The Inhomogeneous MUSIG Model: Validation and Comparison with TOPFLOW experiments

Th. Frank[1], J. Shi[2], M.-H. Prasser[2], E. Krepper[2]

[1]ANSYS Germany, Otterfing

[2]Inst. of Safety Research, FZR, Dresden

Thomas.Frank@ansys.com

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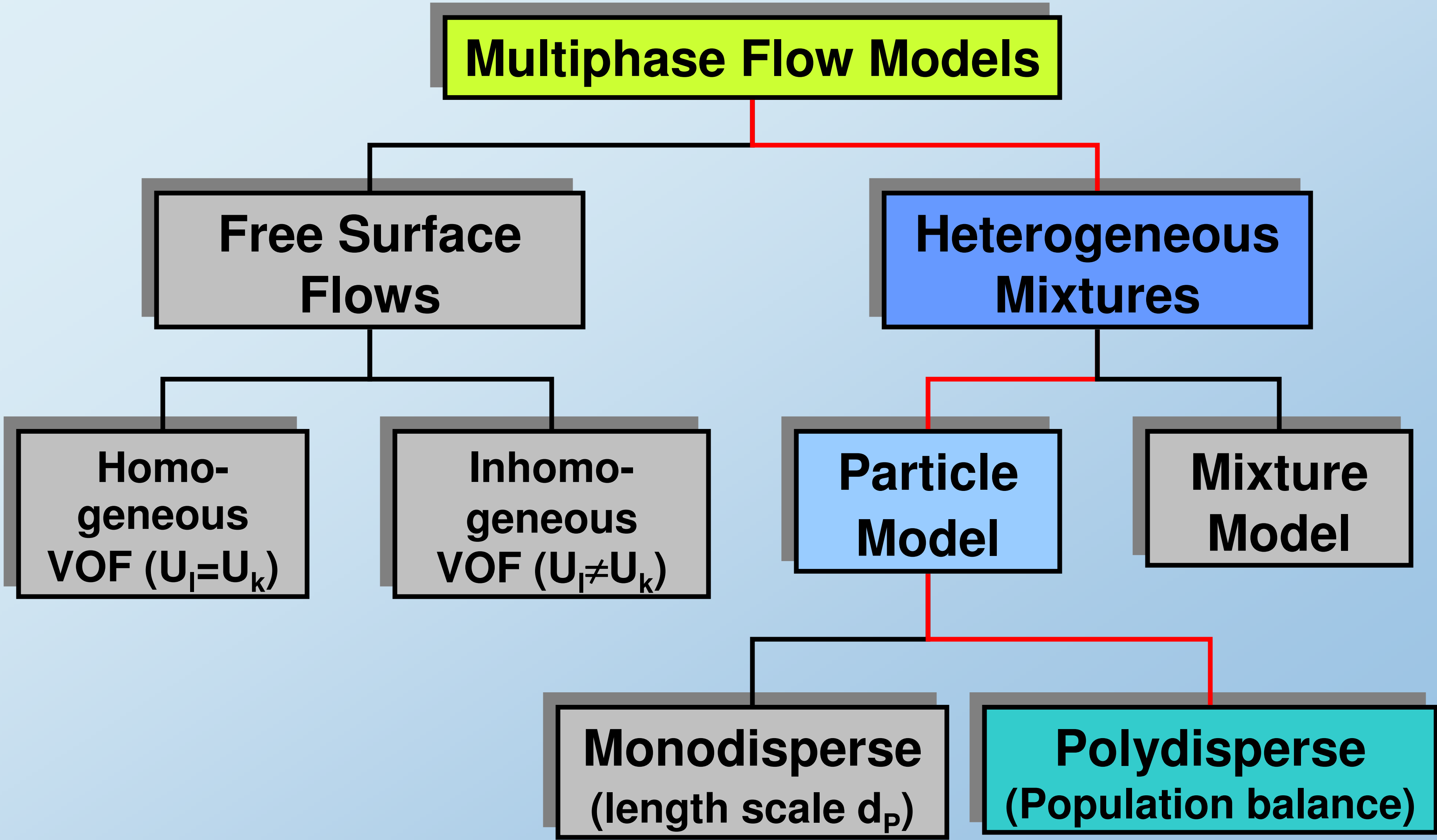
Modeling Strategies



Polydispersed bubbly flow caused by breakup & coalescence

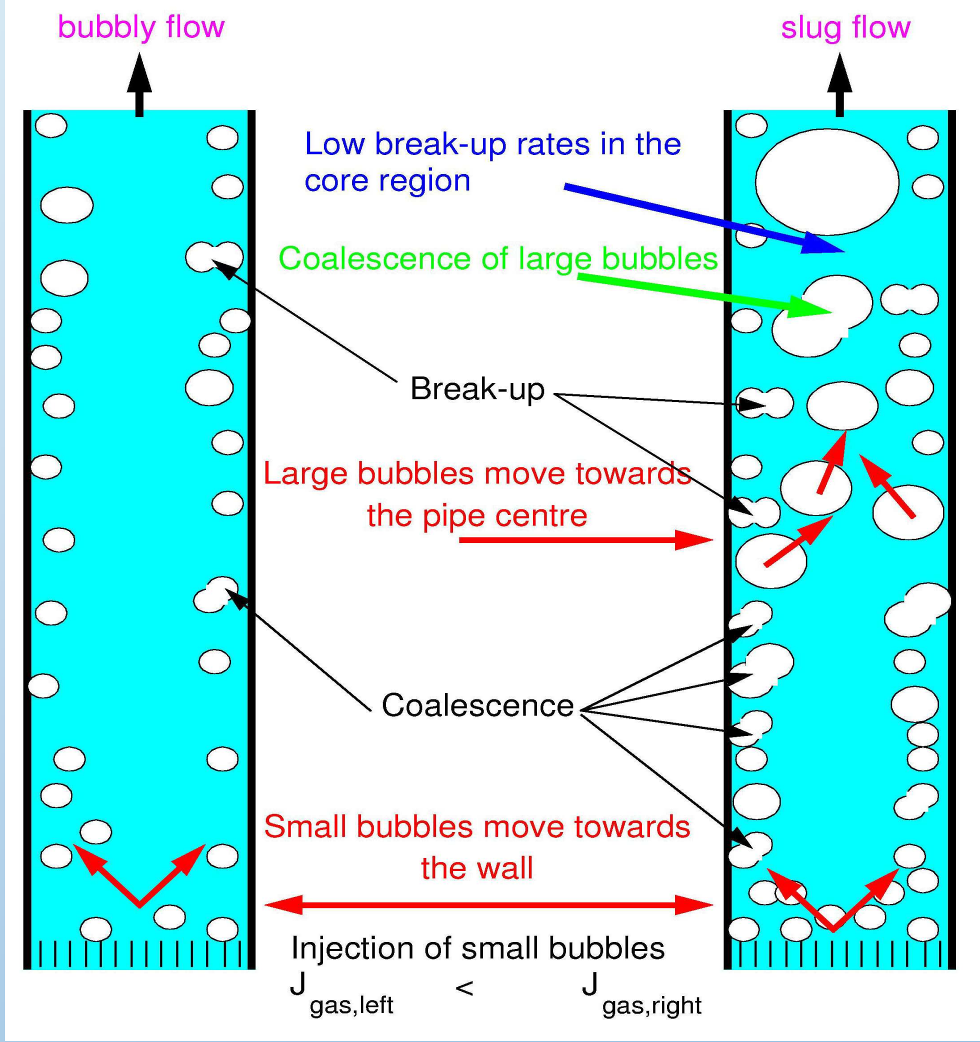
Transition from disperse bubbly flow to slug flow:

- coalescence of bubbles
- turbulent bubble breakup

bubble size distribution;
polydisperse bubbly flow

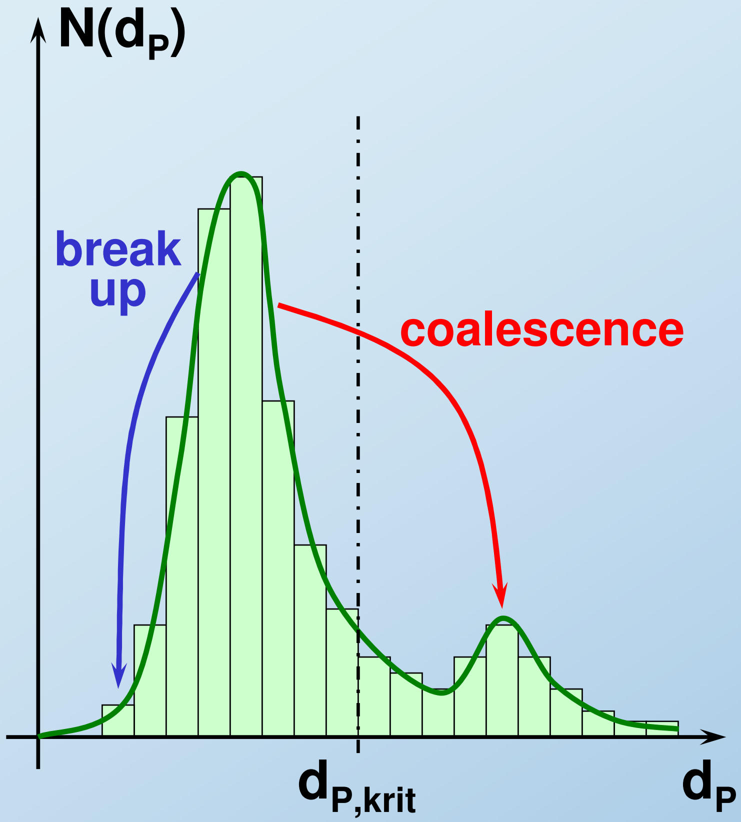
counter-current radial motion of small and large bubbles;
more than one velocity field

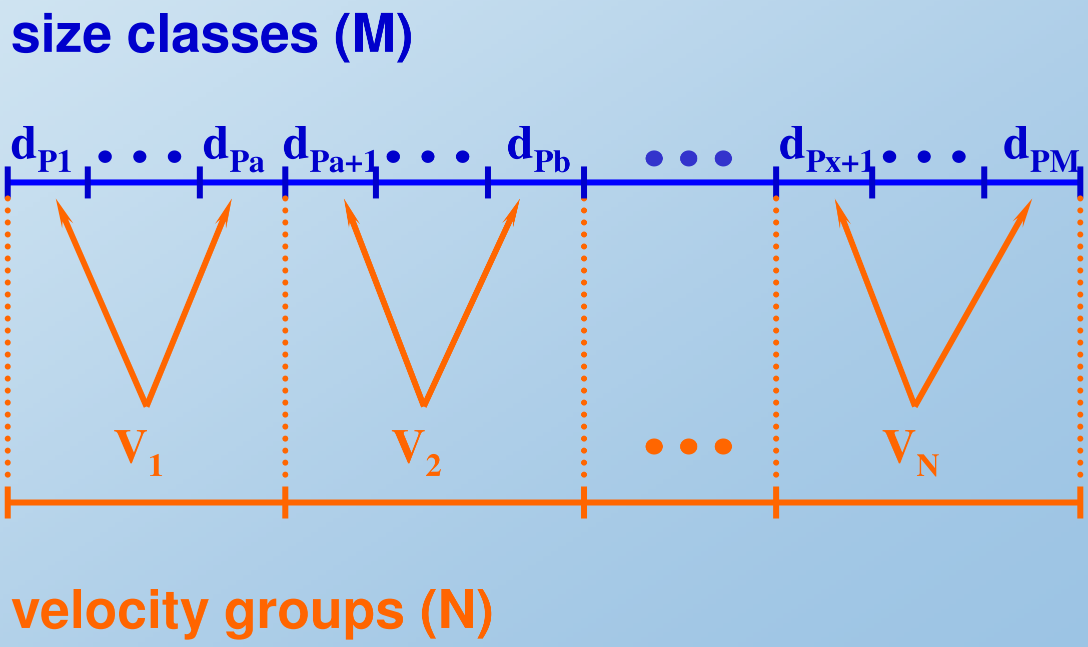
new population balance model (inhomogeneous MUSIG)



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





The inhomogeneous MUSIG model

Inhomogeneous MUSIG model solves for:

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

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

$$g=1,\ldots,N \bullet M$$
$$j=1,\ldots,N$$

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

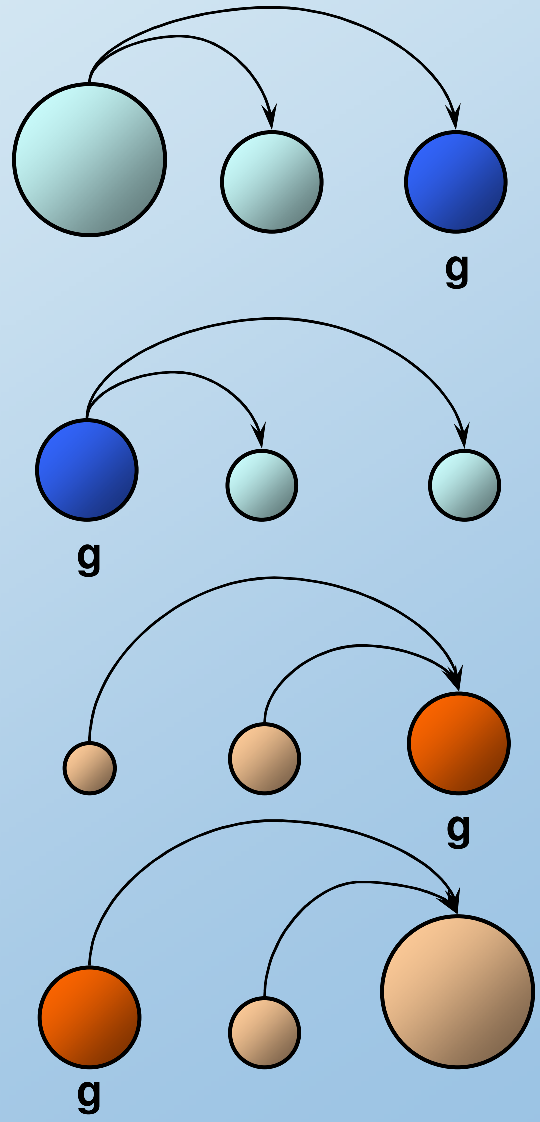
The inhomogeneous MUSIG model

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

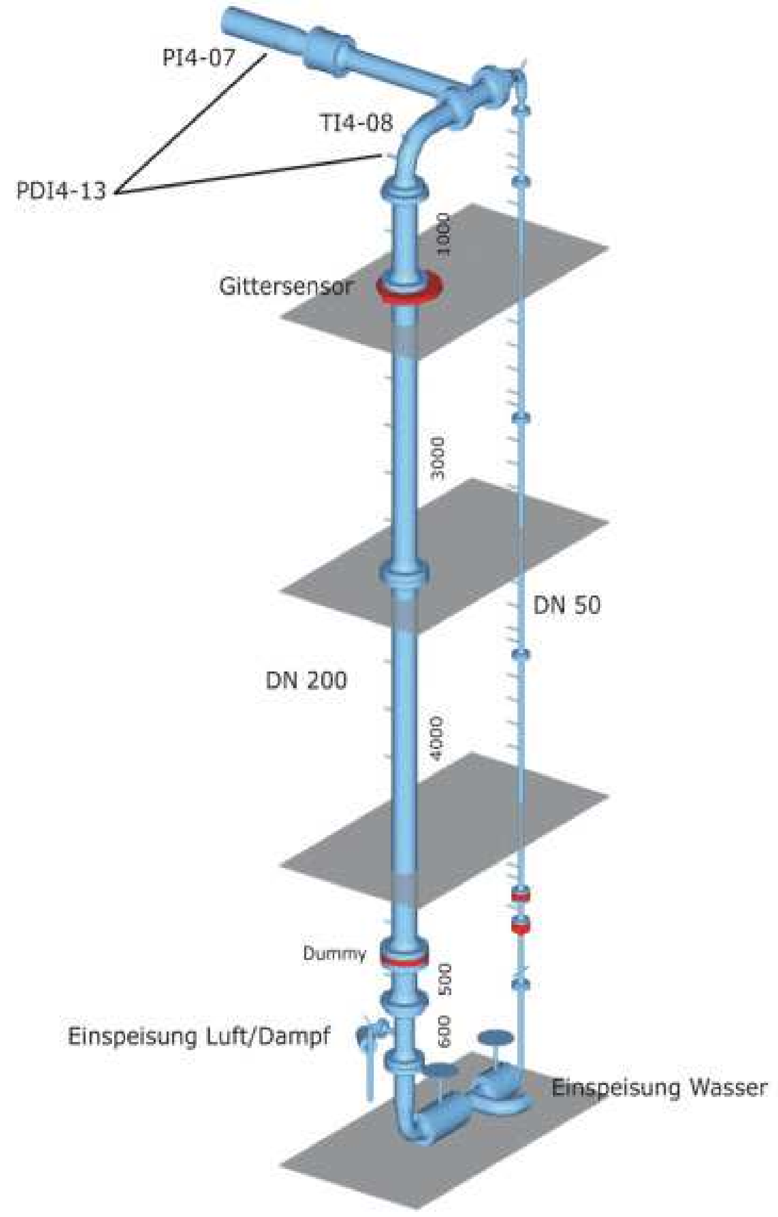
$$- \underbrace{\rho_d r_{dg} \sum_{h=1}^{g-1} B_{gh}}_{\text{breakup death}}$$

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

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

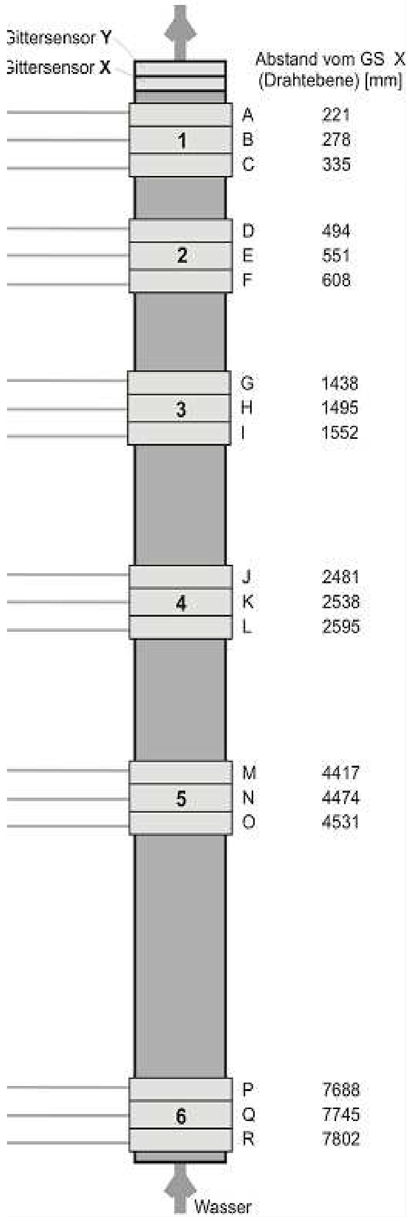


The TOPFLOW test facility at FZR



- **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 $d_P=0,\ldots,13$mm
  - equal diameter discretization ($\Delta d_P=0.619$mm)

  - Air1 vel. group : $d_{P,min}=0.31$ mm ; $d_{P,max}=4.02$mm
  - Air2 vel. group : $d_{P,min}=4.64$ mm ; $d_{P,max}=8.36$mm
  - Air3 vel. group : $d_{P,min}=8.98$ mm ; $d_{P,max}=12.69$mm

3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

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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

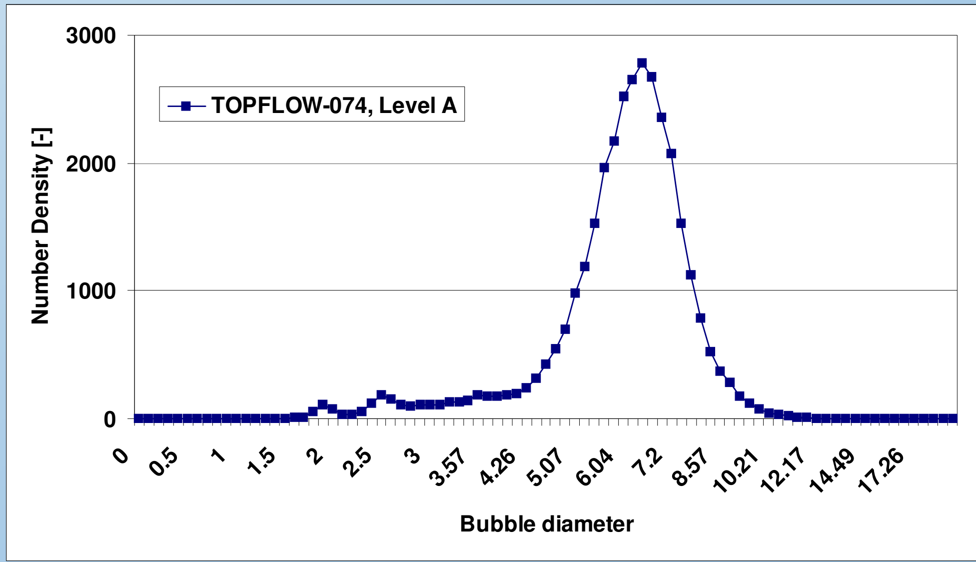
Cases 1-3 and 5:

- inlet nozzle injection
  - 80% of VF in class 7 (Air1)
  - 20% VF in Air1, Air2, Air3

  equally distributed over all remaining size classes

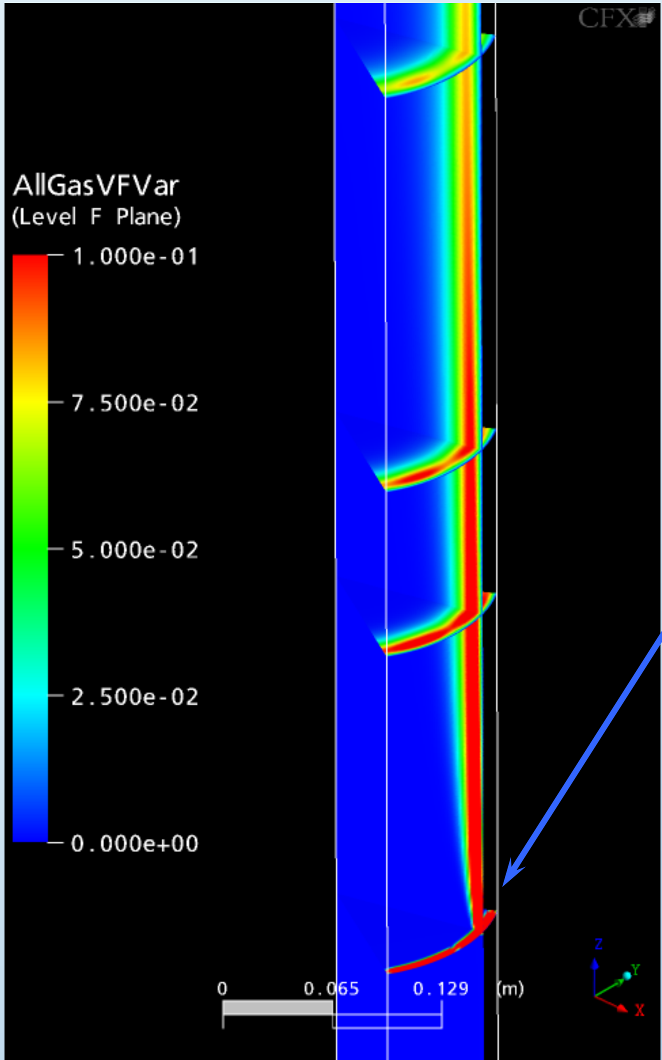
Case 4:

- inlet nozzle injection
  - Air1 VF = 0.844% of VF
  - Air2 VF = 88.72% of VF
  - Air3 VF = 10.93% of VF



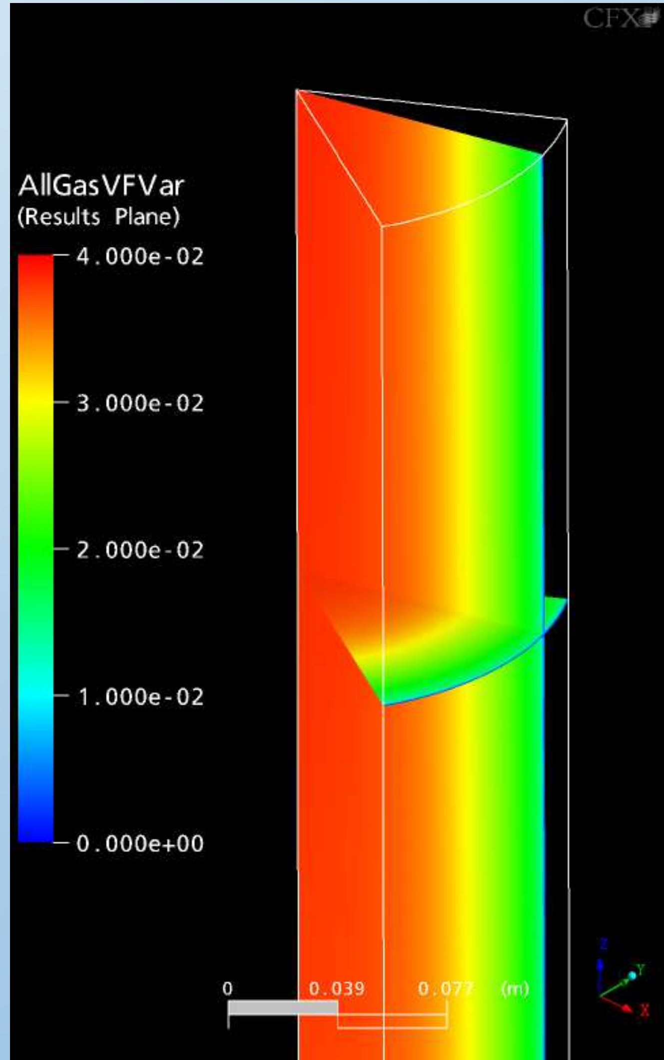
Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

Inlet level level F

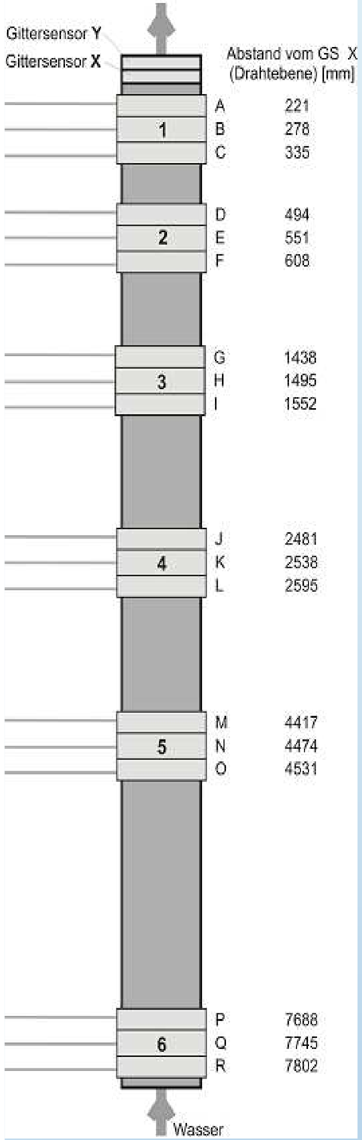


- TOPFLOW-074 best results obtained in **Case 4**
- near wall gas injection at z=0.0m
- level R results show core peak in air VF profiles

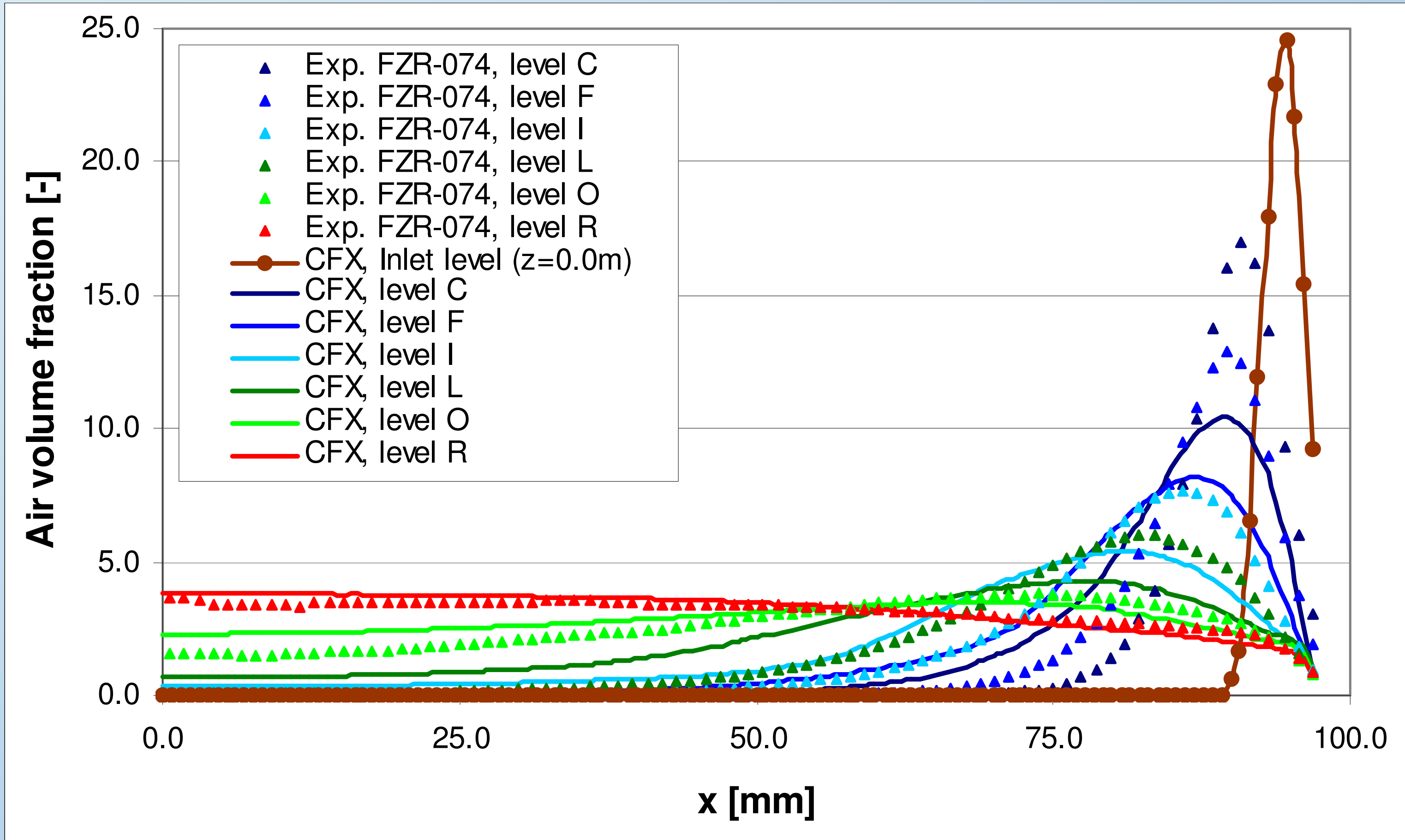
level R



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

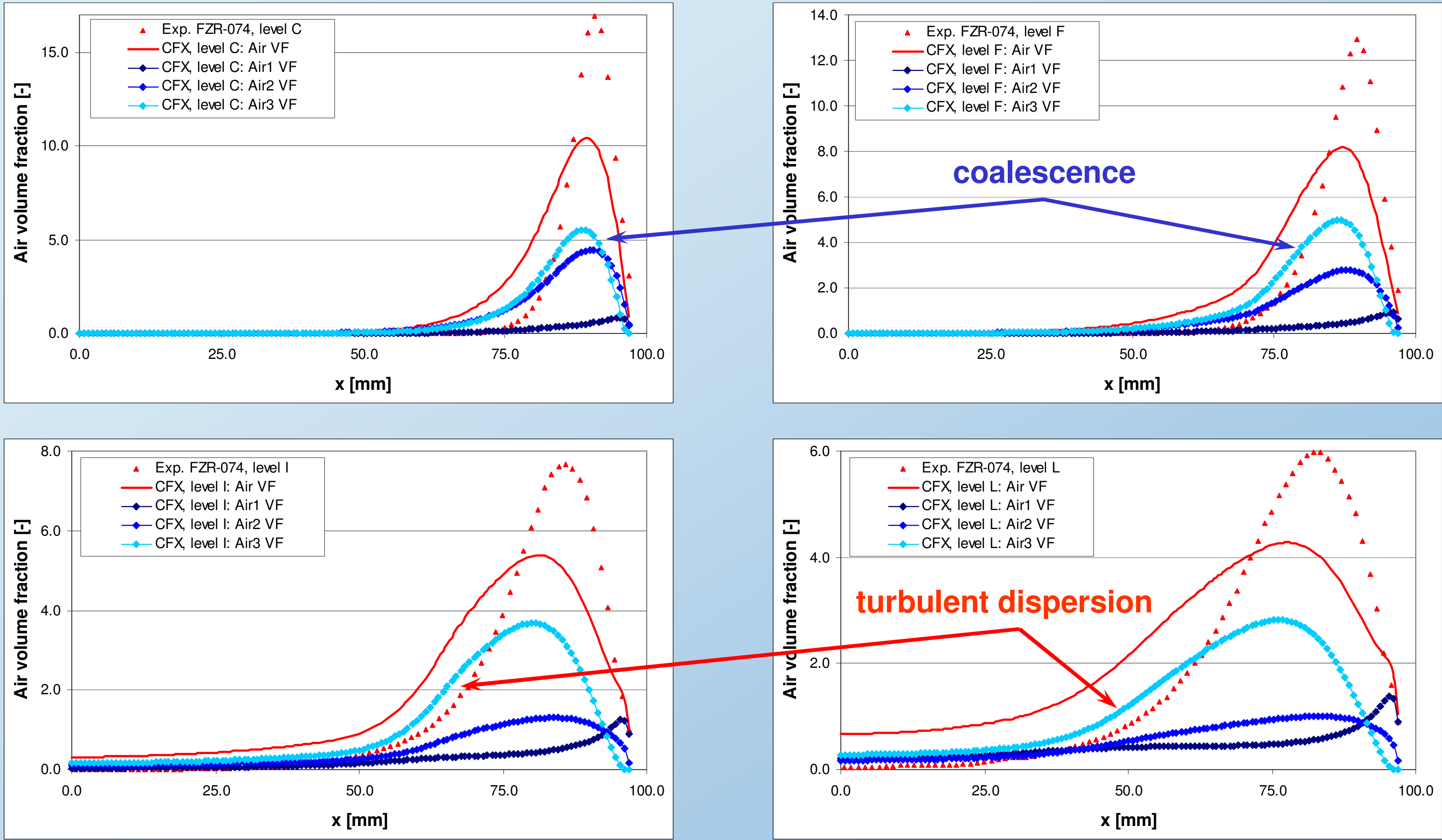


- good agreement at levels L through R
- too fast spreading of the bubble plume from inlet

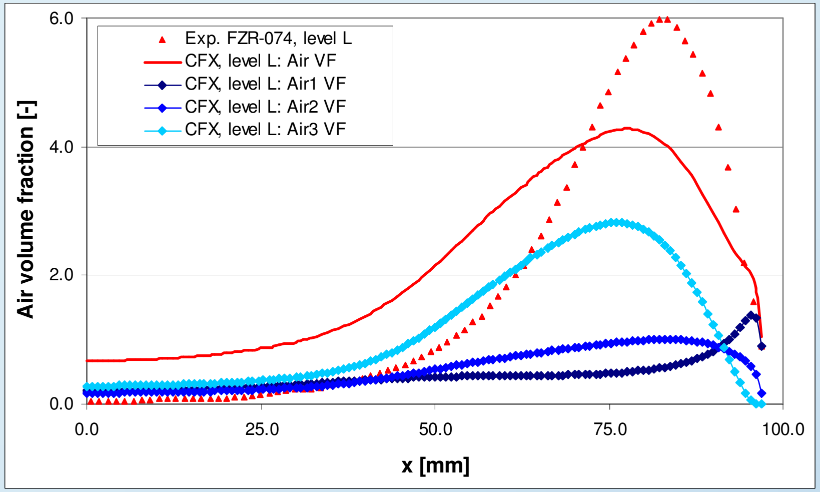


Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

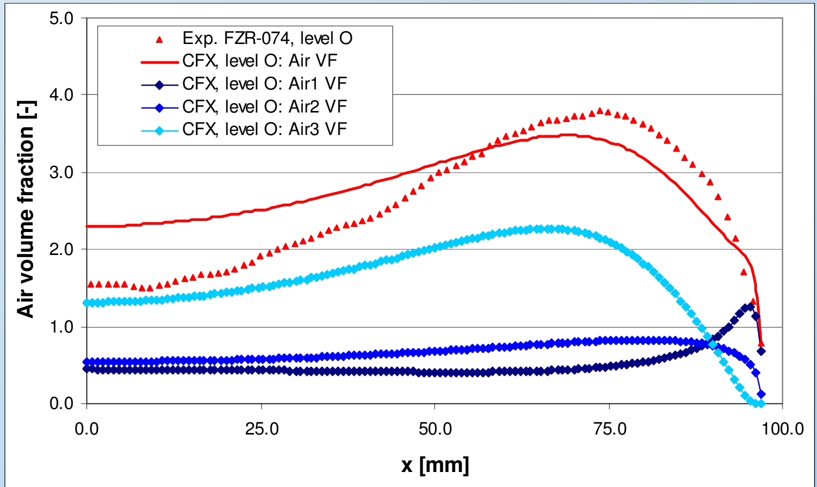
level C (z=0.335m) to level L (z=2.595m)

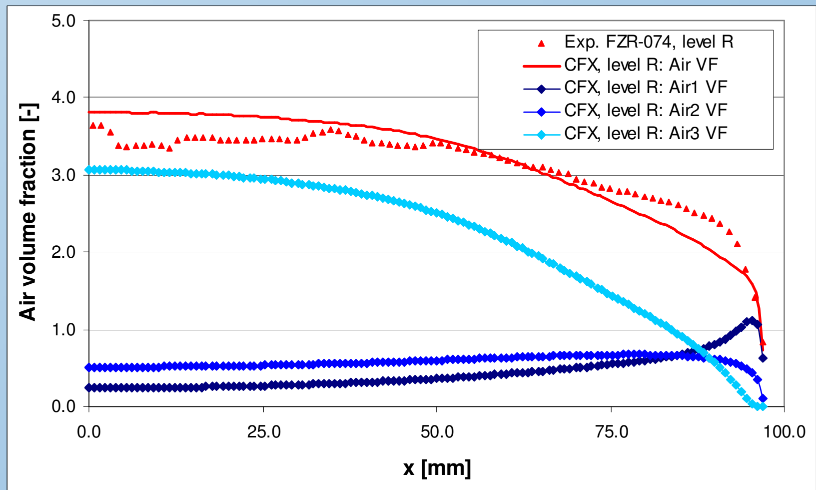


Case 4: 3x7 inhomogeneous MUSIG simulations for TOPFLOW-074

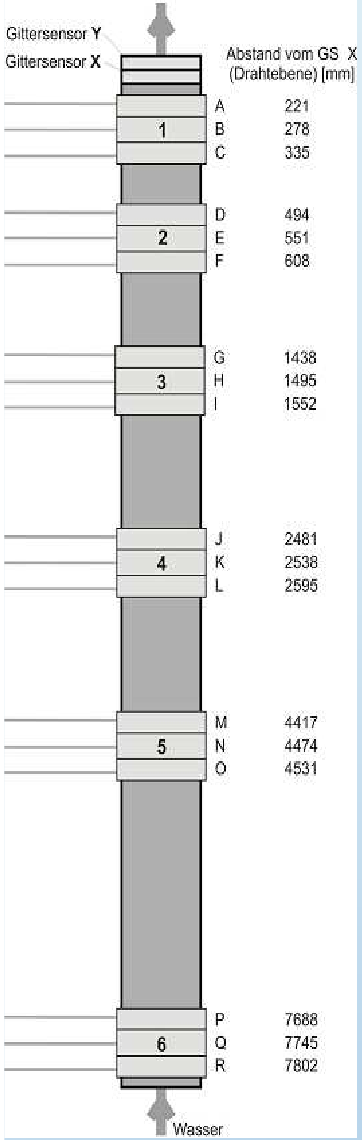


- Air VF at level L (z=2.595m), level O (z=4.531m) and level R (z=7.802m)
- agreement with experiments improves with increasing height
- good prediction of radial demixing processes for different bubble size classes

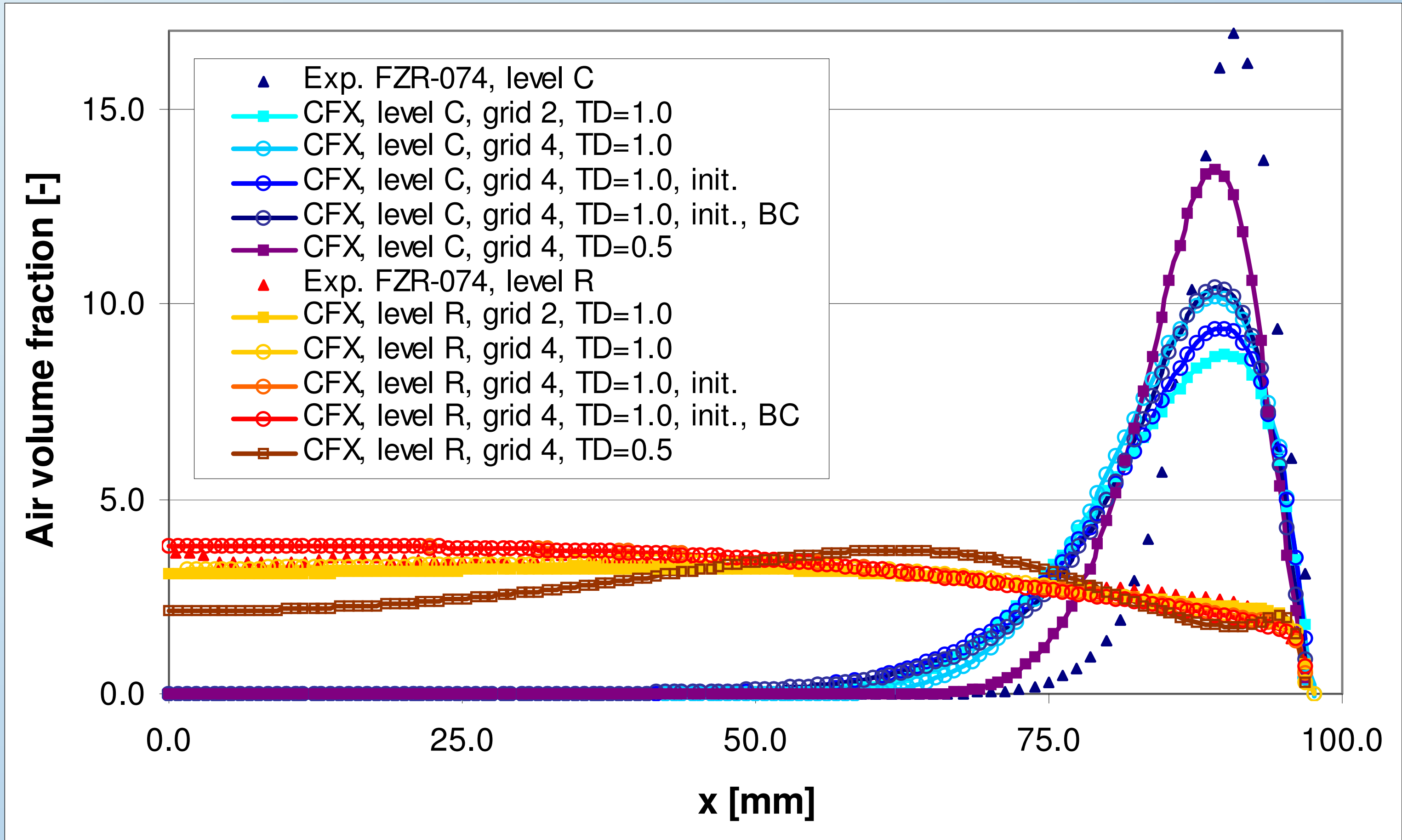




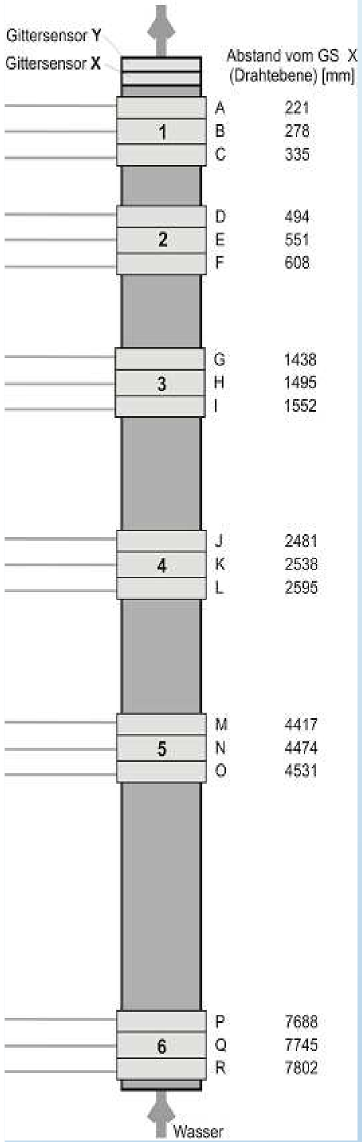
Overall Comparison of different Validation Tests



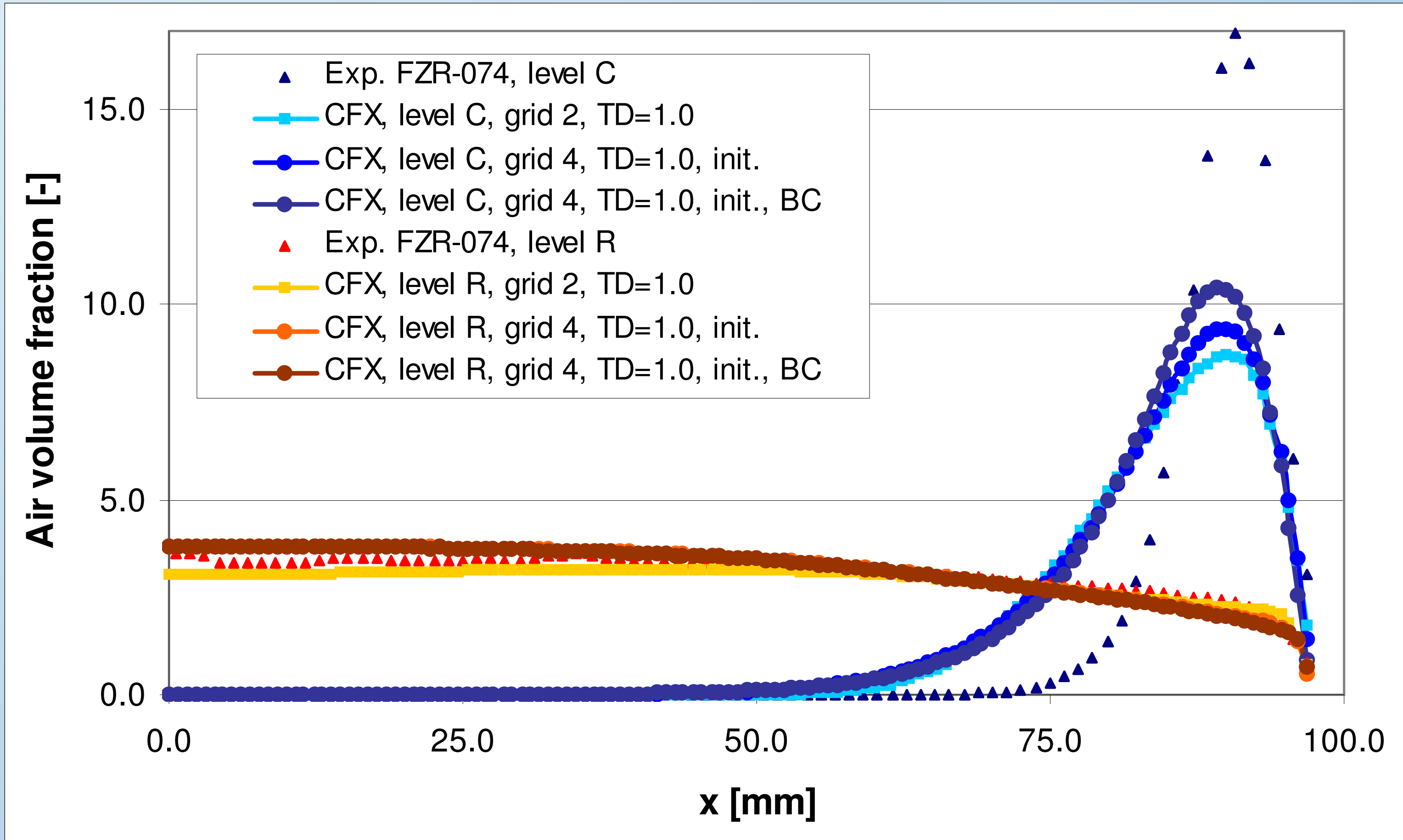
- C and R level results for Cases 1- 5



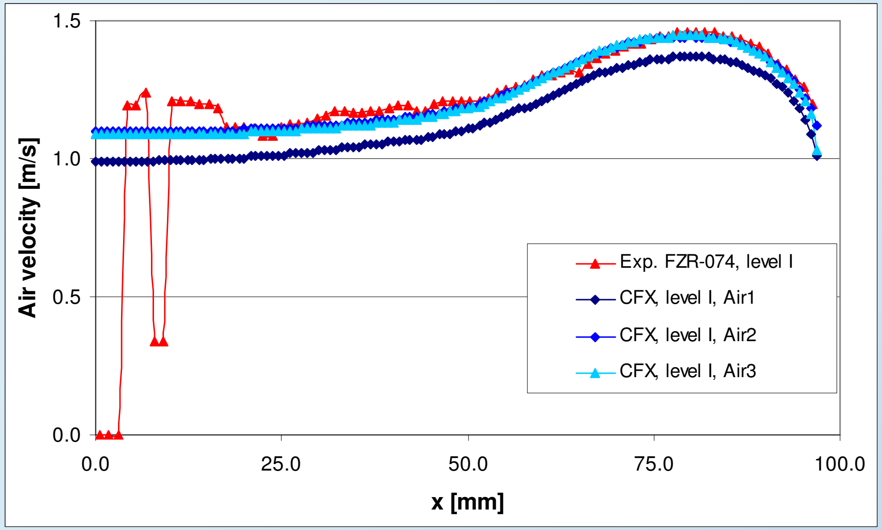
Overall Comparison of different Validation Tests

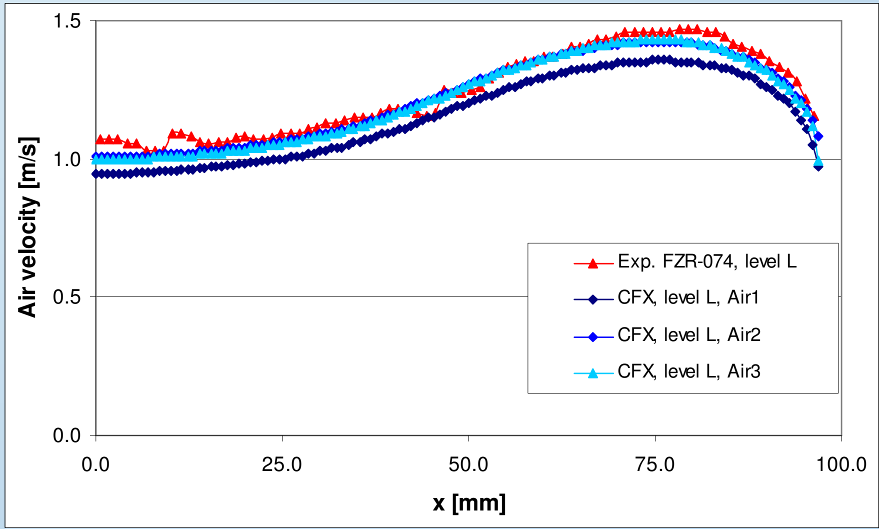


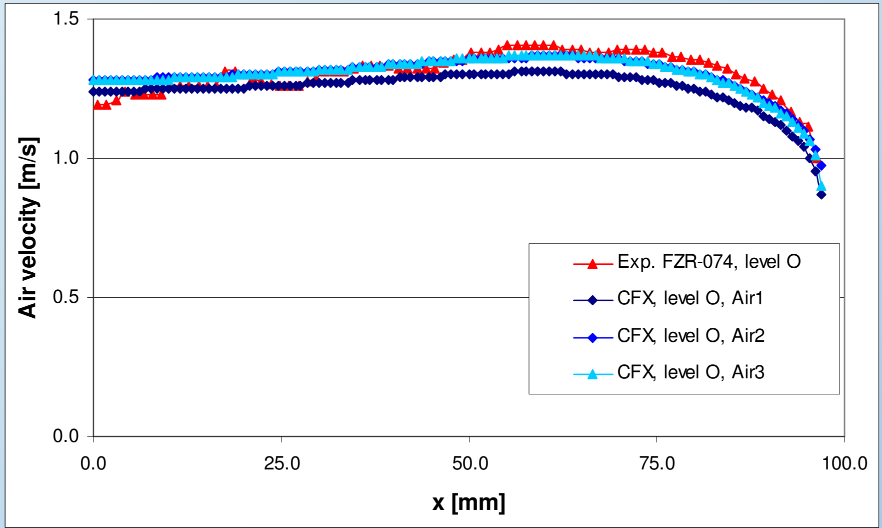
- C and R level results for Cases 1, 3 and 4

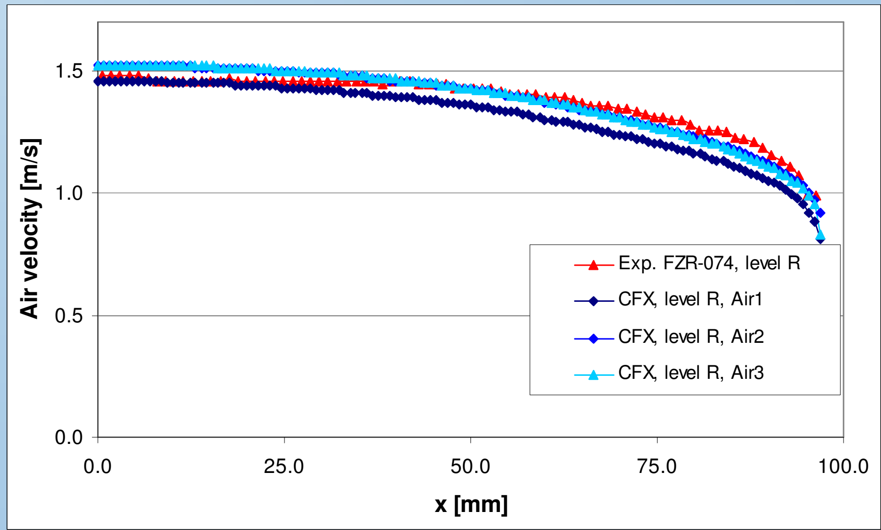


Case 4: Velocity Profiles
I   R Level Comparison with Exp.

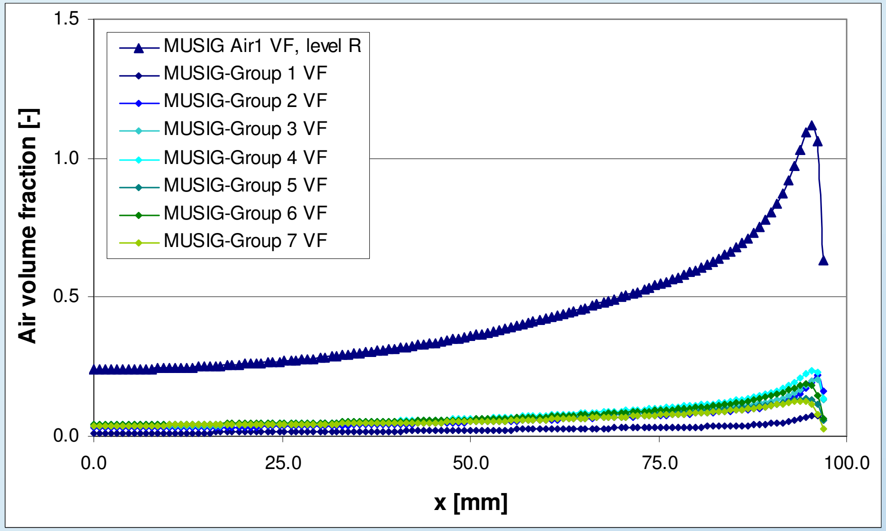


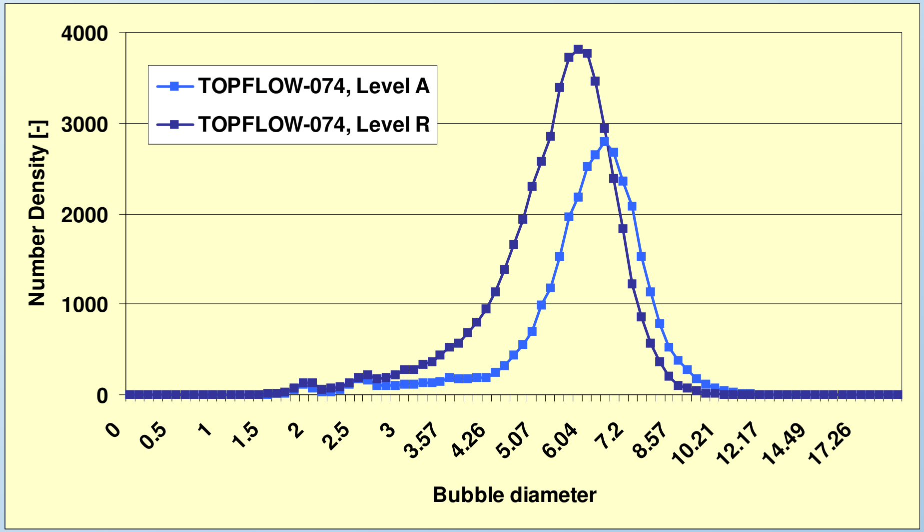


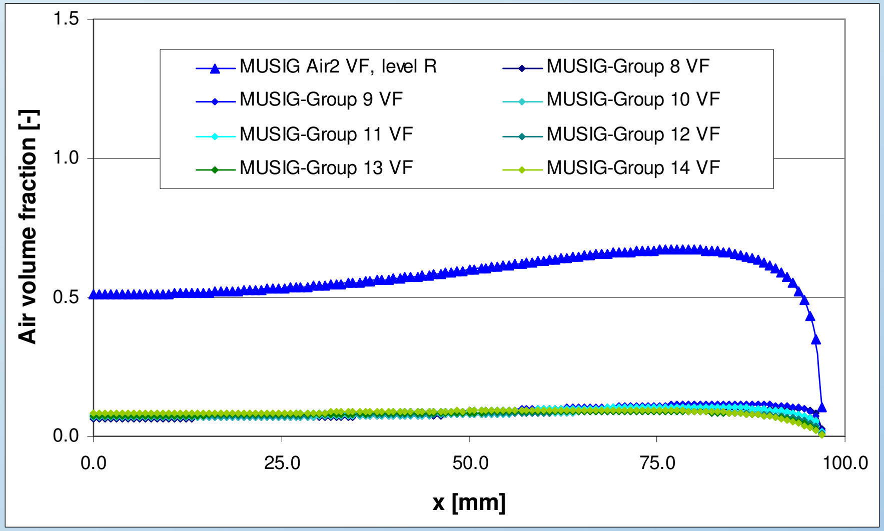


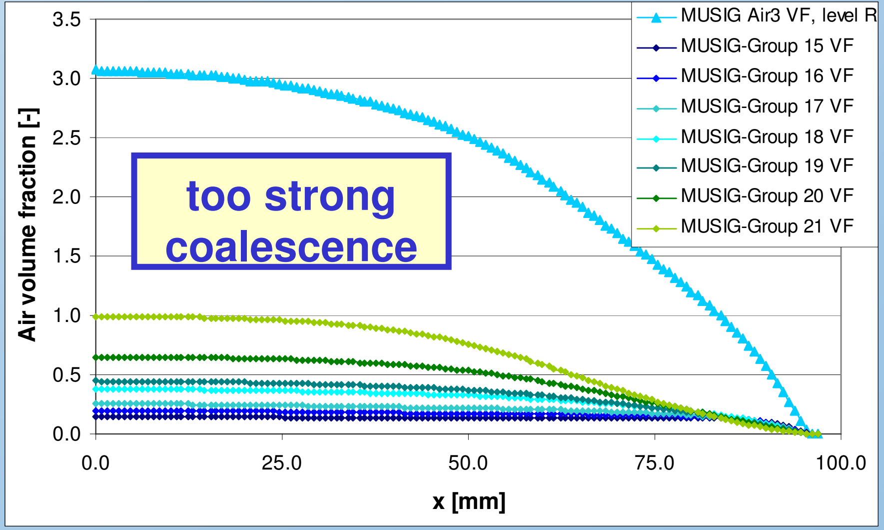


Case 4: Evolution of Bubble Size Distribution – Level R









Summary & Conclusions

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- 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