Non-drag Forces in Gas-Liquid Bubbly Flows and Validation of Existing Formulations

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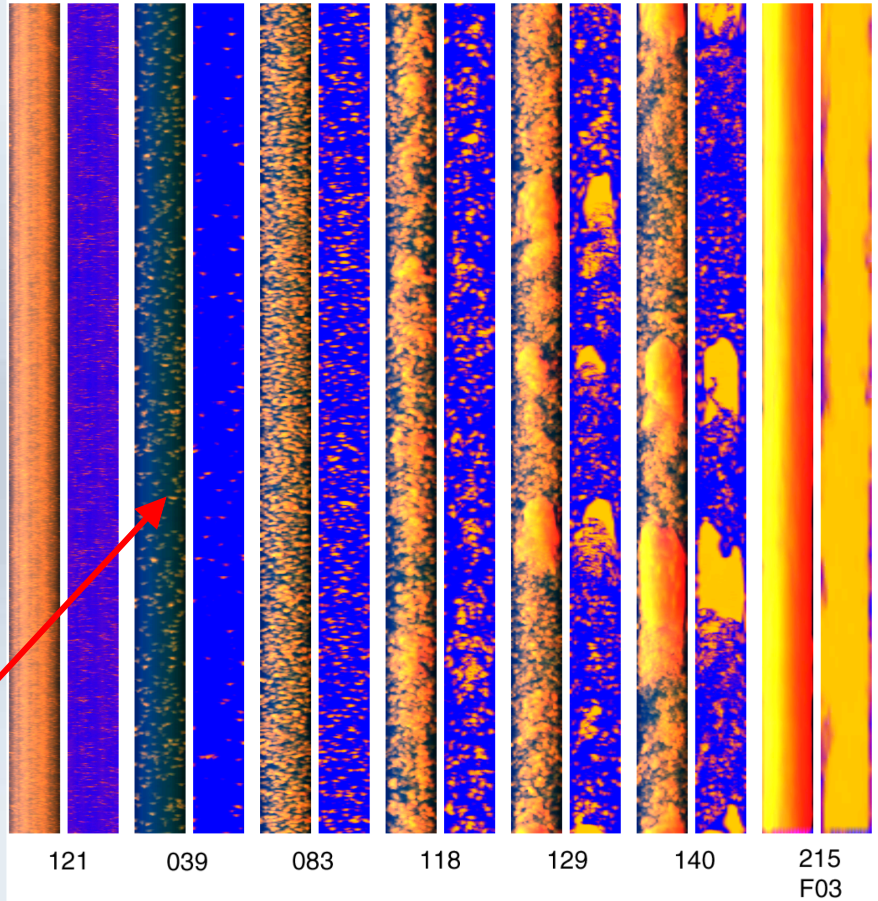
Contents

Different Types of Bubbly Flows

- **Finely disperse (121)**
- **Bubbly flow**
  - Void maximum near the wall (039)
  - Transition region (083)
  - Centred void fraction maximum (118)
  - Centred void fraction maximum bimodal (129)
- **Slug flow (140)**
- **Annular flow (215)**



Experiments by Prasser et al., FZR

Test case FZR-074:
dilute bubbly flow with near wall maximum of void fraction

Eulerian Modelling of Multiphase Flow

Averaged conservation equations

- **Mass, momentum, energy equation for each phase**
- **turbulence model equations (e.g. k-ε / k-ω SST model)**

$$\frac{\partial}{\partial t}\left(\rho_k r_k\right)+\nabla\left(\rho_k r_k \mathbf{U}_k\right)=0$$

$$\frac{\partial}{\partial t}\left(\rho_k r_k \mathbf{U}_k\right)+\nabla\cdot\left(\rho_k r_k \mathbf{U}_k \mathbf{U}_k\right)=-r_k \nabla P-\nabla\cdot\left(r_k \Pi^k\right)+\mathbf{F}_k+\mathbf{I}_k$$

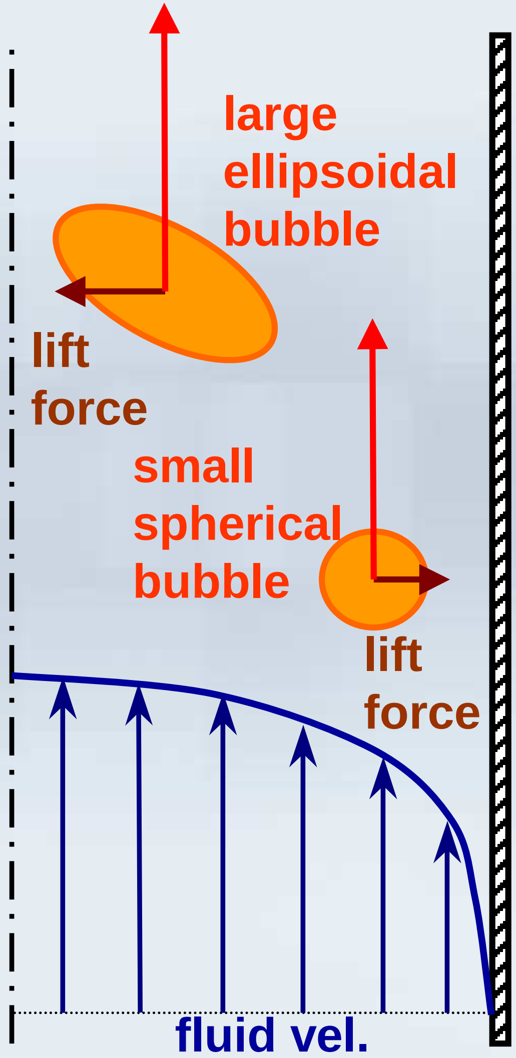
$$\mathbf{I}_k=\underbrace{\mathbf{F}_D}_{\text{drag}}+\underbrace{\mathbf{F}_L}_{\text{lift}}+\underbrace{\mathbf{F}_{WL}}_{\text{wall lubrication}}+\underbrace{\mathbf{F}_{TD}}_{\text{turbulent dispersion}}+\underbrace{\mathbf{F}_{VM}}_{\text{virtual mass}}$$

- **additional interfacial forces important for accurate predictions of e.g. gas-liquid flows**
- **non-drag force terms need empirical closure**

Additional lateral forces – Lift force

Physical mechanism:

- acts on particles, droplets and bubbles in shear flows
  - due to asymmetric wake
  - due to deformed asymmetric particle shape
- sign change of bubble lift indicated by measurements
- found in DNS results (Ervin & Trygvasson)



Additional lateral forces – Lift force

Modelling:

$$\mathbf{F}_L = C_L r_G \rho_L (\mathbf{U}_L - \mathbf{U}_G) \times \nabla \times \mathbf{U}_L$$

Many available correlations for $C_L = C_L(\mathrm{Re}_P, \mathrm{Re}_\nabla, Eo)$

Bubbles:

- **Mei & Klausner**
- **Legendre & Magnaudet**
- **Tomiyama (shape deform.)**

Solid Particles:

- **McLaughlin**
- **Saffman & Mei**
- **Moraga et al. (asym. wake)**

Tomiyama's Lift force correlation

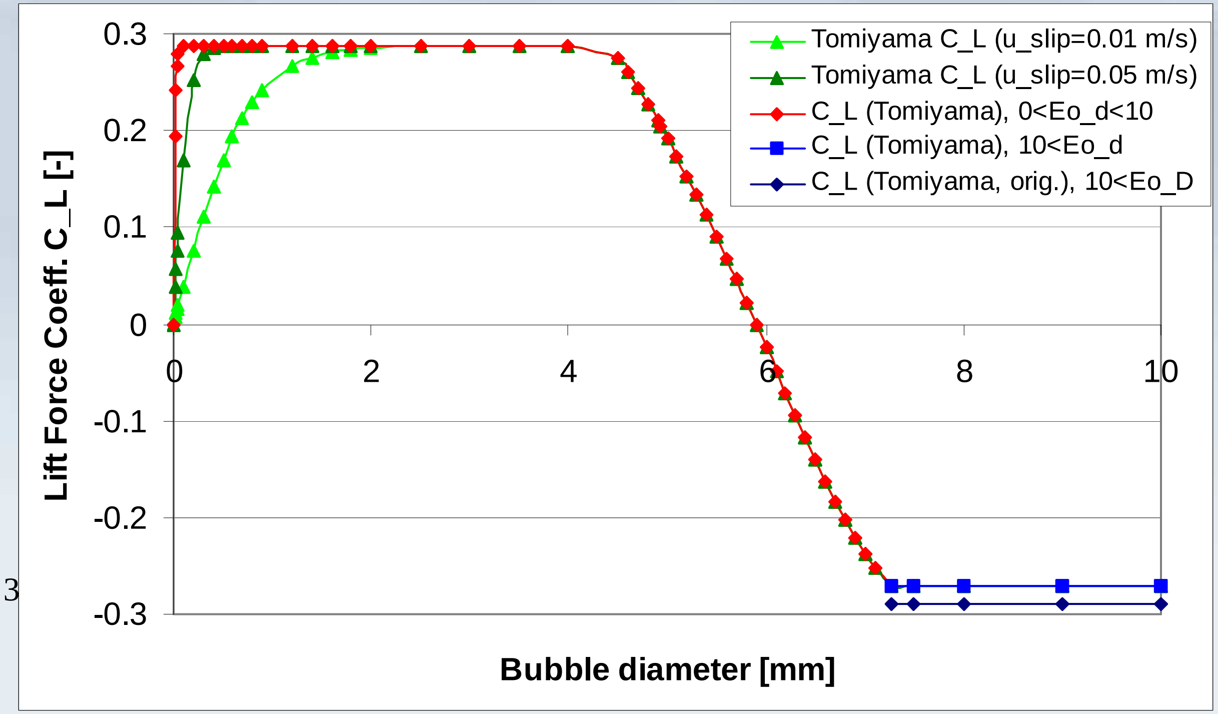
$$C_L = \begin{cases} \min\left[0.288\tanh(0.121\cdot \mathrm{Re}_P),\ f(Eo_d)\right] & Eo_d < 4 \\ f(Eo_d) = 0.00105 Eo_d^3 - 0.0159 Eo_d^2 - 0.0204 Eo_d + 0.474 & 4 \le Eo_d \le 10.0 \\ -0.27 & Eo_d > 10.0 \end{cases}$$

modified Eo_d number:

$$Eo_d = \frac{g(\rho_L - \rho_G)d_H^2}{\sigma}$$

horizontal bubble length scale:

$$d_H = d_P(1 + 0.163\cdot Eo^{0.757})^{1/3}$$

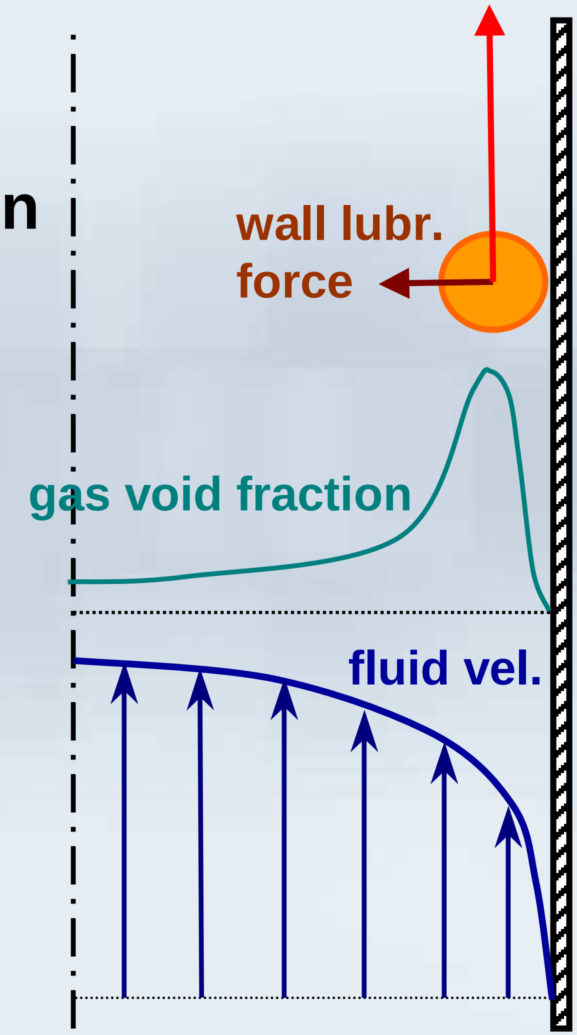


Additional lateral forces – Wall lubrication force

Surface tension prevents bubbles from approaching solid walls very close

- à **near wall area of low gas void fraction**
- à **modelled by a wall force, pushing bubbles away from walls**

$$\mathbf{F}_{WL} = -C_{wall} r_G \rho_L \left| \mathbf{U}_{rel} - \left(\mathbf{U}_{rel} \cdot \mathbf{n}_W \right) \mathbf{n}_W \right|^2 \mathbf{n}_W$$



Antal’s model (1991):

$$C_{wall} = \max \left\{ 0, \ \frac{C_{W1}}{d_P} + \frac{C_{W2}}{y_W} \right\}$$

$$C_{W1} = -0.01 \quad ; \quad C_{W2} = 0.05$$

Tomiyama's wall lubrication force model

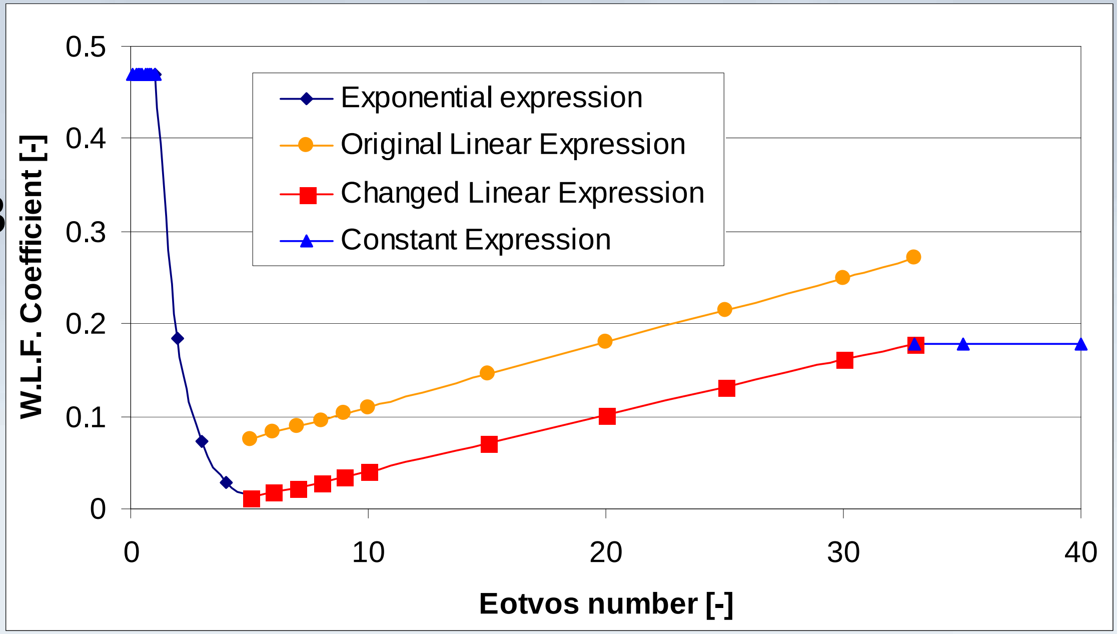
Tomiyama's model (1998):

$$C_{wall} = C_W(\mathrm{Eo}) \cdot \frac{d_P}{2}\left(\frac{1}{y_W^2} - \frac{1}{(D - y_W)^2}\right)$$

$$\mathrm{Eo} = \frac{g(\rho_F - \rho_P)d_P}{\sigma}$$

$$C_W(Eo) = \begin{cases} e^{-0.933Eo+0.179} & 1 \le Eo \le 5 \\ 0.007Eo + 0.04 & 5 \le Eo \le 33 \\ 0.179 & 33 < Eo \end{cases}$$

- **geometry dependend model due to pipe diameter D !**



Deficiencies of prior wall lubrication force models

Antal / CFX-5.7:

- $F_W \sim 1 / y_W$
- geometry independent
- F_W too small to balance F_L and F_{TD} in some validation cases
- small influence on flow by change in model parameters

Tomiyama:

- $F_W \sim 1 / y_W^2$
- amplitude depends on Eo
- contains the pipe diameter
  à not applicable to complex geometry
- no adjustable model parameter

Proposed modified wall lubrication force formulation

Proposed modified formulation:

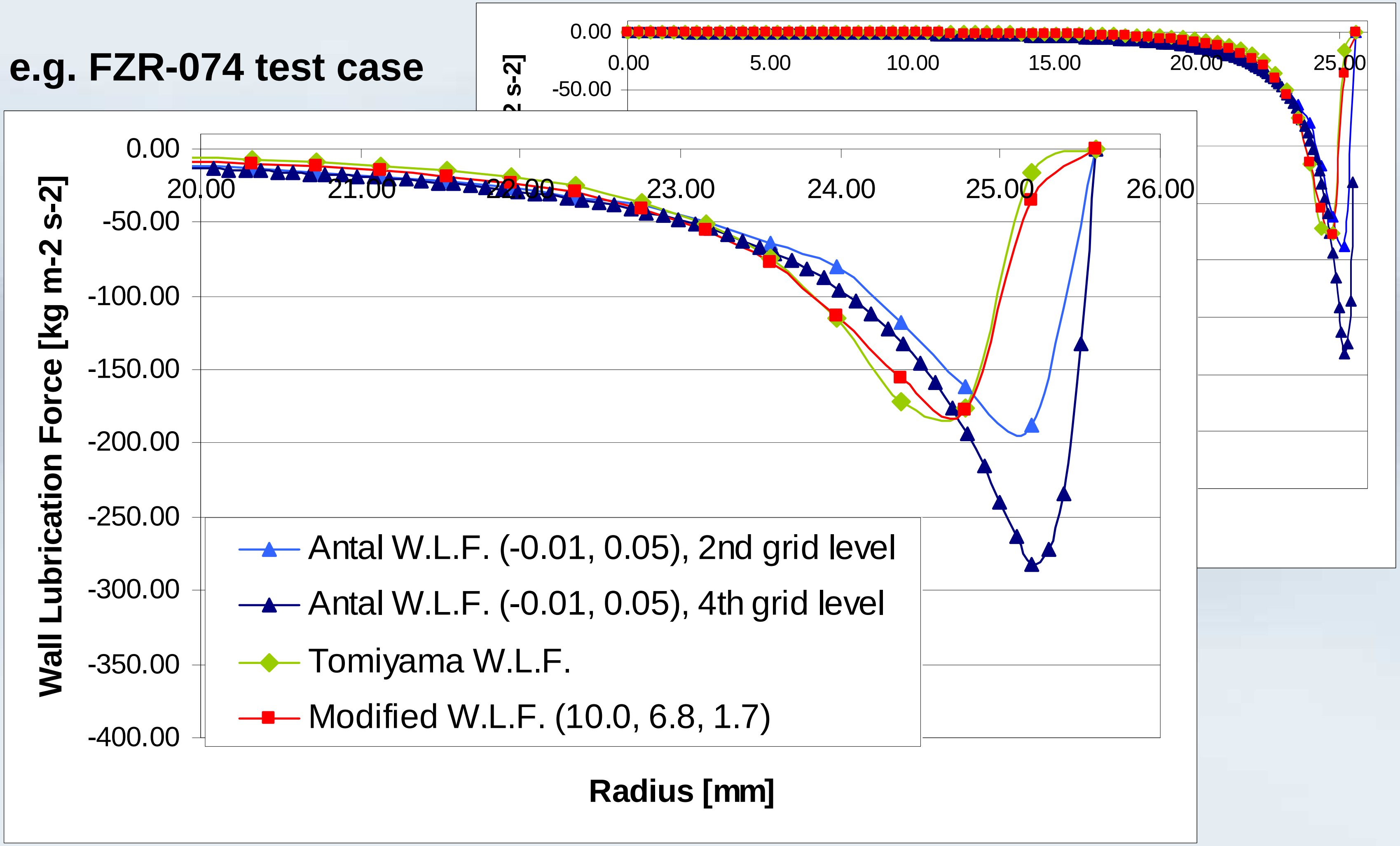
$$C_{wall} = C_W(\mathrm{Eo}) \cdot \max\left\{0, \frac{1}{C_{WD}} \cdot \frac{1 - \dfrac{y_W}{C_{WC} d_P}}{y_W \cdot \left(\dfrac{y_W}{C_{WC} d_P}\right)^{p-1}}\right\}$$

- **geometry independent formulation**
- **preserved dependency of amplitude on Eo number (from Tomiyama's model)**
- **variable potential law $F_W \sim 1 / y_W^p$ with : p~1.5-2**
- **C_{WC} – cut-off coefficient; C_{WD} – damping coefficient**
- **recovers the behavior of Tomiyama's model with:**

$C_{WC}=10.0$; $C_{WD}=6.8$; $p=1.7$

Comparison of wall lubrication force models

e.g. FZR-074 test case



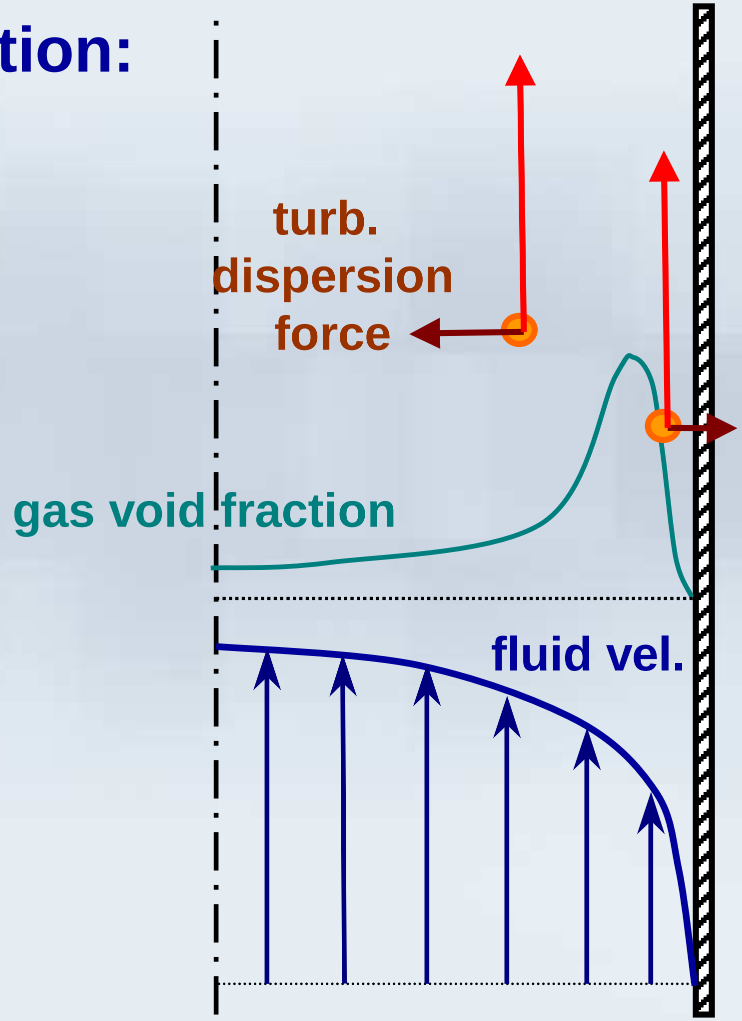
Additional lateral forces: Turbulent dispersion force

Drew & Lahey (RPI model) formulation:

$$\mathbf{F}_{TD} = -C_{TD}\rho_L K_L \nabla r_G$$

$C_{TD} \cong 0.1, \ldots, 0.5$ (?)

- à **Equalization of the gas volume fraction distribution**
- à **C_{TD} depends on Stokes number**
- à **different attempts for accurate derivation of C_{TD} models:**
  - **Lahey et al. (1993)**
  - **Lopez de Bertodano (1998)**
  - **Drew & Passman (1999, 2001)**
  - **Moraga et al. (2003), …**



Turbulent dispersion force – The Favre Averaged Drag (FAD) model

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Issa & Gosman, Carrica et al. and Burns (FAD model):

- derivation of F_{TD} from double averaging of the interphase drag term in momentum equation
- general form of turbulent dispersion force:

$$\mathbf{F}_{TD} = D_{\alpha\beta} A_{\alpha\beta} \frac{\nu_{t\alpha}}{\sigma_{r\alpha}} \left(\frac{\nabla \overline{r_\beta}}{\overline{\overline{r_\beta}}} - \frac{\nabla \overline{r_\alpha}}{\overline{\overline{r_\alpha}}} \right)$$

- for disperse two-phase flow (r_G+r_L=1) we can establish equivalence relation to the Drew & Lahey (RPI) model:

$$\mathbf{F}_{TD} = -C_{TD} \rho_L k_L \nabla r_G$$

$$C_{TD} = \frac{C_\mu}{\sigma_{rL}} \frac{\overline{C}_{LG}}{\rho_L} \frac{k_L}{\varepsilon_L} \left(\frac{1}{\overline{\overline{r_L}}} + \frac{1}{\overline{\overline{r_G}}} \right) = \frac{3}{4} C_D \Big|_{Grace} \frac{\nu_{tL}}{\sigma_{rL}} \frac{U_{rel}}{d_P k_L} \frac{1}{1 - \overline{\overline{r_G}}}$$

Additional lateral forces: The virtual mass force

- **accounts for the acceleration of the fluid mass surrounding the bubble/particle**

$$\mathbf{F}_{VM} = -C_{VM} r_G \rho_L \left(\frac{D\mathbf{U}_G}{Dt} - \frac{D\mathbf{U}_L}{Dt} \right)$$

- **important for transient / strongly accelerated gas-liquid flows, where ρ_α/ρ_β<<1**
- **C_{VM}=0.5 (analytical) or dependent on acceleration number A_C (e.g. Odar&Hamilton, Cook&Harlow, Niemann&Laurien)**

Force balance analysis for a generic 3-phase test case

- generic 3-phase test case à Virtual mass force neglectable
- FAD TD and lift forces of opposite sign for both bubble size classes
- VM force neglectable; W.L.F. very small for 2nd disperse phase

j_L=1.0167 m/s
j_G=0.04236 m/s
α_1=2%
α_2=2%
d_{P1}=4.0,…,4.8mm
d_{P2}=6.0,…,7.0mm

Grace drag

Tomiyama lift

Tomiyama W.L.F.

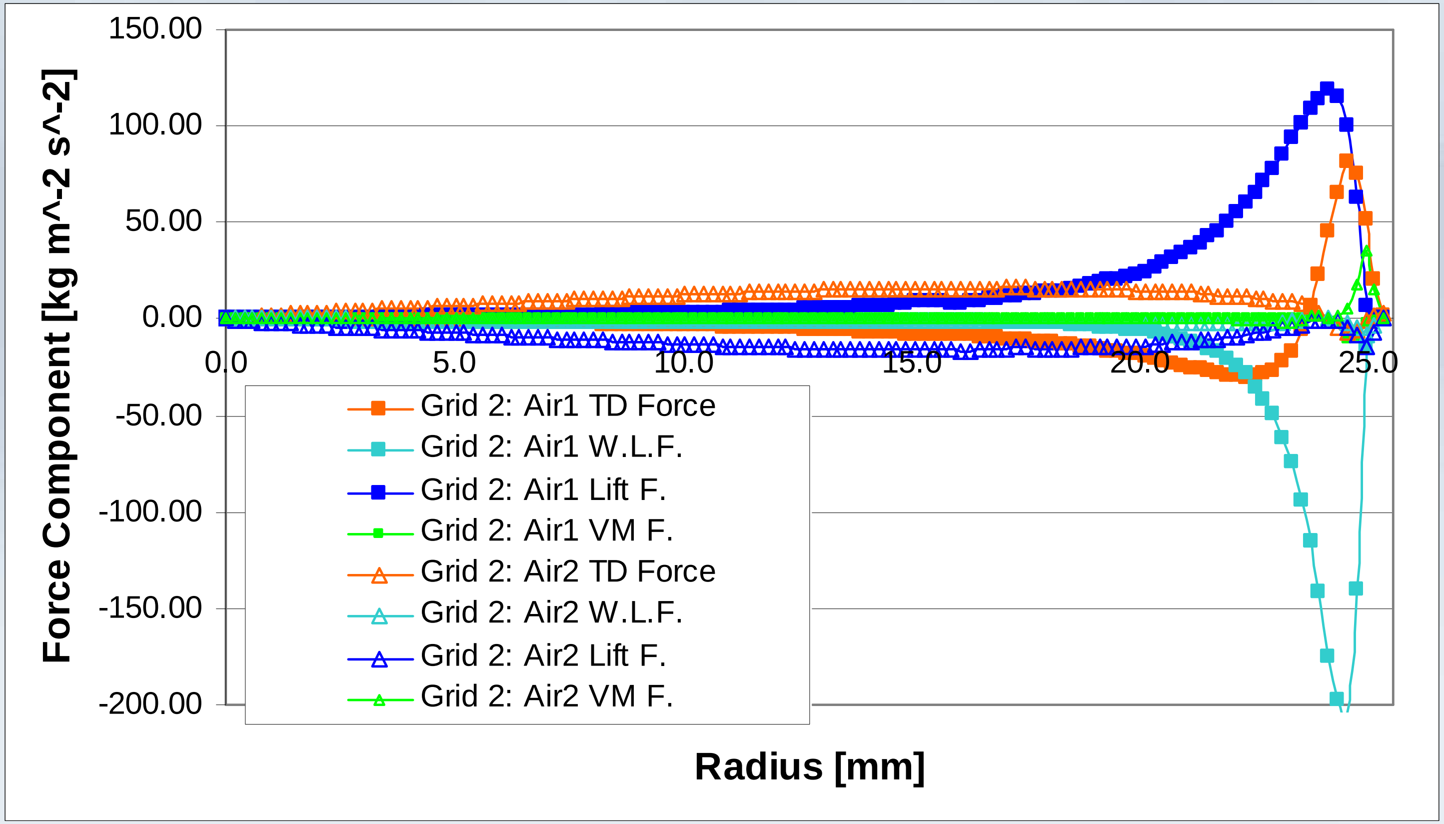
FAD TD

Sato model

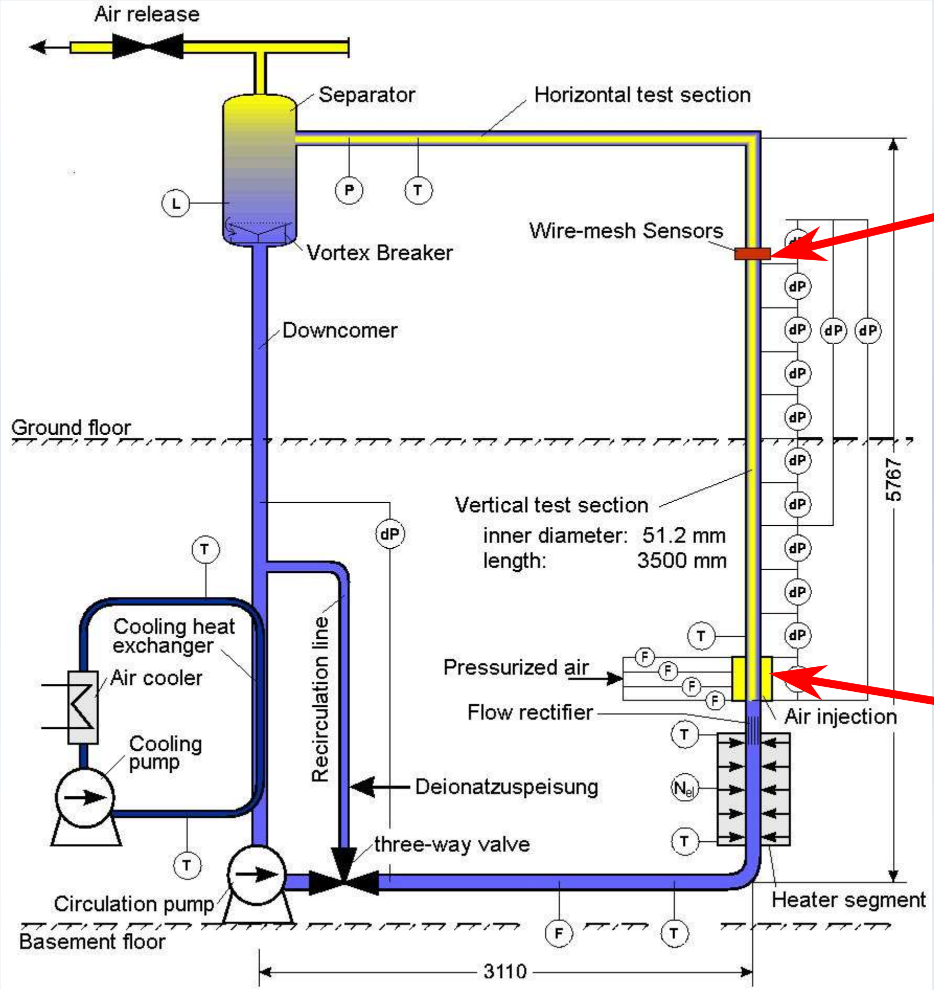
SST turb. model

Δt=0.002s

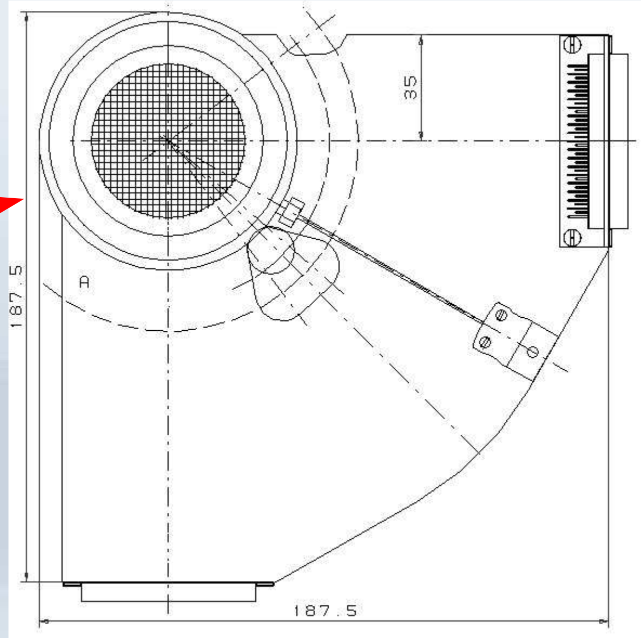
2500 Iterations



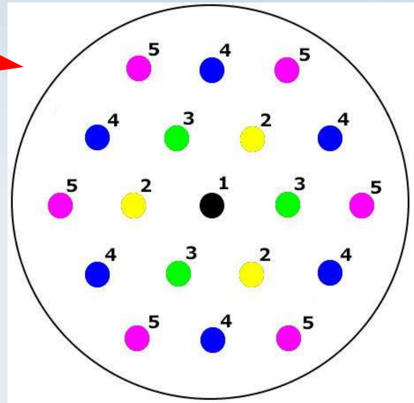
Two-phase bubbly flow measurements at FZR – the MT-Loop test facility



MT-Loop test facility at FZR



Wire-mesh sensor

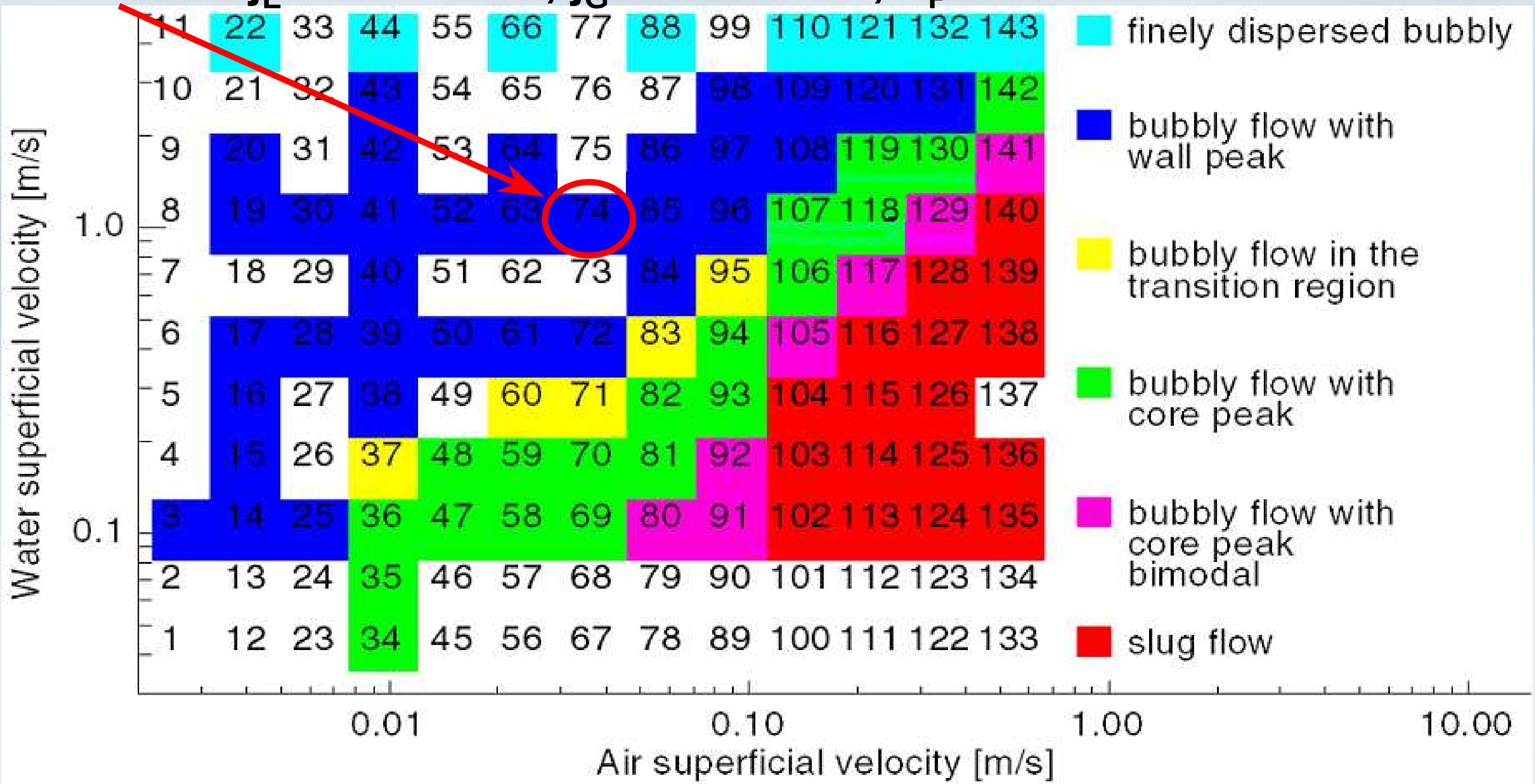


Sparger

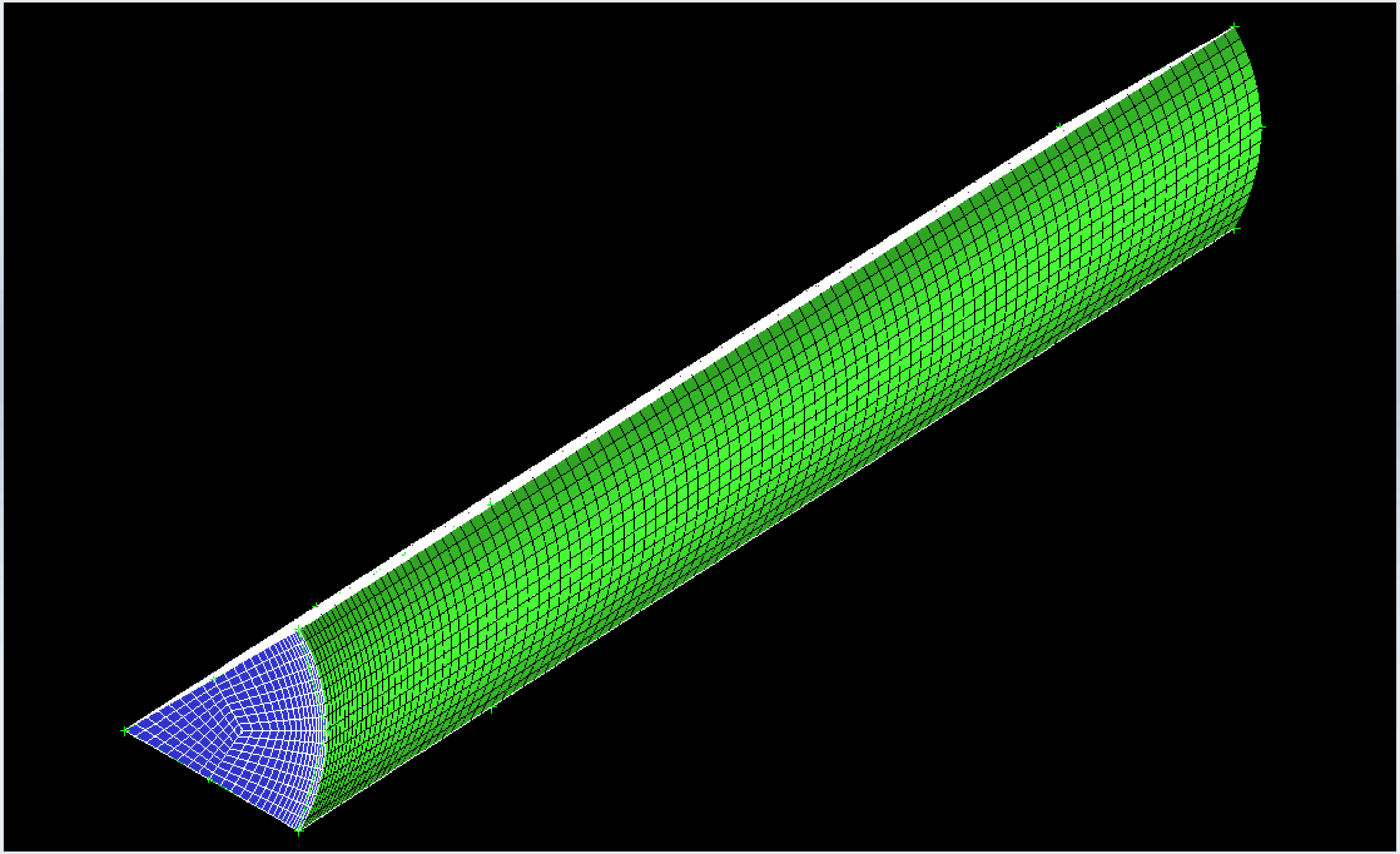
Düsengruppe	Düsenzahl
1	1
2	3
3	3
4	6
5	6

Validation test case definition

- **MT-Loop test matrix**
- **validation focused on FZR-074; many other test cases investigated**
- **FZR-074: j_L=1.0167m/s, j_G=0.0368m/s, d_P=4.8-5.2mm**



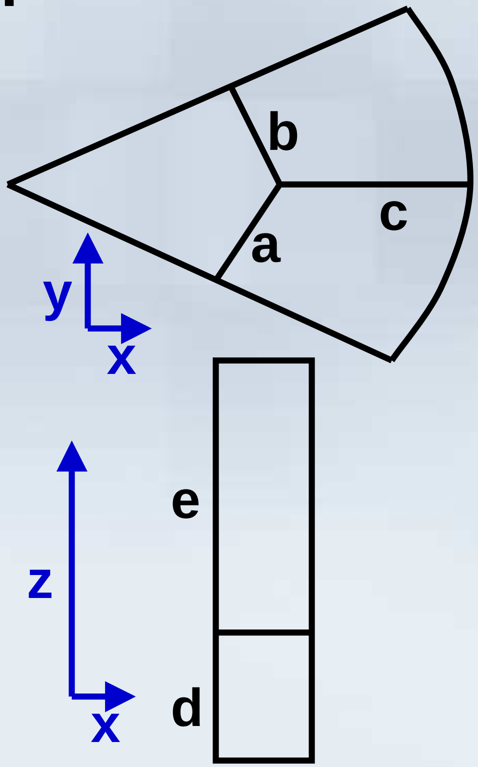
Numerical meshes - 3d grid topology (2nd grid level of refinement)



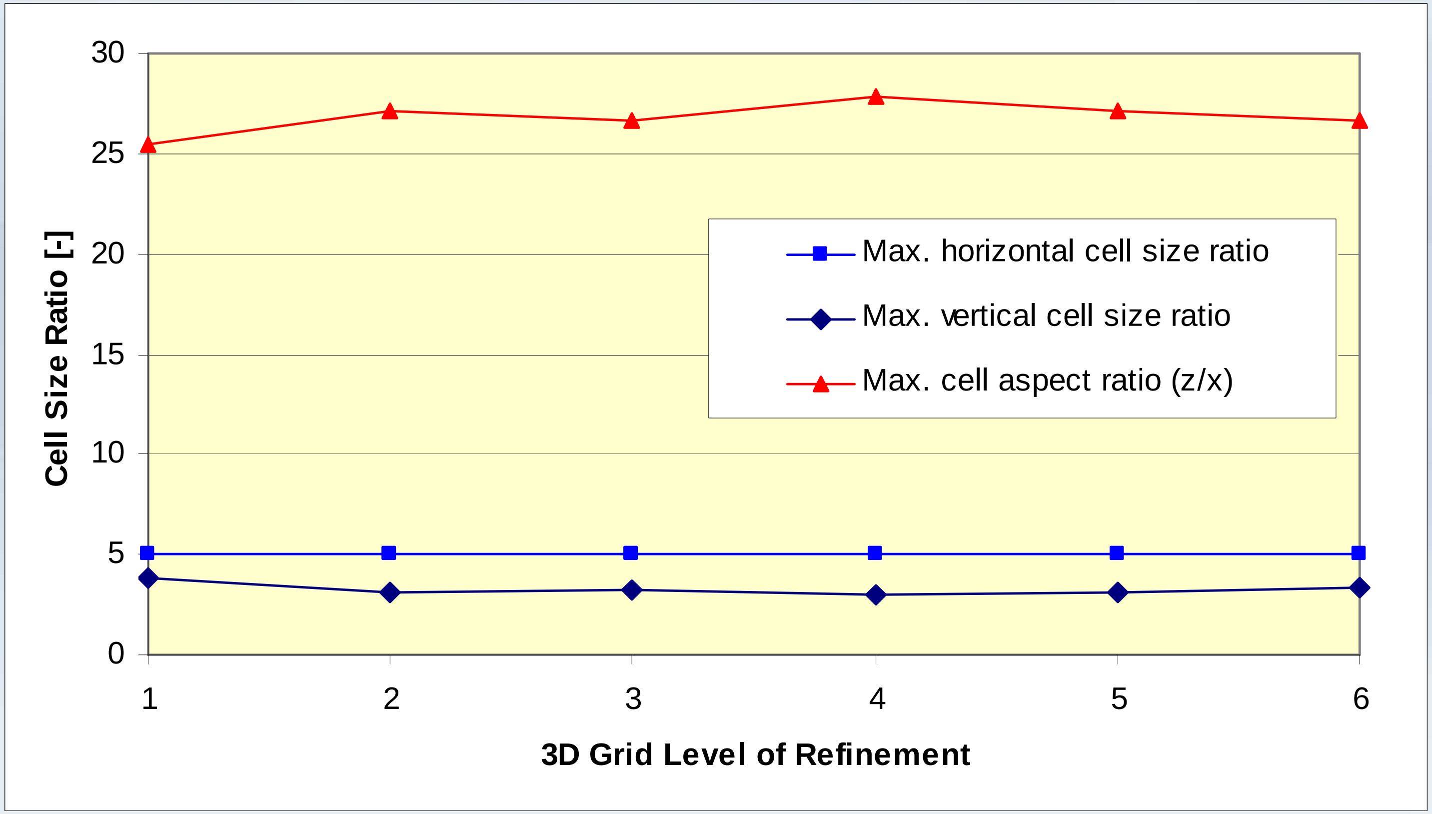
The 3d grid hierarchy

- **Scaling factor between grids is 2 (equal to ~$2^{1/3}$ in each coordinate direction)**
- **ICEM/CFD generated 3d grids with edge parameters:**

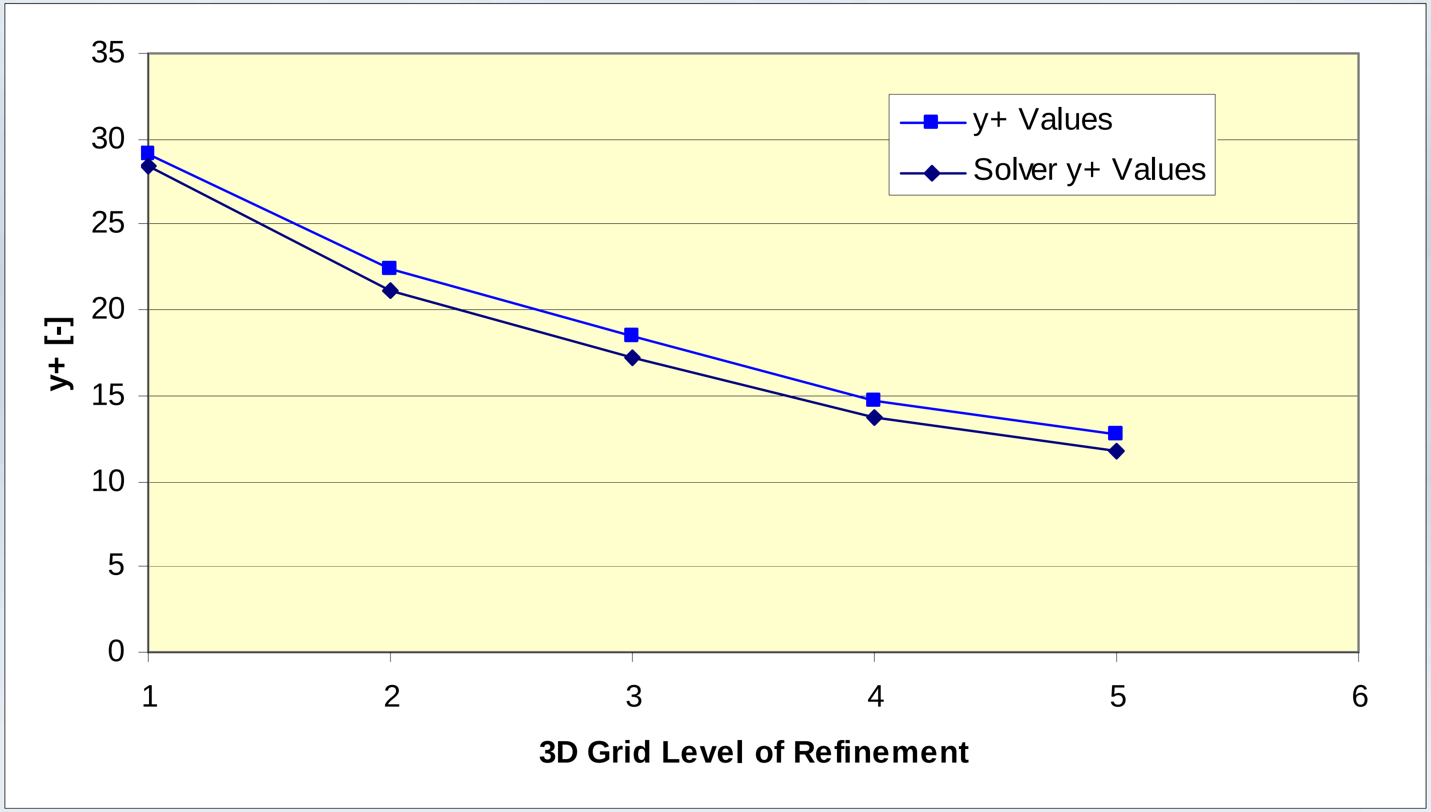
grid level	a	b	c	d	e	No. of CV's
1	6	6	13	26	56	15.744
2	8	8	16	30	70	32.000
3	10	10	20	39	89	64.000
4	13	13	25	47	111	129.402
5	16	16	32	60	140	256.000
6	20	20	40	78	178	512.000



Best Practice Guidelines (BPG) conform study: Wall refinement and cell aspect ratios

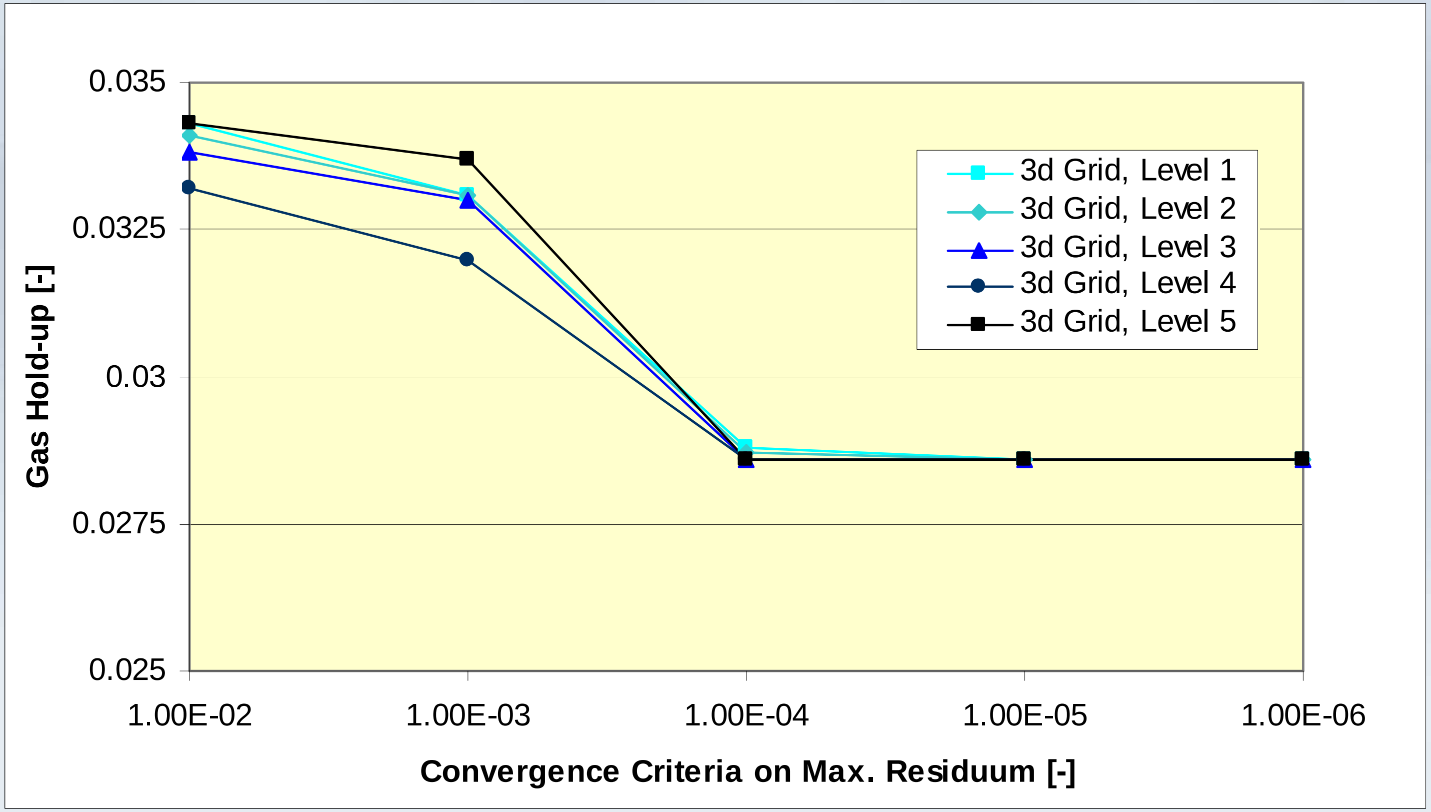


BPG conform study:
Wall function characteristics (SST model)



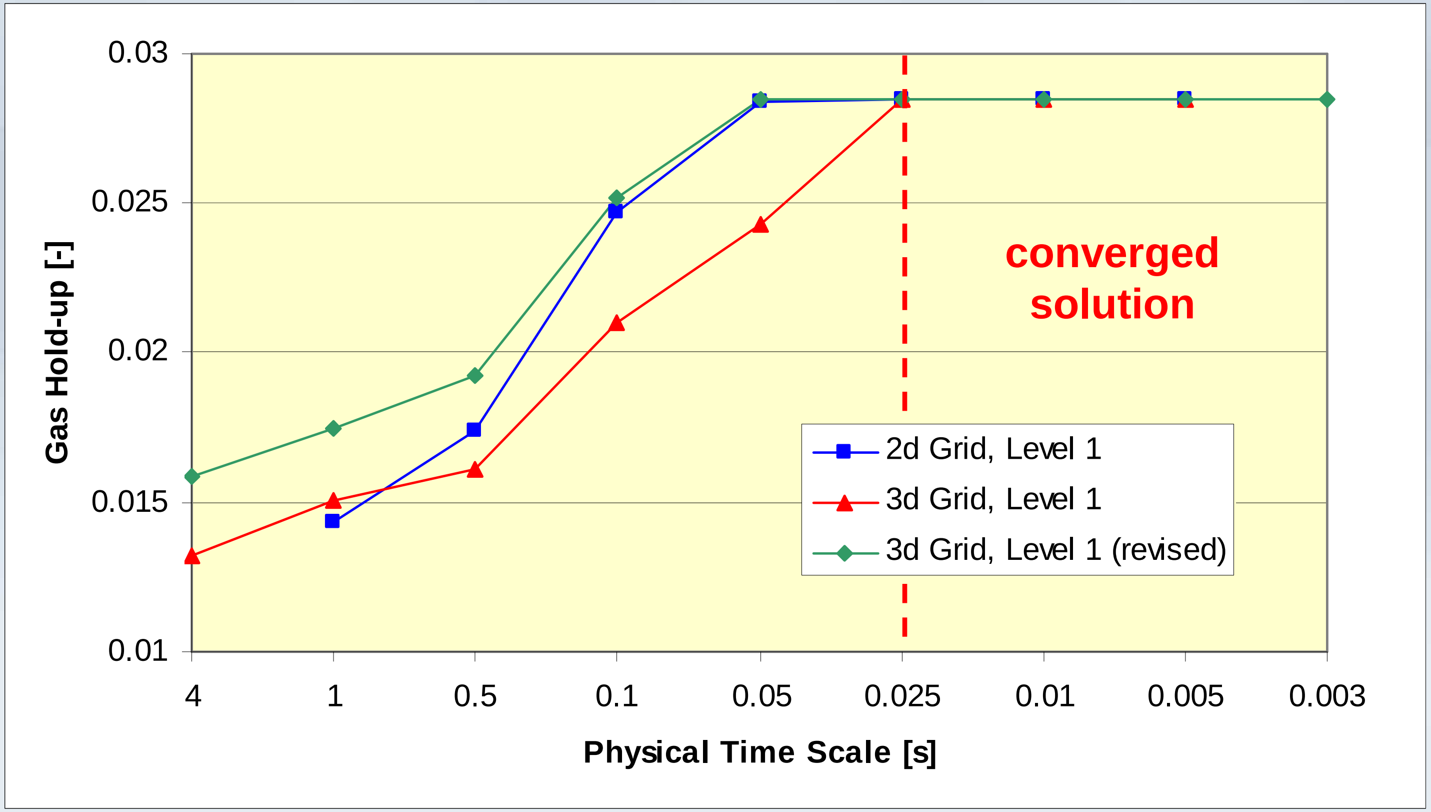
BPG conform study:
Iteration error

- **dependence of gas hold-up vs. convergence criteria; grid dependence; Δt=0.01s, 750 iterations**



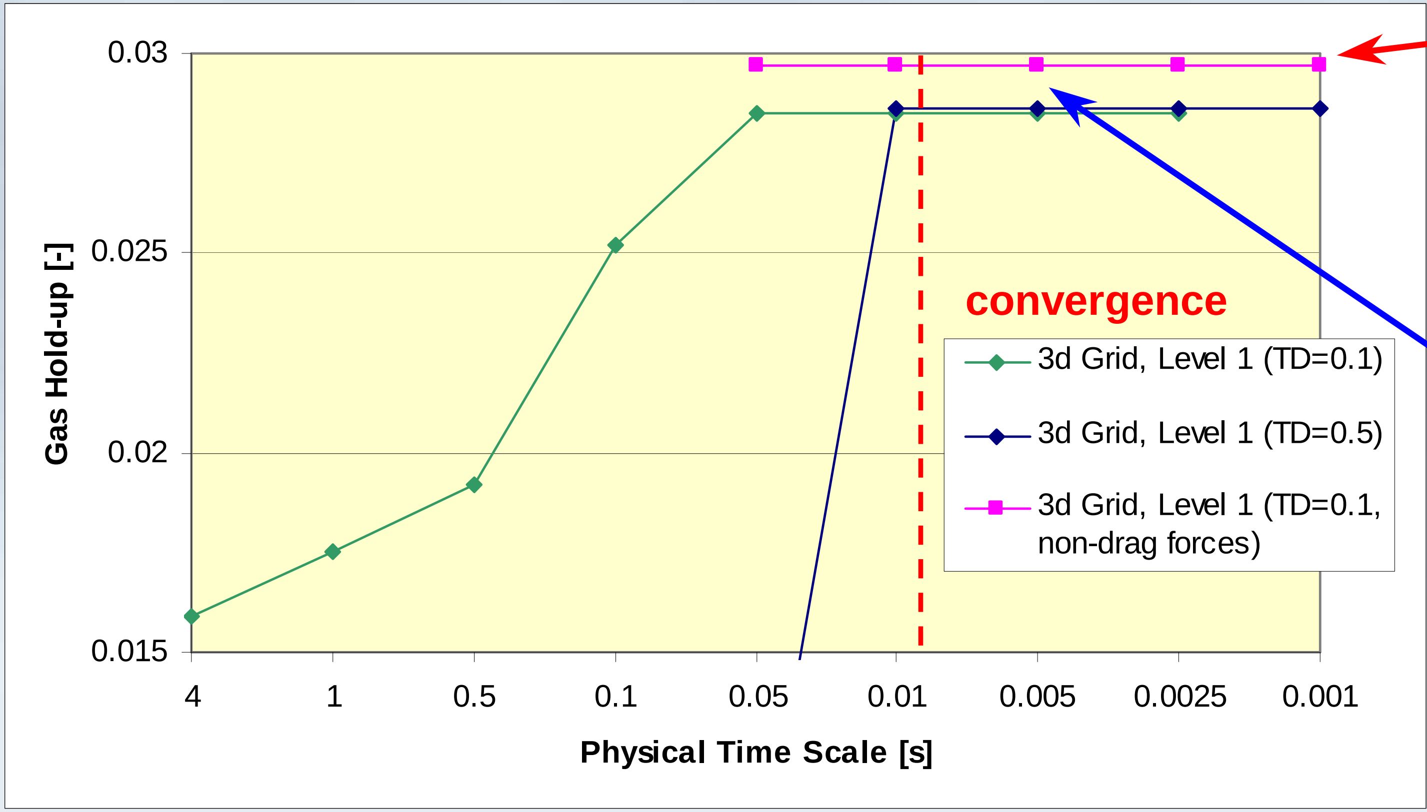
BPG conform study: Convergence in dependence on physical time scale

- **dependence of gas hold-up on physical time scale; convergence & grid dependence**



BPG conform study: Convergence in dependence on additional physical models

- dependence of gas hold-up on physical time scale
- convergence depends on setup of non-drag forces



strong convergence criterion satisfied (max. air momentum residuals < 1.e-5; ~4000 iterations)

gas hold-up reaches steady state; air mass flow imbalance < 0.008% (~1200 iterations)

BPG conform study: Computing resource requirements

Grid Level	CV's	Factor	Procs.	CPU-h	Factor
1	15.744	1.00	1 (HPC)	6.38 h	1.00
2	32.000	2.03	1 (HPC)	11.30 h	1.77
3	64.000	4.07	2 (HPC)	25.82 h	4.05
4	129.402	8.22	2 (HPC)	52.75 h	8.27
5	256.000	16.26	3 (NEC)	100.52 h	15.75
6	512.000	32.52			

Comparison of FAD vs. RPI turbulent dispersion models - I

- **Simulation of Air-Water 2-phase flow; FZR-074**
- **Turbulent dispersion force : RPI TD (C_{TD}=0.5) vs. FAD TD**
- **k-ε vs. SST turbulence model**

Grace drag

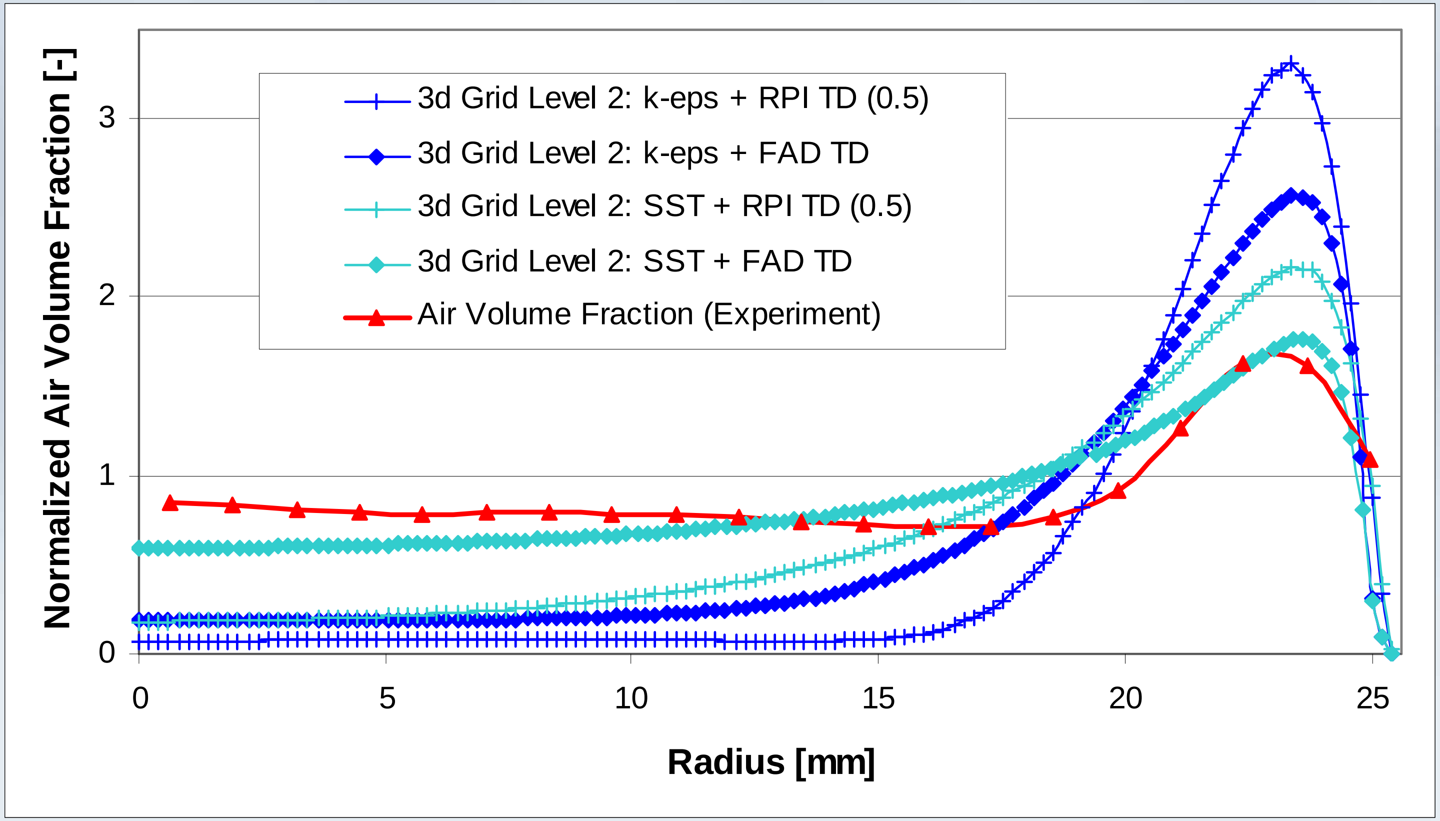
Tomiyama lift

Tomiyama W.L.F.

Sato model

Δt=0.002s

2500 Iterations



Comparison of FAD vs. RPI turbulent dispersion models - II

- **Simulation of Air-Water 2-phase flow; FZR-074**
- **Turbulent dispersion force : RPI TD (C_{TD}=0.5) vs. FAD TD**
- **k-ε vs. SST turbulence model**

Grace drag

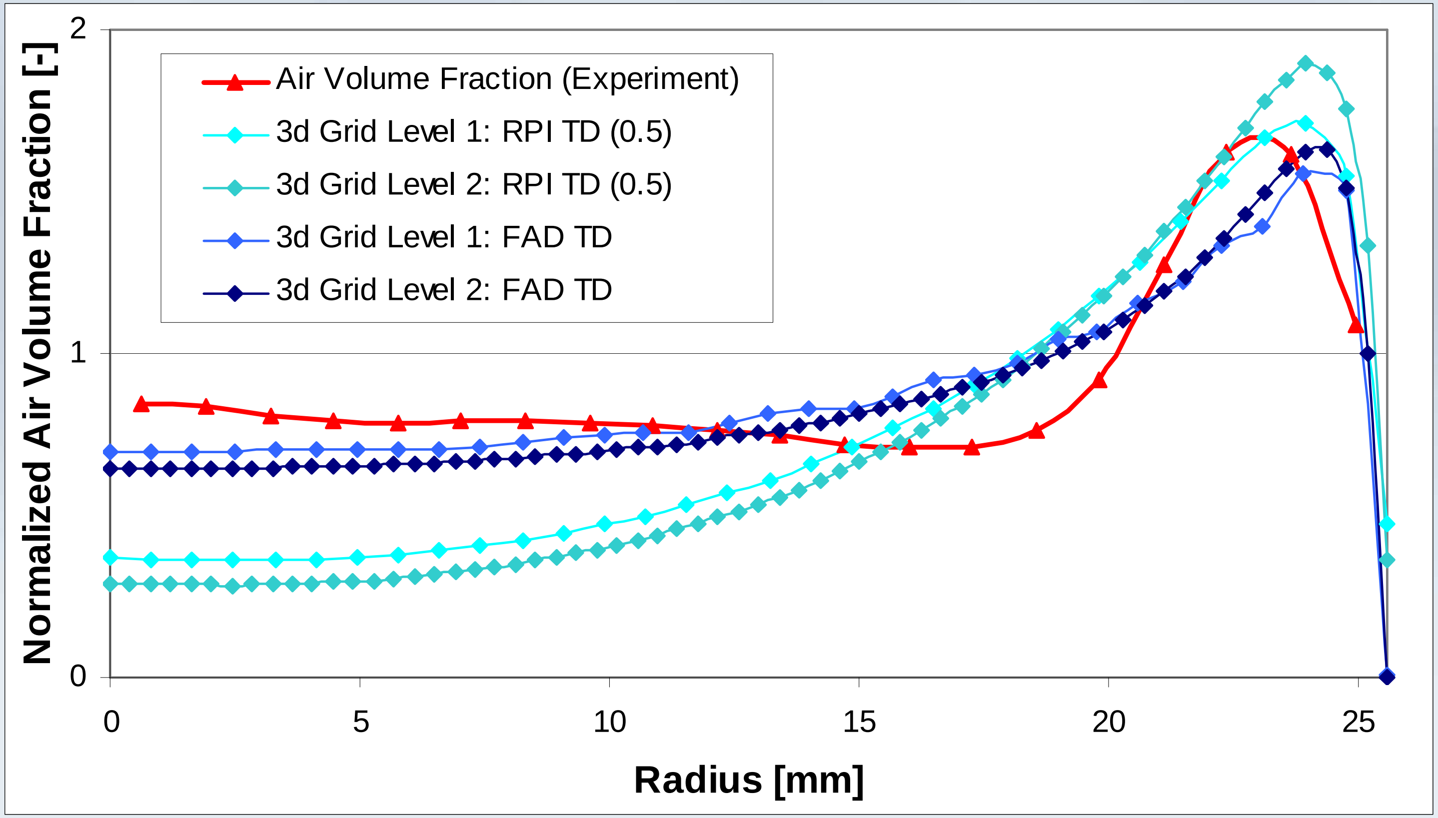
Tomiyama lift

Antal W.L.F.

Sato model

Δt=0.002s

2500 Iterations



Validation & Model parameter variation – I
Test case FZR-074

- **investigation of grid dependence** of the solution (3d grid hierarchy)
- **solution converges with grid refinement**
- **grid independent solution reached on 3rd grid level**

Grace drag

Tomiyama lift

Tomiyama W.L.F.

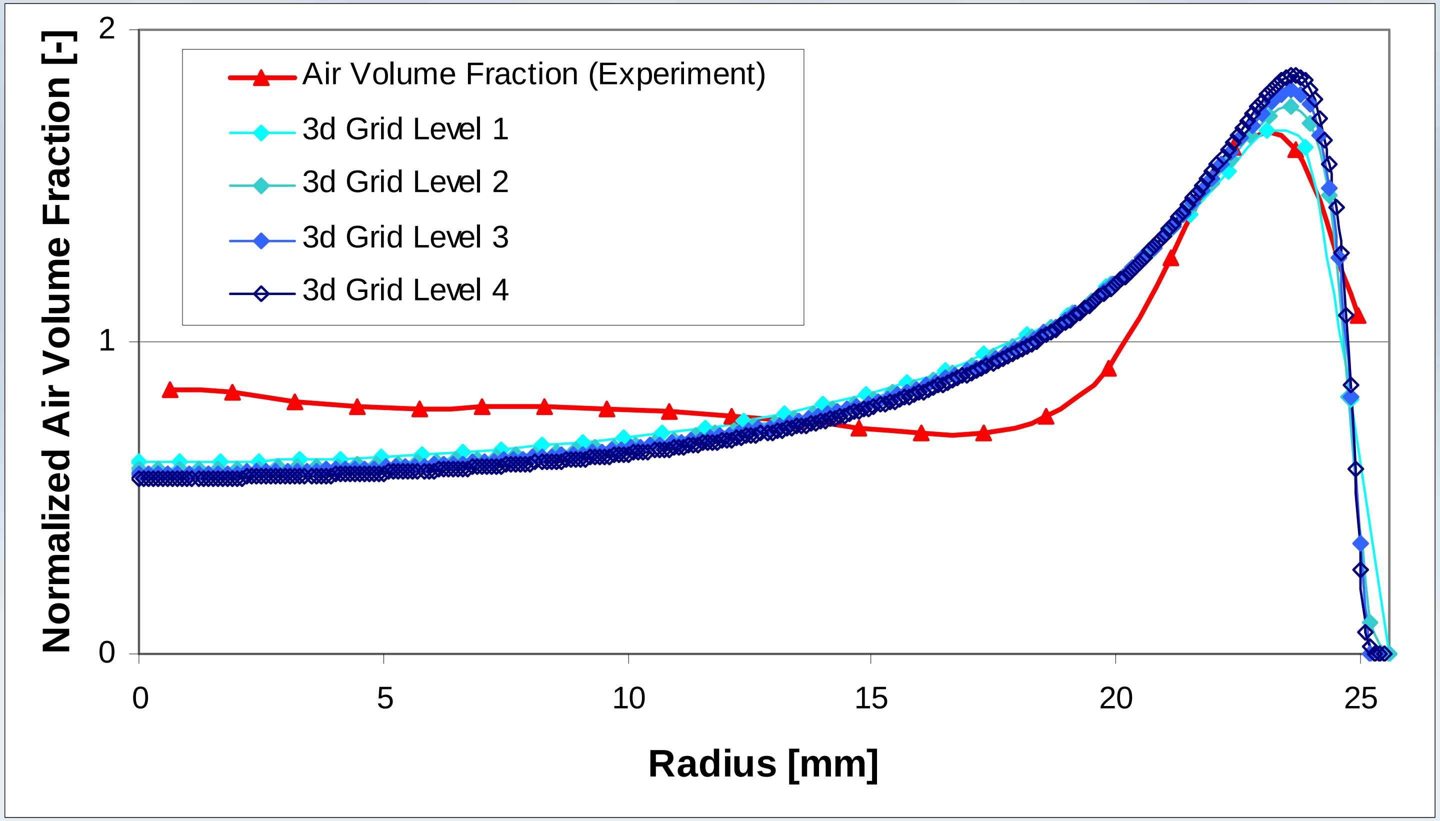
FAD TD

Sato model

SST turb. model

Δt=0.002s

2500 Iterations



Validation & Model parameter variation – II
Test case FZR-074

- grid independent solution still not reached on 4th grid level
- volume fraction wall peak predicted too close to the wall
- amplitude of wall peak too high; Antal W.L.F. too weak

Grace drag

Tomiyama lift

Antal W.L.F.

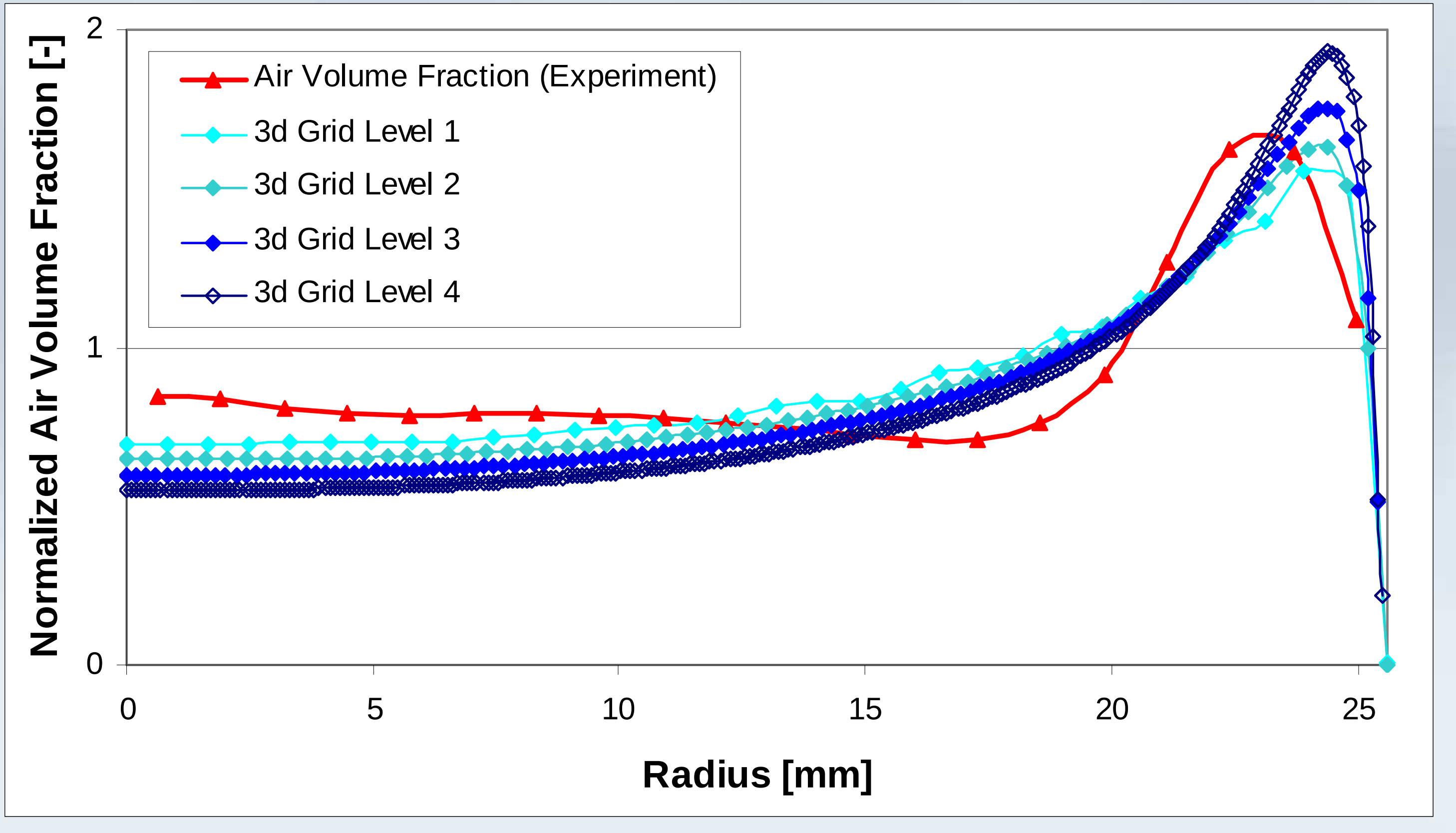
FAD TD

Sato model

SST turb.model

Δt=0.002s

2500 Iterations



Validation & Model parameter variation – III
Test case FZR-074

- **comparison of wall lubrication force models**
- **2^{nd} grid level of mesh refinement**
- **Tomiyama and modified W.L.F. give almost identical results**

Grace drag

Tomiyama lift

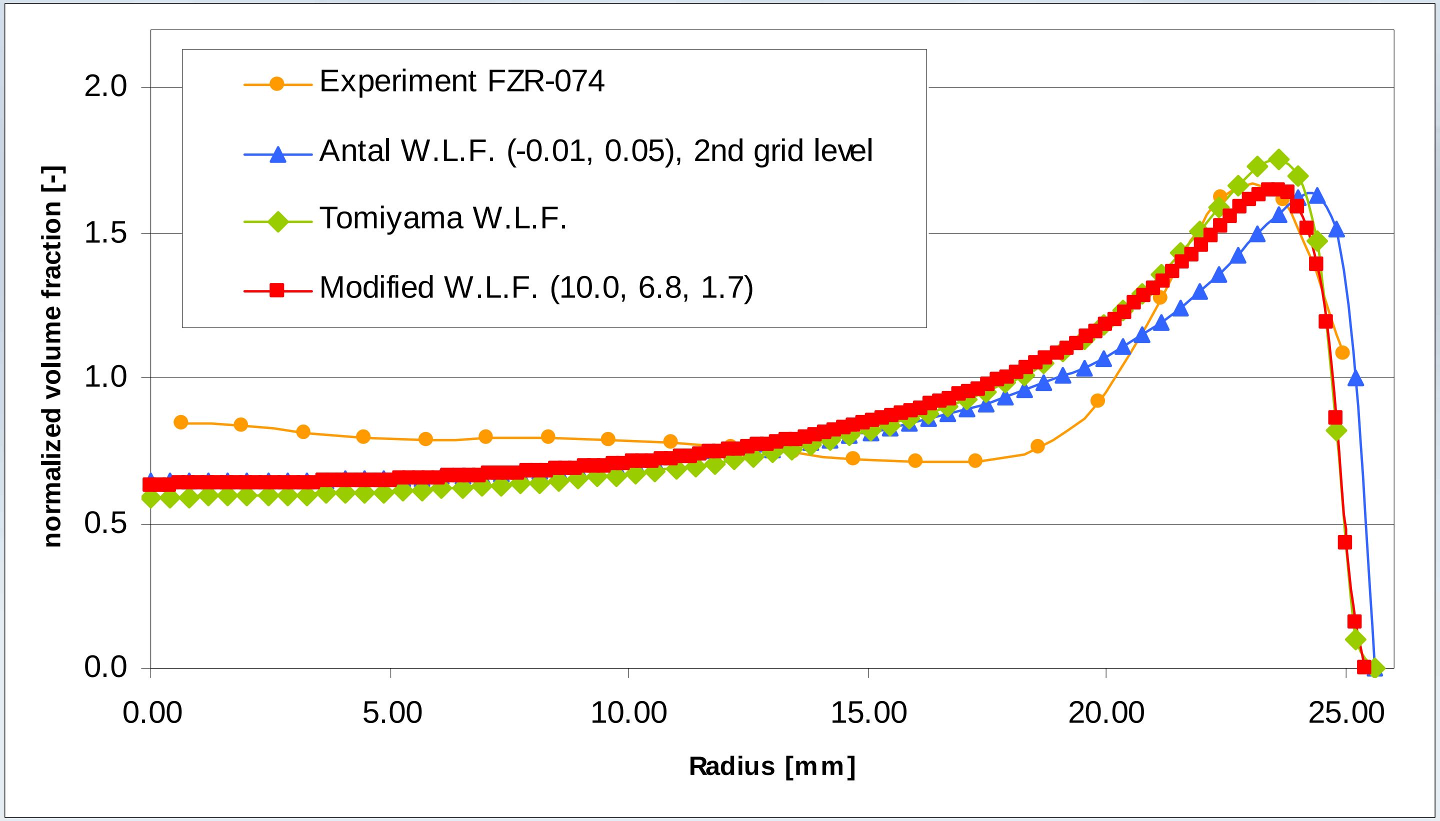
FAD TD

Sato model

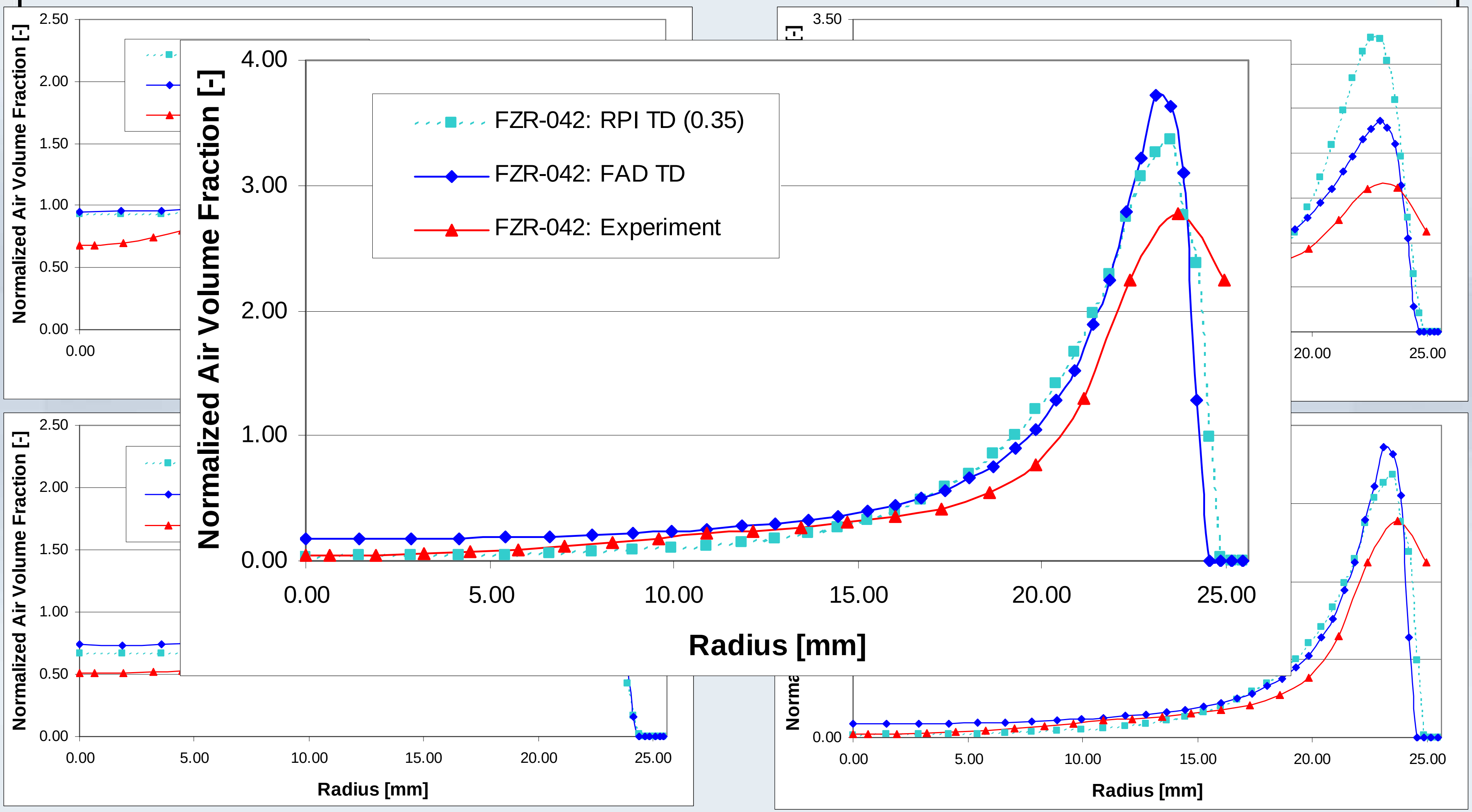
SST turb.model

Δt=0.002s

2500 Iterations



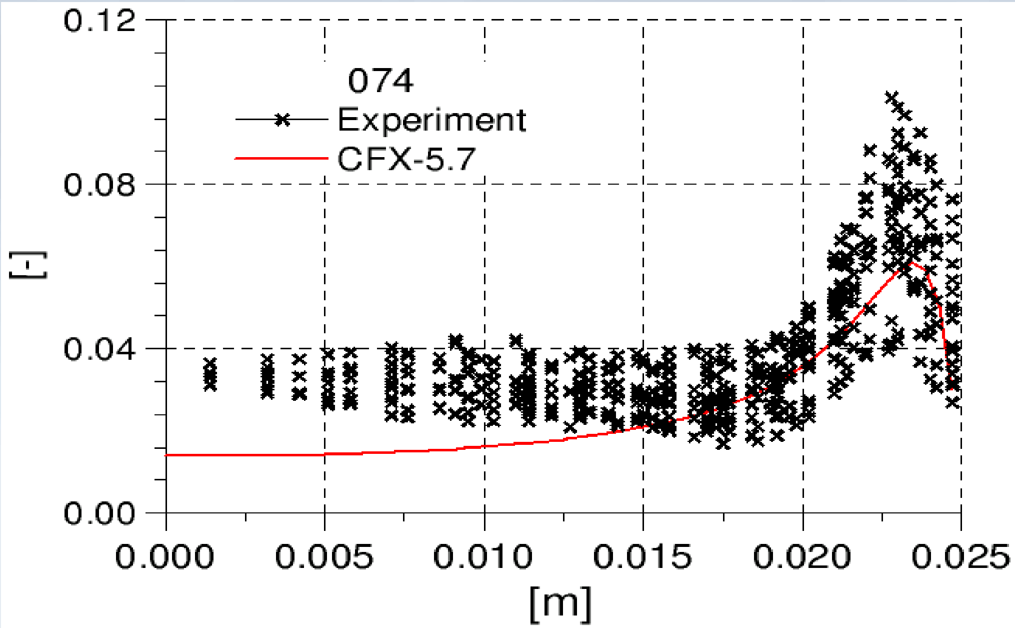
Other test cases: FZR-038 – FZR-042, increasing water superficial velocity

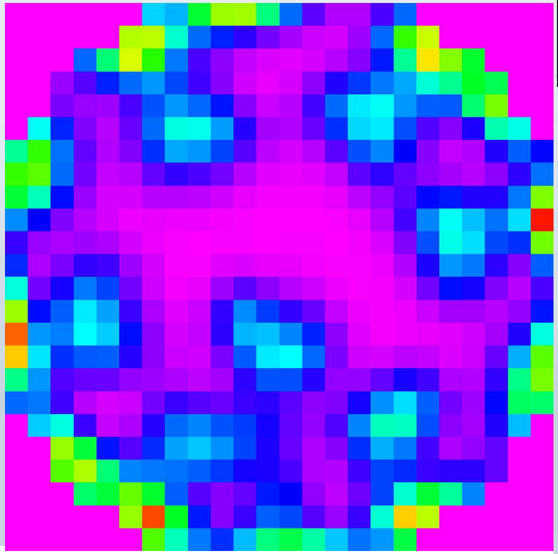


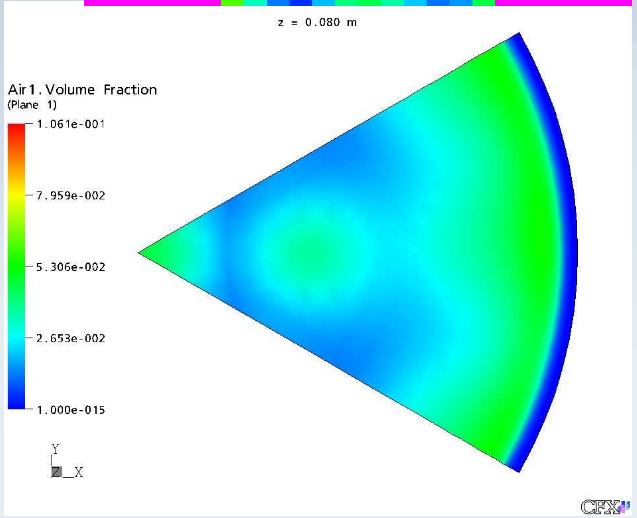
Accuracy of measurements and numerical predictions

- measurement accuracy depends on wire mesh sensor resolution and measurement errors
- numerical simulation is subject to round-off, iteration, solution and model errors

à good agreement between experiments & CFD







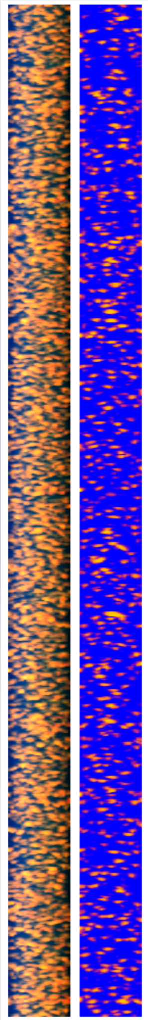
Figures by courtesy of Dr. E. Krepper, FZR

Summary & Discussion

- **Non-drag forces have been implemented in CFX-5.6/5.7**
- **Model closure correlations for disperse bubbly and particle flows available via User Fortran routines**
- **Tomiyama lift and wall lubrication force formulations result in good agreement of CFD results with FZR MT-Loop measurements**
- **Modified W.L.F. formulation gives geometry independent model with same accuracy**
- **Validation carried out for:**
  - ‡ **MT-Loop test matrix with different air/water superficial velocities**
  - ‡ **upward & downward flows; transient change of fluid mass flow**
  - ‡ **bubble diameter range d_P=0.5,…,10.0 mm leading to wall and core peaking in the volume fraction profiles**
  - ‡ **polydispersed air-water flows with up to 5 disperse phases**

Summary & Discussion (cont.)

- Turbulence modeling has significant impact on phase volume fraction distribution
  - à best results with SST turb. model and FAD TD model
  - à FAD TD model is a significant improvement over RPI model
  - à FAD TD model became default in CFX-5.7
- Further validation: FZR TOPFLOW experiments (D=194.1 mm)
- Further development:
  - ‡ higher volume fractions
  - ‡ breakup & coalescence
  - ‡ inhomogeneous MUSIG model for polydispersed flows
  - ‡ phase change models (boiling, condensation)



Thank you !