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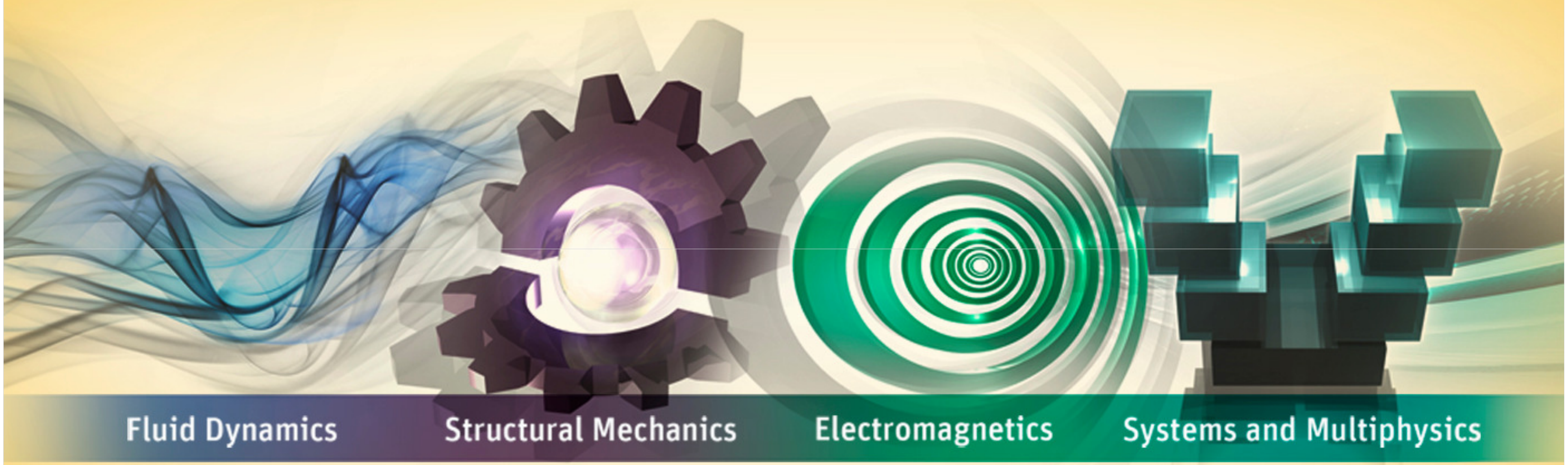
CFD-Modeling of Boiling Processes



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Outline

- Introduction
- Motivation
- Mathematical Formulation
  - Wall Boiling model (RPI)
  - Population Balance approach (MUSIG)
- Validation
  - Roy et al. case
  - DEBORA cases
- Summary & Outlook

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Introduction: R&D Consortium

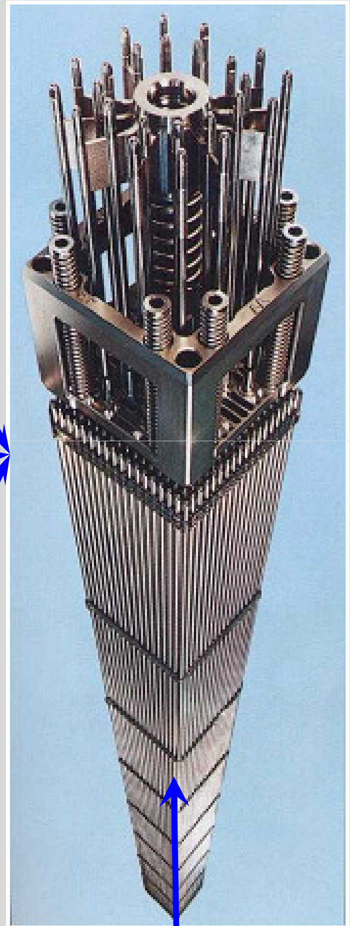
- **R&D Initiative:**
  “Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR”
- **Sept 2009-Sept 2012**

Introduction: 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

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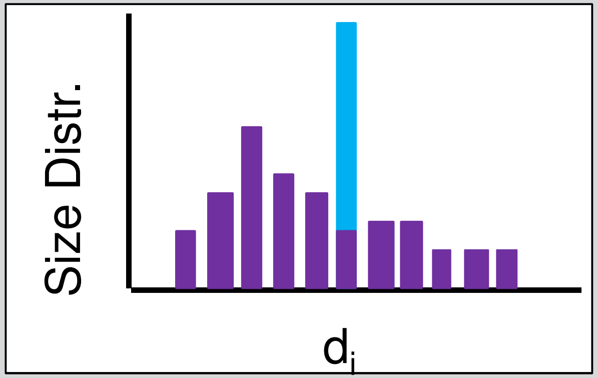
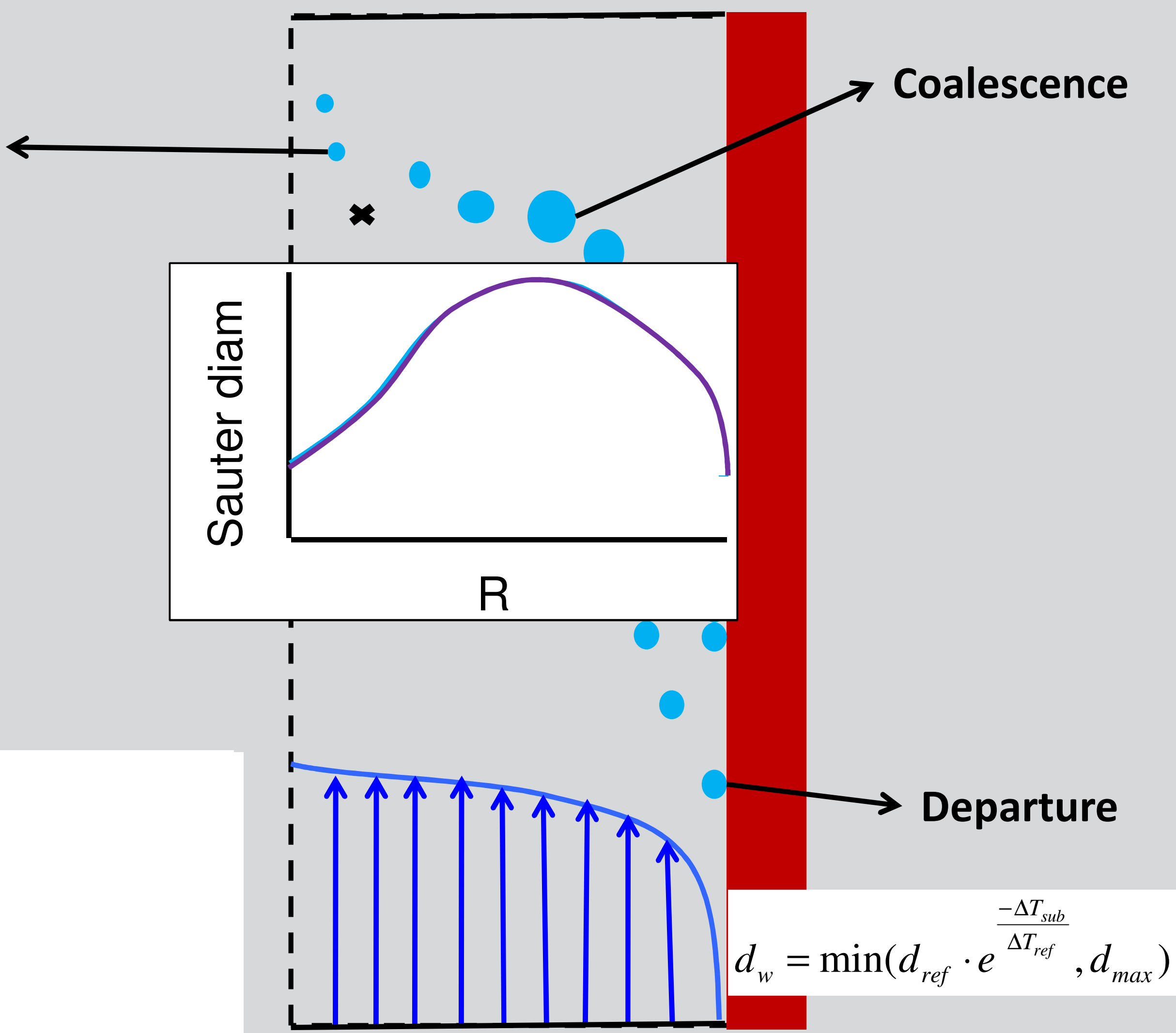
Motivation





$$d_w = \min(d_{ref} \cdot e^{\frac{-\Delta T_{sub}}{\Delta T_{ref}}}, d_{max})$$

MUSIG

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Modelling of Sub-cooled Boiling at a Heated Wall

The RPI Wall Boiling Model:

- Constant pressure → given T_{sat}
- Overall heat flux Q_w given
- Heat flux partitioning:

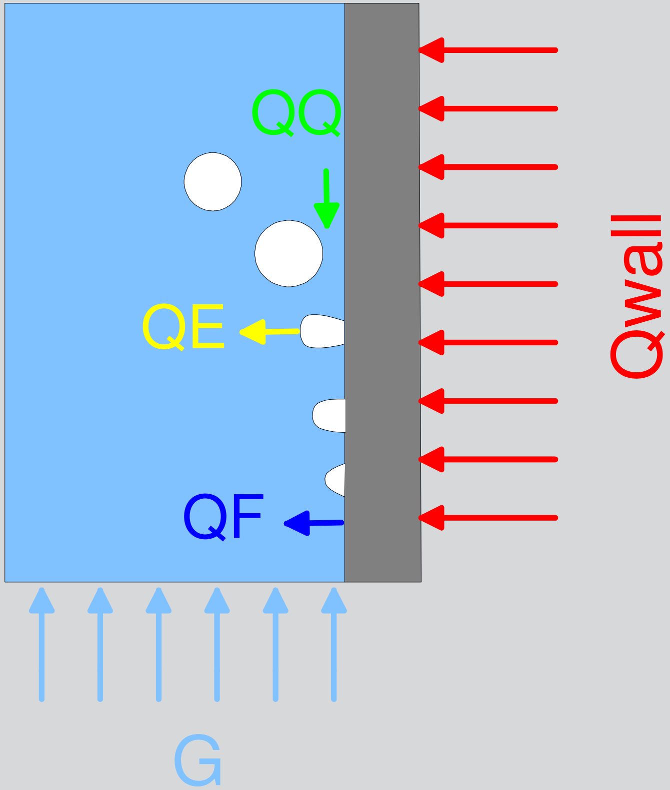
$$Q_w = Q_f + Q_e + Q_q$$

Q_f - single phase convection

Q_e - evaporation

Q_q - quenching

(departure of a bubble from the heated surface → cooling of the surface by fresh water)



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Wall Boiling Sub-models

The RPI model contains sub-models for:

- Heat Flux Partitioning
- Bubble Dynamics
- MPF Turbulence interaction
- Interfacial heat and mass transfer
- Coupled to CHT (1÷1, GGI)
- Coupled to population banlance

Sub-models for non-equilibrium DNB and CHF

- Include convective turbulent heat flux to vapor
- Topological function for flow regime transition

Heat Flux Partitioning:

- ✓Convective turbulent liquid heat flux
- ✓Quenching heat flux
- ✓Evaporative heat flux
- ✓Convective turbulent vapor heat flux, DNB+CHF

Bubble Dynamics:

- ➢ Nucleation site density
- ➢ Bubble departure frequency
- ➢ Bubble departure diameter
- ➢ Area of bubble influence
- ➢ Coupled to MUSIG population balance model

Turbulence Interaction:

- ➢ Turbulent dispersion
- ➢ Bubble induced turbulence

Interfacial Heat and Mass Transfer:

- ➢ Condensation in the subcooled liquid
- ➢ Heat flux to vapour heat transfer
- ➢ Wall vapour mass transfer
- ➢ Interfacial heat transfer / volume condensation

Flow Regime:

- ➢Flow regime transition from bubbly flow to droplets

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

RPI wall boiling model available in ANSYS CFX and ANSYS Fluent

- activated per boundary patch @ individual wall heat flux

Submodels:

- **Nucleation site density**: Lemmert & Chawla , User Defined
- **Bubble departure diameter**:
  Tolubinski & Kostanchuk, Unal, Fritz, User Defined
- **Bubble detachment frequency**:
  Terminal 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
- Mean bubble diameter Kurul & Podowski correlation via CCL/UDF or coupling to population balance model (homog. or inhomog. MUSIG model)
- Wall boiling & CHT in the solid (1:1 and GGI interfaces)

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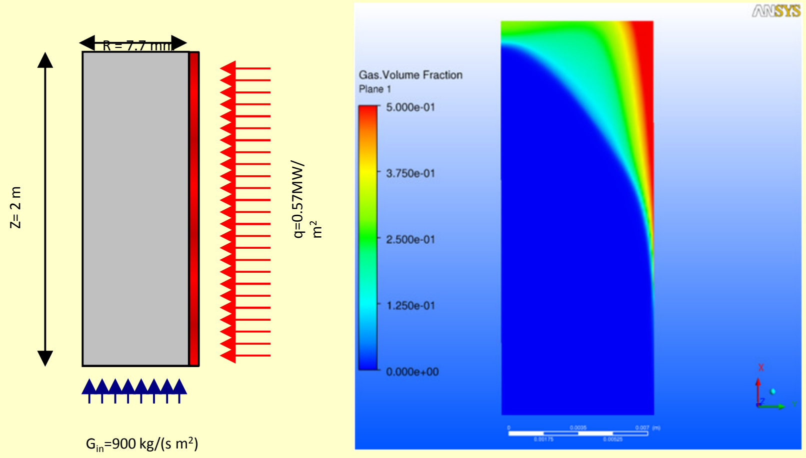
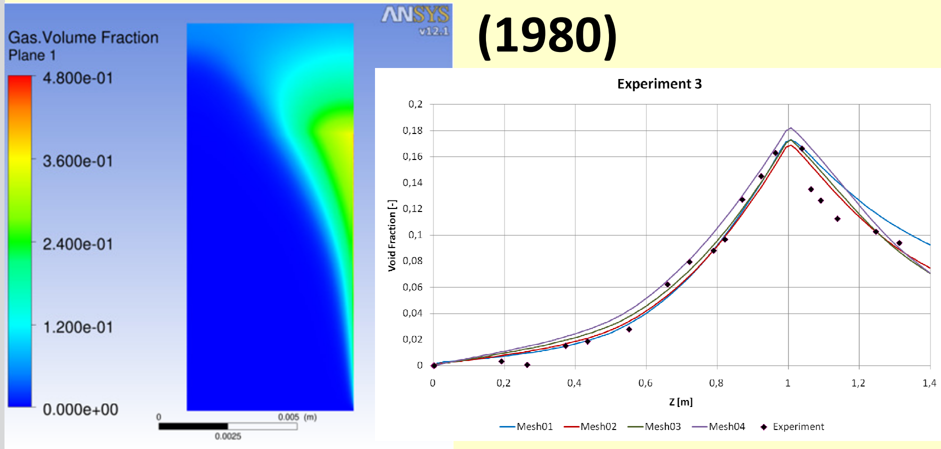
Investigated Boiling Validation Test Cases

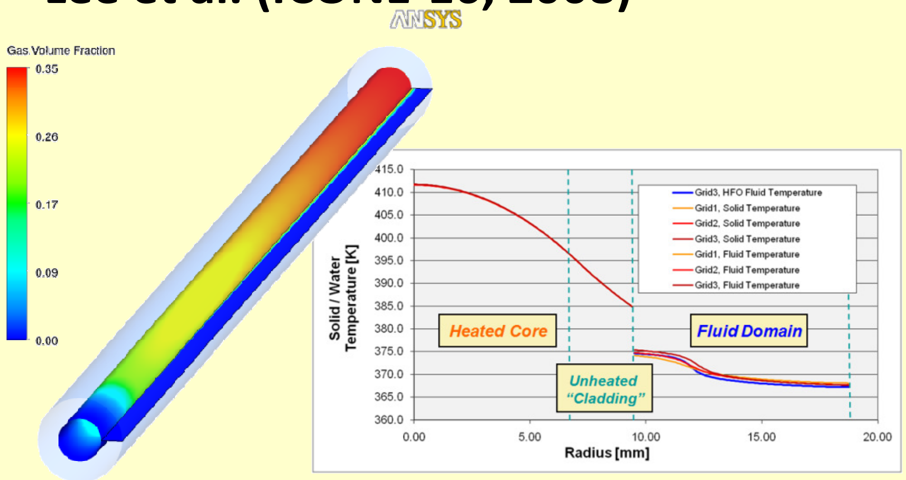
- **Bartolomei et al. (1967,1982)**



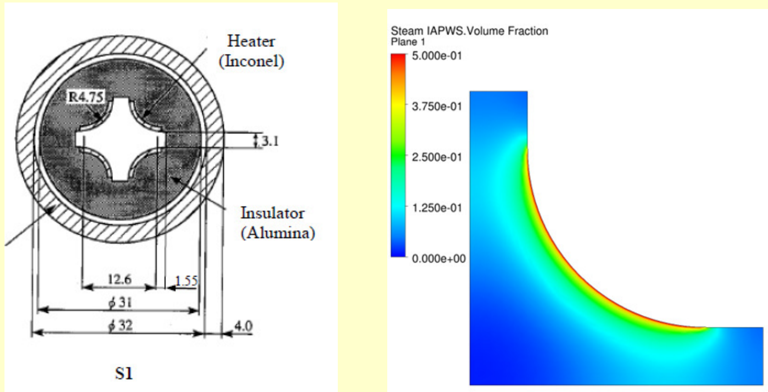
- **Bartolomei with recondensation (1980)**



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



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



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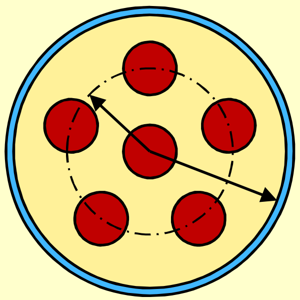
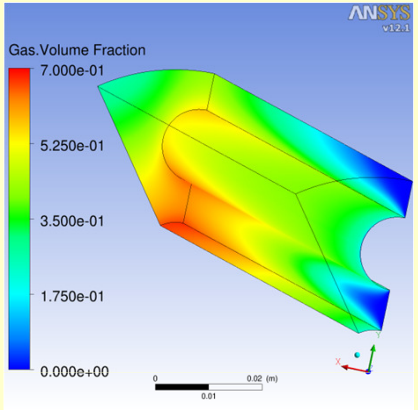
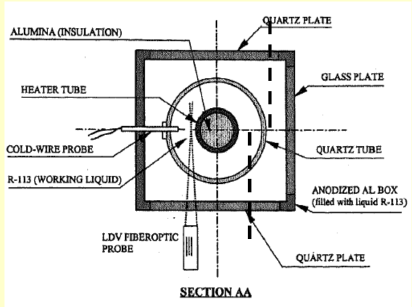
Investigated Boiling Validation Test Cases

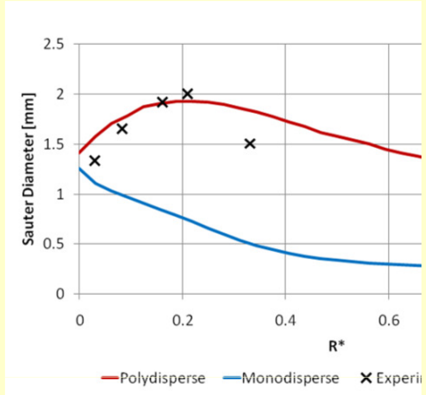
- **FRIGG-6a Test Case (Anglart & Nylund, 1967, 1996 & 1997)**





- **Roy et al. (2002)**





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Coupling Between Wall Boiling Modelling and Population Balance

- **Size fraction equations derived from mass balance**

Std. MUSIG

Mass transfer due to phase change extension

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

- **RPI wall heat partitioning**

$$Q_{wall} = Q_{convl} + Q_{quench} + \dot{m}_{evap} h_{lg}$$

- **At the heated walls one more source term is added to one size fract. Eq.**

$$S_W \left[kg / m^3 s \right] = \dot{m}_{evap} [kg / m^2 s] \frac{S[m^2]}{V[m^3]}$$

RPI: Evaporation rate

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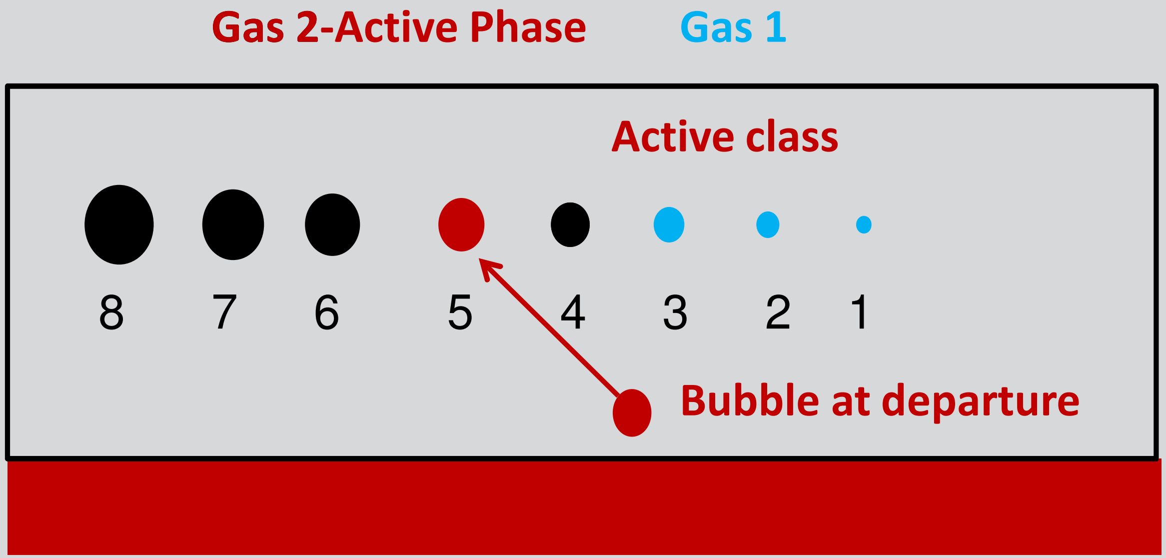
Coupling Between Wall Boiling Modelling and Population Balance

- **Inhomogeneous MUSIG:**



- $\dot{m}_{evap}$ → Size fraction class 5
- $\dot{m}_{evap}$ → Mass conservation Gas 2
- Derived Source Terms → Momentum Gas 2

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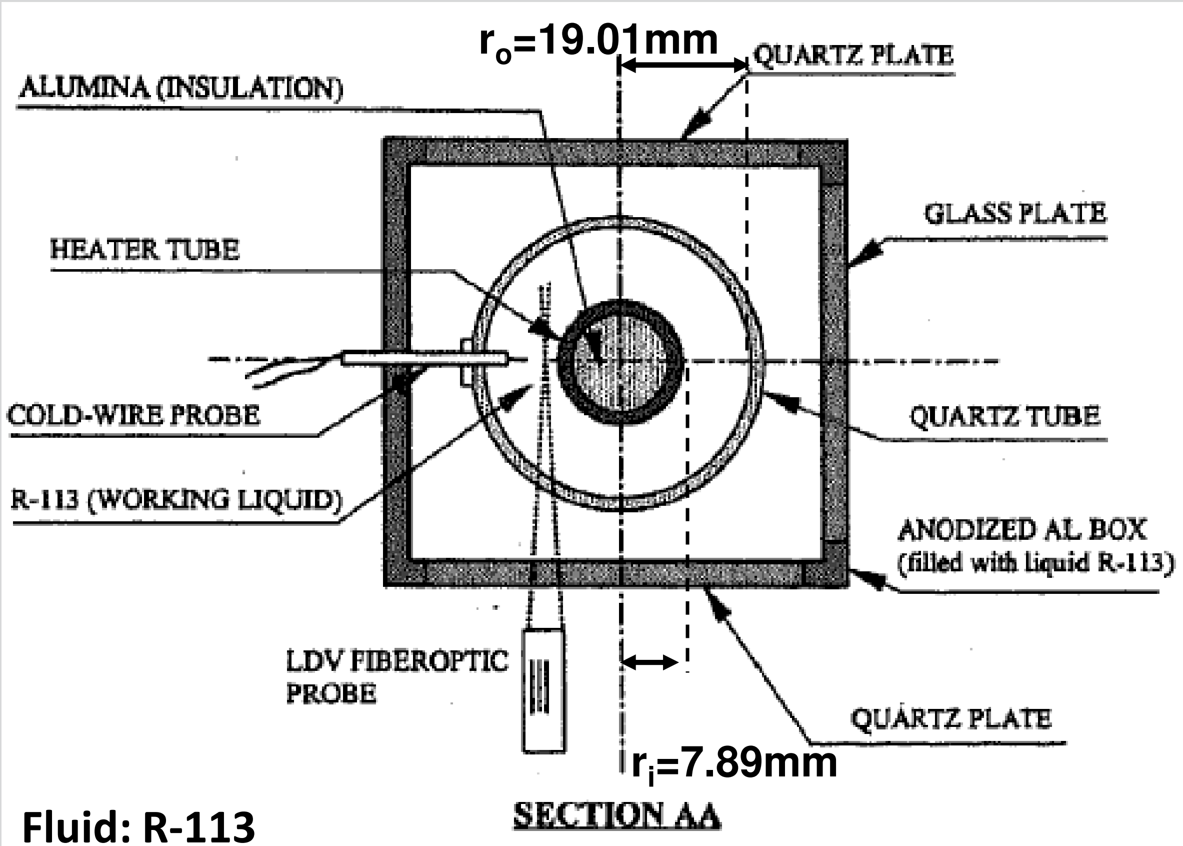
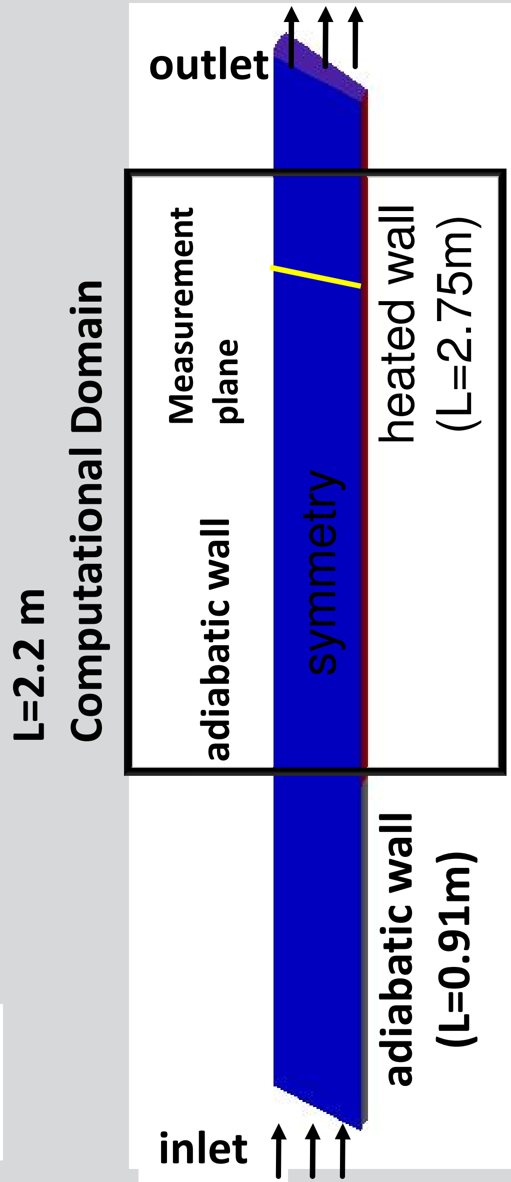
Validation: RPI & homog. MUSIG

Test geometry (Roy et al., 2002)





Fluid: R-113

Pressure	Inlet Temp.	Mass Flux	Power
2.69 bar	50.2 C	784 kg m^{-2} s^{-1}	116 kW m^{-2}

Roy test case: Setup

Main setup parameters:

- **Steady state**
- **High resolution advection scheme**
- **Turbulence model: SST**
- **Morel model for source terms in turb. eq.'s ($C_{\varepsilon,3}$ = 1.0)**
- **Turbulent dispersion (FAD) & drag force**
  → Grace with correction coefficient -0.5
- **Constant value for wall roughness** $$k_r = \eta d_W \left(1 - \frac{Q_{convl} + Q_{quench}}{Q_{wall}}\right)^{\zeta} = 0.575mm$$
- **Wall Contact Model: AF_{liquid} = 1; AF_{gas} = 0**
- **Heat transfer correlation: Tomiyama**

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Roy test case: Setup

Main setup parameters:

- **RPI model & bubble departure diameter: 1.3 mm**
- **Homogenous MUSIG model, 15 bubble classes**
  - d_{min} = 0.25 mm, d_{max} = 3.75 mm
  - Prince/Blanch for coalescence (F_C=4); no breakup (F_B=0)
- **For comparison: monodisperse simulation with Kurul & Podowski assumption on $d_B=f(T_{Sub})=f(T_{Sat-}T_L)$**

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Spatial Grid Independence Analysis

- **Spatial grid hierarchy:**

	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Radial cells	8	16	32	64
Axial cells	220	440	880	1760
Total Cells	1760	7040	28160	112640
y^+_{max}	381	199	104	86

Mesh3	Single phase
y^+_{max}	34

R* dimensionless radius

$$R^* = \frac{R - R_i}{R_o - R_i}$$

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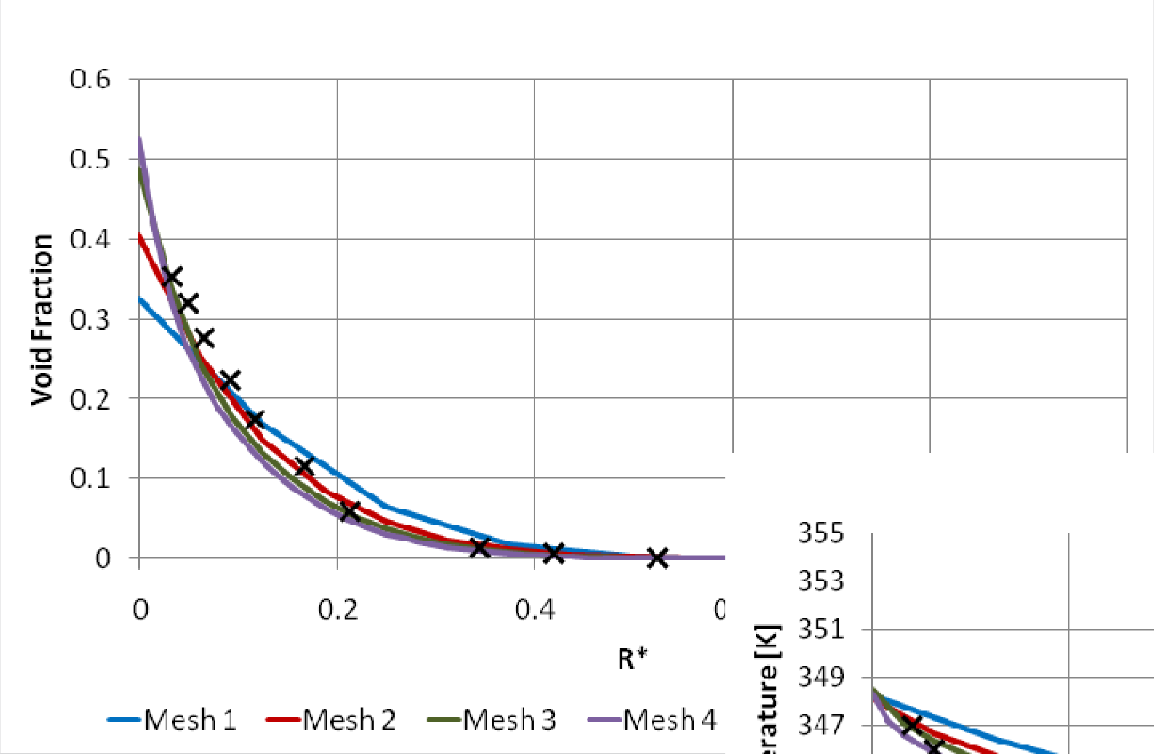
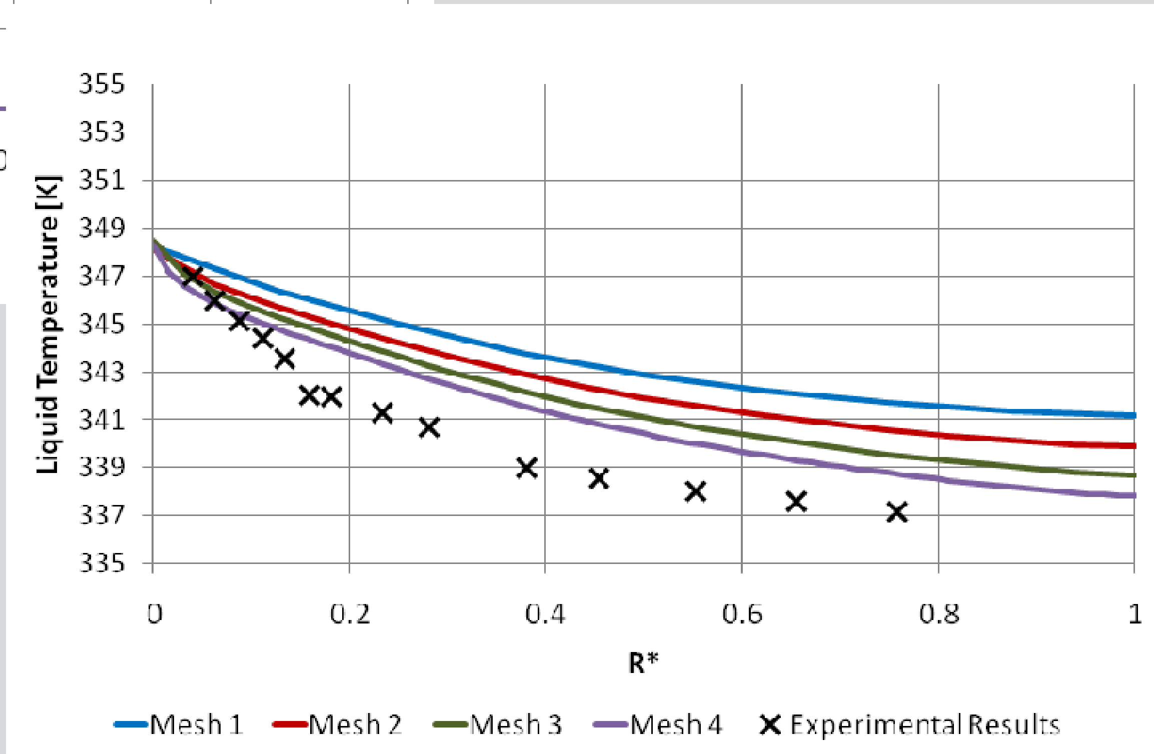
Spatial Grid Independence Analysis





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Analysis of Independence from Bubble Size Class Discretization

- **Bubble size class discretization hierarchy:**

	Discret. 1	Discret. 2	Discret. 3	Discret. 4
Number of classes	7	15	30	60
Diameter step [mm]	0.50	0.23	0.12	0.06

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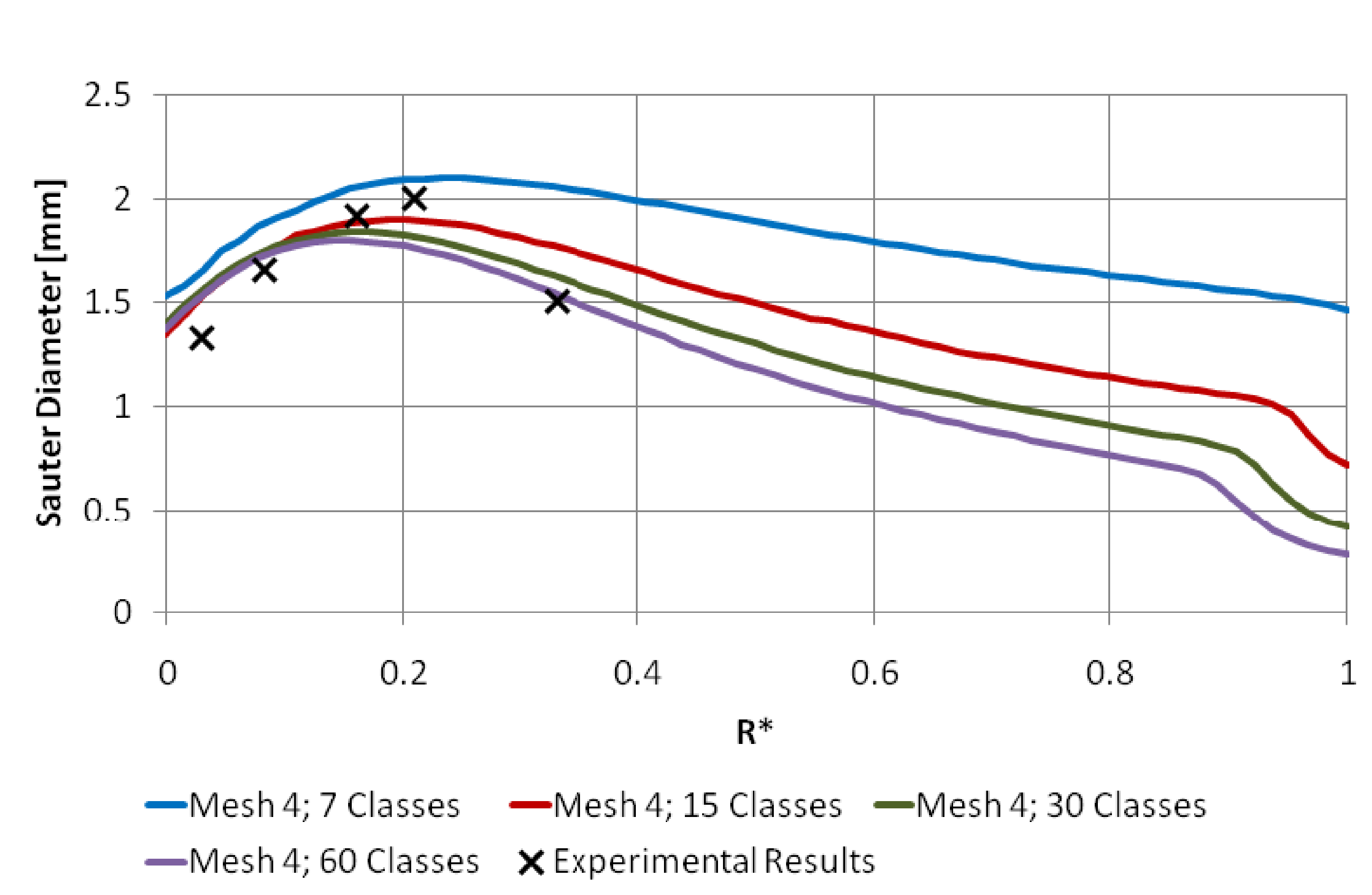
Analysis of Independence from Bubble Size Class Discretization



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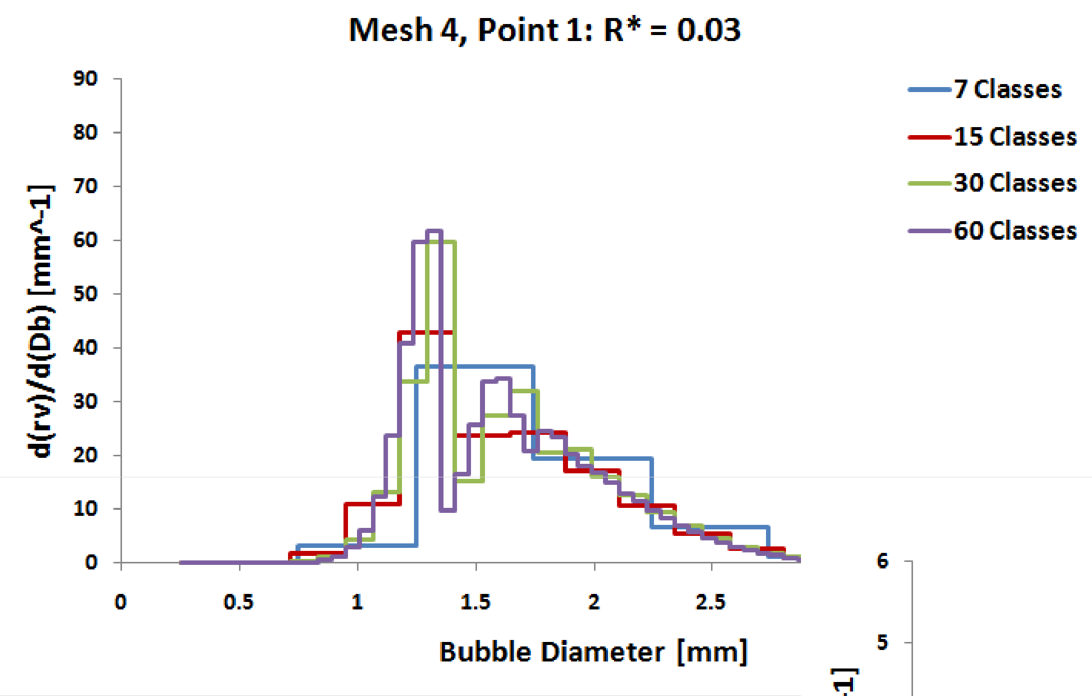
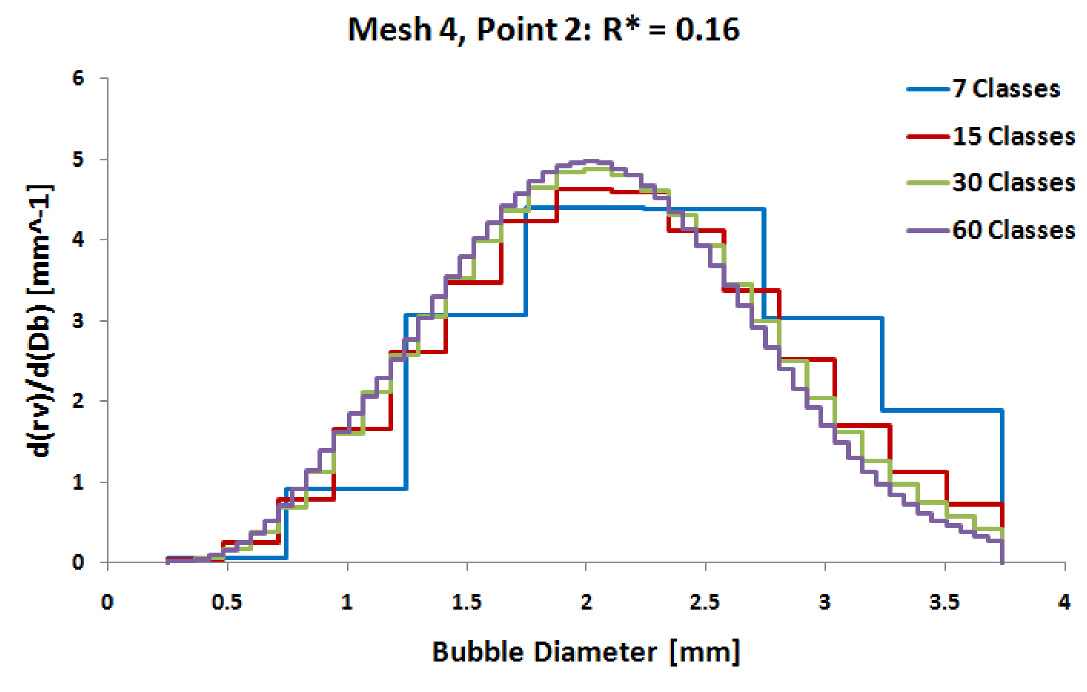
Analysis of Independence from Bubble Size Class Discretization





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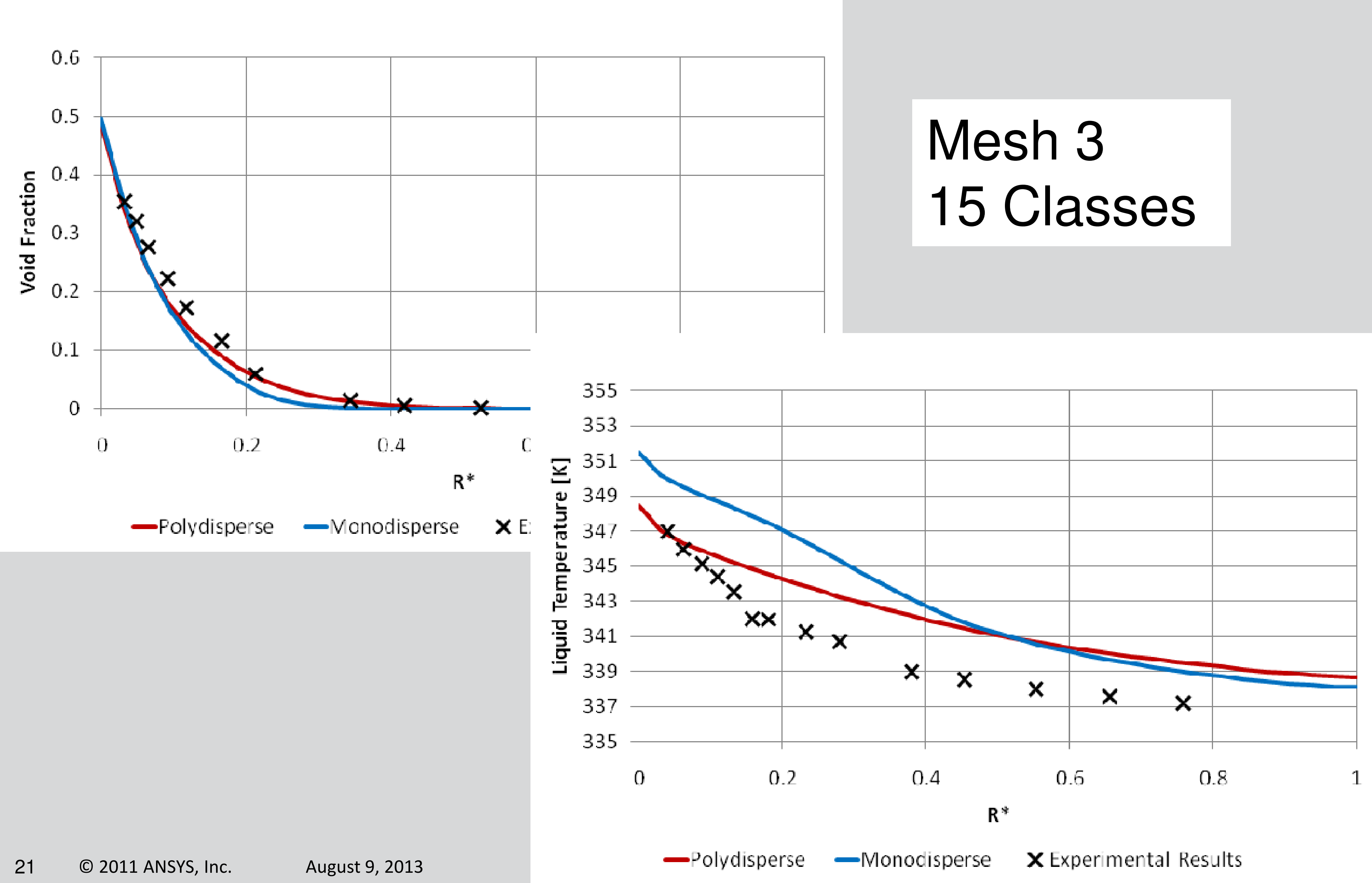
Comparison to K&P Correlation



Mesh 3
15 Classes

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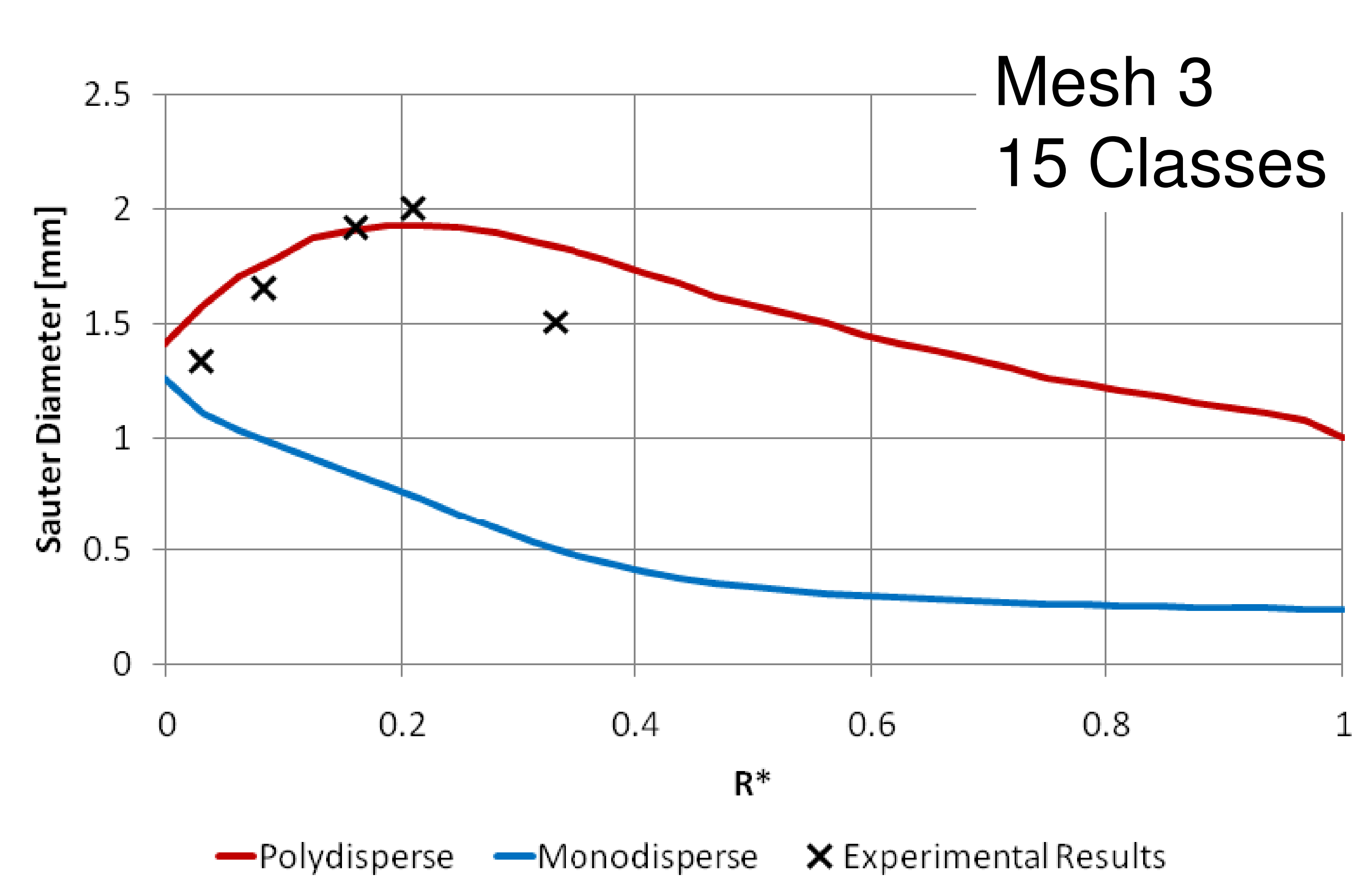
Comparison to K&P Correlation



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Validation: RPI & Inhomog. MUSIG

- DEBORA test cases
- Scaling conditions:
  - Density relation Liquid/Gas
  - Reynolds Number
  - Weber Number
- Replacing water by R12
- More convenient experimental conditions:
  - Pressure
  - Temperature
  - Tube diameter
- Measurement of profiles becomes possible

	Water	R12
Pressure [MPa]	**15.7**	**2.6**
Tsat [°C]	**345**	**87**
Density Liquid [kg/m^3]	590	1020
Density Gas [kg/m^3]	104	172
Viscosity [kg/ms]	6.8e-5	9.0e-5
Surface Tension [N/m]	4.5e-3	1,8e-3
D [m]	**0.012**	**0.02**
V [m/s]	5	2.3
DenLiquid/DenGas	5.6	5.9
Re	5.2e+5	5.2e+5
We	3.3e+3	3.3e+3

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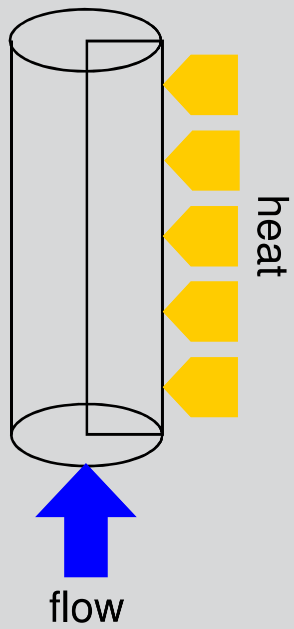
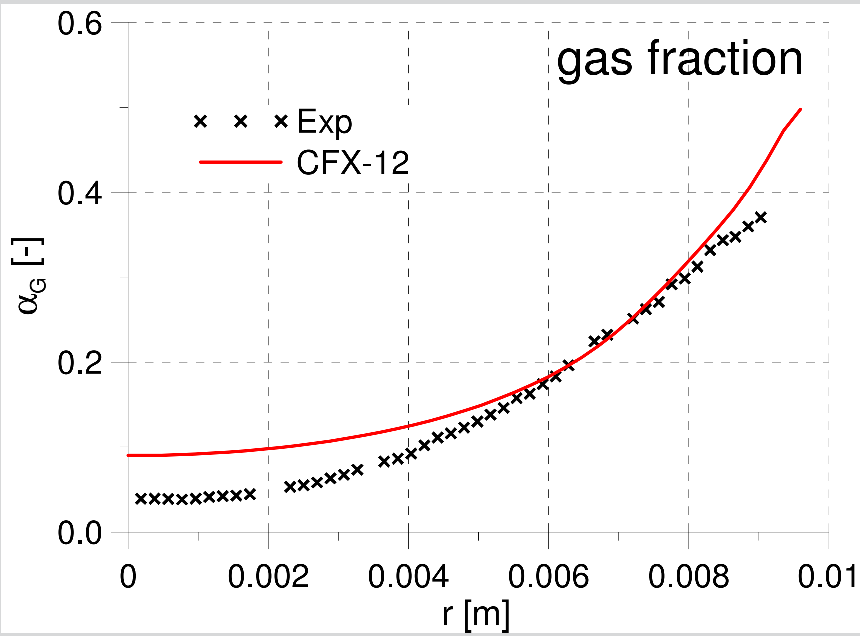
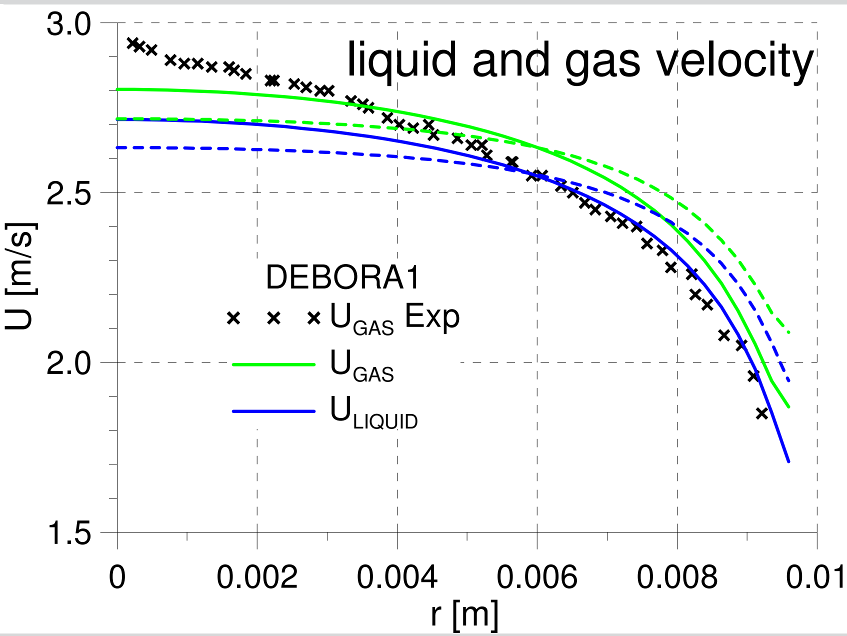
Example: DEBORA Tests (CEA)

- Fluid Dichlorodifluoromethane = R12
- Heated tube D = 19.2 mm over 3.5 m
- Measurement of **profiles** for gas fraction, liquid and gas velocities, temperatures, bubble sizes
- Validation of
  - non drag forces
  - turbulent wall functions

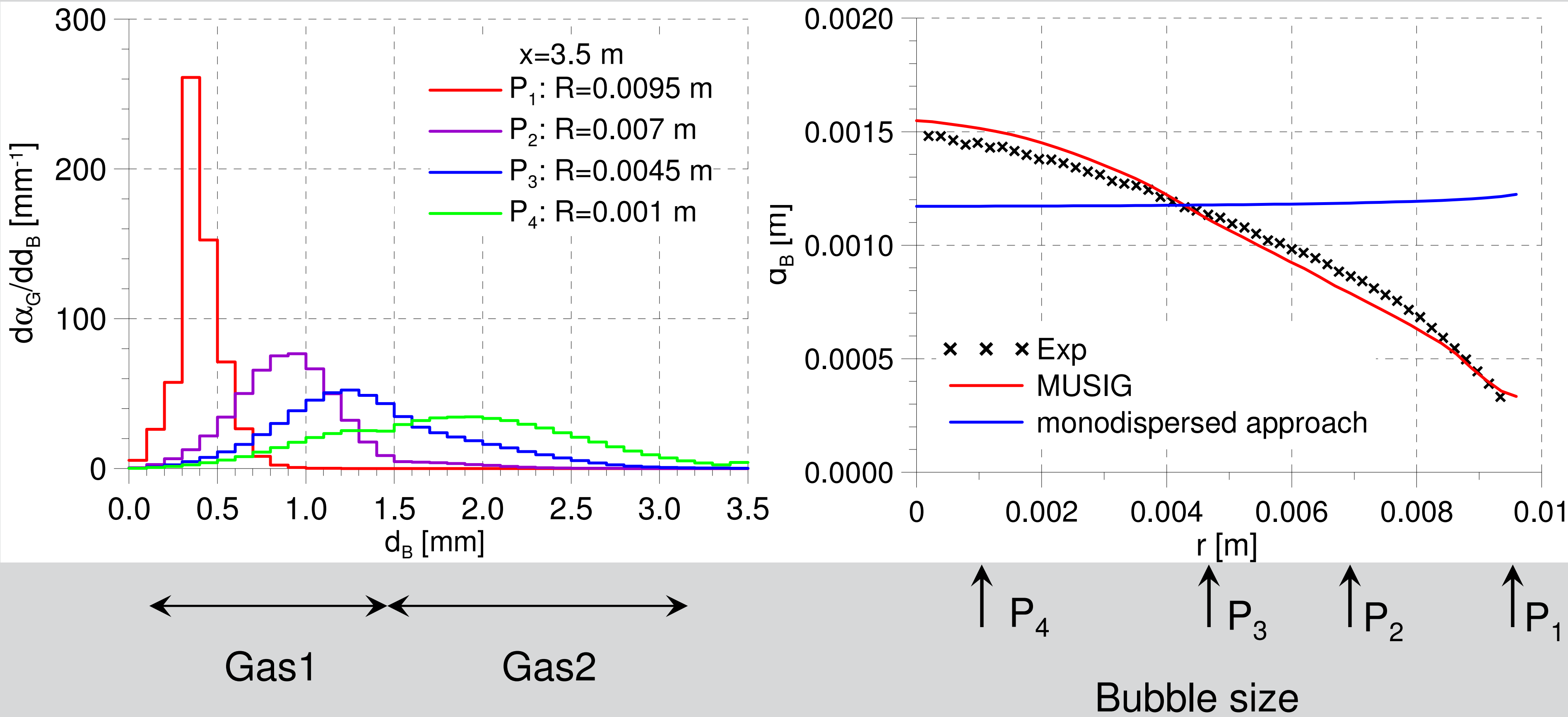






Application of Inhomog. MUSIG

- P = 1.49 MPa; G = 2000 kg m^{-2} s^{-1}; Q = 75 kW m^{-2}; $T_{SAT} - T_{IN}$ = 13.9 K
- 2 disperse phases, 35 MUSIG size groups



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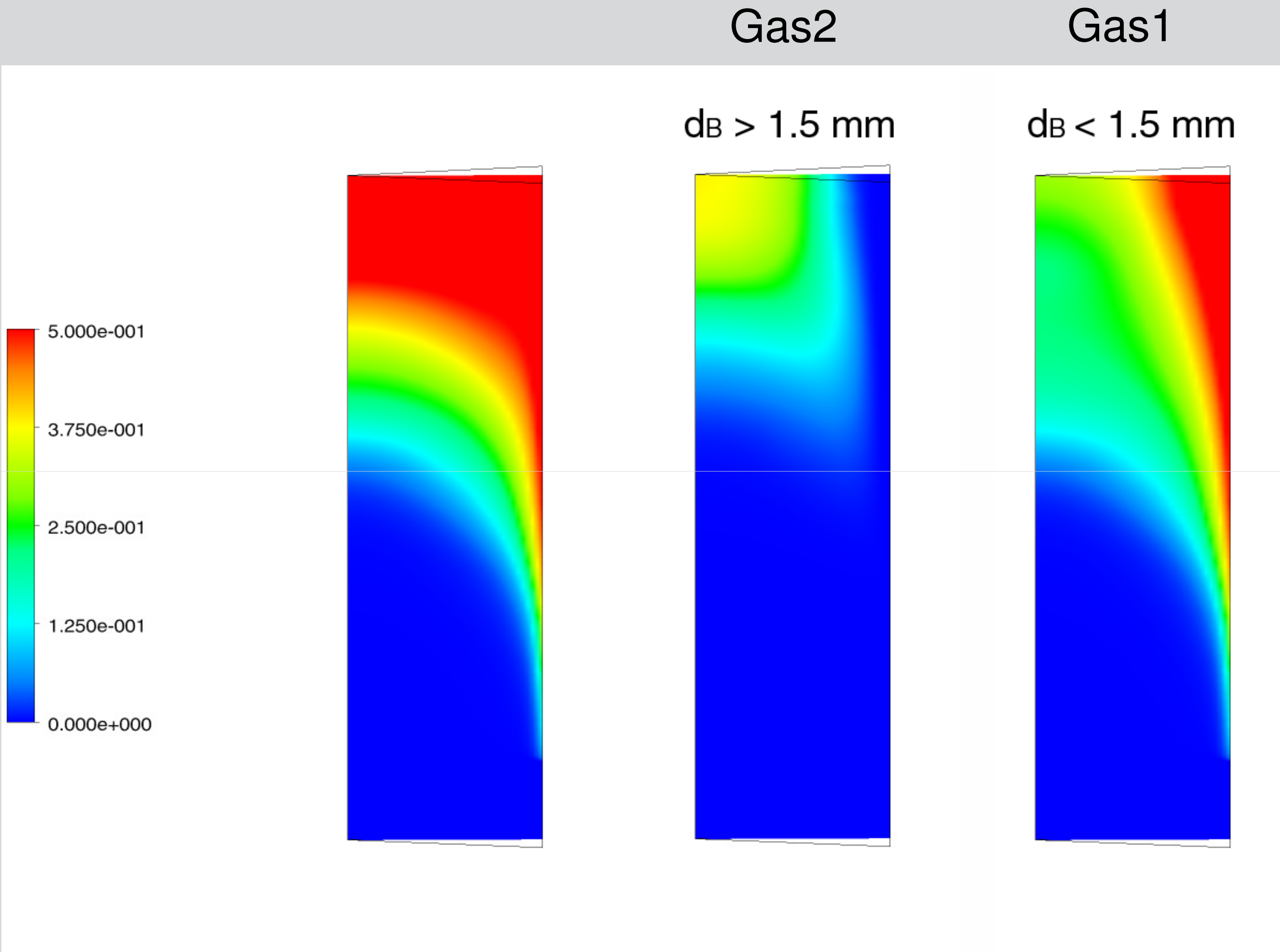
Gas Volume Fraction Distribution



2 dispersed gaseous phases, 10 &15 MUSIG size fractions

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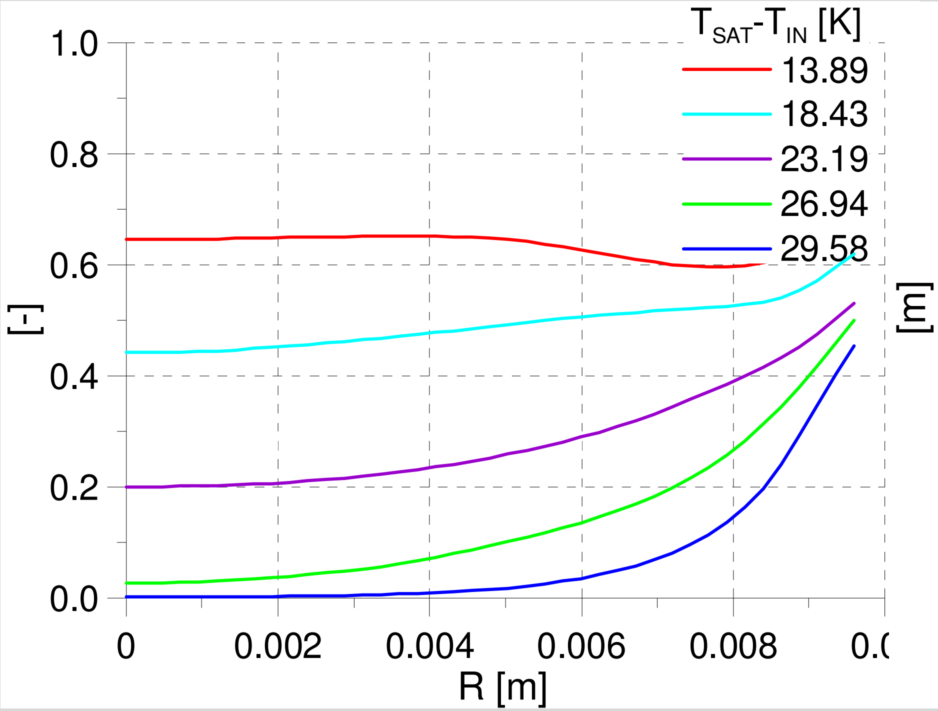
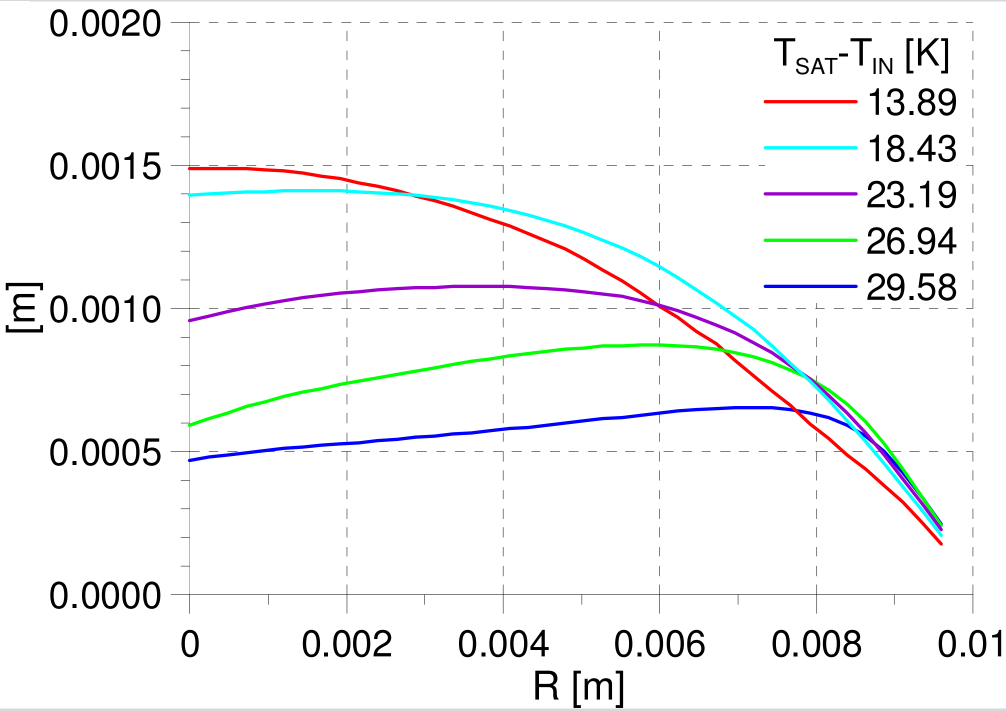
CFD Simulation Results for Variation of Inlet Temperature T_{in}



gas volume fraction



bubble size

- All tests were calculated with the same model parameters
- Shifting of void fraction maximum towards the core can be reproduced

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Summary & Outlook

- **MUSIG-RPI coupling**
  - **Implemented in ANSYS CFX**
  - **Improves the accuracy of the simulations**
  - **Provides more detailed information about bubble size distribution**
  - **Shift of gas void fraction maximum from wall peak to core peak with increased inlet temperature**
- **Homog. model (here) & inhomog. (HZDR) were validated**
- **Open questions, further work necessary:**
  - **Bubble coalescence and fragmentation**
  - **Bubble induced turbulence**

The work was funded by German Federal Ministry of Education and Research

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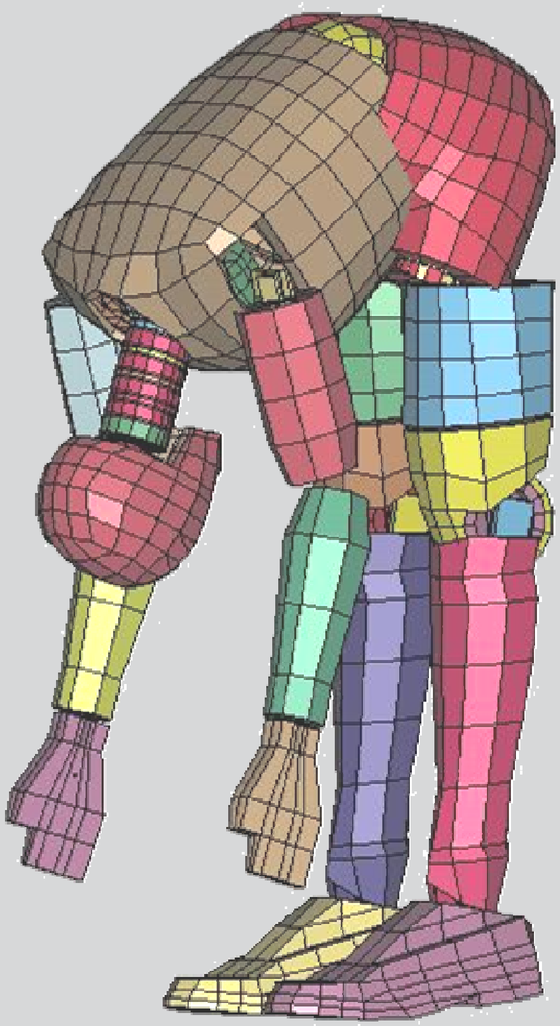

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