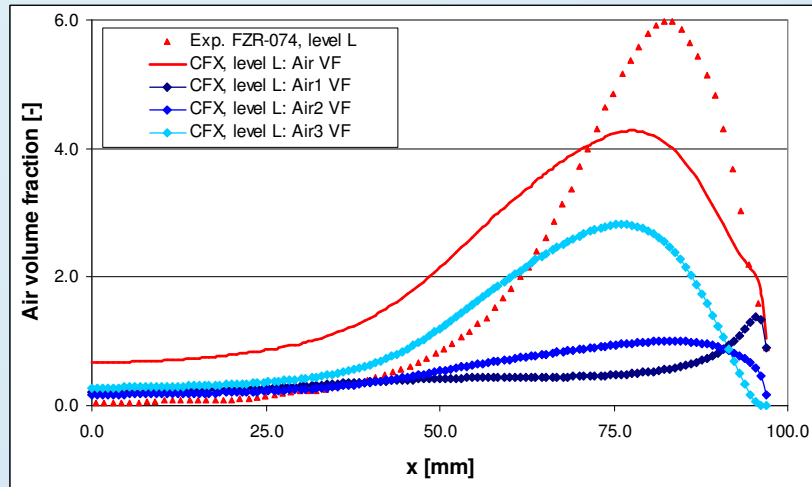
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074



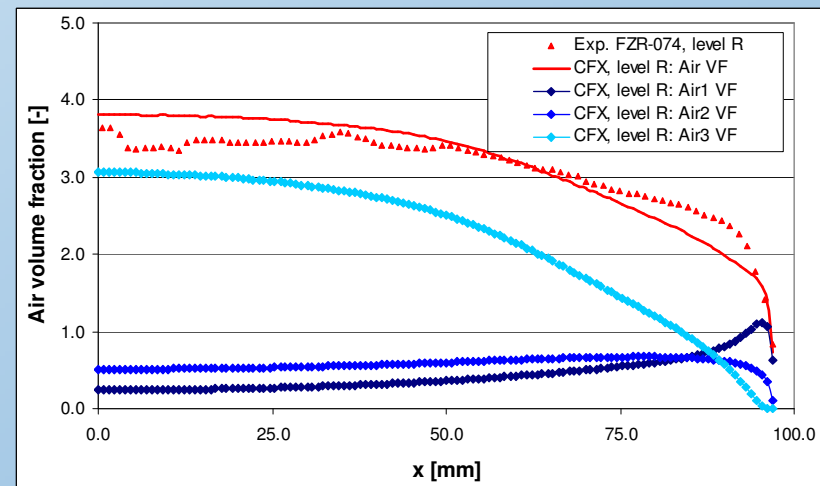
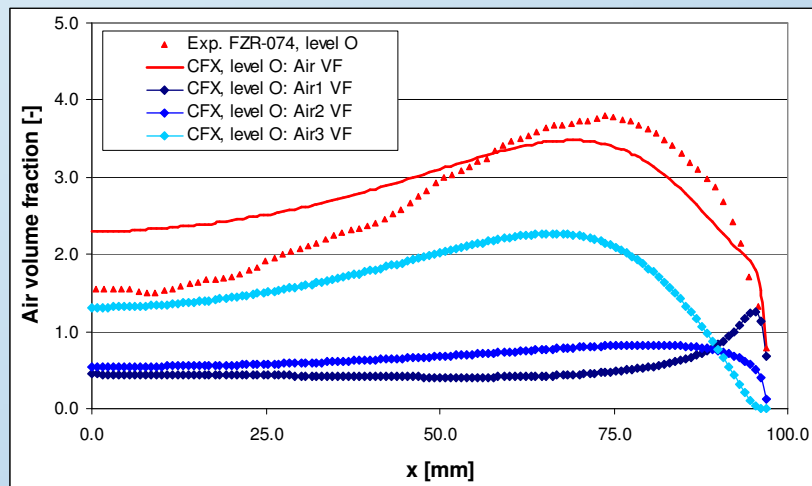
level C (z=0.335m) to level L (z=2.595m)



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



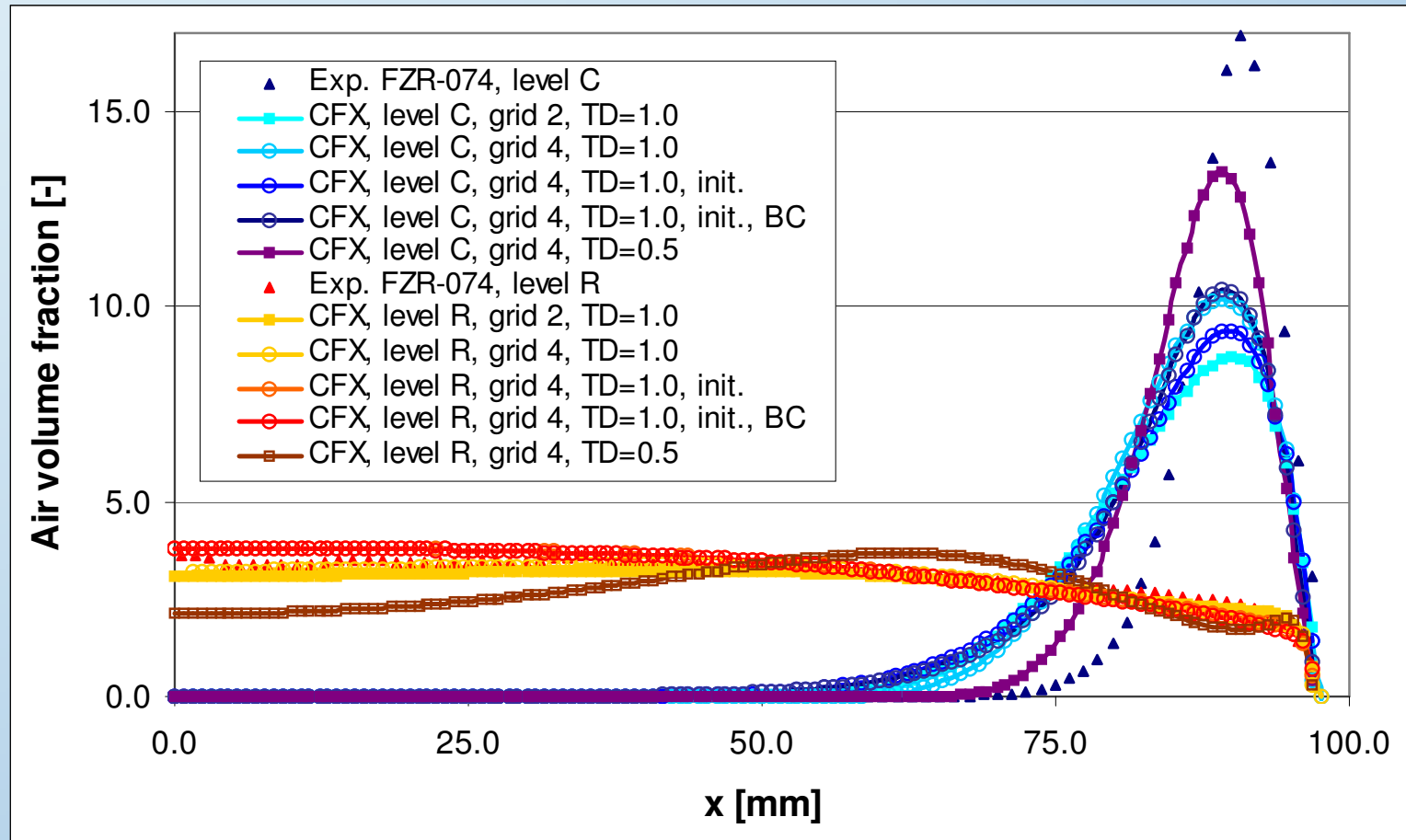
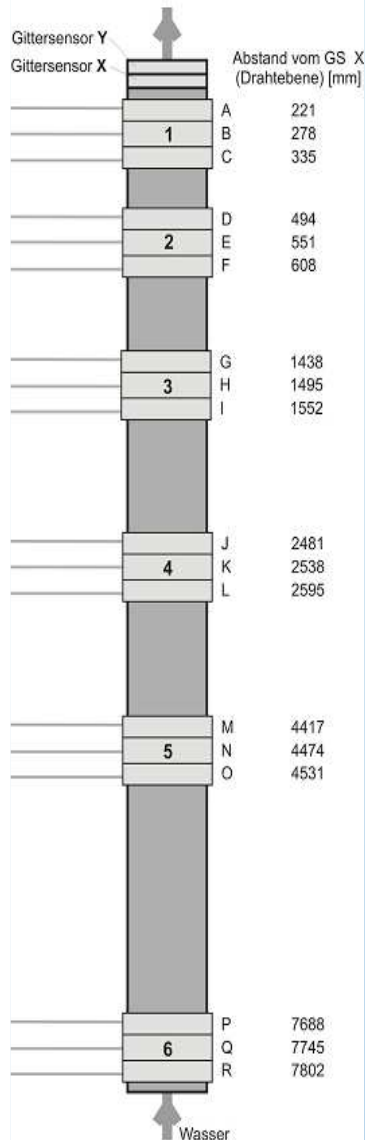
- Air VF at level L ($z=2.595\text{m}$), level O ($z=4.531\text{m}$) and level R ($z=7.802\text{m}$)
- agreement with experiments improves with increasing height
- good prediction of radial demixing processes for different bubble size classes



Overall Comparison of different Validation Tests



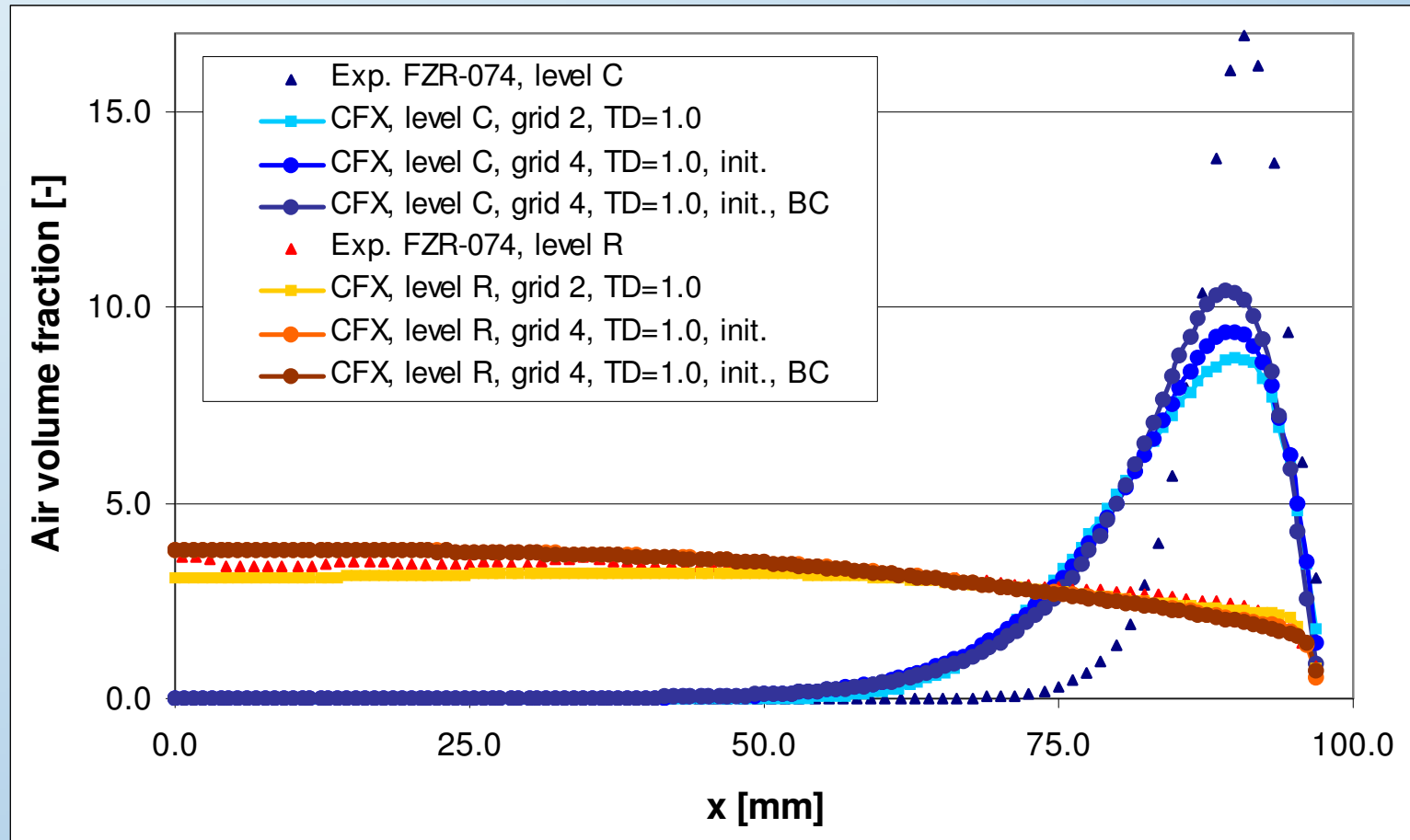
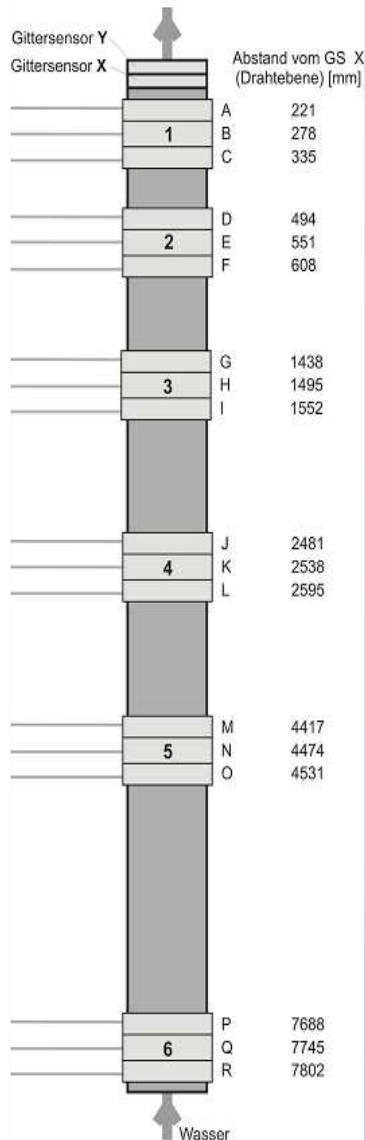
- C and R level results for Cases 1- 5



Overall Comparison of different Validation Tests

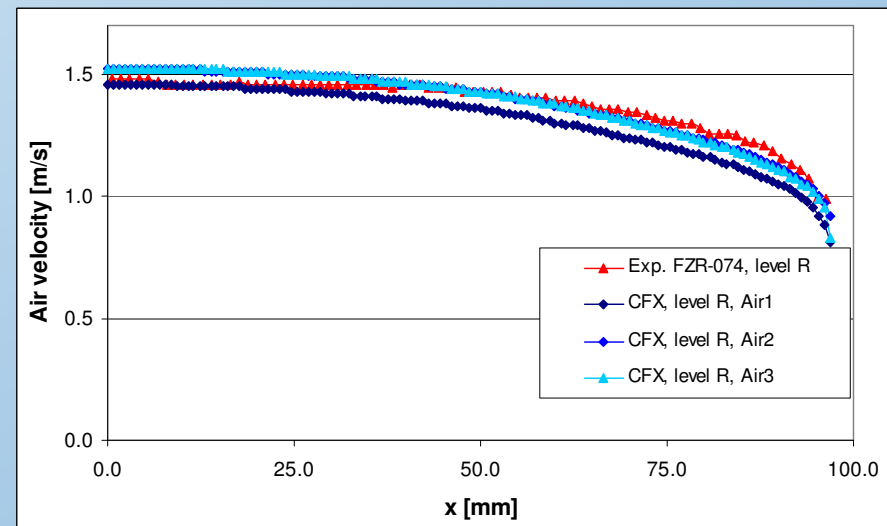
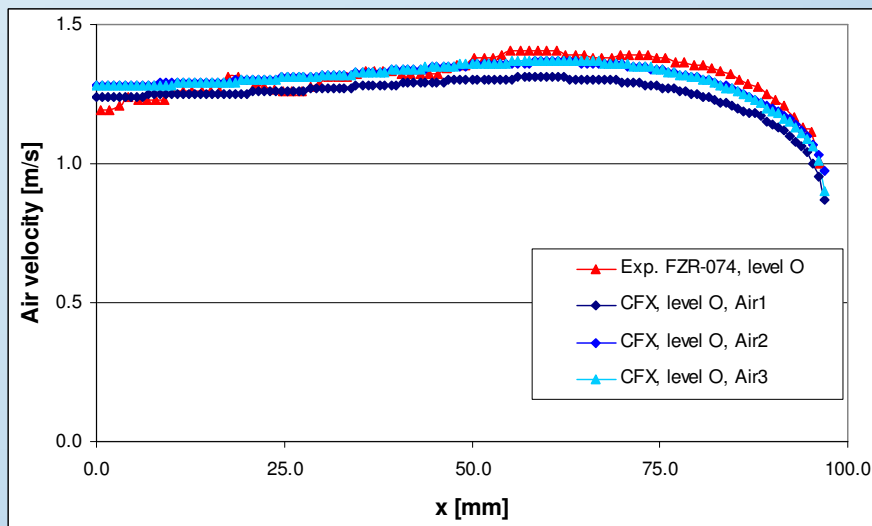
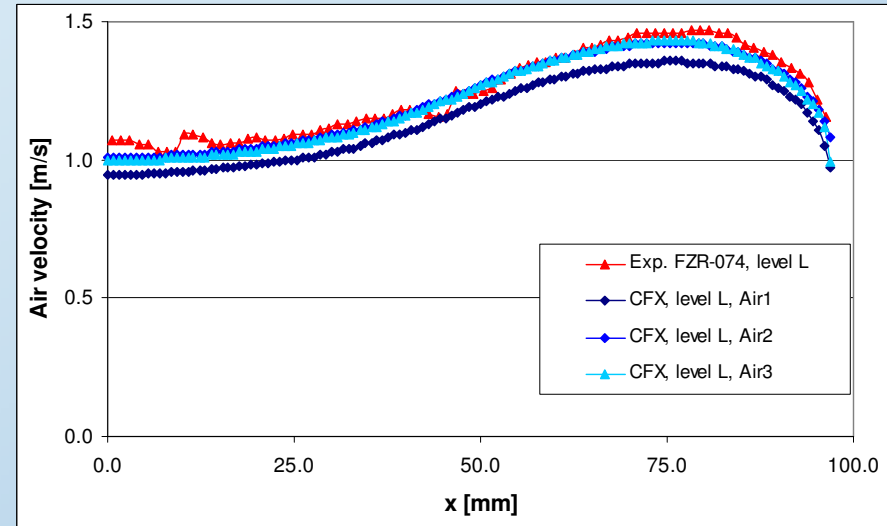
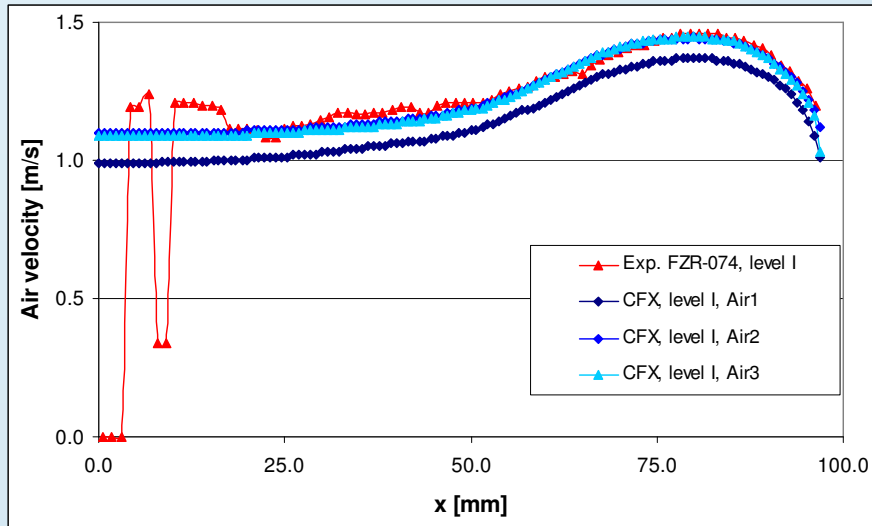


• C and R level results for Cases 1, 3 and 4

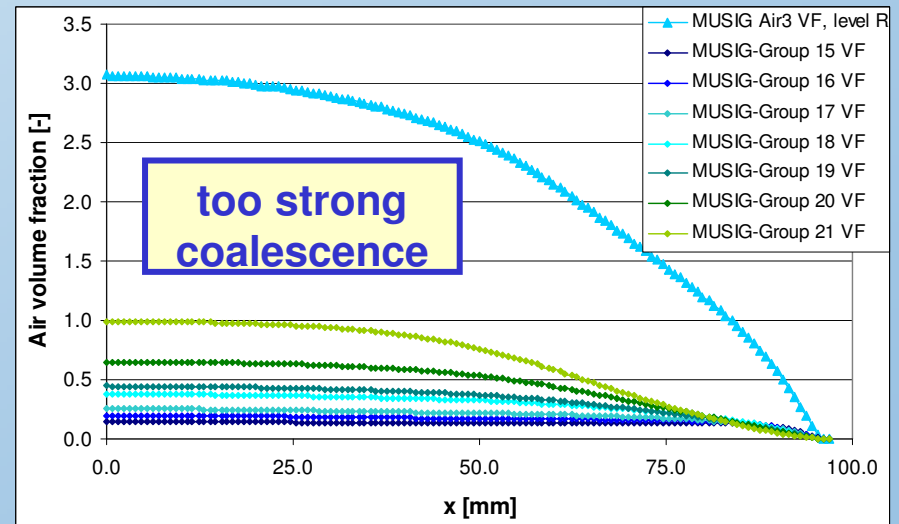
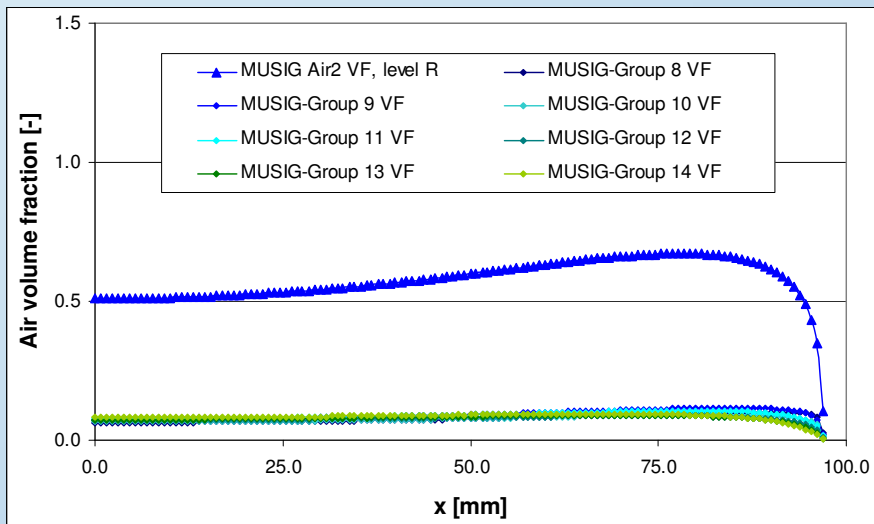
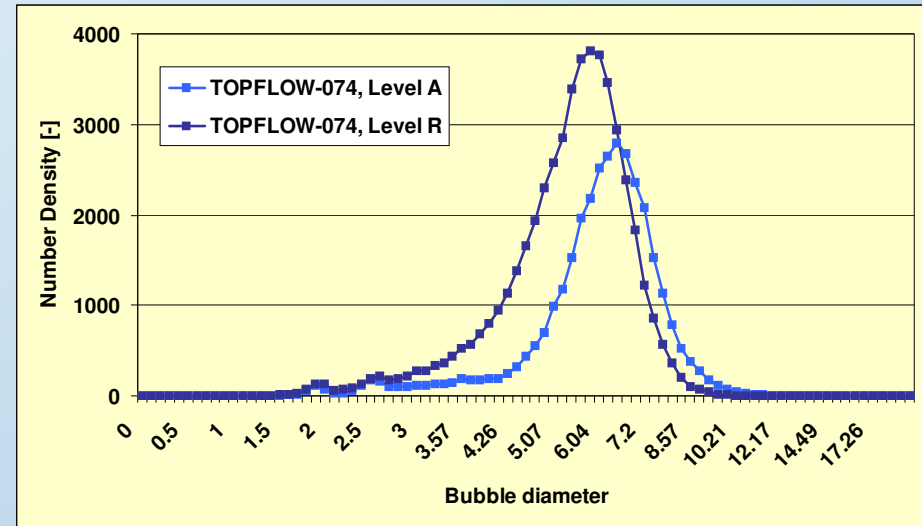
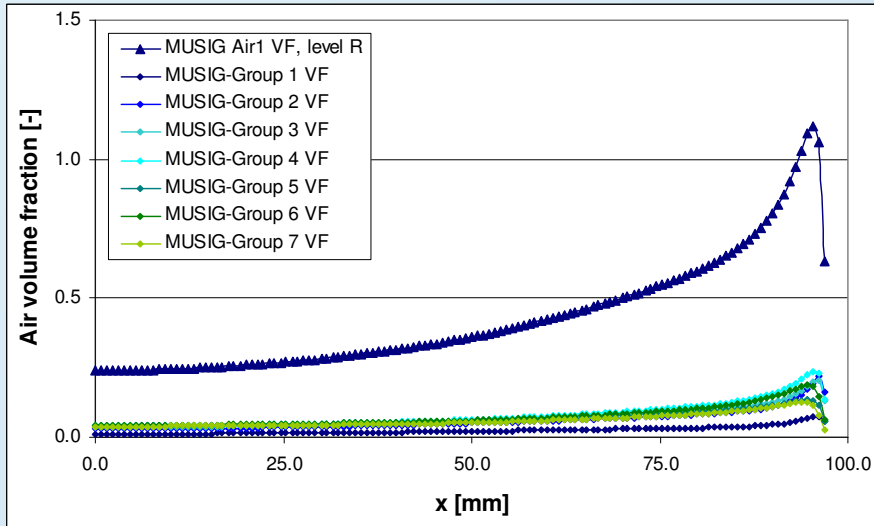


Case 4: Velocity Profiles

I R Level Comparison with Exp.



Case 4: Evolution of Bubble Size Distribution – Level R



- **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**