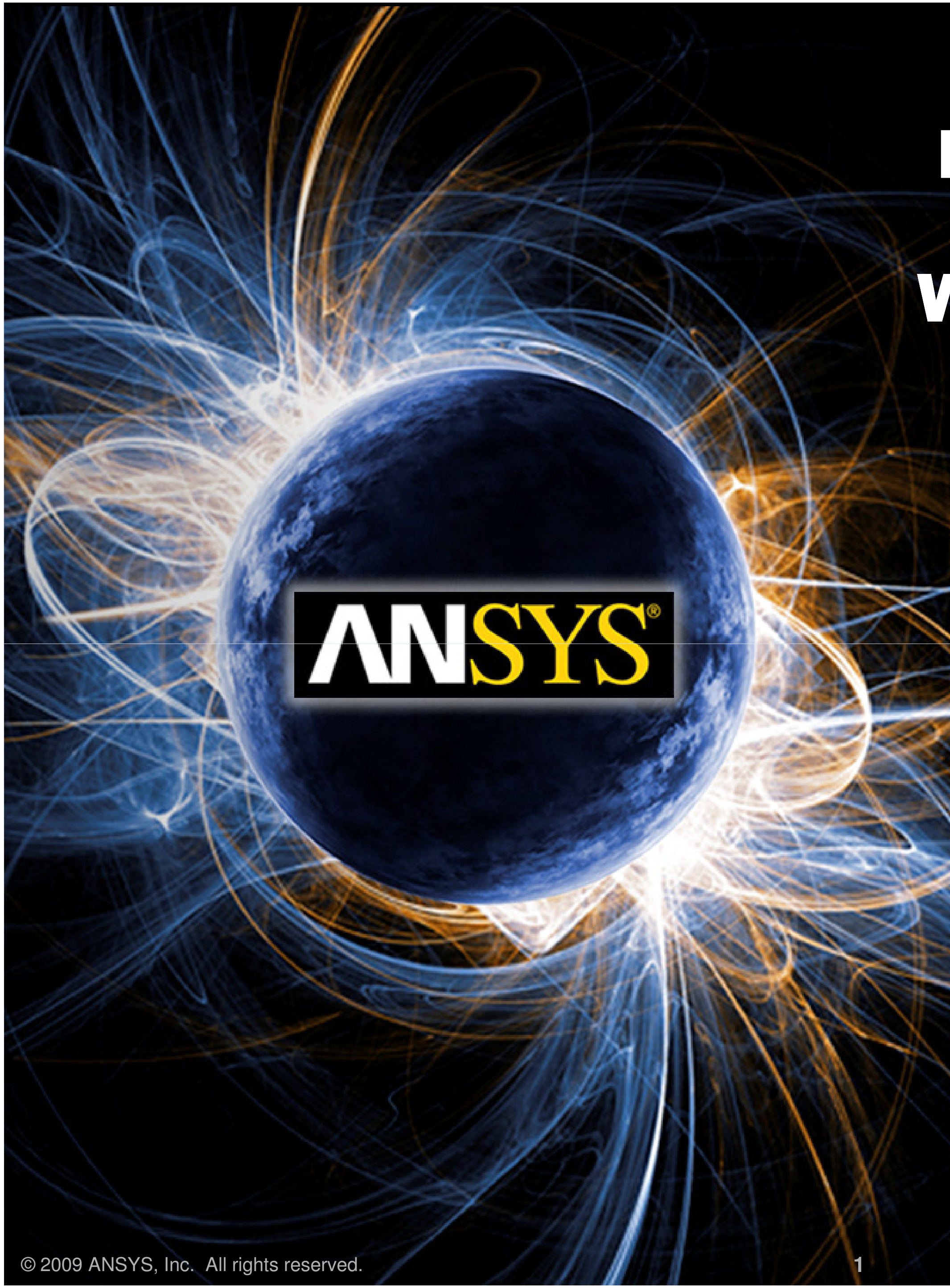

Development and Validation of the Wall Boiling Model in ANSYS CFD

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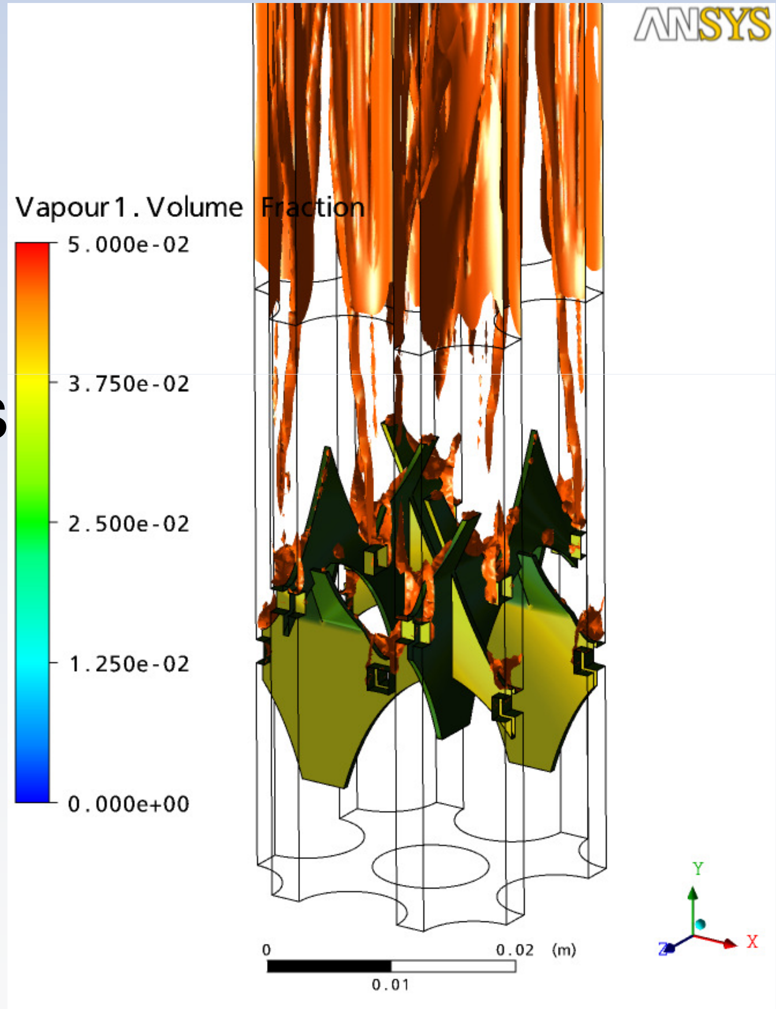
FZ Dresden-Rossendorf (FZD)

Outline

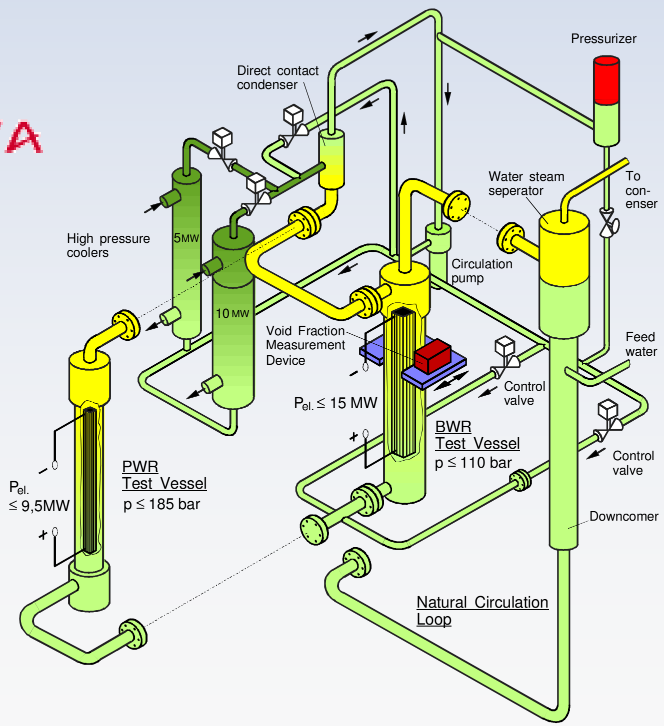
- **Motivation**
- **The wall boiling model in ANSYS CFD**
- **Boiling model validation**
  - Wall boiling in vertical pipes
  - Boiling & recondensation
  - Boiling & CHT
  - FRIGG loop: Boiling in heated rod bundles
- **Summary & Outlook**

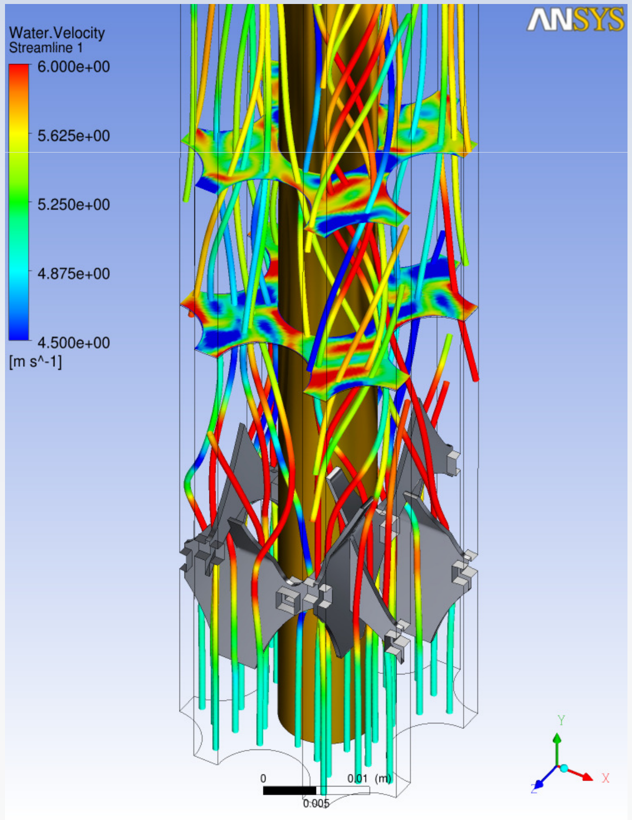


Introduction – Towards CFD for Flows through Nuclear Fuel Assemblies

- Prediction of boiling flow through fuel assemblies
- Optimization of fuel assembly and spacer grid design
- Replacement/supplementation of very expensive experiments by knowledge obtained from CFD simulations

AREVA



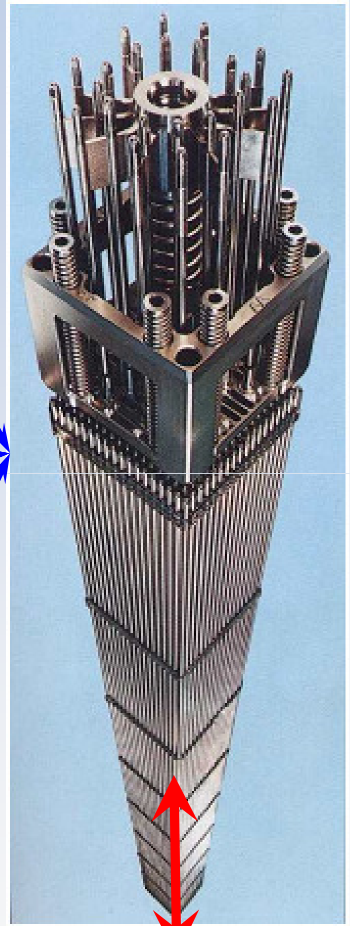


CFD Simulation for Fuel Assemblies in Nuclear Reactors

Material Properties

Turbulence

Multiphase Flow Modeling



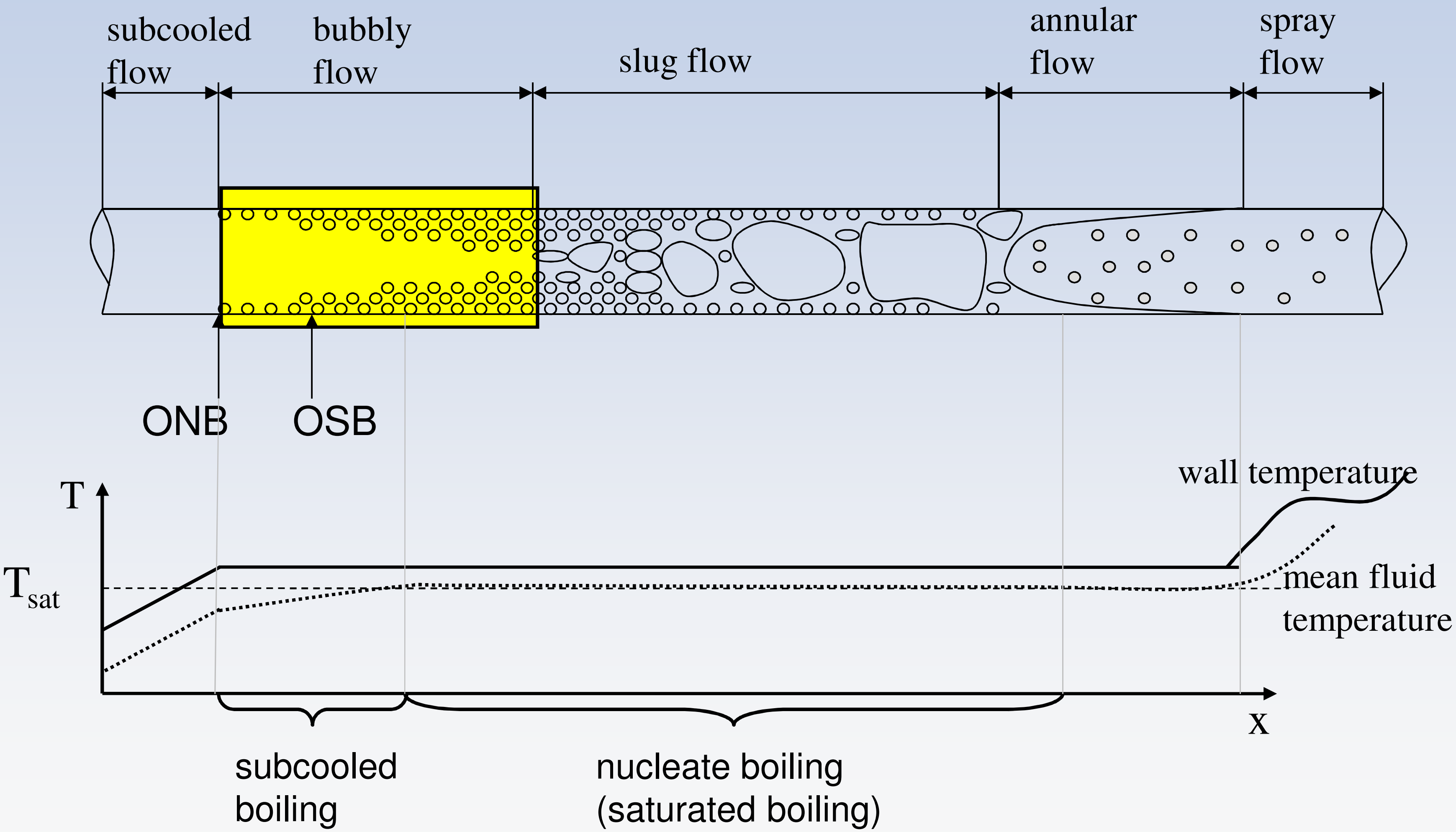
Wall Boiling & Bulk Condensation

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

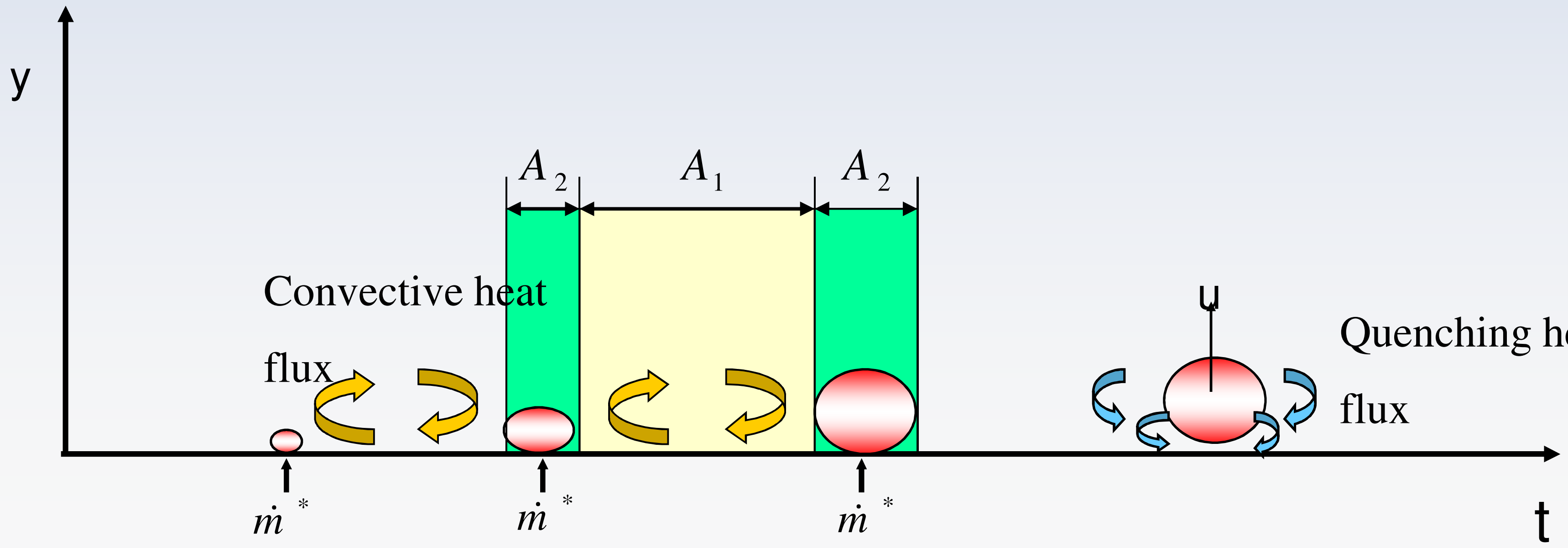
Mechanistic wall heat partioning model:

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

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

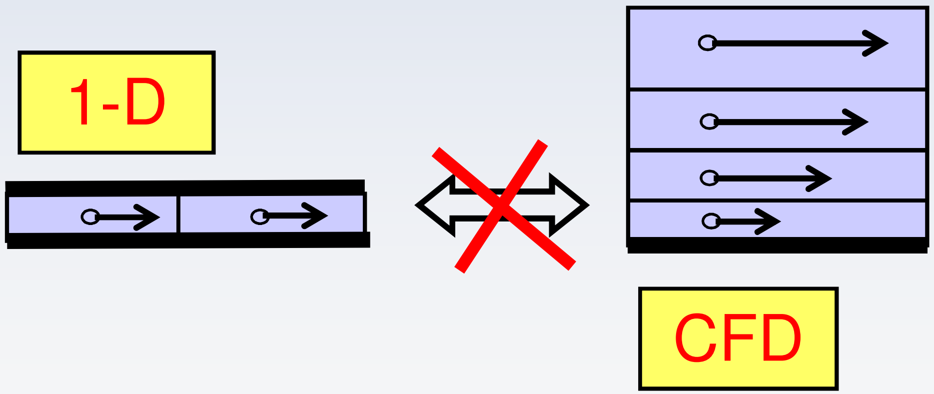


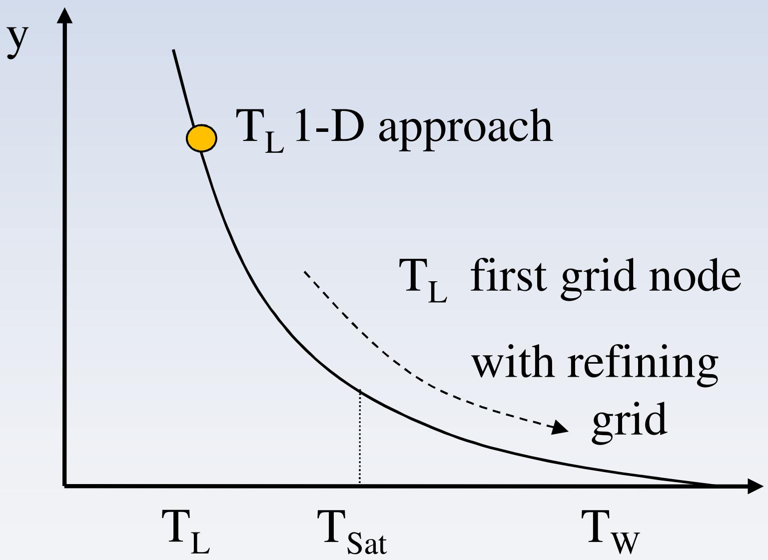
Grid Dependent Correlations

- **Quenching heat flux**

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

$$h_Q = 2f\sqrt{\frac{t_W \rho_L C_{PL} \lambda_L}{\pi}}$$





Grid Dependent Correlations

- **Evaporation heat flux**

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

d_W – bubble departure diameter

n – nucleation site density per m²

f – bubble departure frequency

$$\dot{m} = \frac{\pi\, d_W^3}{6} \rho_G \, f \, n$$

$$d_W = \min\left\{1.4mm, 0.6\,\mathrm{mm} \cdot \exp\left(-\frac{T_S\,[\mathrm{K}] - T_L\,[\mathrm{K}]}{45\,[\mathrm{K}]}\right)\right\}$$

- **small quenching & overestimated evaporation on fine grids**
- **wrong heat flux partitioning**

→ tends to film boiling on fine grids (due to $T_L \rightarrow T_W$)

Revisited RPI Boiling Model

- Grid invariance of the model required
- determine T_L from temperature wall function (Kader, 1981)

$$T^+ = \Pr \cdot y^+ e^{(-\Gamma)} + \left[2.12 \cdot \ln(y^+) + \beta \right] \cdot e^{(-1/\Gamma)}$$

$$y^+ = \frac{\rho_L \cdot \Delta y \cdot u_\tau}{\mu}$$

- from definition of T^+:

$$T^+ = \frac{\rho \cdot c_{PL} \cdot u_\tau}{\dot{q}_W} (T_W - T_L)$$

→ evaluating T^+ at 2 different locations/wall distances y^+

Revisited RPI Boiling Model

- **heat flux in boundary layer identical at both locations**

$$\dot{q}_{W,\, y^+=\text{first cell}} = \frac{\rho \cdot c_{PL} \cdot u_\tau}{T^+_{y^+=\text{first cell}}} (T_W - T_L)_{y^+=\text{first cell}}$$

$$\dot{q}_{W,\, y^+=\text{const}} = \frac{\rho \cdot c_{PL} \cdot u_\tau}{T^+_{y^+=\text{const}}} (T_W - T_L)_{y^+=\text{const}}$$

heat fluxes are equal

$$T_W - T_L \Big|_{y^+=\text{const}} = \frac{T^+_{y^+=\text{const}}}{T^+_{y^+=\text{first cell}}} \cdot \left(T_W - T_L \Big|_{y^+=\text{first cell}} \right)$$

- **additional factor in correlations for** $d_W,\ \dot{q}_F,\ \dot{q}_Q$
- **assumption of y^+_{const}=250; model parameter**
- **Replace (T_W-T_L) in submodel expressions with the above relation**

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

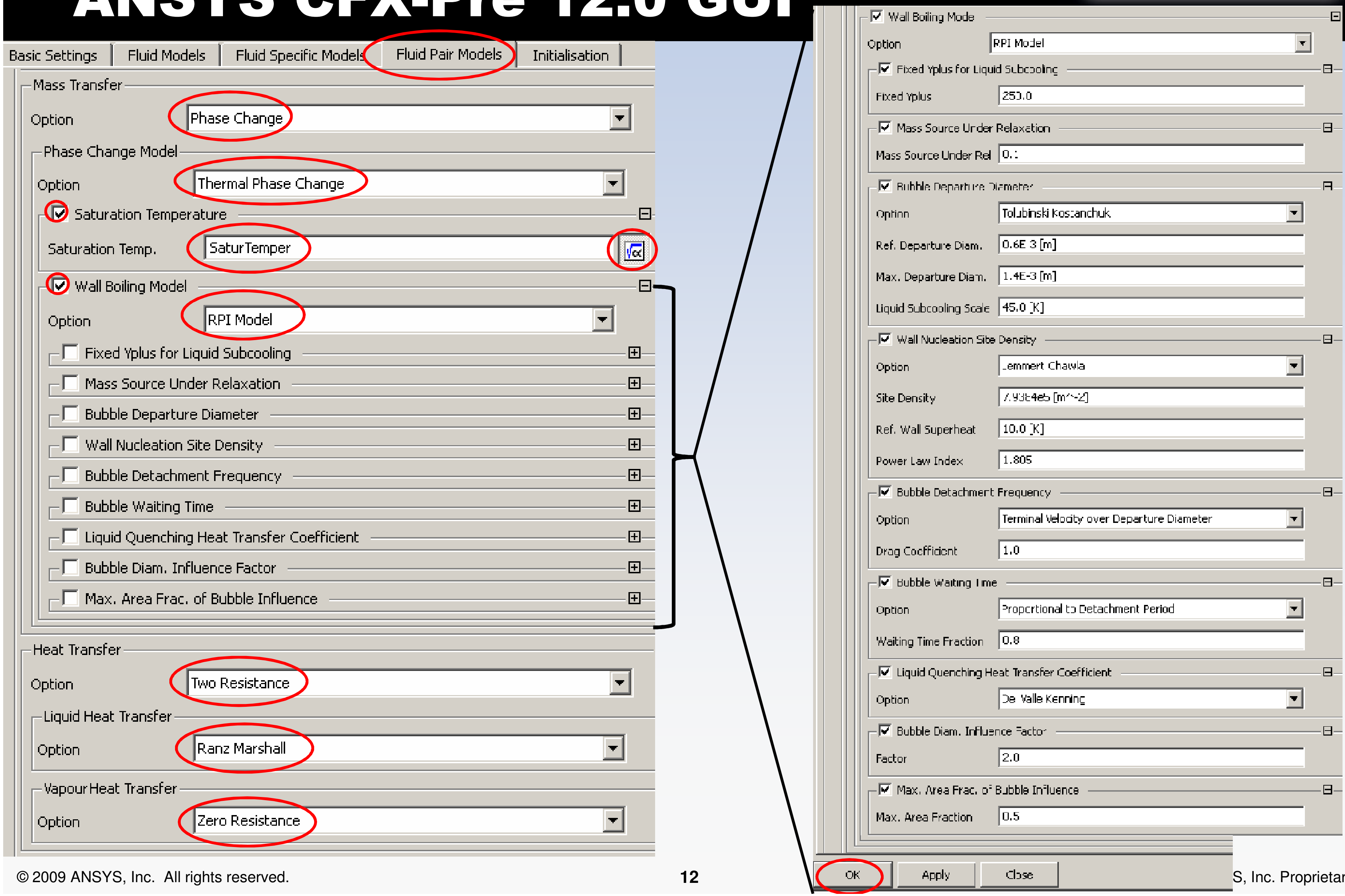
– Bubble waiting time:
  Proportional to Detachment Period, User Defined

– Quenching heat transfer: Del Valle & Kenning, User Defined

– Turbulent Wall Function for liquid convective heat transfer coefficient

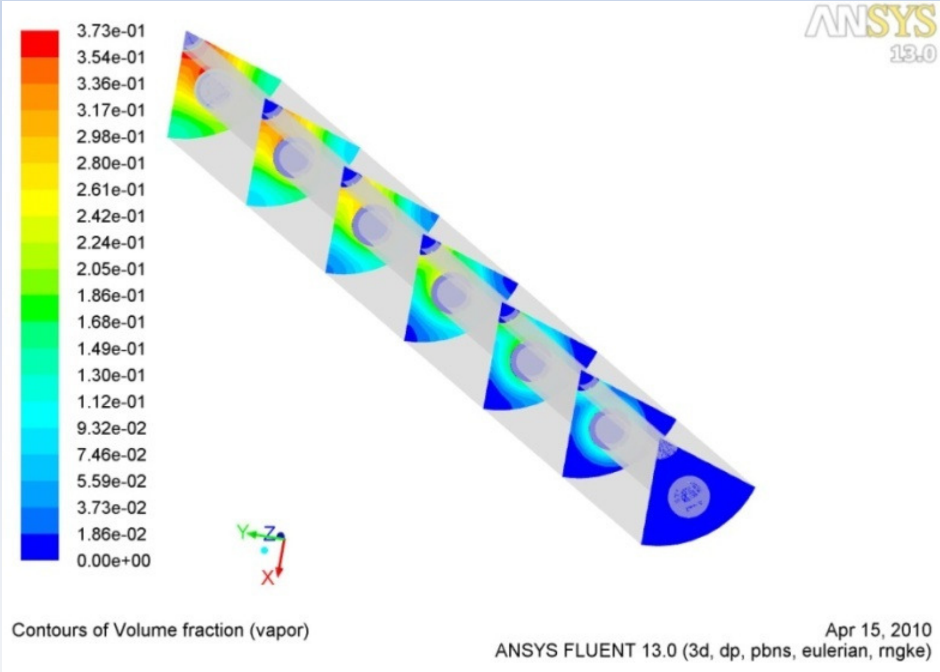
- **Correlation for bulk flow mean bubble diameter required:**
  → e.g. Kurul & Podowski correlation via CCL
- **Supported combination of wall boiling & CHT in the solid**
  – GGI & 1:1 solid-fluid interfaces

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



ANSYS Fluent 13.0
Wall Boiling Modeling

- **Wall boiling**
  - Based on same RPI nucleate boiling & heat flux partitioning model
  - Non-equilibrium subcooled boiling
  - Will support super-heated vapor (convective heat flux to vapor)



Contours of vapor volume fraction in a heated rod bundle

ANSYS CFX R&D
Development Work in Progress

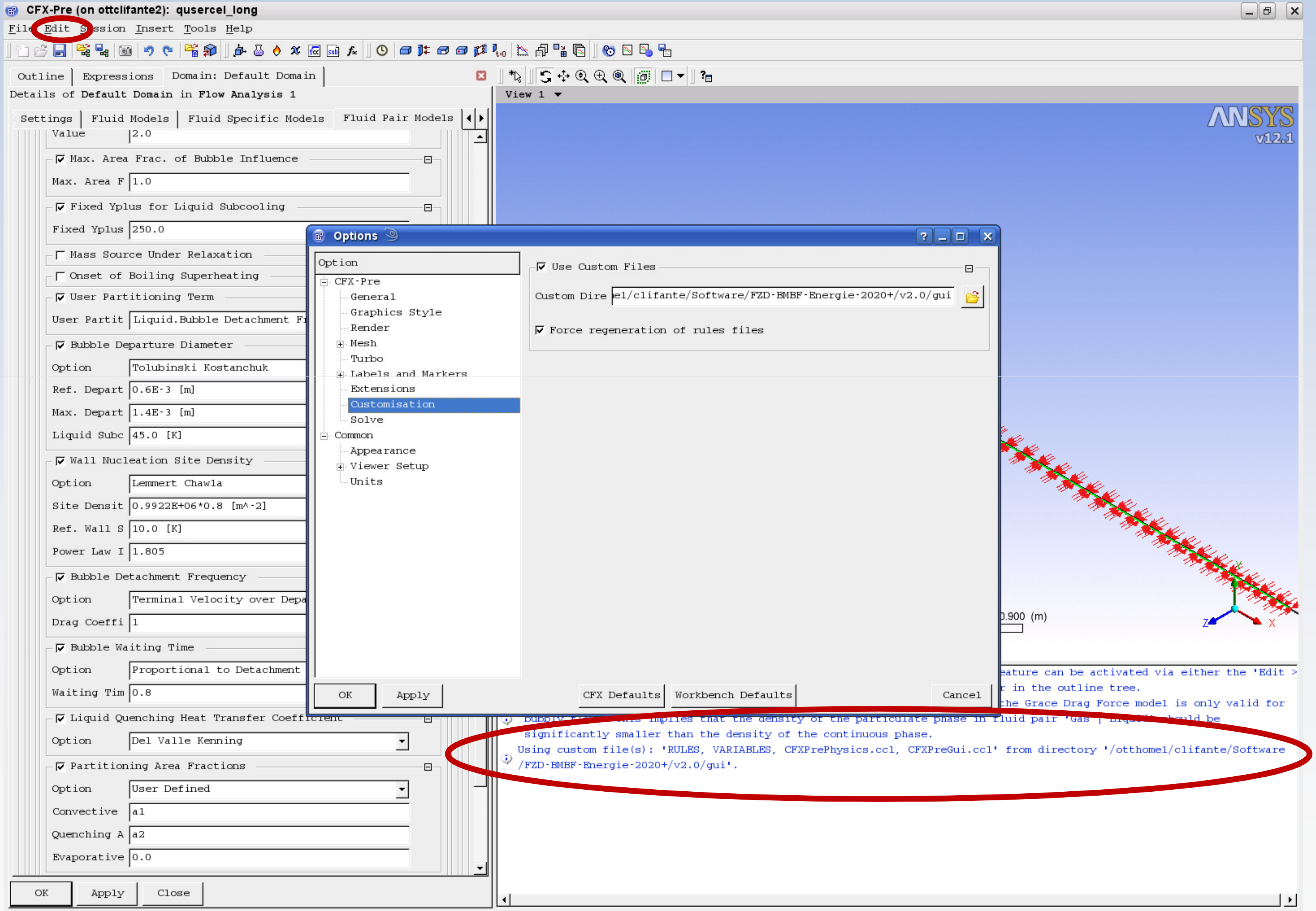
- **Ongoing R&D and development:**
  - Provide more user interfaces to the RPI boiling model
  - User defined area fractions A_1 and A_2
  - User defined terms for convective, quenching and evaporative heat fluxes Q_F, Q_Q, Q_E
  - User defined 4th component of wall heat partitioning, e.g. heat flux to vapor
  - CFX5Pre GUI extension
  - Extended output to CFD-Post
- **All extensions are part of a collaborative R&D project with FZD → customized CFX solver**

New Capabilities: CCL Access to Area Fractions

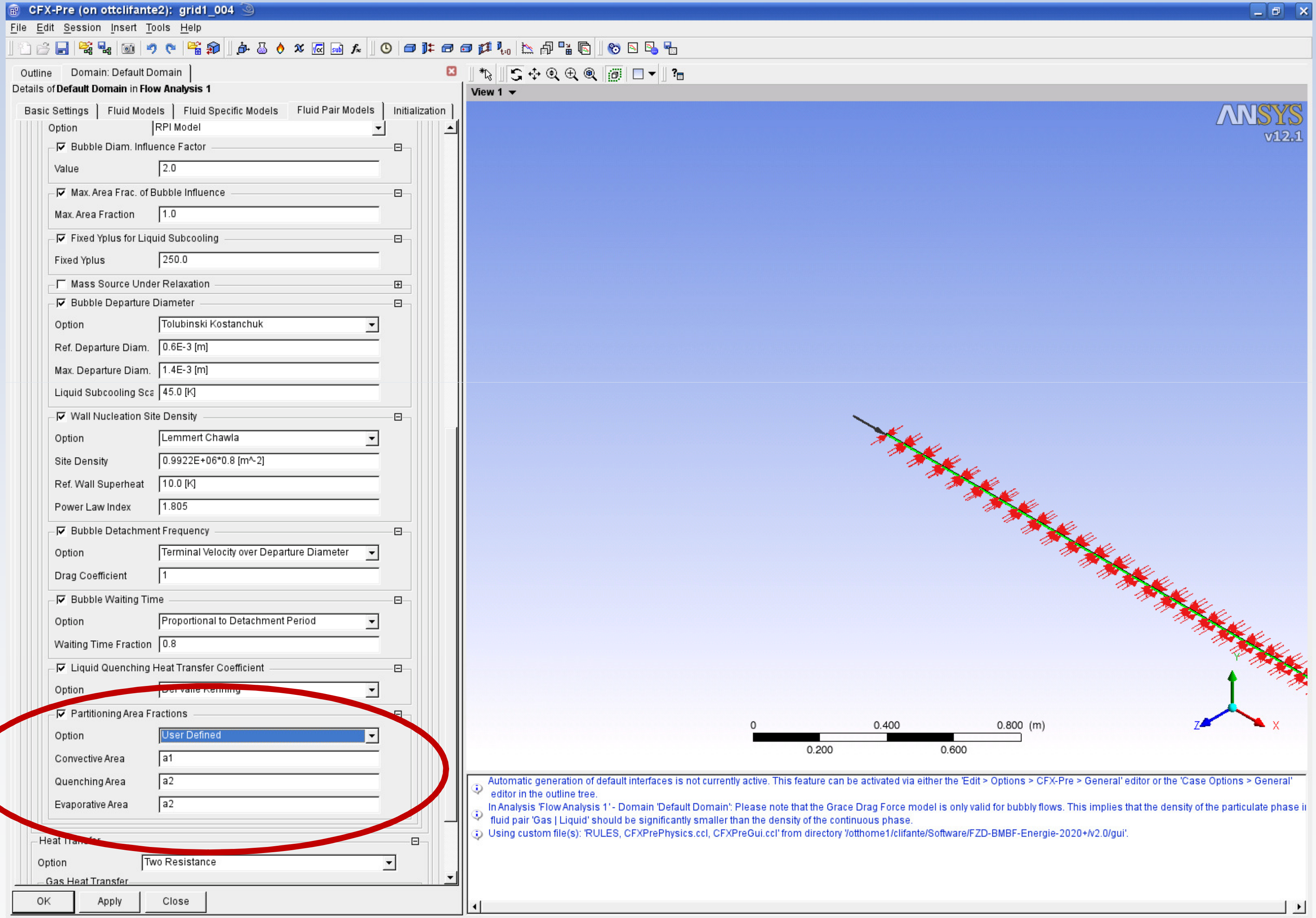
```
MASS TRANSFER:
  Option = Phase Change
  PHASE CHANGE MODEL:
    Option = Thermal Phase Change
    WALL BOILING MODEL:
      Bubble Diameter Influence Factor = 2.0
      Fixed Yplus for Liquid Subcooling = 250.0
      Maximum Area Fraction of Bubble Influence = 1.0
      Option = RPI Model
      BUBBLE DEPARTURE DIAMETER:
        Liquid Subcooling Scale = 45.0 [K]
        Maximum Departure Diameter = 1.4E-3 [m]
        Option = Tolubinski Kostanchuk
        Reference Departure Diameter = 0.6E-3 [m]
      END
      BUBBLE DETACHMENT FREQUENCY:
        Drag Coefficient = 1
        Option = Terminal Velocity over Departure Diameter
      END
      BUBBLE WAITING TIME:
        Option = Proportional to Detachment Period
        Waiting Time Fraction = 0.8
      END
      LIQUID QUENCHING HEAT TRANSFER COEFFICIENT:
        Option = Del Valle Kenning
      END
      PARTITIONING AREA FRACTIONS:
        Convective Area = a1
        Evaporative Area = a2
        Option = User Defined
        Quenching Area = a2
      END
      WALL NUCLEATION SITE DENSITY:
        Option = Lemmert Chawla
        Power Law Index = 1.805
        Reference Nucleation Site Density = 0.9922E+06*0.8 [m^-2]
        Reference Wall Superheat = 10.0 [K]
      END
    END
  END
END
```

- **WALL BOILING MODEL**
  - **PARTITIONING AREA FRACTIONS**
  - **Option = *Standard / User Defined***
  - **Under *User Defined* *convective*, *quenching* and *evaporative* area can be introduced**

New capabilities: CFX5Pre GUI Extension



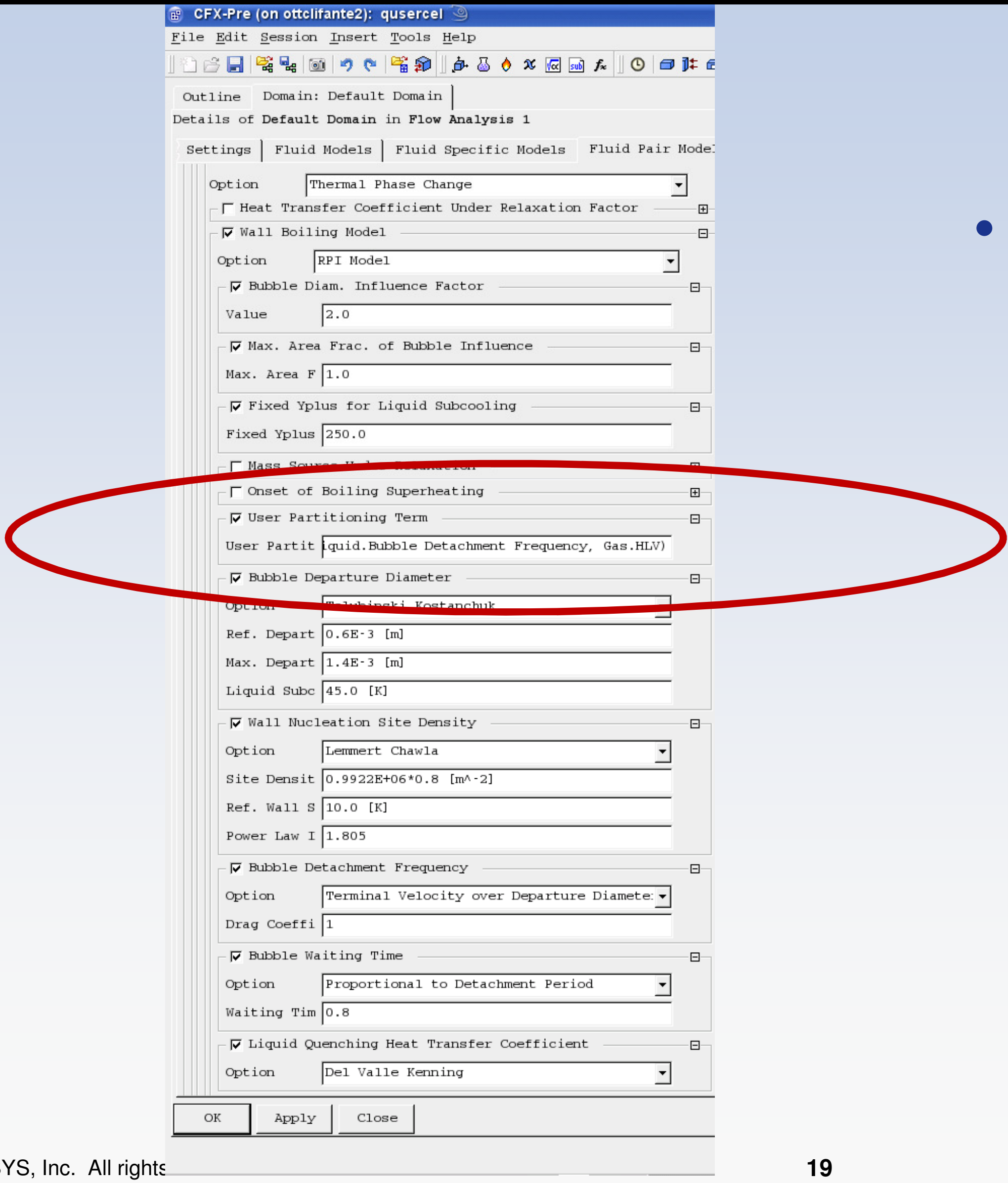
New capabilities: CFX5Pre GUI Extension



CCL & User Routine for 4th Wall Heat Partitioning Component

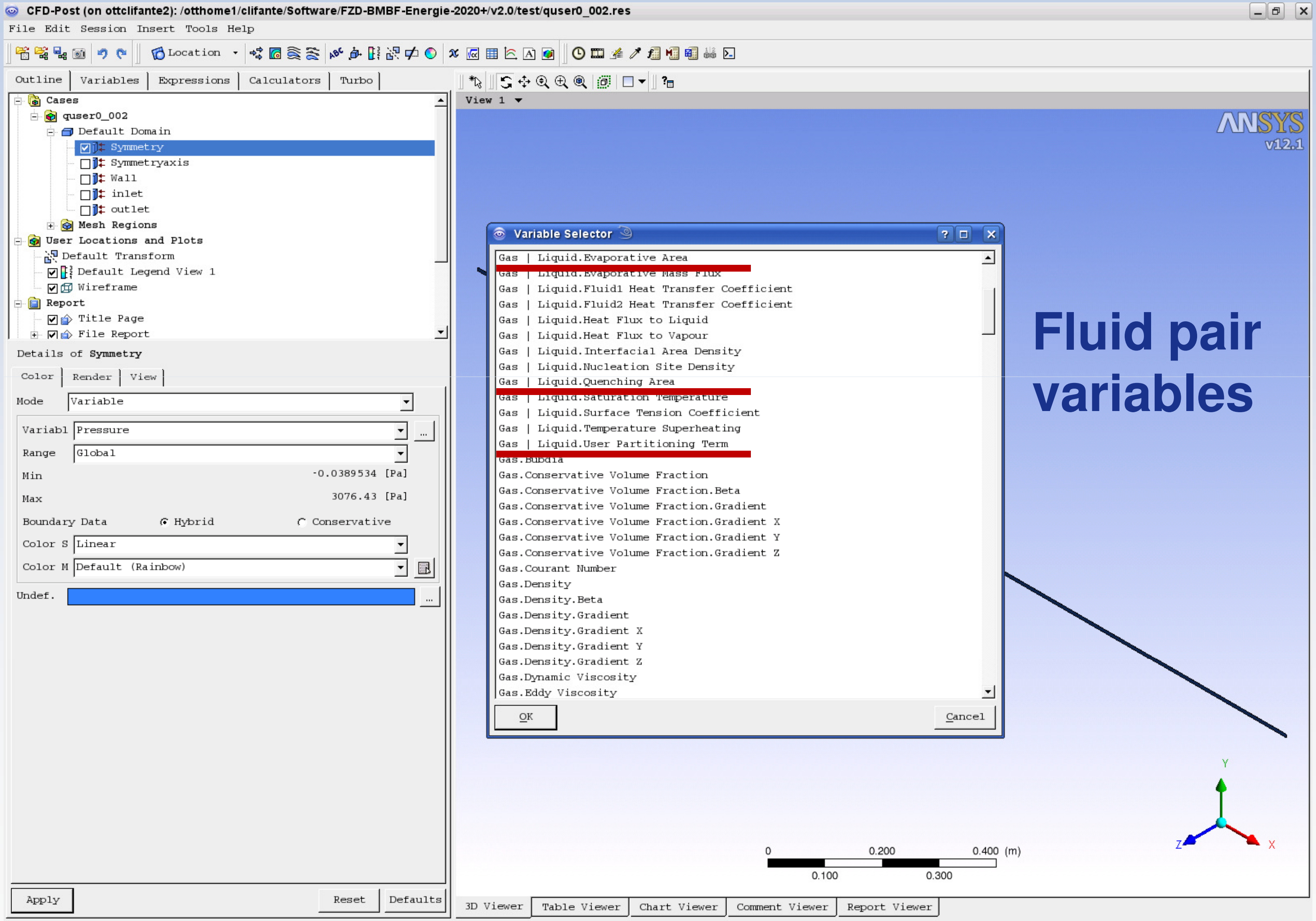
```
      Option = Fluid Dependent
    END
  END
  FLUID PAIR: Gas | Liquid
    INTERPHASE HEAT TRANSFER:
      Option = Two Resistance
      FLUID1 INTERPHASE HEAT TRANSFER:
        Option = Zero Resistance
      END
      FLUID2 INTERPHASE HEAT TRANSFER:
        Option = Ranz Marshall
      END
    END
    INTERPHASE TRANSFER MODEL:
      Interfacial Area Density = AreaDensity
      Maximum Volume Fraction for Area Density = MaxVFforArea
      Minimum Volume Fraction for Area Density = MinVFforArea
      Option = Particle Model
    END
    MASS TRANSFER:
      Option = Phase Change
      PHASE CHANGE MODEL:
        Option = Thermal Phase Change
        WALL BOILING MODEL:
          Bubble Diameter Influence Factor = 2.0
          Fixed Yplus for Liquid Subcooling = 250.0
          Maximum Area Fraction of Bubble Influence = 1.0
          Option = RPI Model
          User Partitioning Term = USERPARTTERM(Gas | Liquid.Bubble \
            Departure Diameter,Gas | Liquid.Nucleation Site Density, Gas | \
            Liquid.Temperature Superheating, Gas | Liquid.Temperature \
            Subcooling, Gas.Density,Gas | Liquid.Bubble Detachment \
            Frequency, Gas.HLV)
          BUBBLE DEPARTURE DIAMETER:
            Liquid Subcooling Scale = 45.0 [K]
            Maximum Departure Diameter = 1.4E-3 [m]
            Option = Tolubinski Kostanchuk
            Reference Departure Diameter = 0.6E-3 [m]
          END
          BUBBLE DETACHMENT FREQUENCY:
            Drag Coefficient = 1
            Option = Terminal Velocity over Departure Diameter
          END
          BUBBLE WAITING TIME:
            Option = Proportional to Detachment Period
            Waiting Time Fraction = 0.8
          END
          LIQUID QUENCHING HEAT TRANSFER COEFFICIENT:
            Option = Del Valle Kenning
          END
          PARTITIONING AREA FRACTIONS:
            Convective Area = a1
            Evaporative Area = 0.0
            Option = User Defined
            Quenching Area = a2
          END
```

CCL & User Routine for 4th Wall Heat Partitioning Component



- **Customization of CFX5Pre for the extension of the RPI wall heat flux partitioning algorithm with a 4th component of the wall heat flux splitting**

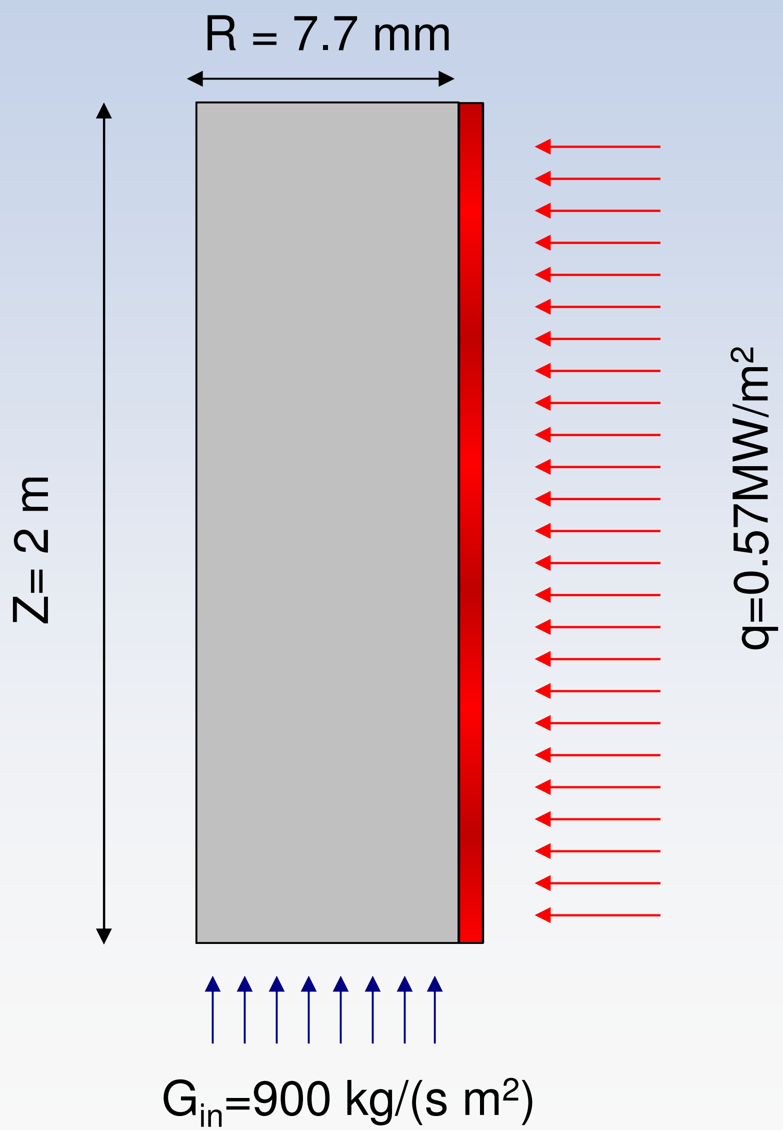
Extended CFX5Post Output



Fluid pair variables

The Bartolomej et al. Testcase (1967,1982)

The Bartolomej Test Case



Variable	Value
P	4.5MPa
R	7.7 mm
G_{in}	900 kg/(s m2)
$\dot{q}$	0.57MW/m2
Subcooling	58.2 K

Multiphase Flow Model

- **Steam-Water 2-phase flow:**
  - Water: continuous phase
  - Water Steam: disperse bubbles (particle model)
- **Material properties (EOS):**
  - IAPWS-IF97 water - water steam property tables
- **Modified law for interfacial area**
  - Kurul & Podowski type bulk bubble diameter: $d_B=f(T_{sub})$
  - Accounting for higher volume fraction of the steam phase
- **Turbulence Model**
  - SST turbulence model for continuous phase
  - 0-eq. disperse phase turb. model + Sato bubble induced turbulence

Inter-Phase Mass, Momentum and Energy Transfer

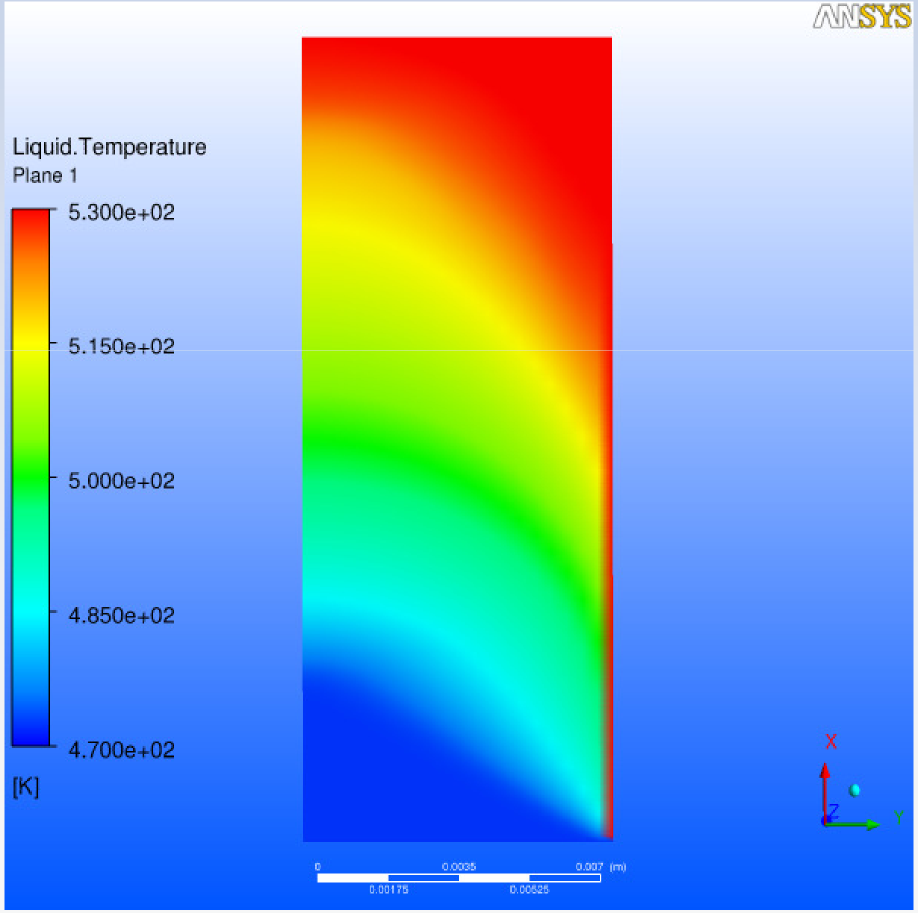
- **Mass transfer model**
  - Thermal Phase Change Model (bulk boiling/condensation model)
  - RPI wall boiling model
- **Momentum transfer models**
  - Grace drag
  - FAD turbulent dispersion force
  - Tomiyama lift force
  - Wall lubrication force (none, Antal, Frank, Tomiyama)
- **Heat transfer models**
  - Water: Thermal Energy
  - Water Steam: Saturation temperature
  - Two resistance model
  - Ranz Marshall correlation for bubble heat transfer

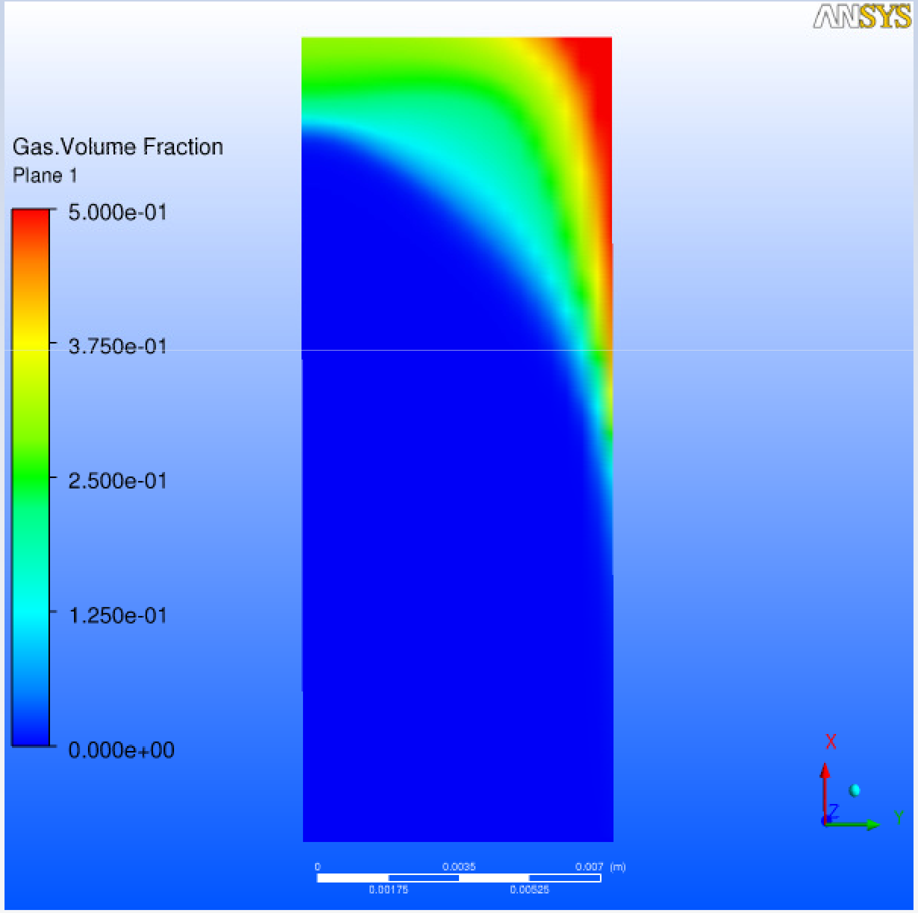
Numerical Grids

- **Validation on mesh hierarchy with regular refinement factor of 4 (2d meshes)**

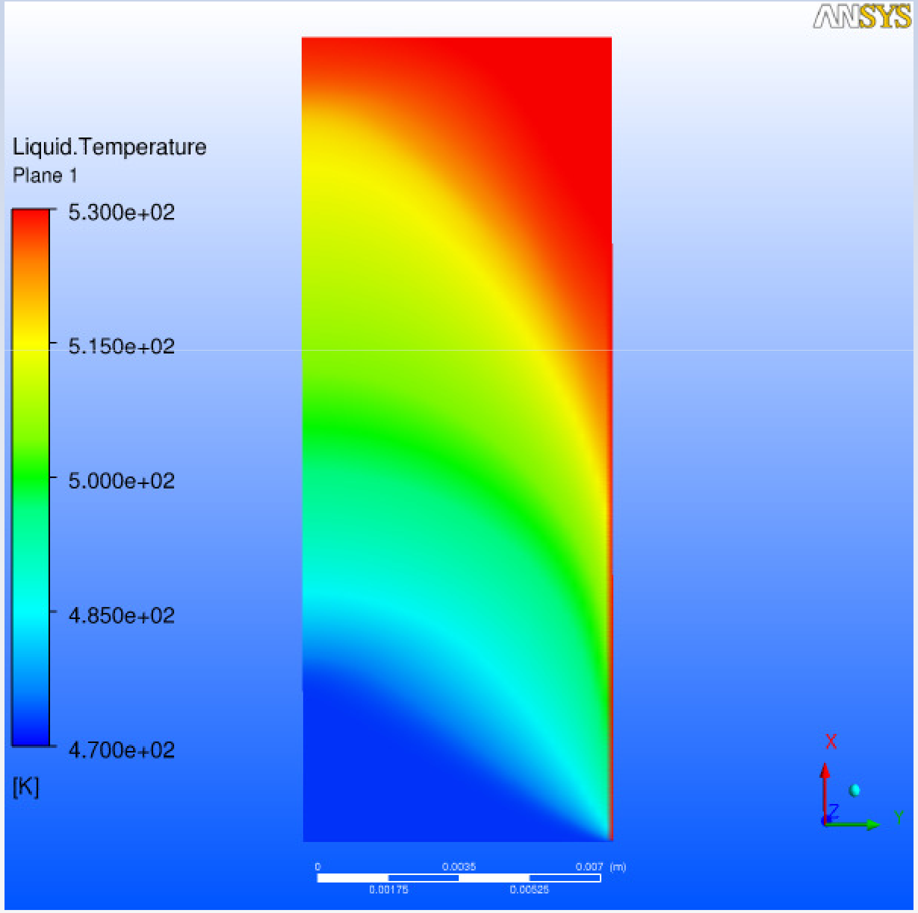
Grid	Grid1	Grid2	Grid3
# Nodes (uniform)	20x150	40x300	80x600
Max y^+	264	133	69
Δt [s]	10^{-2}	10^{-3}	5×10^{-4}

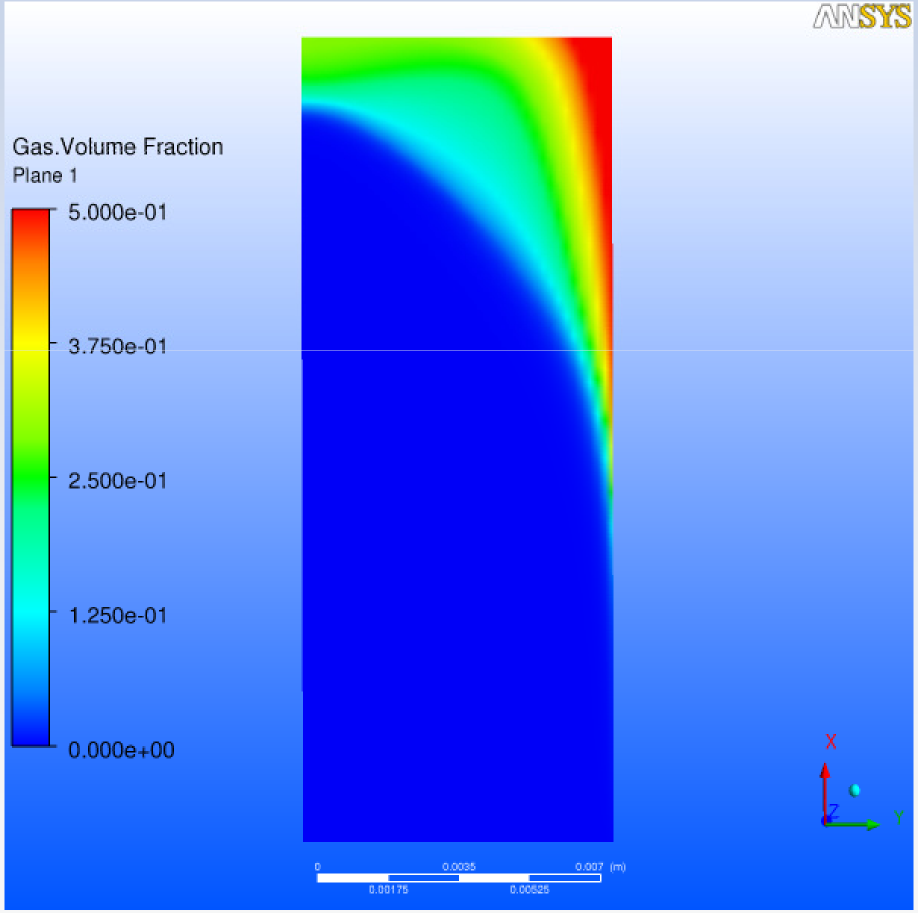
Grid1


Liquid.Temperature
Plane 1
5.300e+02
5.150e+02
5.000e+02
4.850e+02
4.700e+02
[K]
0
0.0035
0.007 (m)
0.00175
0.00525
X
Z
Y

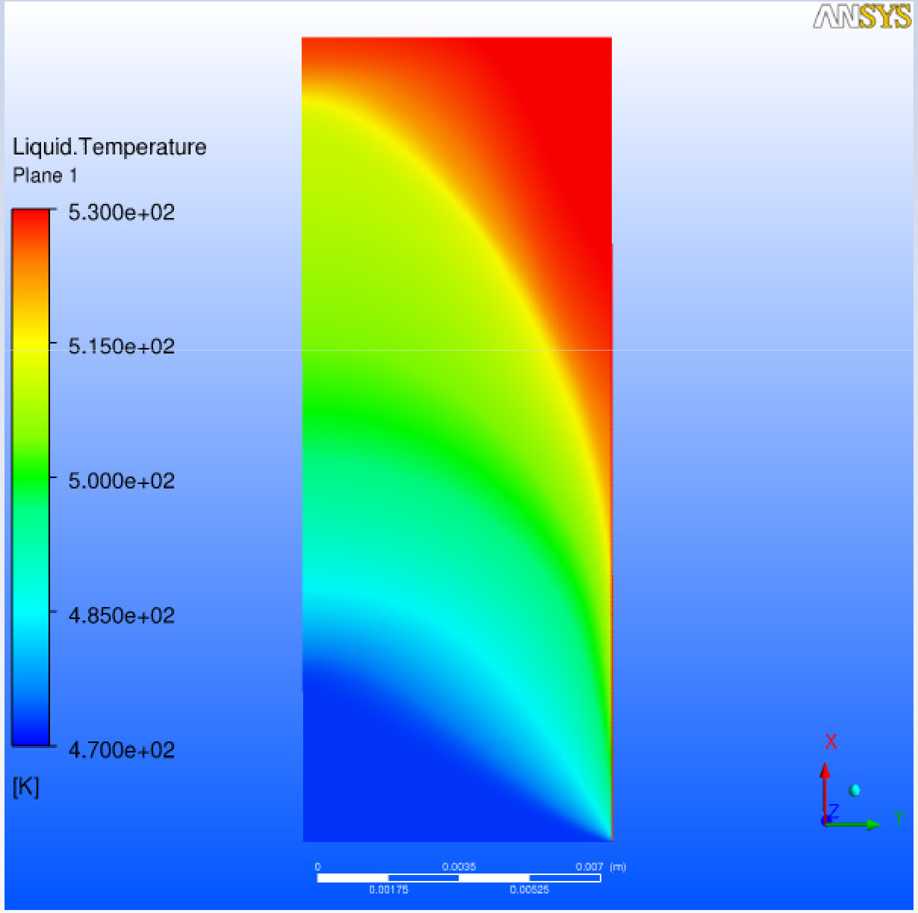

Gas.Volume Fraction
Plane 1
5.000e-01
3.750e-01
2.500e-01
1.250e-01
0.000e+00
0
0.0035
0.007 (m)
0.00175
0.00525
X
Z
Y

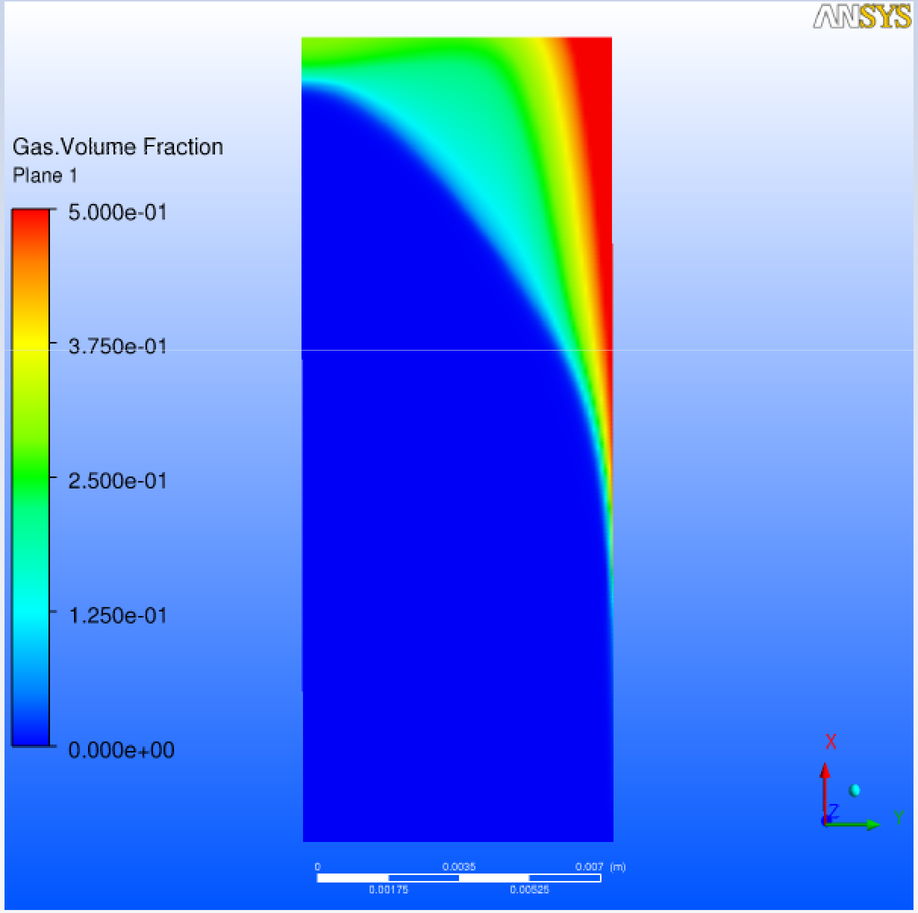
Grid 2


Liquid.Temperature
Plane 1
5.300e+02
5.150e+02
5.000e+02
4.850e+02
4.700e+02
[K]
0
0.0035
0.007 (m)
0.00175
0.00525

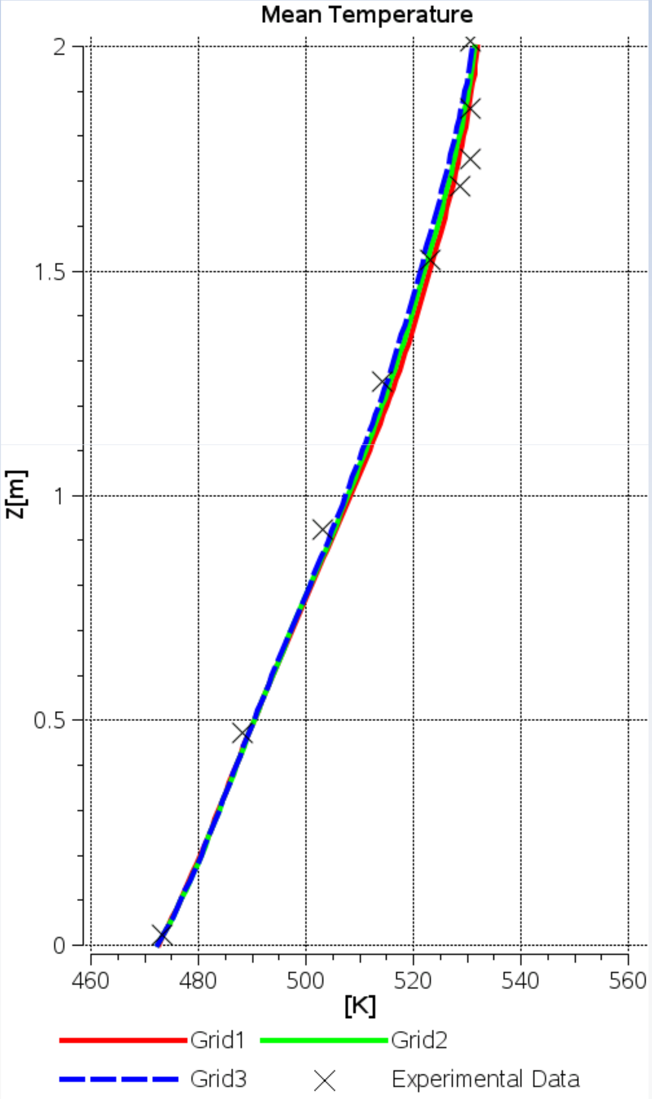

Gas.Volume Fraction
Plane 1
5.000e-01
3.750e-01
2.500e-01
1.250e-01
0.000e+00
0
0.0035
0.007 (m)
0.00175
0.00525

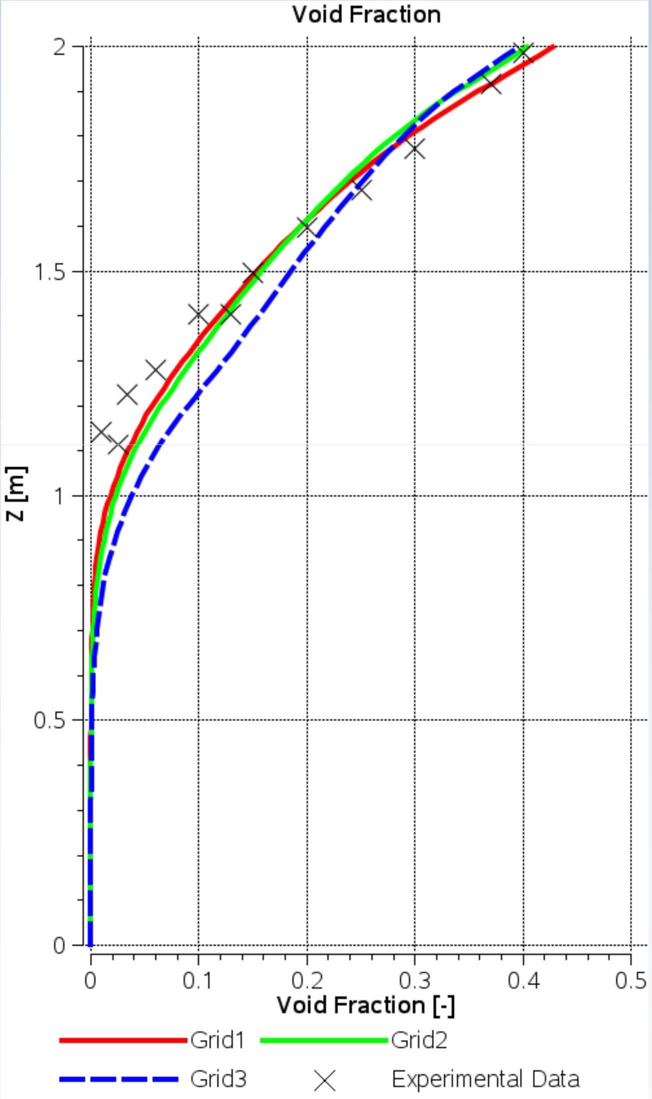
Grid 3


Liquid.Temperature
Plane 1
5.300e+02
5.150e+02
5.000e+02
4.850e+02
4.700e+02
[K]
0
0.0035
0.007 (m)
0.00175
0.00525
X
Y
Z


Gas.Volume Fraction
Plane 1
5.000e-01
3.750e-01
2.500e-01
1.250e-01
0.000e+00
0
0.0035
0.007 (m)
0.00175
0.00525
X
Y
Z

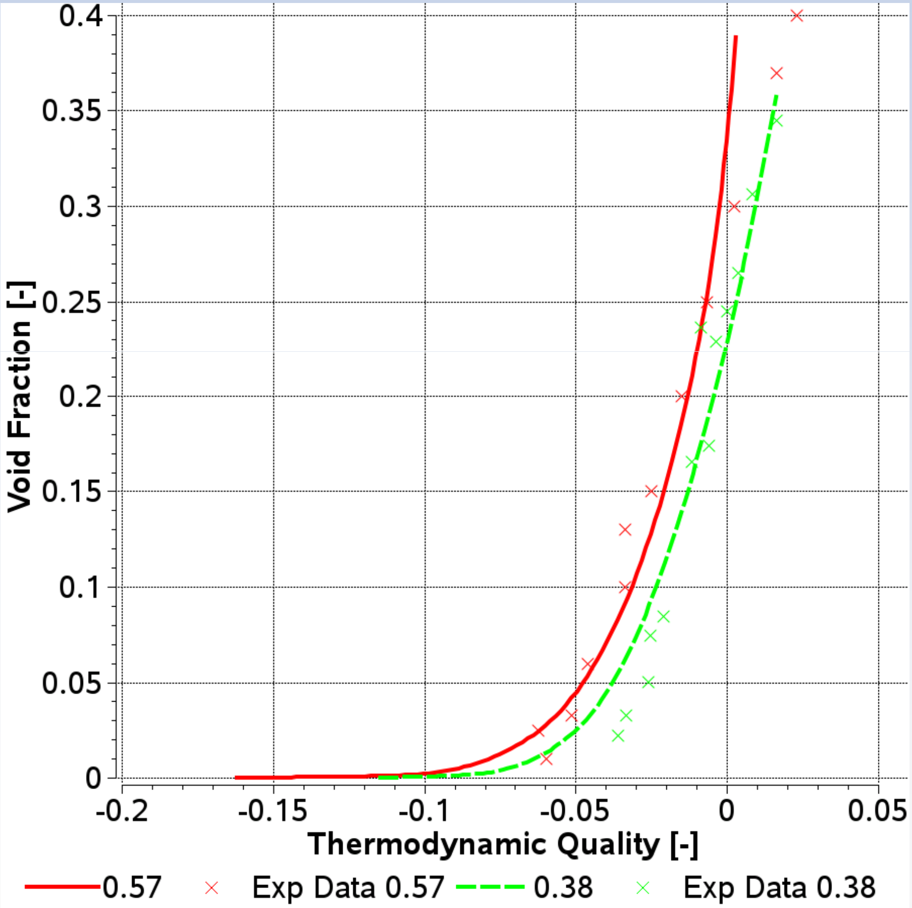
Comparison to Experimental Data



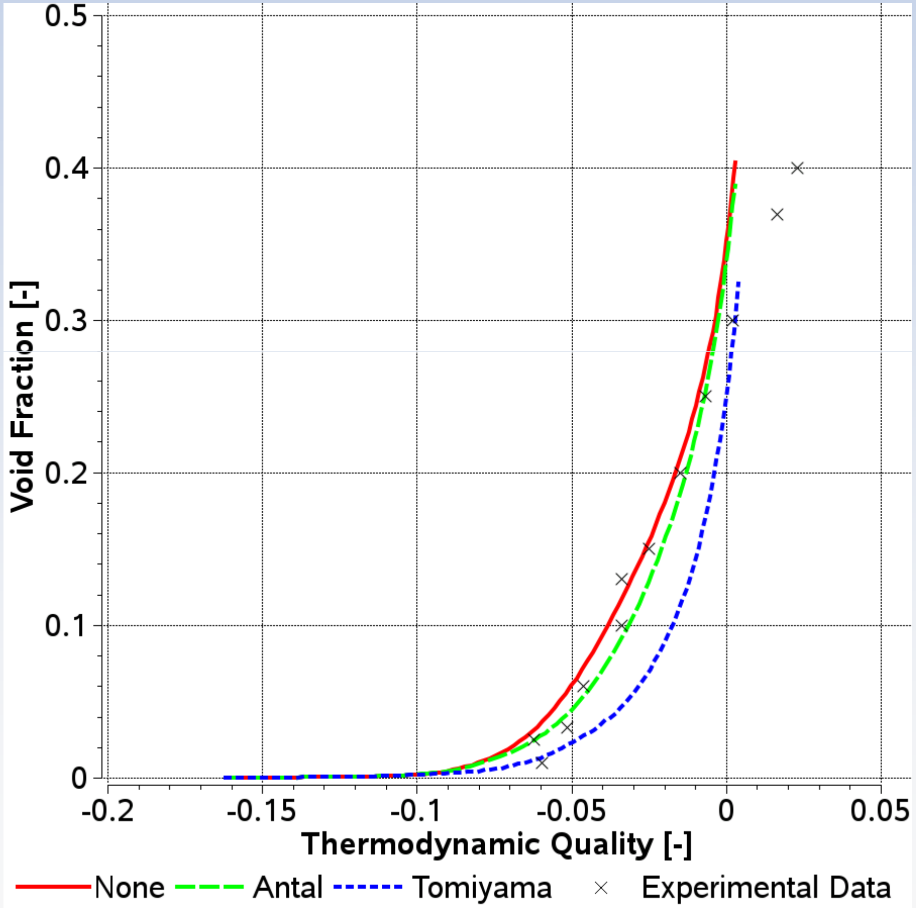


Comparison to Experimental Data - Parameter & Model Variation

Influence of wall heat flux:



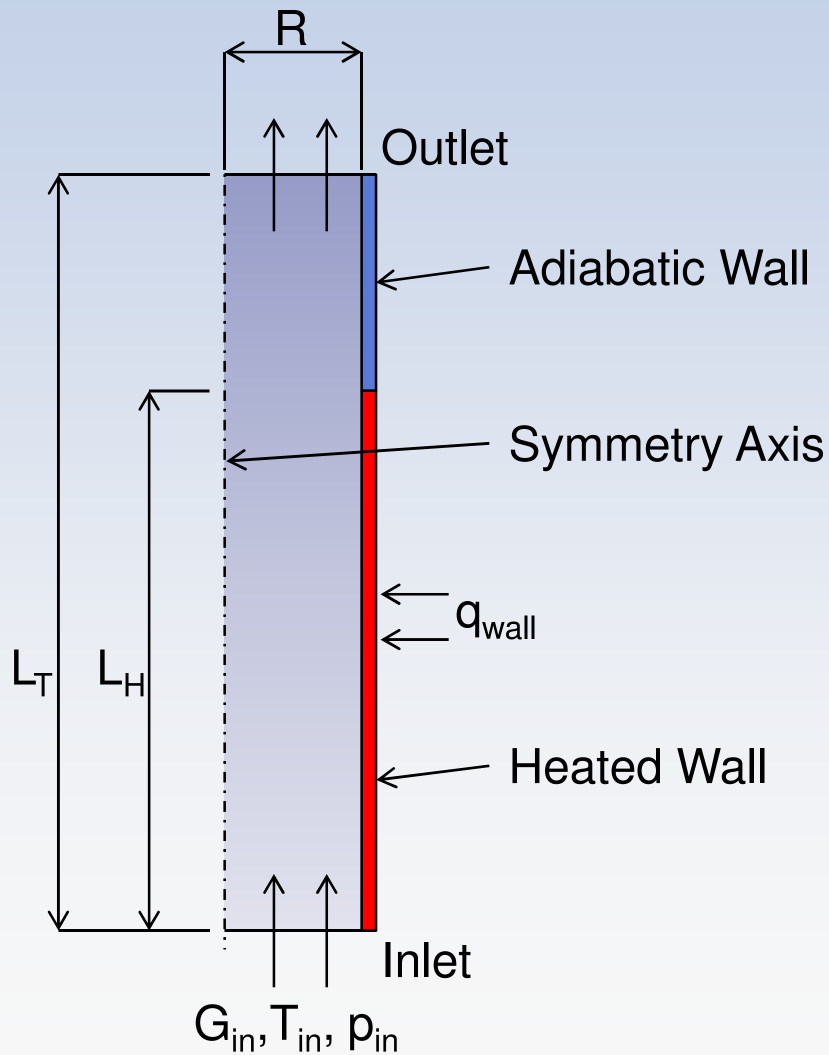
Influence of wall lubrication force model:



The Bartolomej et al. Testcase with Recondensation
(Bartolomeij et al. (1980))

Geometry & Flow Parameters

- **Geometry**
  - Pipe flow; axial symmetry
  - Inner radius of pipe **R = 6.015 mm**
  - Total pipe length **L_T= 1.4 m**
  - Heated section length **L_H= 1.0 m**
- **Flow parameters**
  - Upward directed water flow
  - Pressure @Inlet **p_{in} = 6.89 Mpa**
  - Parameter Investigation
    - Mass flux @Inlet **G_{in}**
    - Liquid Temperature @Inlet **T_{in}**
    - Wall heat flux **q_{wall}**



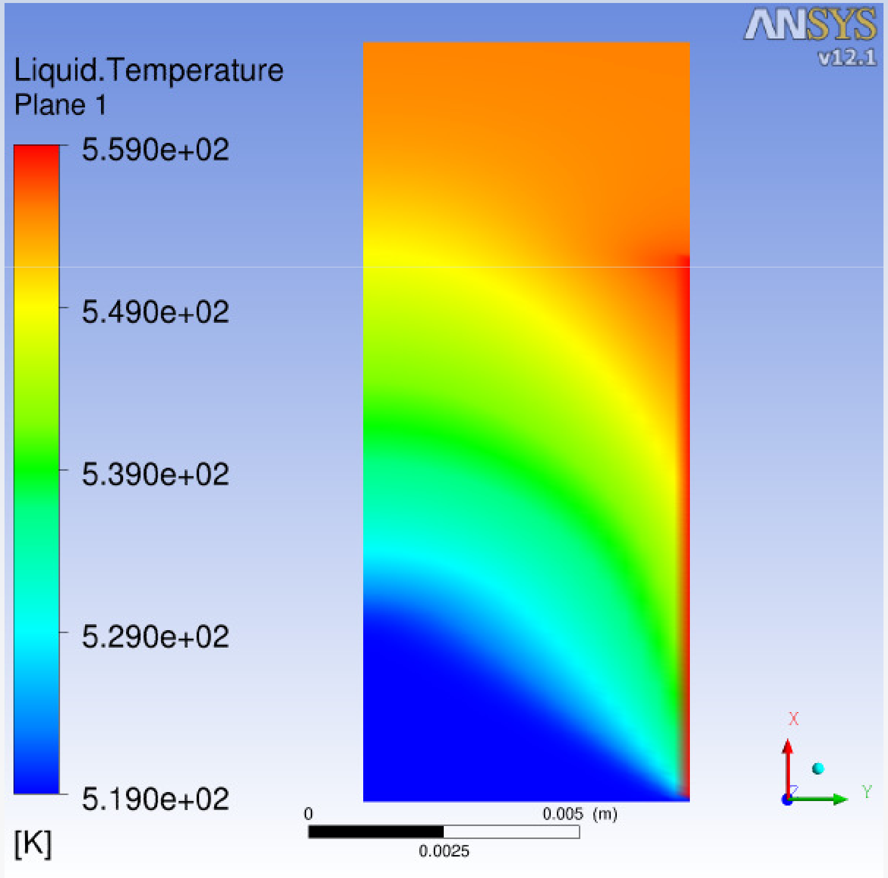
Testcase Parameters

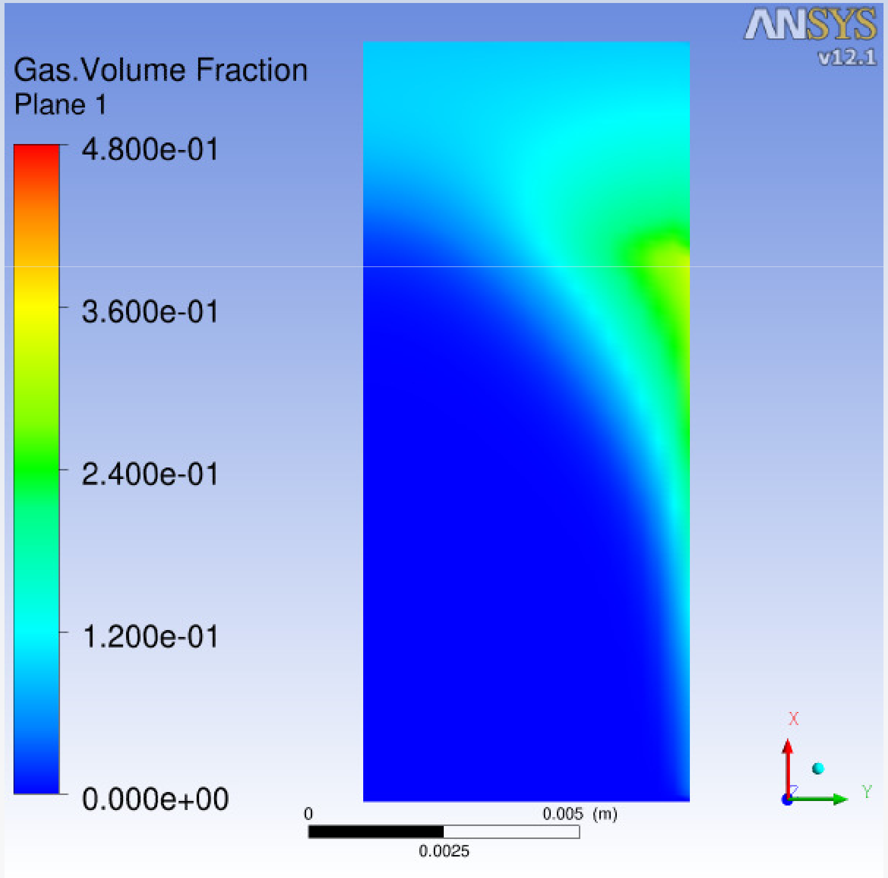
- **Measurement data of zonal-averaged cross-sectional steam volume fraction distribution over pipe length are available for 3 different parameter setups:**

Experiment No.	q_{Wall} [MW m^-2]	G_{in} [kg m^-2 s^-1]	T_{in} [K]
2	1.2	1500	495
3	0.8	1500	519
5	0.8	1000	503

Experiment No. 3 (Mesh01)

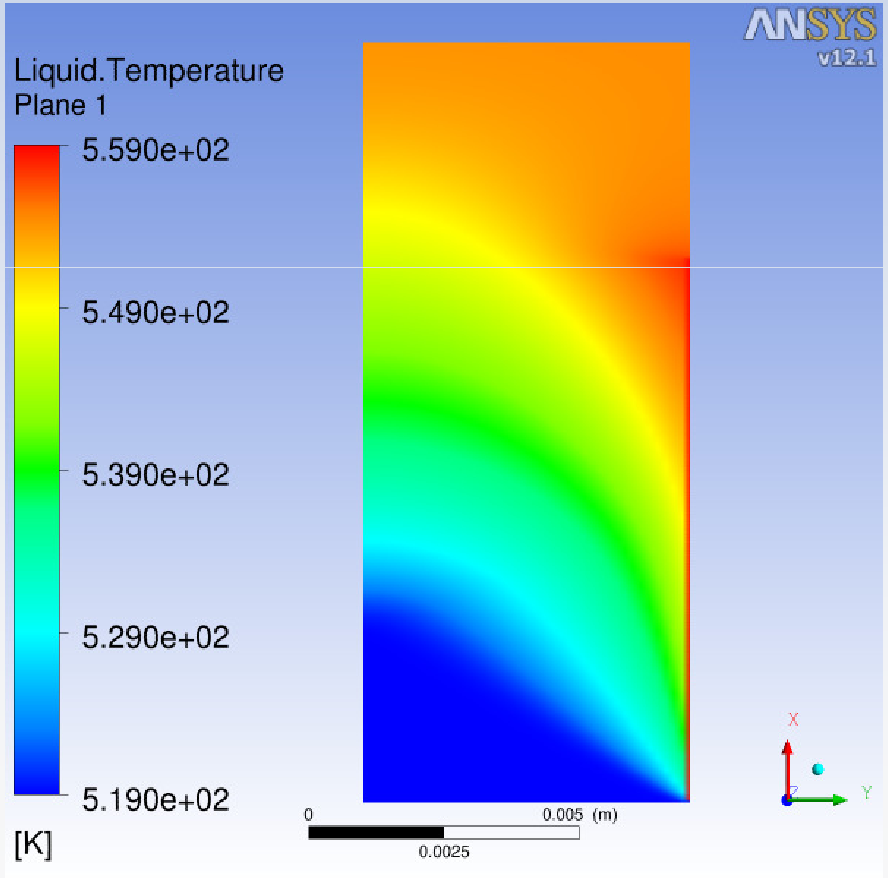
- **Distribution of water temperature and steam volume fraction**

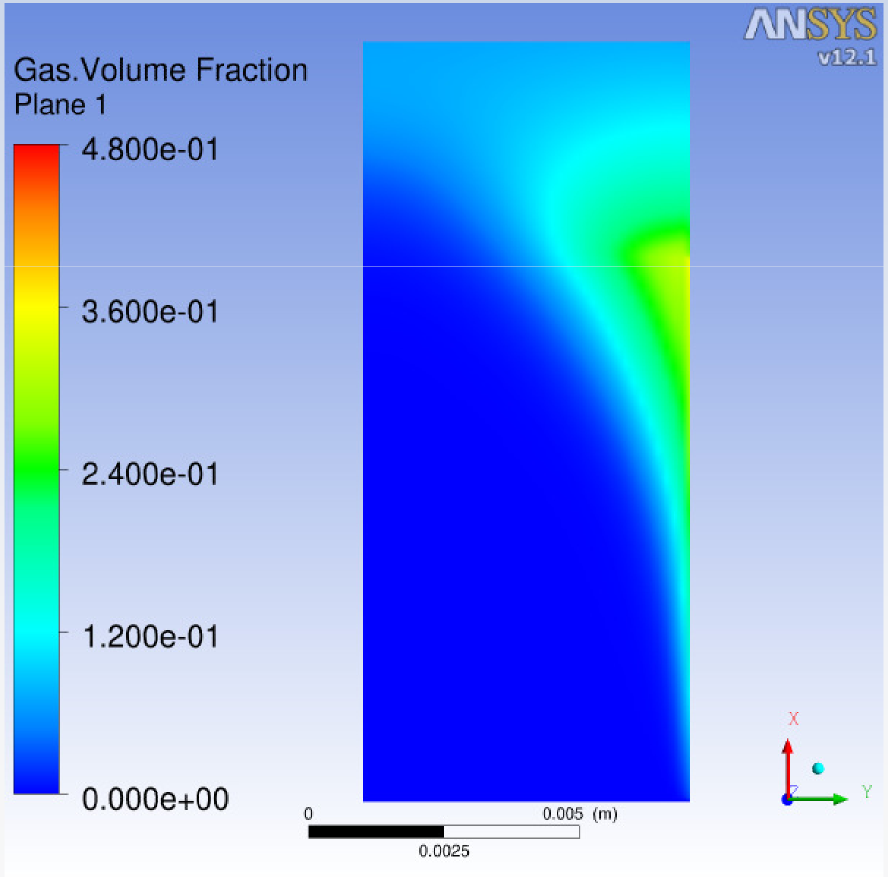




Experiment No. 3 (Mesh02)

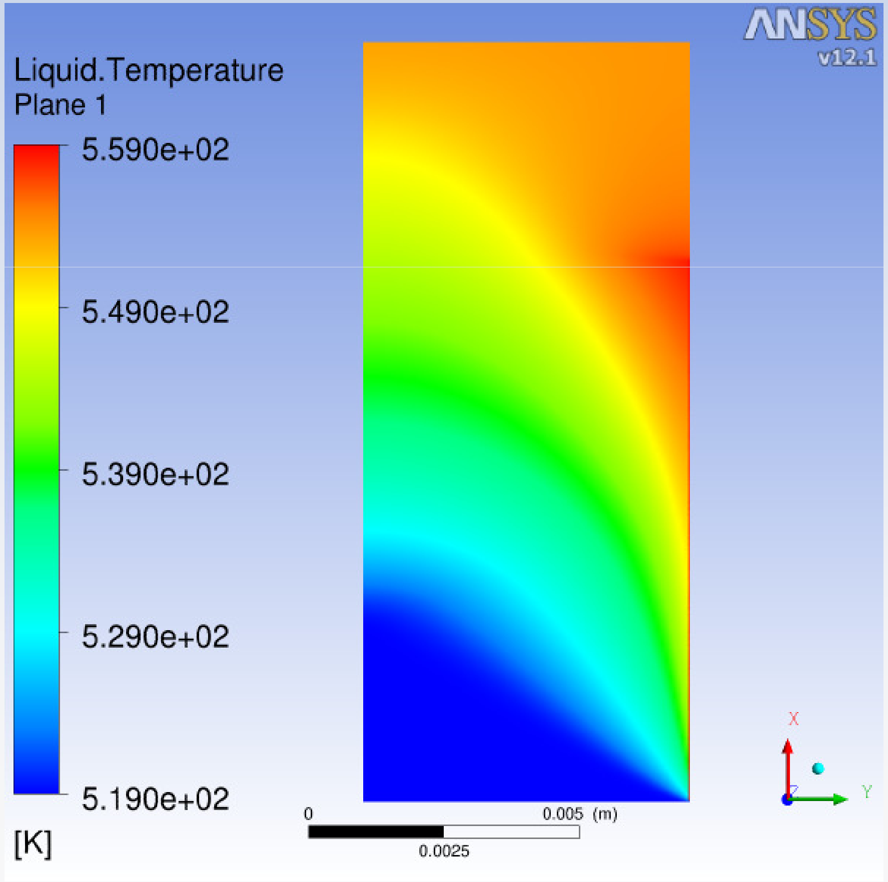
- **Distribution of water temperature and steam volume fraction**

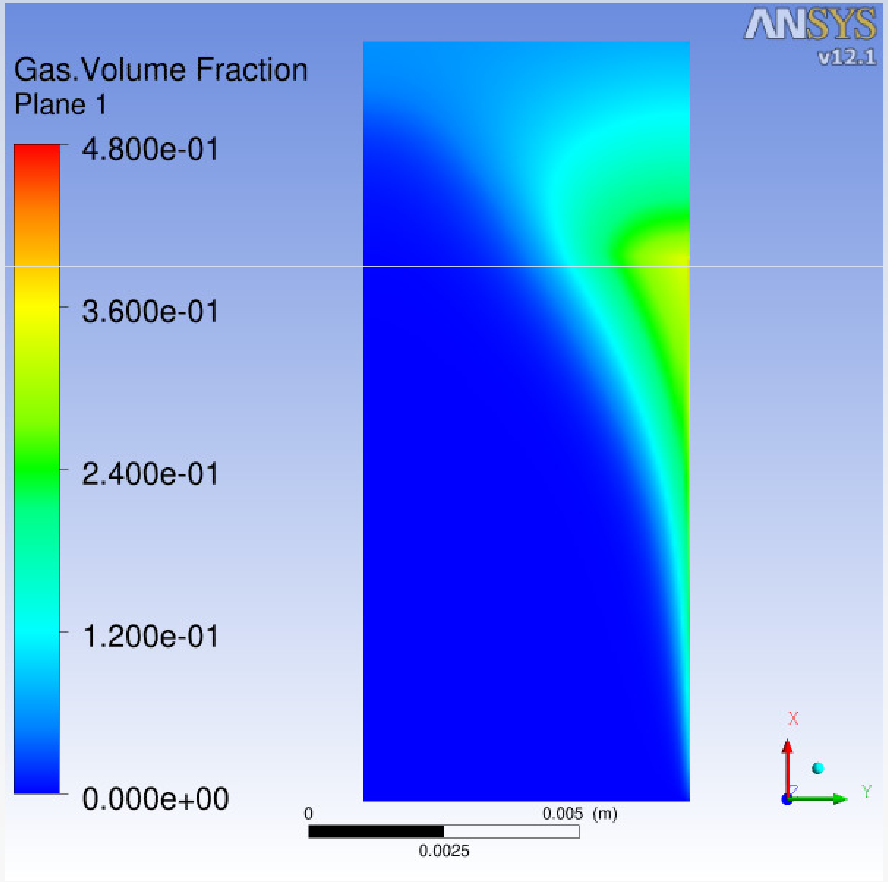




Experiment No. 3 (Mesh03)

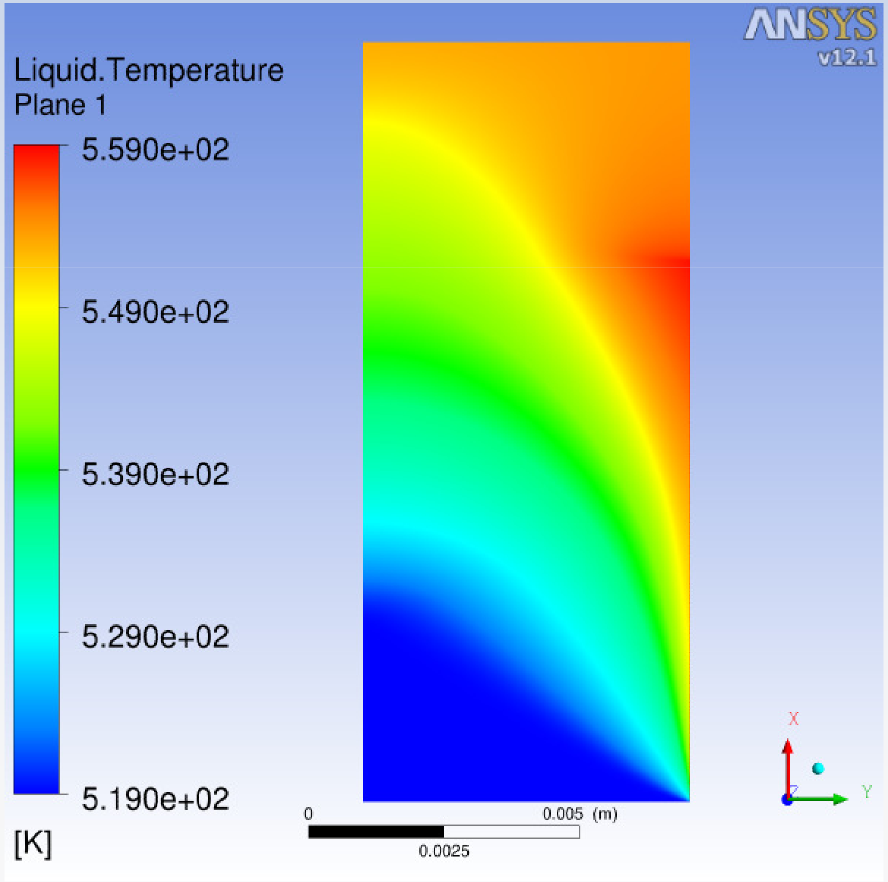
- **Distribution of water temperature and steam volume fraction**

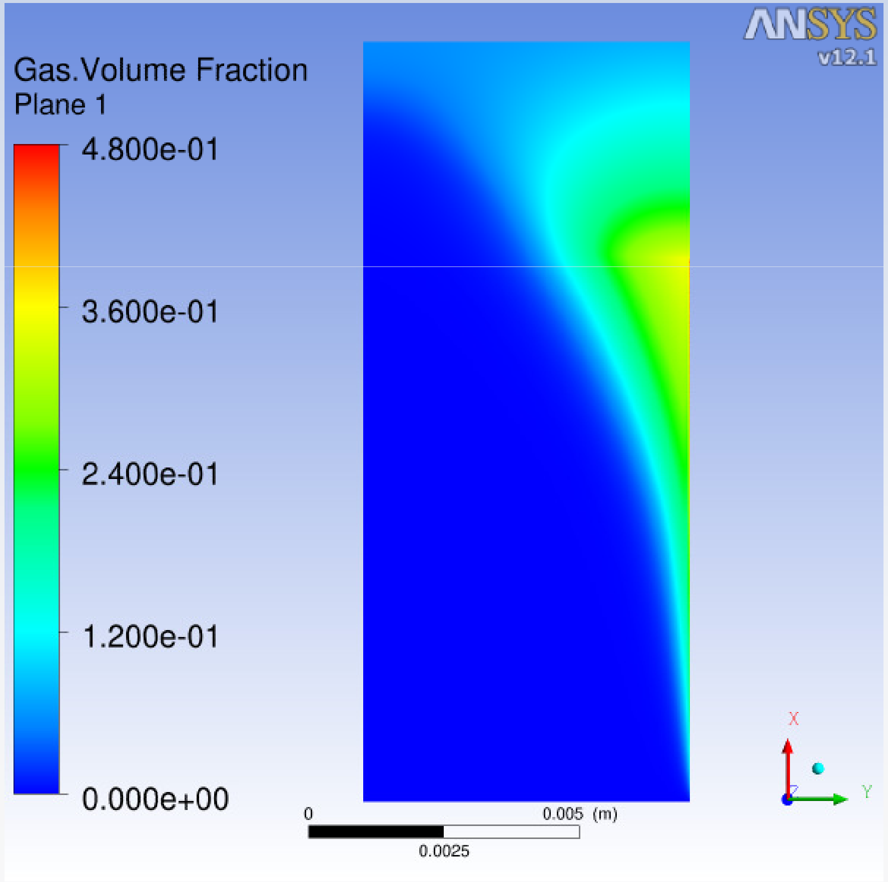




Experiment No. 3 (Mesh04)

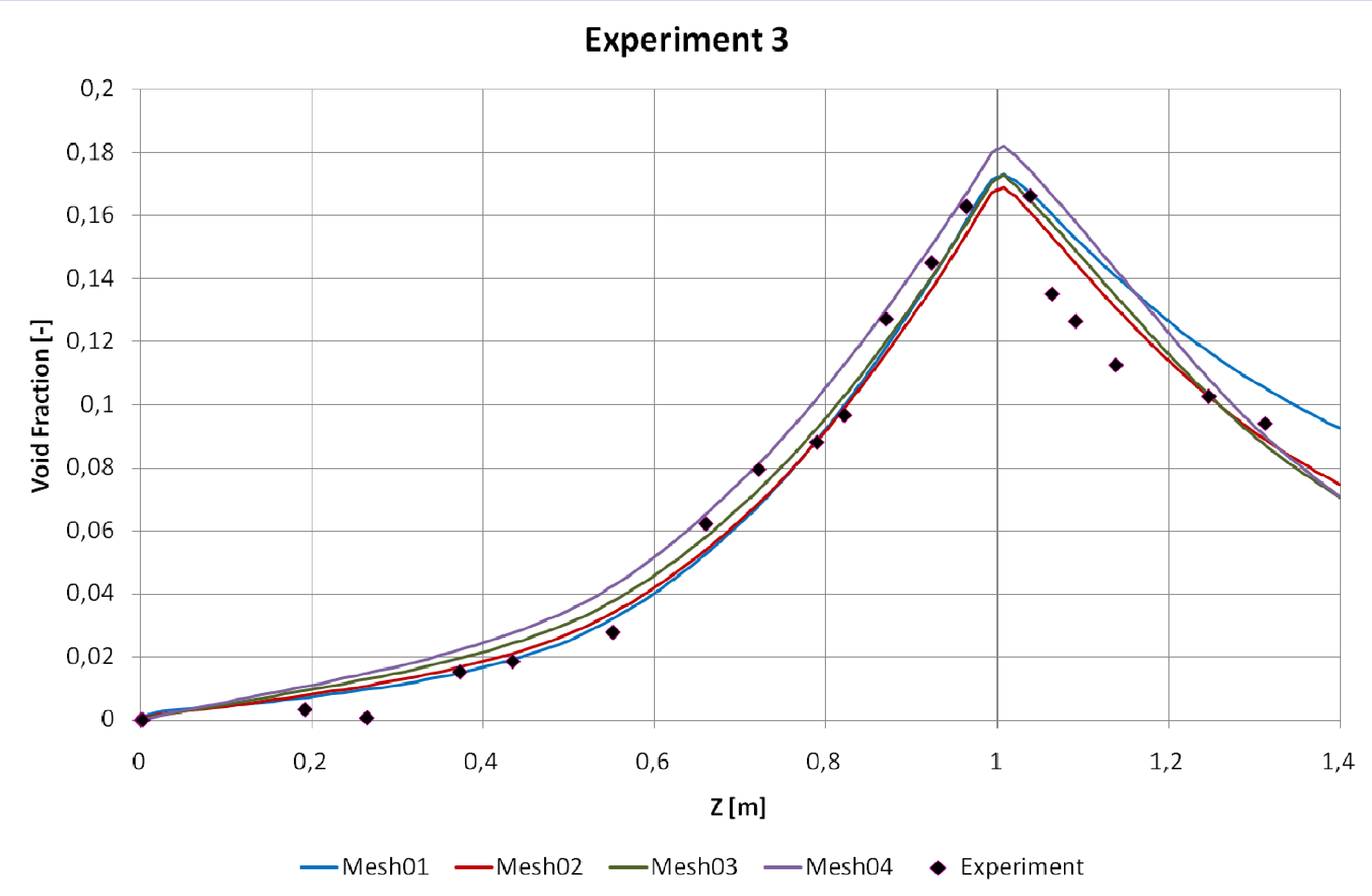
- **Distribution of water temperature and steam volume fraction**





Experiment No. 3

- **Comparison of cross-sectional averaged steam volume fraction to experimental data**



Interface Heat Transfer Models

- **Investigation of the influence of different interface heat transfer models for liquid phase**
  – Ranz-Marshall (Baseline Setup)

    $$\mathrm{Nu} = 2 + 0.6\,\mathrm{Re}^{0.5}\mathrm{Pr}^{0.3}$$

  – Hughmark

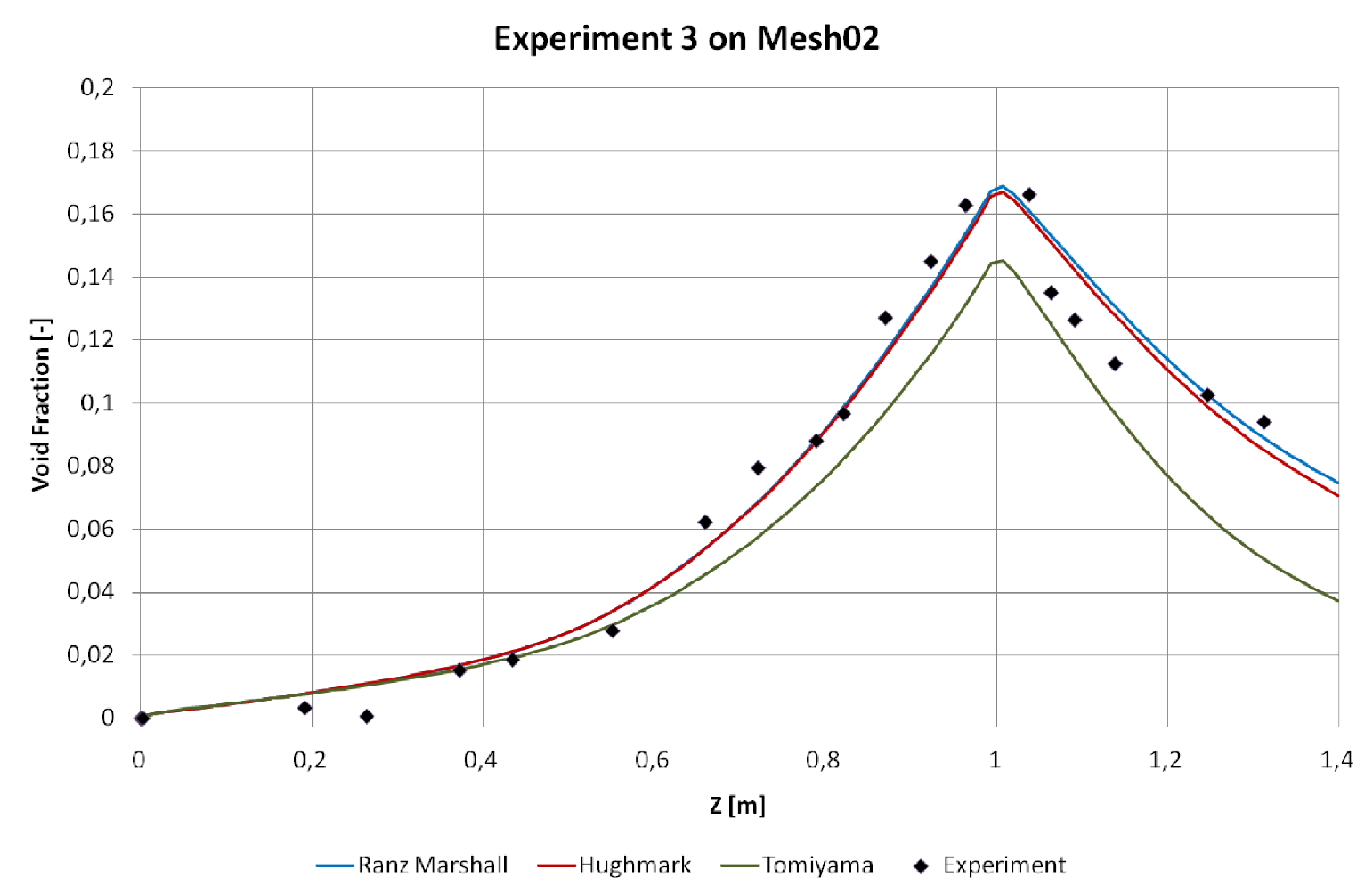
    $$\mathrm{Nu} = 2 + 0.6\,\mathrm{Re}^{0.5}\mathrm{Pr}^{0.3} \qquad 0 \le \mathrm{Re} \le 776.06$$

    $$\mathrm{Nu} = 2 + 0.27\,\mathrm{Re}^{0.5}\mathrm{Pr}^{0.3} \qquad 776.06 \le \mathrm{Re}$$

  – Tomiyama

    $$\mathrm{Nu} = 2 + 0.15\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.5}$$

Interphase Heat Transfer Model

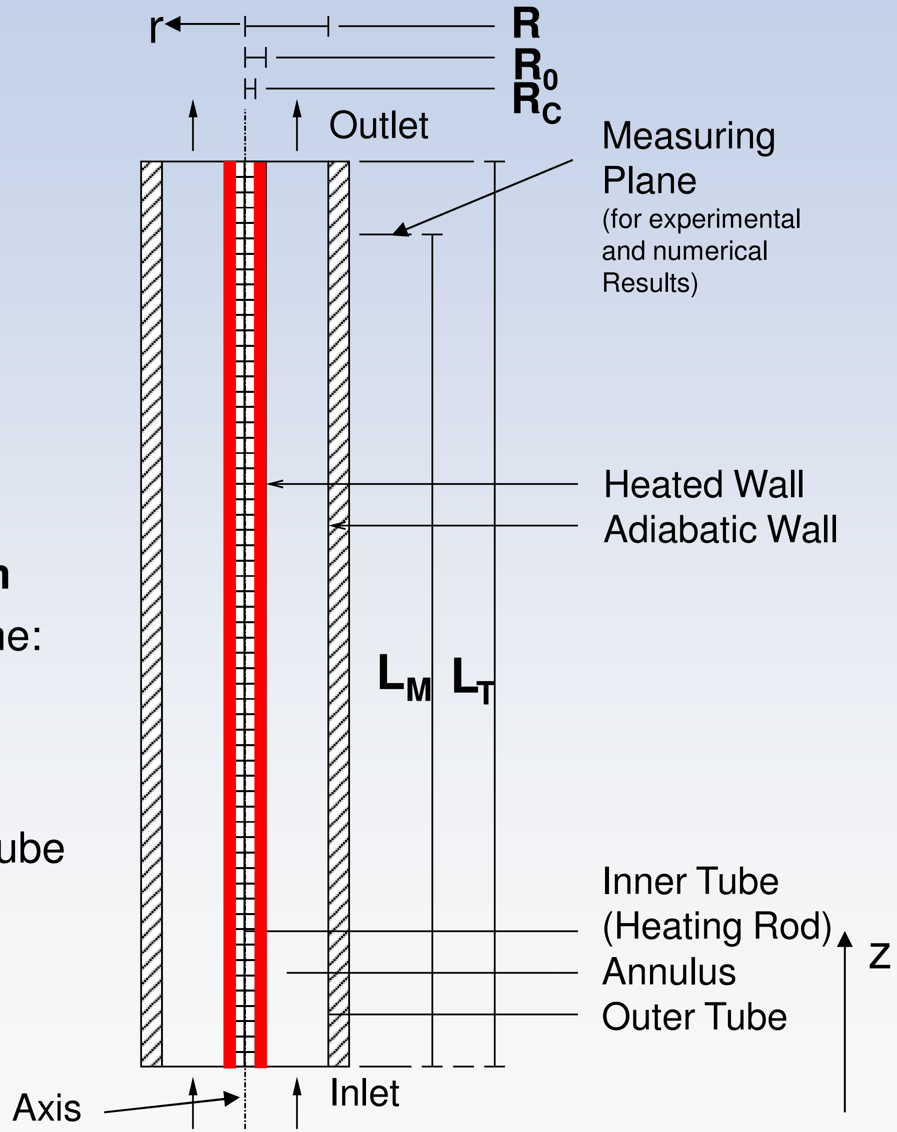


The Lee et al. Testcase (ICONE-16, 2008)

Lee et al. (2008) Experiment

- **Axially symmetric circular annulus**
- **Radial dimensions**
  - Inner radius of outer tube: **R = 18.75 mm**
  - Outer radius of inner tube: **R_0 = 9.5 mm**
  - Core radius: **R_C = 3/4 R_0**
  - Annulus width: **9.25 mm**
- **Axial dimensions**
  - Total heating section height: **L_T = 1670 mm**
  - Distance between inlet and measuring plane: **L_M = 1610 mm**
- **Radial Position: R_P**
  - Dimensionless, radial distance from inner tube (R_P = 0) to outer tube (R_P = 1) across the annulus:

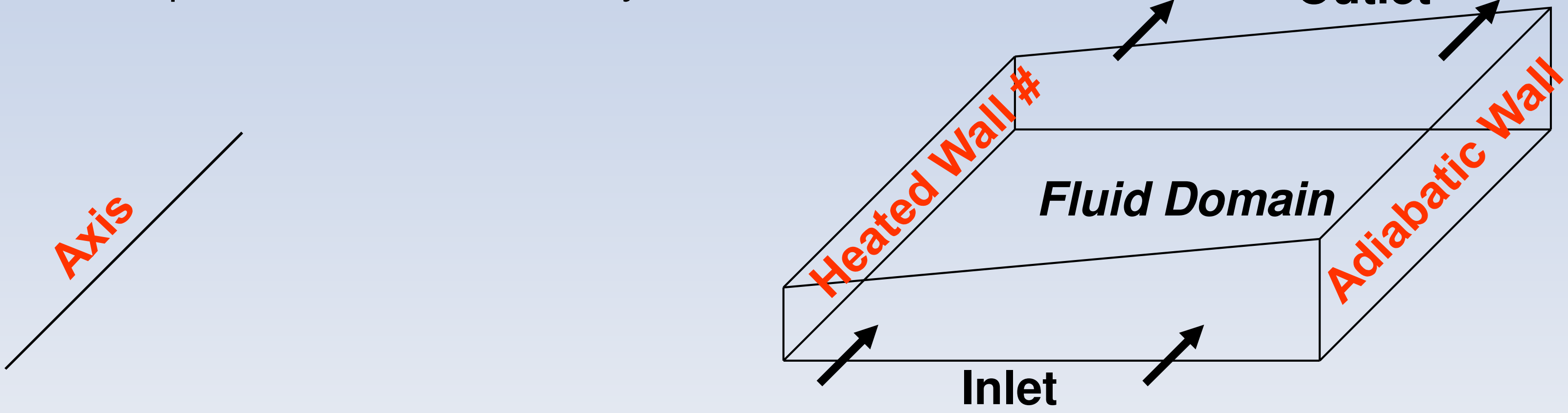
$$R_P = \frac{(r - R_0)}{(R - R_0)}$$



Investigated Geometry Configurations

HFO (Heat Flux Only): Fluid Domain (Annulus)

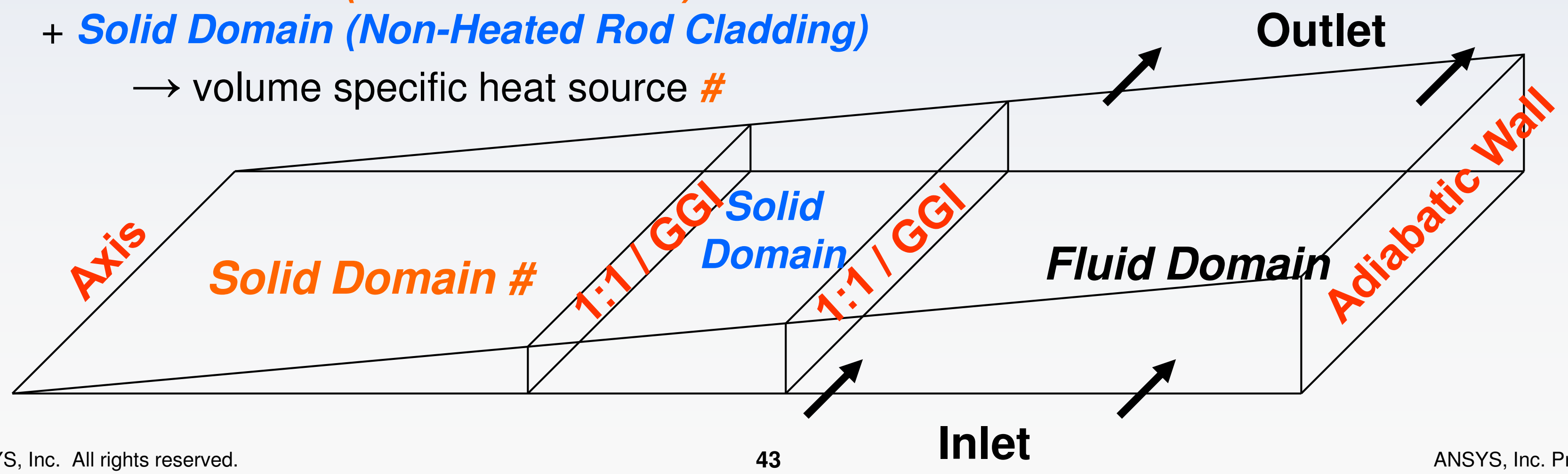
⟶ area specific heat flux boundary condition #



CHT (Conjugated Heat Transfer): Fluid Domain (Annulus)

+ *Solid Domain (Heated Rod Core)*
+ *Solid Domain (Non-Heated Rod Cladding)*

⟶ volume specific heat source #



Selected Testcase Conditions

- Selected two (out of 12) datasets:

Set 25
(least of all steam)

Set 16
(most of all steam)

- Parameter comparison

Set No.*	q" [kW m^-2]	G [kg m^-2s]	T_{in} [℃]	P_{in} [kPa]
16	320.4	718.8	83.8	121.1
25	220.0	1057.2	90.1	134.4

Model Parameter Modifications in Comparison to PWR Conditions

ANSYS

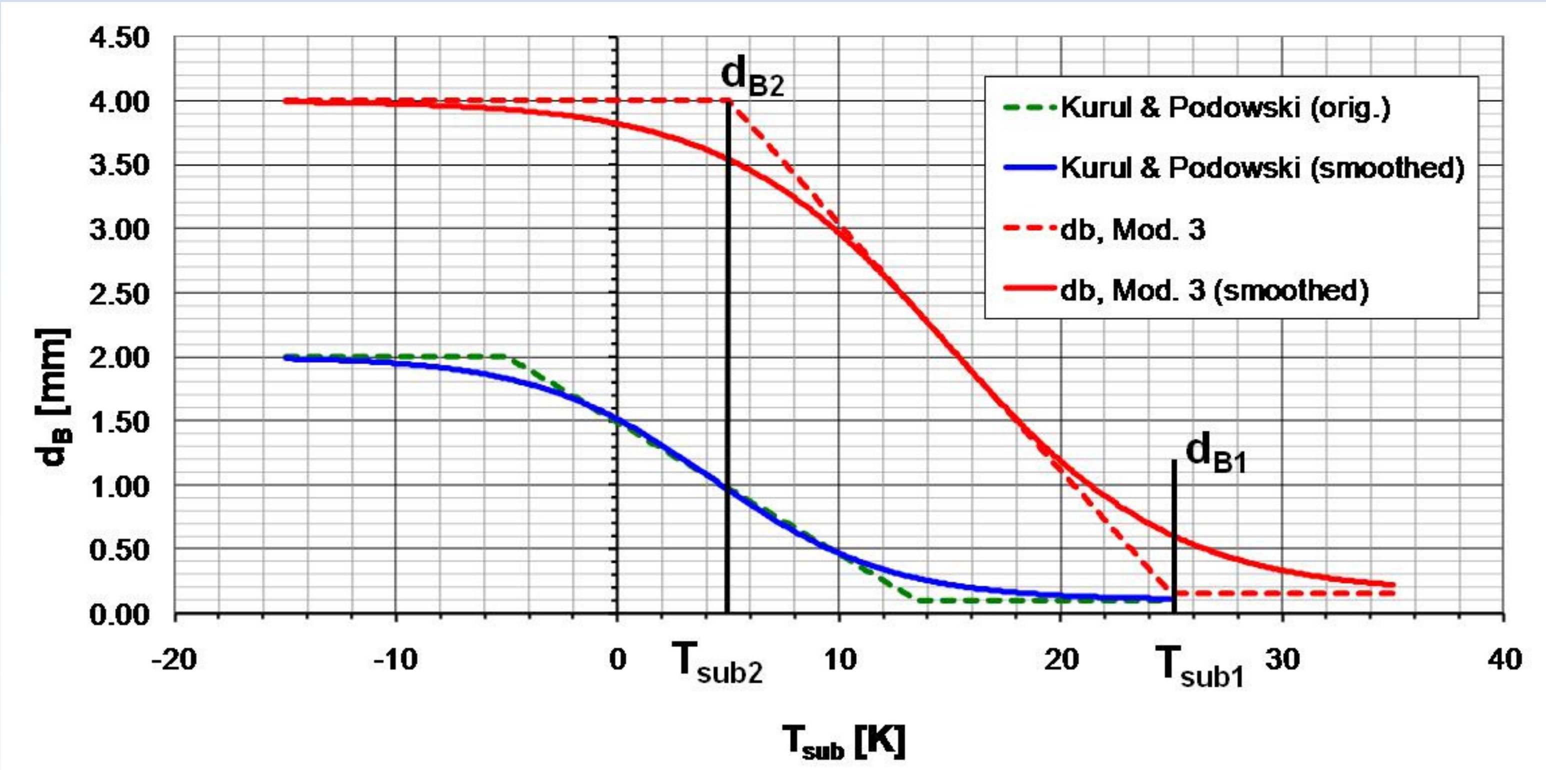
Found that submodels need modifications for BWR conditions (see also Tu&Yeoh, Anglart et al., Krepper, Koncar):

1. **Bulk bubble diameter**
   Kurul & Podowski → $d_{B,max}$~1.5mm @ wall
   modified d_B law → $d_{B,max}$~4.0mm @ wall
2. **Bubble departure diameter**
   Tolubinski & Kostanchuk → d_W ~0.5mm max.
   const. bubble dept. diam. → d_W =1mm - 3mm
3. **A_2 - Wall area fraction influenced by steam bubbles**
   default → 0.5
   increased up to 1.0

Modification for Bulk Bubble Diameter Correlation

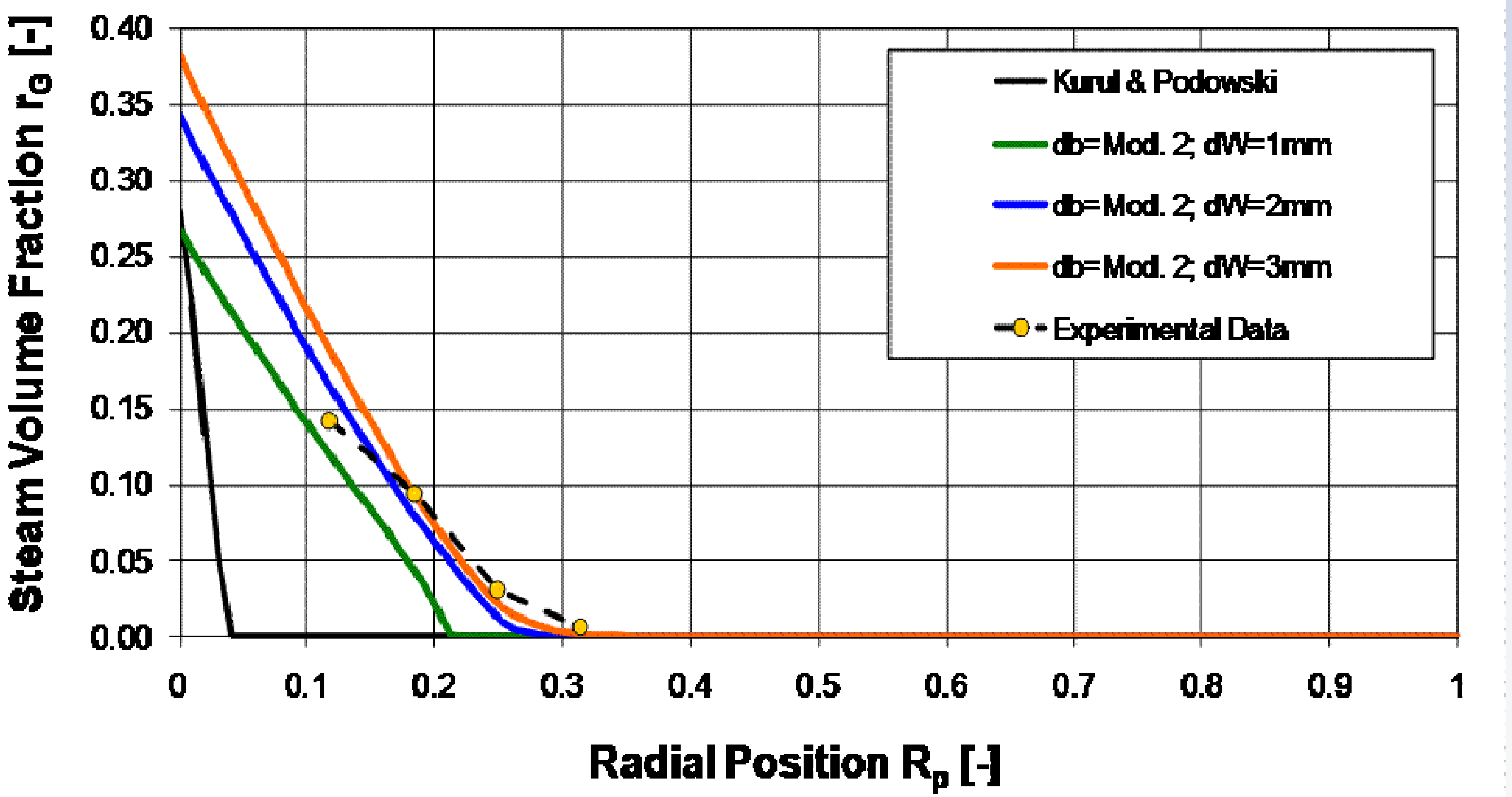
- **Modified Kurul & Podowski (1991) law:**

$$d_B = \frac{d_{B1}\left(T_{sub} - T_{sub,2}\right) + d_{B2}\left(T_{sub,1} - T_{sub}\right)}{T_{sub,1} - T_{sub,2}}$$



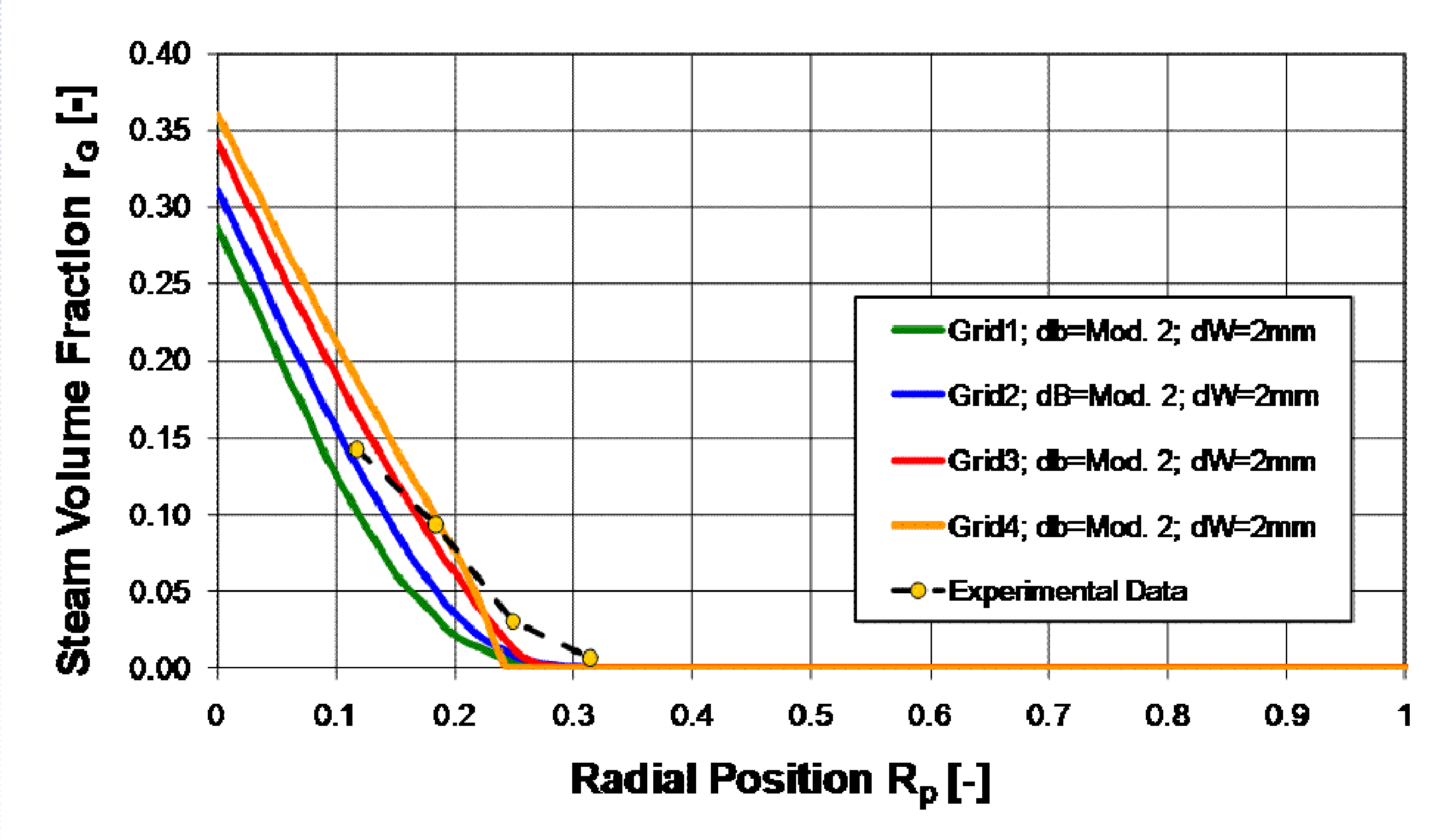
Set25: Variation of Bubble Departure Diameter

- Tolubinski & Kostanchuk (1970) vs. const. bubble departure diameter d_W=1,…,3mm
- Measurement cross section @ z = 1610 [mm]



Set25: Grid Independence

- Steam volume fraction on mesh1 - mesh4
- Measurement cross section @ z = 1610 [mm]



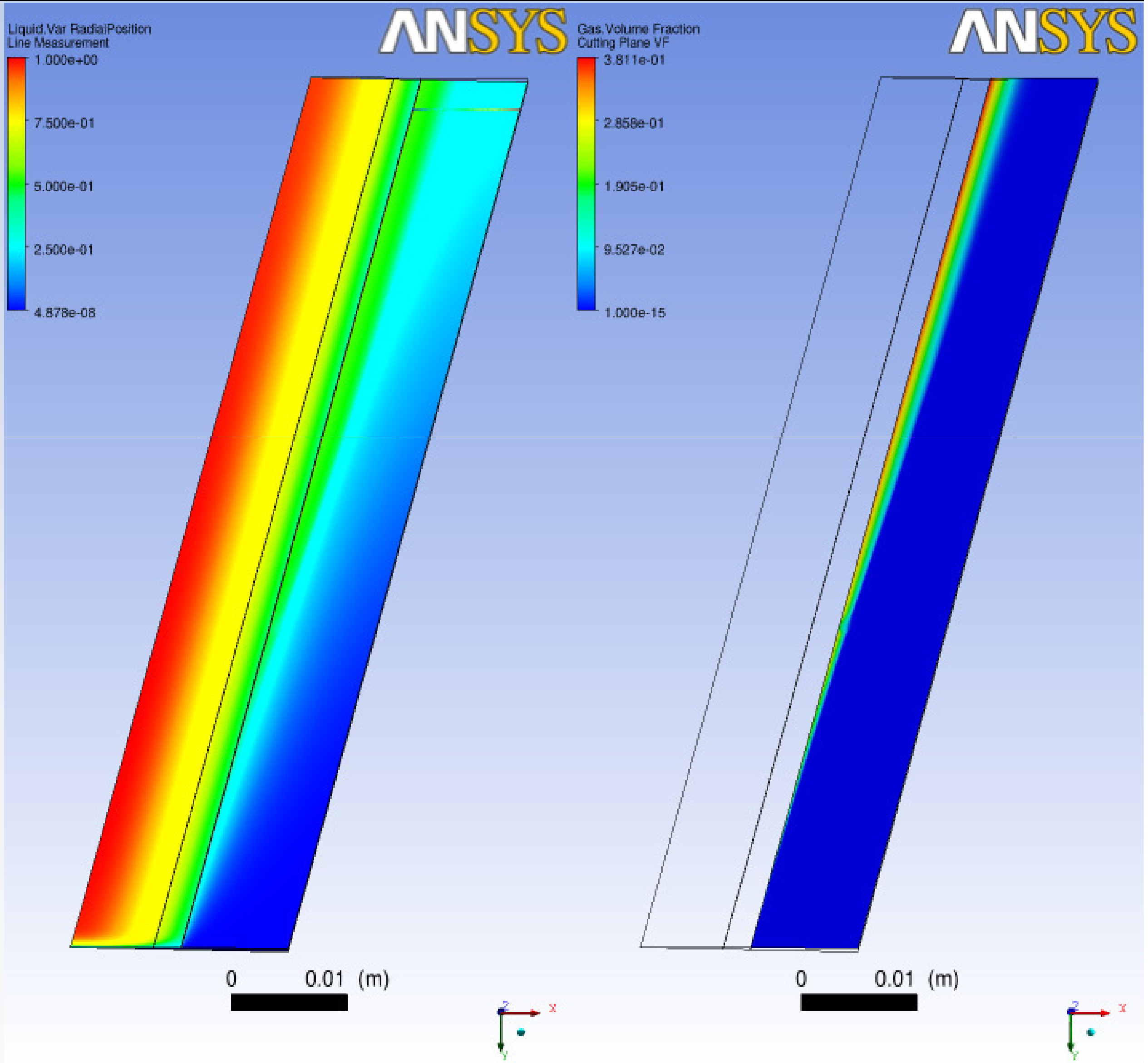
The Lee et al. Testcase (ICONE-16, 2008) : Conjugate Heat Transfer

The RPI Wall Boiling Model: Lee et al. Testcase with CHT

- Specific energy source in solid material, Set25 (equiv. to q_{Wall}):

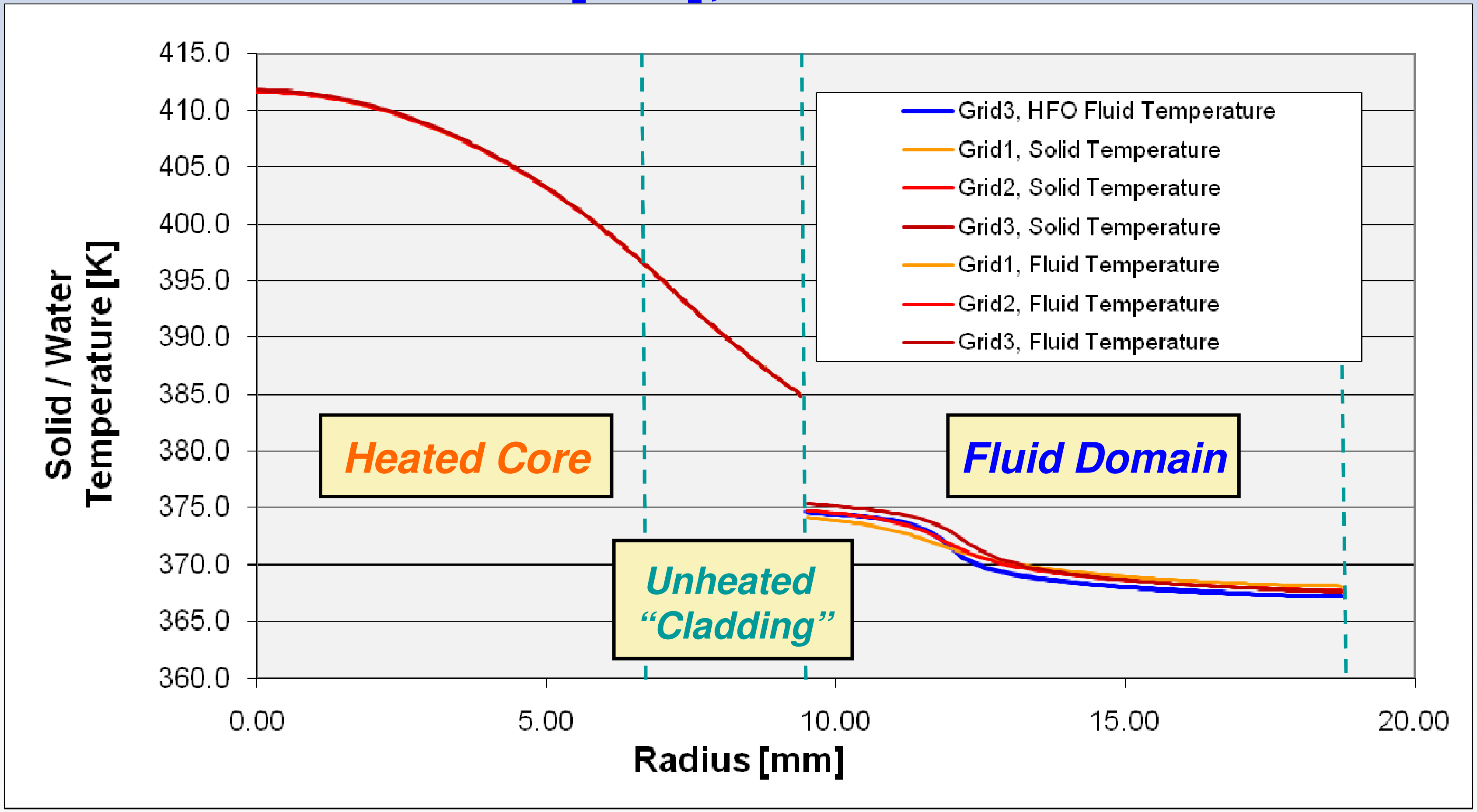
  $E_{Core}=8.23 \cdot 10^{7}$ [W/m³]

- Temperature and Steam VF distribution in vertical plane



The RPI Wall Boiling Model: Lee et al. Testcase with CHT

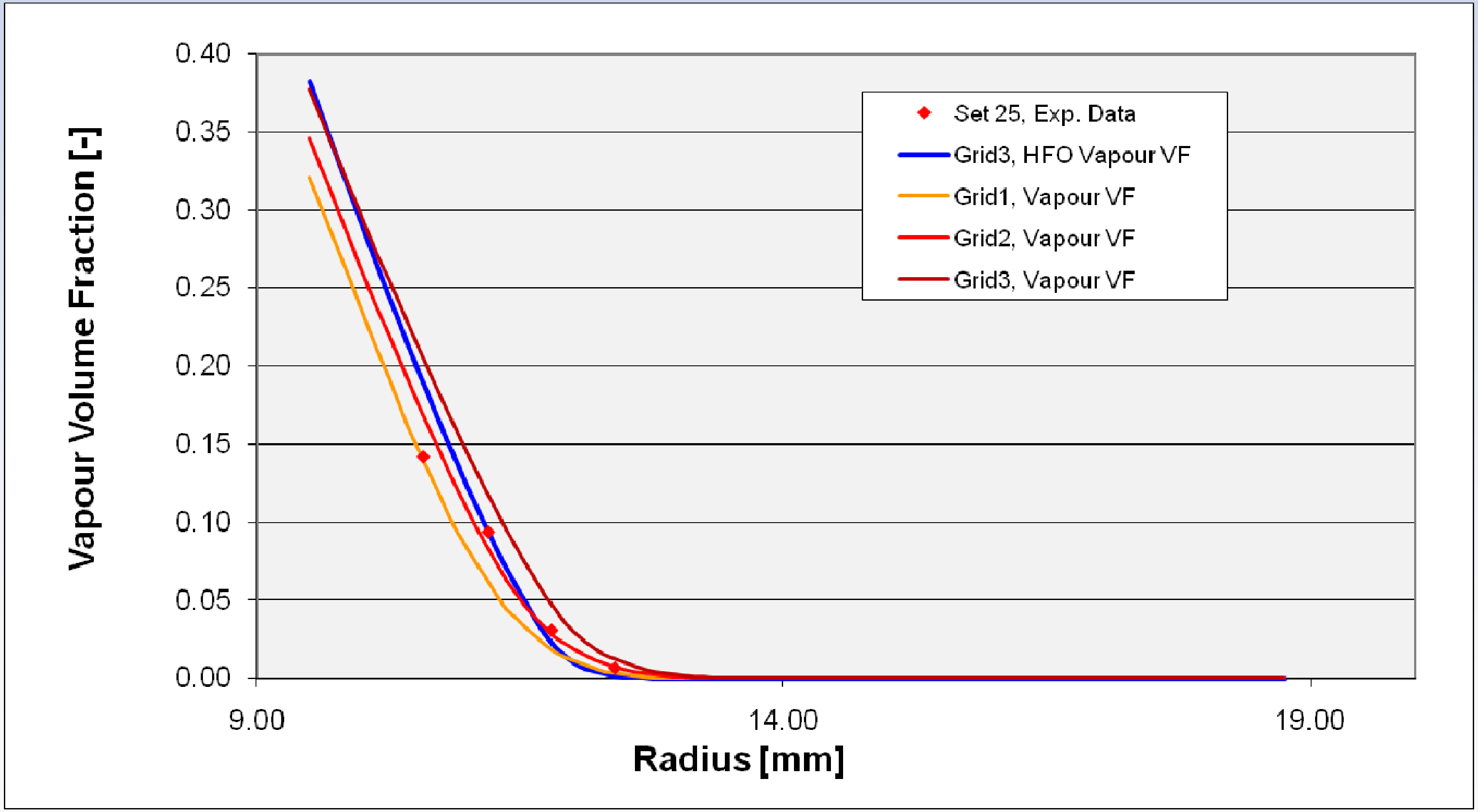
Set25 & CHT: Grid independence for temperature distribution @ z=1610[mm]; 1÷1 mesh interface



The RPI Wall Boiling Model: Lee et al. Testcase with CHT

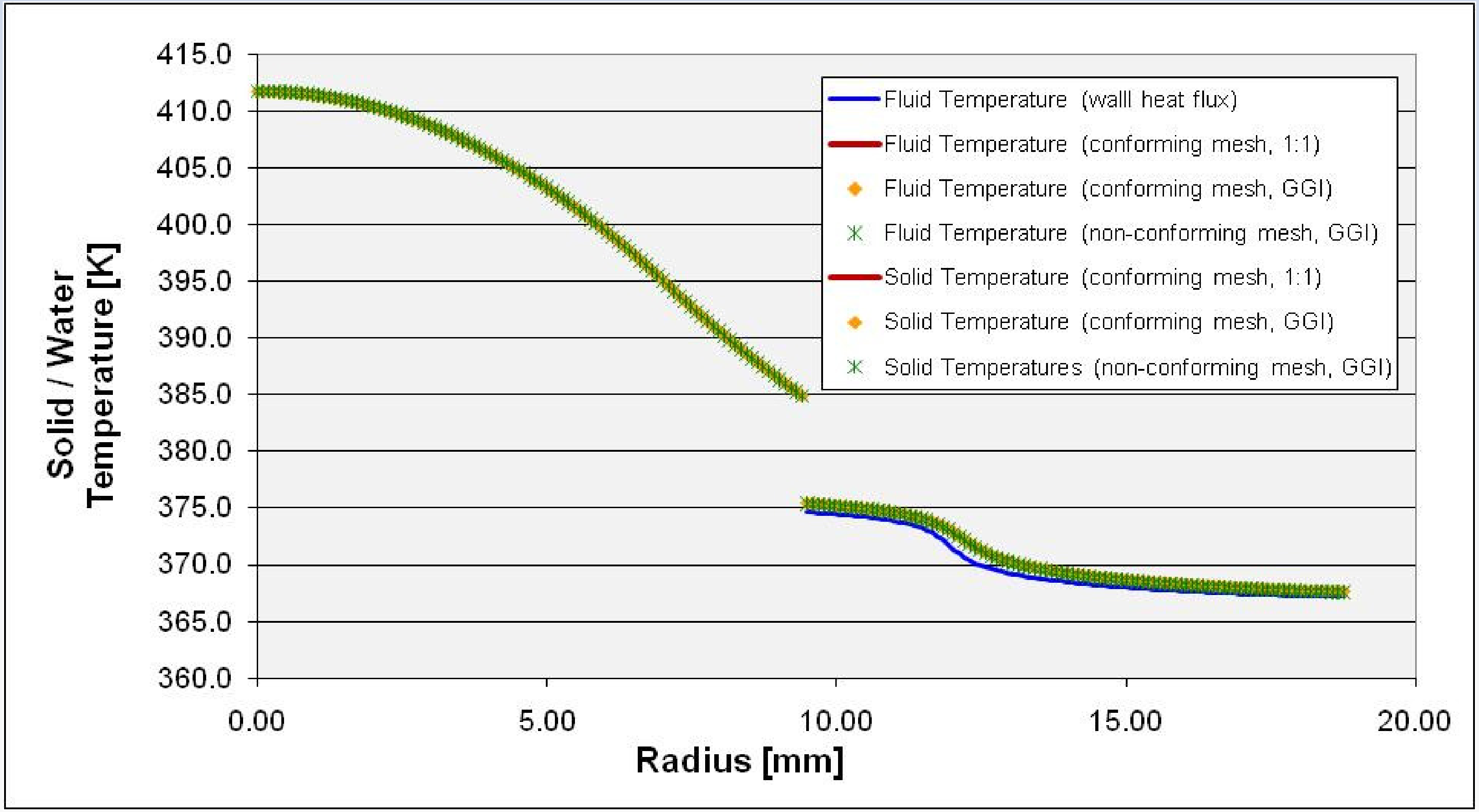
Set25 & CHT: Vapour VF distribution @ z=1610[mm]

1÷1 mesh interface



The RPI Wall Boiling Model: Lee et al. Testcase with CHT

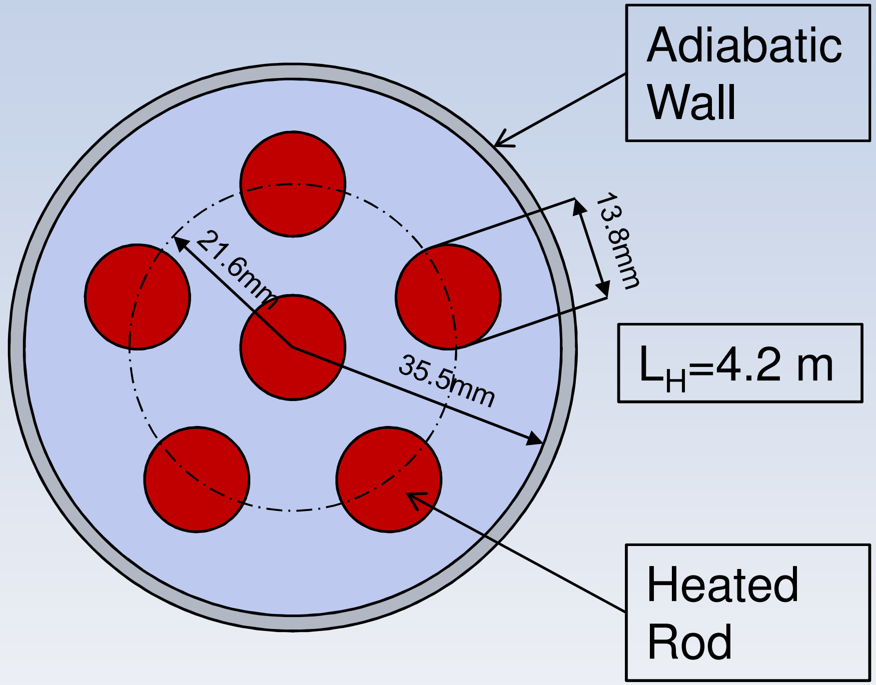
- **Comparison of temperature distributions for conforming vs. non-conforming mesh, 1÷1 vs. GGI**



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

FRIGG-6a Test Case Description

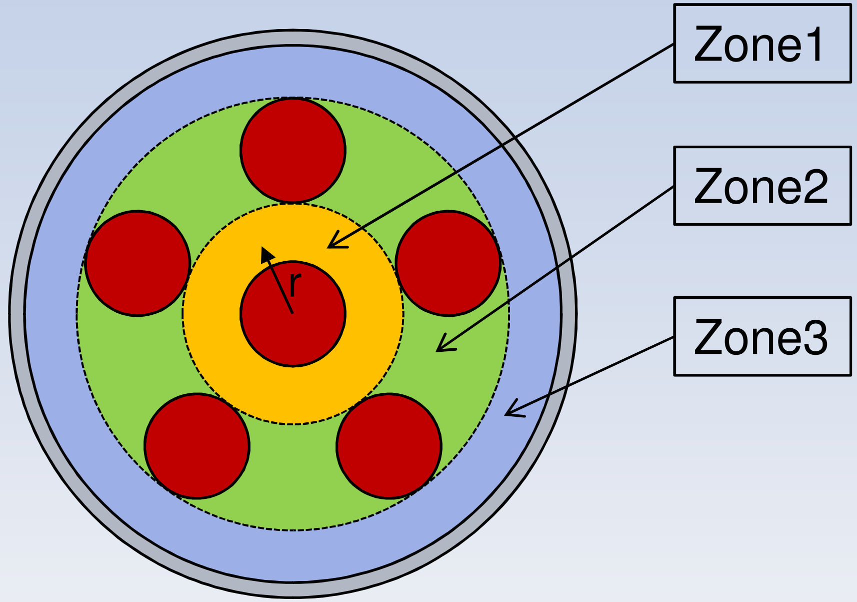
- **Geometry (FT-6a)**
  - Six electrically heated rods placed in a vertical adiabatic pipe



- **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



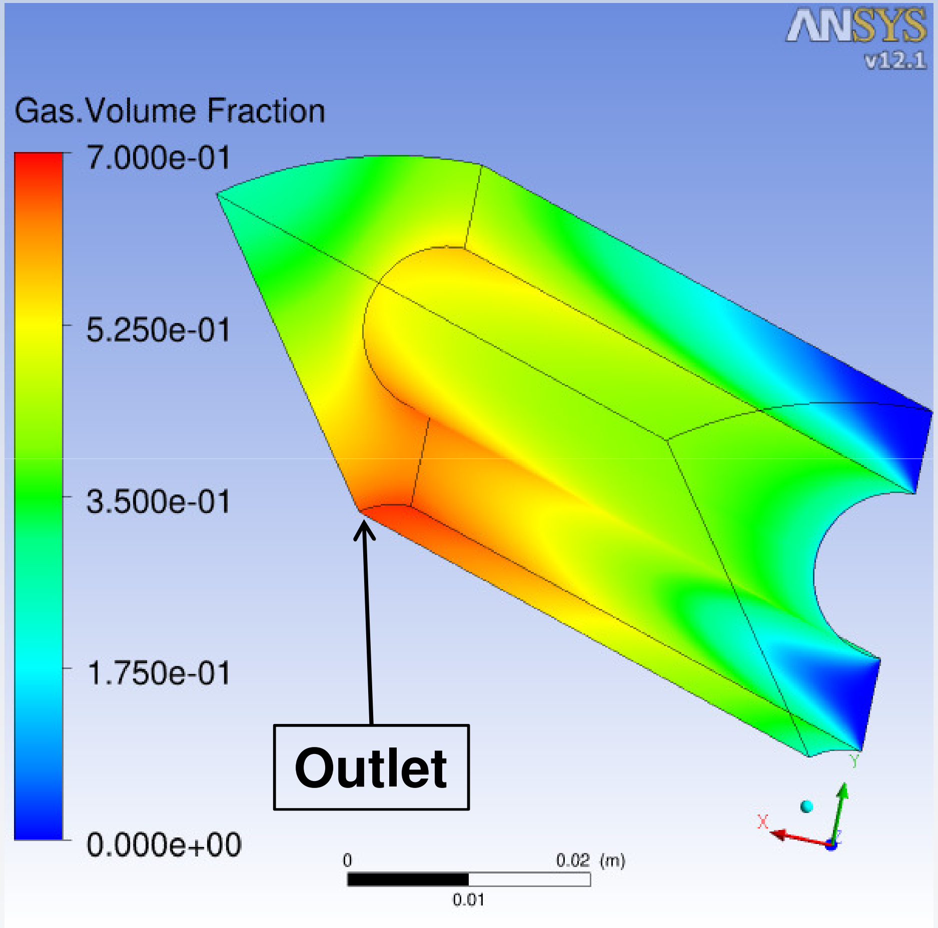
Defintion of Zones:

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

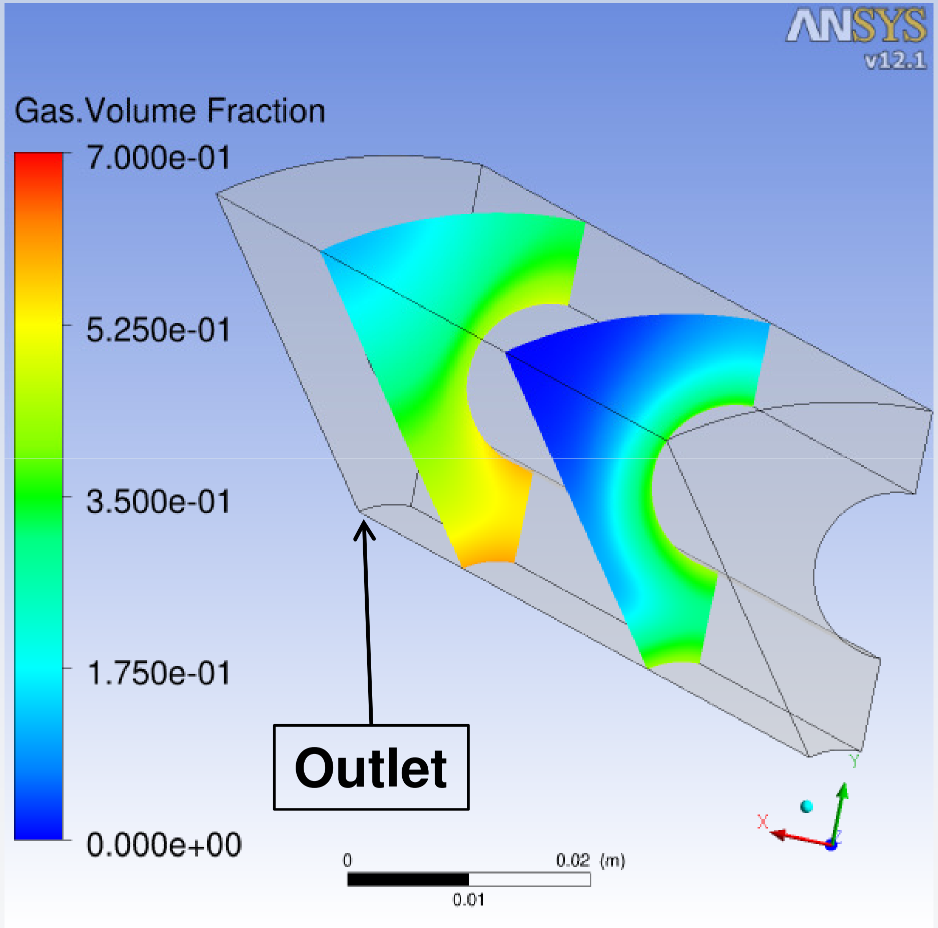
FRIGG-6a Test Case
Mesh Refinement Hierarchy

	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

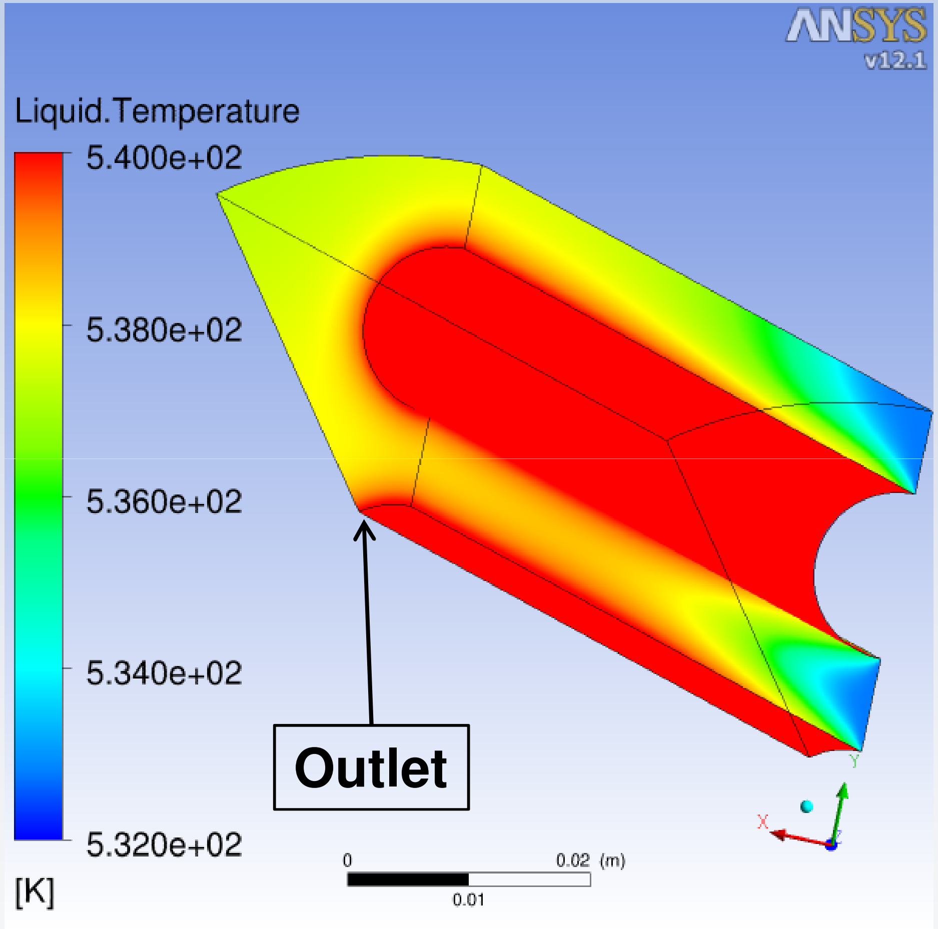


Plot of gas volume fraction (Mesh03, SST)

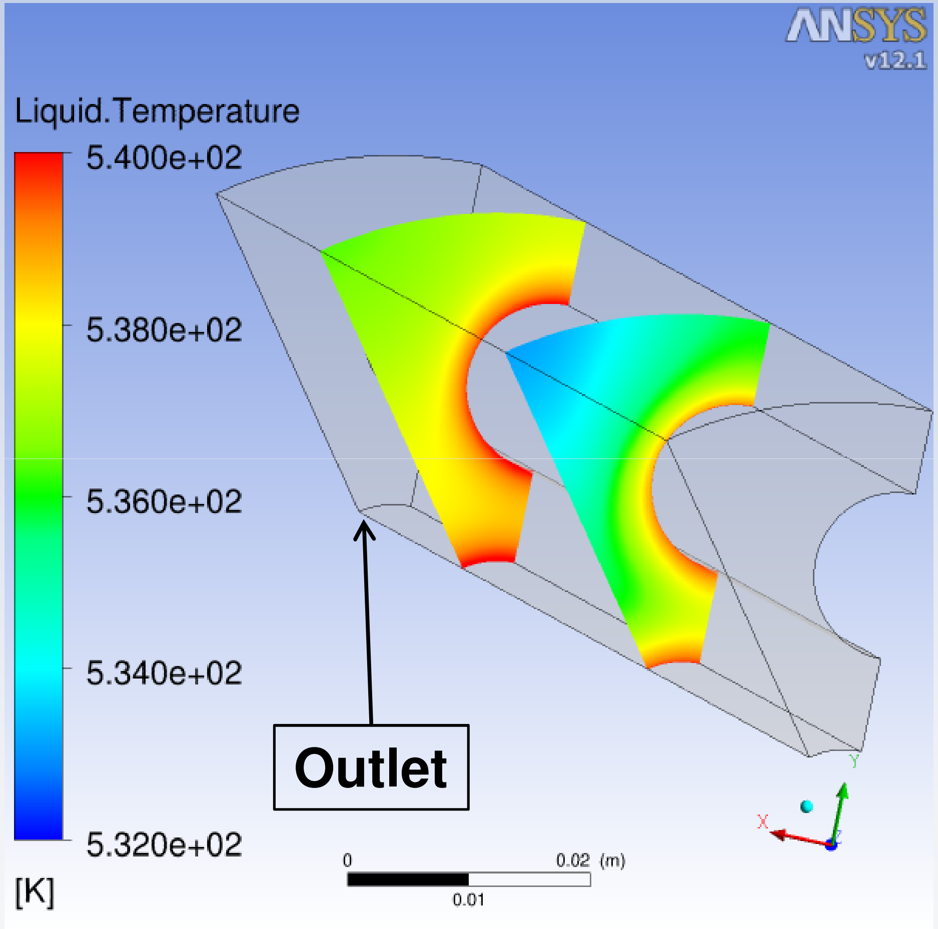


Two cross-sectional distributions of gas volume fraction (Mesh03,SST)

FRIGG-6a Test Case
Baseline Setup: SST

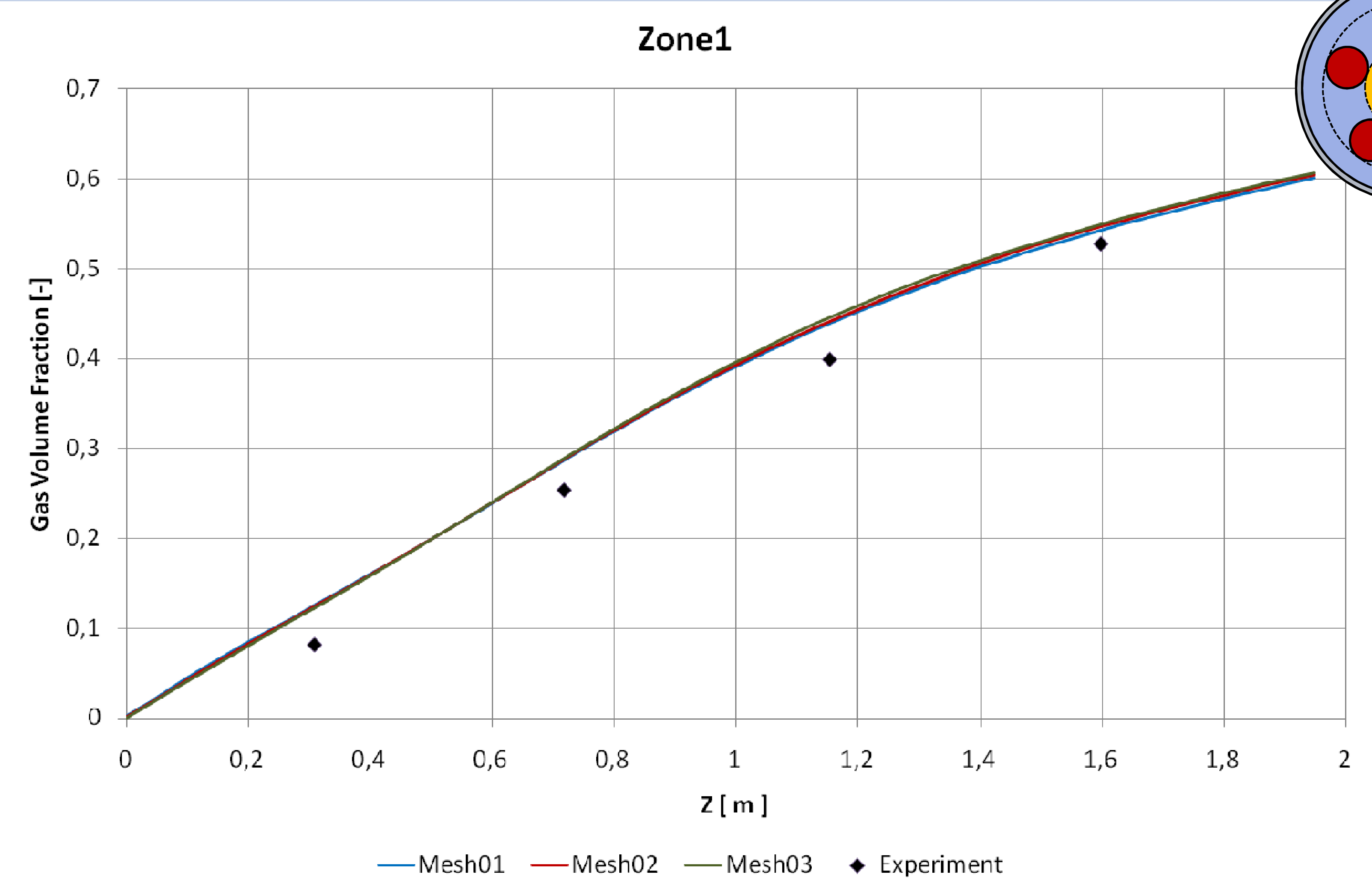


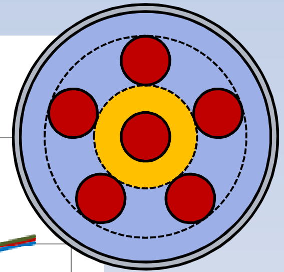
Plot of liquid temperature (Mesh03,SST)



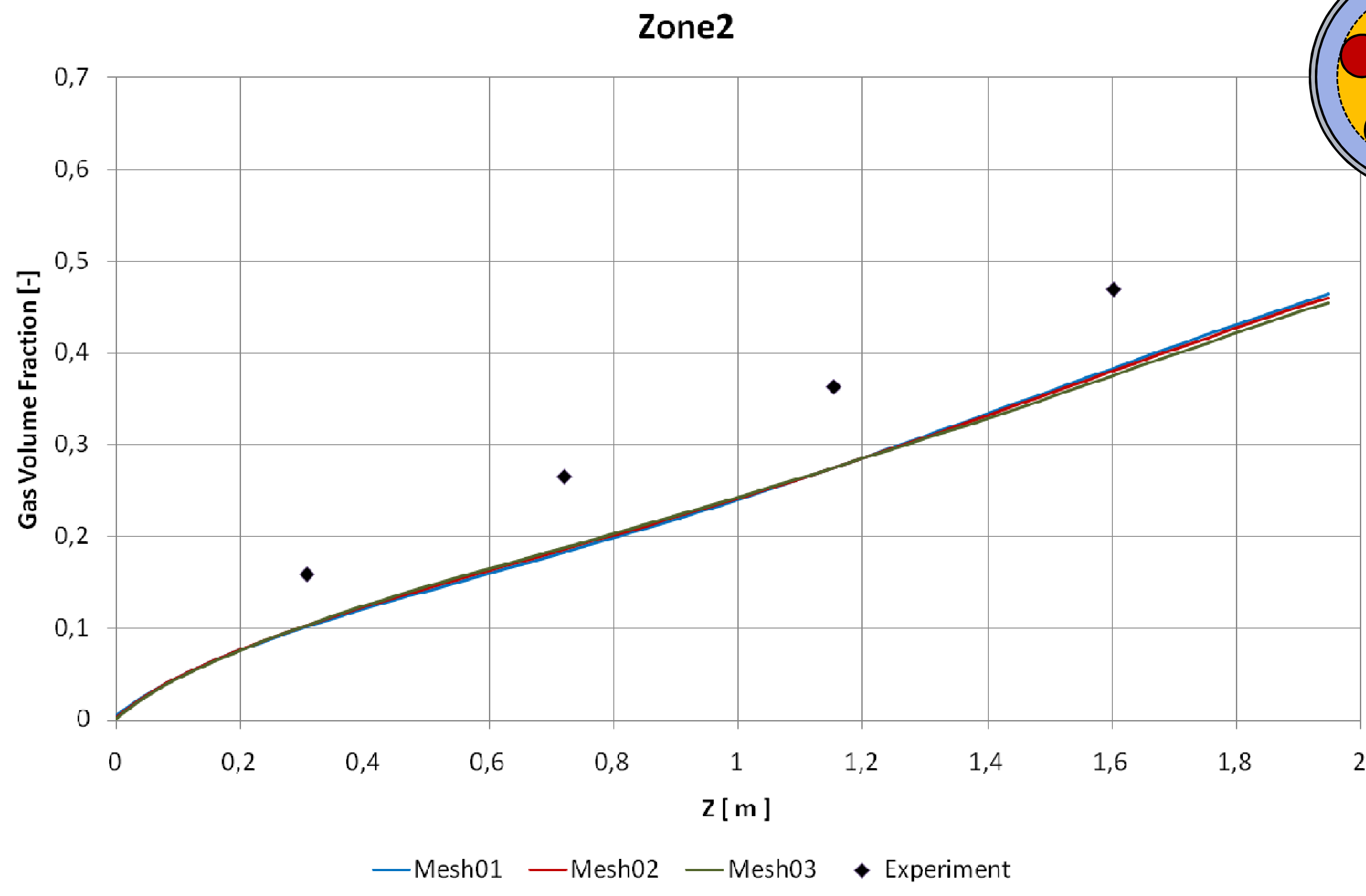
Two cross-sectional distributions of liquid temperature (Mesh03,SST)

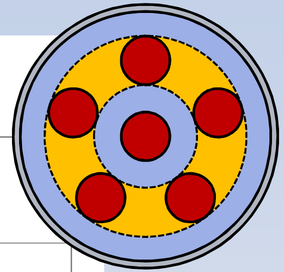
FRIGG-6a Test Case
Mesh Comparison



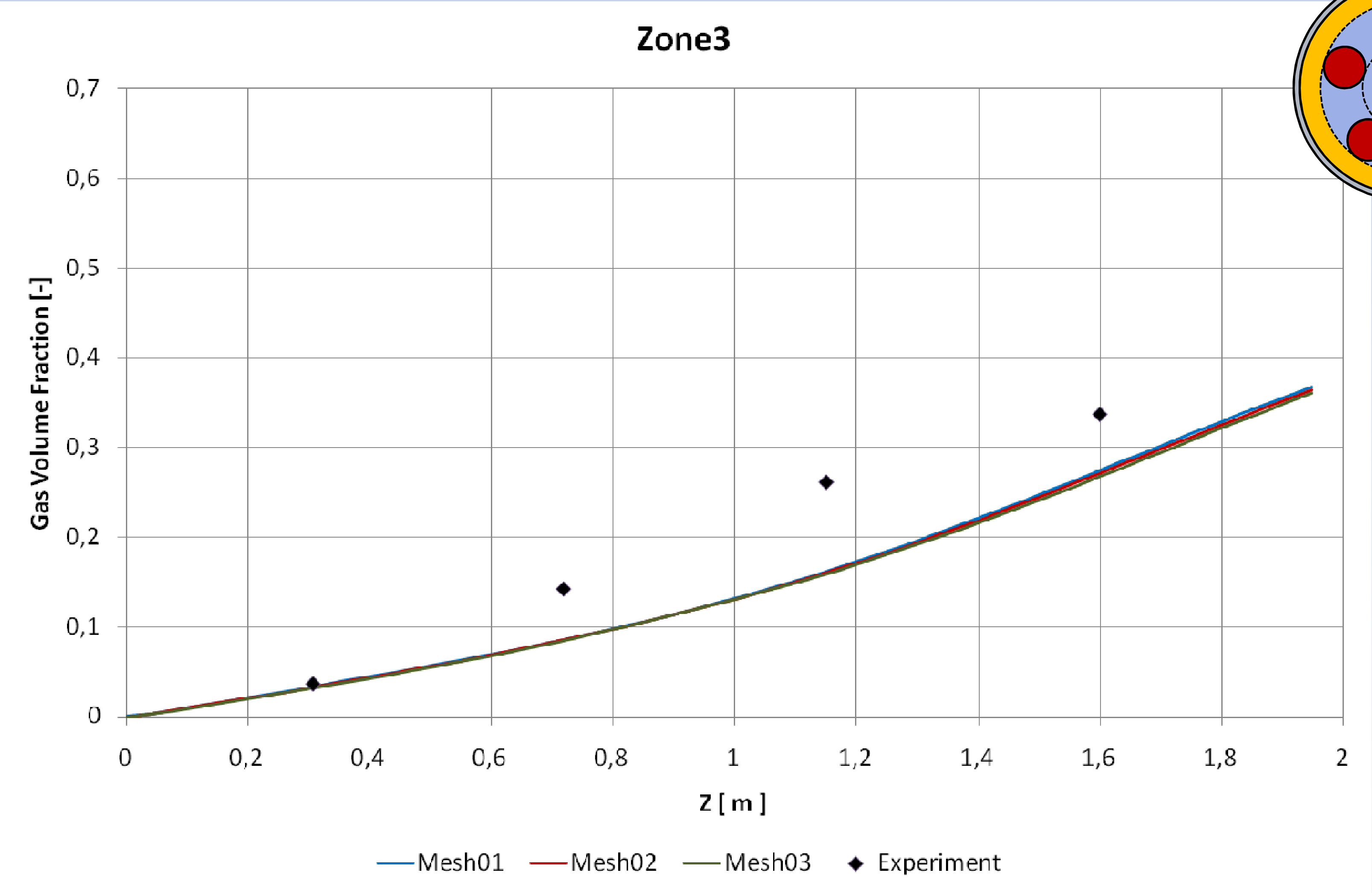


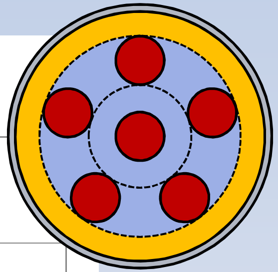
FRIGG-6a Test Case
Mesh Comparison





FRIGG-6a Test Case
Mesh Comparison



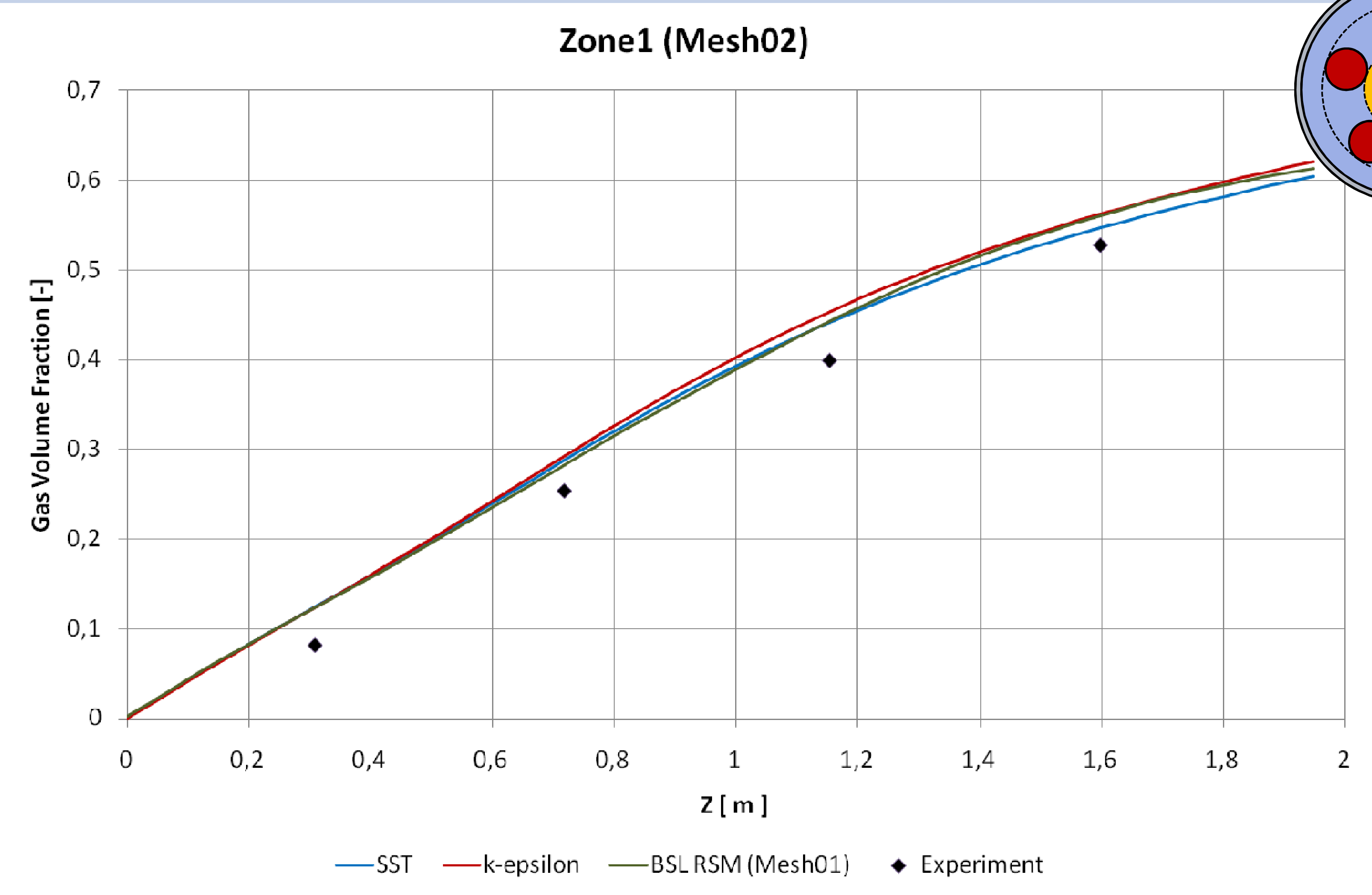


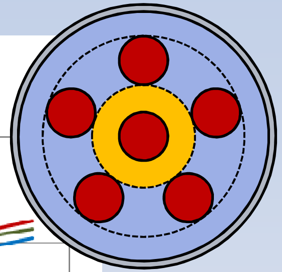
Turbulence Modeling in Rod Bundles

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

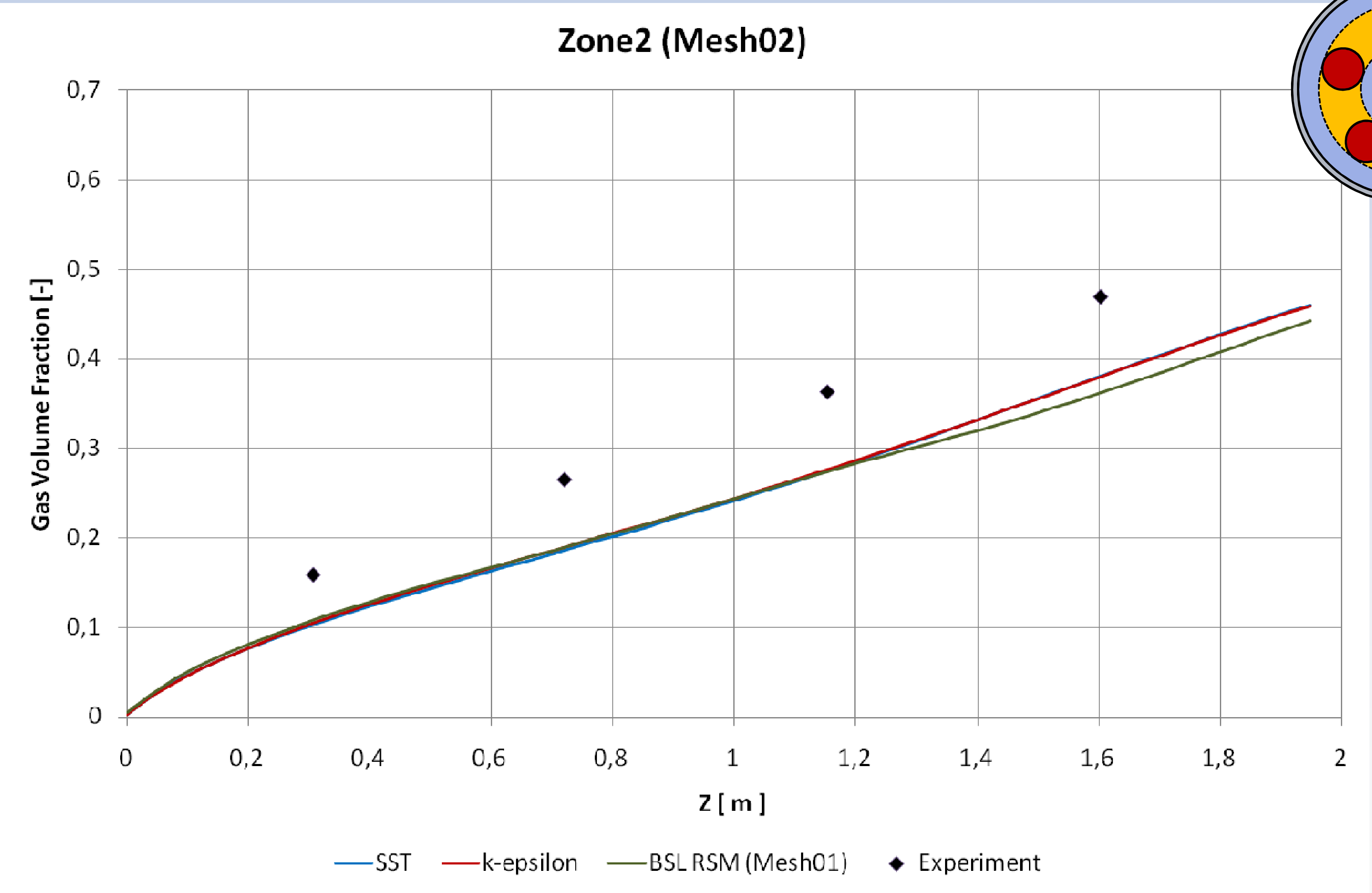
    → Can be relevant for safety!

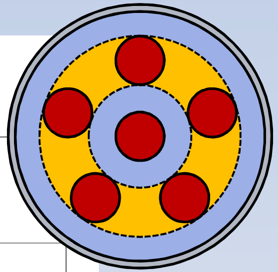
FRIGG-6a Test Case
Turbulence Model Comparison



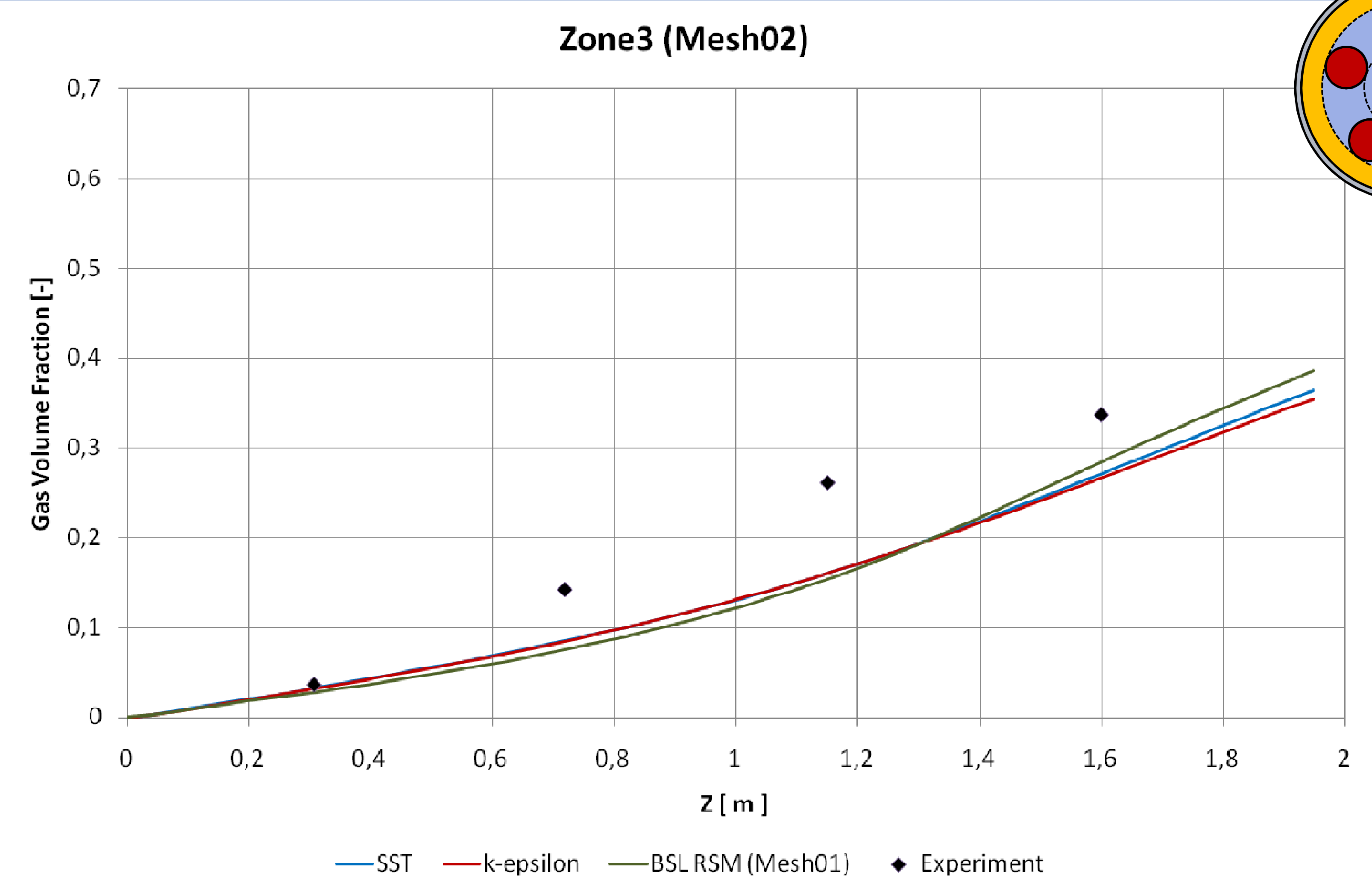


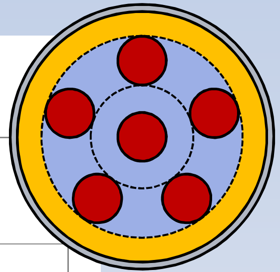
FRIGG-6a Test Case
Turbulence Model Comparison



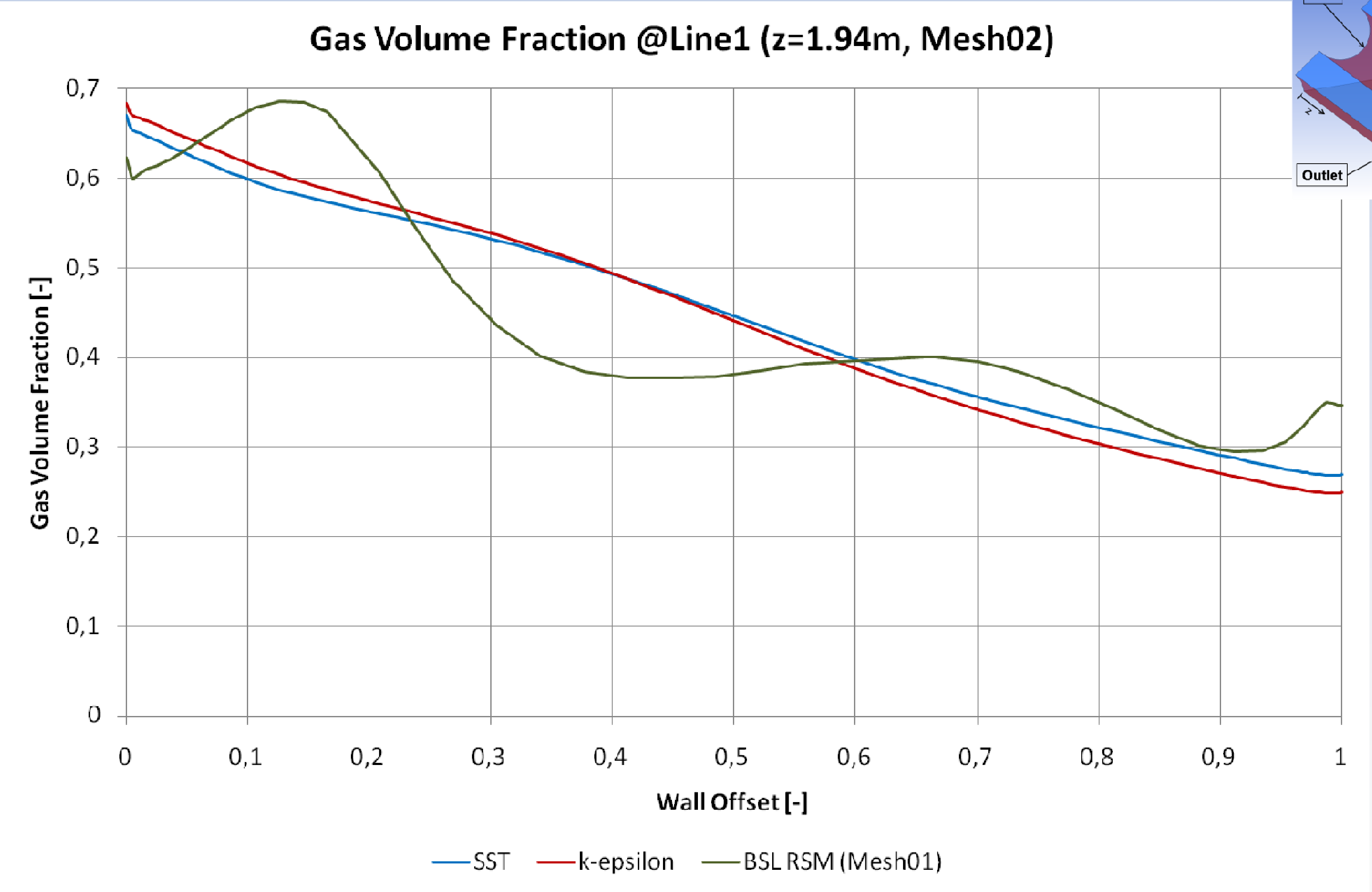


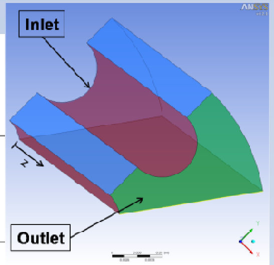
FRIGG-6a Test Case
Turbulence Model Comparison





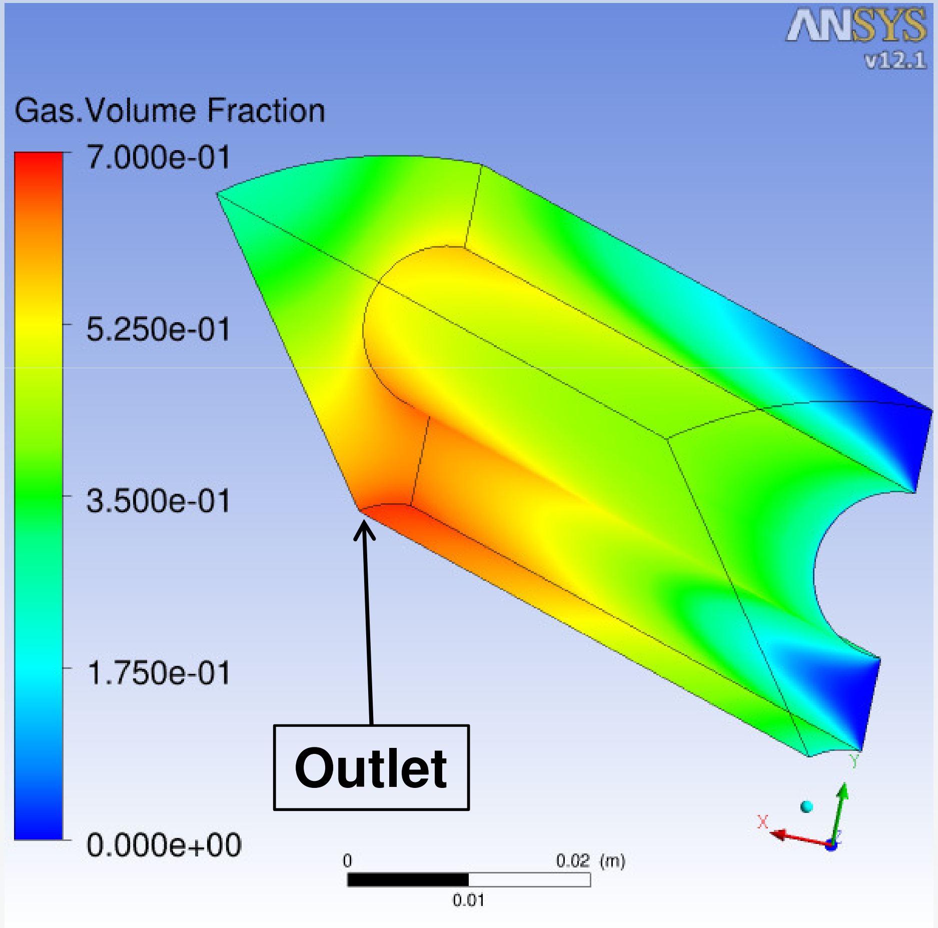
FRIGG-6a Test Case
Turbulence Model Comparison



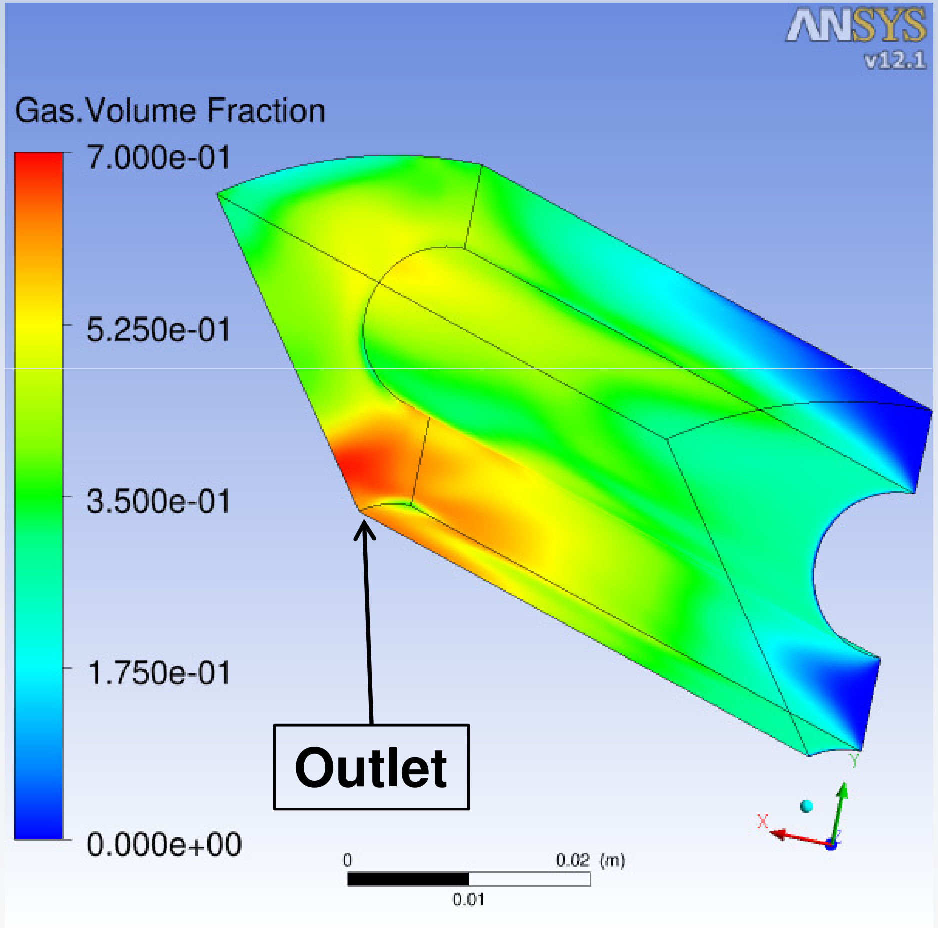


FRIGG-6a Test Case
Turbulence Model Comparison

SST model



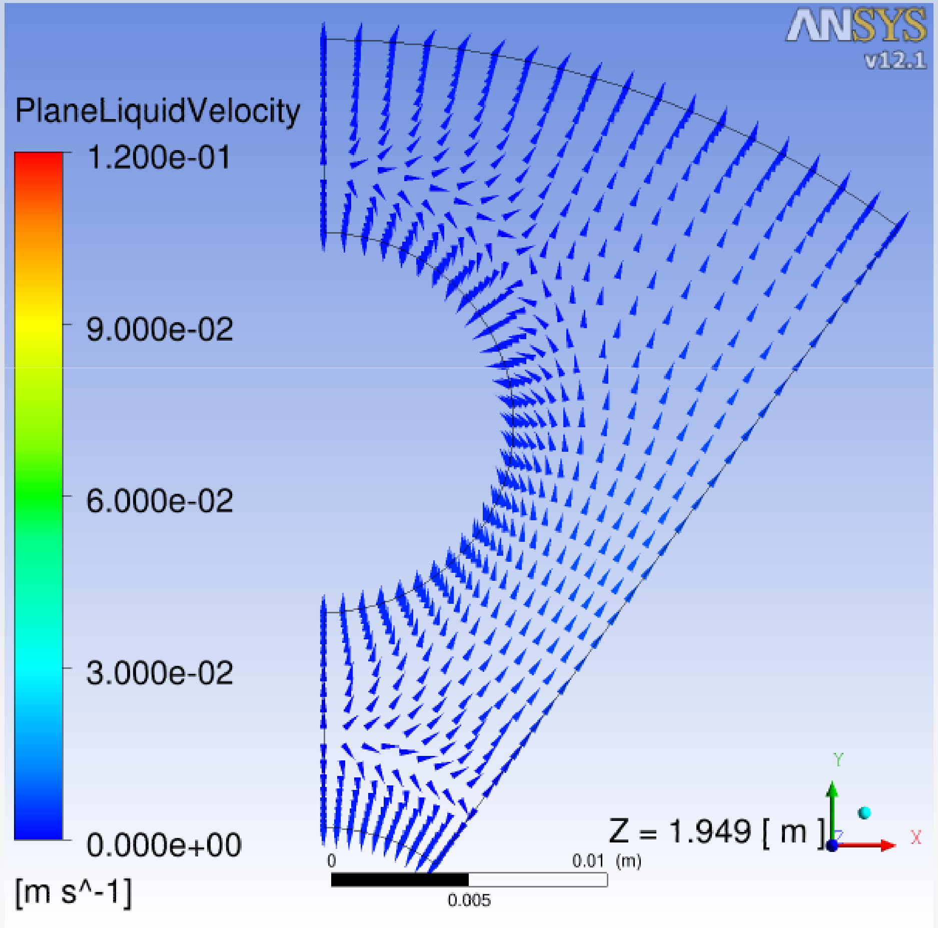
BSL RSM model



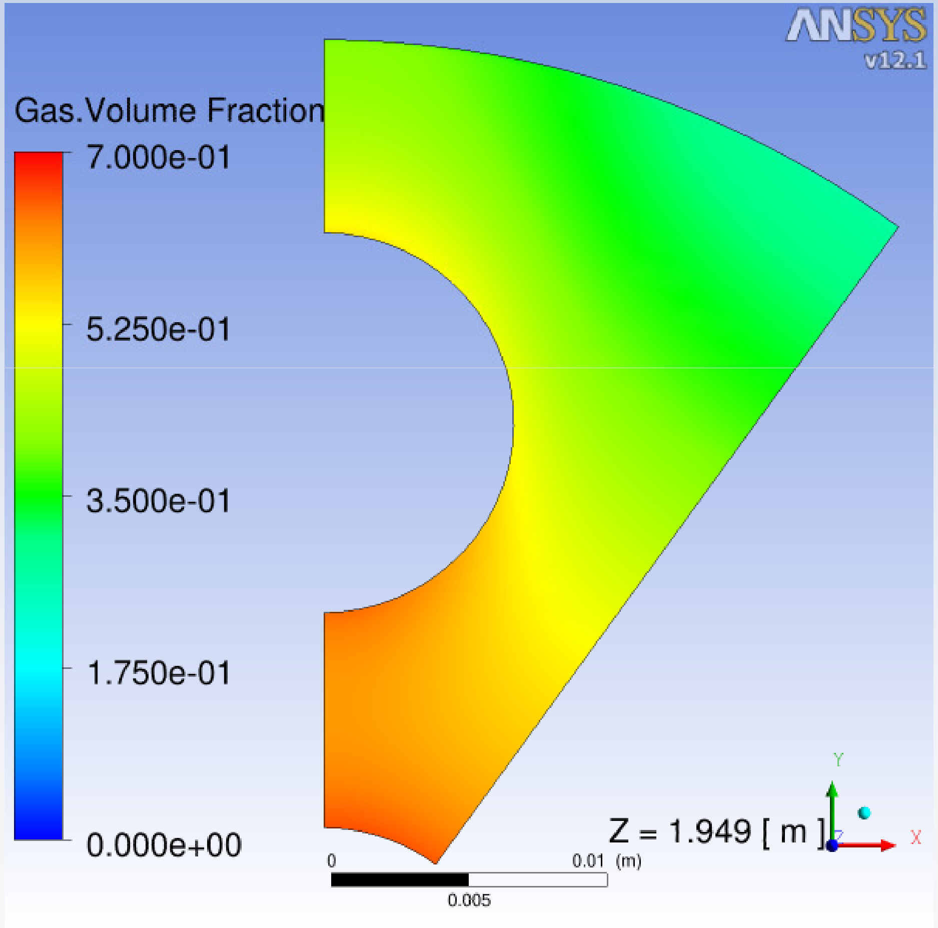
Plot of gas volume fraction

FRIGG-6a Test Case
Turbulence Model Comparison

- **SST model → NO secondary flows**



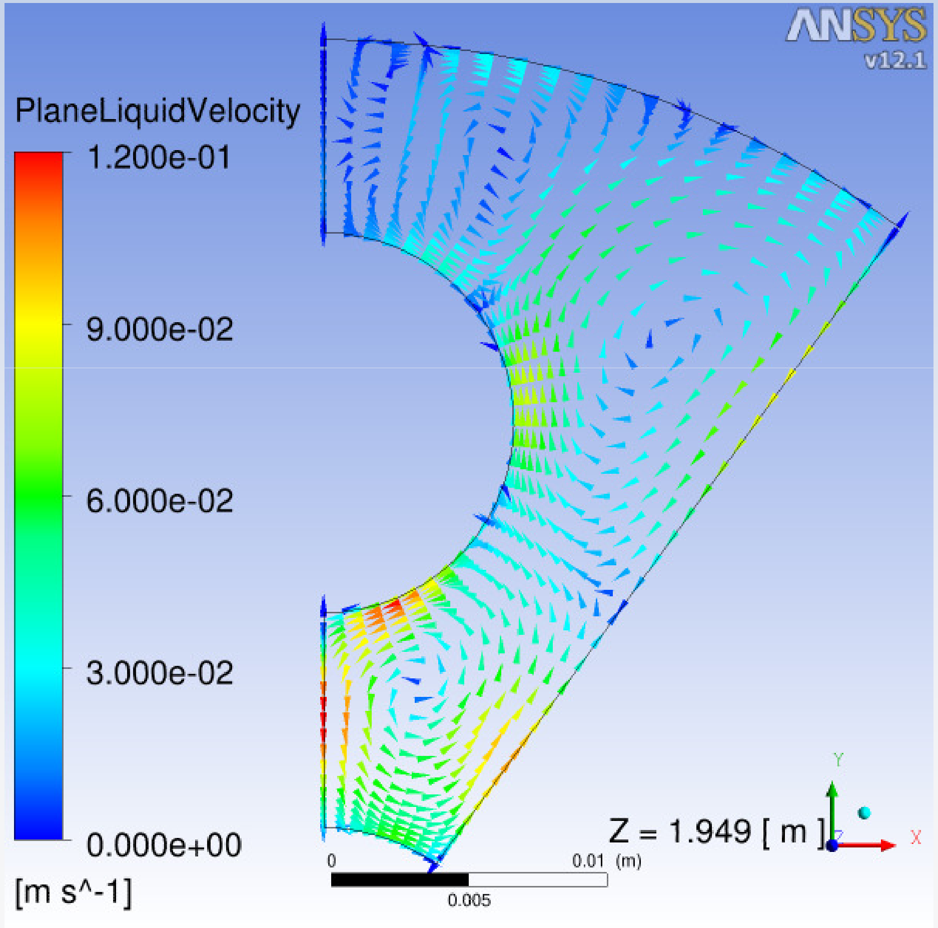
Plot of gas volume fraction (Outlet)



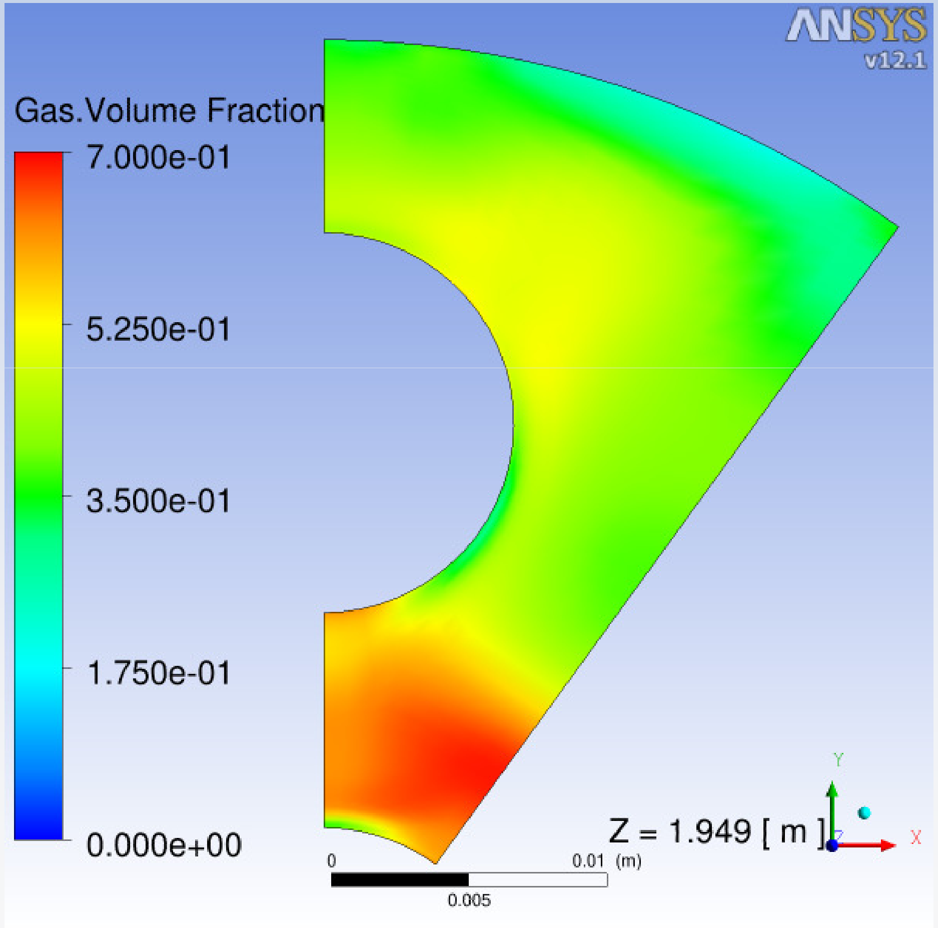
Contour plot of gas volume fraction (Outlet)

FRIGG-6a Test Case
Turbulence Model Comparison

- **BSL RSM model → secondary flows**



Plot of gas volume fraction (Outlet)

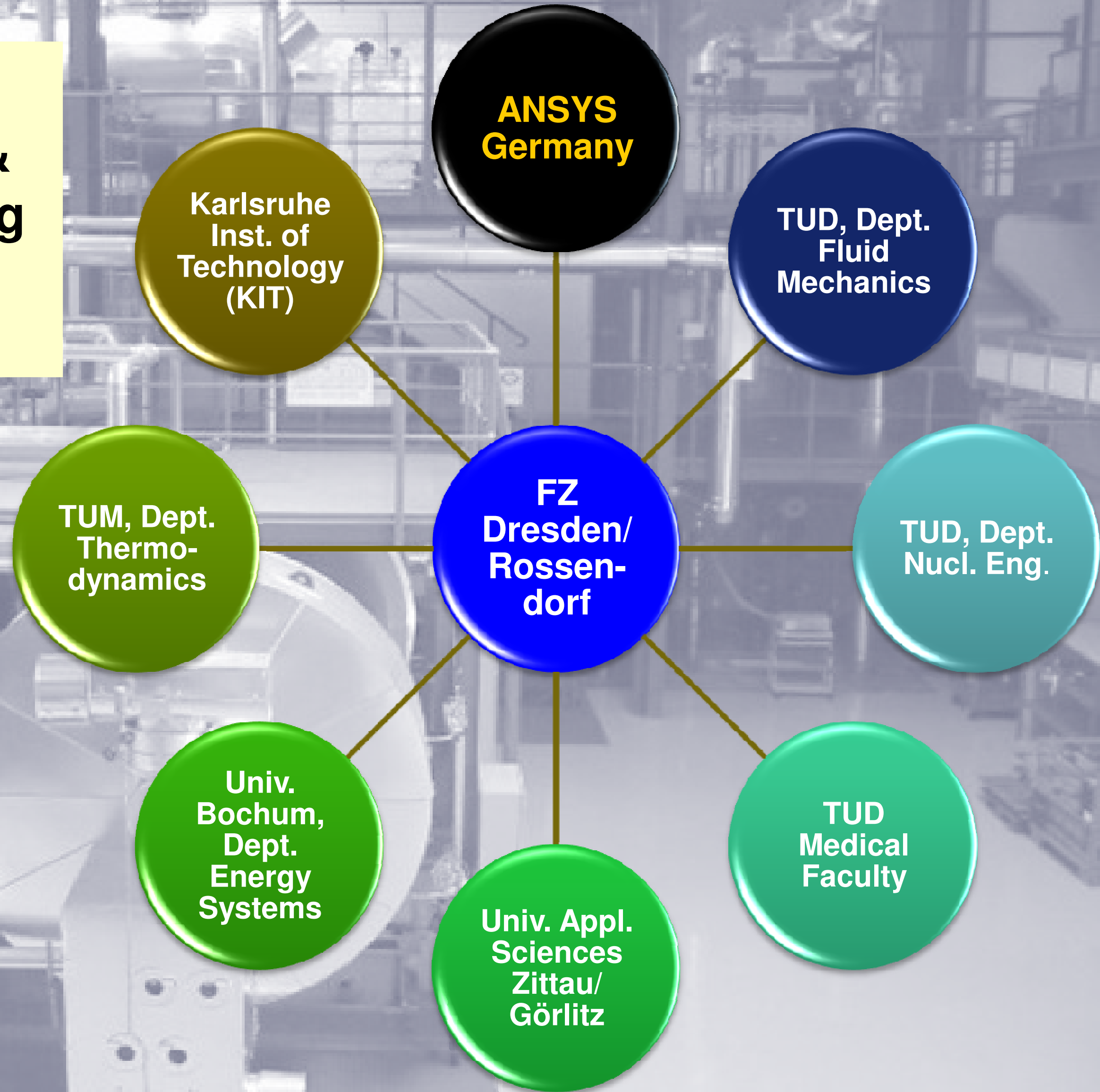


Contour plot of gas volume fraction (Outlet)

New R&D Consortium

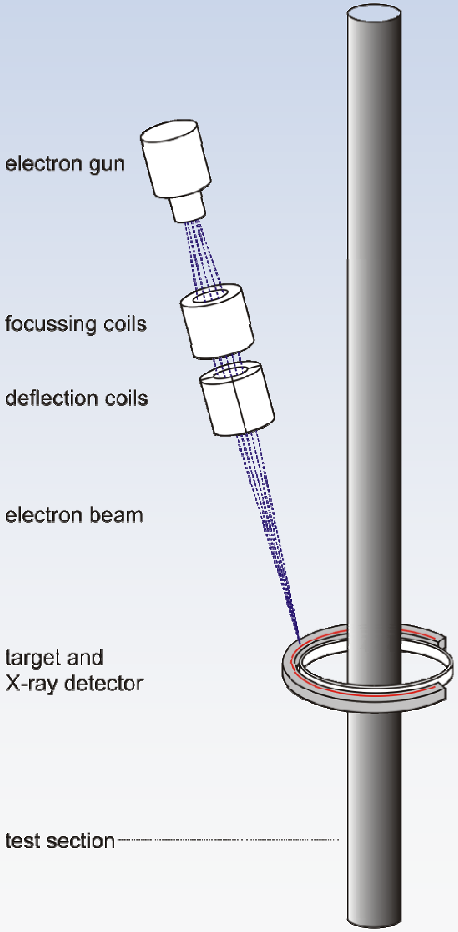
R&D Initiative:

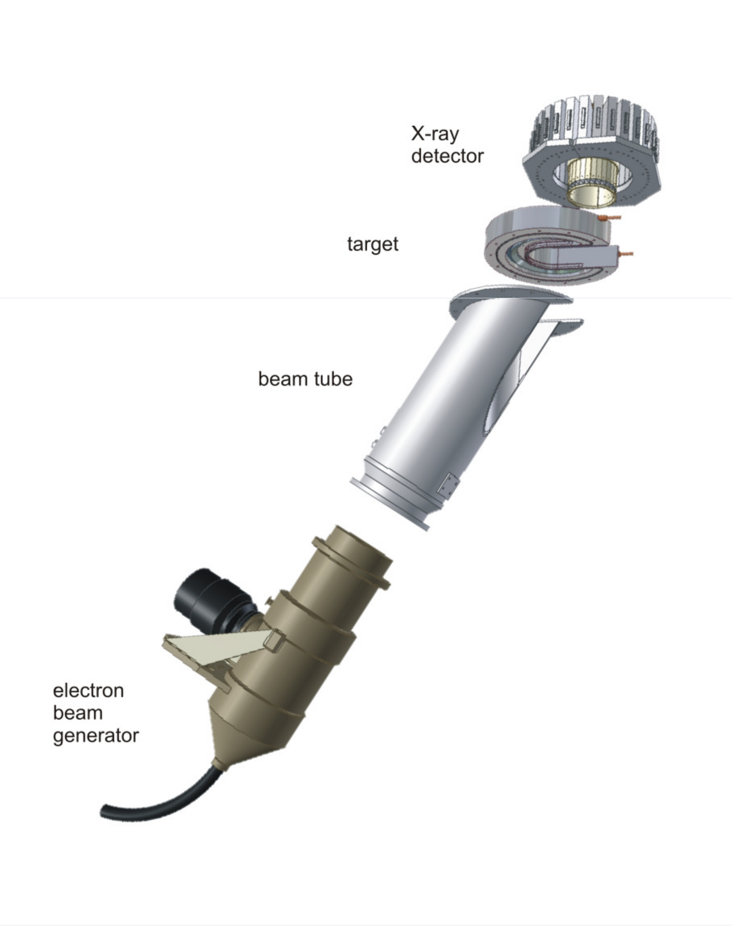
"Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR"



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:**



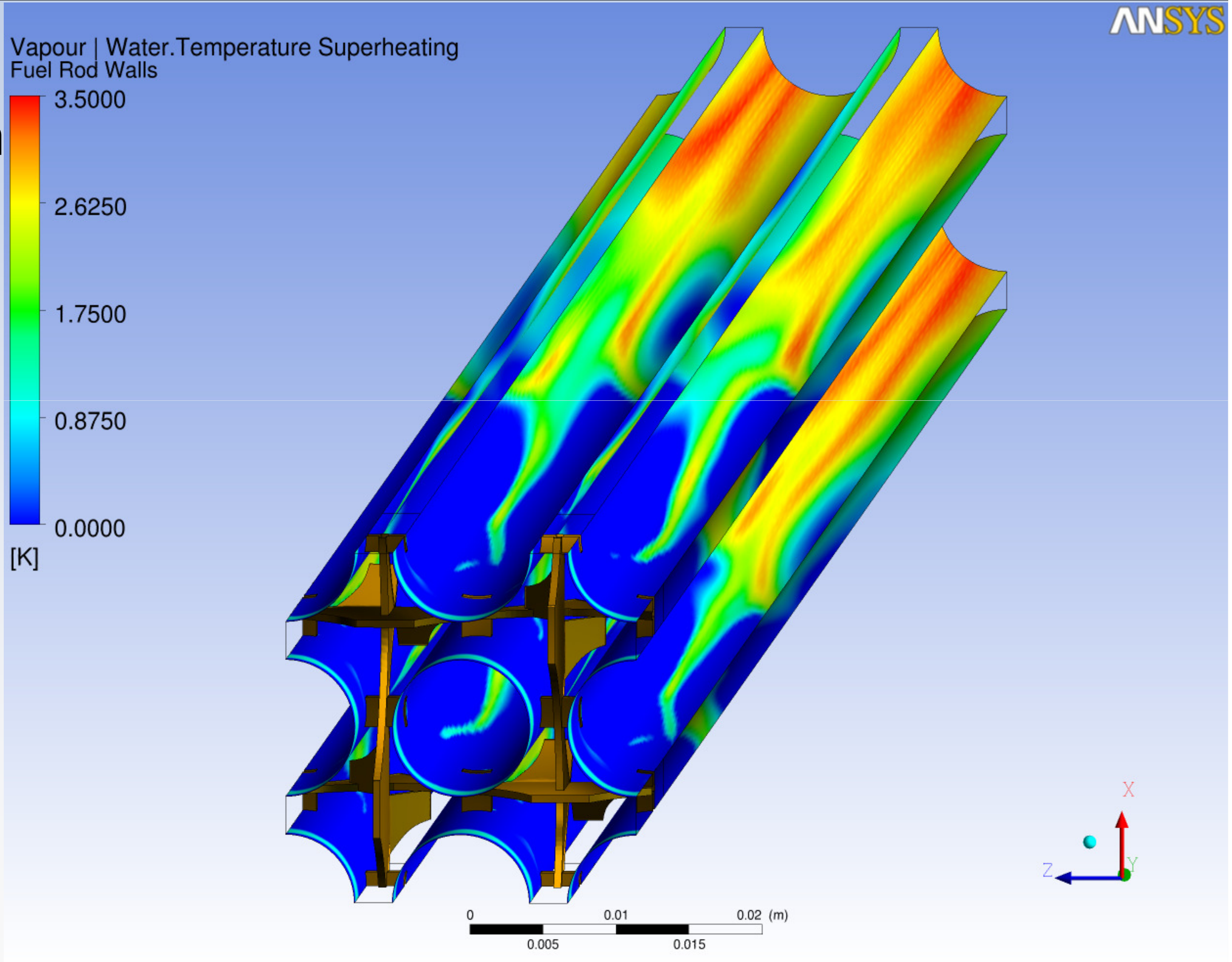


Images by courtesy of U. Hampel, FZD

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

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

Wall superheat T_W-T_{Sat}



Summary & Outlook

- **Overview on ANSYS CFD boiling model development and validation**
- **Continuous effort in model improvement, R&D**
- **Emphasis in validation on BPG, comparison to data, geometry & grid independent modeling**
- **Complex MPF phenomena**
  → number of uncertainties remaining for further investigations → detailed experiments
- **Outlook:**
  - Ongoing & customer driven CFD model development
  - Research cooperation with Industry & Academia
  - Coupling of wall boiling model to inhomogeneous MUSIG
  - Extension of the wall heat partitioning in wall boiling model

ANSYS

ANSYS

CFX

ANSYS FLUENT

ICEM CFD

Thank You!