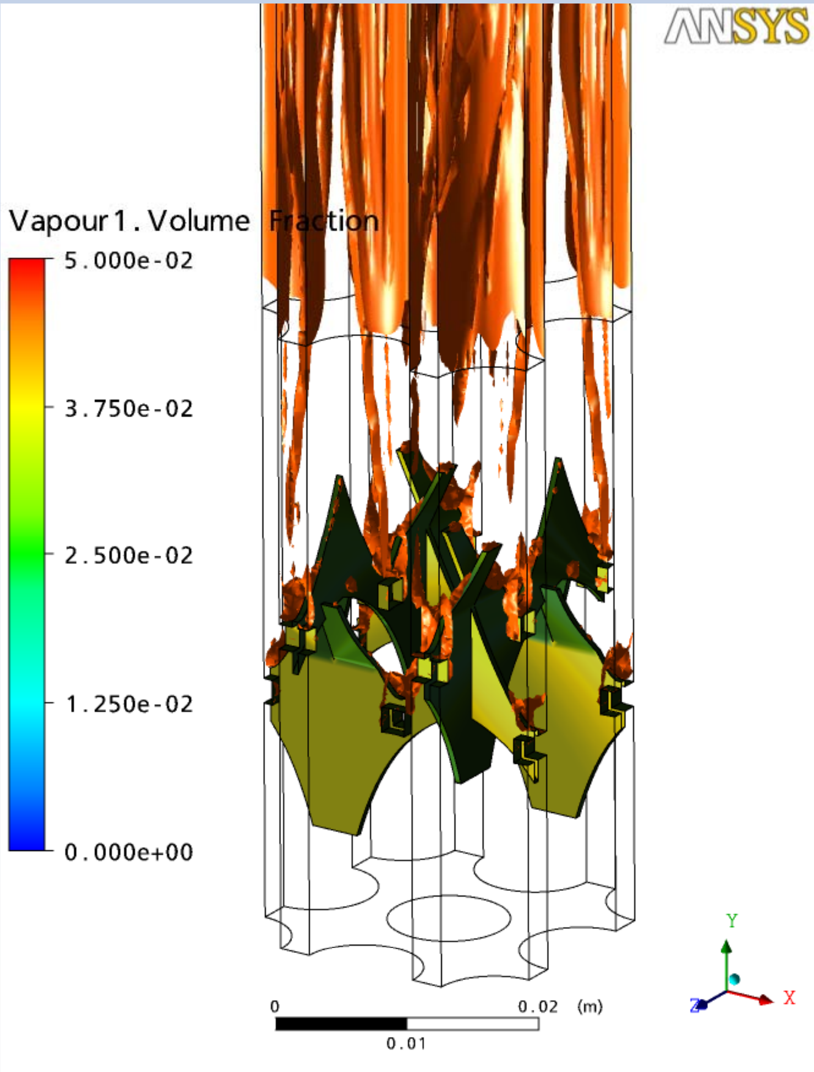
Development and Validation of Eulerian Multiphase Flow Models in ANSYS CFD

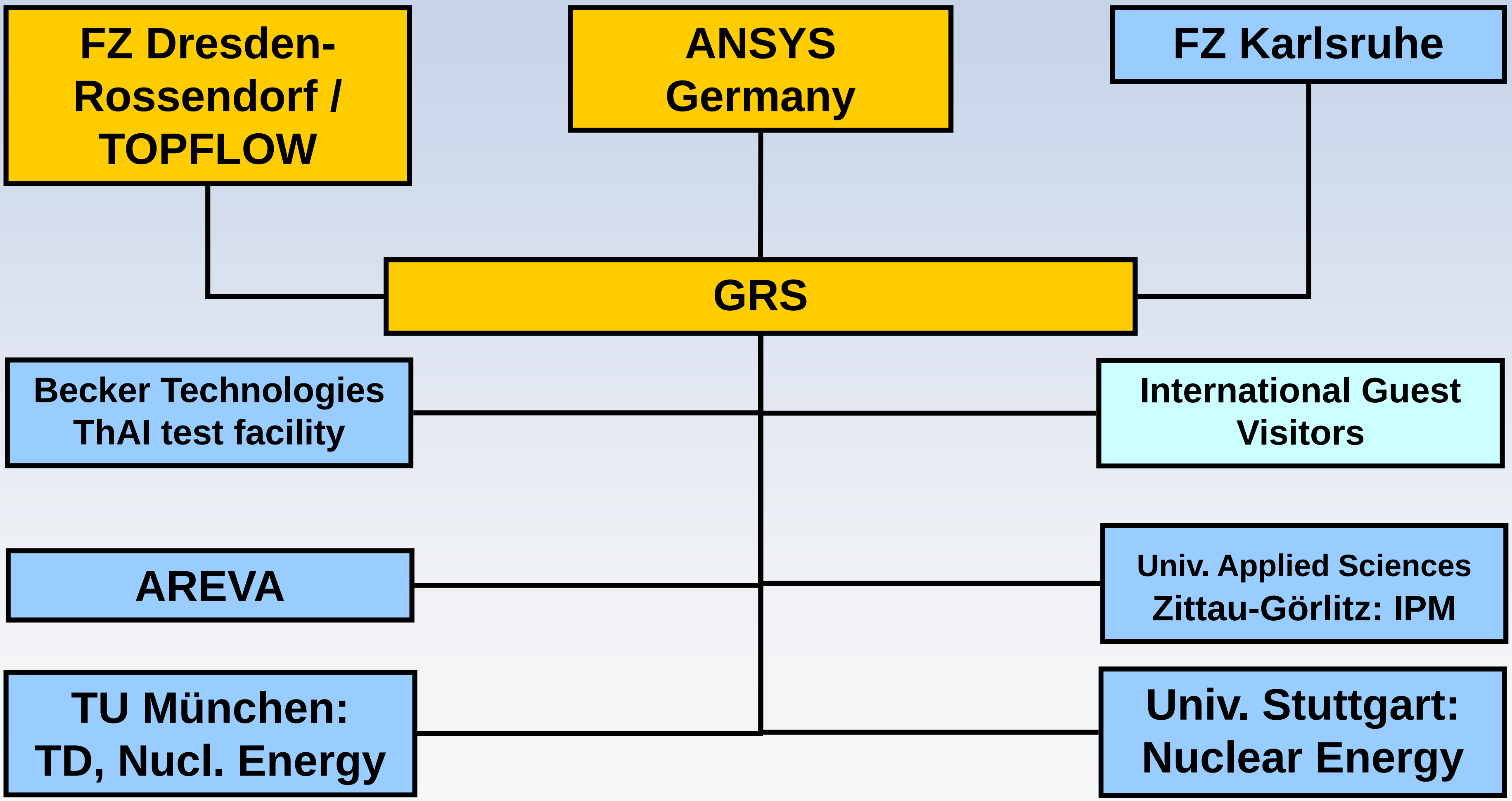
Thomas Frank
ANSYS Germany
Thomas.Frank@ansys.com

Outline

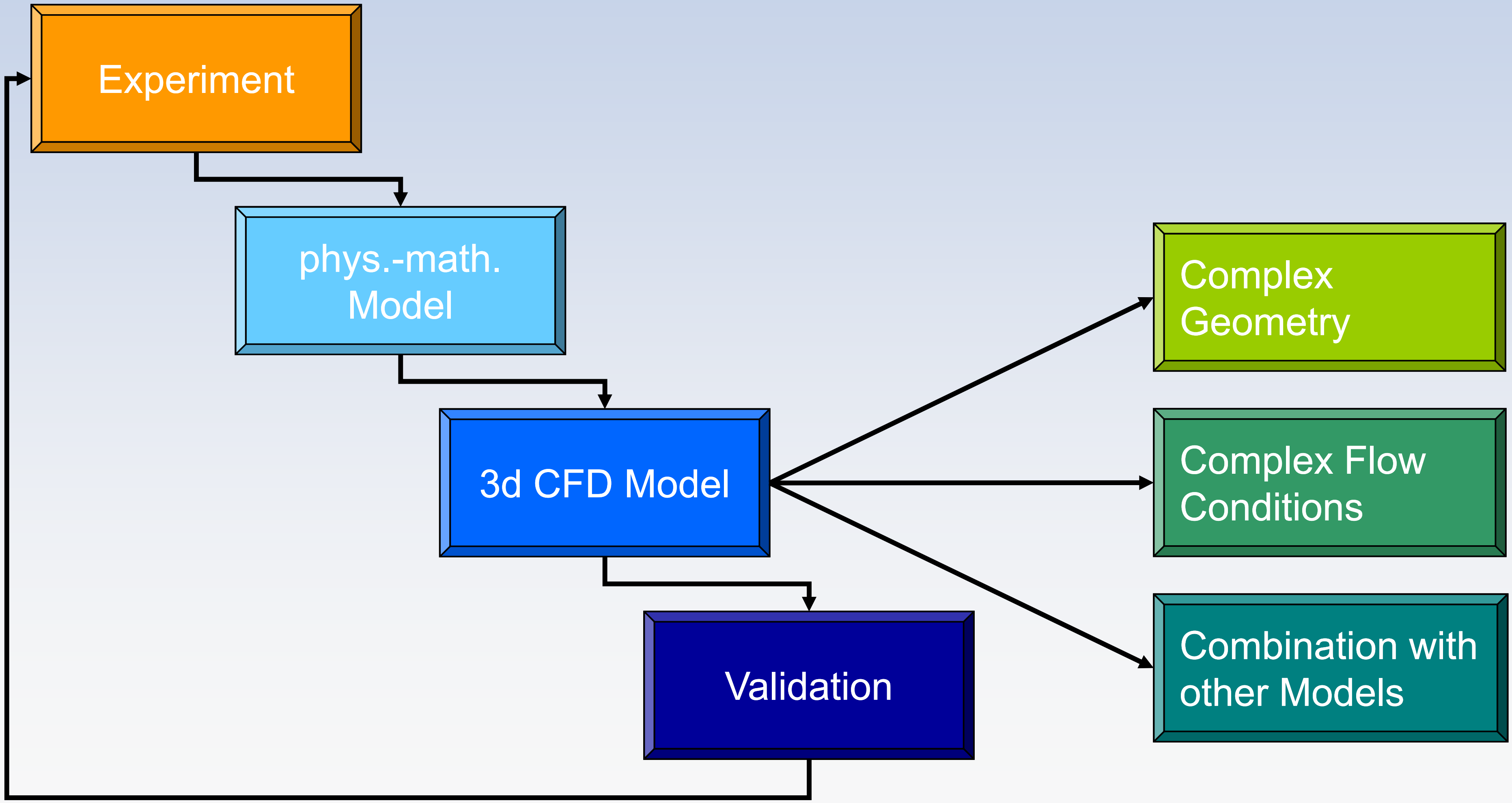
- Introduction
- MPF model validation for adiabatic air-water flows
- Polydisperse MPF model validation – MUSIG model
- Validation of the RPI wall boiling model
- The FRIGG testcase for boiling flow in rod bundles
- RPI & MUSIG model
- Summary & Outlook



ANSYS as Part of the German CFD Network in Nuclear Reactor Safety



Methodology of CFD Model Development & Validation



Eulerian MPF Modeling - The Particle Model

Mass weighted averaged conservation equations

- Mass, momentum, energy transport equations for each phase

$$\frac{\partial}{\partial t}\left(\rho_k r_k\right) + \nabla\left(\rho_k r_k \mathbf{U}_k\right) = \sum_{\substack{l=1 \\ l\neq k}}^{N} \Gamma_{kl}$$

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

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

- turbulence models for each phase
  (e.g. k-ε / k-ω SST model, 0-eq. disp. phase turb. model, Sato model)
- heat transfer equations for each phase with interfacial transfer closure
- interfacial forces need empirical closure
- high void fraction effects, bubble induced turbulence, etc.

Lift force, Wall lubrication force & turbulent dispersion

Lift force:

- due to asymmetric wake and deformed asymmetric particle shape

→ Tomiyama C_L correlation

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

$$C_L = C_L(\mathrm{Re}_P, \mathrm{Re}_\nabla, Eo)$$

Wall lubrication force:

- surface tension prevents bubbles from approaching solid walls

→ Antal, Tomiyama & Frank W.L.F. models

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

$$C_{wall} = C_W(\mathrm{Eo}, \mathrm{y/d_P})$$

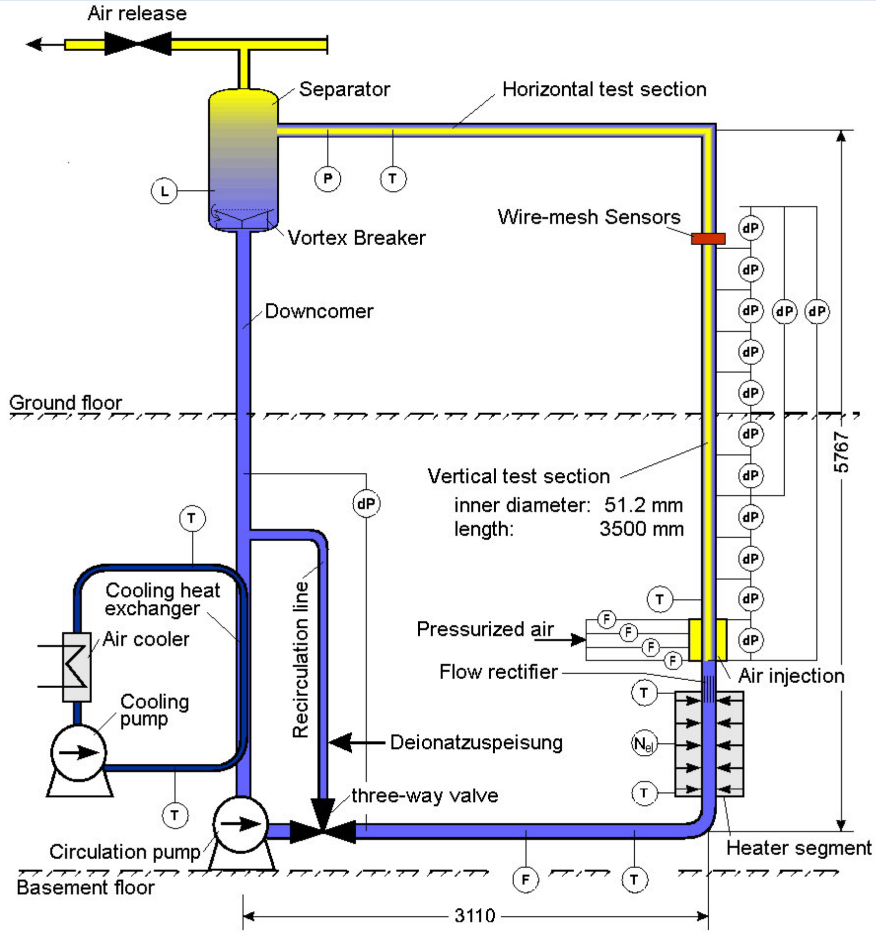
Turbulent dispersion force:

- turbulent dispersion = action of turb. eddies via interphase drag

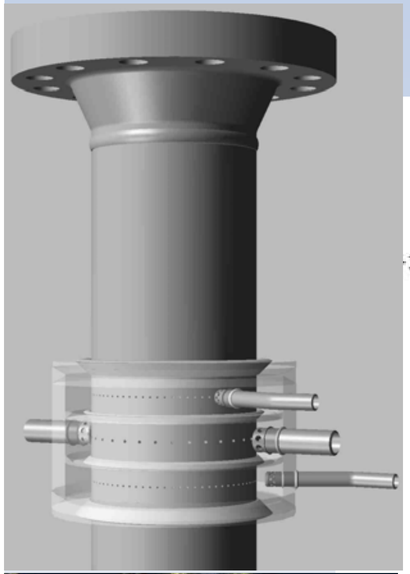
$$\mathbf{F}_{TD} = \frac{3}{4} \rho_F \frac{\overline{C_D}}{d_P} \frac{\nu_{tF}}{\sigma_{rF}} \left| U_F - U_P \right| \overline{r_P} \left(\frac{\nabla \overline{r_P}}{\overline{r_P}} - \frac{\nabla \overline{r_F}}{\overline{r_F}} \right)$$

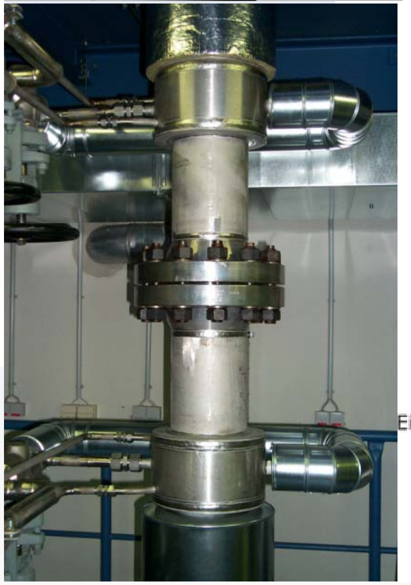
FAD model by
Burns et al. (ICMF'04)

Bubbly Flow Model Validation
FZR MT-Loop and TOPFLOW Database

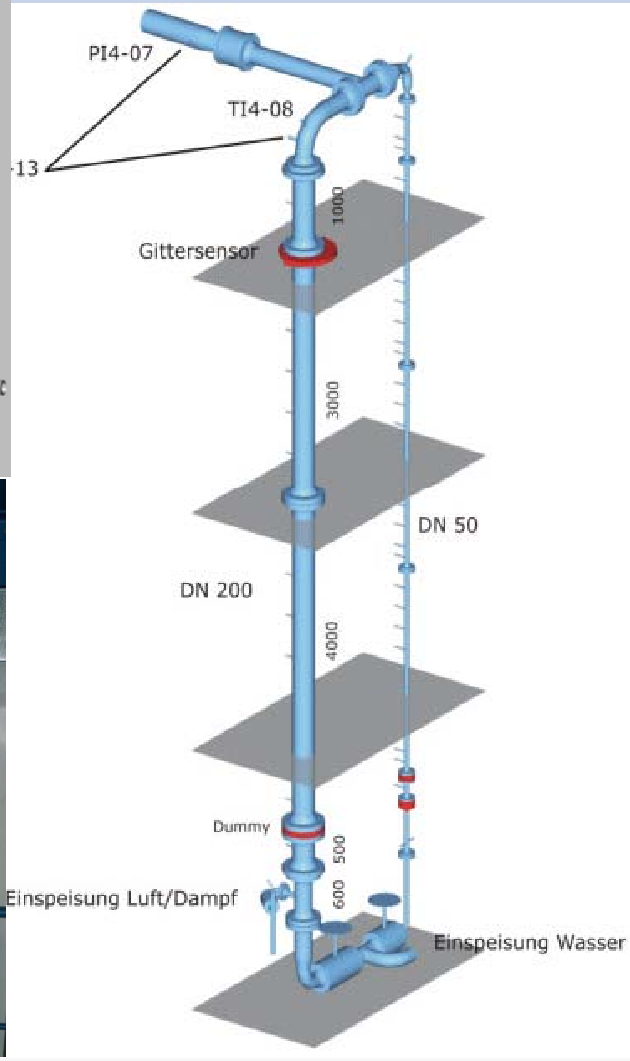


MT-Loop



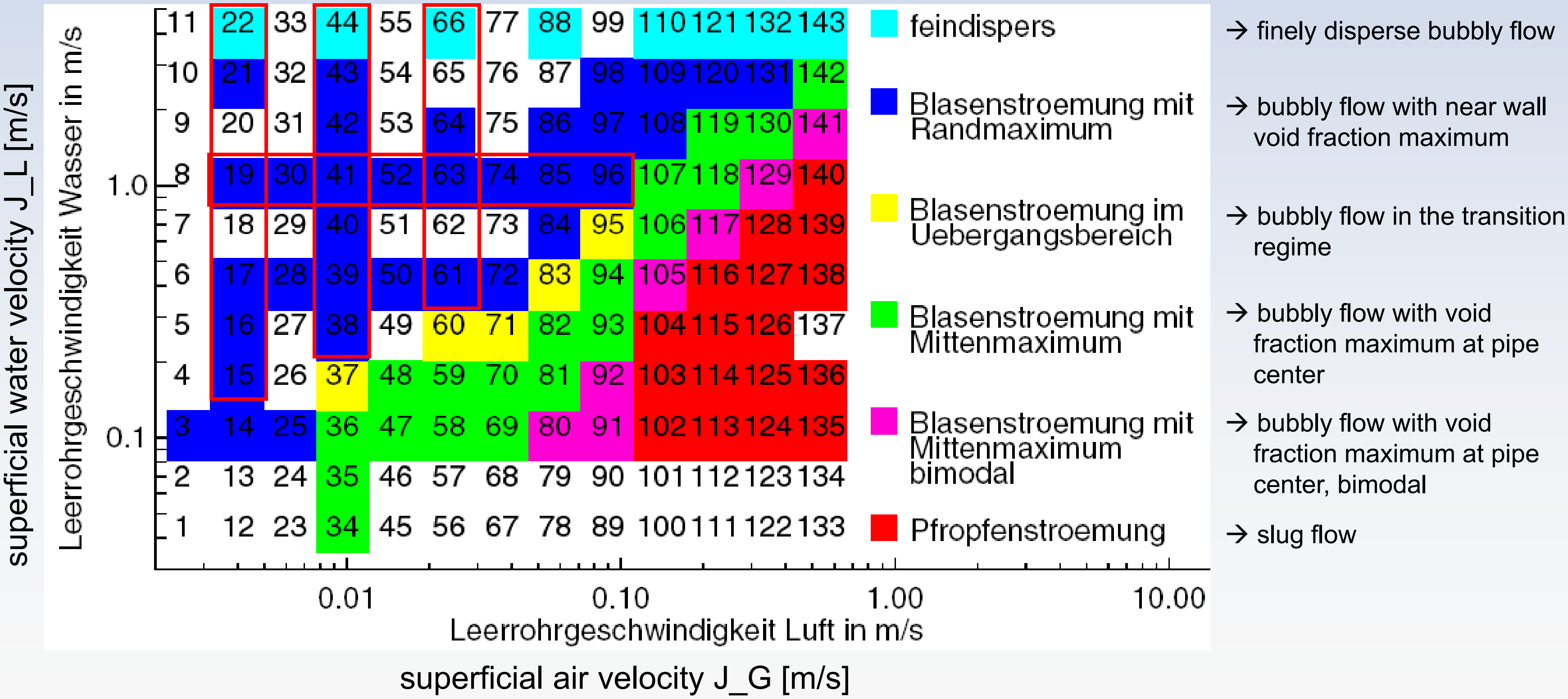


TOPFLOW

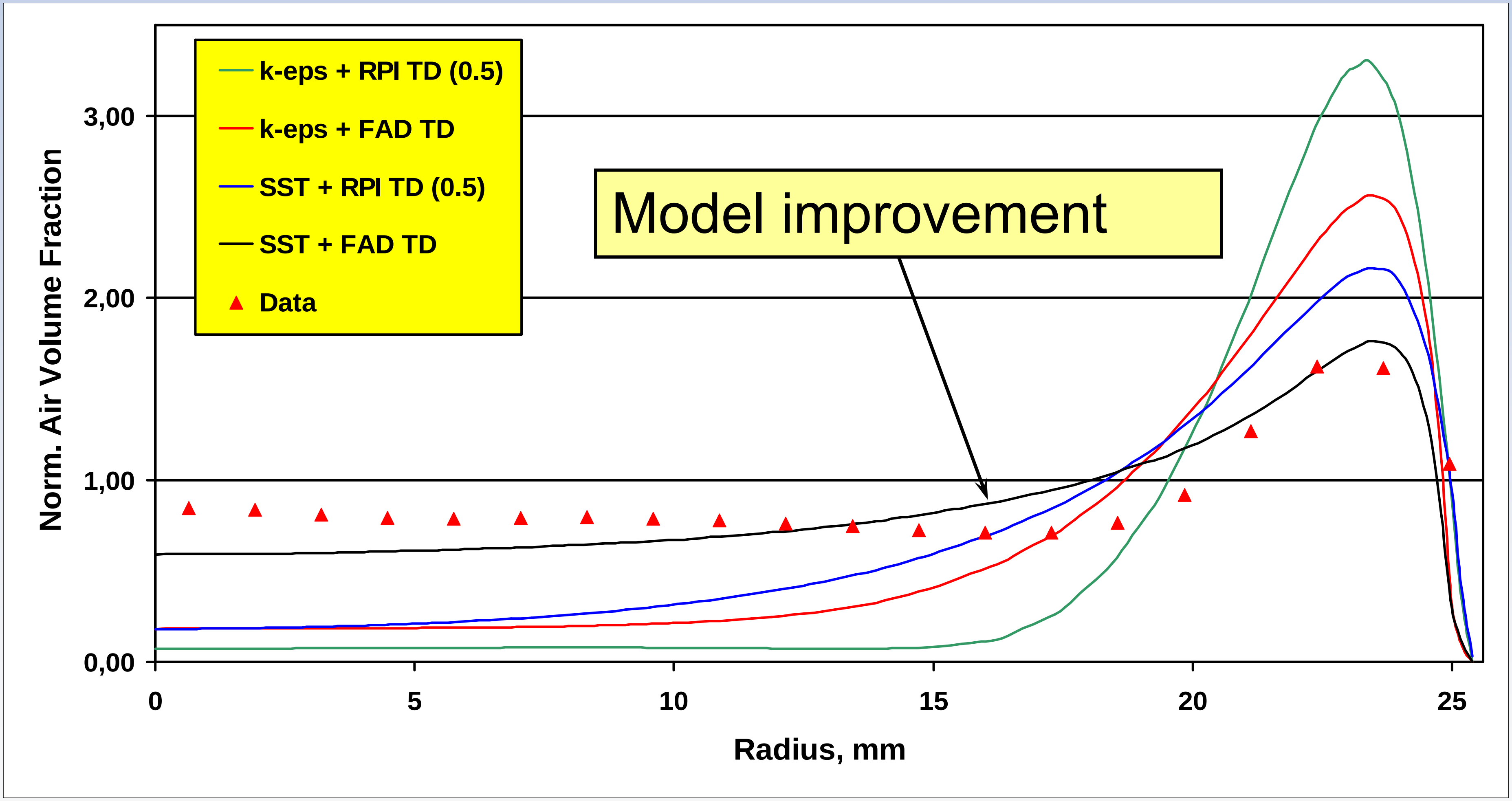


CFX Model Validation
MT-Loop & TOPFLOW Test Matrix

- M01 experimental test series on MT-Loop
- evaluation based on air volume fraction profiles at L/D=59,2 (z=3.03m) from the sparger system
- ▭ - numerically investigated test case conditions



Validation: Bubbly Flows
Turbulent Dispersion Force

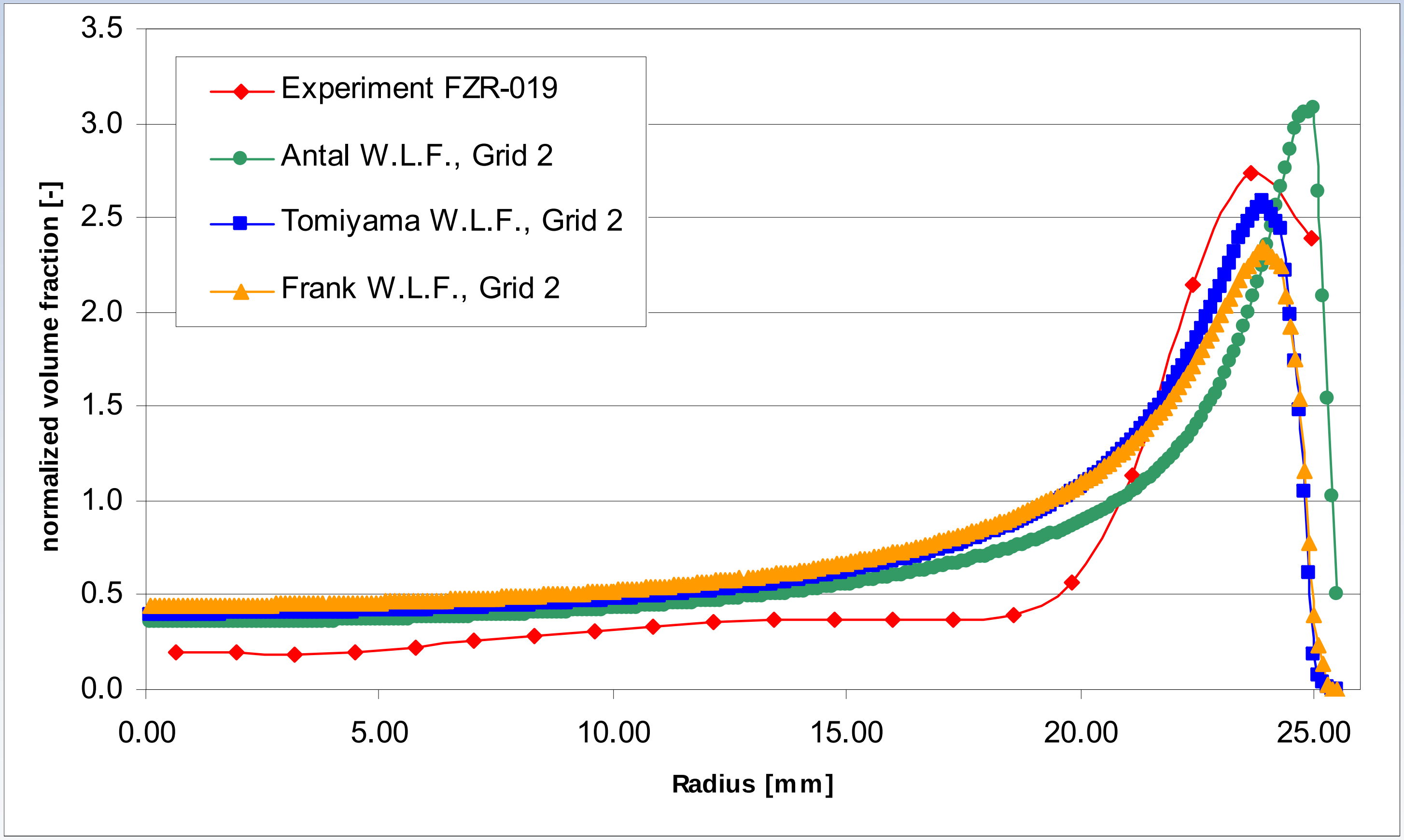


Monodispersed Bubbly Flow
MT-Loop Test Case FZR-019

FZD-019:

J_L=1.017 m/s
J_G=0.004 m/s
d_P=4.8 mm

Grace drag
Tomiyama lift
T./A./F. Wall L. Force
FAD Turb. Disp.
SST turb. model
Sato model
Δt=0.002s
2210 Iterations

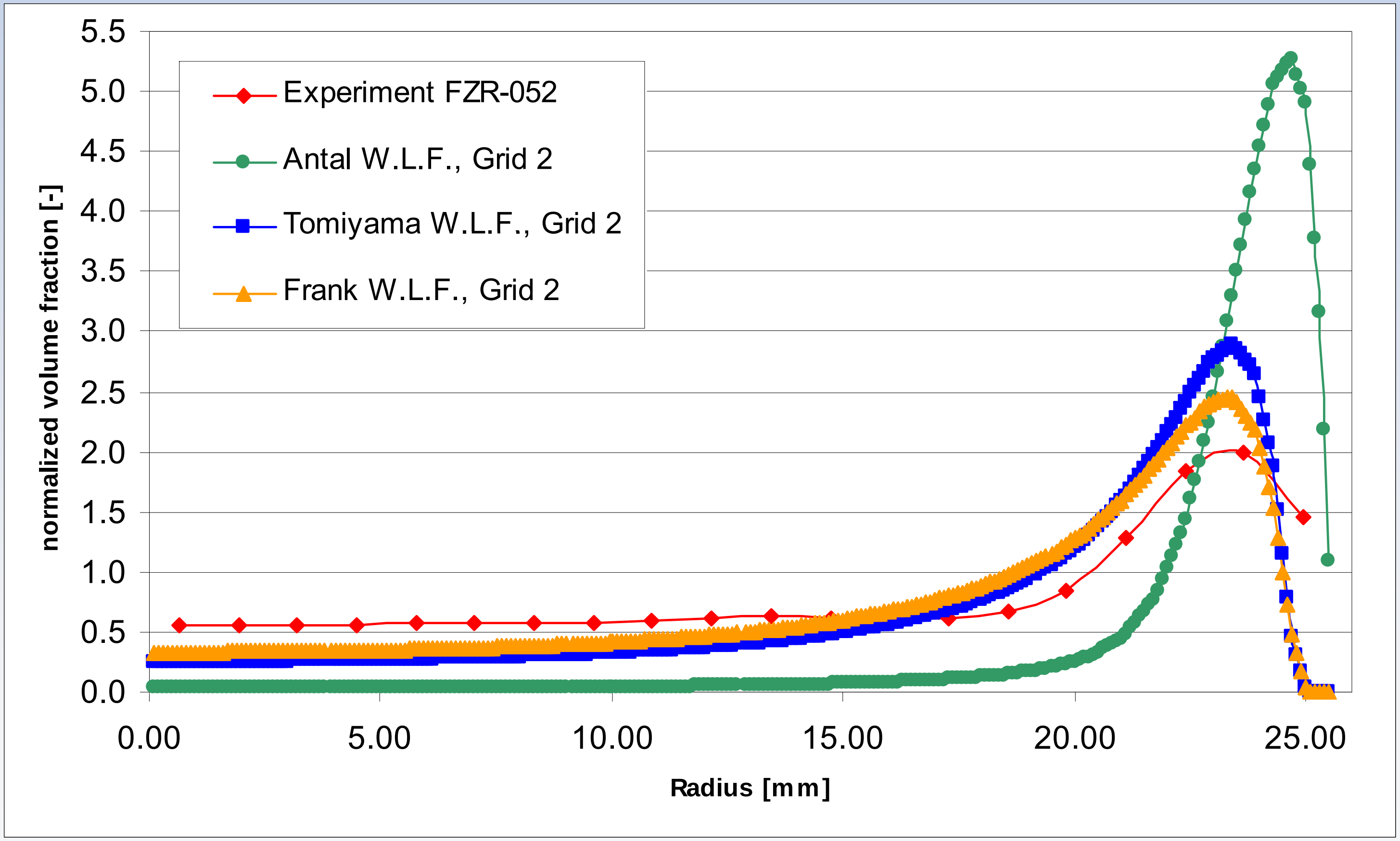


Monodispersed Bubbly Flow MT-Loop Test Case FZR-052

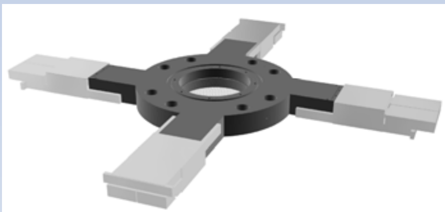
FZD-052:

J_L=1.017 m/s
J_G=0.0151 m/s
d_P=4.4 mm

Grace drag
Tomiyama lift
T./A./F. Wall L. Force
FAD Turb. Disp.
SST turb. model
Sato model
Δt=0.002s
2400 Iterations

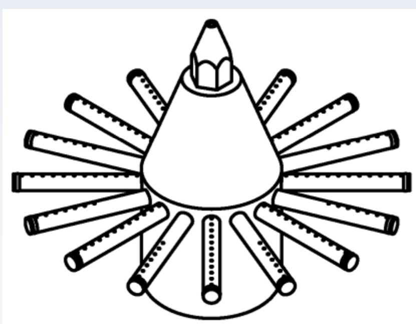


TOPFLOW Test Facility @ FZD

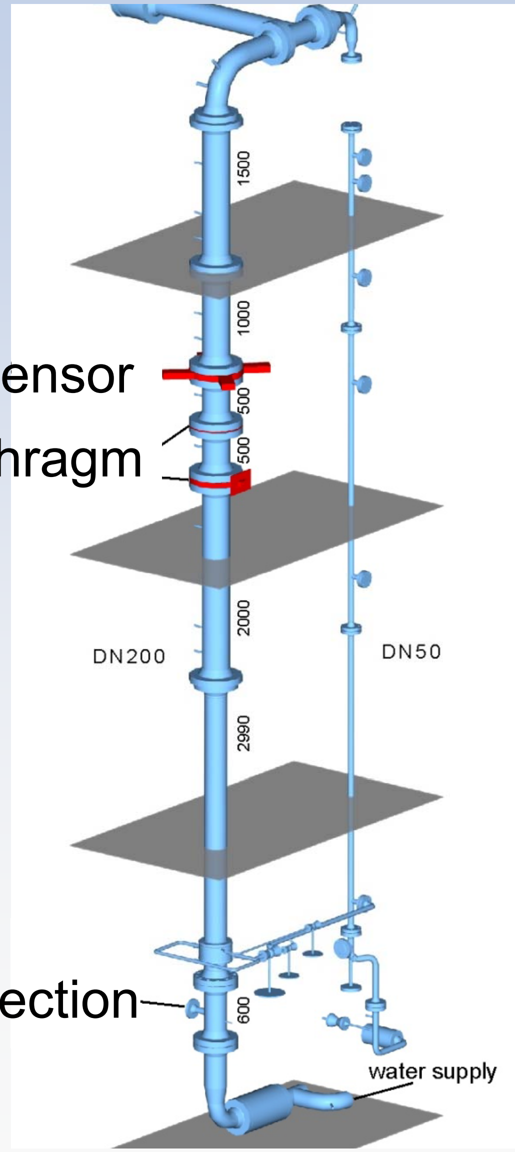


wire-mesh sensor

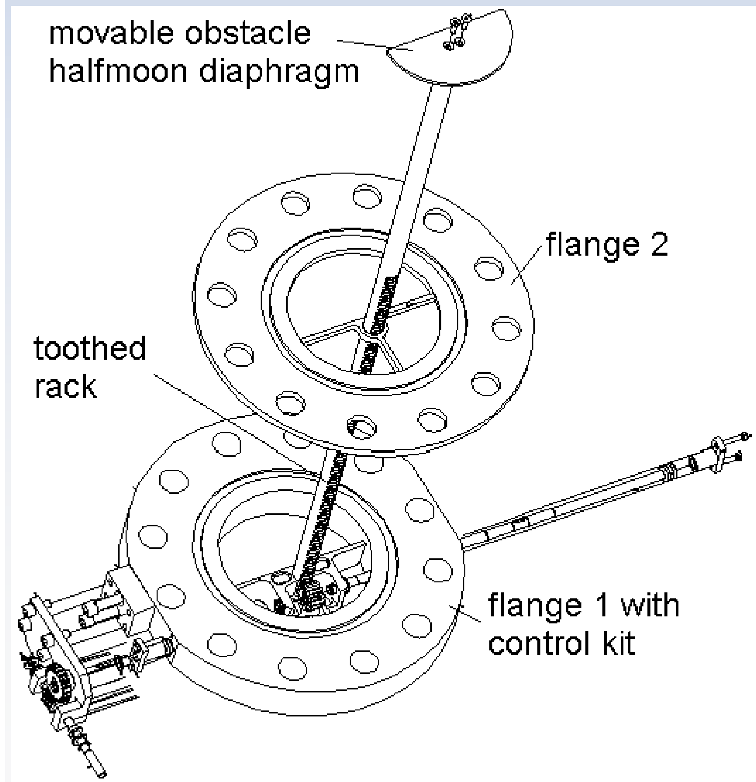
movable diaphragm



gas injection



movable diaphragm

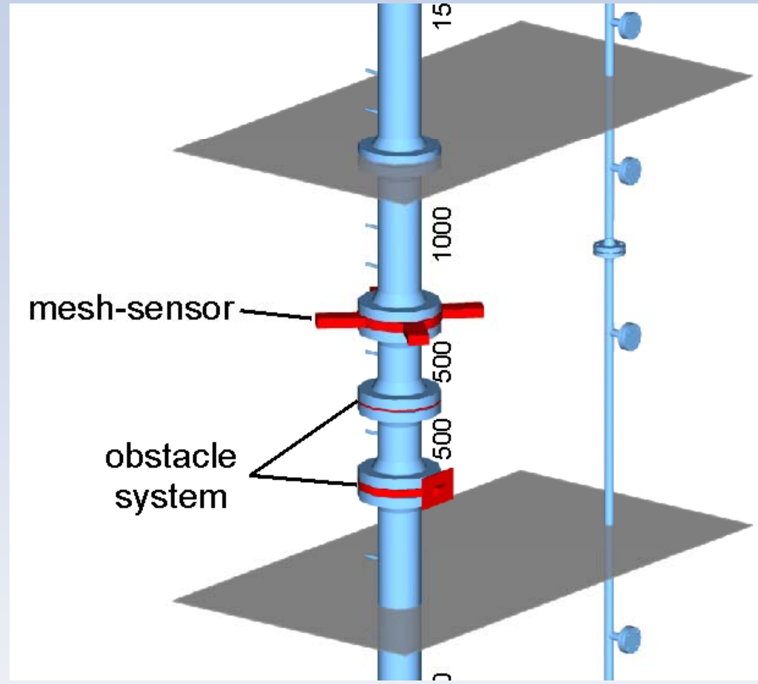


TOPFLOW-074 Test Case Conditions from Test Matrix

- Selection of test case conditions:

superficial gas velocity

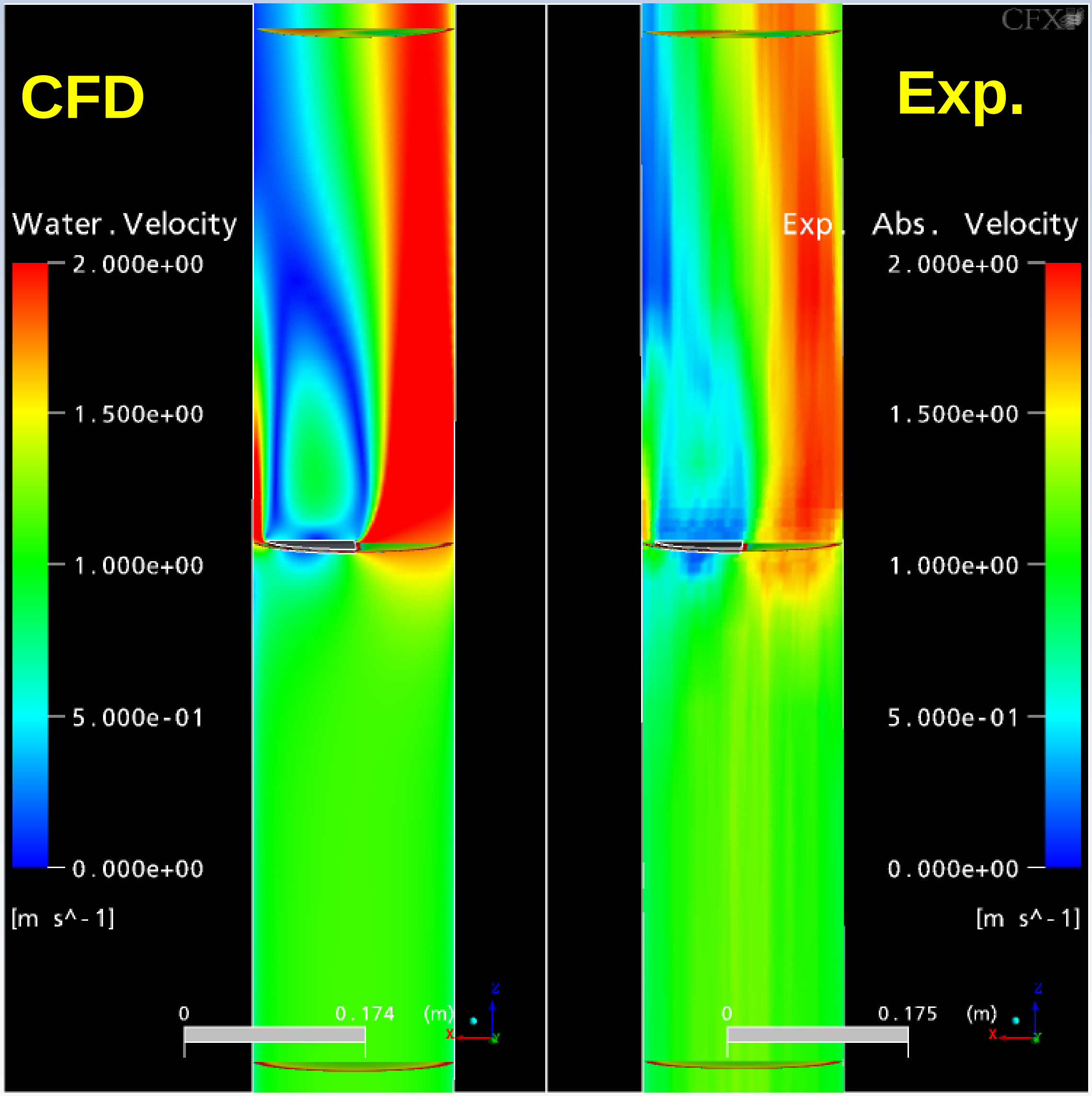
superficial water velocity m/s	0.0368	0.0574	0.0898	0.14	0.219	0.342	0.534	0.835
1.611	075	086	097	108	119	130	141	152
1.017	074	085	096	107	118	129	140	151
0.405	072	083	094	105	116	127	138	149
0.102	069	080	091	102	113	124	135	146



- TOPFLOW-074 test case was subject of validation in the past
- Superficial velocities: J_G=0.0368 m/s
  J_L=1.017 m/s
- Wire-mesh sensor measurements at locations:
  z=±10, 15, 20, 40, 80, 160, 250, 520mm

3d Bubbly Flow Around Obstacle
Water Velocity Comparison

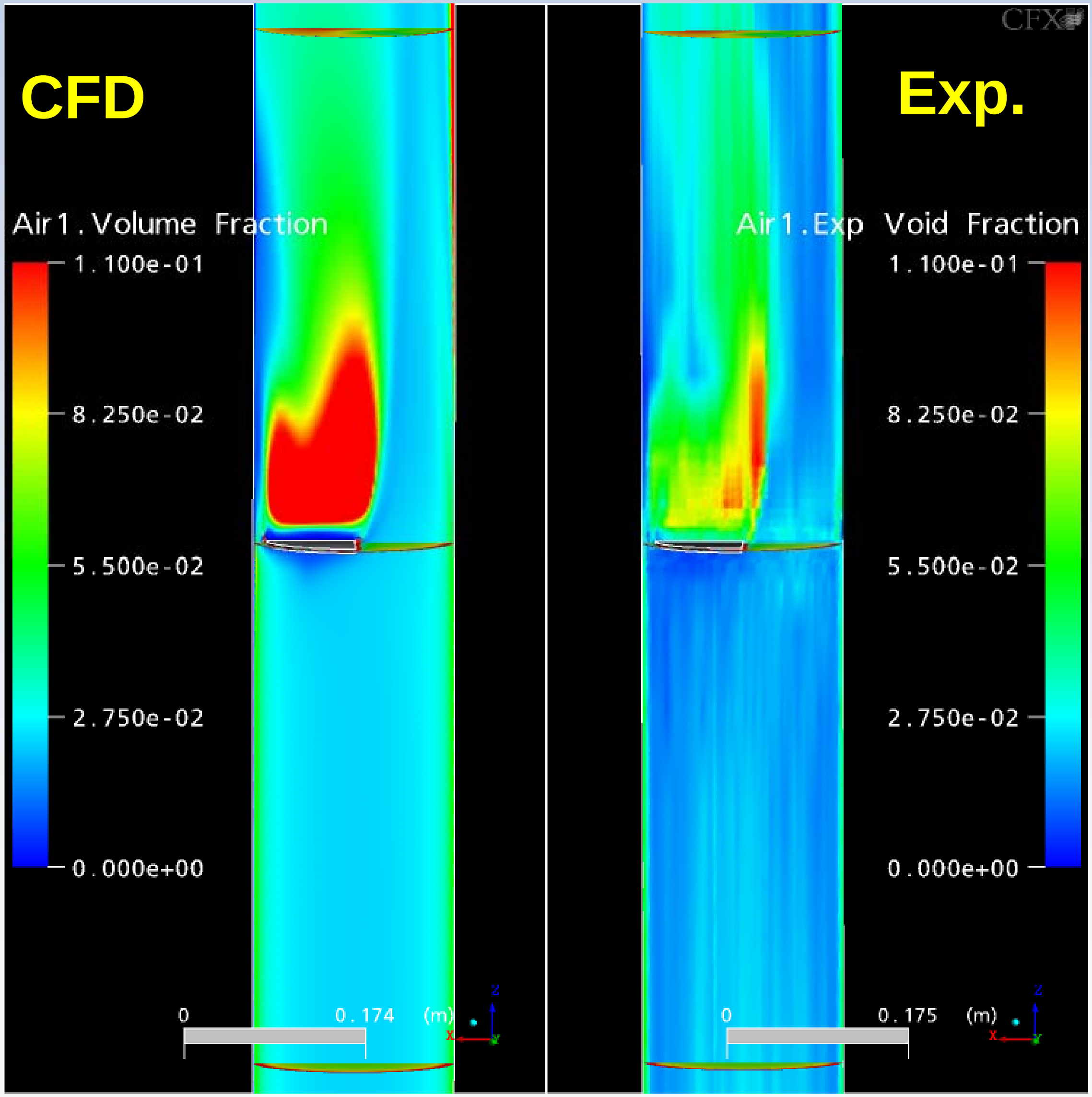
- Comparison
  CFD ⇔ Experiment
- Absolute water velocity distribution in symmetry plane
- Import of exp. data into CFX-Post
- Pre-interpolation of exp. data to Δz=0.01m



3d Bubbly Flow Around Obstacle
Air Void Fraction Comparison

ANSYS

- Comparison
  CFD ⇔ Experiment
- Air void fraction distribution in symmetry plane



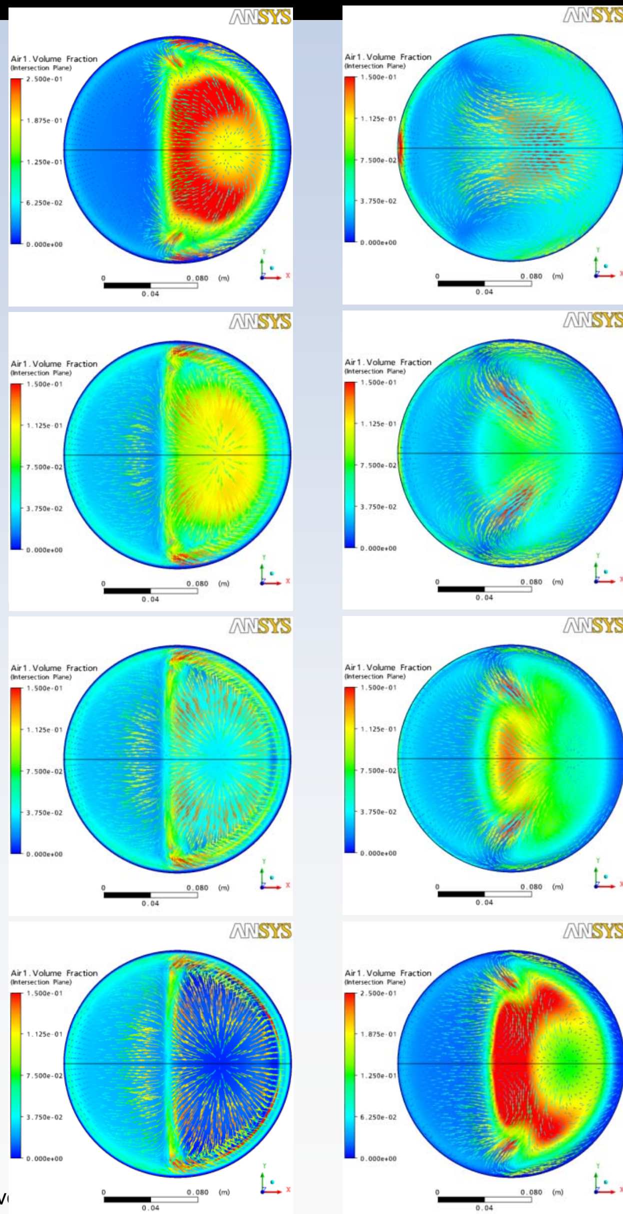
3d Bubbly Flow Around Obstacle
Air Void Fraction Comparison

4) z=40mm

3) z=20mm

2) z=15mm

1) z=10mm

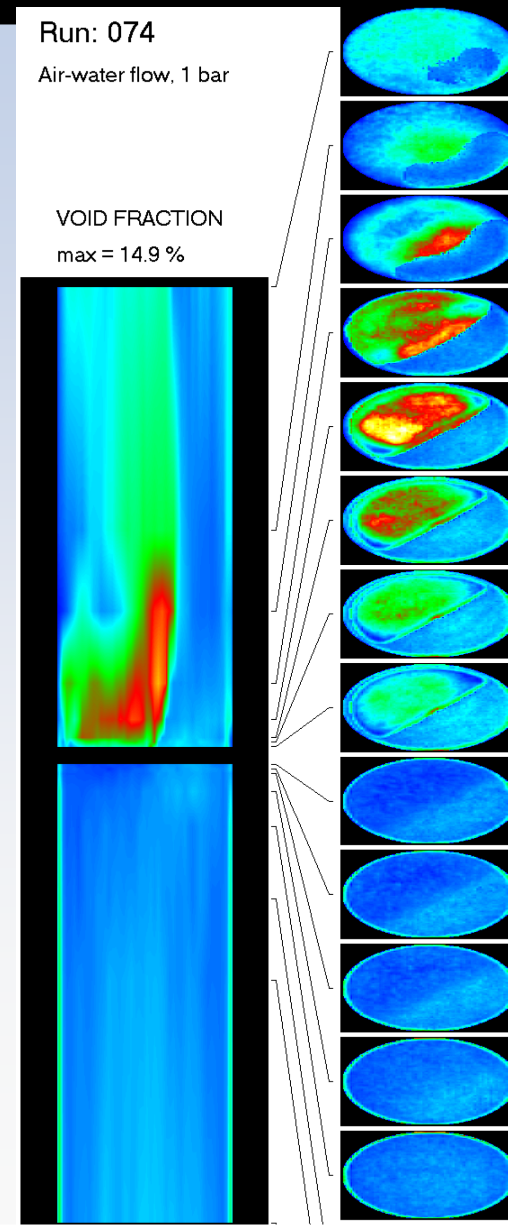


8) z=520mm

7) z=250mm

6) z=160mm

5) z=80mm



8)

7)

6)

5)

4)

3)

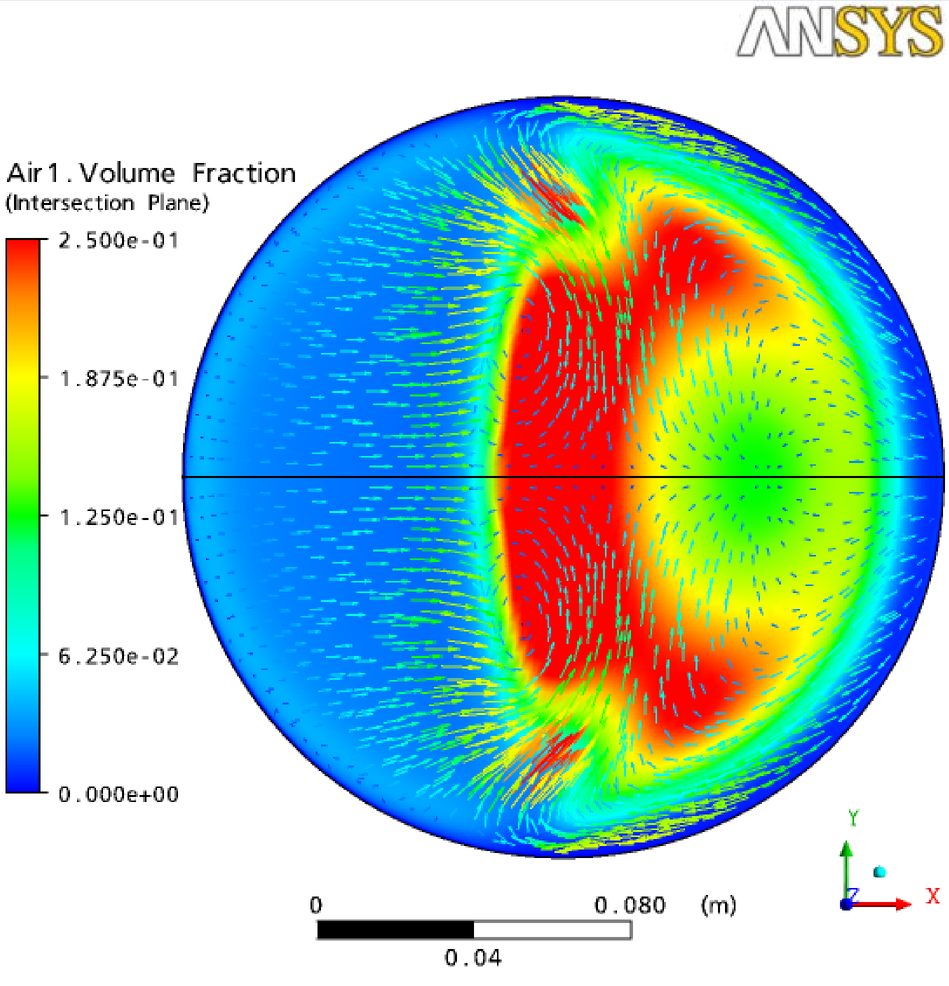
2)

1)

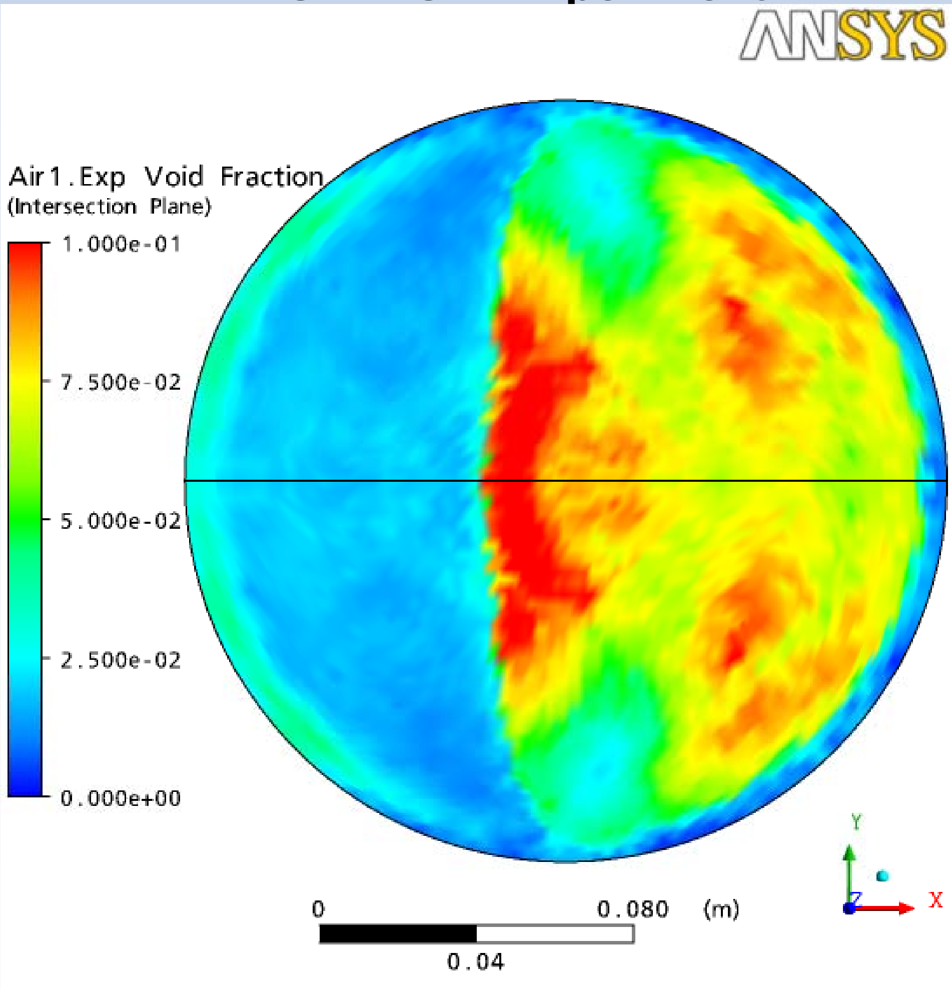
3d Bubbly Flow Around Obstacle
Cross-Sectional Air Void Fraction

5) z=80mm

CFX Simulation

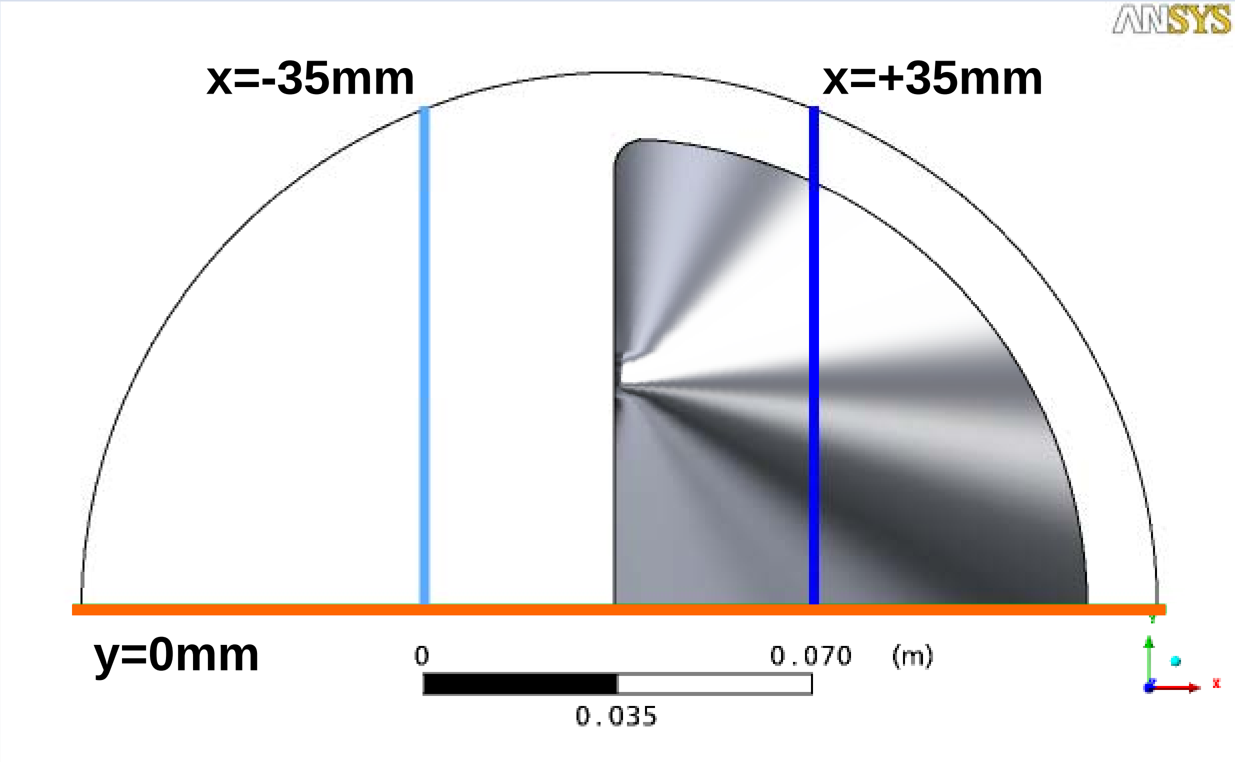


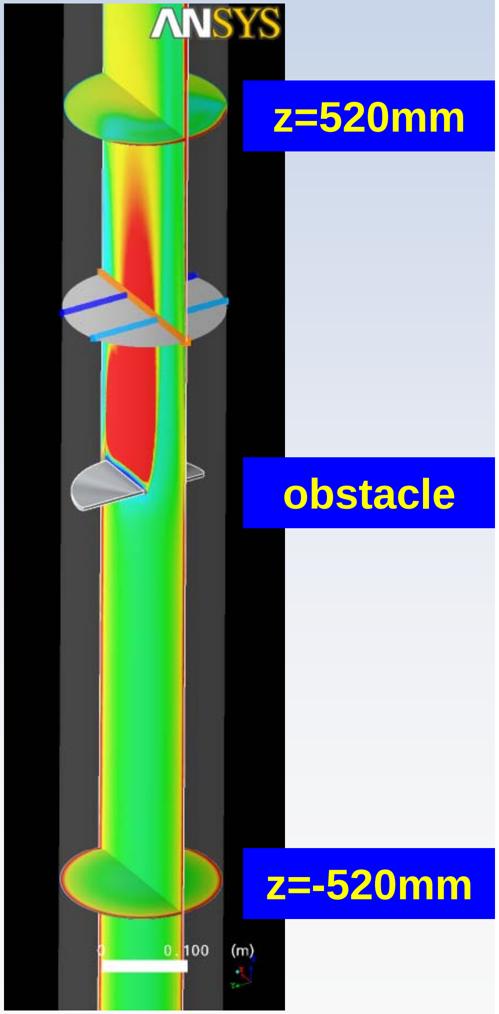
TOPFLOW Experiment



ANSYS CFX ⇔ Experimental Data Quantitative Comparison

- Quantitative data comparison @ cross sections z=±10, ±15, ±20, ±40, ±80, ±160, ±250, ±520mm:
  - absolute water velocity
  - air volume fraction

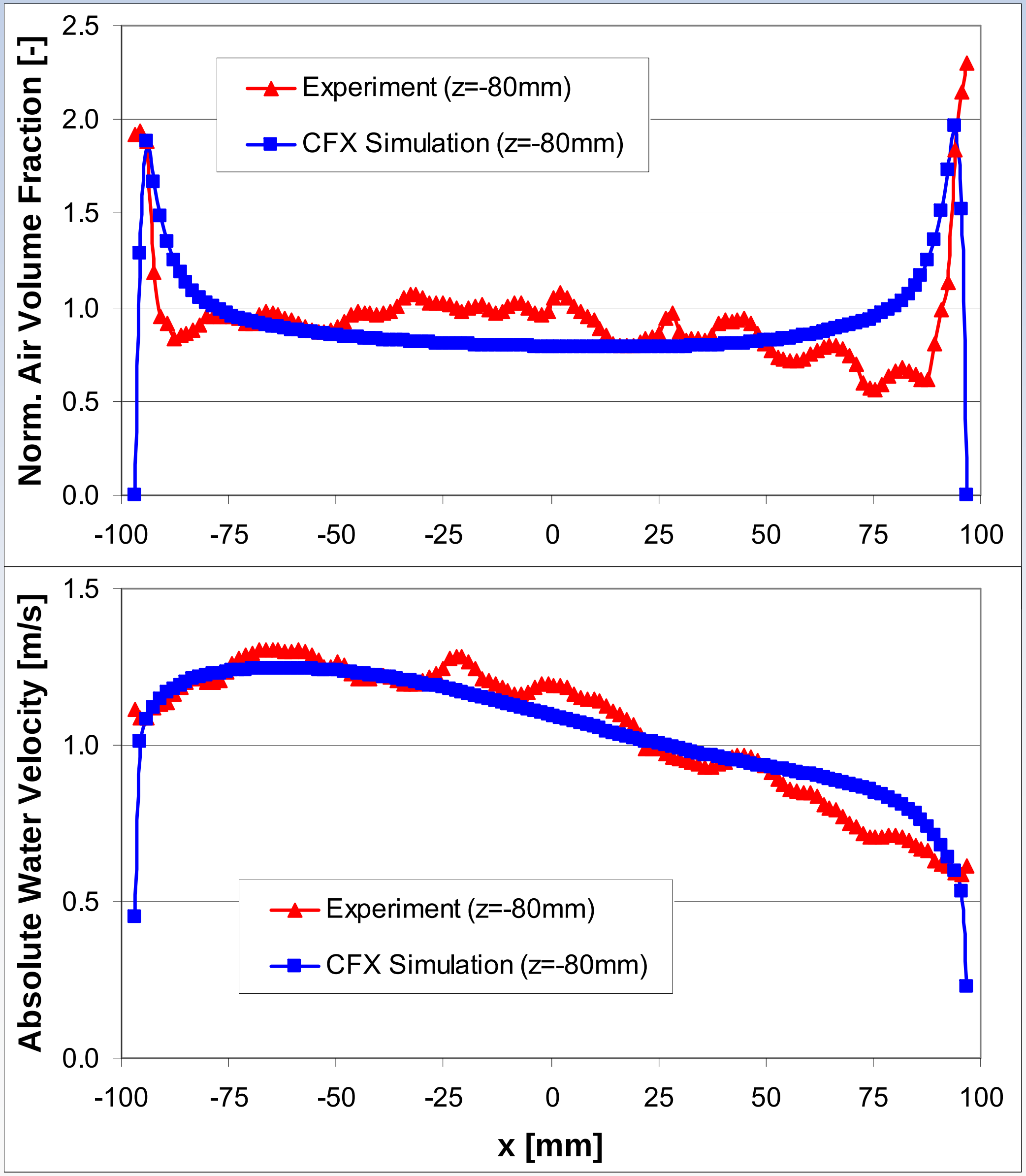


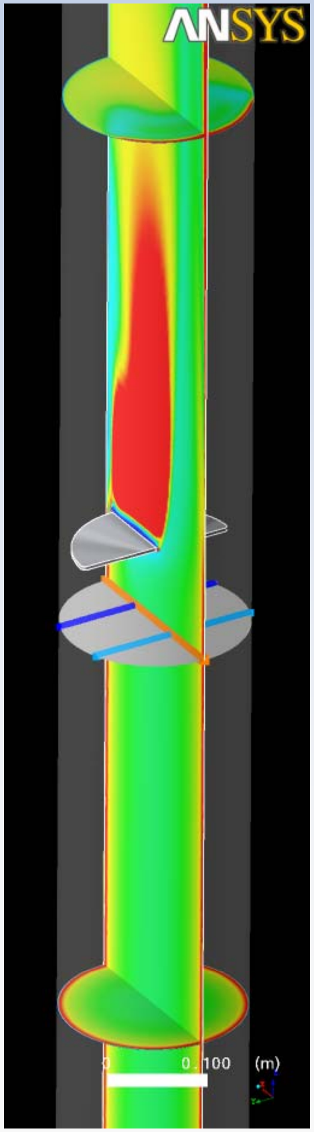


ANSYS CFX ⇔ Experimental Data Quantitative Comparison

z=-80mm

y=0mm

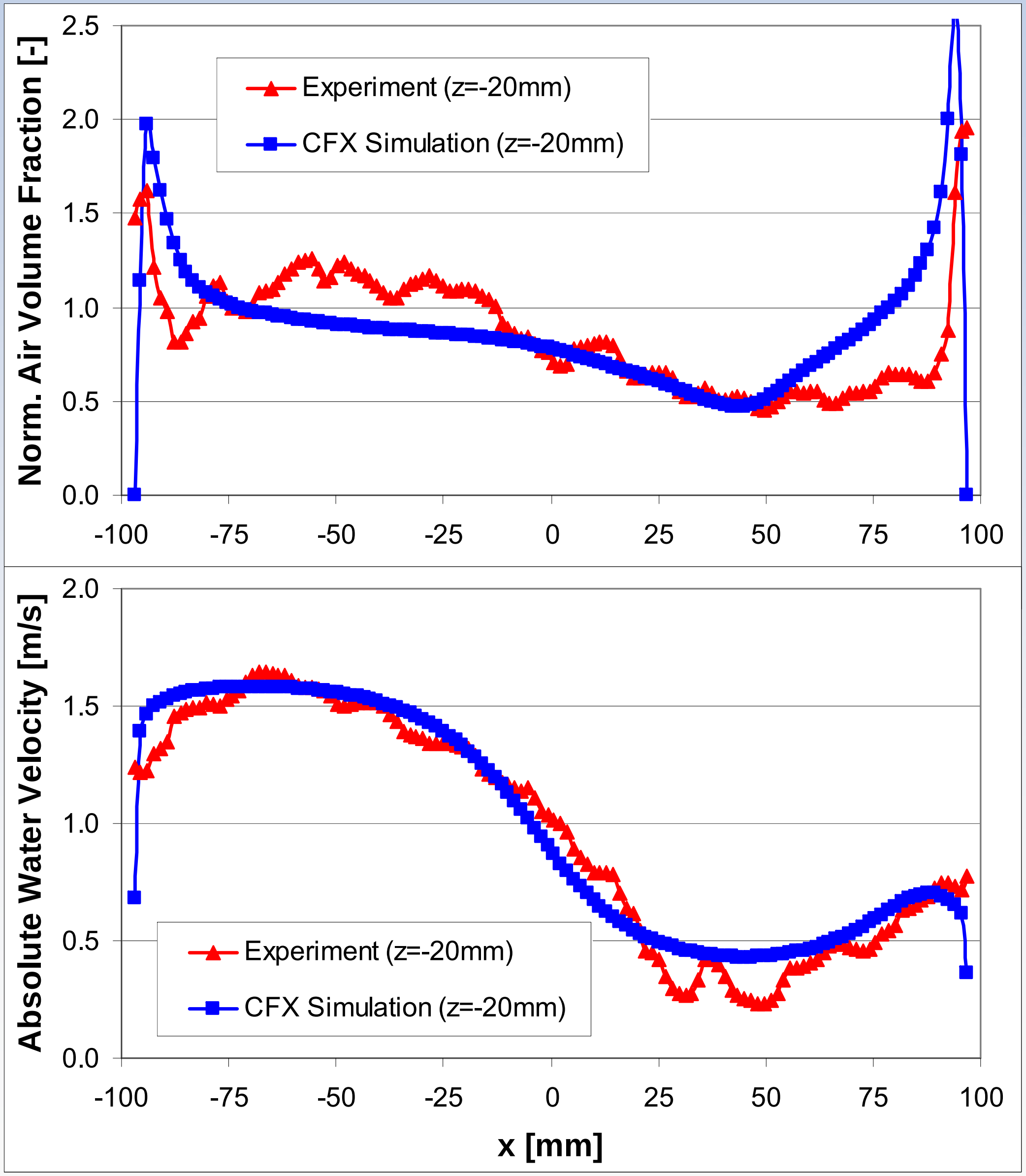


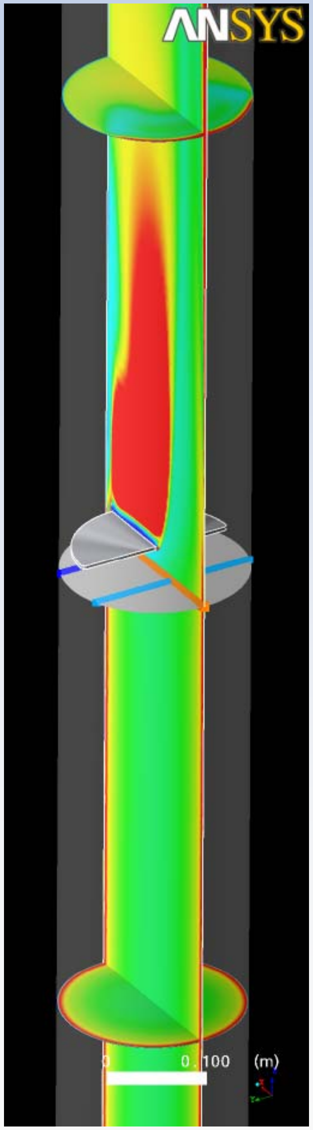


ANSYS CFX ⇔ Experimental Data
Quantitative Comparison

z=-20mm

y=0mm

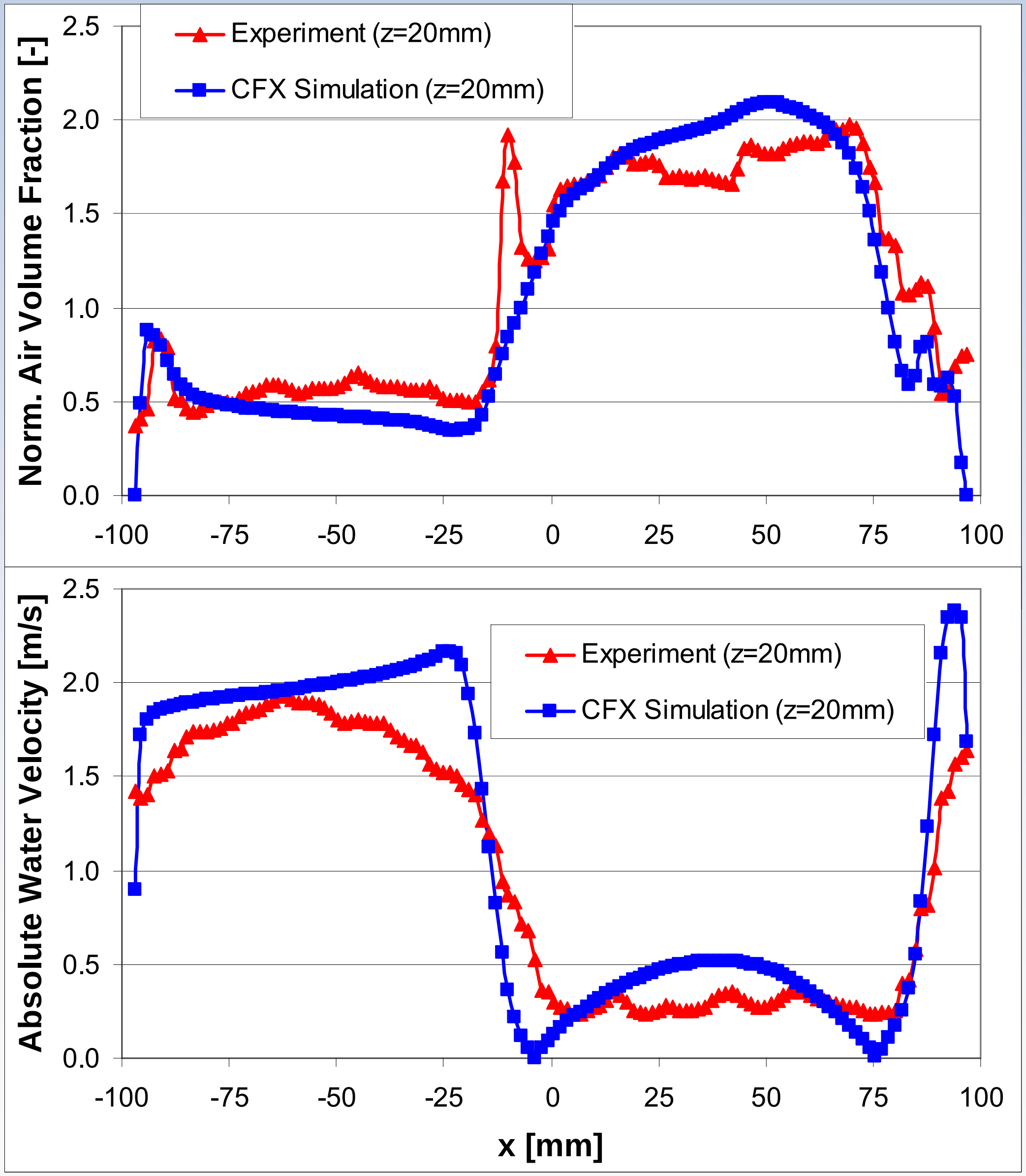


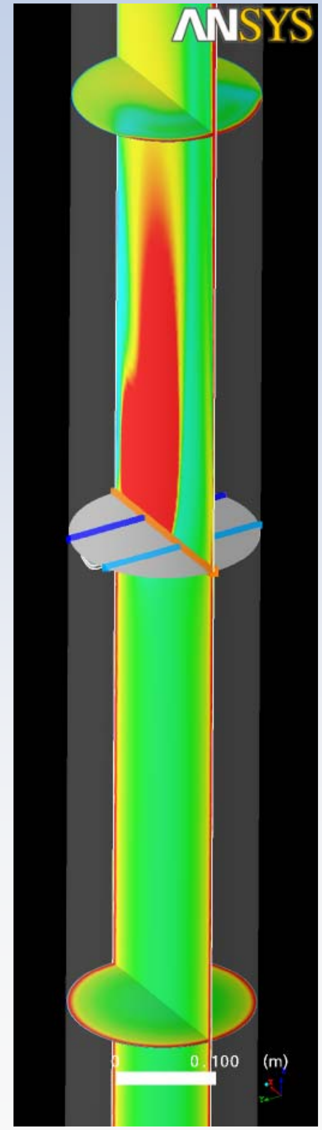


ANSYS CFX ⇔ Experimental Data Quantitative Comparison

z=20mm

y=0mm

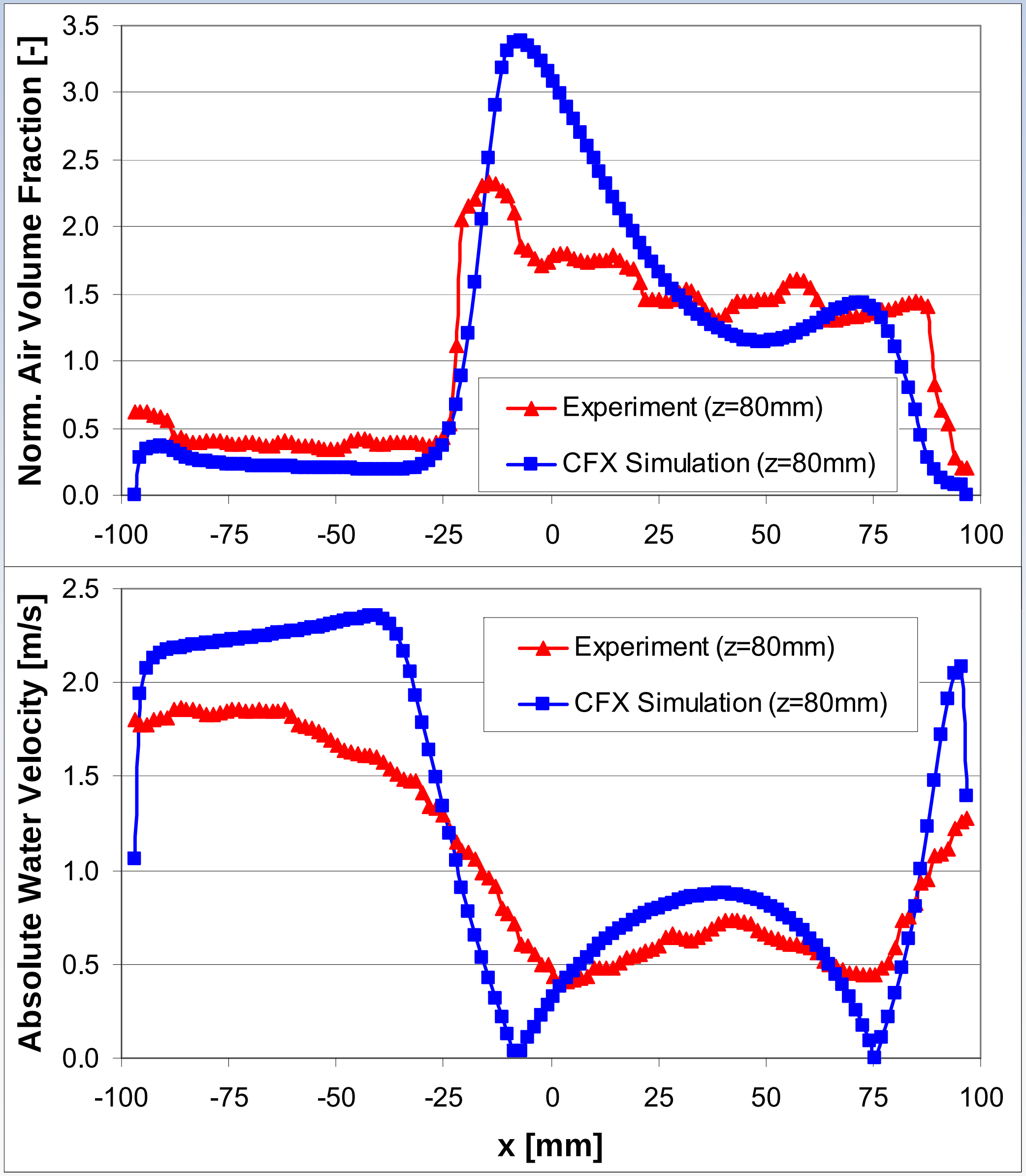


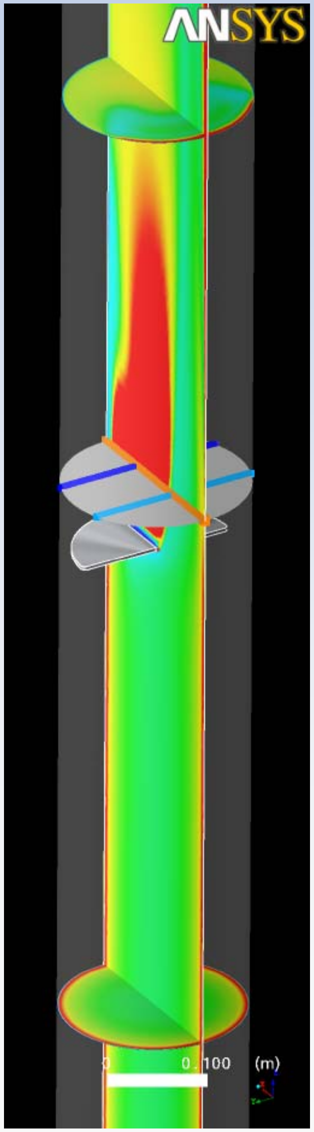


ANSYS CFX ⇔ Experimental Data Quantitative Comparison

z=80mm

y=0mm

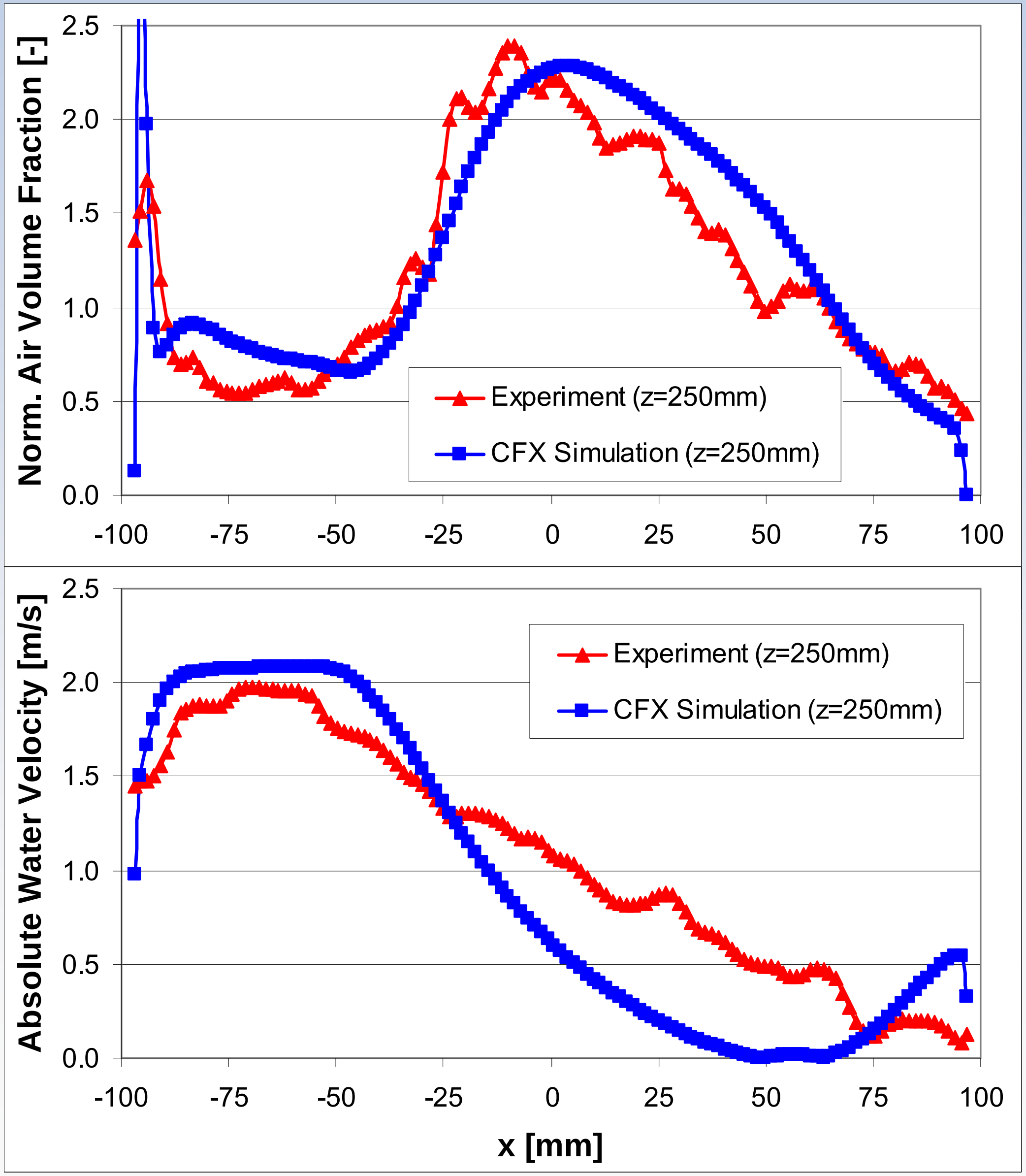


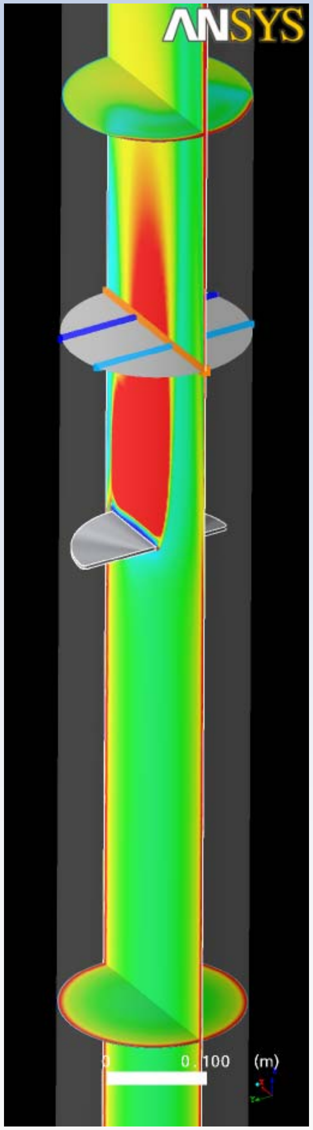


ANSYS CFX ⇔ Experimental Data Quantitative Comparison

z=250mm

y=0mm





Polydispersed Bubbly Flow Caused by Breakup & Coalescence

Transition from disperse bubbly flow to slug flow:

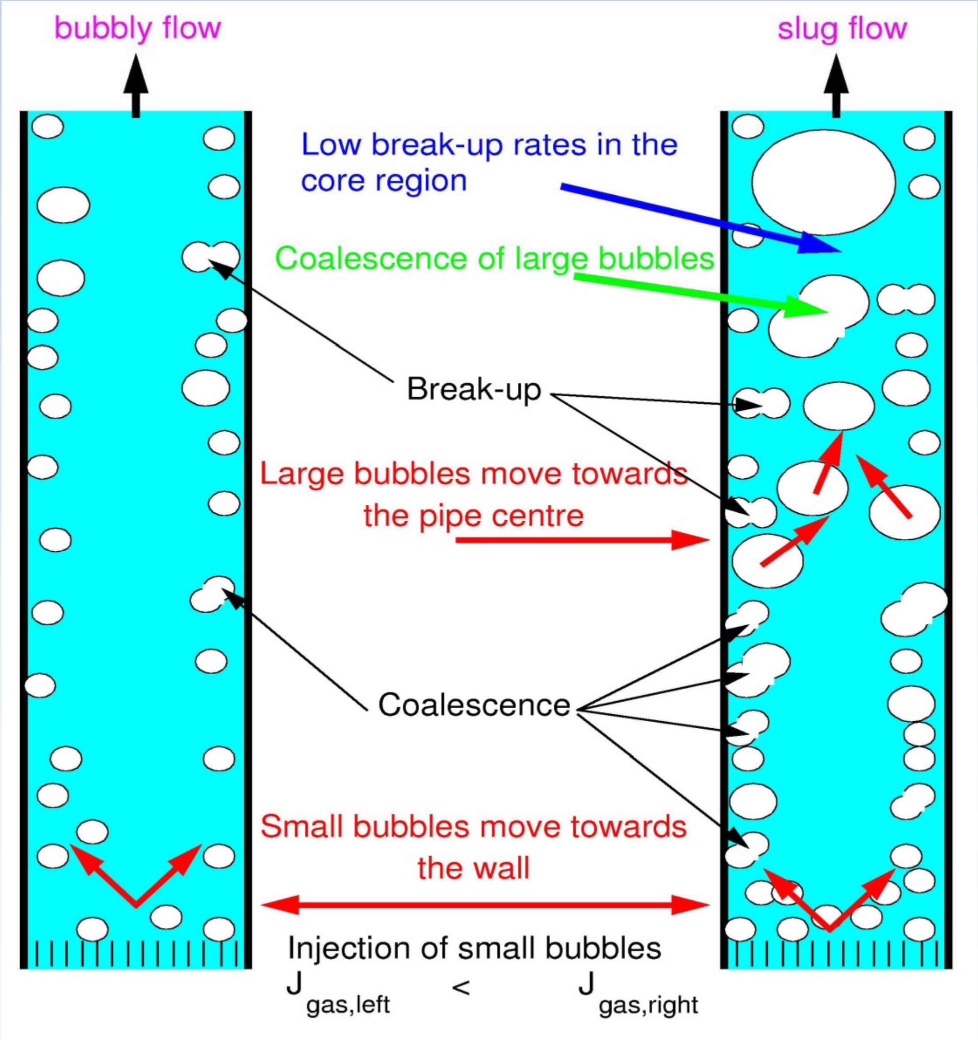
Balance between:

- coalescence of bubbles
- turbulent bubble breakup

→ bubble size distribution; polydisperse bubbly flow

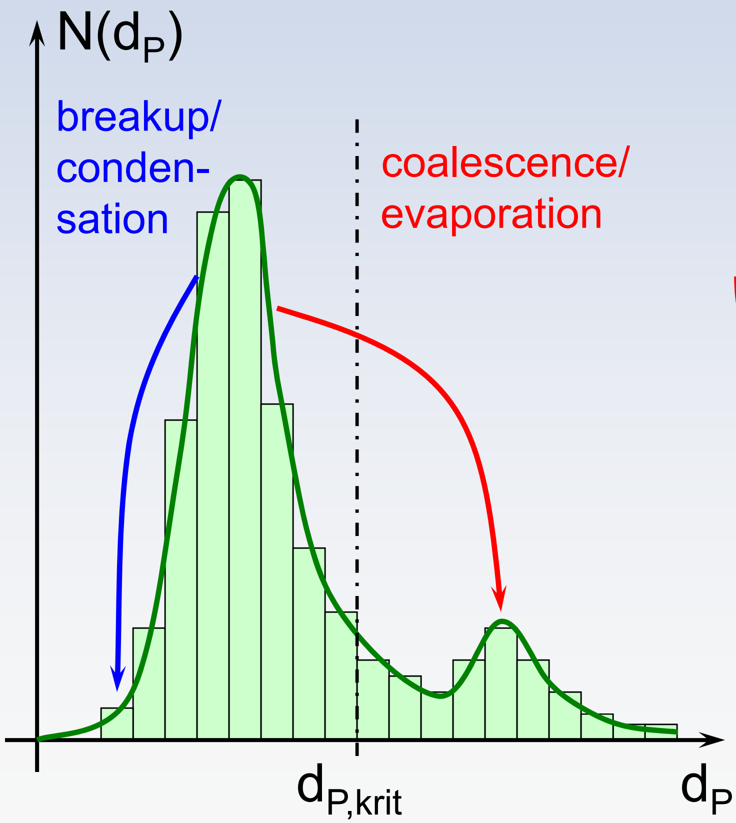
→ counter-current radial motion of small and large bubbles; more than one velocity field

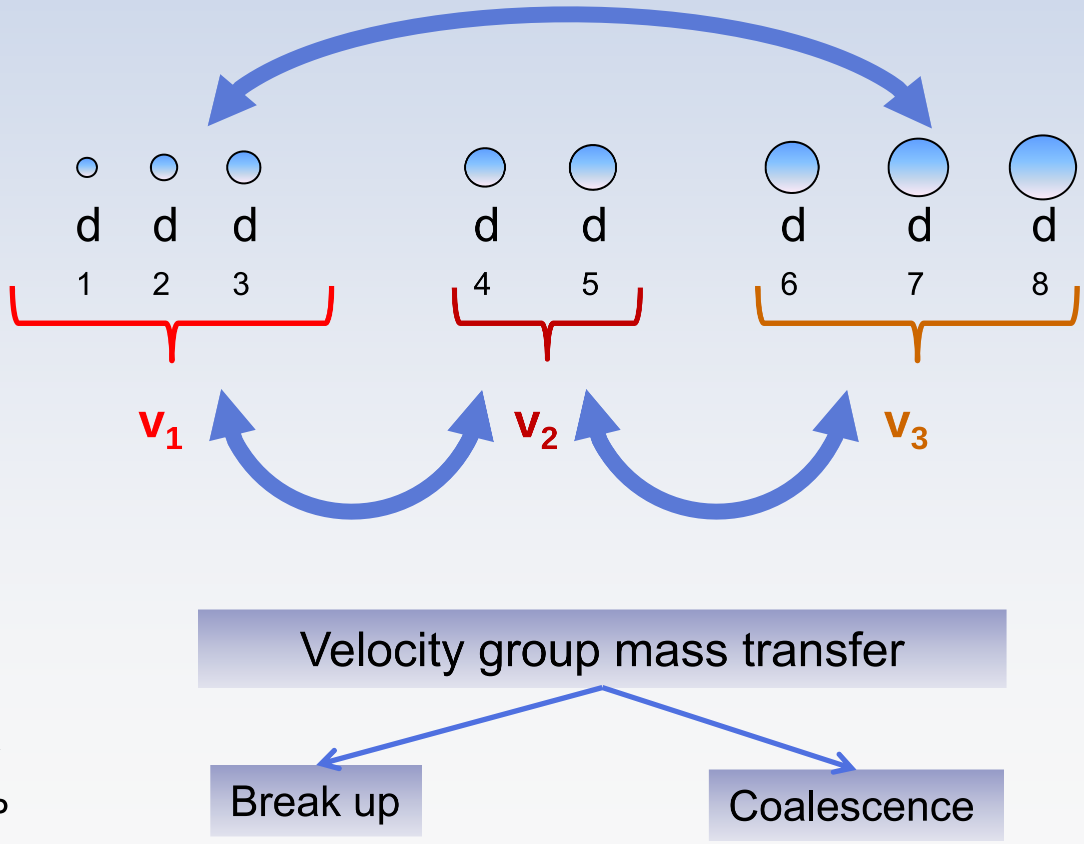
→ new population balance model (inhomogeneous MUSIG)



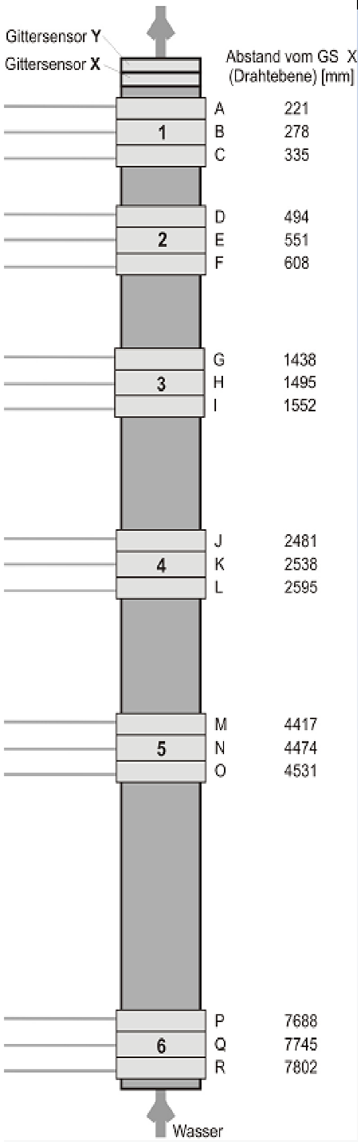
Inhomogeneous MUSIG Model

- momentum equations are solved for N gas phases (vel. groups)
- size fraction equations for M_i bubble size classes in each vel. group
- bubble coalescence and break-up over all ΣM_i MUSIG groups

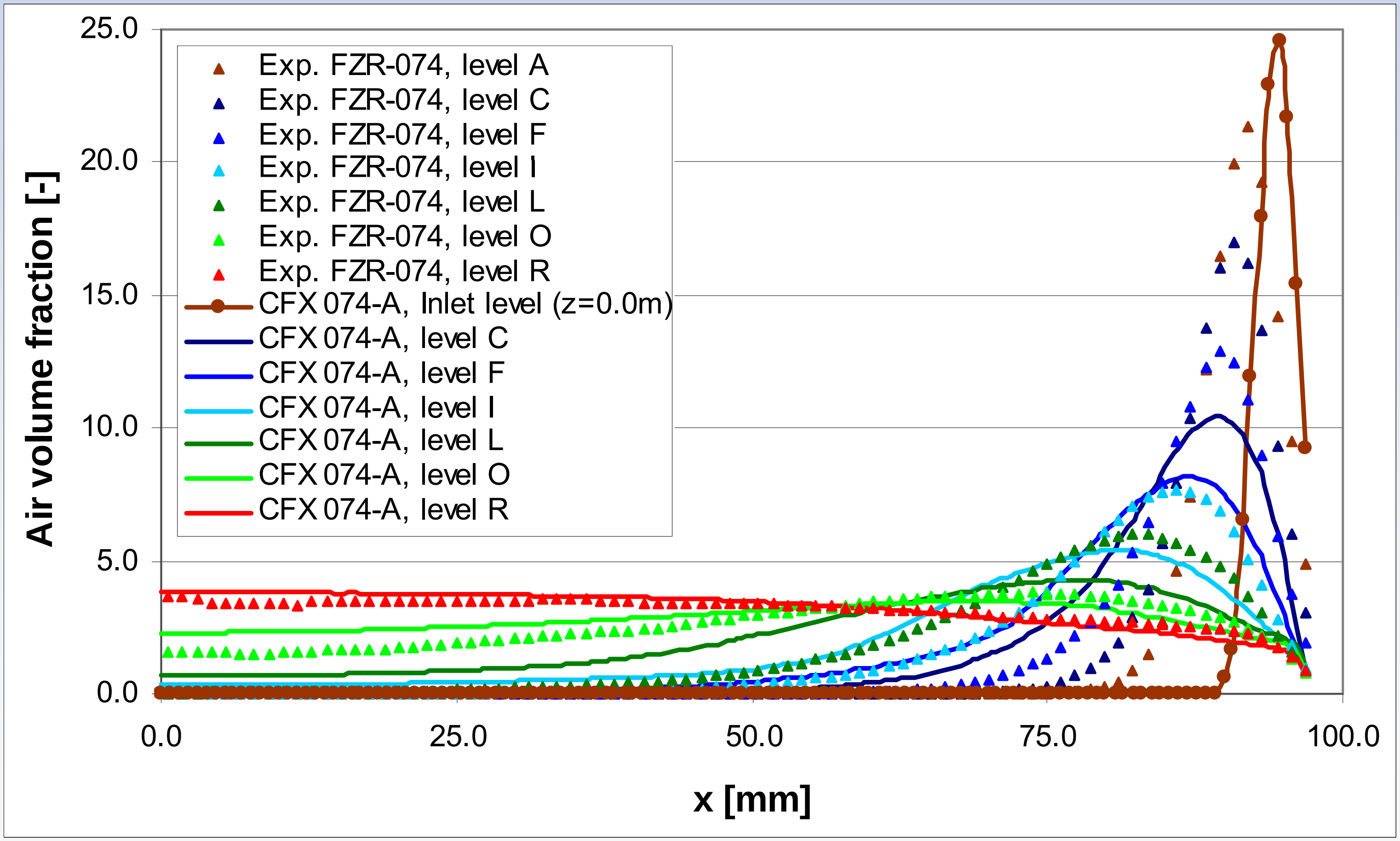




Validation of 3x7 Inhomogeneous MUSIG Model on TOPFLOW-074



- good agreement at levels A, L through R
- too fast spreading of the bubble plume from inlet due to too intensive turbulent dispersion



MUSIG Model Extension

New terms

- Basic population balance equations

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

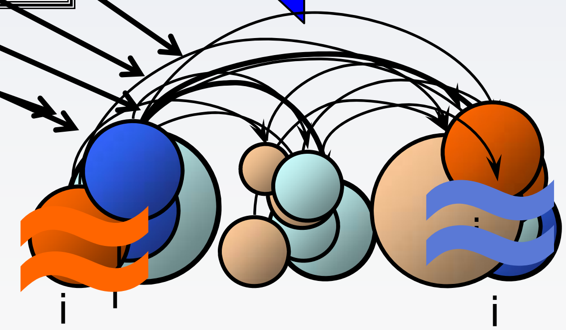
Bubble number density

Breakup/Coalescence terms

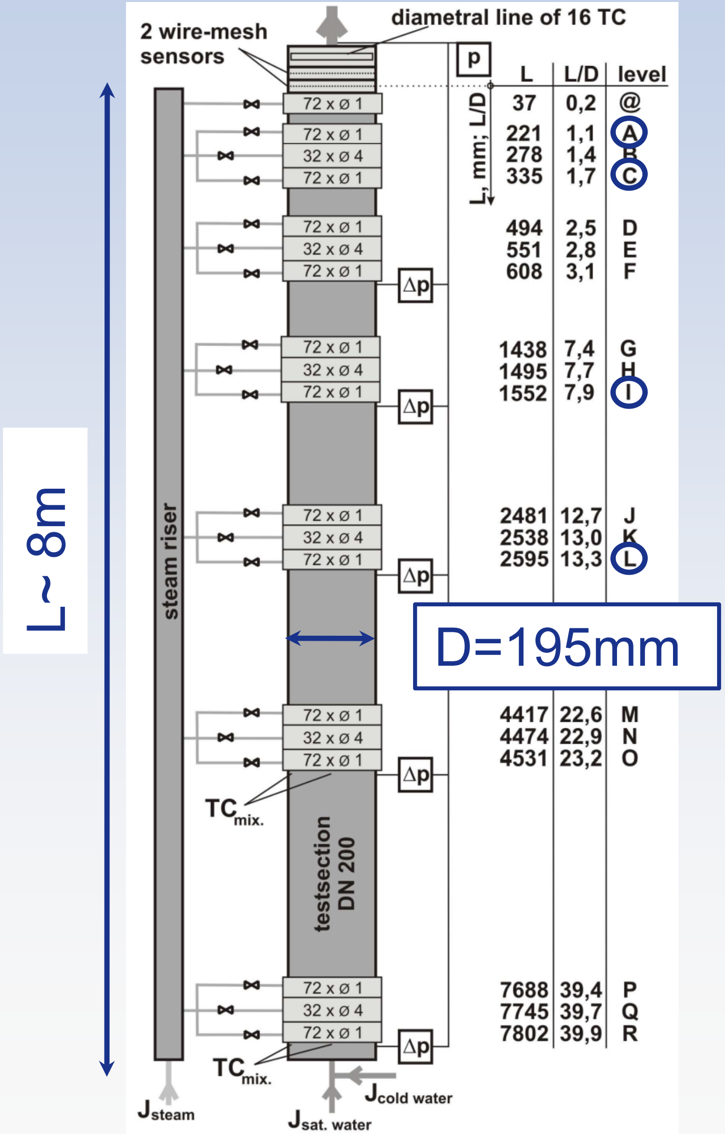
- Size fraction equations

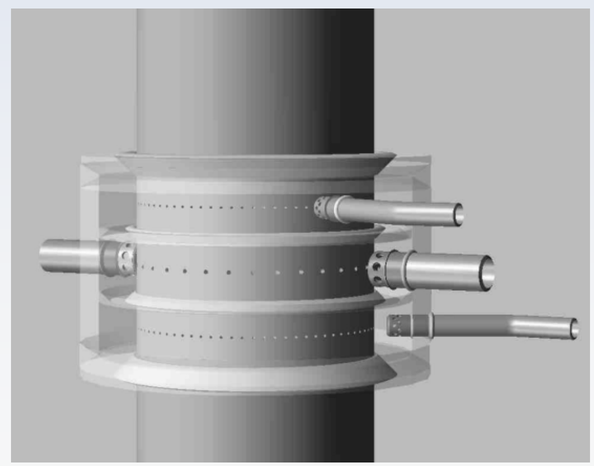
$$\boxed{\frac{\partial}{\partial t}(\rho_i r_d f_i) + \frac{\partial}{\partial x^j}(\rho_i r_d U_i^j f_i) = S_{B_B} - S_{D_B} + S_{B_C} - S_{D_C} + S_i}$$

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



TOPFLOW Test Facility @ FZD

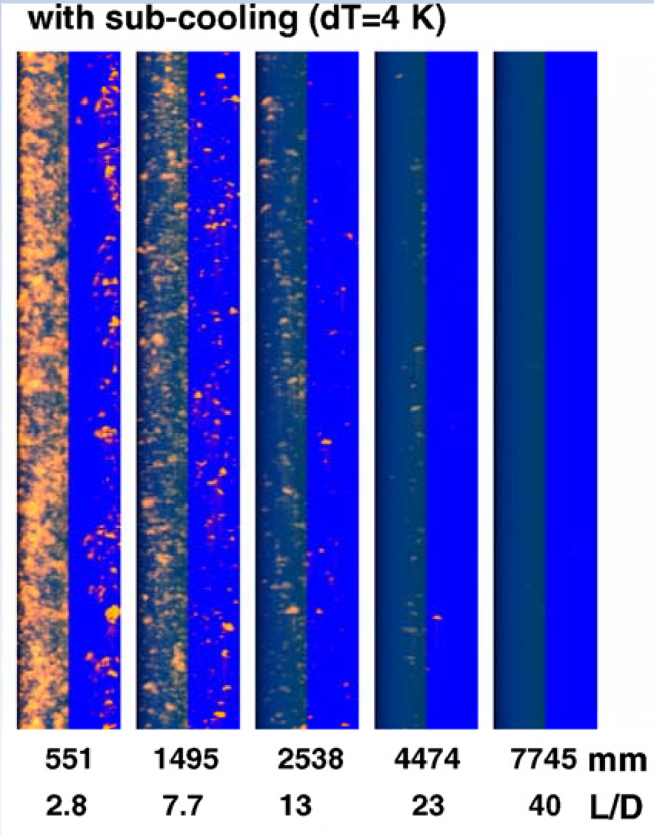




Courtesy of FZD

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

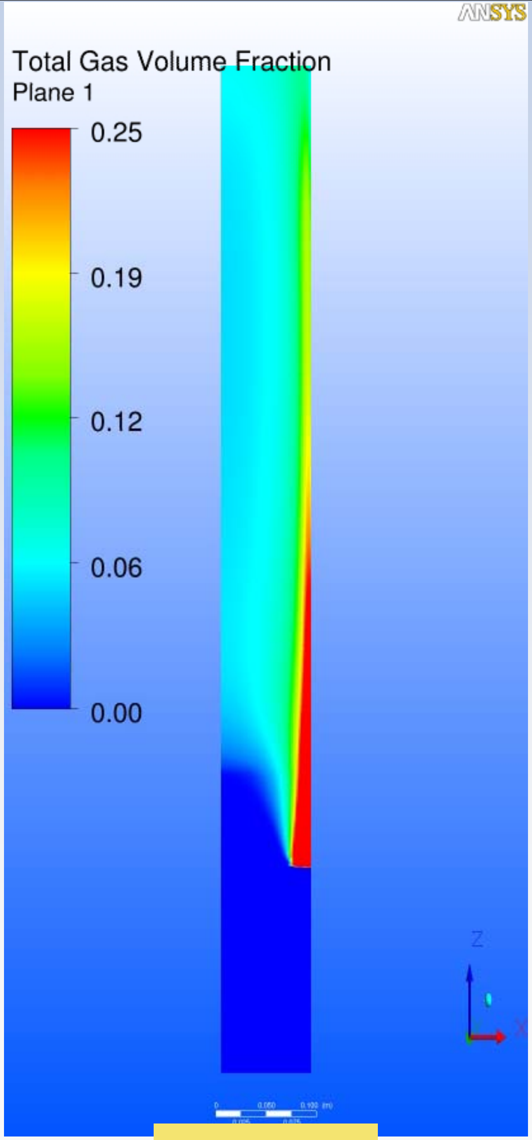
Physical Model Setup

- Standard MUSIG & Extended MUSIG
  - 25 bubble size classes
  - 3 velocity groups:
    0→3 [mm],3→6 [mm], 6→30 [mm]
  - Arranged in accordance with critical Tomiyama bubble diameter for bubble size dependent lift force
  - Break up model: Luo & Svendsen (F_B=0.025)
  - Coalescence model: Prince & Blanch (F_C=0.05)

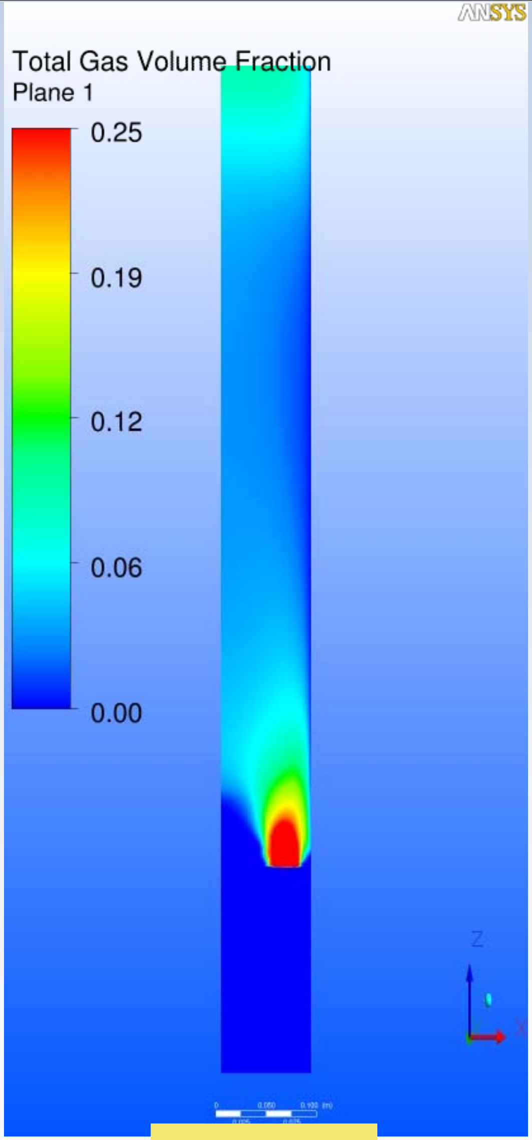
TOPFLOW Condensation Testcase

	Inlet BC	Inlet Position	WLF	TD Force	Heat Transfer
Config 1	D_{inj} = 4mm	Source point @ Wall	-	CTD=1.0	$Nu=2+0.6Re_p^{0.5}Pr^{0.3}$
Config 2	D_{inj}= 4 mm	Source point @ 75 mm	F_{WLF}	CTD=1.5	$Nu=2+0.15Re_p^{0.8}Pr^{0.5}$
Config 3	D_{inj}= 1 mm	Source point @ 75 mm	F_{WLF}	CTD=1.5	$Nu=2+0.15Re_p^{0.8}Pr^{0.5}$

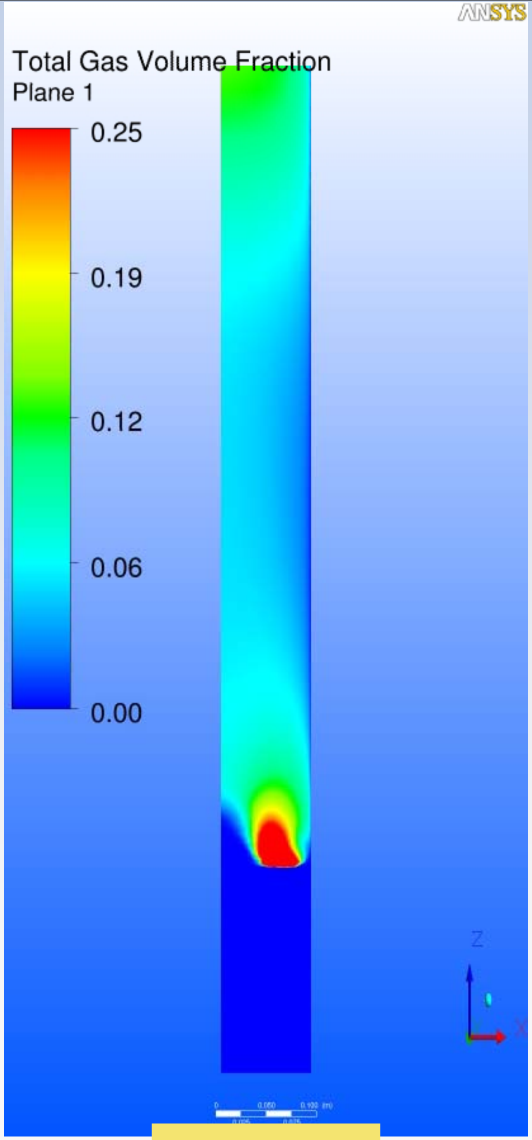
Results: Vapor Volume Fraction



Config 1

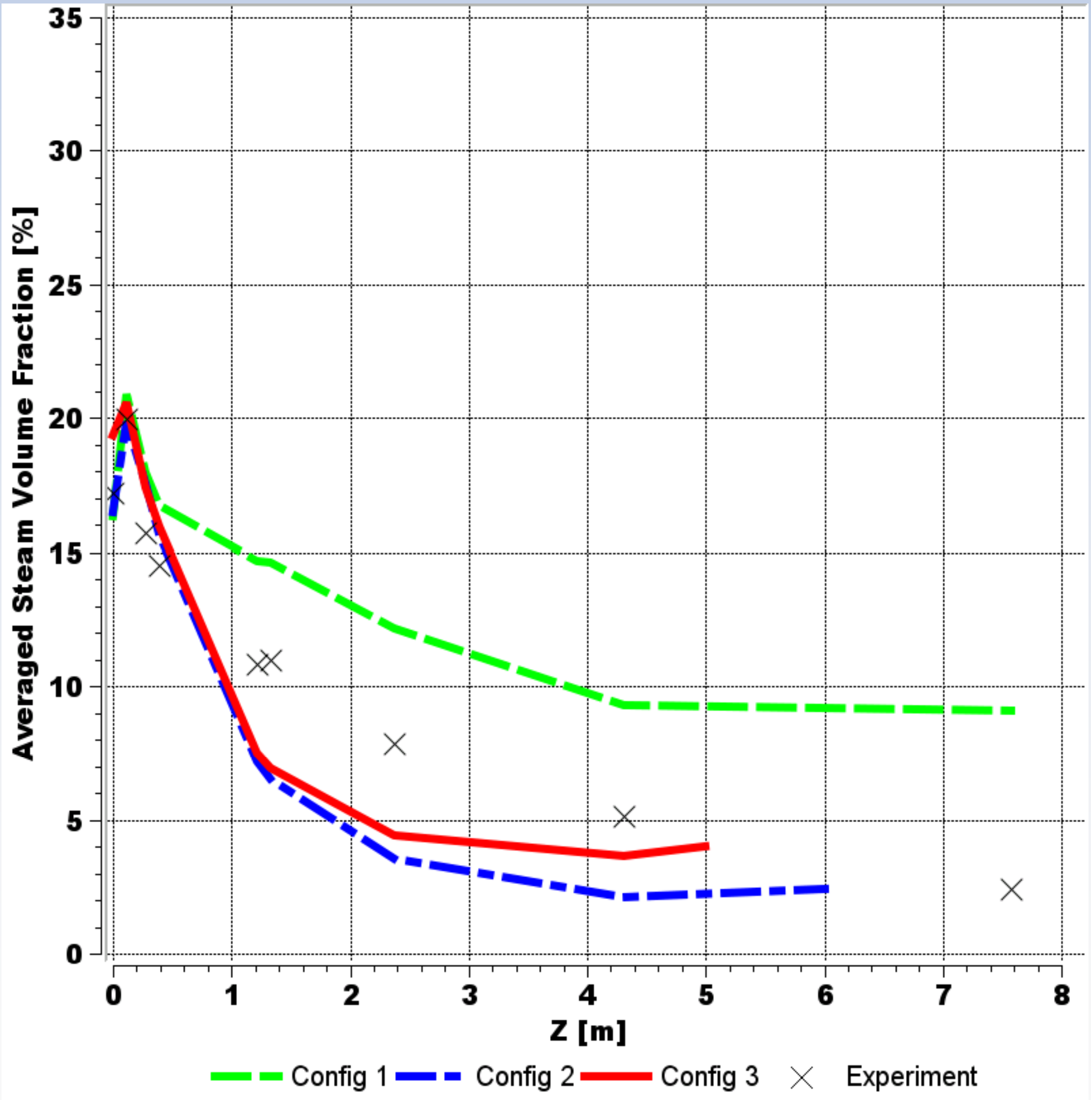


Config 2

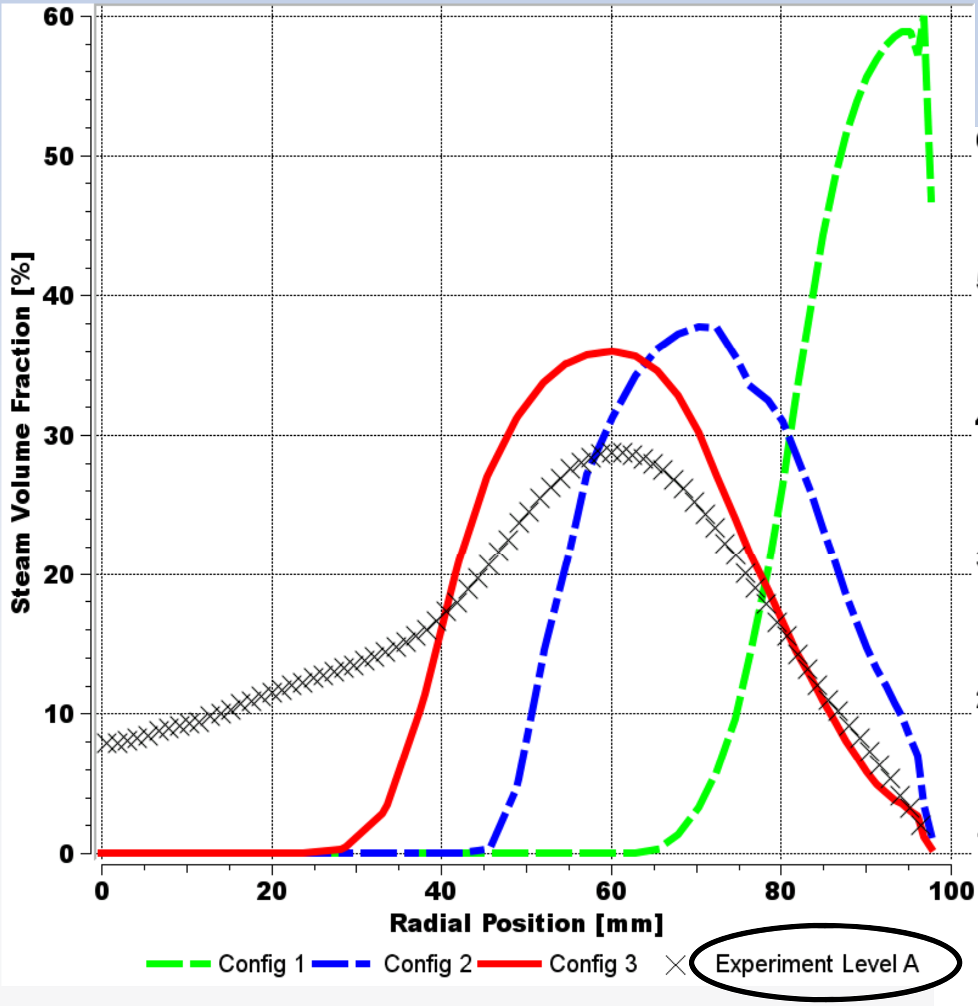


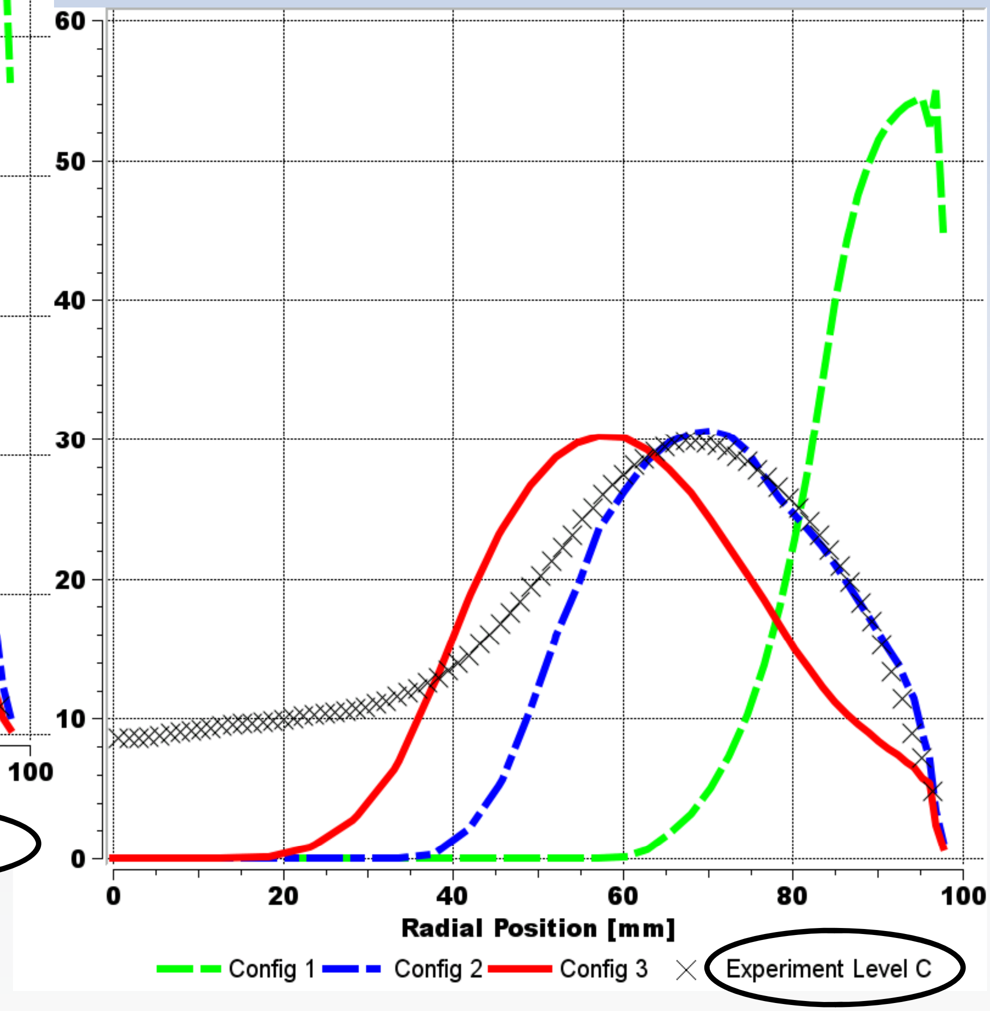
Config 3

Results: Vertical Averaged Steam Distribution

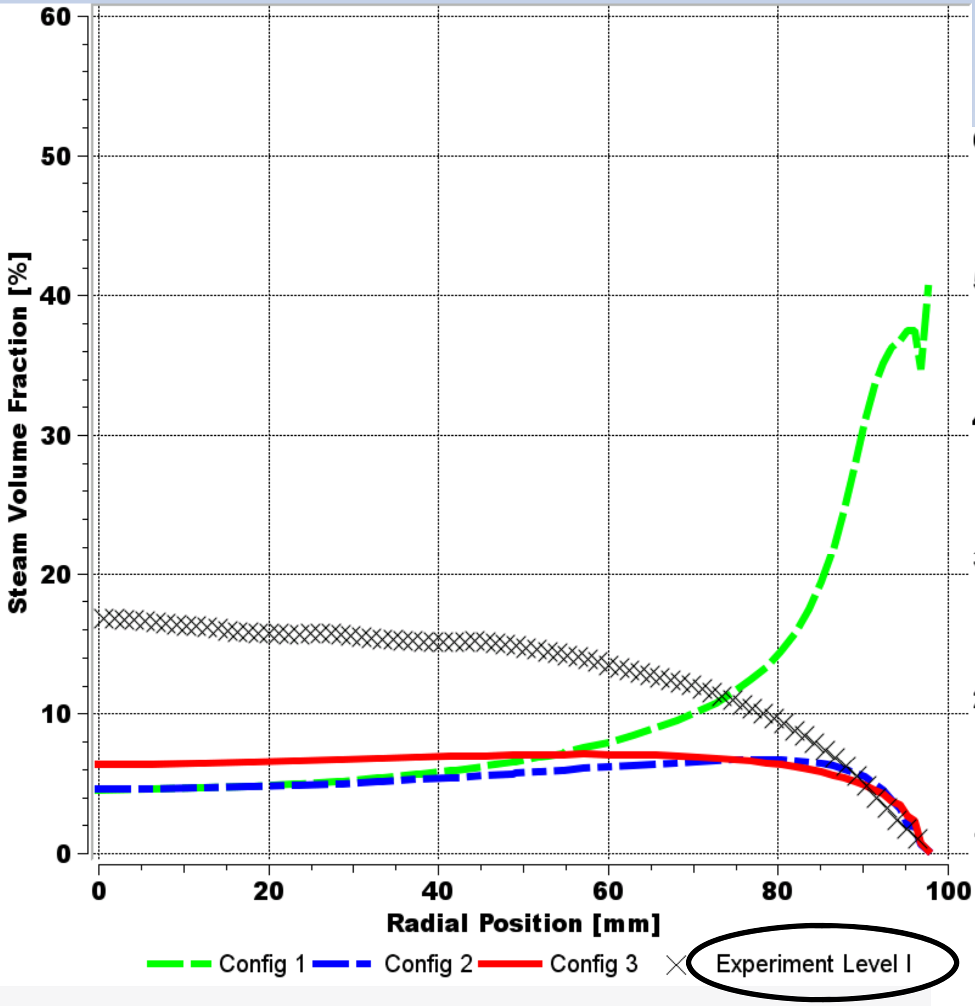


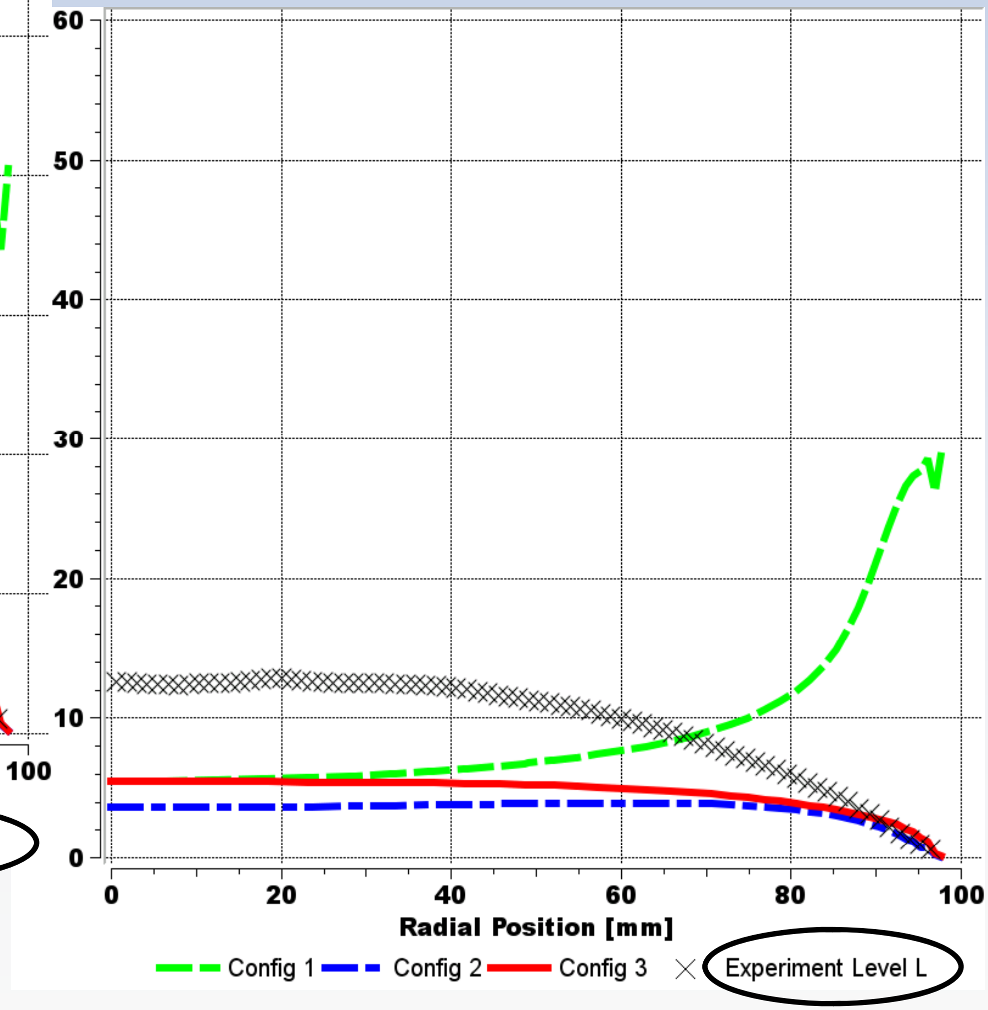
Results: Radial Steam Distribution



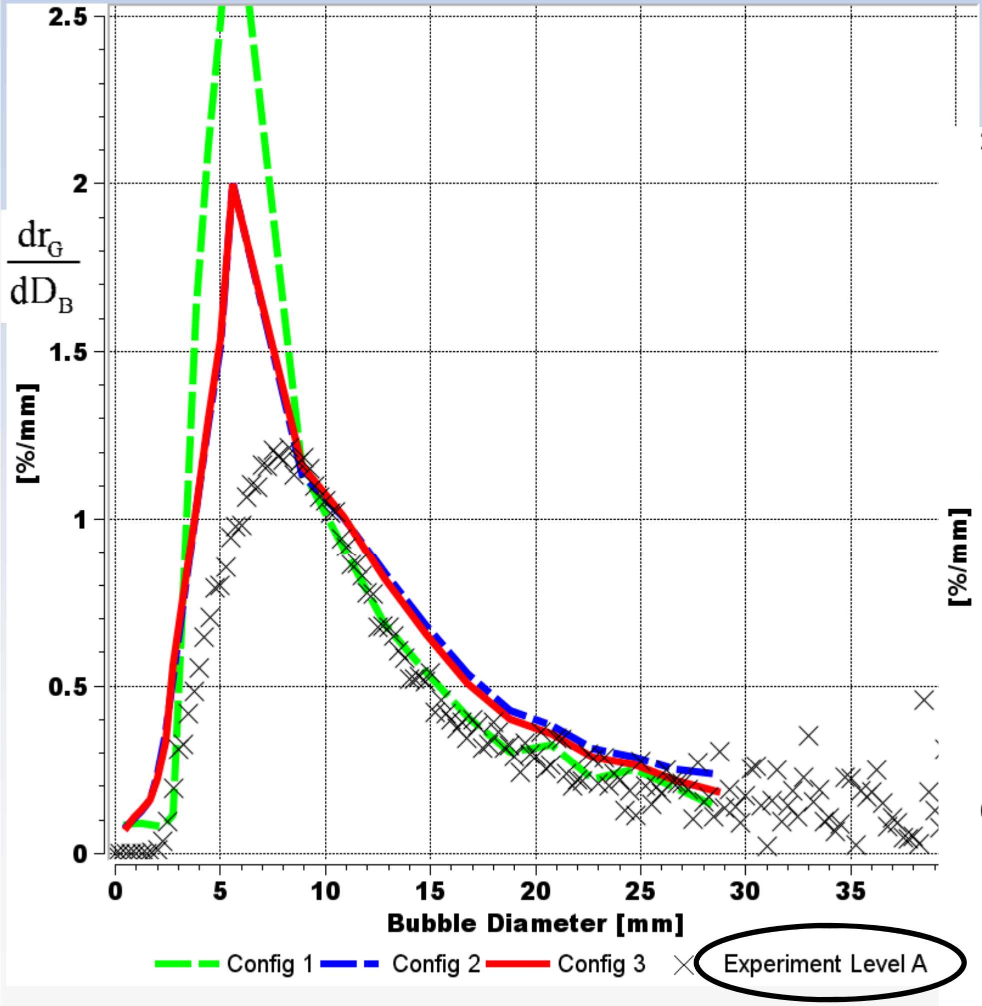


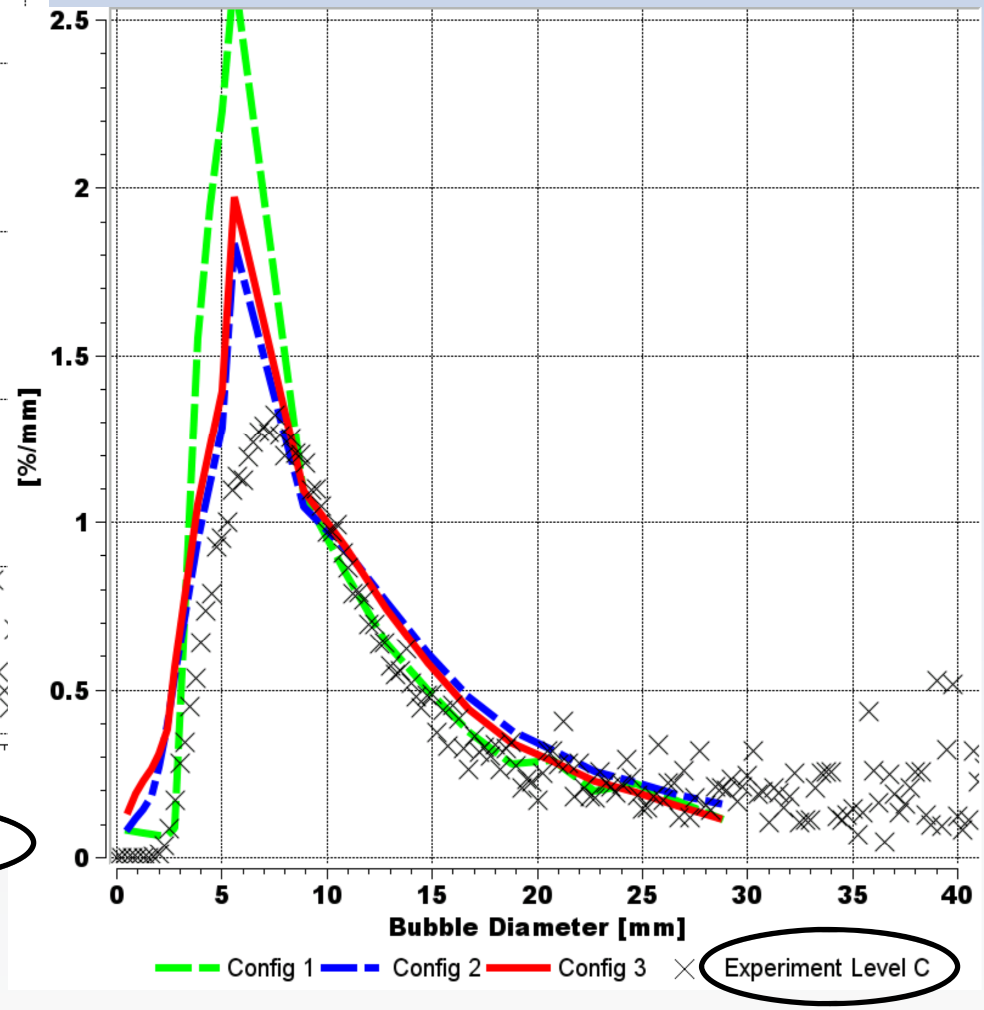
Results: Radial Steam Distribution



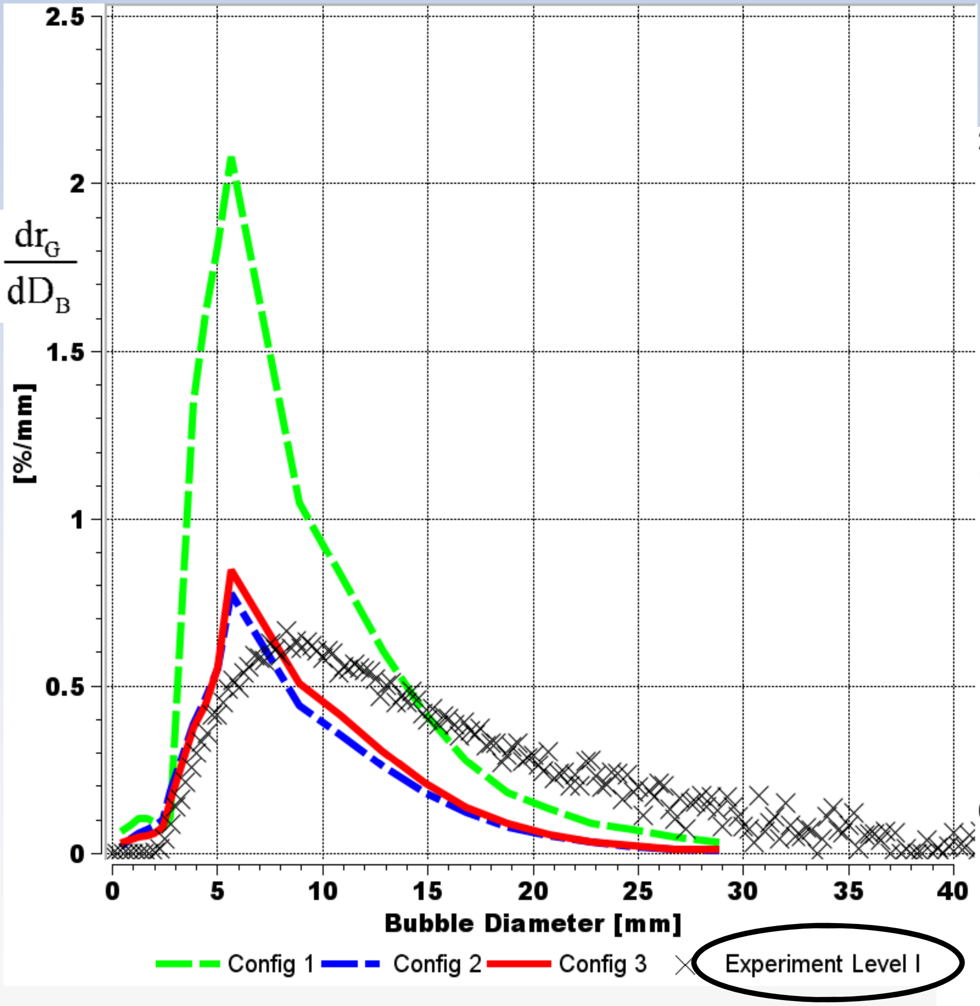


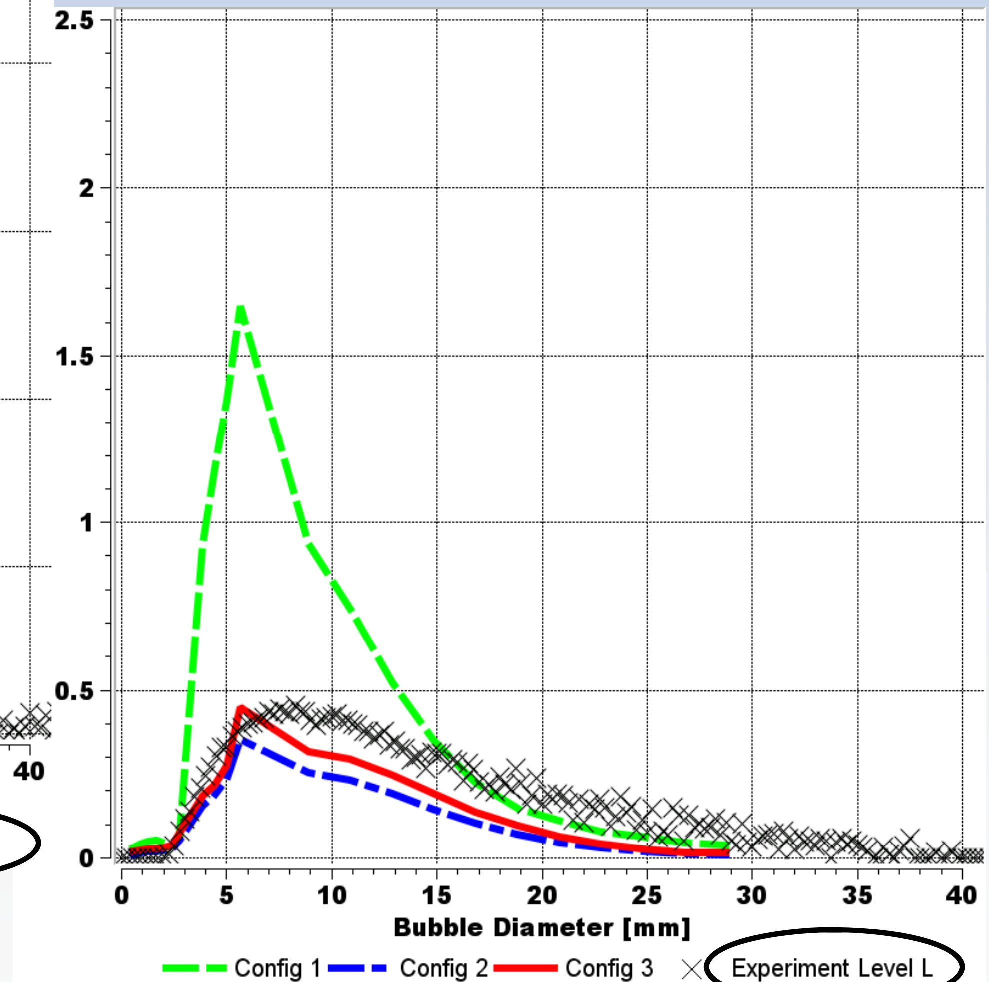
Results: Bubble Size Distribution





Results: Bubble Size Distribution



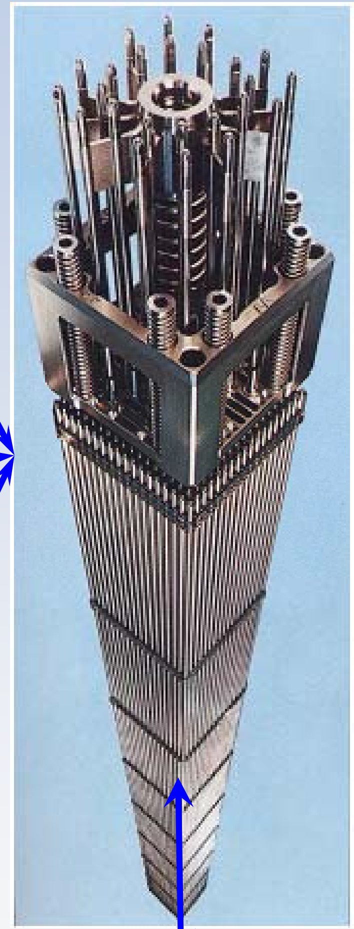


CFD Simulation for Fuel Assemblies in Nuclear Reactors

Material Properties

Turbulence

Multiphase Flow Modeling



Wall Boiling & Bulk Condensation

Conjugate Heat Transfer (CHT)

FSI: Stresses & Deformations

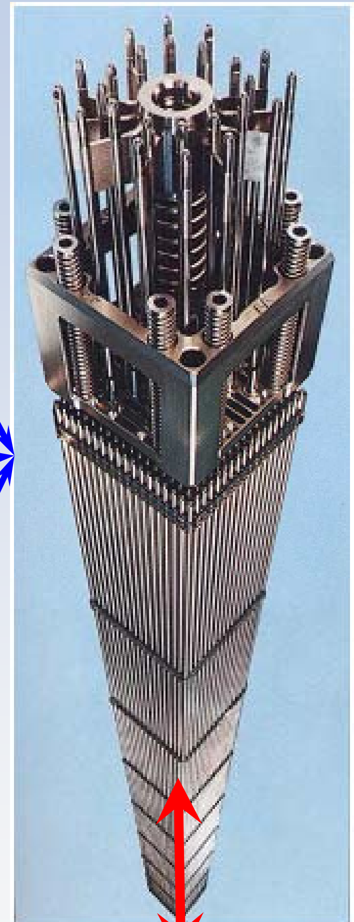
Validation against Experiments

CFD Simulation for Fuel Assemblies in Nuclear Reactors

Material Properties

Turbulence

Multiphase Flow Modeling



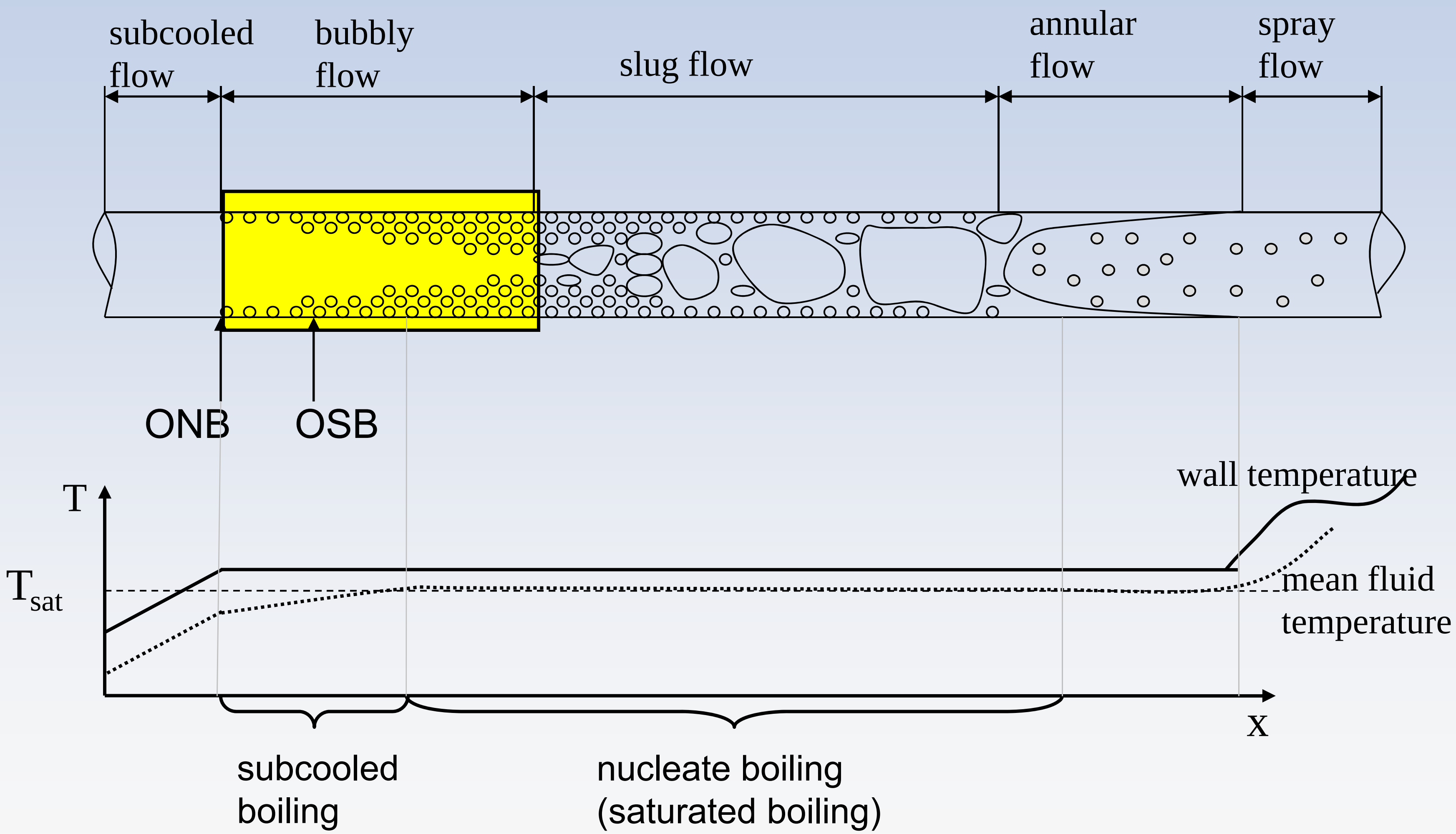
Wall Boiling & Bulk Condensation

Conjugate Heat Transfer (CHT)

FSI: Stresses & Deformations

Validation against Experiments

Multiphase Flow Regimes for Boiling Water Flow



Flows with Subcooled Boiling (DNB) – RPI-Wall Boiling Model

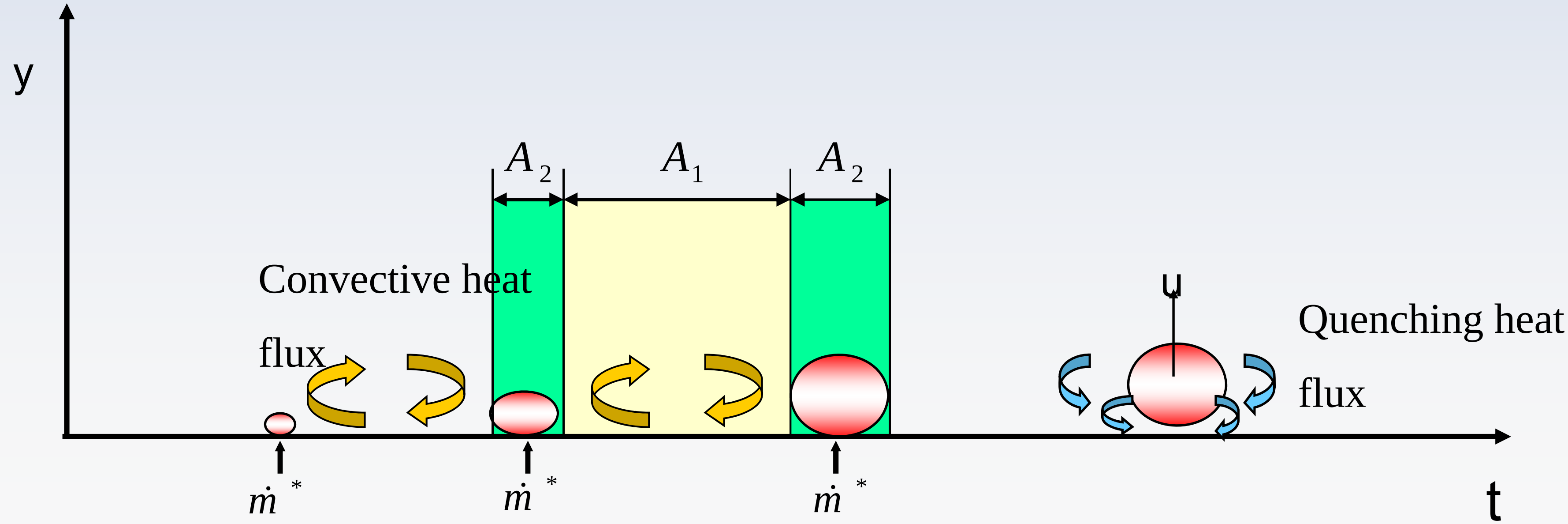
Mechanistic wall heat partioning model:

$$\dot{q}_{Wall} = \dot{q}_F + \dot{q}_Q + \dot{q}_E$$

convective heat flux
$$\dot{q}_F = A_1 \cdot h_F \cdot (T_W - T_L)$$

quenching heat flux
$$\dot{q}_Q = A_2 \cdot h_Q \cdot (T_W - T_L)$$

evaporation heat flux
$$\dot{q}_E = \dot{m} \cdot (h_G - h_L)$$



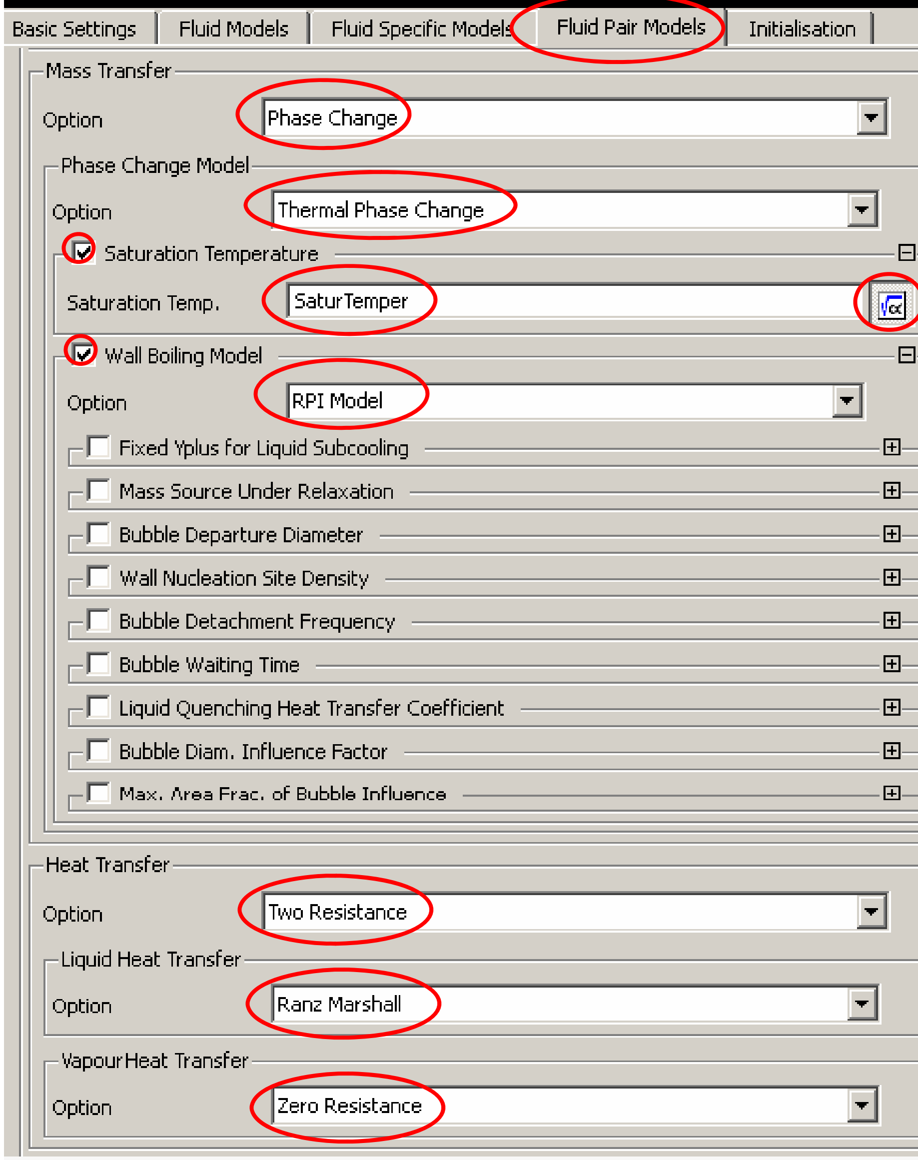
RPI-Wall Boiling Model – Submodels for Model Closure

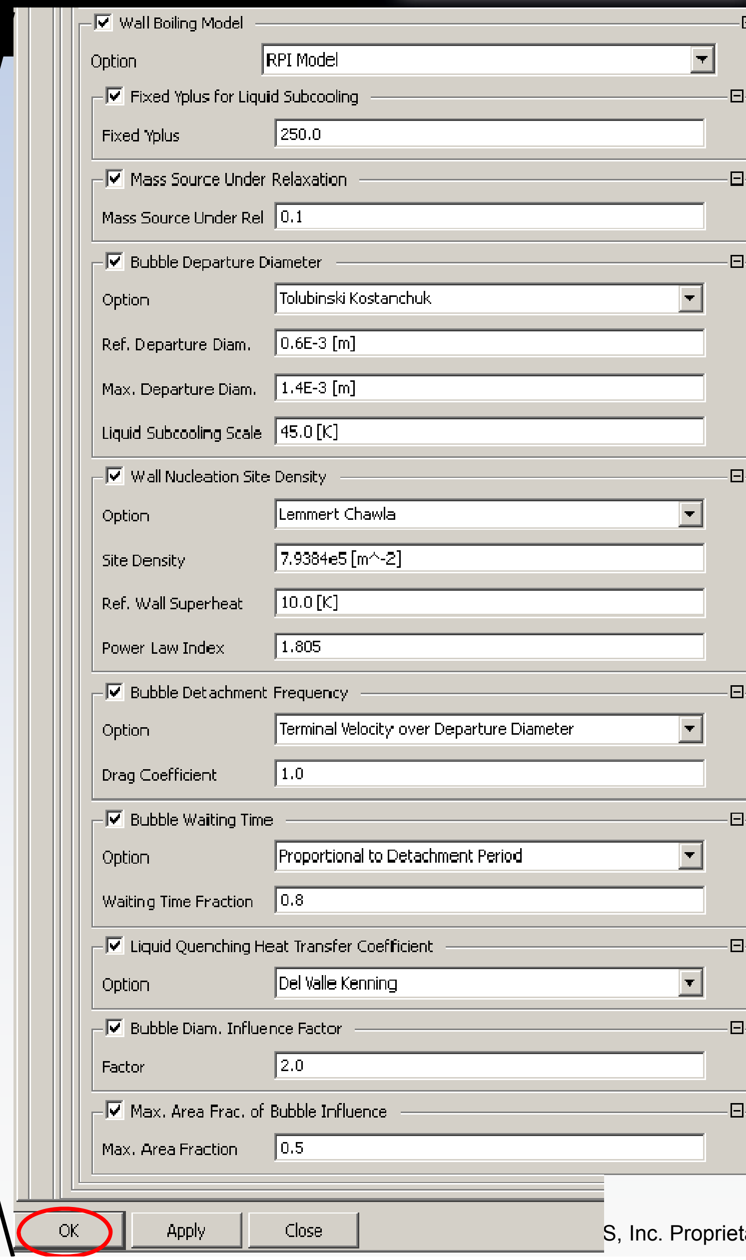
Submodels for closure of RPI wall boiling model:

- Nucleation site density: Lemmert & Chawla , User Defined
- Bubble departure diameter:
  Tolubinski & Kostanchuk, Unal, Fritz, User Defined
- Bubble detachment frequency:
  Terminal rise velocity over Departure Diameter, User Defined
- Bubble waiting time:
  Proportional to Detachment Period, User Defined
- Quenching heat transfer: Del Valle & Kenning, User Defined
- Turbulent Wall Function for liquid convective heat transfer coefficient

- Correlation for bulk flow mean bubble diameter required:
  → e.g. Kurul & Podowski correlation via CCL
- Supported combination of wall boiling & CHT in the solid
  - GGI & 1:1 solid-fluid interfaces

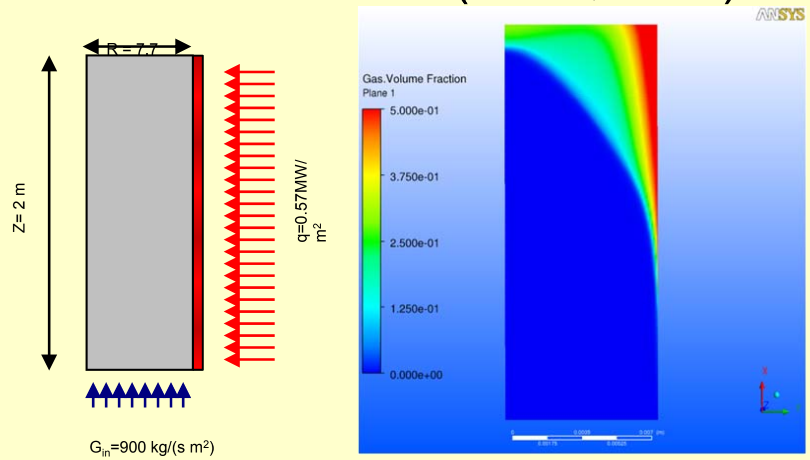
RPI Wall Boiling Model in the ANSYS CFX-Pre 12.0 GUI



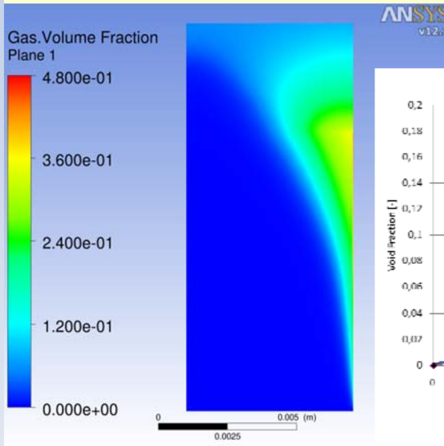


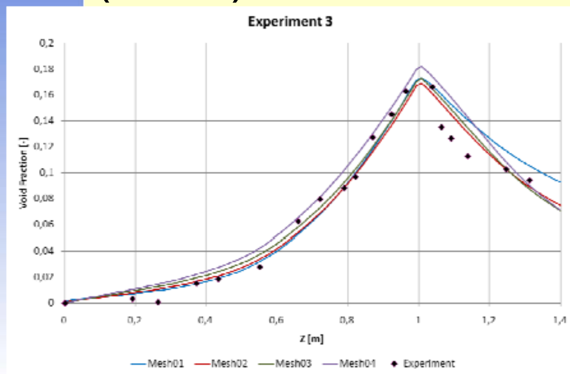
Investigated Boiling Testcases

- Bartolomei et al. (1967,1982)

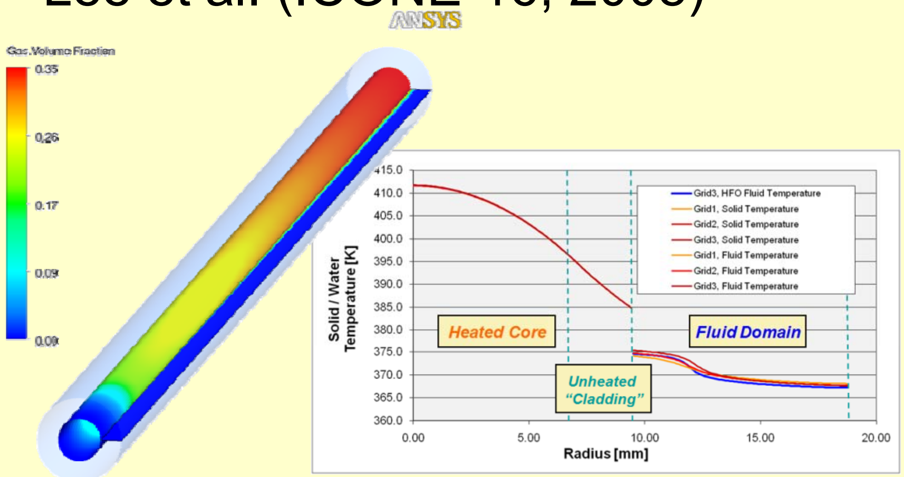


- Bartolomei with recondensation (1980)

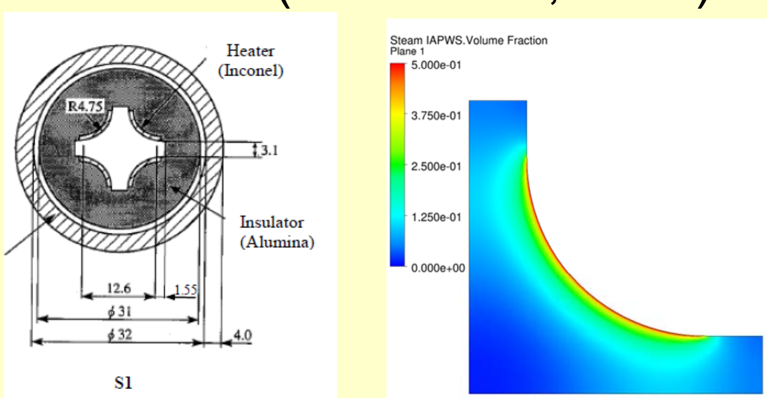




- Lee et al. (ICONE-16, 2008)



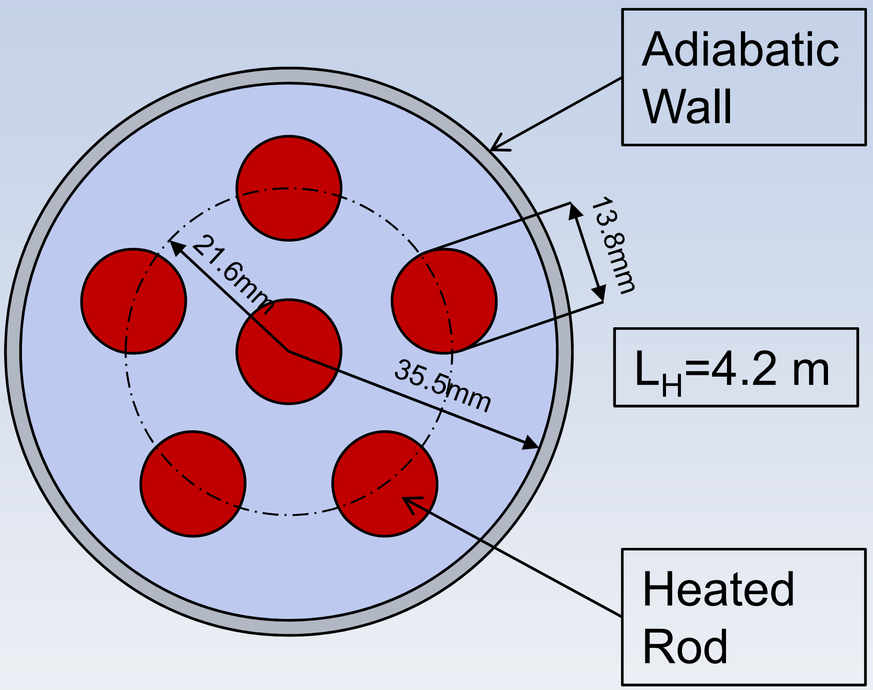
- OECD NEA PSBT subchannel benchmark (1987-1995, 2009)



FRIGG-6a Test Case (Anglart & Nylund, 1967, 1996 & 1997)

FRIGG-6a Test Case Description

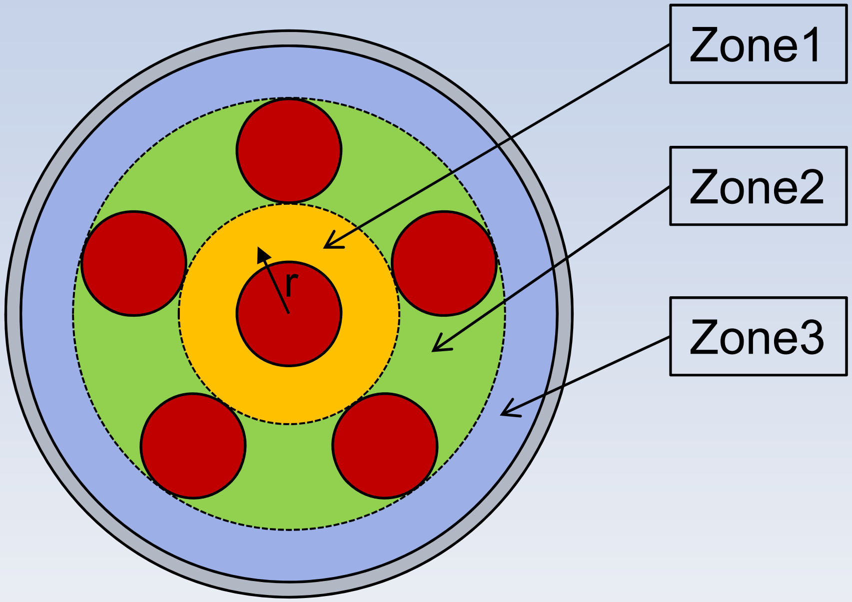
- Geometry (FT-6a)
  - Six electrically heated rods placed in a vertical adiabatic pipe



- Flow Parameters
  - Upward directed subcooled water flow
  - Mass flux @Inlet $G_{in} = 1163\ kg\ m^{-2}\ s^{-1}$
  - Pressure @Inlet $p_{in} = 5\ MPa$
  - Rod wall heat flux $q_{Rod} = 0.522\ MW\ m^{-2}$
  - Liquid subcooling @Inlet $T_{sub} = 4.5\ K$

FRIGG-6a Test Case Experimental Data

- Determination of experimental data by gamma ray attenuation method:
  – Measurements of area averaged gas volume fraction in different cross-sectional zones along the test section



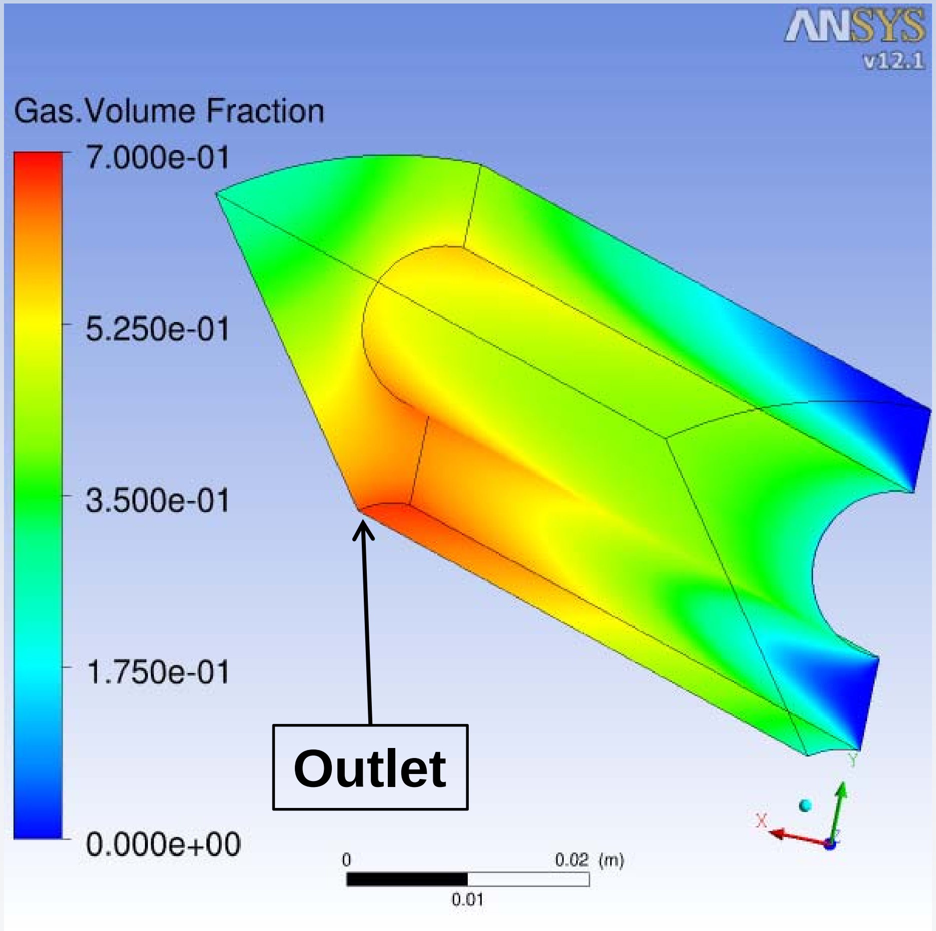
Defintion of Zones:

- Zone1 (r < 14.6 mm)
- Zone2 (14.6 mm < r < 28.6 mm)
- Zone3 (r > 28.6 mm)

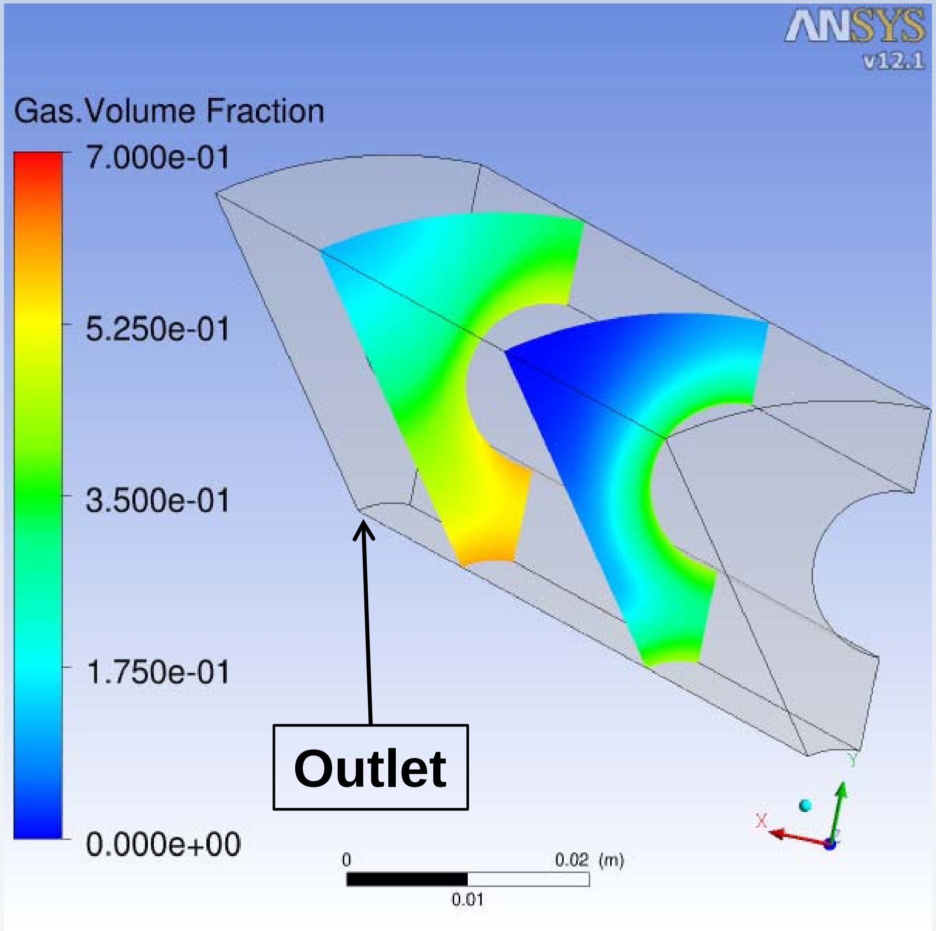
FRIGG-6a Test Case
Mesh Refinement Hierarchy

	Mesh01	**Mesh02**	**Mesh03**
No. Elements	**699 x 150 (104 850)**	**2796 x 300 (838 800)**	**11184 x 600 (6 710 800)**
No. Nodes	116 421	884 639	6 892 869
Max y^+	180	94	51
Min Angle [deg]	51.9	50.4	49.64
Min Determinant	0.84	0.91	0.98
Numerical Effort	**~ 90 minutes @ 6 CPU's**	**~ 17 hours @ 16 CPU's**	**~ 6 days @ 40 CPU's**

FRIGG-6a Test Case
Baseline Setup: SST → Steam VF

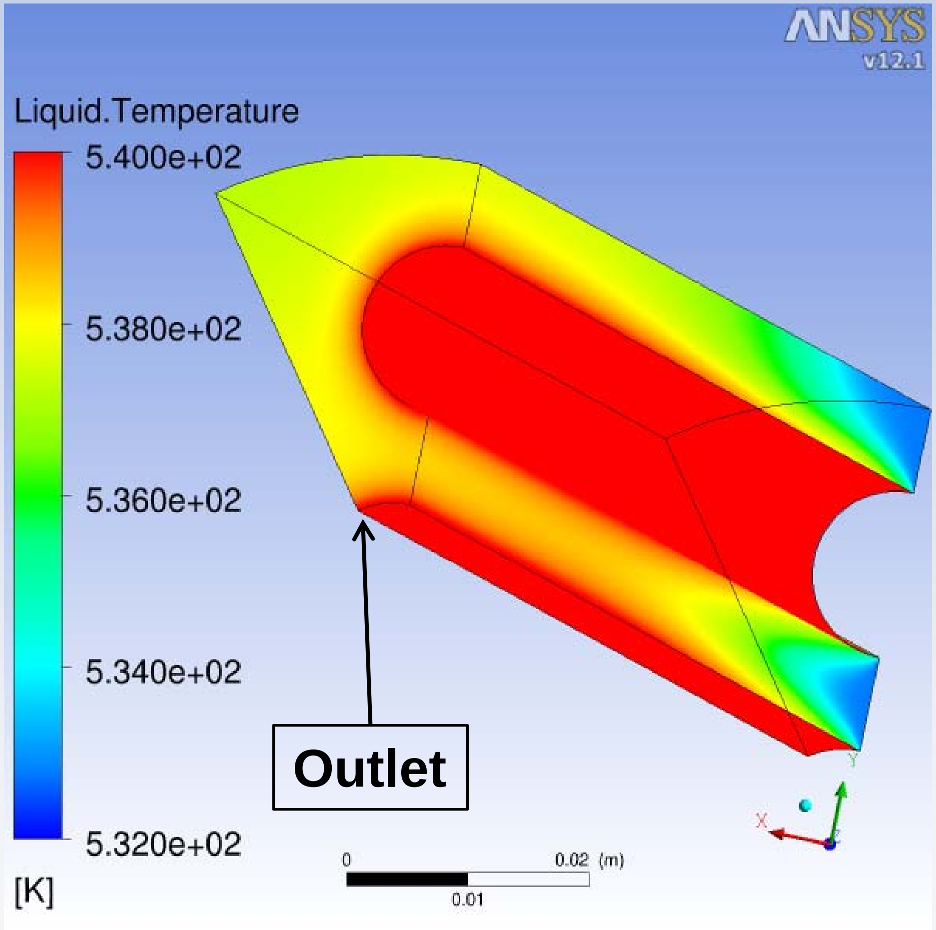


Plot of steam volume fraction (Mesh03, SST)

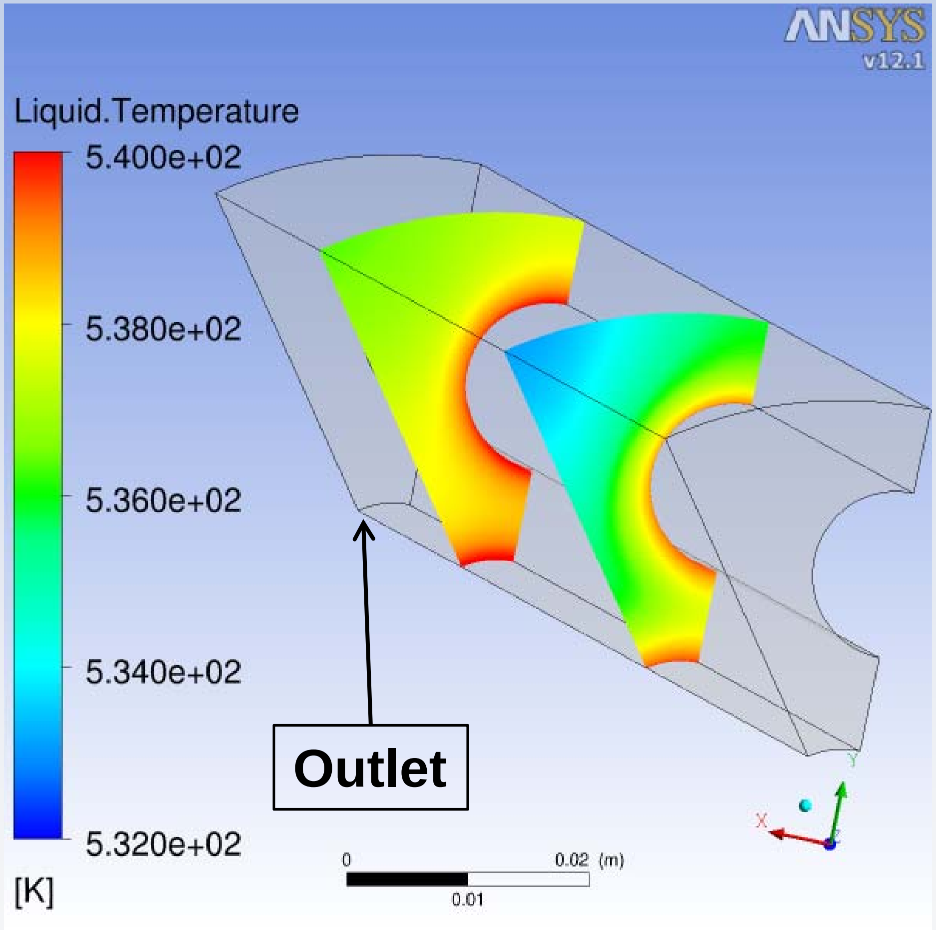


Two cross-sectional distributions of steam volume fraction (Mesh03,SST)

FRIGG-6a Test Case
Baseline Setup: SST → T_L

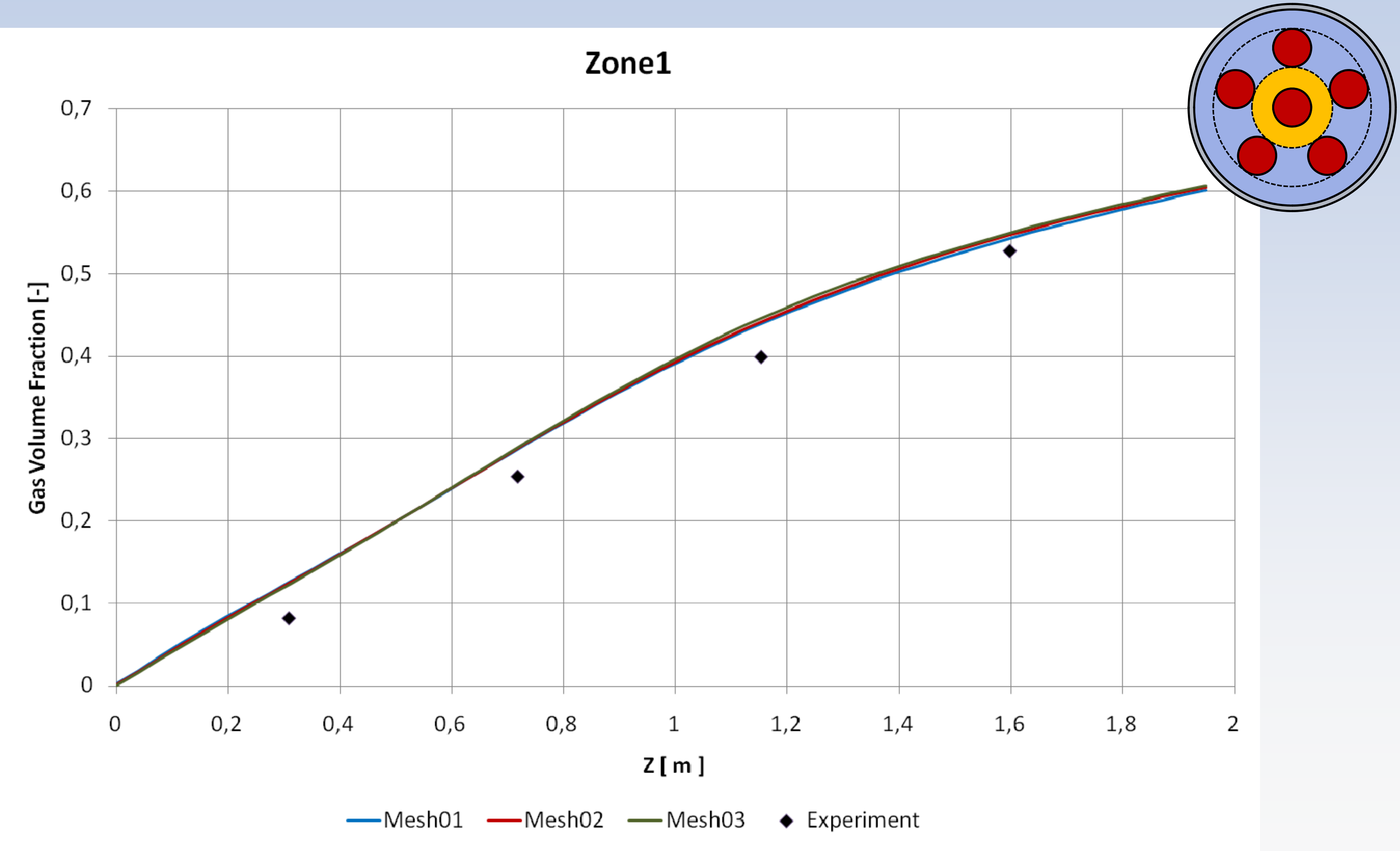


Plot of liquid temperature (Mesh03,SST)



Two cross-sectional distributions of liquid temperature (Mesh03,SST)

FRIGG-6a Test Case
Mesh Comparison

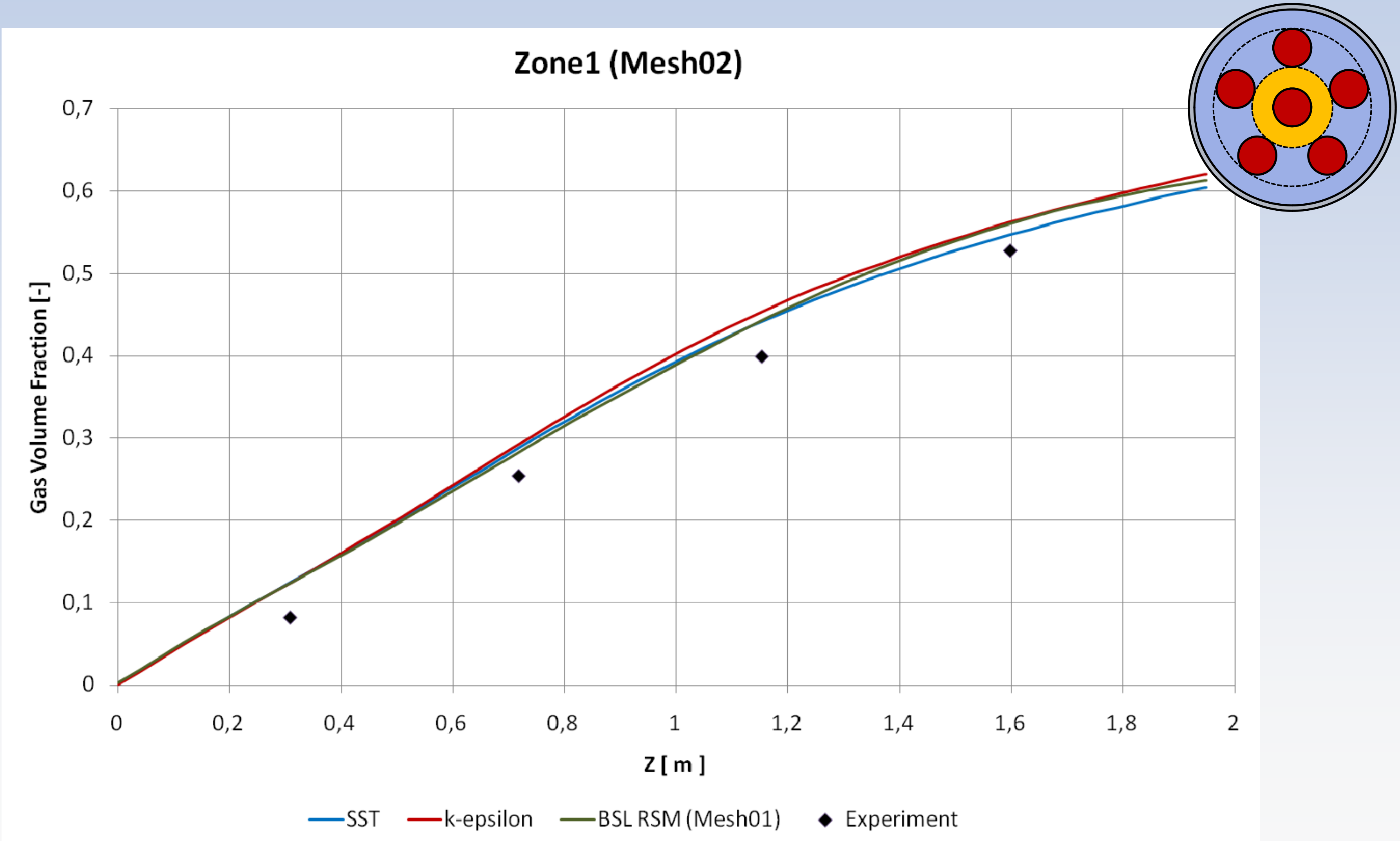


Turbulence Modeling in Rod Bundles

- So far good comparison, but…
  - Wall friction in rod bundles leads to secondary flows
  - Anisotropic turbulence
  - SST $\Rightarrow$ BSL RSM
  - Does not influence so much cross-sectional averaged flow properties
  - Secondary flows affect steam & temperature distributions on heated wall surfaces

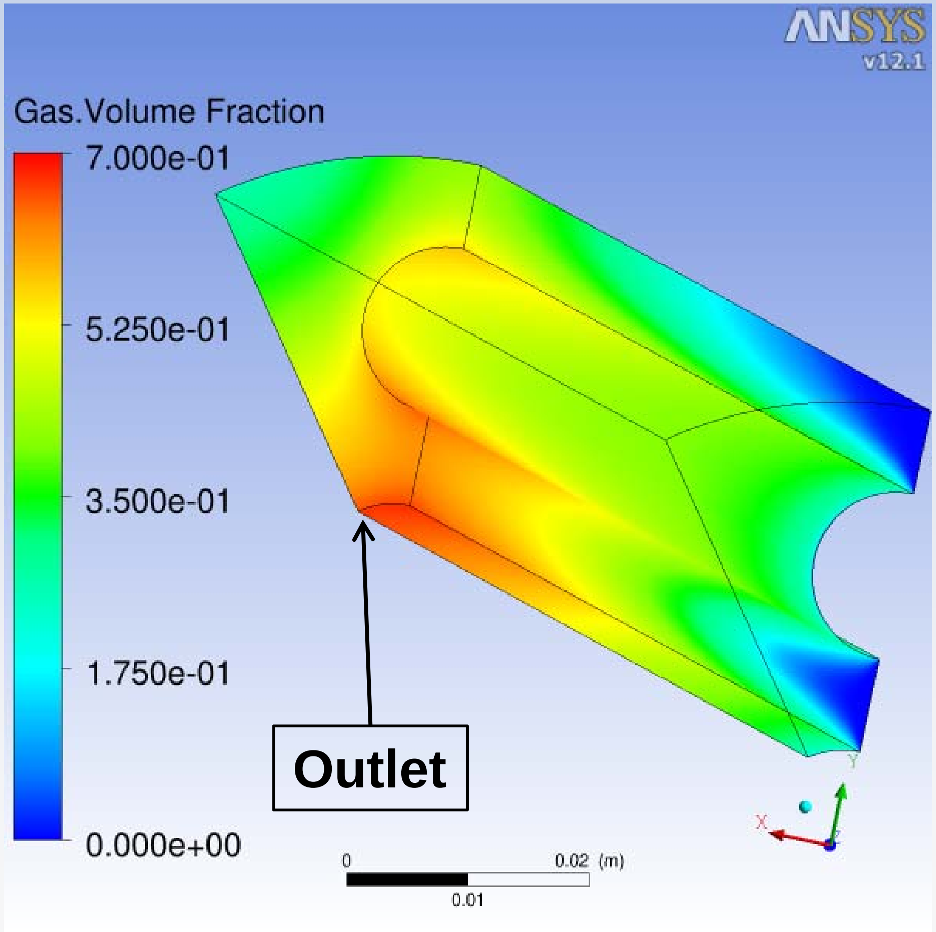
    → Can be relevant for safety!

FRIGG-6a Test Case
Turbulence Model Comparison

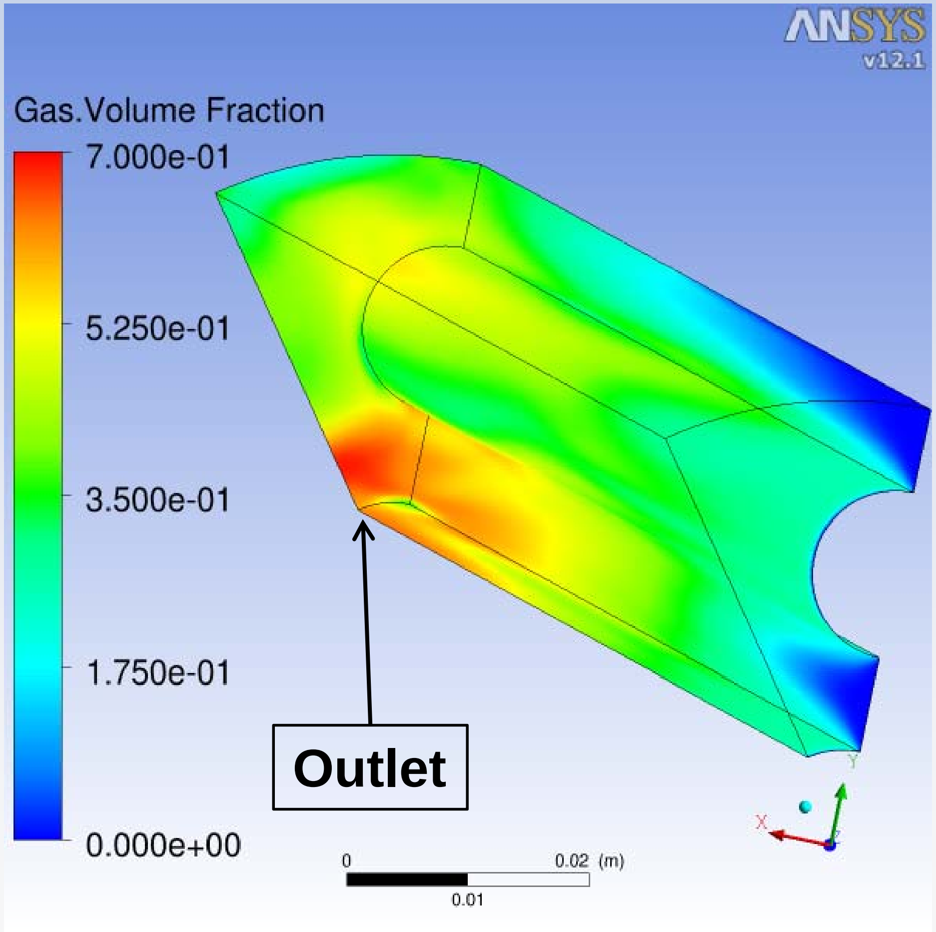


FRIGG-6a Test Case
Turbulence Model Comparison

SST model



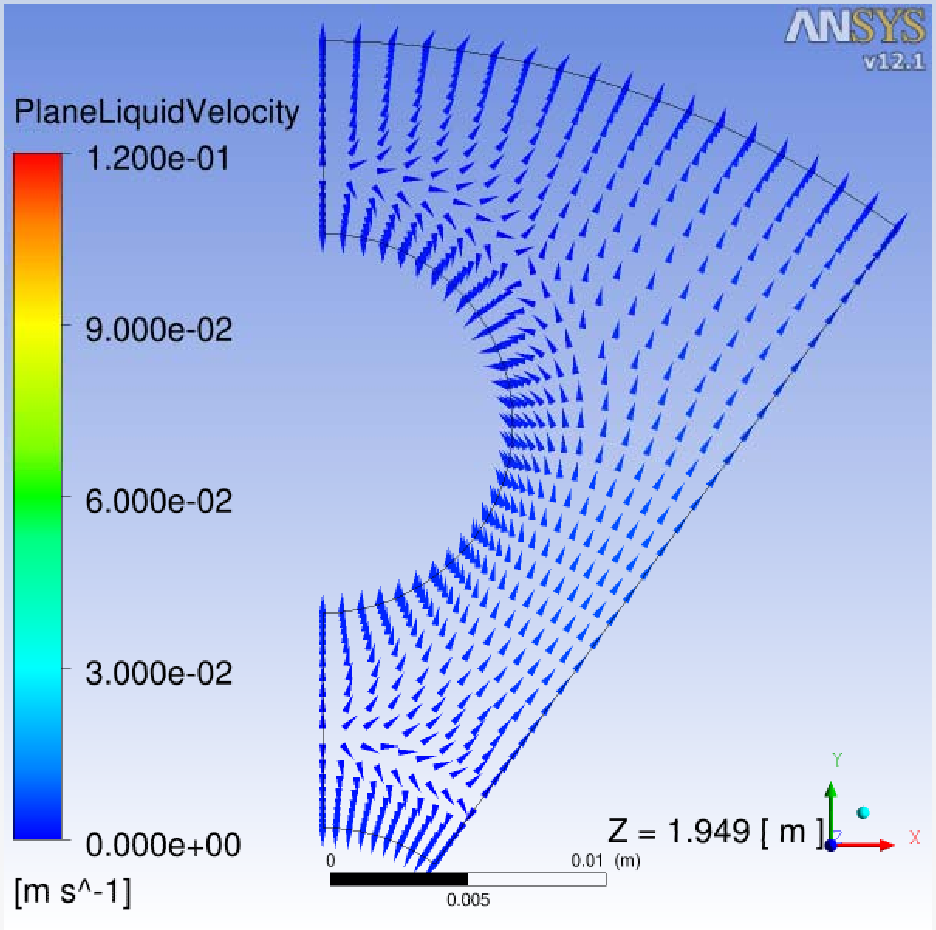
BSL RSM model



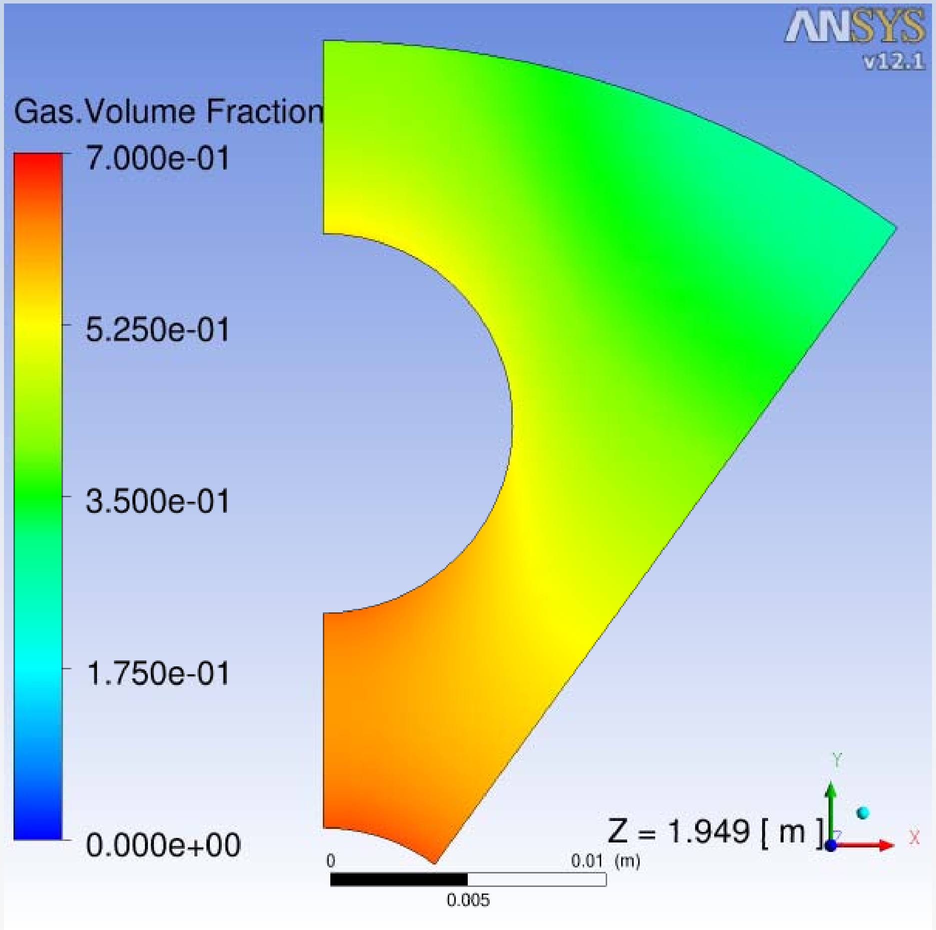
Steam volume fraction

FRIGG-6a Test Case
Turbulence Model Comparison

- SST model → NO secondary flows



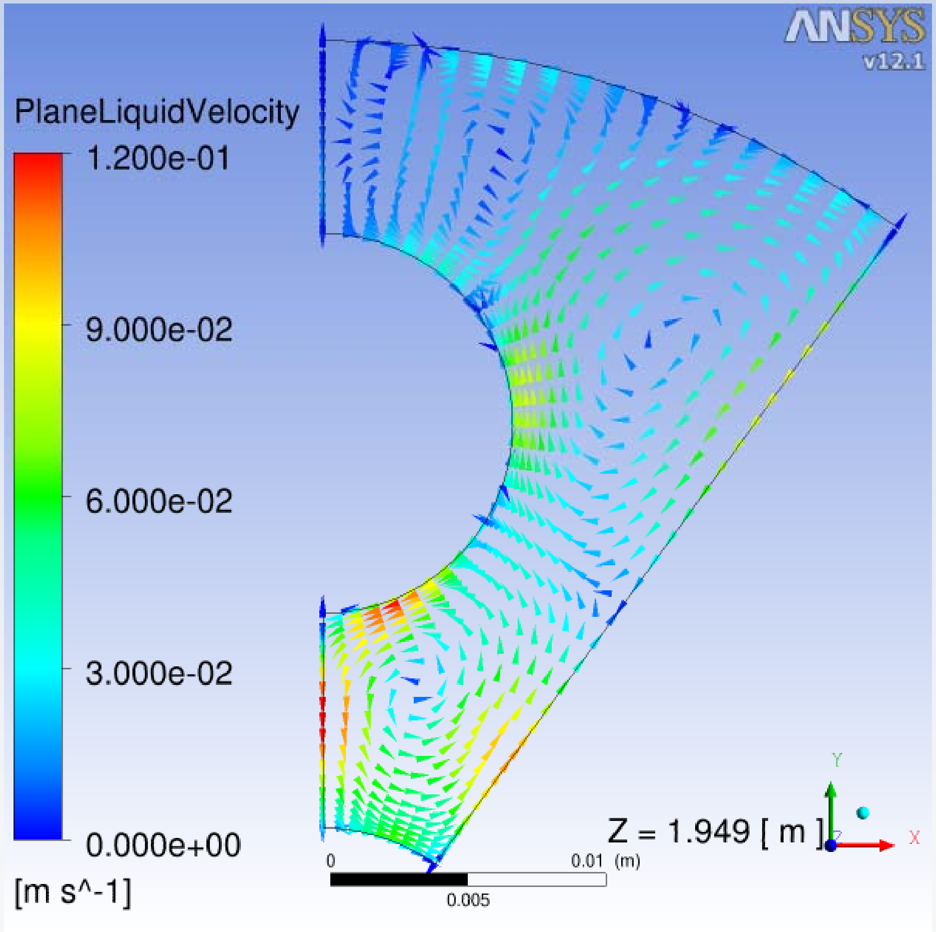
Liquid velocity in cross section (Outlet)



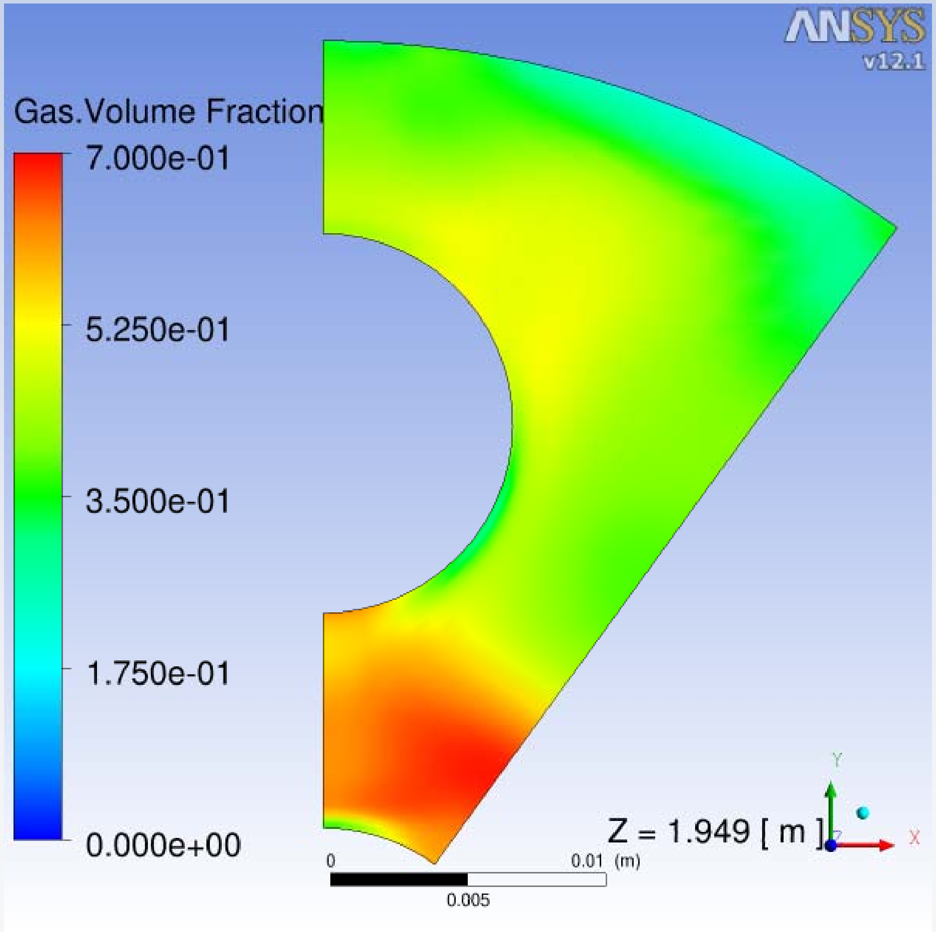
Contour plot of steam volume fraction (Outlet)

FRIGG-6a Test Case
Turbulence Model Comparison

- BSL RSM model → secondary flows



Liquid velocity in cross section (Outlet)

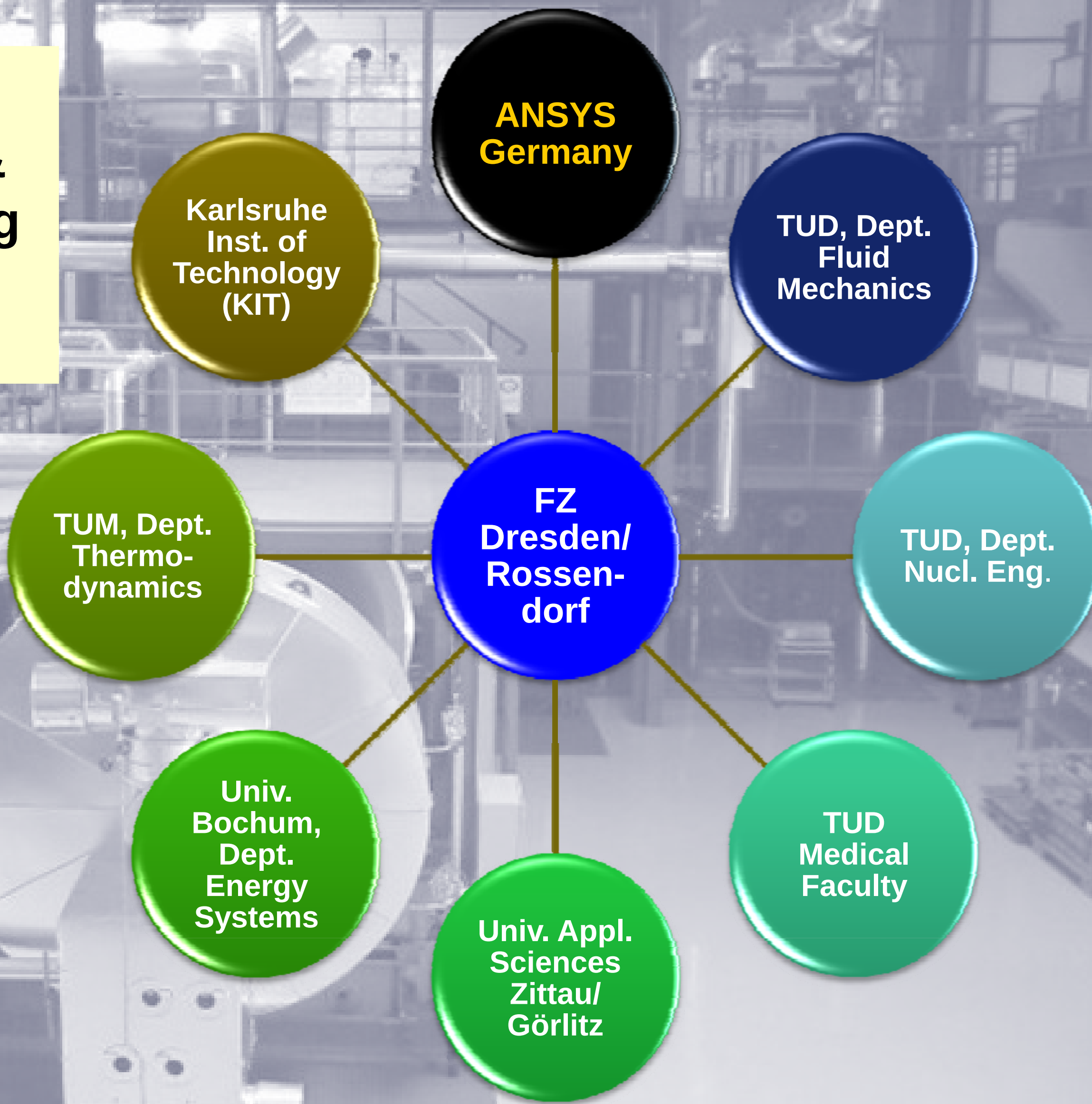


Contour plot of steam volume fraction (Outlet)

New R&D Consortium

R&D Initiative:

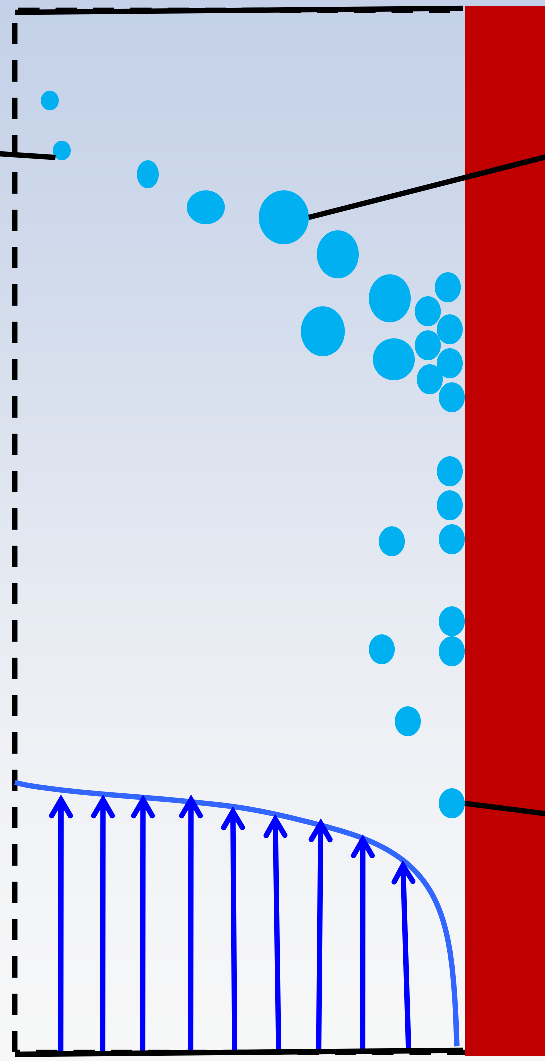
"Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR"



Coupling of RPI Wall Boiling Model with Homog./Inhomg. MUSIG

Cust. Solv. v1

Condensation (MUSIG model extension) ✓



CFX 12.1

Bubble breakup & coalescence (MUSIG Model) ✓

Coupling

Cust. Solv. v3 ✓

Bubble departure Wall Boiling Model (RPI) ✓

CFX 12.1

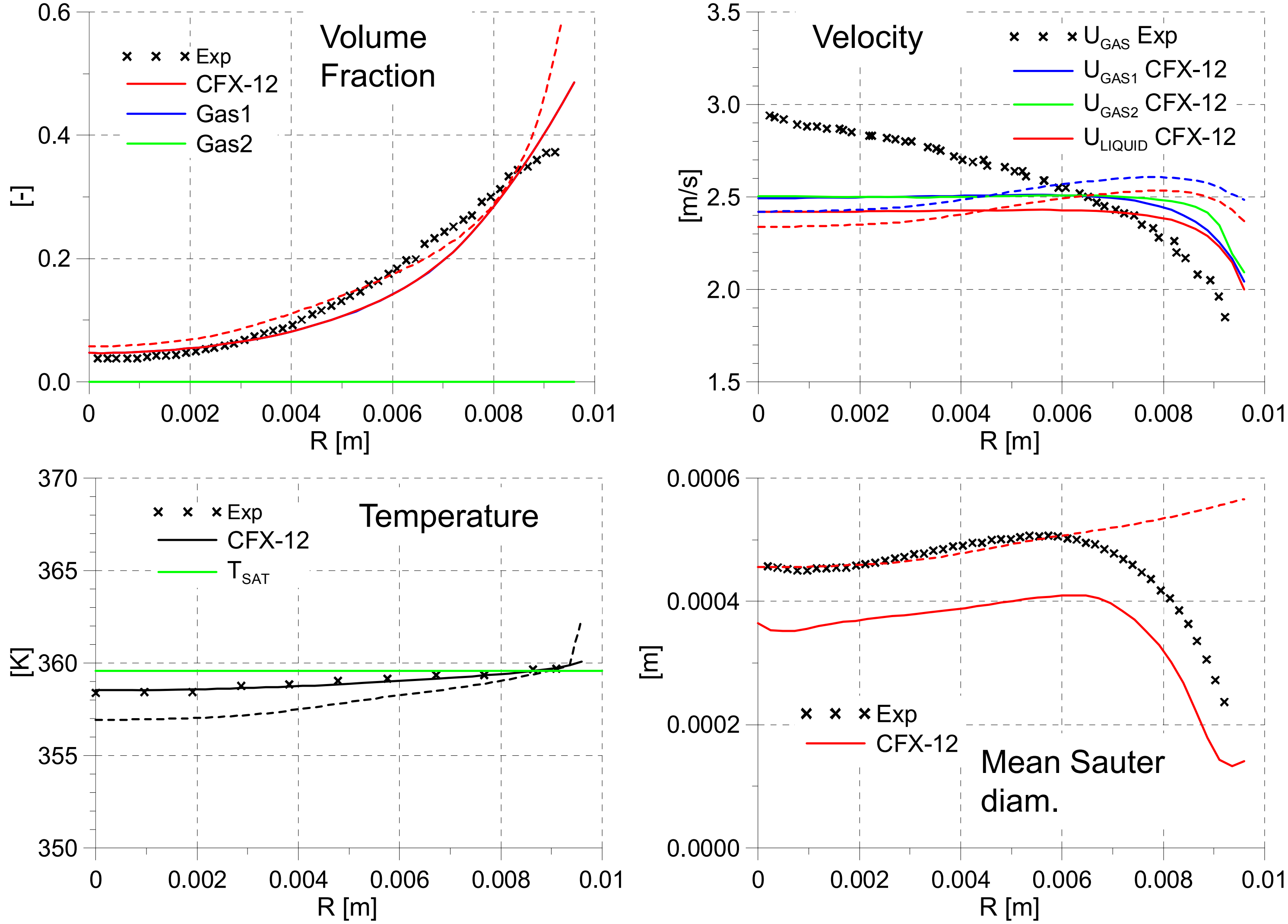
Cust. Solv. v2

Future model extensions:

- Bubble departure diameter computed from equilibrium of forces
- Include further phenomena

DEBORA Testcase: RPI & MUSIG

dashed lines – $d_B=f(T_{sat}-T_L)$; solid lines – d_B as mean Sauter diam. from MUSIG group

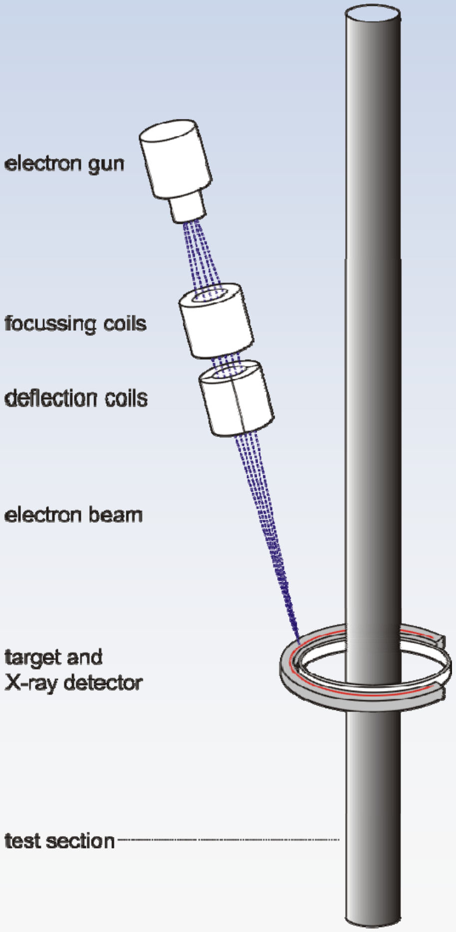


- Inhomog. MUSIG
- Phase change
- Breakup &
- Coales-cence
- RPI

By courtesy of E. Krepper, FZD

Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR

- **Ultrafast electron beam X-ray CT of fuel rod bundle in titanium pipe on TOPFLOW @ FZD:**

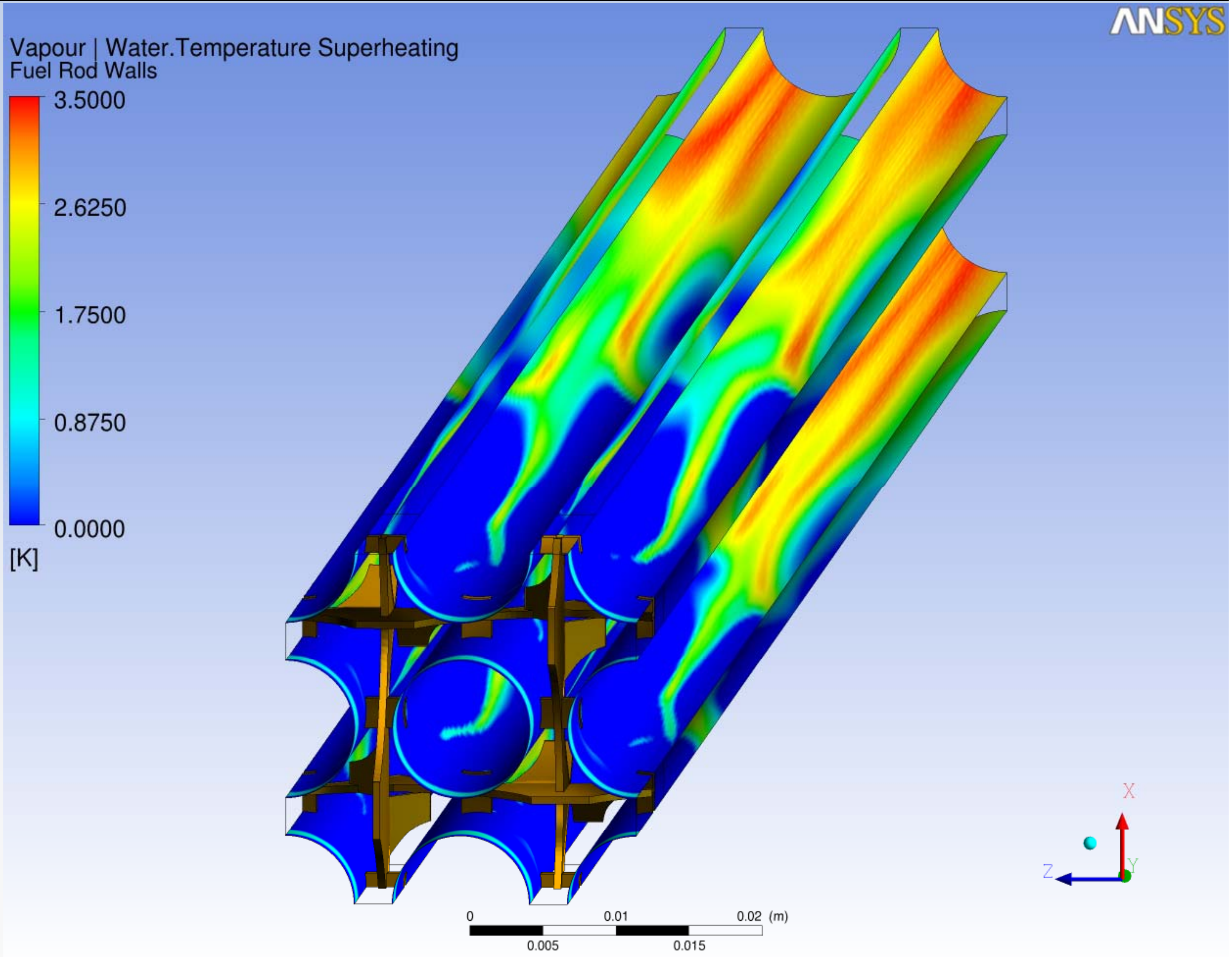


Images by courtesy of U. Hampel, FZD

Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR

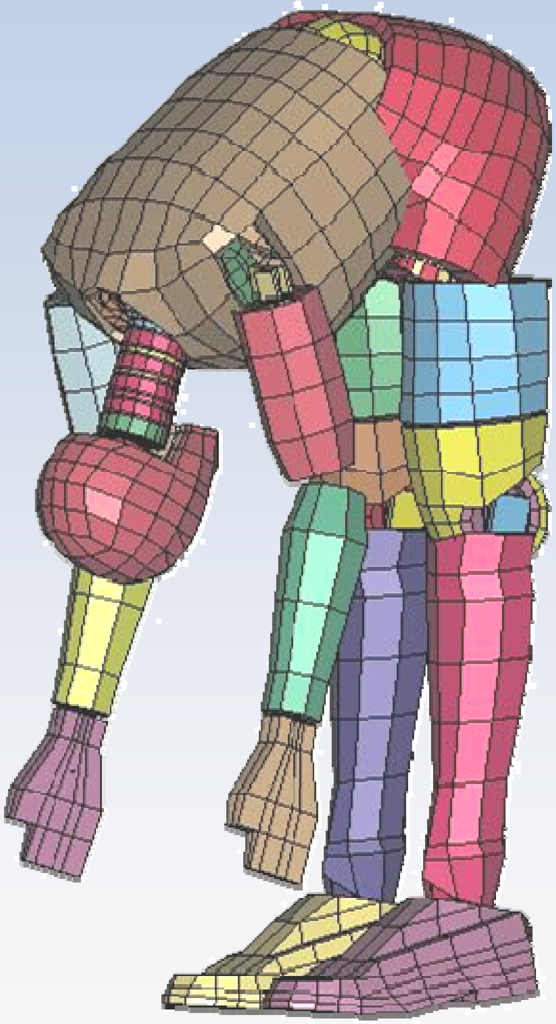
Wall boiling simulation in 3x3 rod bundle with spacer grid:

Wall superheat T_W-T_{Sat}



Summary & Outlook

- Overview on ANSYS CFD multiphase flow model development and validation
- Continuous effort in model improvement, R&D
- Emphasis in validation on BPG, comparison to data, geometry & grid independent modeling
- High interoperability of physical models
- Outlook:
  – Ongoing & customer driven CFD model development
  – Research cooperation with Industry & Academia
  – More & more complex MPF phenomena
  – Coupling of wall boiling model to inhomogeneous MUSIG
  – Extension of the wall heat partitioning in wall boiling model



Thank You!