Advances in the Simulation of Boiling Steam-Water Flow through Fuel Assembly Subchannels and Rod Bundles

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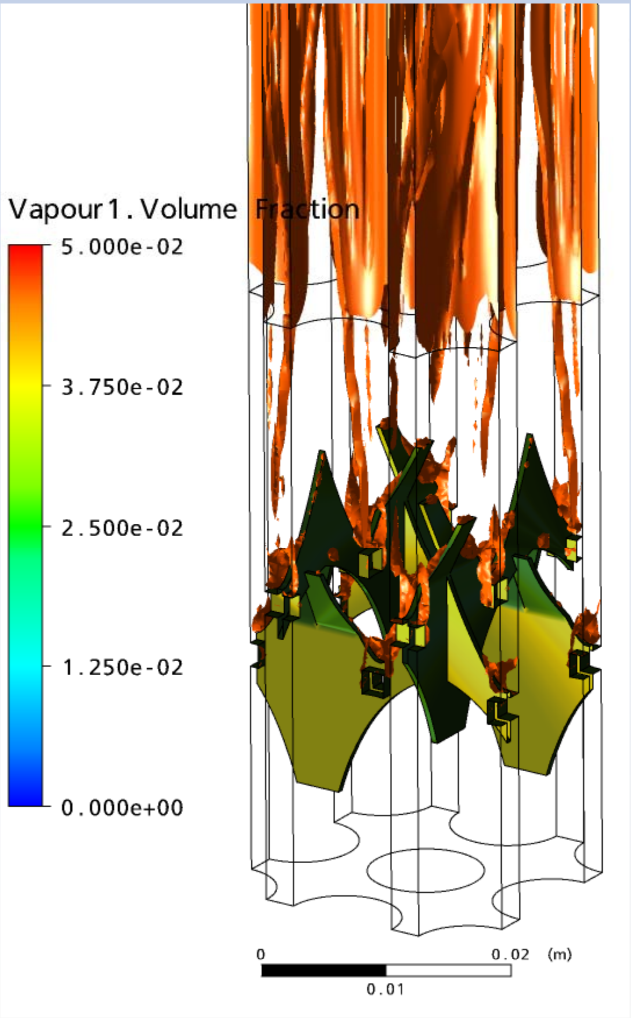
Outline

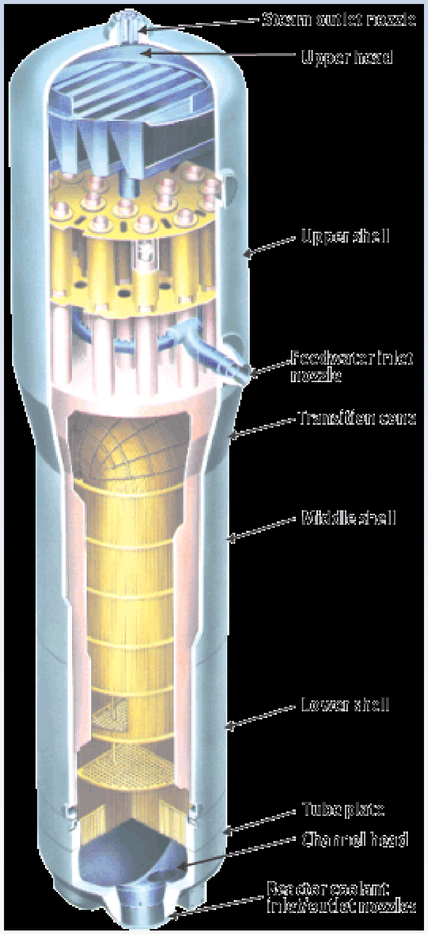
- Introduction
- Development of subcooled nucleate boiling model:
  - The modified RPI wall boiling model
  - Extensions to the RPI model
  - Coupling of RPI & MUSIG
- Validation & application of the boiling model in ANSYS CFD
  - Boiling & recondensation
  - FRIGG loop: Boiling in heated rod bundles
- Summary & Outlook



Boiling Flow Applications

ANSYS

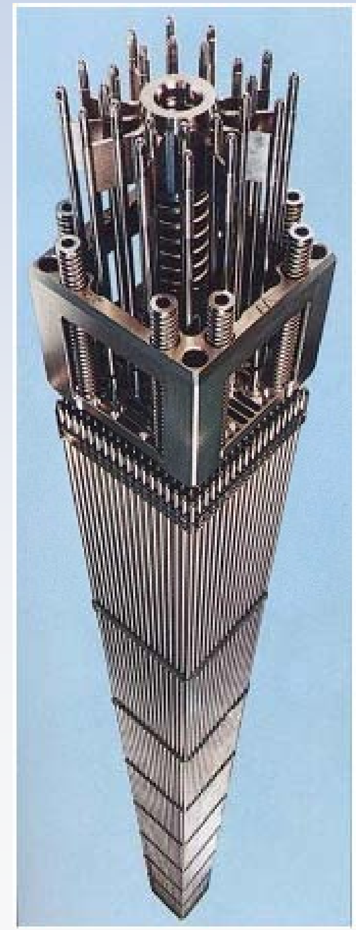
Steam Generators



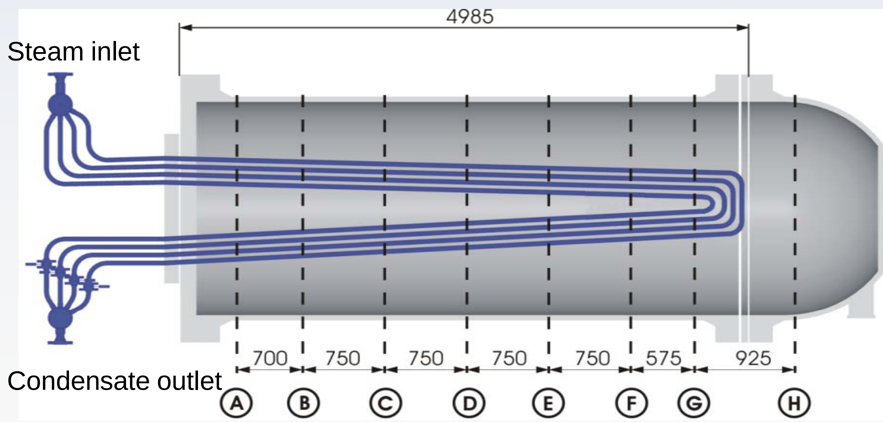
Process Technology

Engine cooling water jackets

Fuel Assemblies



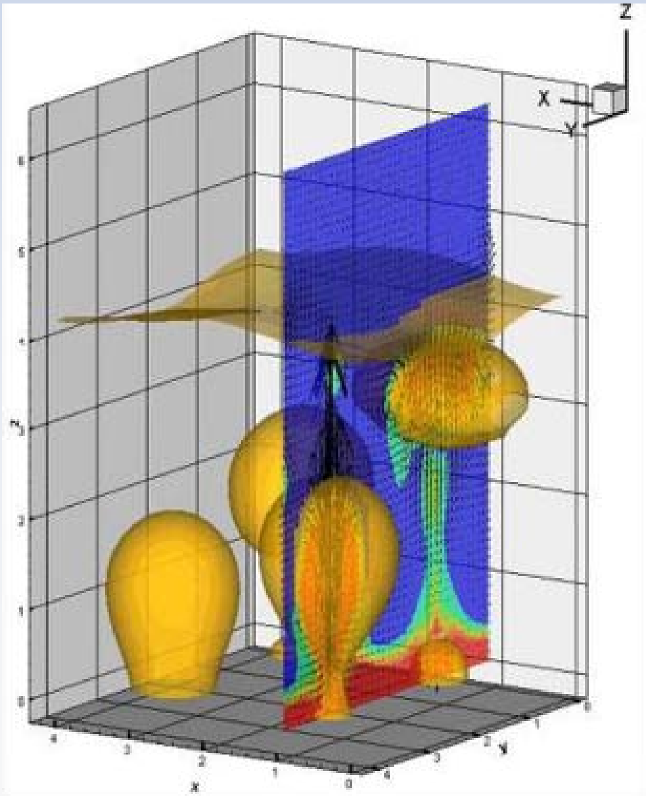
Steam Condensers



Wall Boiling Modeling

Why special modeling for wall boiling?

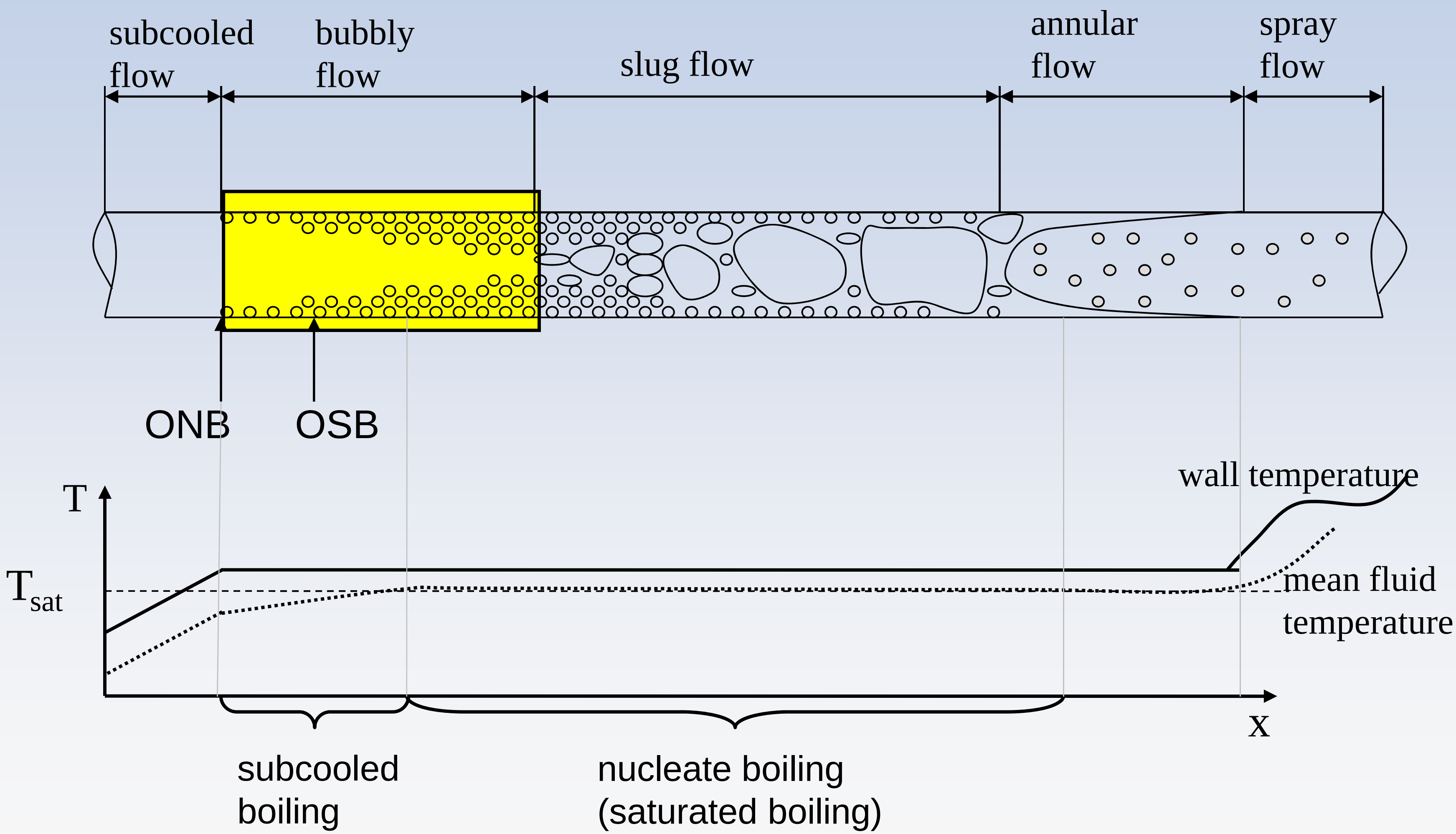
- For subcooled flows with superheated walls, standard thermal phase change models for bulk boiling/condensation will underpredict mass transfer rates
- Accounts for steam bubble growth on nucleation sites and bubble departure
- Mechanistic model for wall driven boiling



Model outline:

- Mechanistic wall heat flux splitting
  → convective heat transfer, evaporation, quenching
- Empirical submodels required for closure
- Available for different BC's:
  prescribed T_{wall} or q_{wall}, CHT walls
- Activated per boundary patch with individual T_{wall} or q_{wall}

Multiphase Flow Regimes for Boiling Water Flow



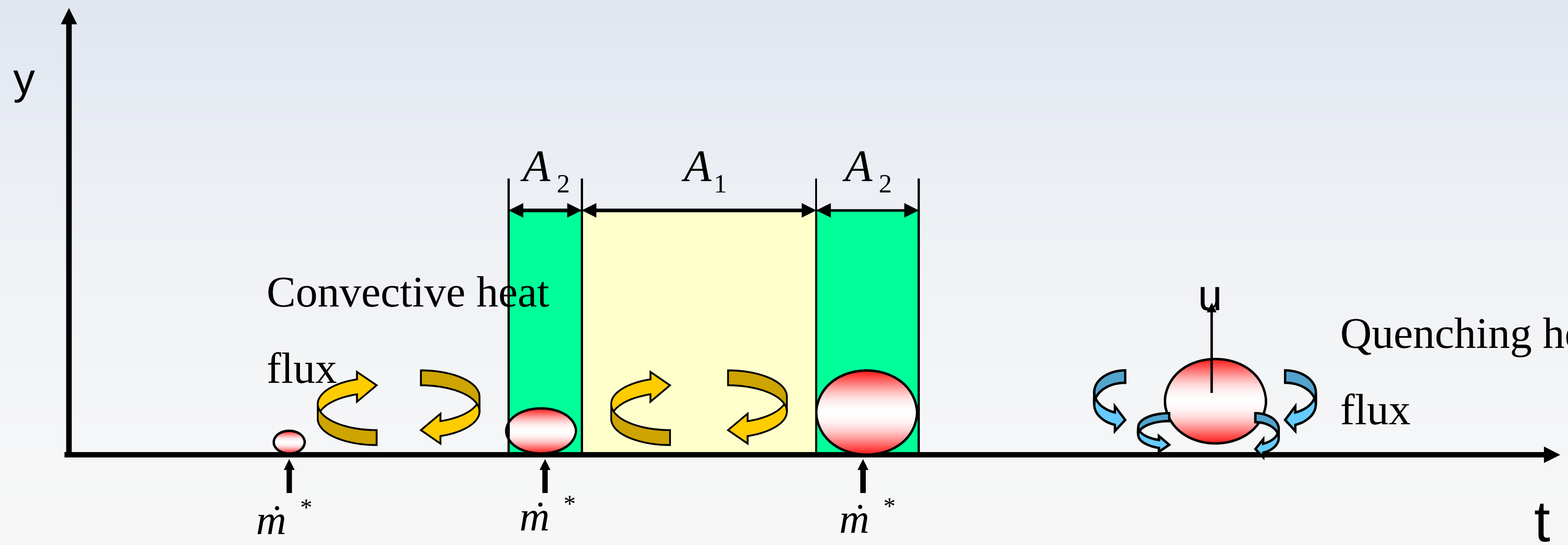
Mechanistic wall heat partioning model:

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

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

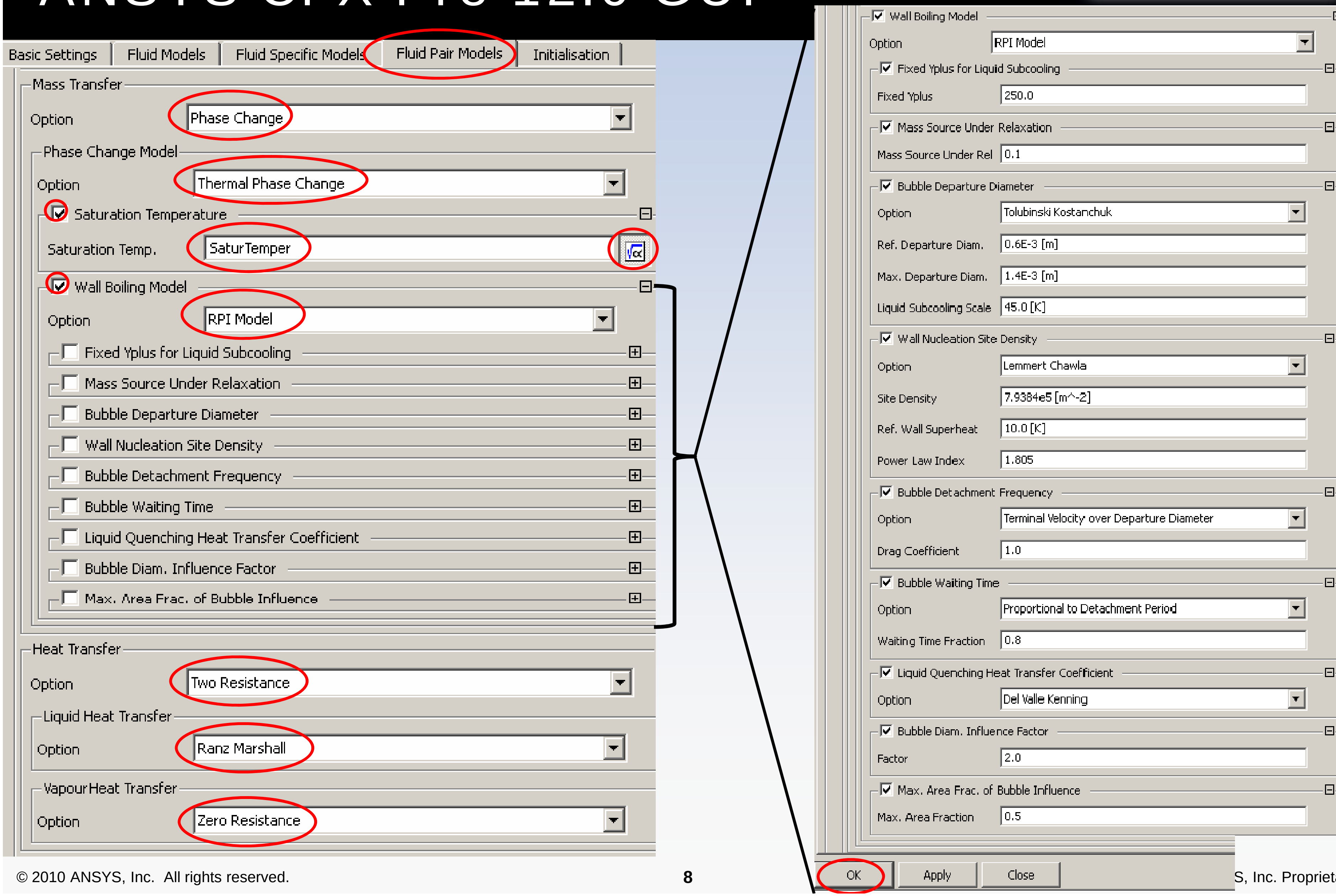
Submodels for closure of RPI wall boiling model:

- 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

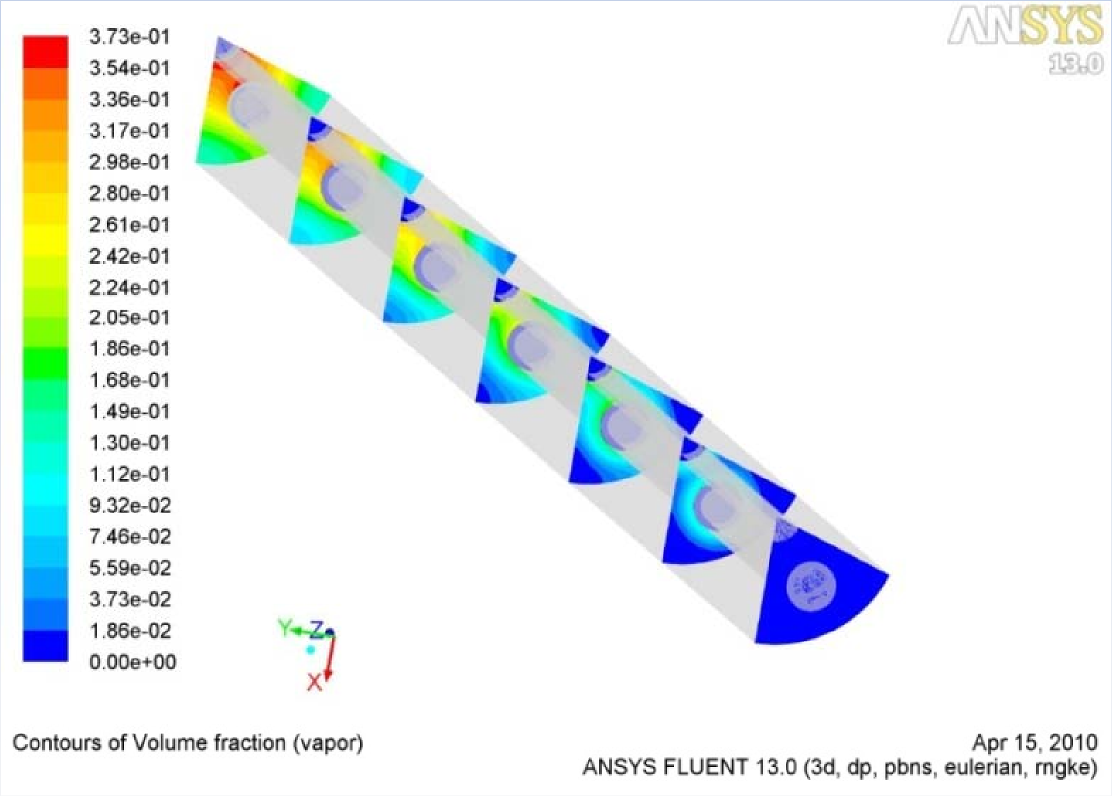
RPI Wall Boiling Model in the ANSYS CFX-Pre 12.0 GUI

ANSYS



ANSYS Fluent 13.0
Wall Boiling Modeling

- ANSYS Fluent 13.0:
  - Based on same RPI nucleate boiling & heat flux partitioning model
  - Non-equilibrium subcooled boiling
  - Supports 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

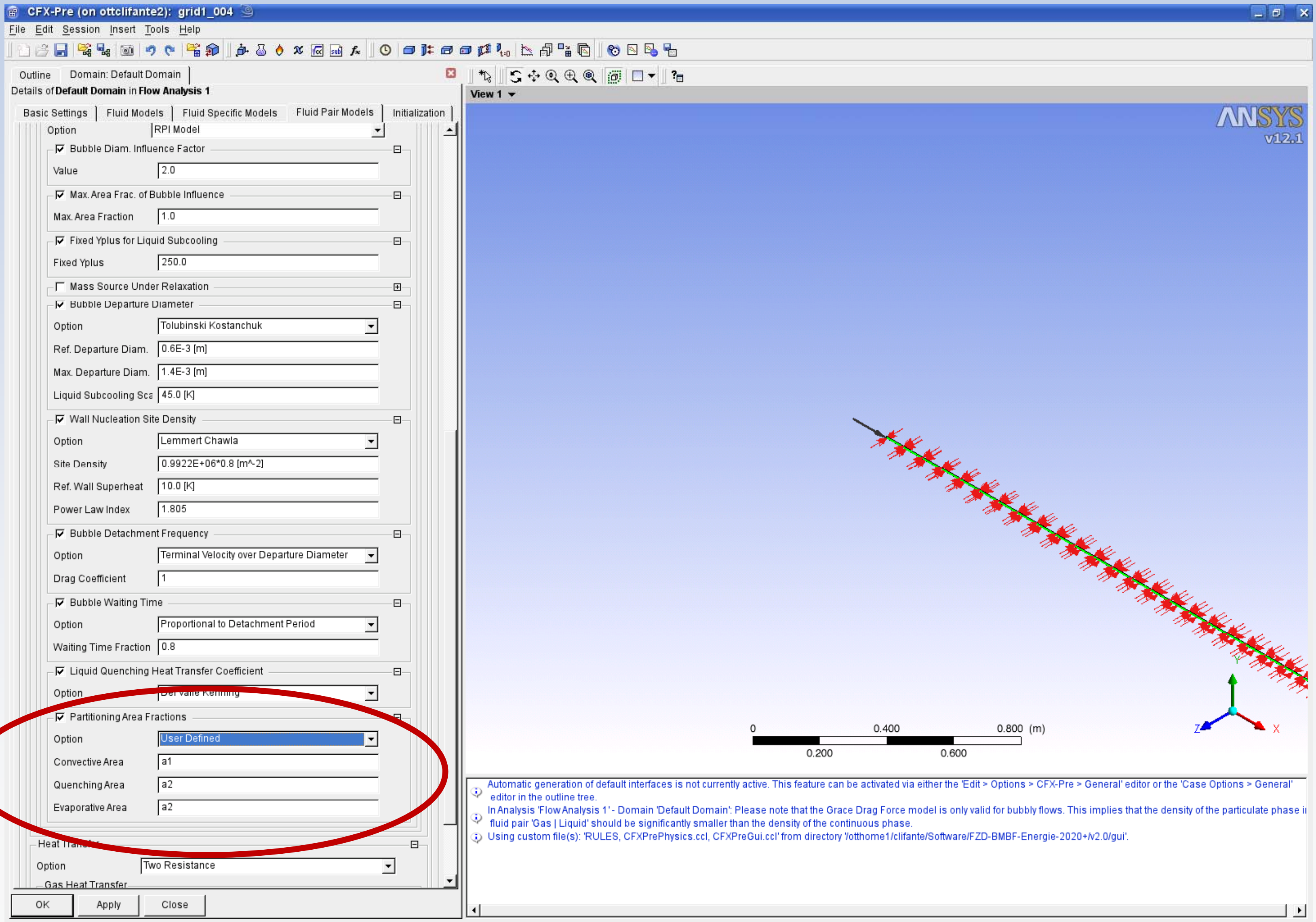
- Ongoing R&D and development:
  - Provide more user interfaces to the RPI boiling model
  - User defined area fractions A_1 and A_2
  - User defined terms for convective, quenching and evaporative heat fluxes Q_F, Q_Q, Q_E
  - User defined 4th component of wall heat partitioning, e.g. convective heat flux to vapor
  - CFX5Pre GUI extension
  - Extended output to CFD-Post
  - Coupling of RPI wall boiling & MUSIG
- 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

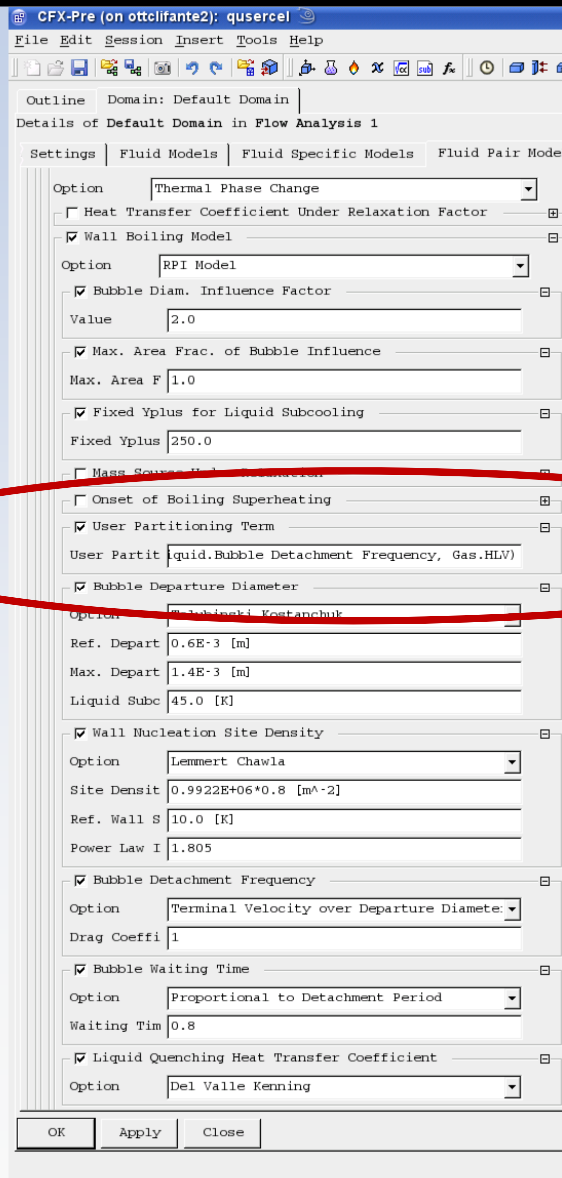


CCL & User Routine for 4th Wall Heat Partitioning Component

```
    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
```

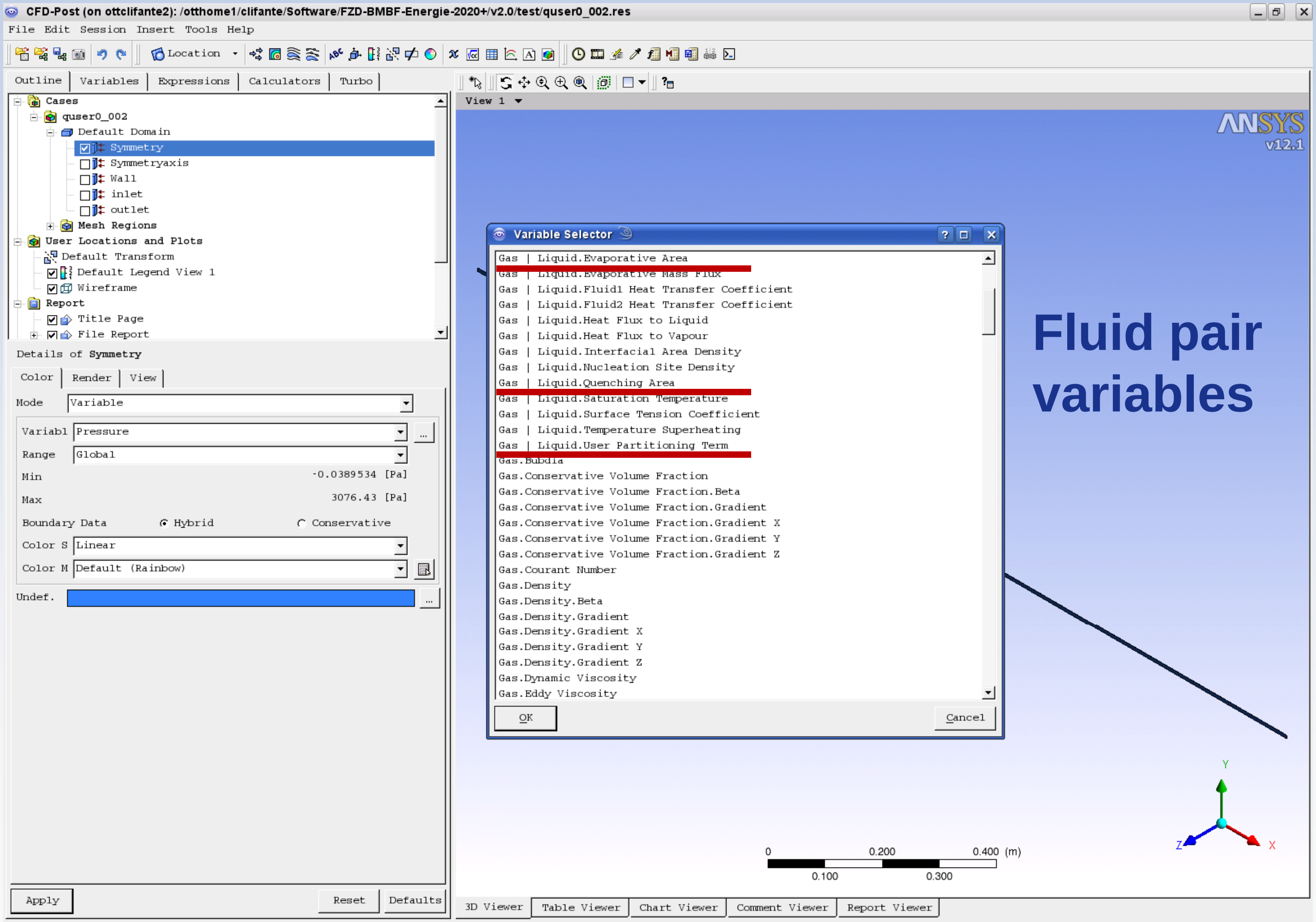
- **Introduction of 4th component of the wall heat flux partitioning via CCL or User Fortran**

CCL & User Routine for 4th Wall Heat Partitioning Component



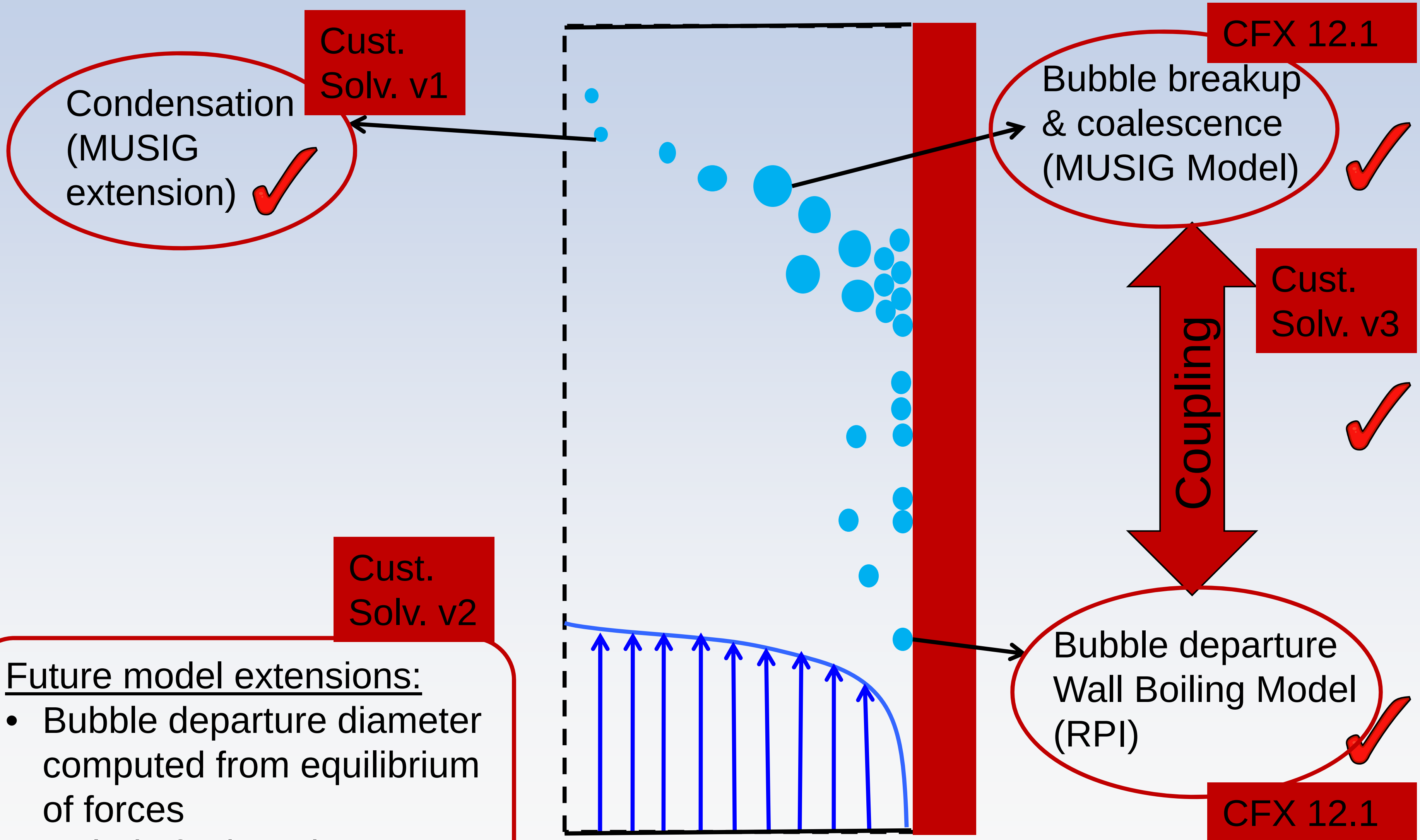
- **Customization of CFX5Pre for the extension of the RPI wall heat flux partitioning algorithm → 4th component of the wall heat flux splitting**

Extended CFX5Post Output



Fluid pair variables

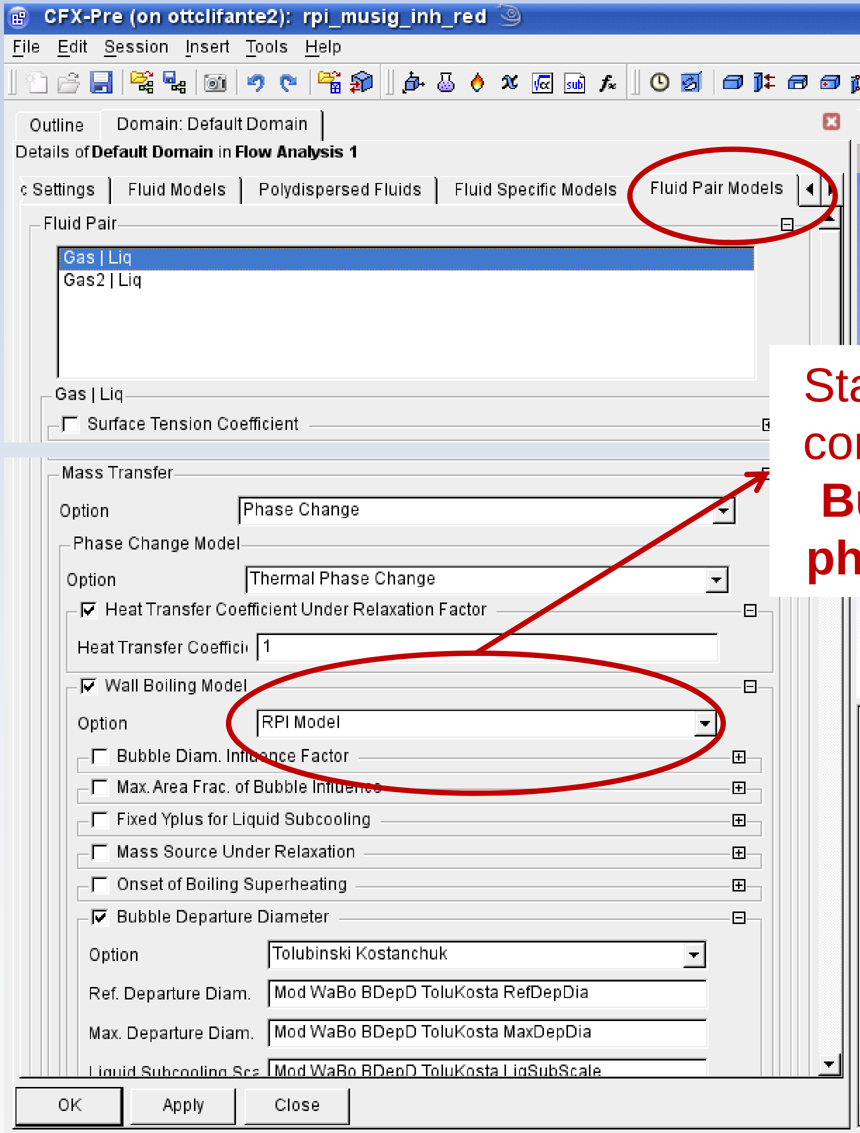
Coupling of RPI Wall Boiling Model with Homog./Inhomg. MUSIG

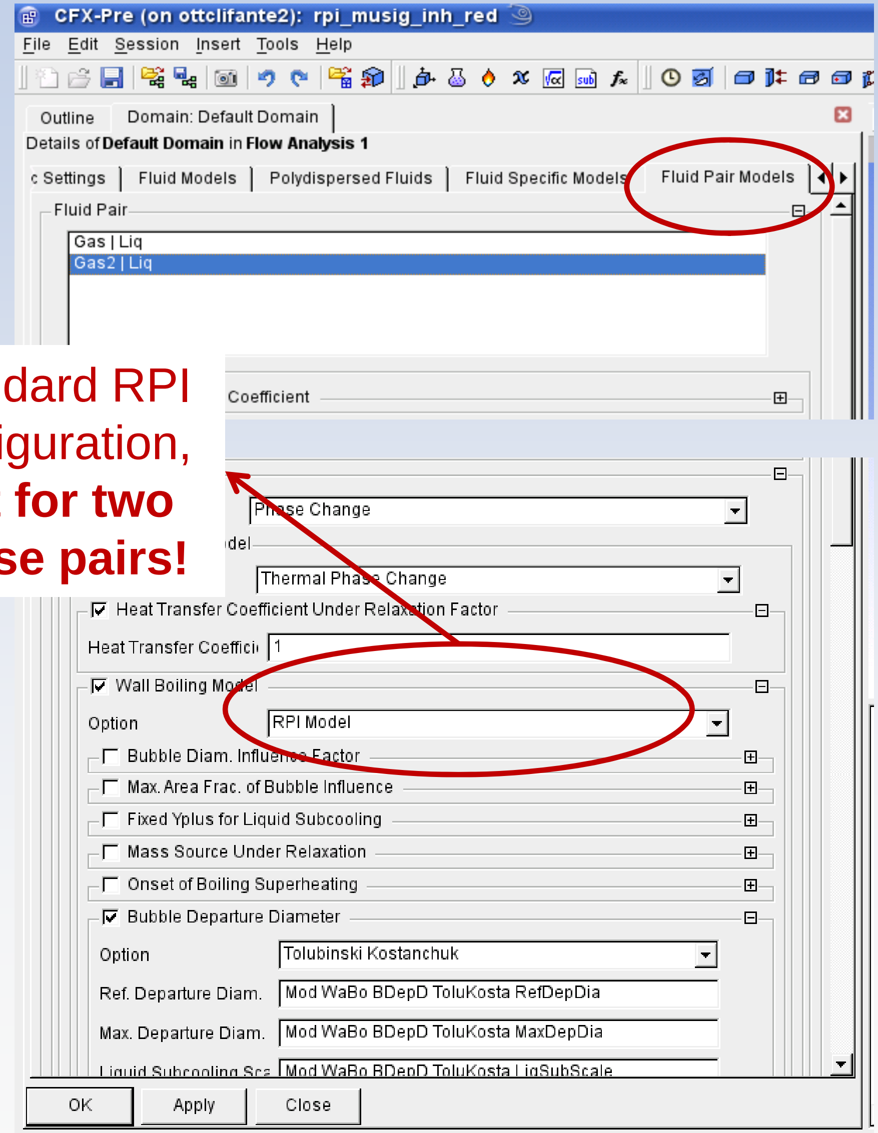


<u>Future model extensions:</u>

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

CFX5Pre Customization: Inhomogeneous MUSIG & RPI

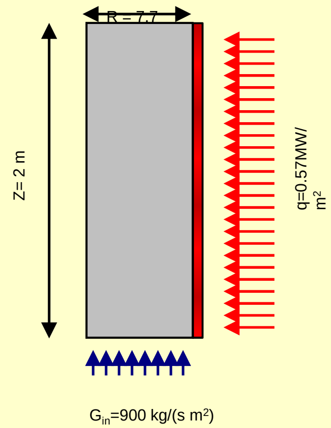


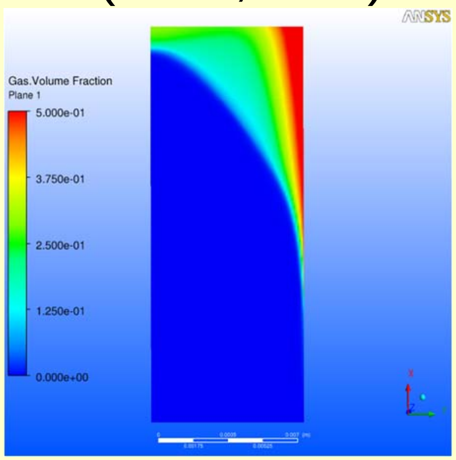


Standard RPI configuration,
But for two phase pairs!

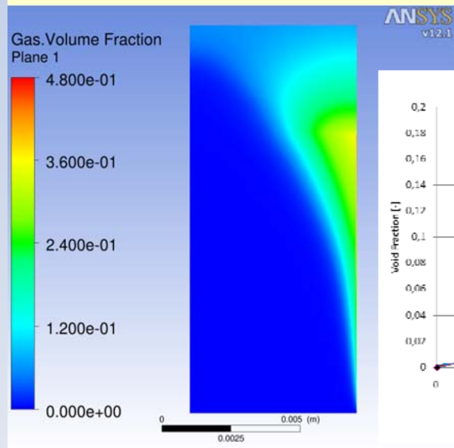
Investigated Boiling Testcases

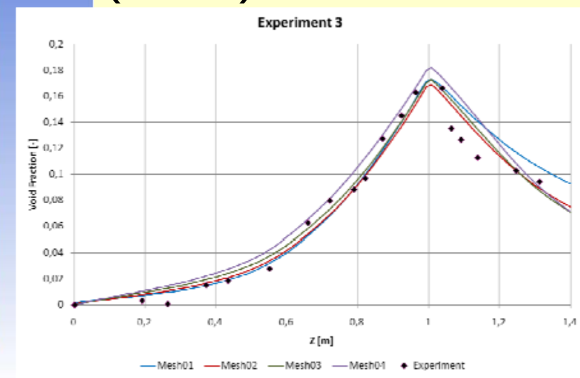
- Bartolomei et al. (1967,1982)



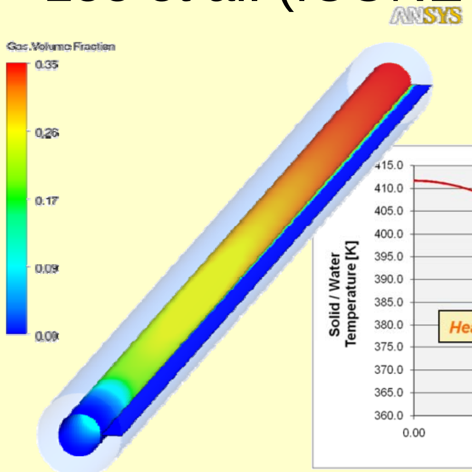


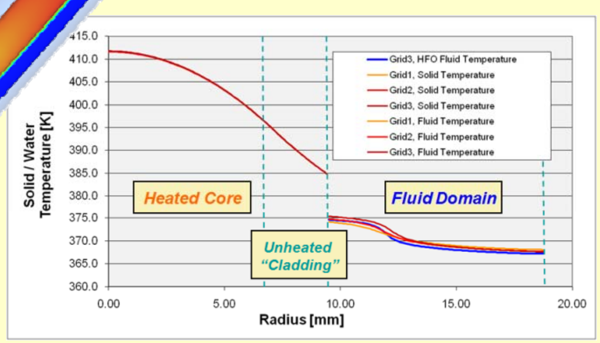
- Bartolomei with recondensation (1980)



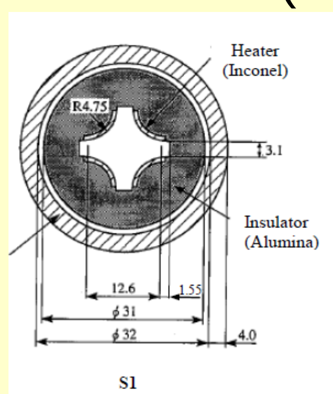


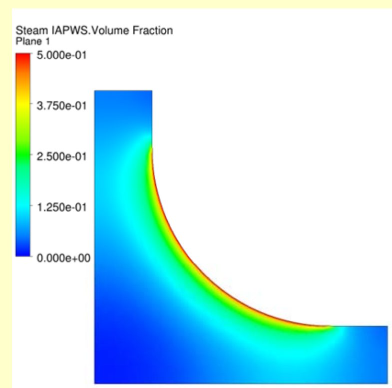
- Lee et al. (ICONE-16, 2008)





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





– Model Validation –

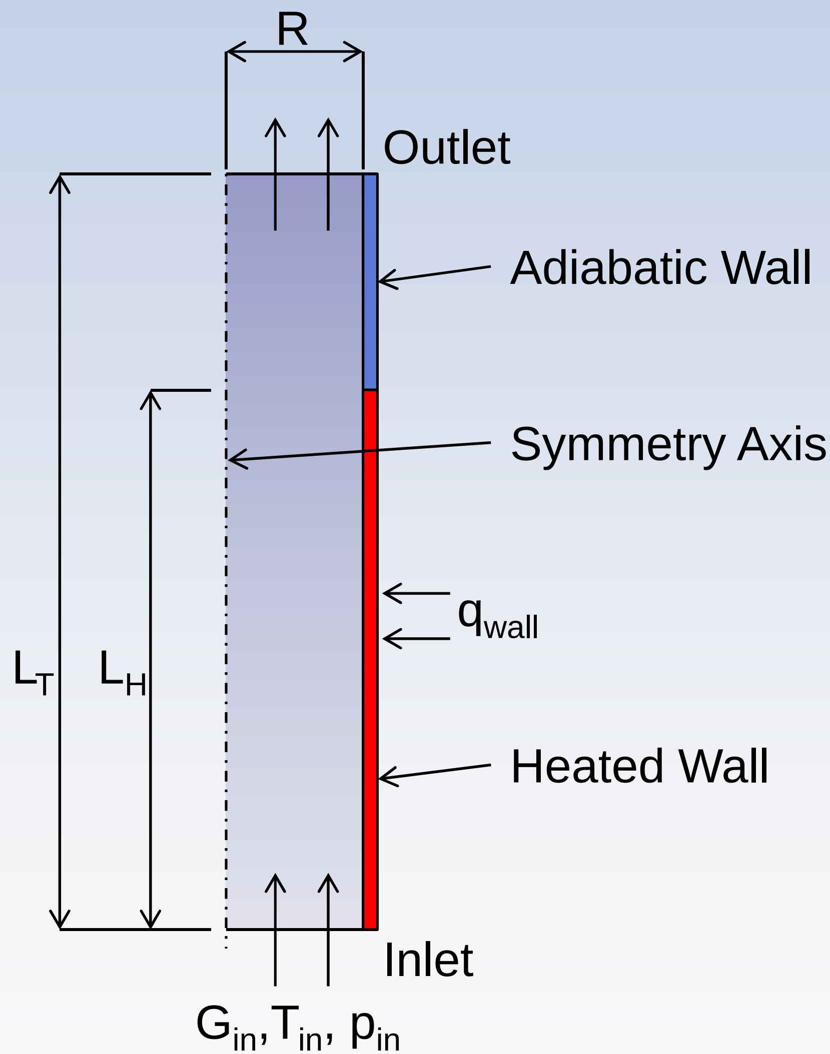
The Bartolomej et al. Testcase with Recondensation
(Bartolomeij et al., 1980)

Availability of Testcases to ANSYS Customers

- ANSYS maintains a database of validation testcases (not only for multiphase flows)
- Bartolomei, Lee & FRIGGS testcases are available to ANSYS customers through ANSYS customer support
- Datasets of the testcases include:
  - Mesh hierarchy
  - CFD setup (baseline & parametric studies)
  - Basic post-processing and comparison to data
  - Documentation (report, paper or PPT)

Geometry & Flow Parameters

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



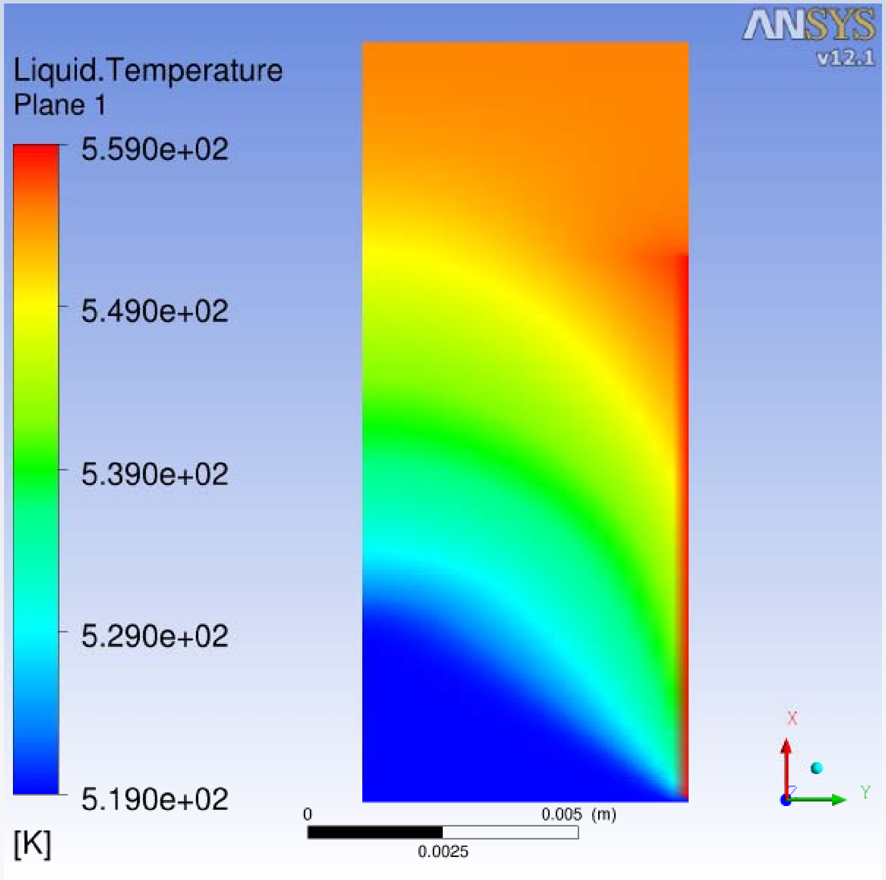
Testcase Parameters

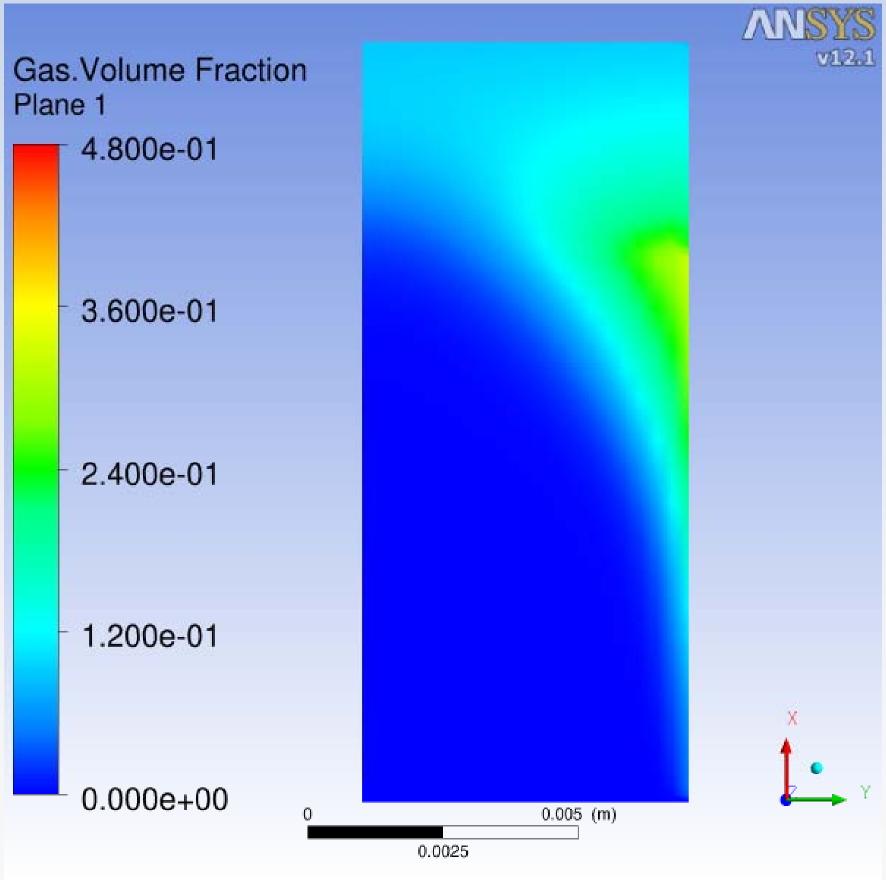
- Measurement data of zonal-averaged cross-sectional steam volume fraction distribution over pipe length are available for 3 different parameter setups:

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)

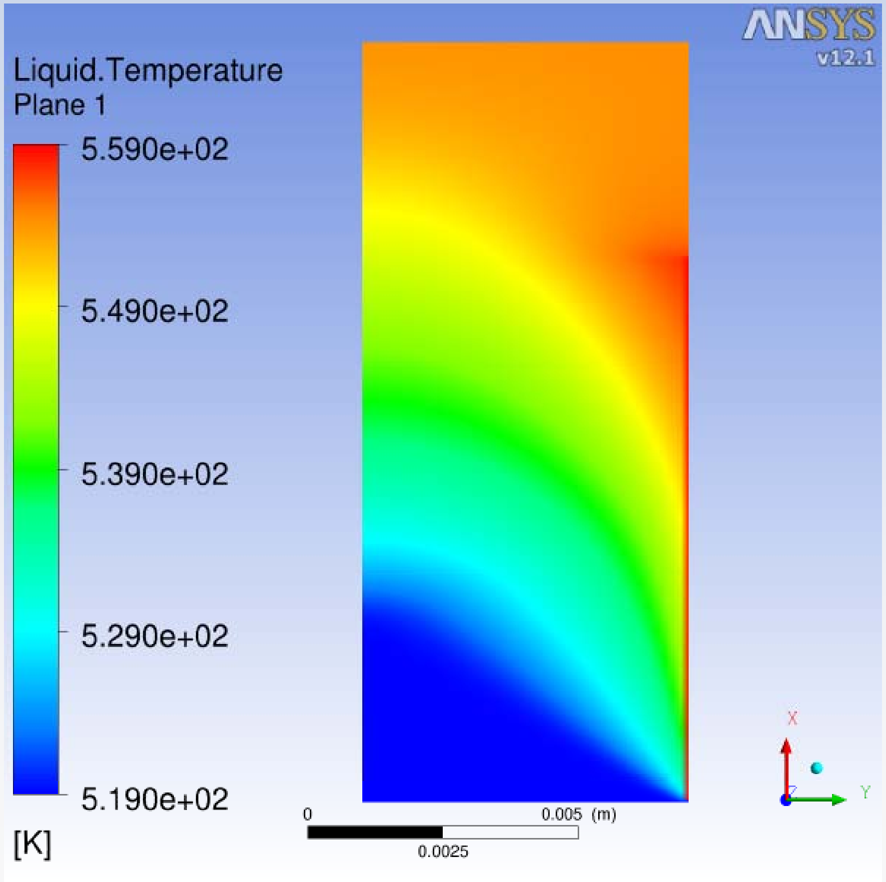
- Distribution of water temperature and steam volume fraction

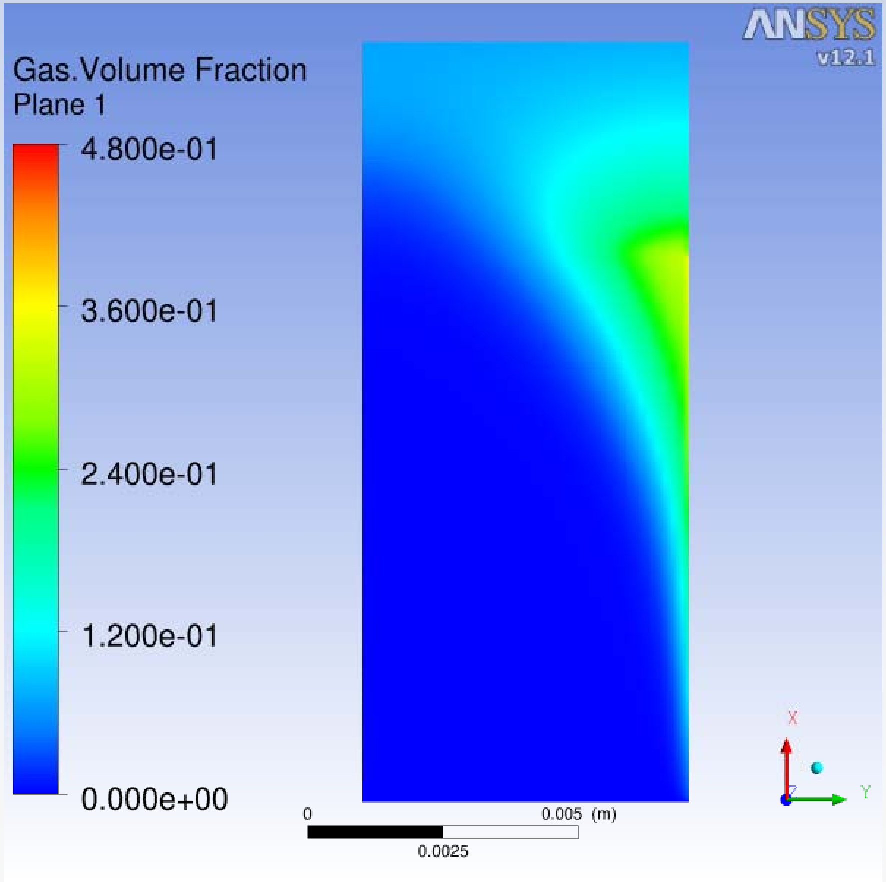




Experiment No. 3 (Mesh02)

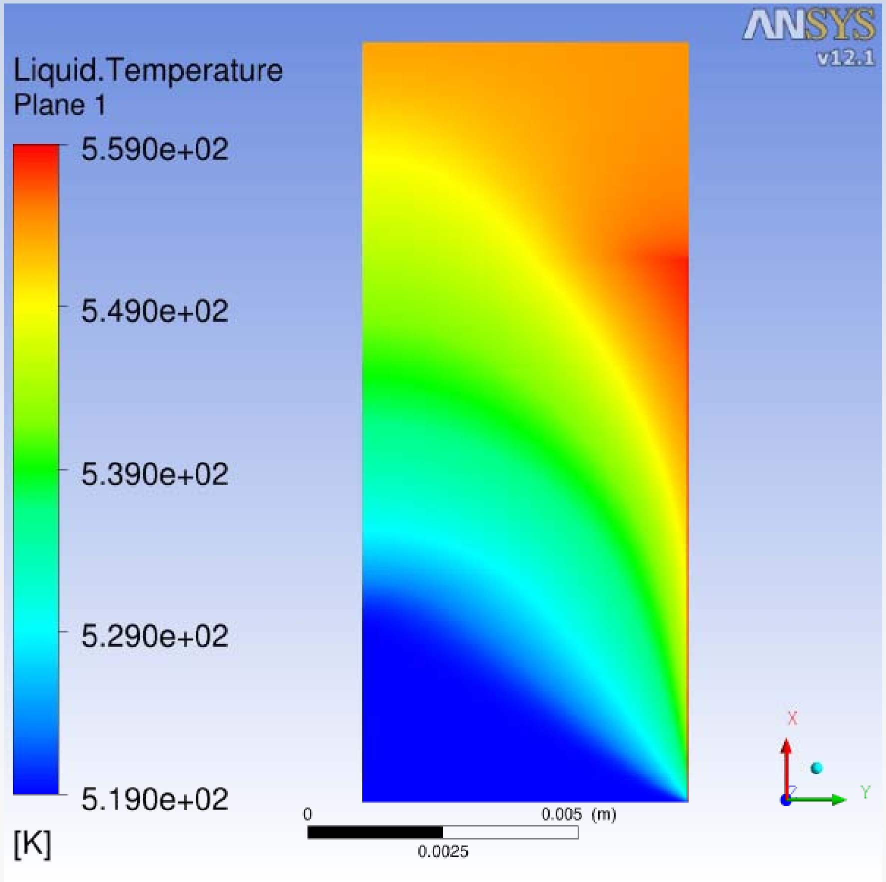
- Distribution of water temperature and steam volume fraction

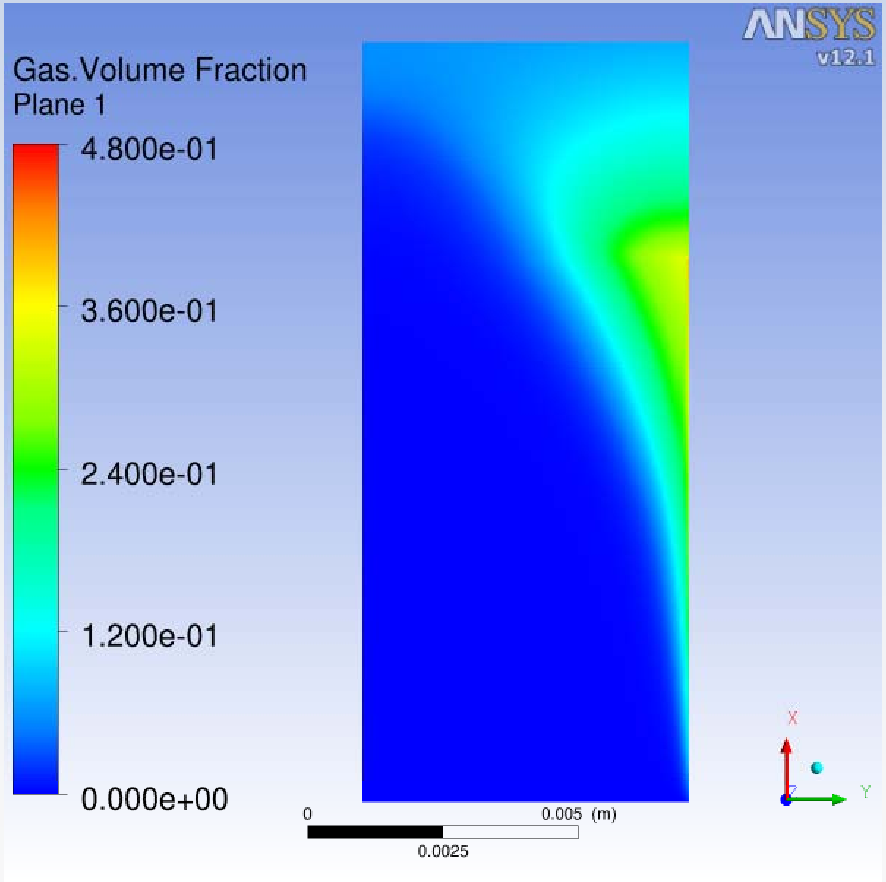




Experiment No. 3 (Mesh03)

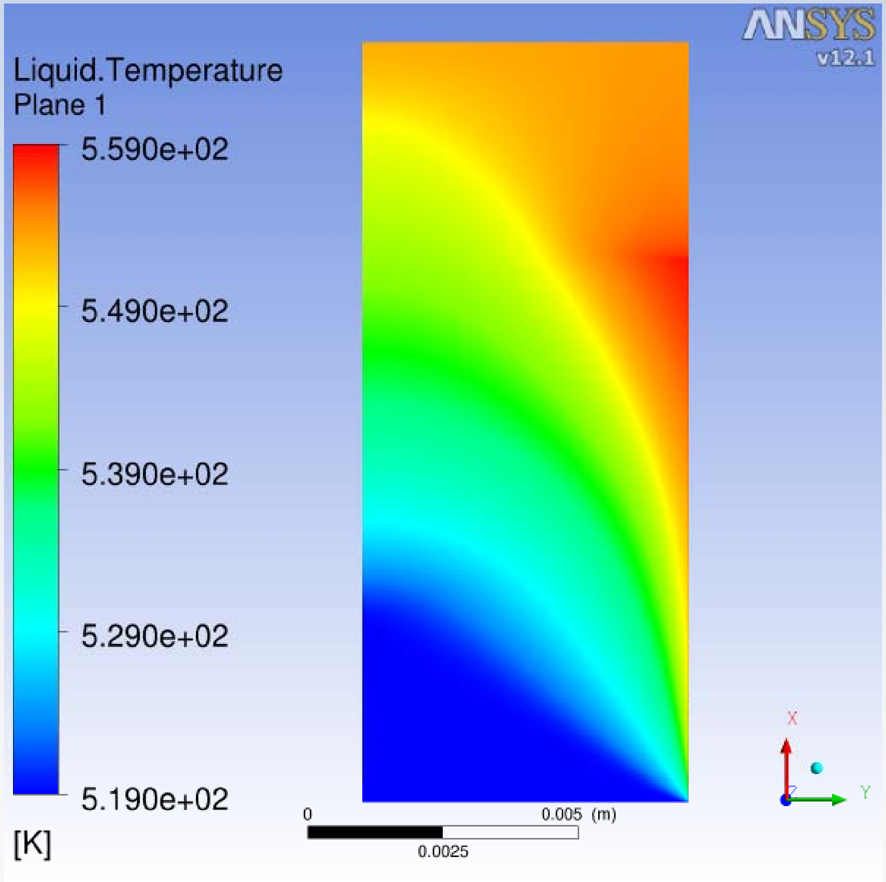
- Distribution of water temperature and steam volume fraction

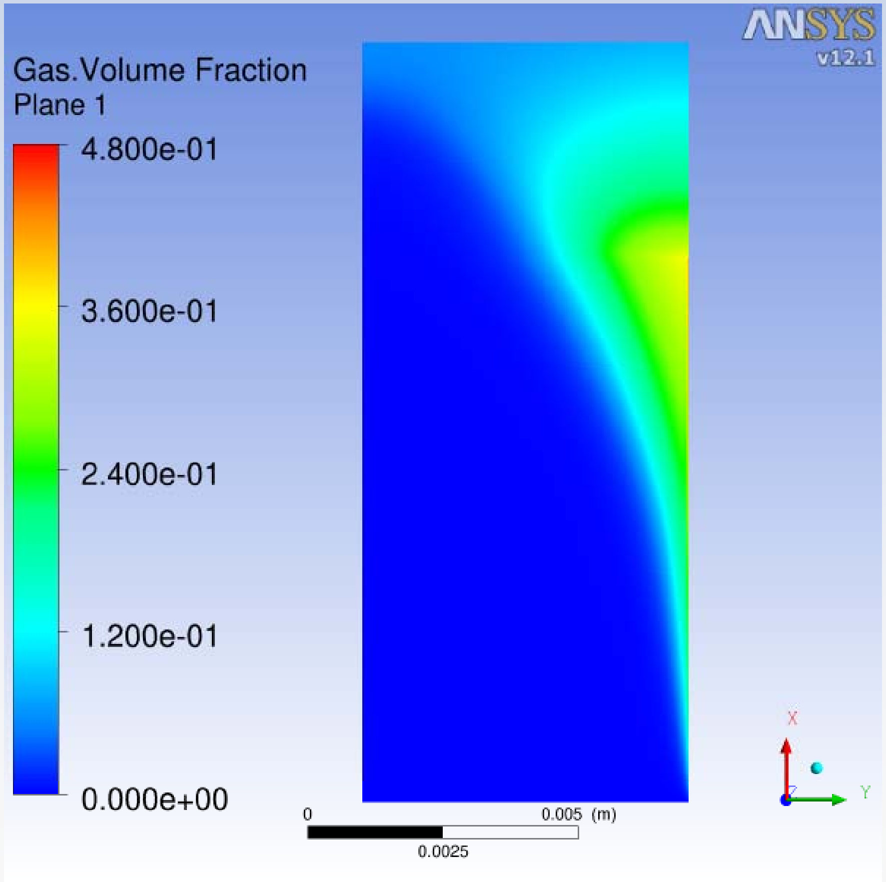




Experiment No. 3 (Mesh04)

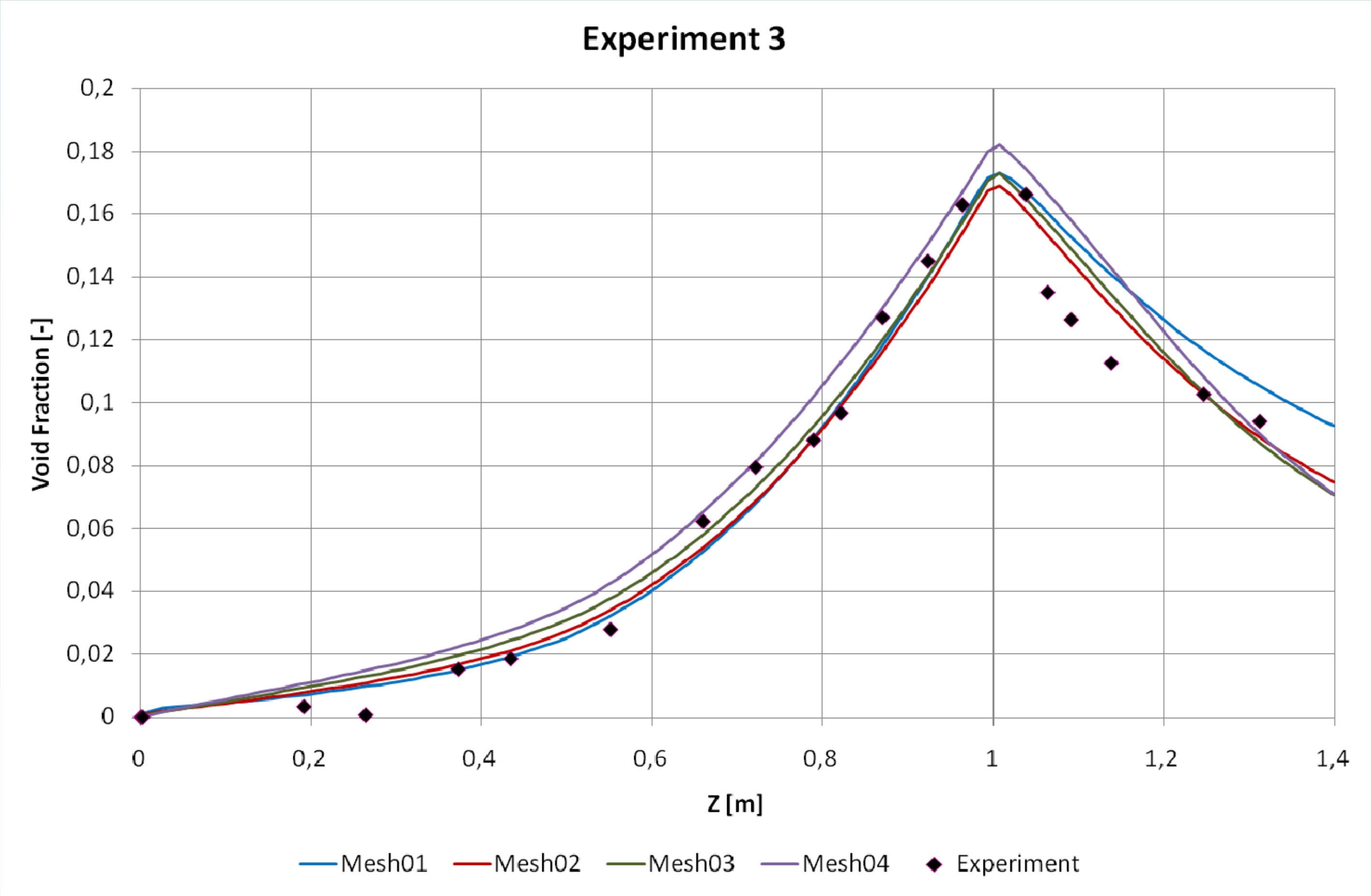
- Distribution of water temperature and steam volume fraction





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)

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

  - Hughmark

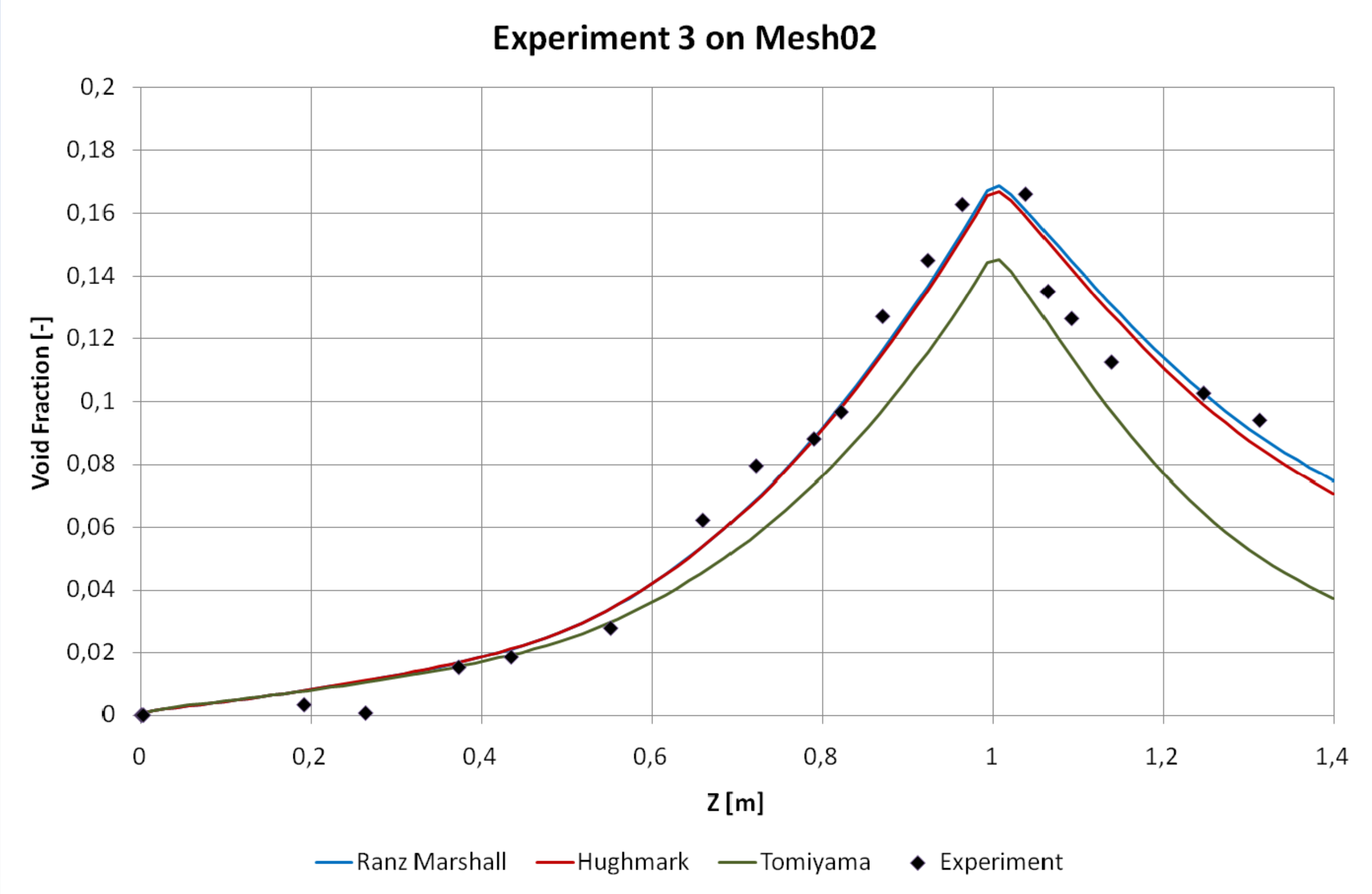
$$Nu = 2 + 0.6\,Re^{0.5} Pr^{0.3} \qquad 0 \le Re \le 776.06$$

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

  - Tomiyama

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

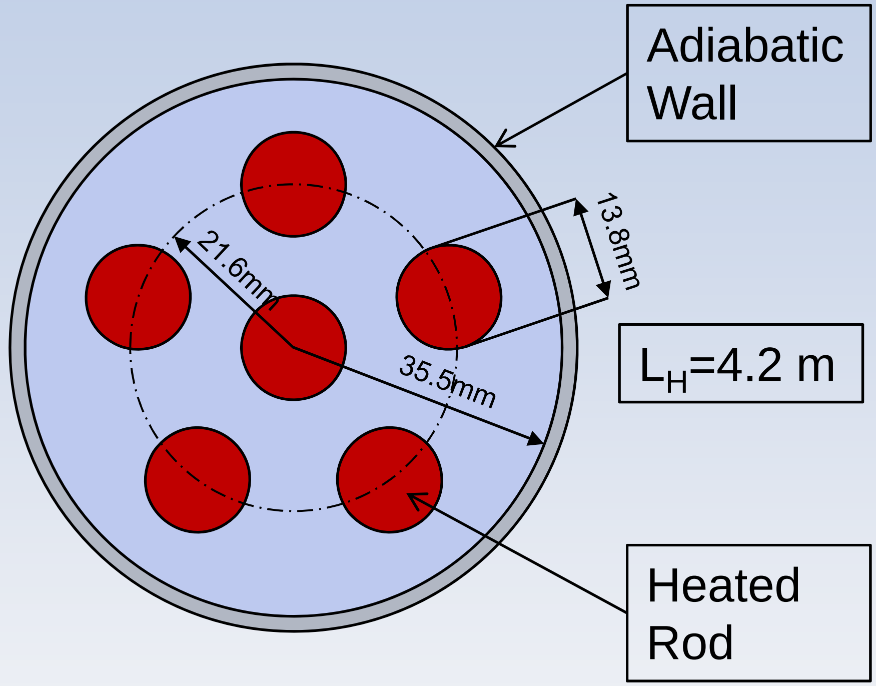
Interphase Heat Transfer Model



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

FRIGG-6a Test Case Description

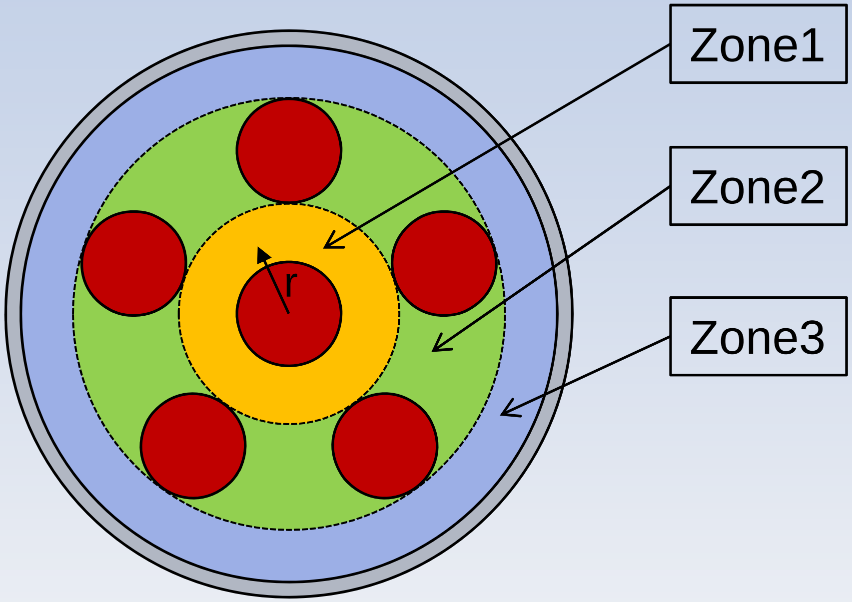
- Geometry (FT-6a)
  - Six electrically heated rods placed in a vertical adiabatic pipe



- 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



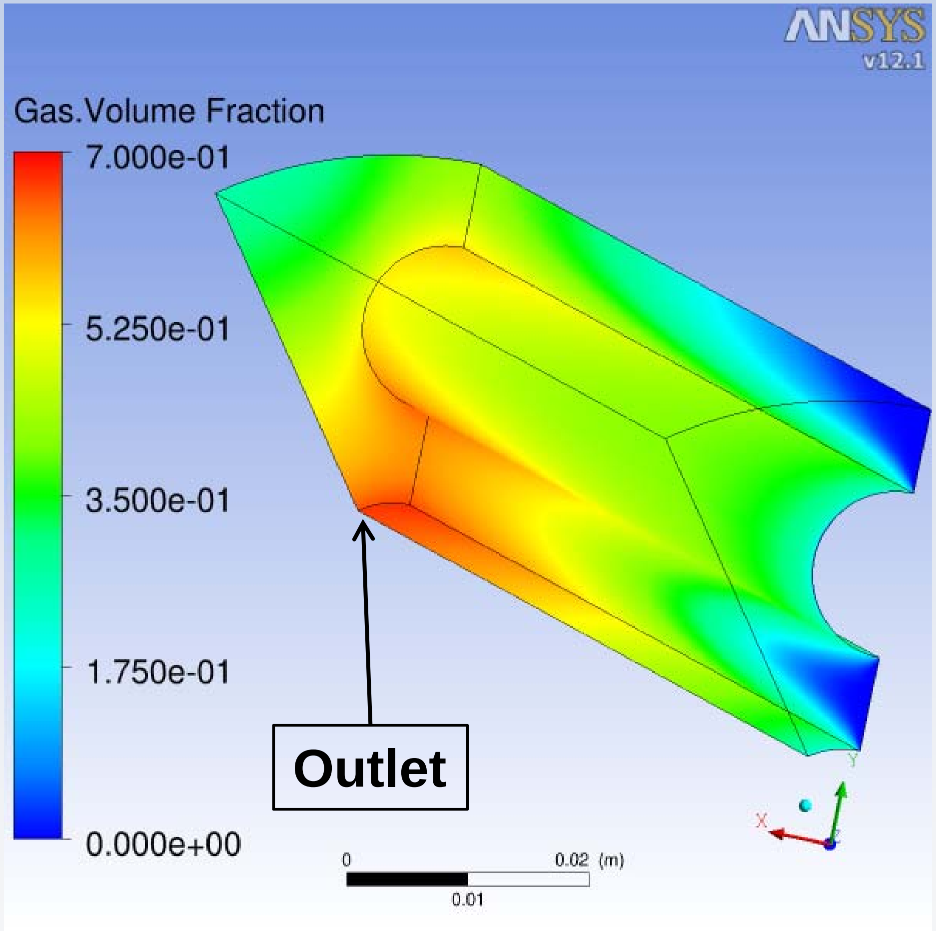
Defintion of Zones:

- Zone1 ($r < 14.6$ mm)
- Zone2 ($14.6 \text{ mm} < r < 28.6$ mm)
- Zone3 ($r > 28.6$ mm)

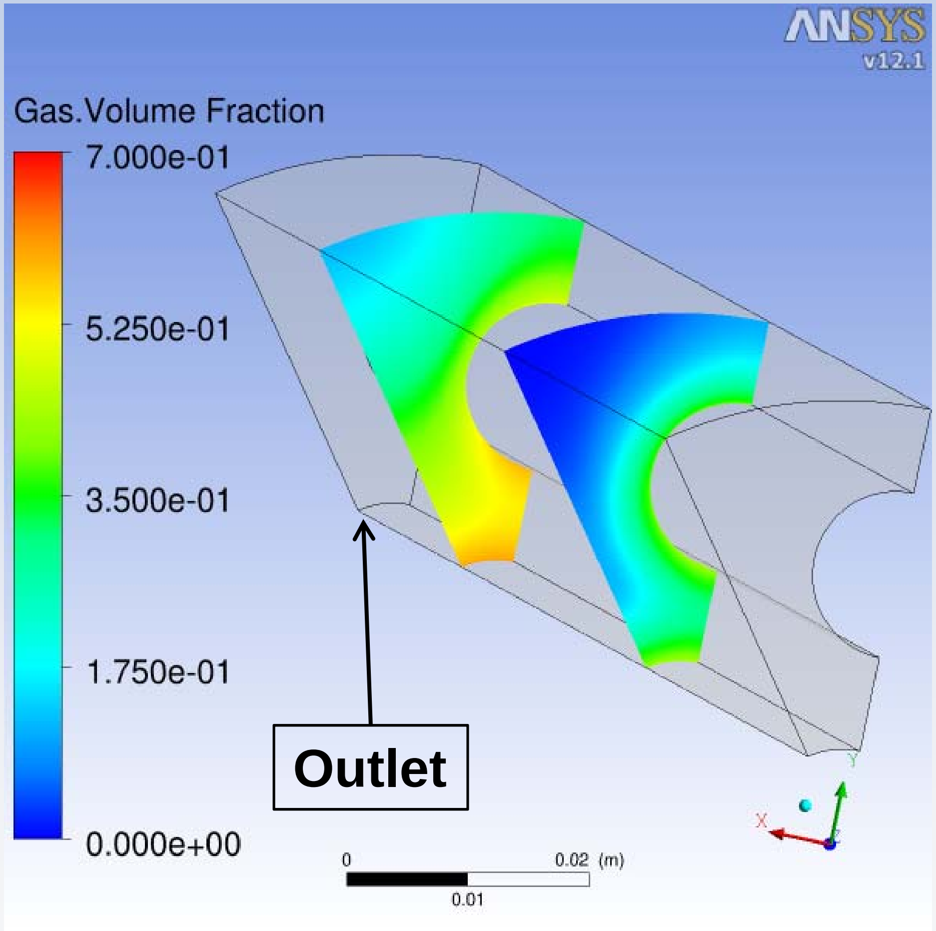
FRIGG-6a Test Case
Mesh Refinement Hierarchy

	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

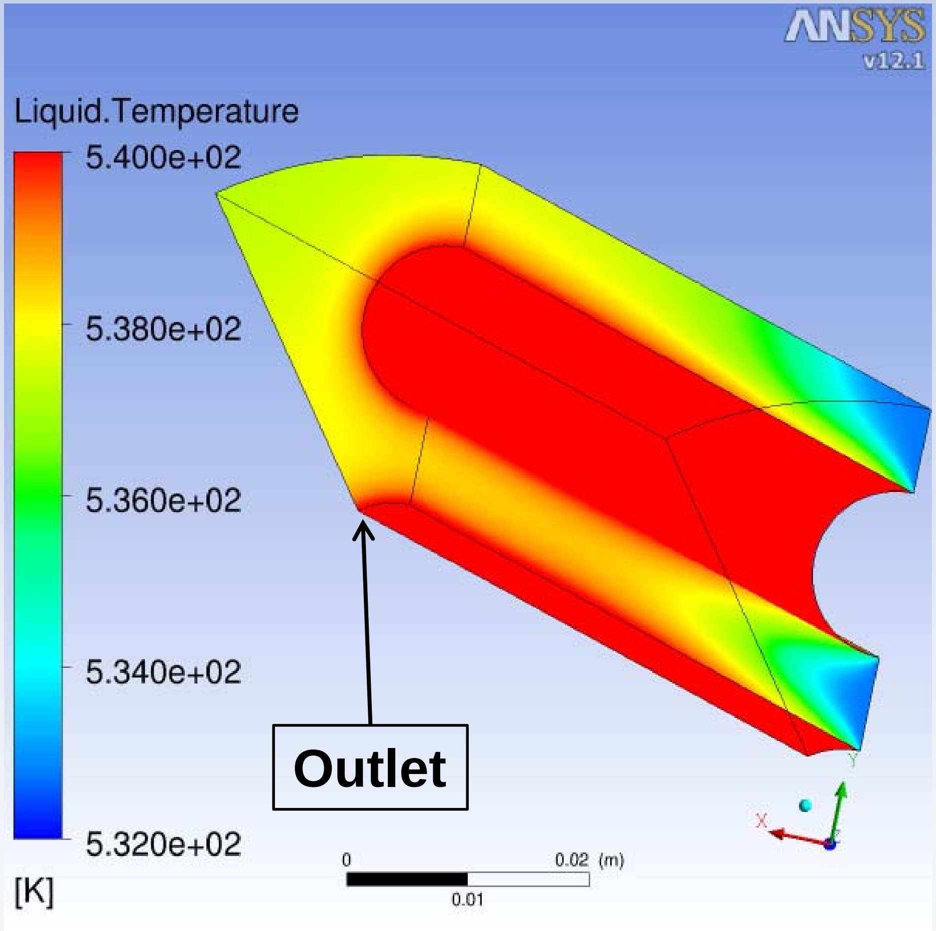


Plot of gas volume fraction (Mesh03, SST)

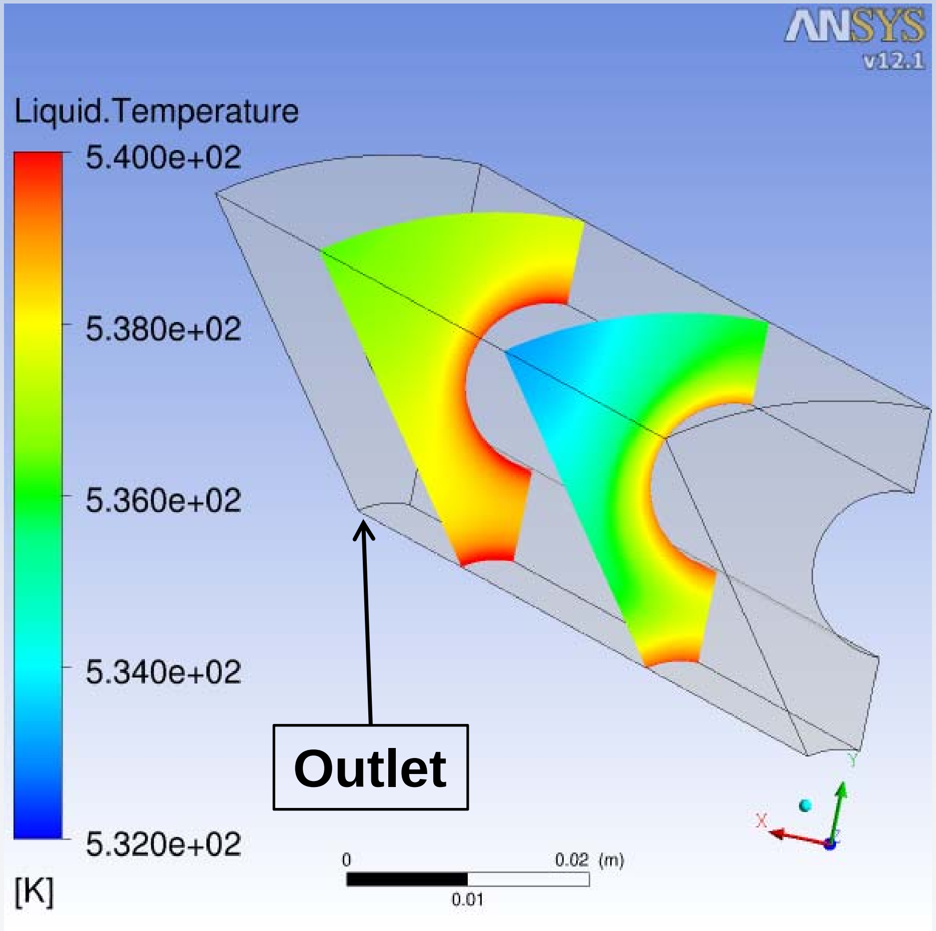


Two cross-sectional distributions of gas volume fraction (Mesh03,SST)

FRIGG-6a Test Case
Baseline Setup: SST

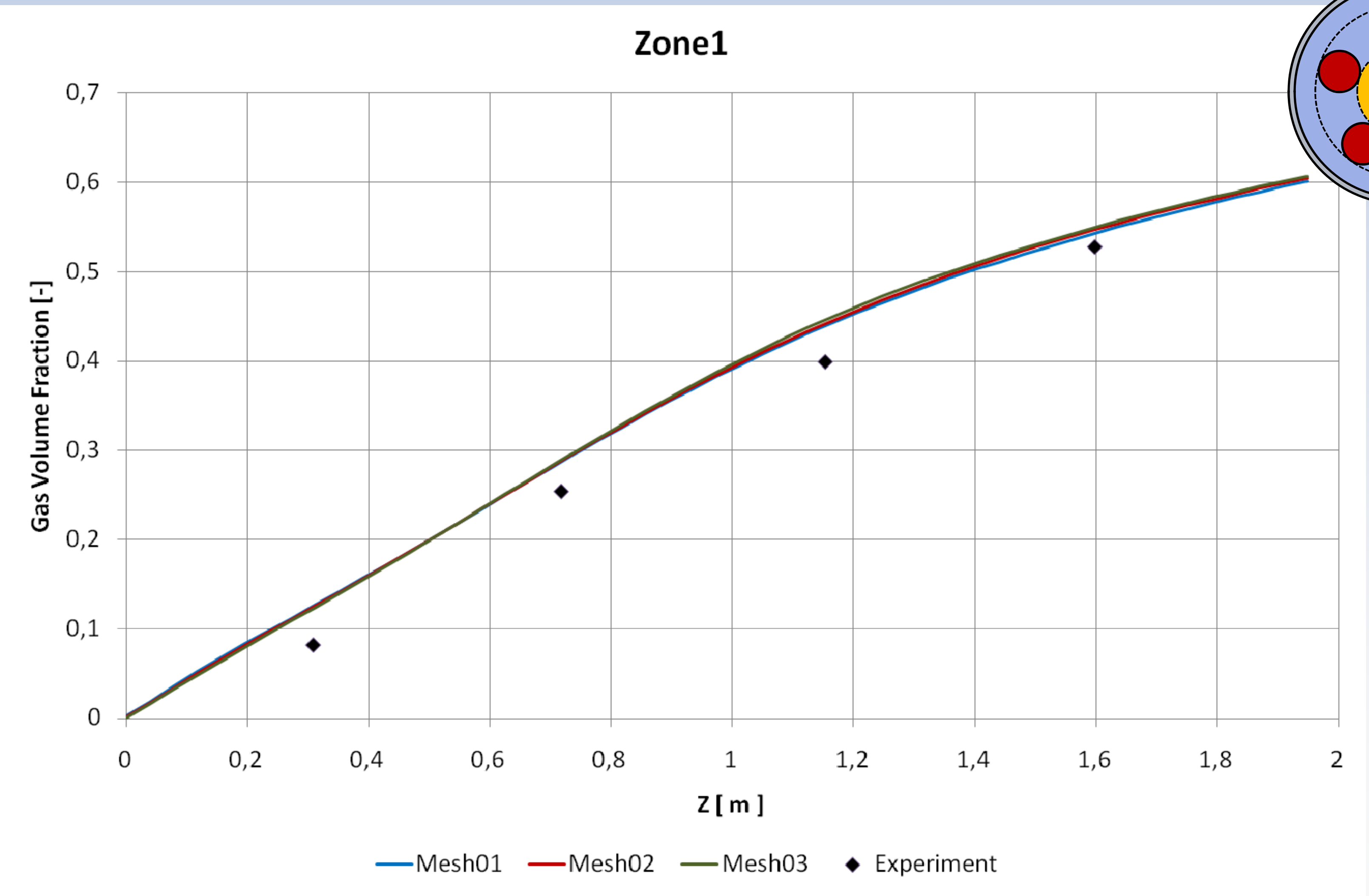


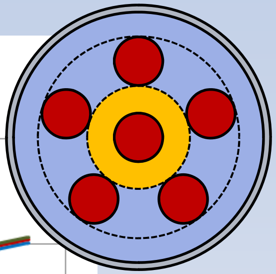
Plot of liquid temperature (Mesh03,SST)



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

FRIGG-6a Test Case
Mesh Comparison



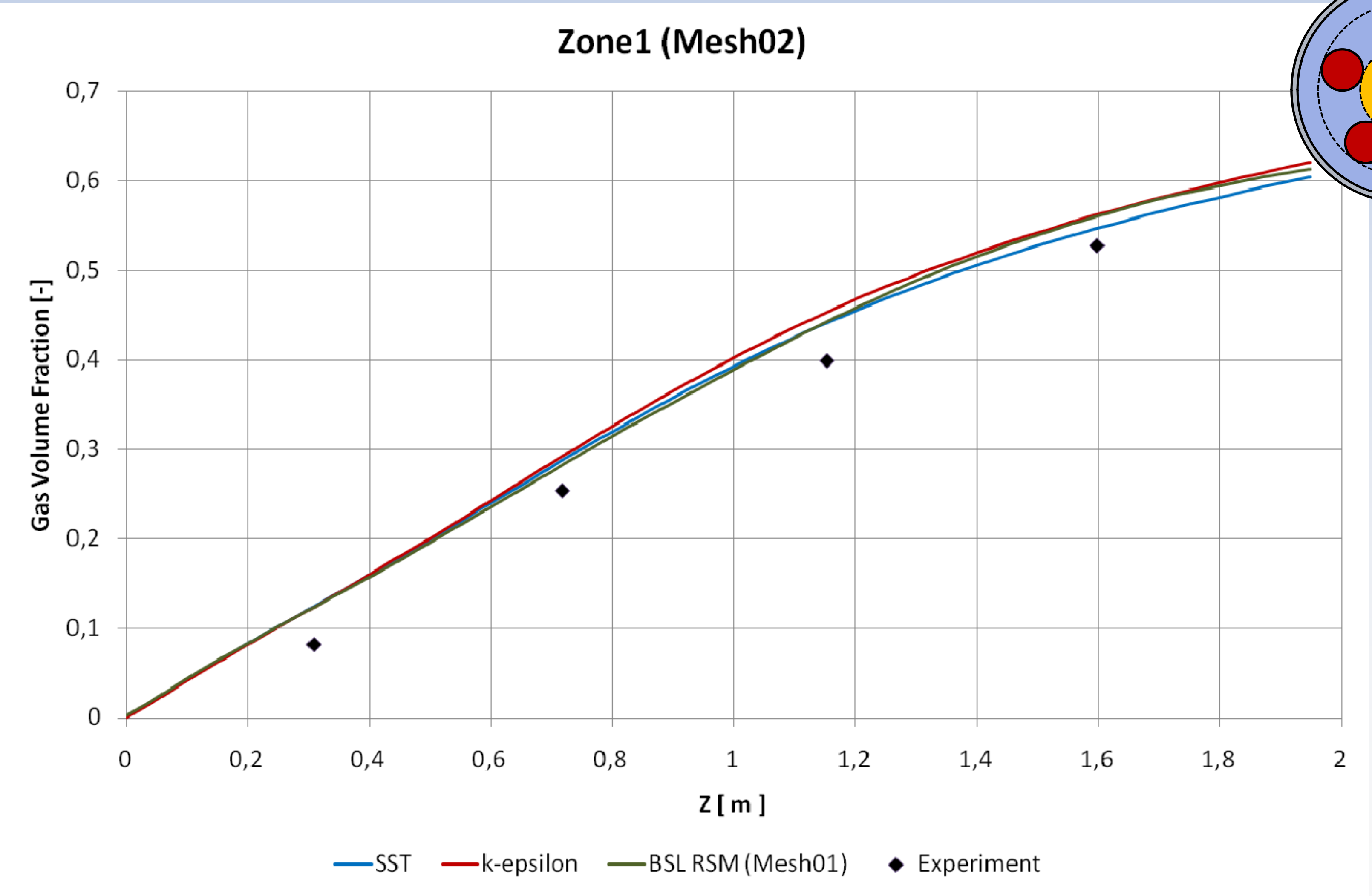


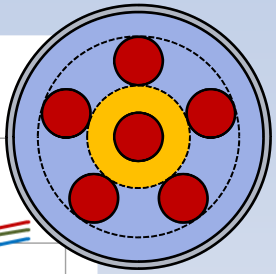
Turbulence Modeling in Rod Bundles

- 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 wall surfaces

    → Can be relevant for safety!

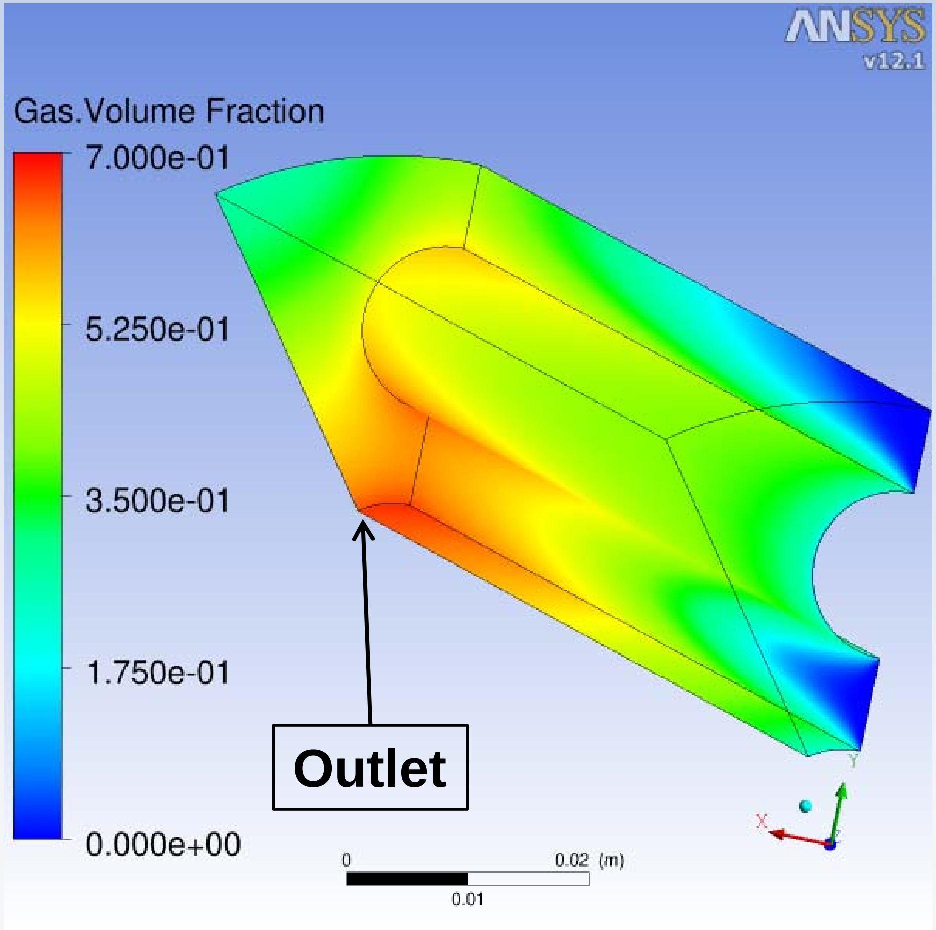
FRIGG-6a Test Case
Turbulence Model Comparison



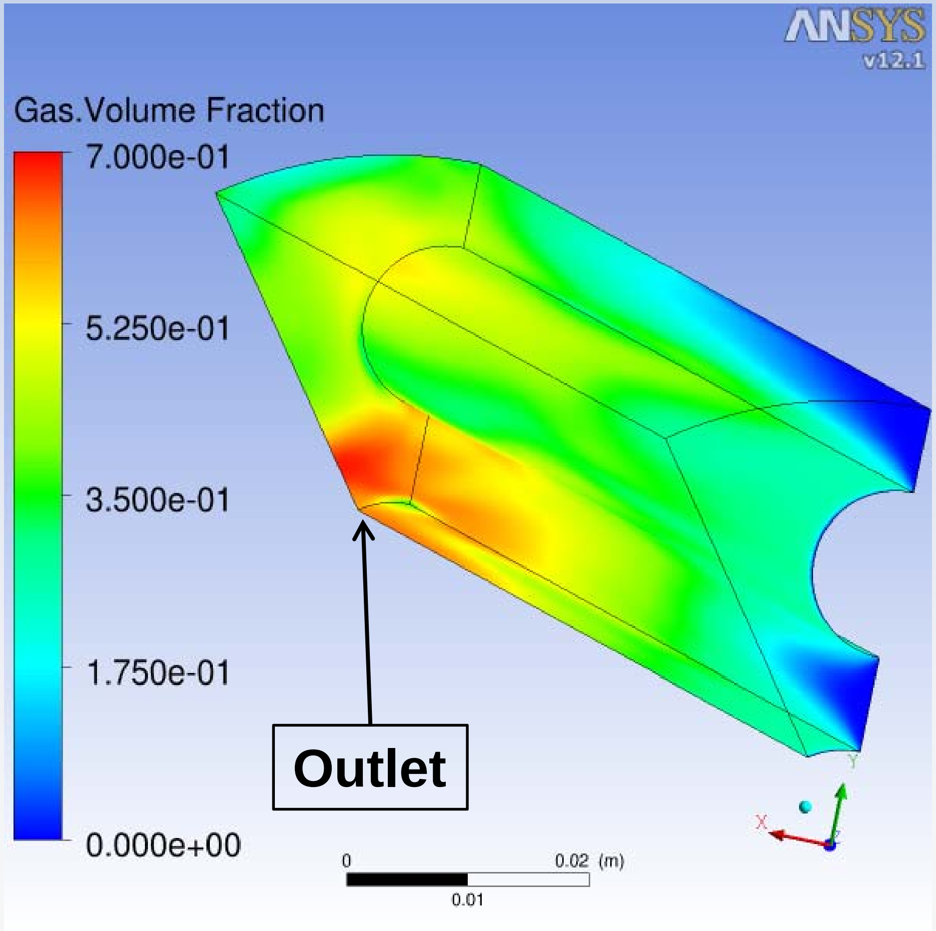


FRIGG-6a Test Case
Turbulence Model Comparison

SST model



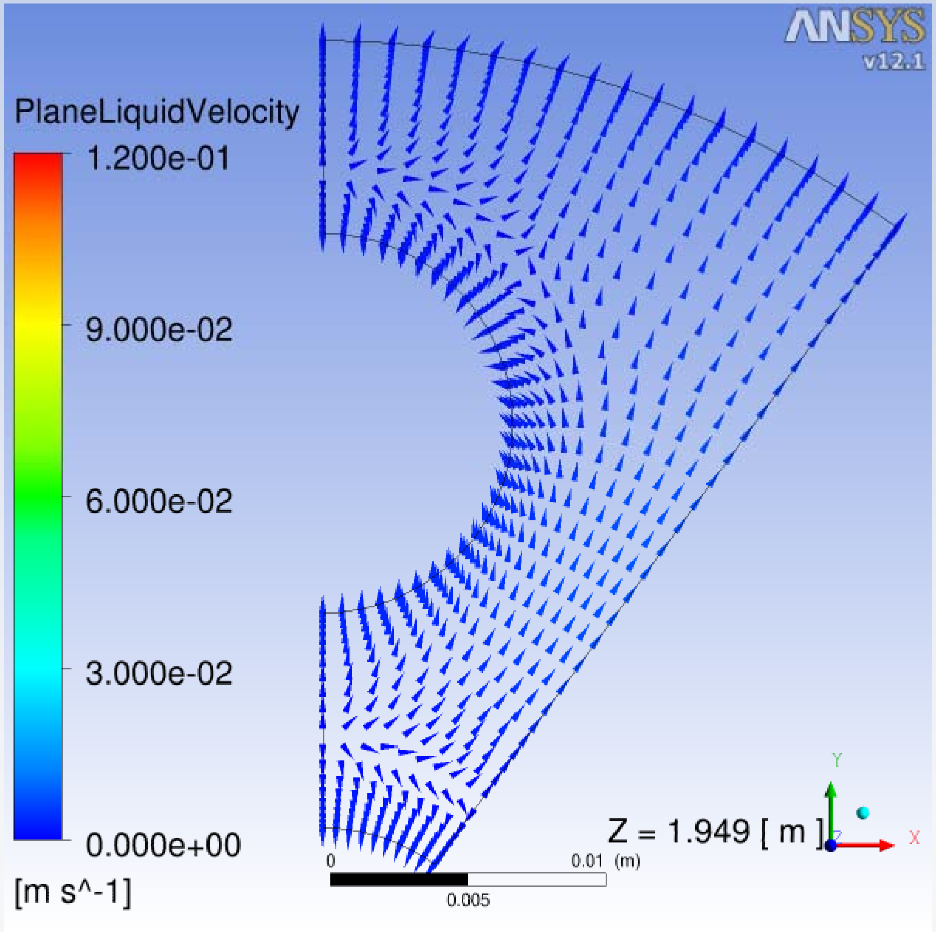
BSL RSM model



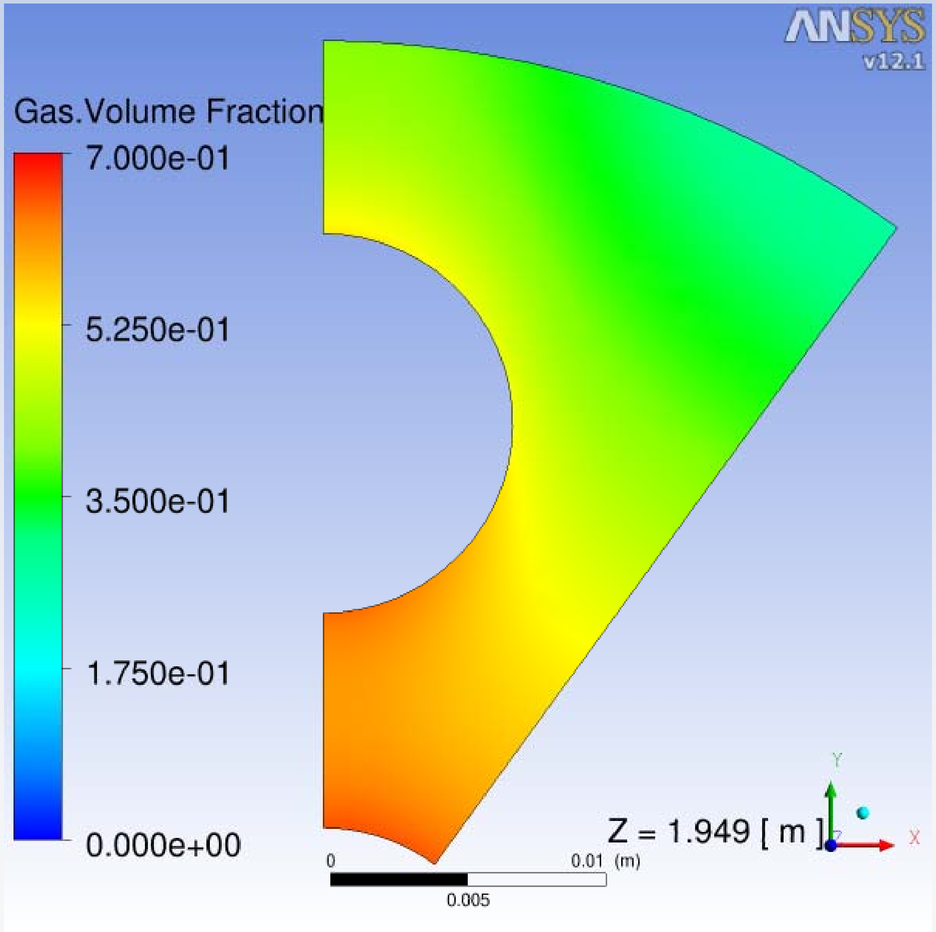
Plot of gas volume fraction

FRIGG-6a Test Case
Turbulence Model Comparison

- SST model → NO secondary flows



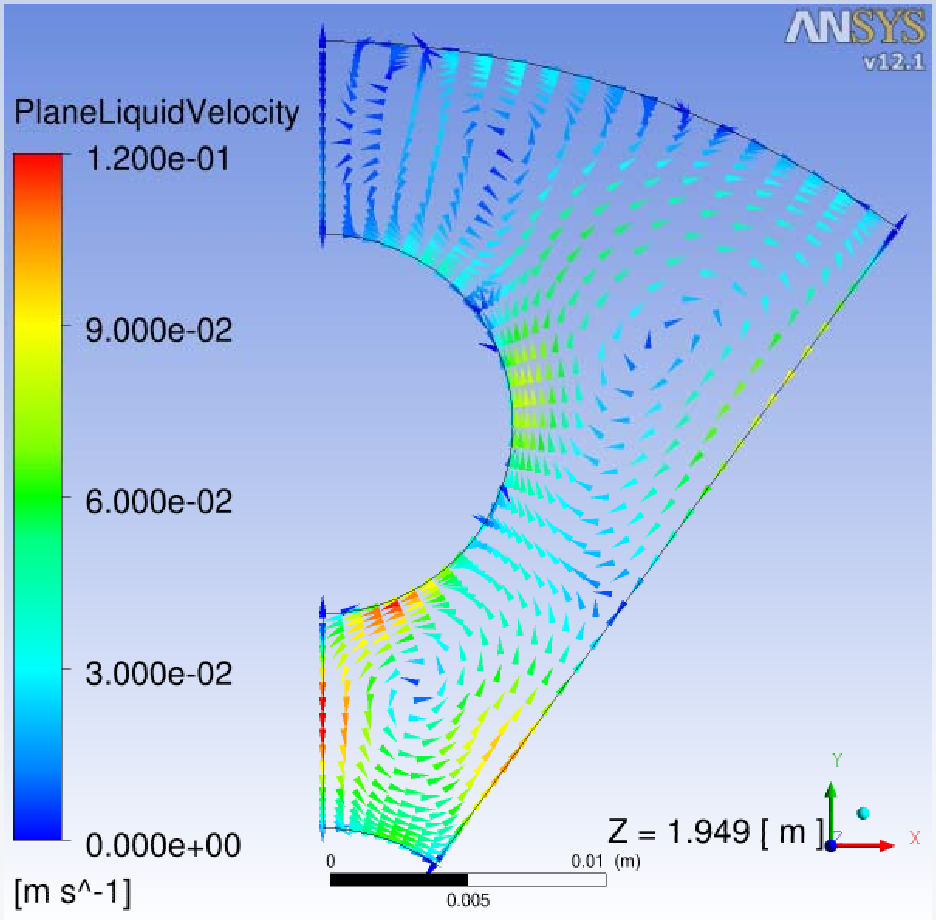
Plot of gas volume fraction (Outlet)



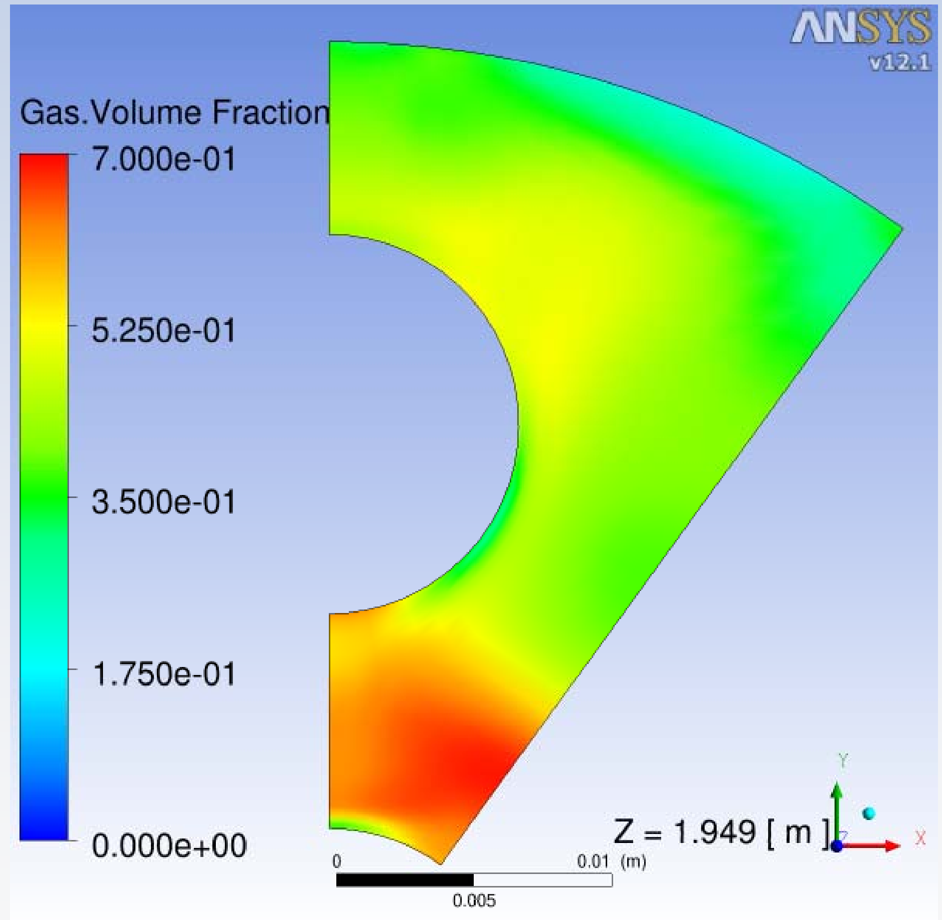
Contour plot of gas volume fraction (Outlet)

FRIGG-6a Test Case
Turbulence Model Comparison

- BSL RSM model → secondary flows



Plot of gas volume fraction (Outlet)

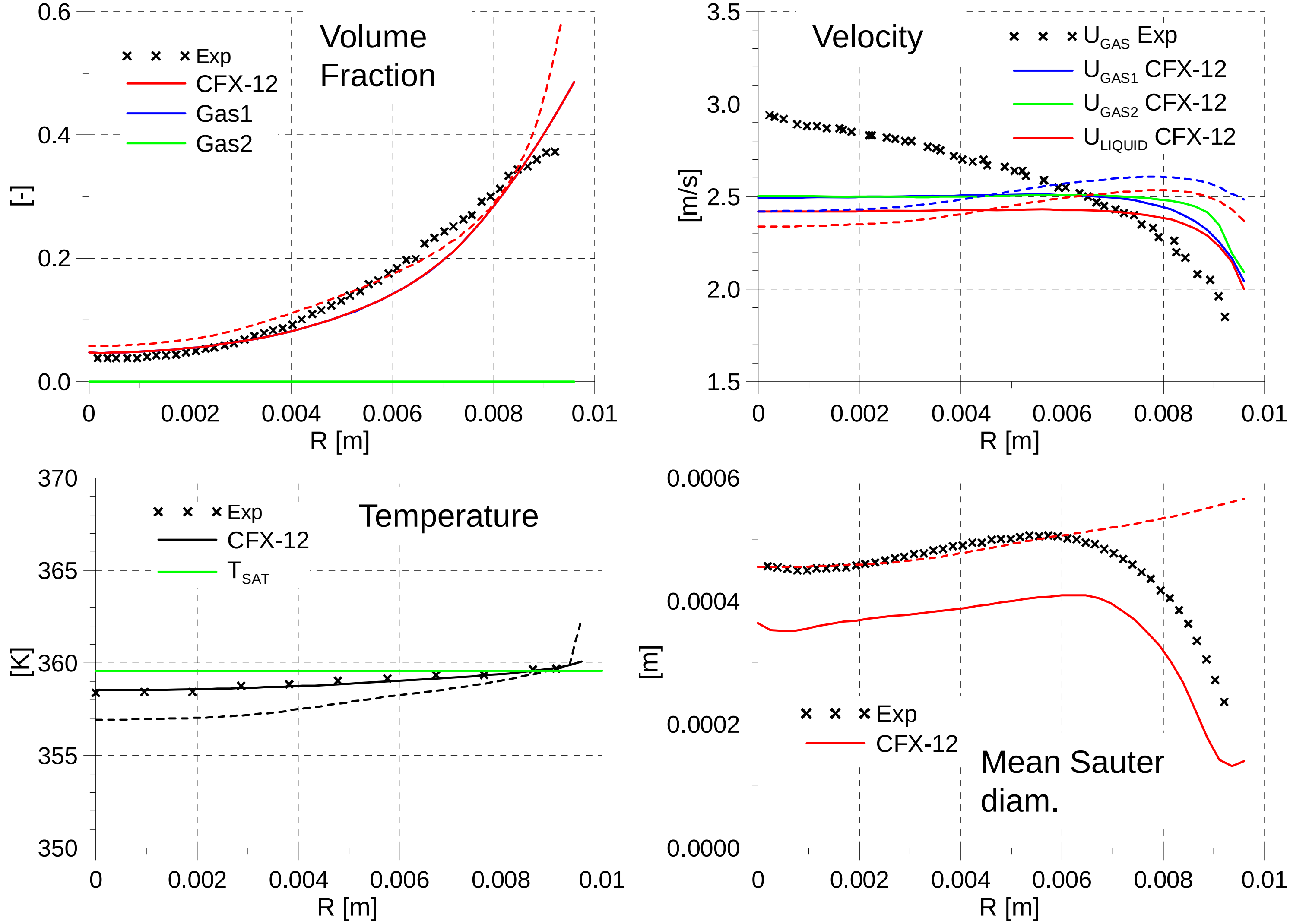


Contour plot of gas volume fraction (Outlet)

DEBORA Testcase
- RPI & MUSIG -

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

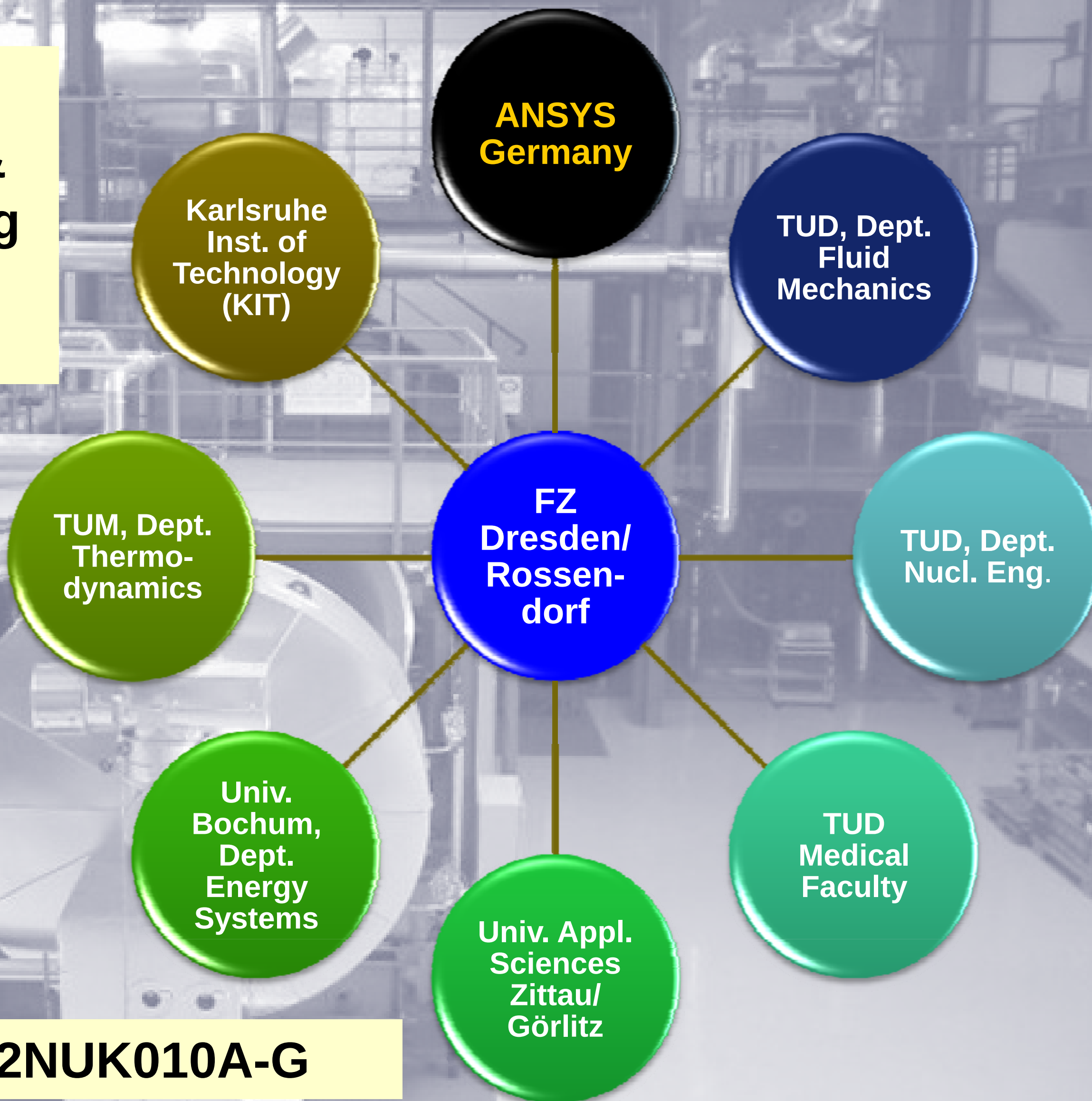
By courtesy of E. Krepper, FZD

R&D Consortium

ANSYS

R&D Initiative:

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

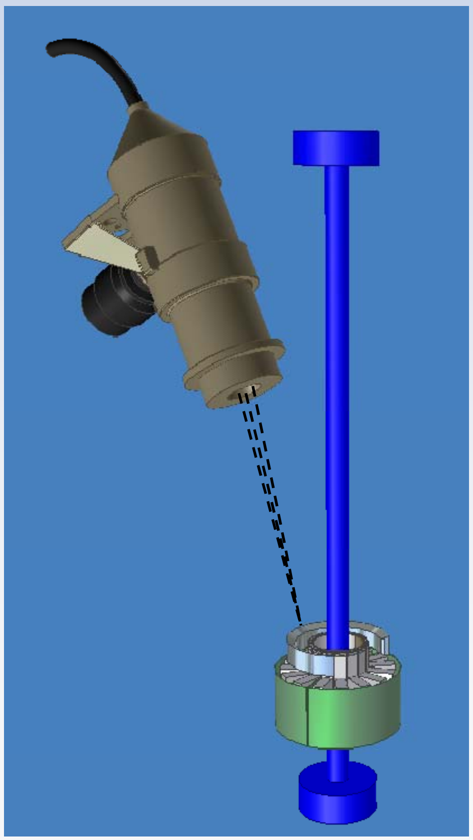


BMBF Project Grant No. 02NUK010A-G

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

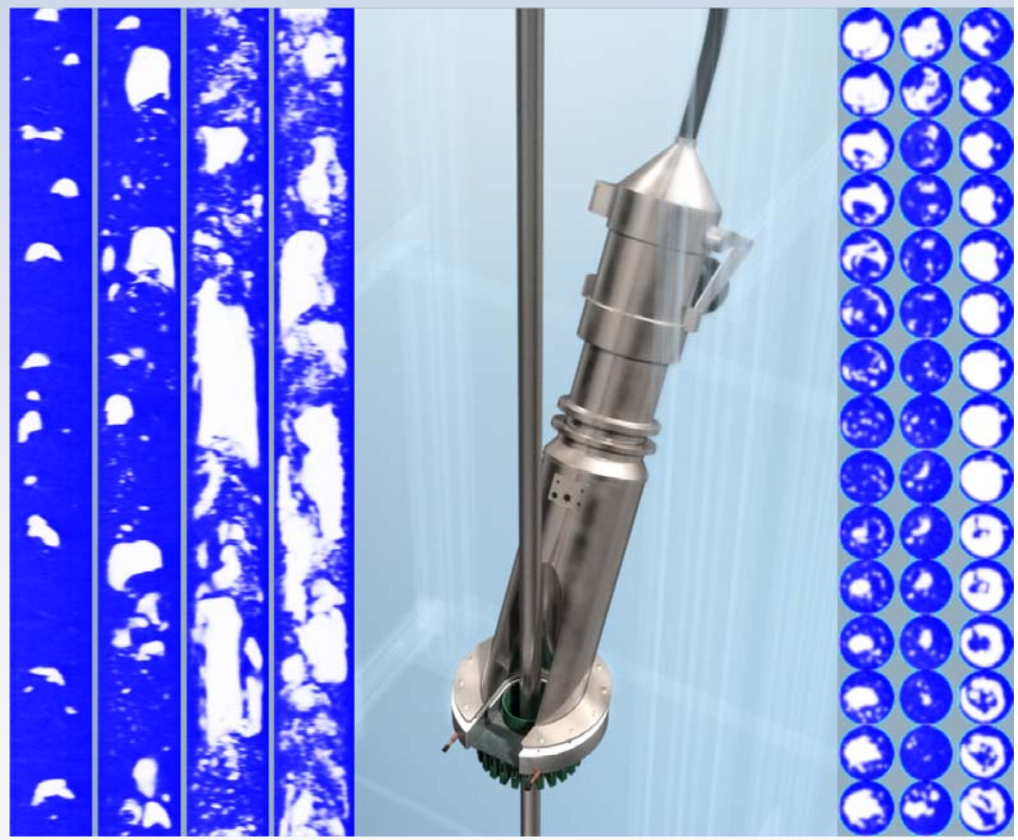
- **Ultrafast electron beam X-ray CT (ROFEX) of heated rod bundle in titanium pipe on TOPFLOW @ FZD:**

Principle



Setup

High resolution volume fraction & velocity measurements



Images by courtesy of U. Hampel, F. Fischer, FZD

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 & requiring further investigations → detailed experiments
- Outlook:
  - Ongoing & customer driven CFD model development
  - Research cooperation with Industry & Academia
  - Extension of the wall heat partitioning in wall boiling model
  - Increase range of model applicability

Acknowledgement

Bundesministerium
für Bildung
und Forschung

This research has been supported by the

German Ministry of Education & Research (BMBF)

under the contract number 02NUK010G in the project:

"Modeling, Simulation and Experiments for Boiling Processes in Fuel Assemblies of Pressurized Water Reactors (PWR)"

in the framework of the German CFD Network on Nuclear Reactor Safety Research and Alliance for Competence in Nuclear Technology, Germany and the BMBF funding framework for basic research Energy-2020+.

Thank You!