Prediction of Convective Boiling up to Critical Heat Flux (CHF) Conditions for Test Facilities with Vertical Heaters

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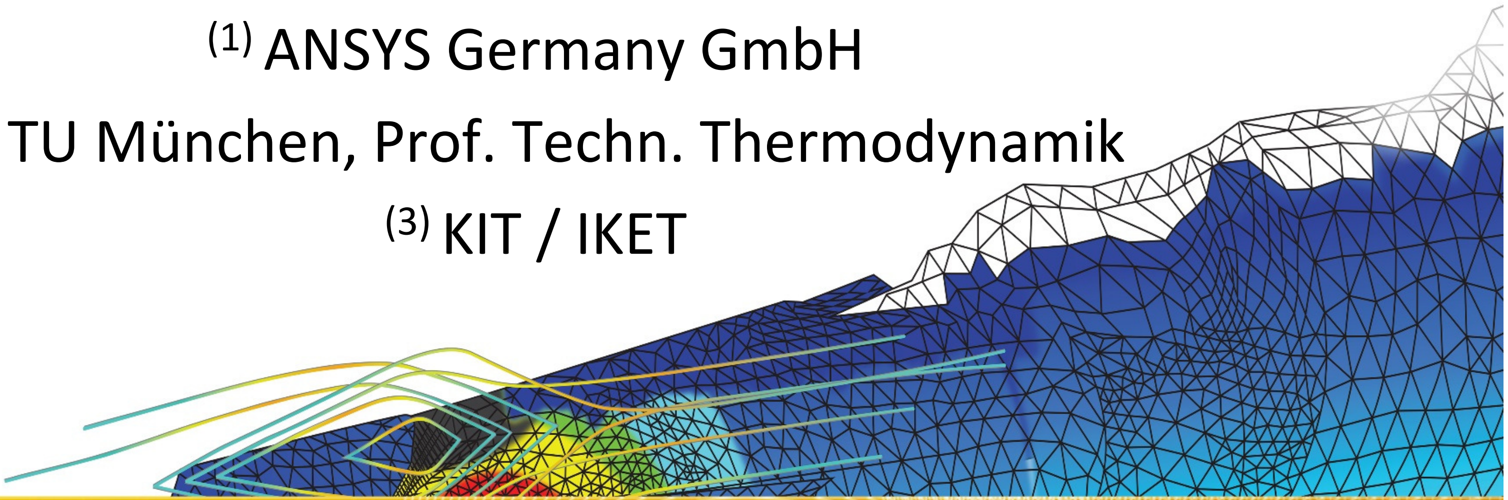
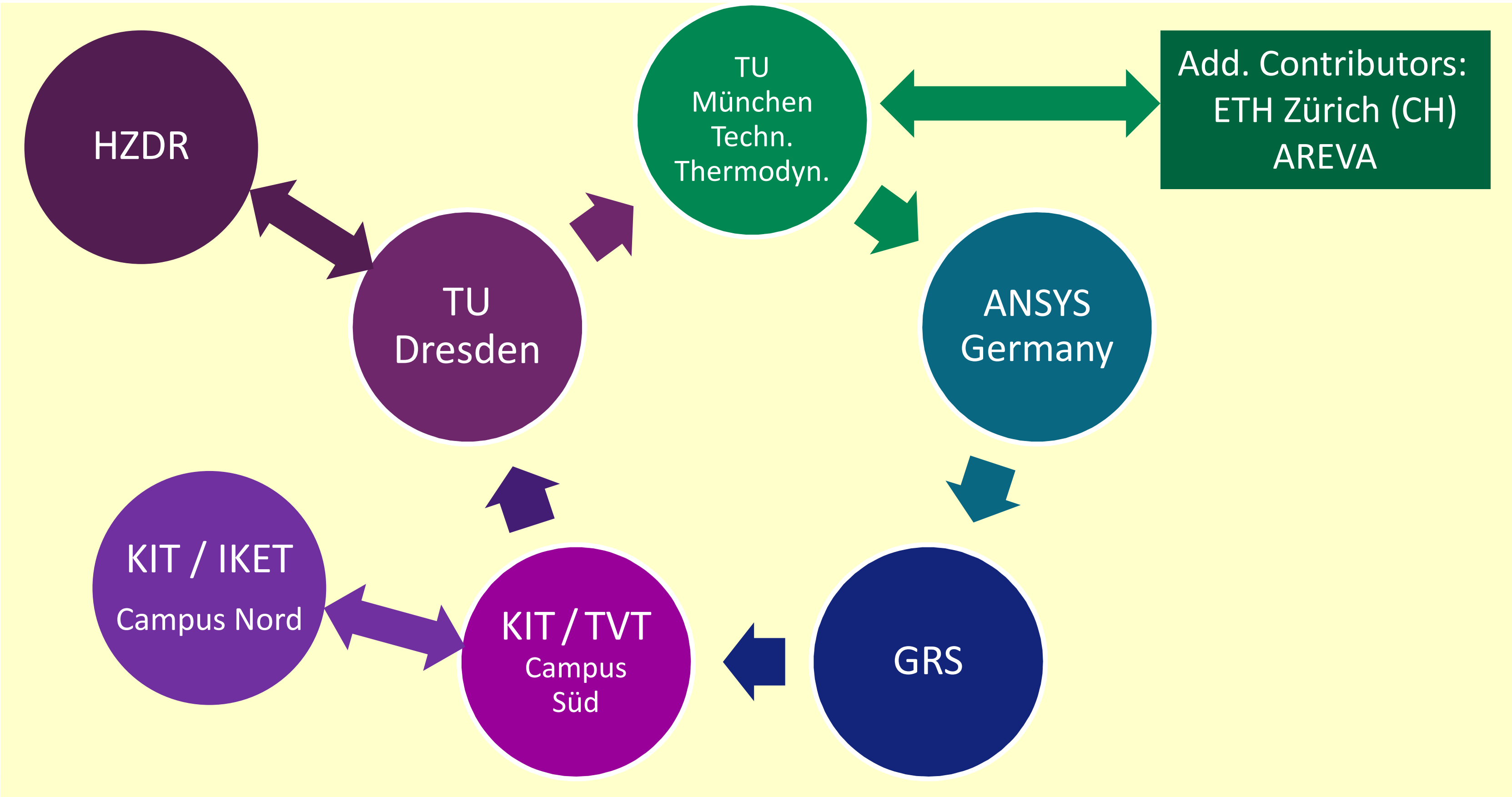


Outline

- The NUBEKS R&D consortium (2014-2018)
- What is Critical Heat Flux (CHF)?
- Model formulation for CFD simulation of CHF
  - Extended RPI model ⇔ Inhomogeneous MUSIG ⇔ CHT
- The TU Munich test facility (Copper heater, NOVEC-649)
  - CHF simulation and model validation
- The KIT COSMOS-L test facility (ZircAlloy, Water)
  - The test matrix
  - CHF simulations and results discussion
- Concluding remarks and outlook

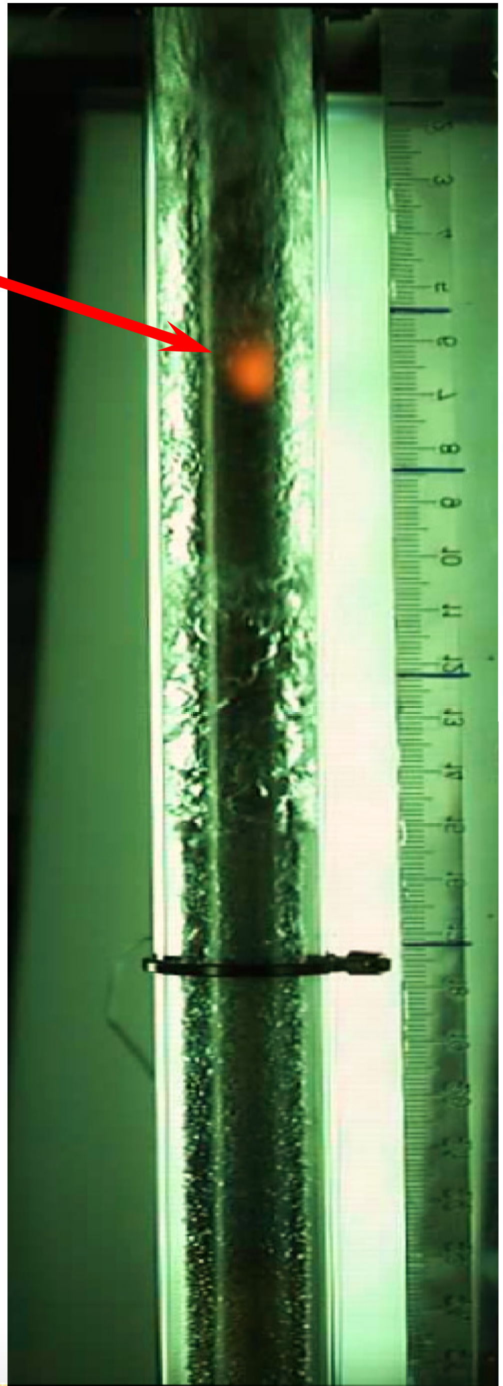
The NUBEKS R&D Consortium

- R&D Consortium (July 2014 – June 2018):
  „CFD Methods for the Prediction of Critical Heat Flux“
  NUBEKS – Numerische Beschreibung Kritischer Siedevorgänge



What is Critical Heat Flux (CHF)?

- Critical Heat Flux (CHF):
  - Sometimes referred to as the boiling crisis or departure from nucleate boiling (DNB)
  - With increased wall heat flux, suddenly the heat transfer at a heater surface becomes inefficient.
    - → Applied heat can no longer be removed from the heater surface by so far acting heat transfer mechanisms, i.e. mainly by evaporation/boiling
    - → Sudden excursion of wall temperature
    - → Can lead up to destruction of the heater material (melting)
- CHF mechanisms / explanations:
  - Near wall vapor bubble crowding
  - Vapor film @ wall is shielding the heater wall from subcooled liquid
  - Sublayer dryout, i.e. liquid film underneath vapor layers close to heater wall are drying out ⇒ dry patch formation
  - …



CHF at upper end of heater rod in COSMOS-L, Image by courtesy of Florian Kaiser, KIT / IKET

Model Formulation for CFD Simulation of CHF
- Extended RPI Wall Boiling Model -

- The extended RPI Wall Boiling Model accounts in addition for the convection to the vapor phase
- Heat flux partitioning:

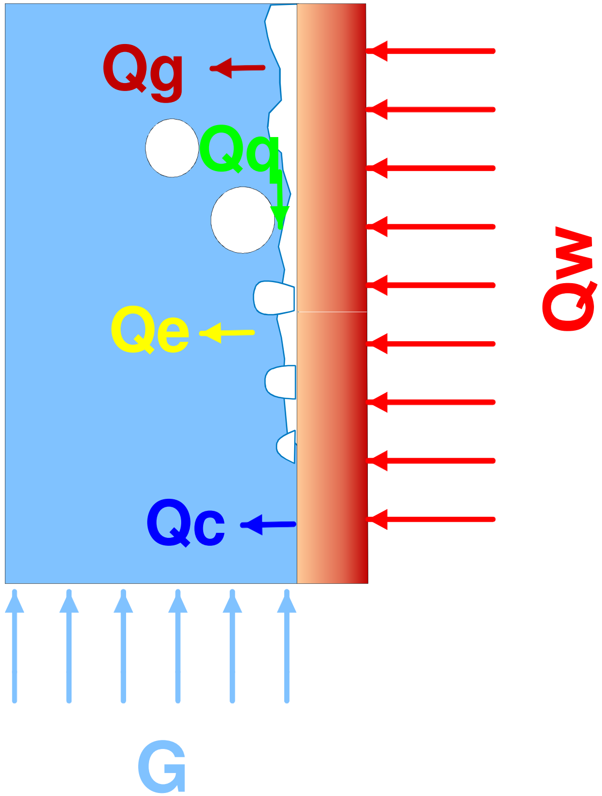
$$Q_W = f(\alpha_l) \cdot \left(Q_c + Q_q + Q_e\right) + \left(1 - f(\alpha_l)\right) \cdot Q_g$$

Q_c : single phase convection to liquid

Q_e : evaporation

Q_q : quenching

Q_g : single phase convection to gas



Model formulation for CFD simulation of CHF
Extended RPI Wall Boiling Model: Partitioning

- Area fraction influenced by bubbles

$$A_2 = min\left(\pi d_W^2 n, min(A'_{2,max}, 1)\right) \pi d_W^2 n$$

- Area fraction influenced by single phase convection

$$A_1 = 1 - A_2$$

- Convection to liquid

$$Q_c = A_1 \cdot (T_W - T_l) \cdot \frac{\rho_l c_{p,l} u_l^*}{T_l^+}$$

- Quenching

$$Q_q = A_2 \cdot (T_W - T_l) \cdot 2\lambda_l f \sqrt{\frac{t_w}{\pi a_l}}$$

- Evaporation

$$Q_e = min(A'_{2,max}, A_2) \cdot \frac{\pi d_W^3}{6} \cdot \rho_g f h_{lg}$$

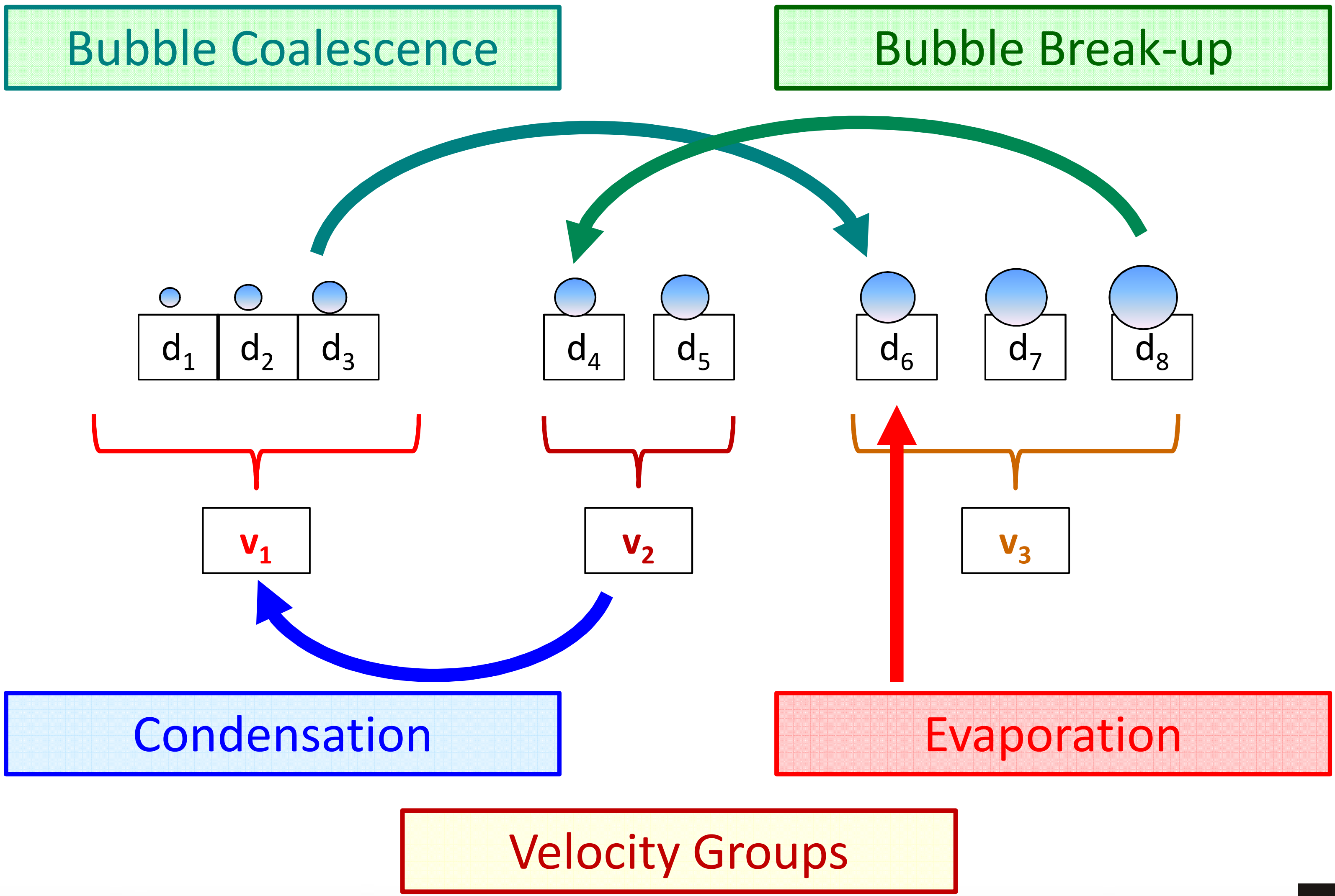
- Convection to gas

$$Q_c = (T_W - T_g) \cdot \frac{\rho_g c_{p,g} u_g^*}{T_g^+}$$

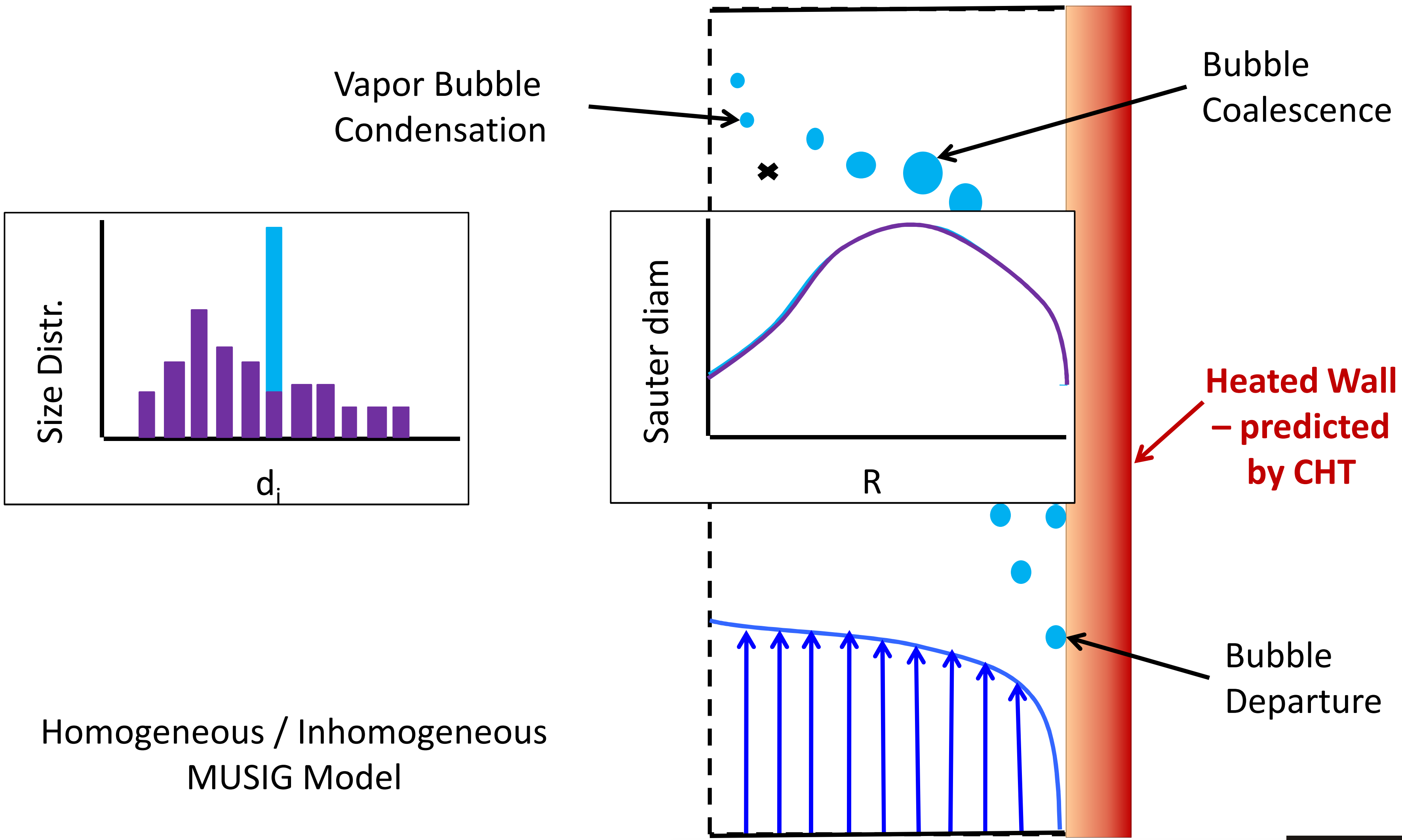
Model Formulation for CFD Simulation of CHF
The MUSIG Model

- MUSIG = Multiple Size Group Model
  - Discrete Population Balance Model for poly-dispersed flows
  - Particle size distribution is discretized by assigning bubbles to different 'size groups'
- Homogeneous MUSIG
  - Assumes single velocity field for all bubble classes (one dispersed phase)
  - Valid for bubbly flows in spherical / elliptic regime and when lift force can be neglected
- Inhomogeneous MUSIG
  - Allows multiple velocity fields for groups of bubble classes (more than one dispersed phase, i.e. more than 1 set of N.-S. eq.'s)
  - Several bubble size classes can belong to the same 'velocity group'
  - Useful when different bubble size classes have very different velocity fields, e.g. due to change of sign of the lift force.
    - **Allows for separation of bubbles of different diameter based on acting forces and governing physics**

Model Formulation for CFD Simulation of CHF MUSIG + Interphase Mass Transfer



Model Formulation for CFD Simulation of CHF MUSIG + Wall Boiling



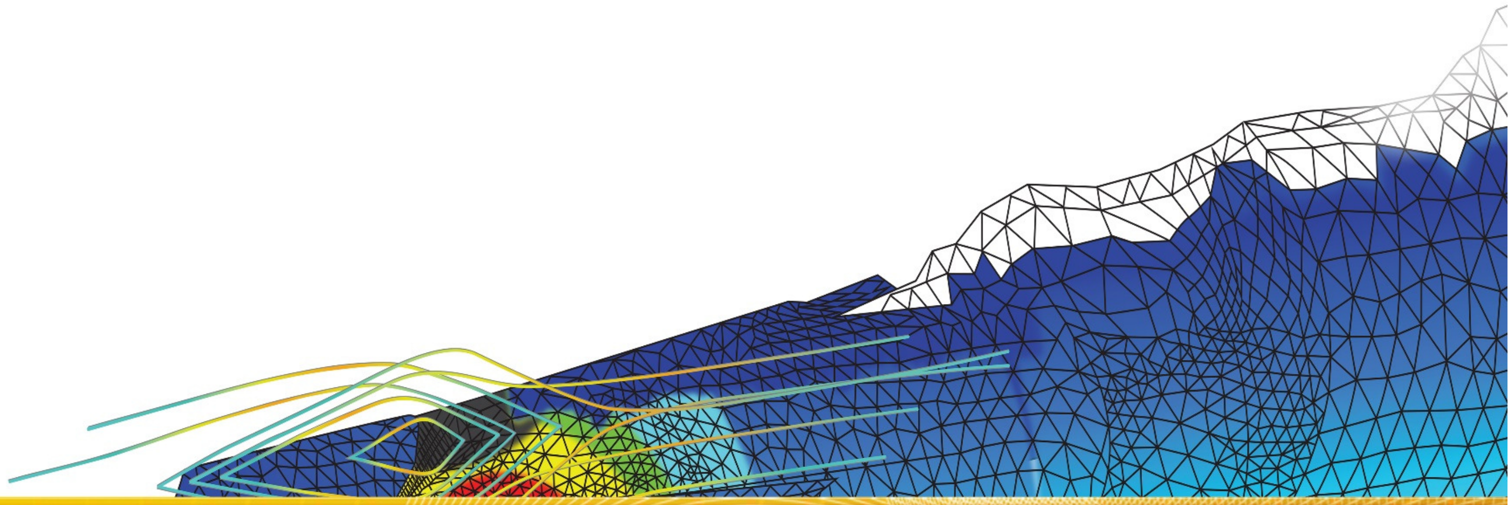
Homogeneous / Inhomogeneous MUSIG Model

Model Formulation for CFD Simulation of CHF

Extended RPI wall boiling model ⇔ Inhomogeneous MUSIG ⇔ CHT

Analysis Type	**Steady State with pseudo-time scale Δt= 0.001 [s] (TUM) / 0.005 [s] (KIT)**	
Interfacial forces	Lift	Tomiyama
	Drag	Grace
	Turbulent Dispersion	FAD model
Boiling Model	**Non-equilibrium RPI model**	**Gas crit vf = 0.8 (TUM) / 0.6 (KIT)** **Maximum Area Fraction of Bubble Influence = 10**
	Bubble Departure Diameter	**Tolubinski et al. (default)**
	Nucleation Site Density	**Lemmert et al. (default)**
Vapor heat transfer	**Thermal Energy**	
Turbulence model	**SST**	Homogeneous SST Turbulence Model
Interphase Heat Transfer	**MUSIG**	Two-Resistance Model Liquid Phase: Tomiyama / Gas Phase(s): Nu = 6

The Planar Copper Heater – NOVEC-649 Test Facility (TUM/TD)



The TU Munich Test Facility
- Planar Copper Heater in Vertical Channel -

Experiments at TU Munich, Dept. Techn. Thermodyna-mics by:

- **Prof. Thomas Sattelmayer**
- **Dr. Christoph Hirsch**
- **Moritz Bruder**
- **Paul Riffat**

Reference:

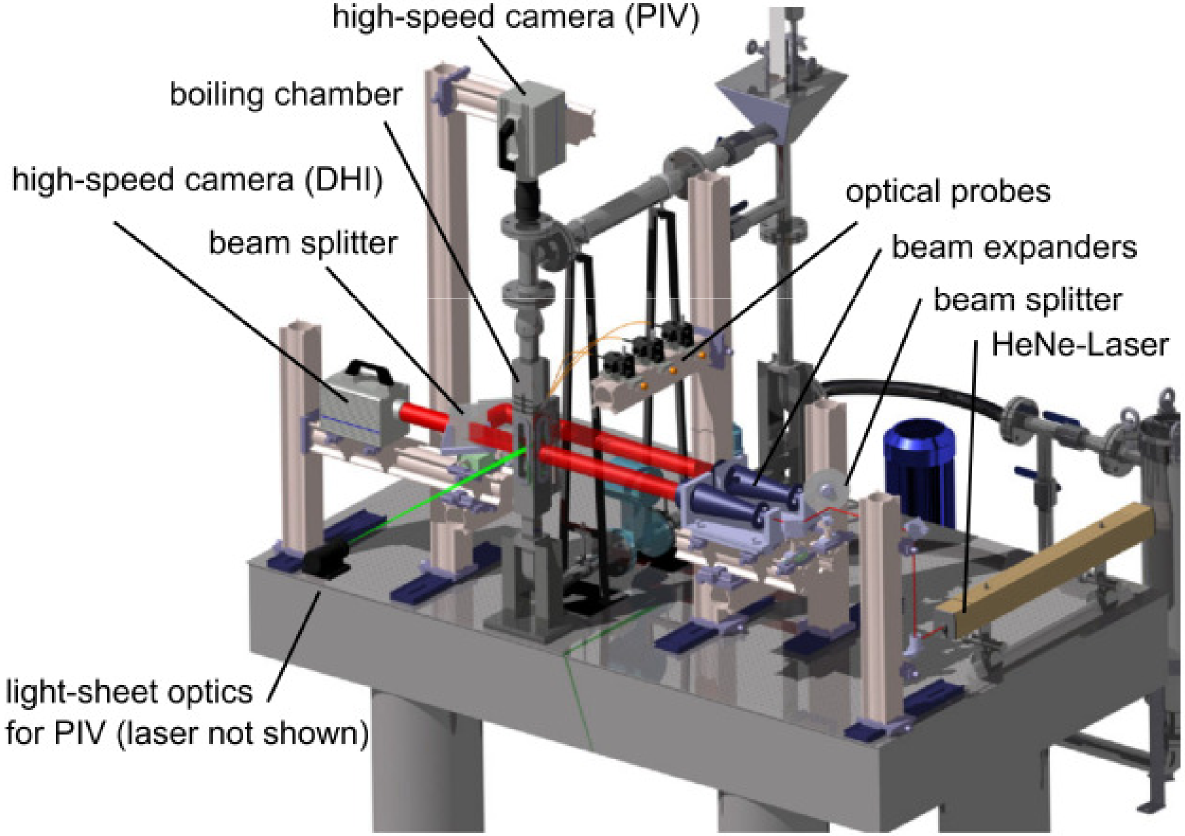
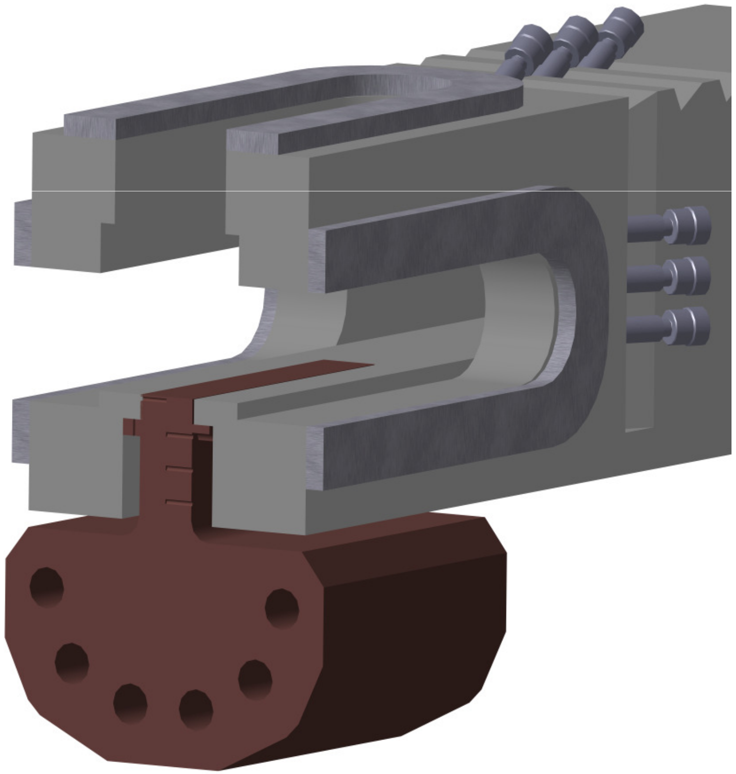
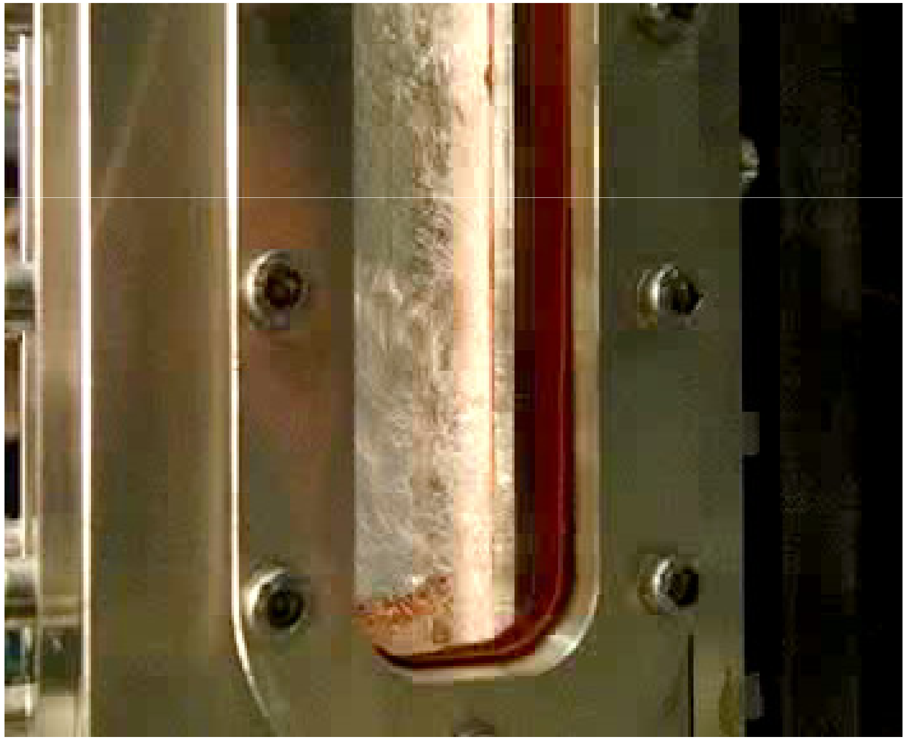


Image by courtesy of G. Bloch, T. Sattelmayer (TUM/TD)

The TU Munich Test Facility
- Planar Copper Heater in Vertical Channel -

- The TUM/TD wall boiling test facility & boiling experiments
- Subcooled liquid : Novec-659 Refrigerant





Images by courtesy of G. Bloch, T. Sattelmayer (TUM/TD)

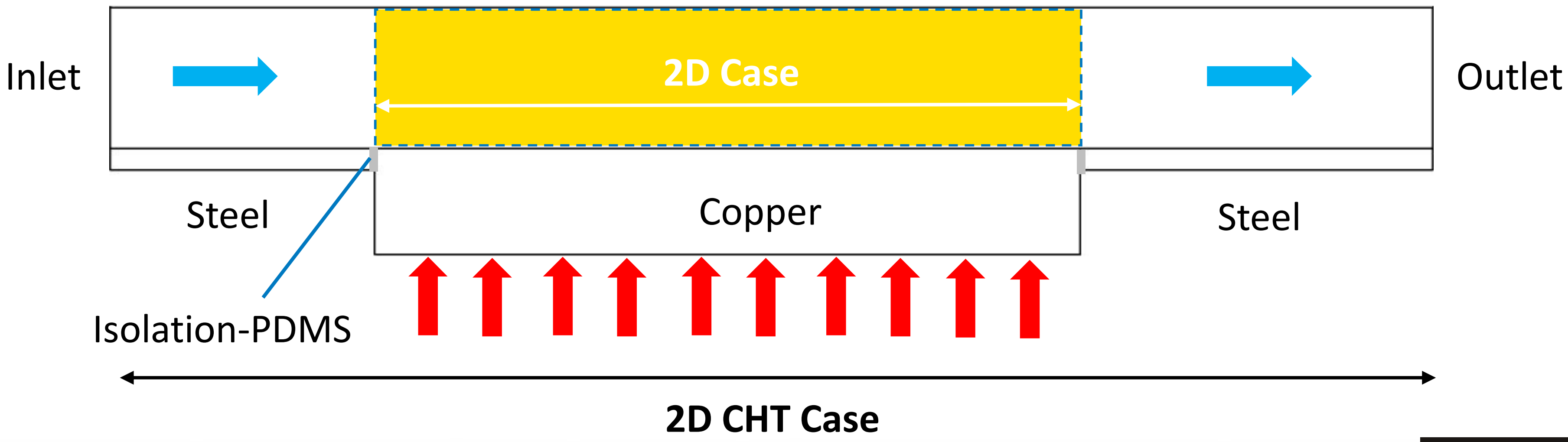
The TU Munich Test Facility - Reference Case

- Reference case operating conditions:
  - Pressure = 1 bar
  - Coolant Mass Flux = 1000 [kg/m²s]
  - Liquid SubCooling = 9 [K] $\rightarrow T_{L,\ Inlet} = T_{sat} - 9$ [K]
  - Wall heat flux : varying from zero to onset of CHF

- Comparison to data:
  - Boiling curve : Wall Heat Flux over Wall Superheat ($T_{Wall} - T_{Sat}$)
  - Wall heat flux at onset of CHF
  - Radial volume fraction profiles (optical fiber measurements)

The TU Munich Test Facility - Computational Domain

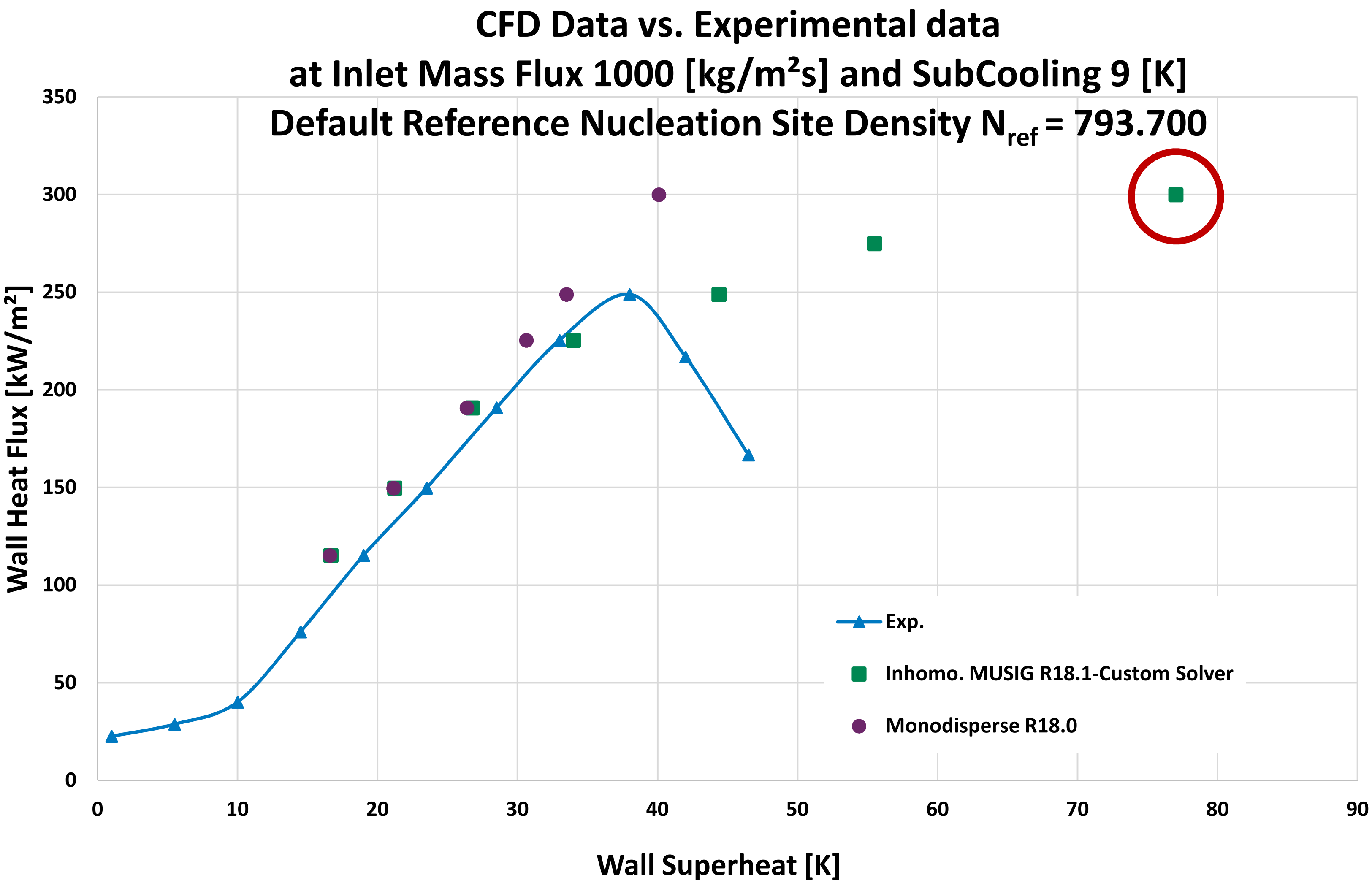
- Simplification to 2D computational domain
- Copper heater taken into account as 2d CHT domain
  - Application of the wall heat flux to outer wall of the copper domain with insulated interfaces to the stainless steel parts
- NOVEC-649: P_{ref} = 1 bar ; T_{sat} = 322.15 [K]



The TU Munich Test Facility - MUSIG Model Setup

- Inhomogenoues MUSIG with two velocity groups
  - **10 Size Groups for the first velocity group (VapourSmall Phase)**
  - **5 Size Groups for the second velocity group (VapourBig Phase)**
- Transition diameter is set to the critical diameter where the lift coefficient changes sign
  - **At constant NOVEC-649 properties @ the reference pressure and temperature this diameter is almost equal to 1.7 mm**
- Diameter of the Size Groups are equidistantly distributed within each of the two velocity groups
  - **Minimum diameter: 0.2 mm**
  - **Maximum diameter: 10 mm**
- Turb. Coalescence Coefficient (Prince and Blanch Model) = 2.5,…,**10**
  - **established by parameter variation**

The TU Munich Test Facility - Boiling Curve



The TU Munich Test Facility
- Nucleation Site Density Variation

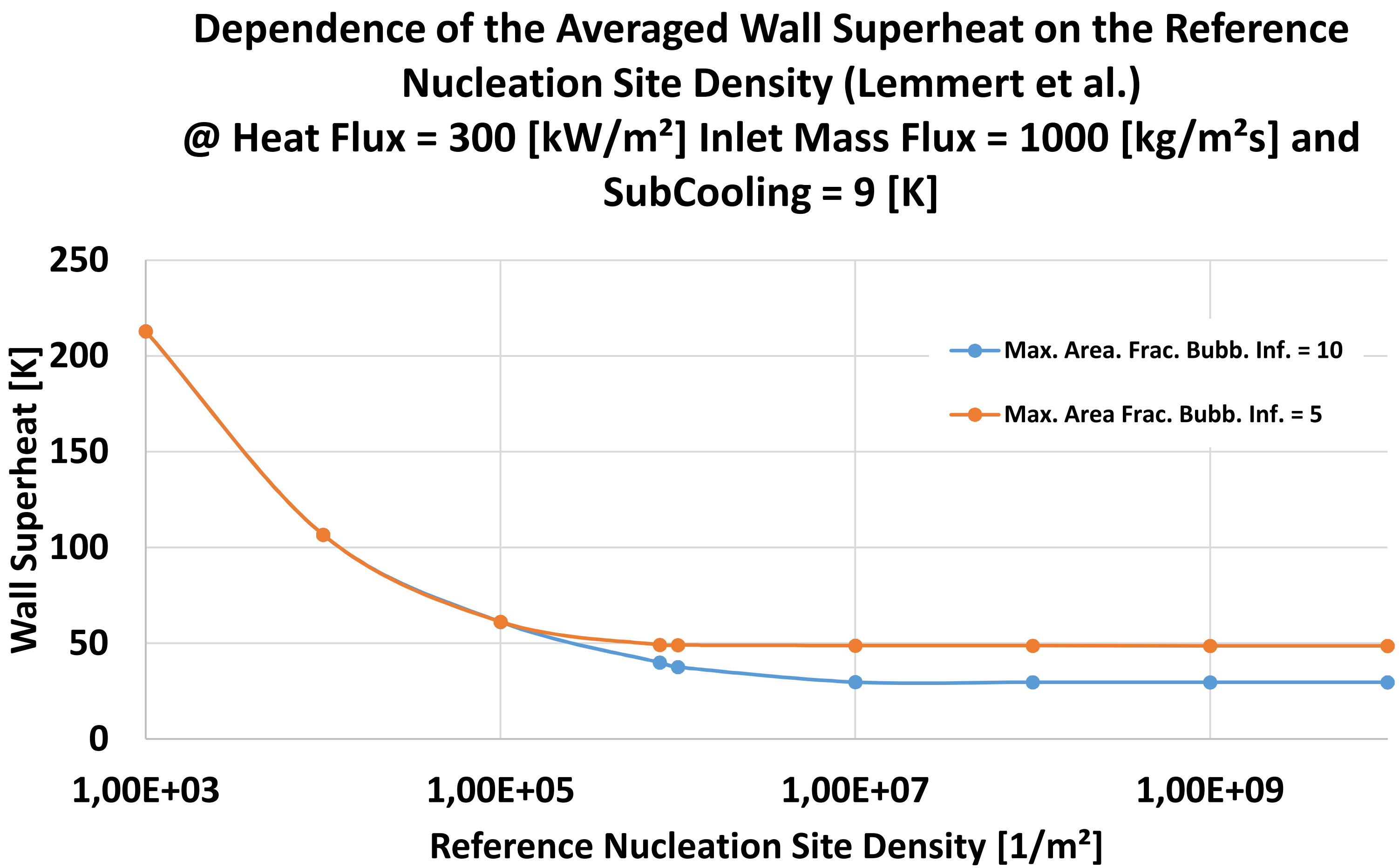
- In line with the monodisperse case observation:
  Decreasing reference Nucleation Site Density N_{ref} (Lemmert et al.) from the default value to 1000 for otherwise fixed model parameters.
- Temperature excursion and limited heat transfer to the subcooled liquid might not be due to the onset of NOVEC vapor film at the CHT surface but rather due to the available number of nucleation sites
  - Averaged wall temperature value for monodiserpsed approach
    @ 300 [kW/m²] = 106,72
  - The temperature increase by increasing the wall heat flux is smaller for the case of reduced N_{ref}

$$N = N_{ref}\left(\frac{T_W - T_{Sat}}{\Delta T_{ref}}\right)^p$$

$$N_{ref} = 10.000$$

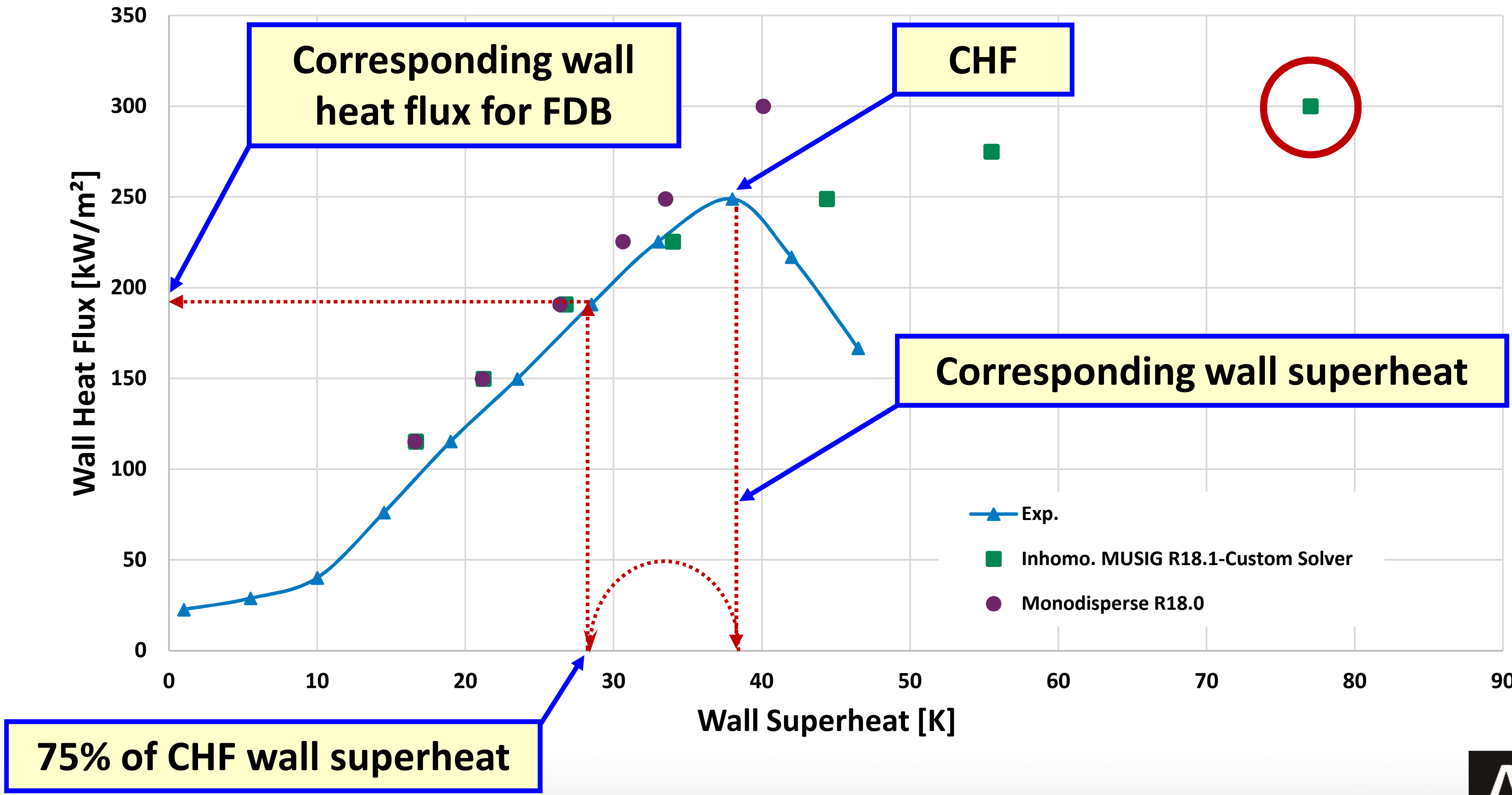
N_{ref}	275[kW/m²]	300[kW/m²]
$79.37E+04^{*}$	58.06	75.29
$1E+04$	100.56	104.95

The TU Munich Test Facility - Nucleation Site Density Variation



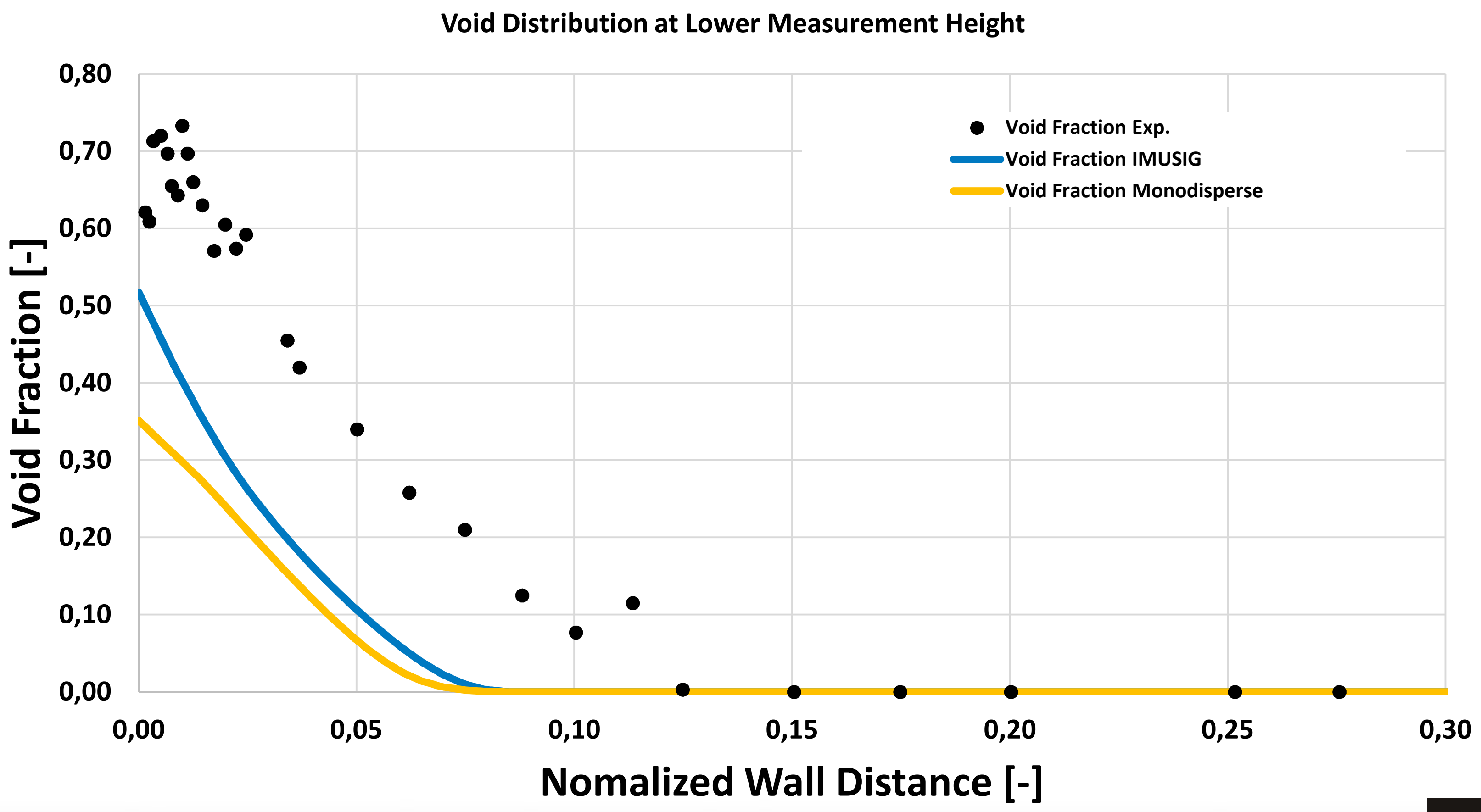
The TU Munich Test Facility – Validation Defining Fully Developed Boiling (FDB) Regime

- The way like conditions for Fully Developed Boiling (FDB) flow regime had been defined by experimentalists (TUM):



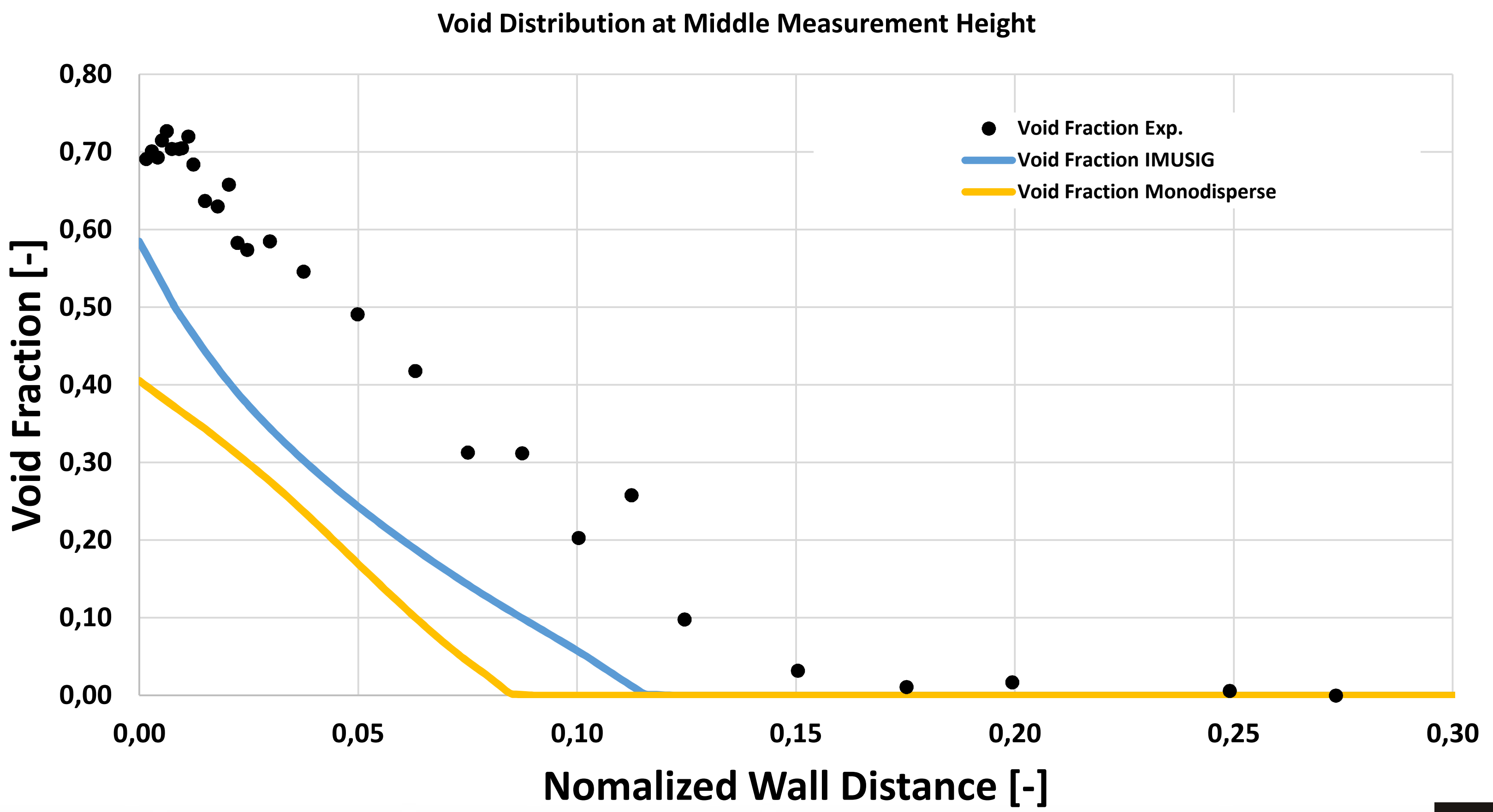
Novec-659 Steam Volume Fraction Profiles @ 75% of CHF - Lowest Position : x=34mm

25 kW/m² corrected heat flux



Novec-659 Steam Volume Fraction Profiles @ 75% of CHF - Middle Position : x=84mm

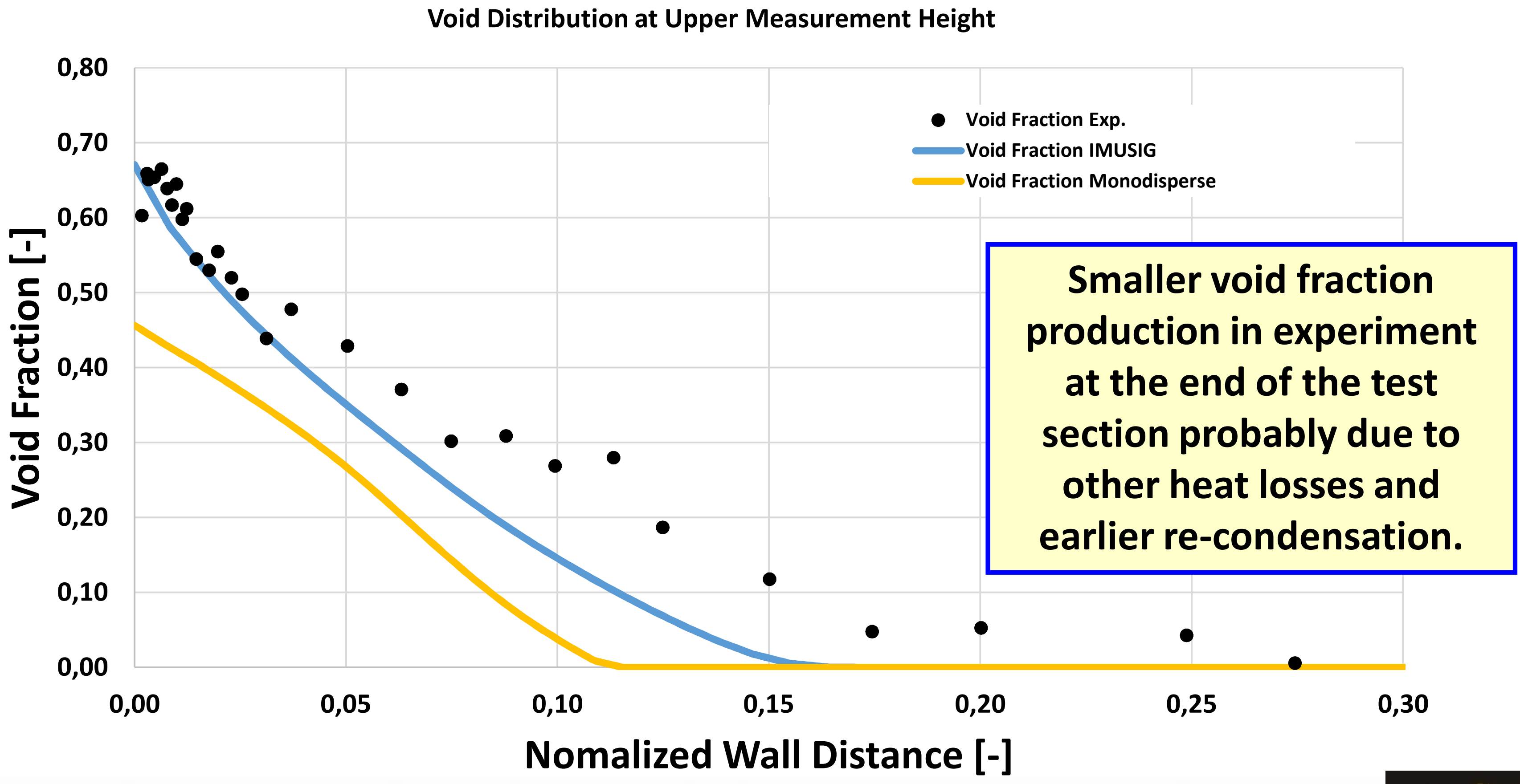
25 kW/m² corrected heat flux



ANSYS

Novec-659 Steam Volume Fraction Profiles @ 75% of CHF - Highest Position : x=154mm

25 kW/m² corrected heat flux



The COSMOS-L Test Facility (KIT/IKET)

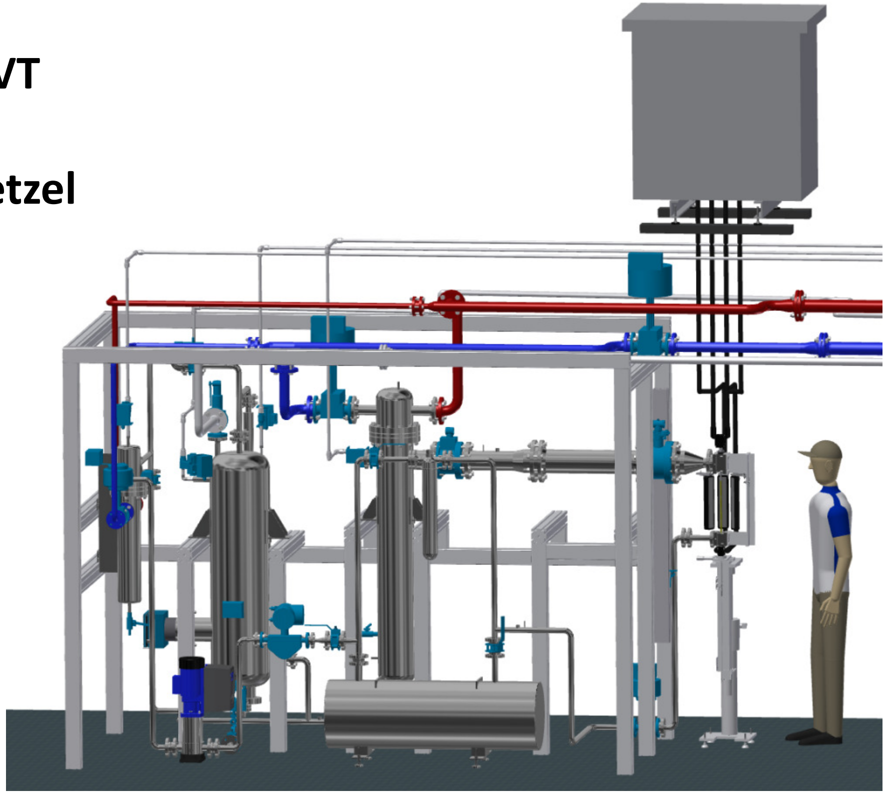
The COSMOS-L Test Facility (KIT)

Experiments by KIT / TVT and KIT / IKET :

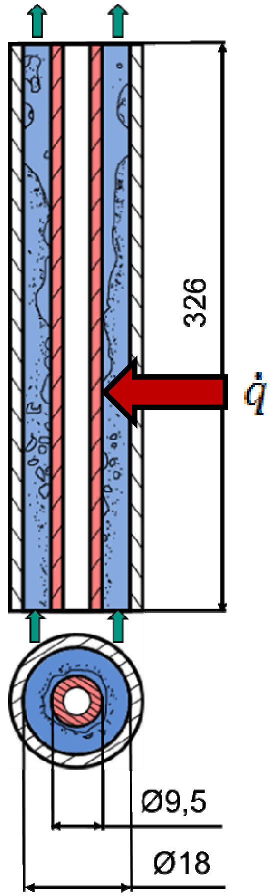
- **Prof. Dr. Thomas Wetzel**
- **Dr. Stephan Gabriel**
- **Florian Kaiser**
- **Wilson Heiler**

Reference:

Christoph Haas:
"Critical Heat Flux for Flow Boiling of Water at Low Pressure on Smooth and Micro-Structured Zircaloy Tube Surfaces",
KIT Scientific Publishing, Karlsruhe, 2012 .

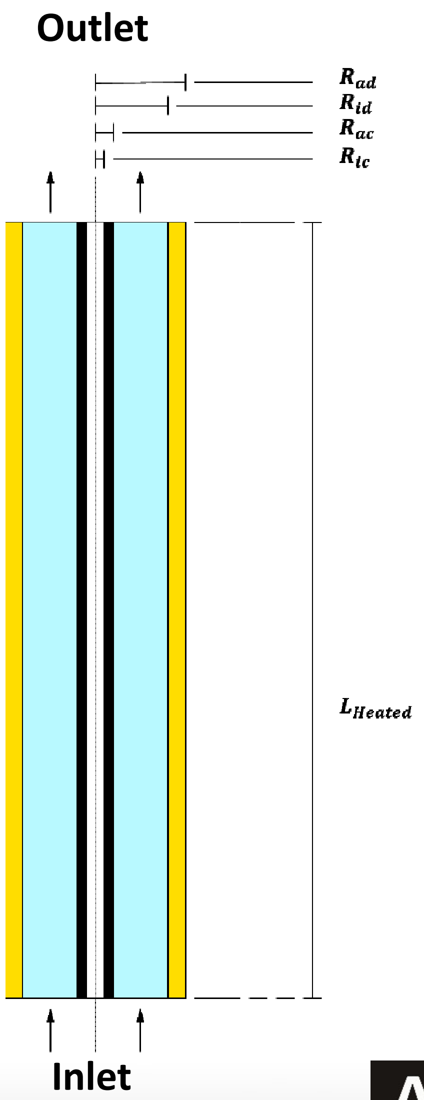


Images by courtesy of St. Gabriel & F. Kaiser (KIT)



The COSMOS-L Test Facility (KIT)

- Axially symmetric
  - Heat Flux prescribed on the inner ZircAlloy heater rod surface
- Radial dimensions
  - Inner radius of Zircaloy-Tube: R_{ic} = 4.18 mm
  - Outer radius of Zircaloy-Tube : R_{ac} =4.75 mm
  - Inner radius of Duran-Domain: R_{id} = 9 mm
  - Outer radius of Duran-Domain : R_{ad} = 10.9 mm
  - Annulus (Water-Domain) width : 4.25 mm
- Axial dimensions
  - Total heating section height: L_{Heated} = 326 mm



CFD Setup Characteristics – iMUSIG

Extended RPI wall boiling model ⇔ Inhomogeneous MUSIG ⇔ CHT

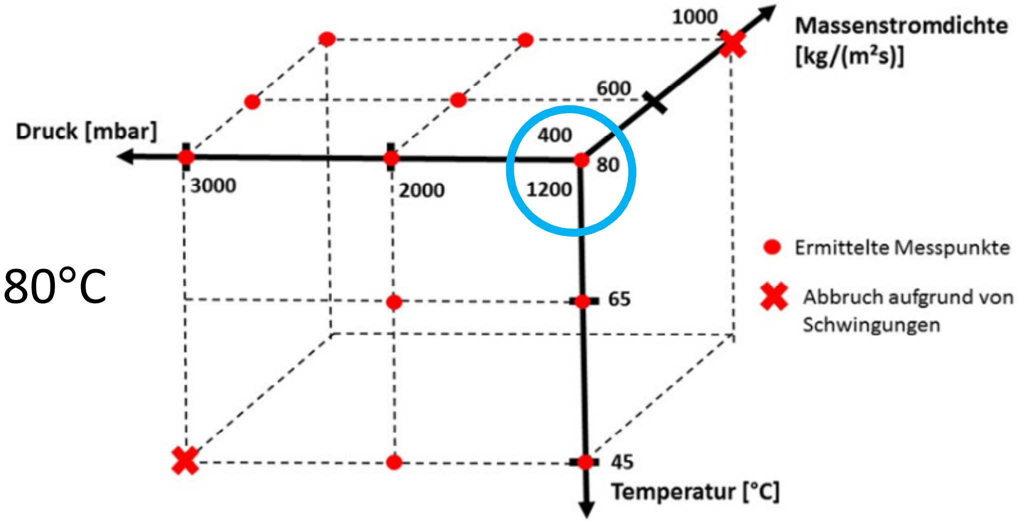
Version	**18.1 + Customized Solver**	
Analysis Type	**Steady runs with fluid time scale Δt= 0.005 [s]**	
Material Properties	**IAPWS IF-97 Library**	
Interfacial forces	Lift	Tomiyama
	Drag	Grace
	Turbulent Dispersion	FAD model
Boiling Model	**Equilibrium RPI model**	**Maximum Area Fraction of Bubble Influence = 10**
	Bubble Departure Diameter	**Tolubinski et al. (default)**
	Nucleation Site Density	**Lemmert et al.(default) / Modified Reference Site Density**
Vapor heat transfer	**Thermal Energy**	
Turbulence model	**SST**	Homogeneous Turbulence
IMUSIG	**Breakup Coeff. = 1.0 ; Turb. Coalescence Coefficient = 10.0**	
	Boundary Conditions: Size Fraction of the smallest group = 1 @ Domain Openings and Domain Initialization	

COSMOS-L: Polydispersed Fluid Resolution

- Two velocity groups with 23 size classes equidistantly distributed within the velocity groups
  - **20 size groups for the first velocity group**
    - Minimum diameter: 0.02 [mm]
    - The smallest bubble diameter been estimated by means of the provided HD videos to be around 0,1-0,2 [mm]
    - Bubble Detachment Diameter (Lift-Off) according to Tolubinski et al. is round about 0.4 mm
  - **3 size groups for the second velocity group**
    - Maximum diameter: 7 mm
  - **Minimum Volume Fraction = 1E-9**
- Transition diameter is the diameter where the Tomiyama Lift coefficient changes sign: 5.33339 [mm] @ 1.2 [bar] & 377.93 [K]

The COSMOS-L Test Facility (KIT)
The Test Matrix

- T80P1200M400
  Operating Conditions
  - Liquid SubCooling: 20 [K]
    i.e. Water Inlet Temperature: 80°C
  - Reference Pressure: 1.2 [bar]
  - Mass Flux : 400 [kg/m²s]



- Calculating boiling curves starting from 400 [kW/m²] Heat Flux
- Further investigated operating conditions:
  - T80P2000M400 – pressure variation
  - T80P2000M600 – add. mass flux variation
  - T65P1200M400 – liquid subcooling variation

COSMOS-L: Material Parameters

- Water / Water Vapor : from IAPWS material library

Material	**IAPWS IF97**
Minimum Temperature	**50 [C]**
Maximum Temperature	**400 [C]**
Minimum Absolute Pressure	**0.8 [bar]**
Maximum Absolute Pressure	**2 [bar]**
Number of Points	**600**

- ZircAlloy-4 : CES Edupack 2010 material data sheet
- Duran glass outer walls : manufacturer material data sheet

  http://www.duran-group.com/de/ueber-duran/duran-eigenschaften.html)

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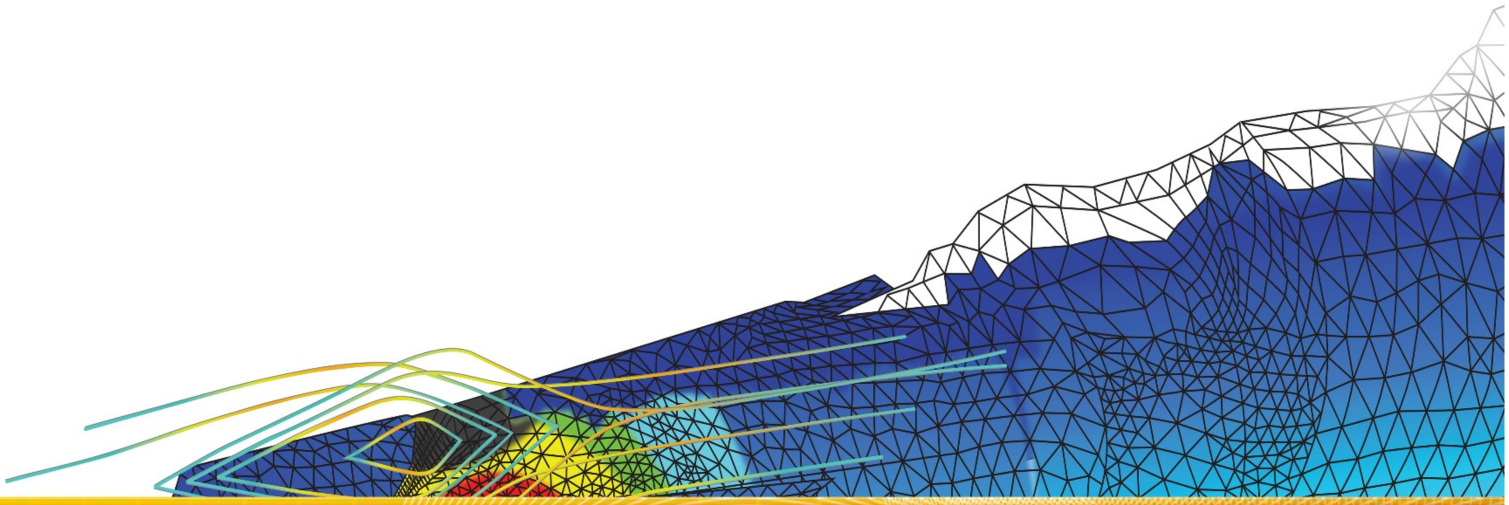
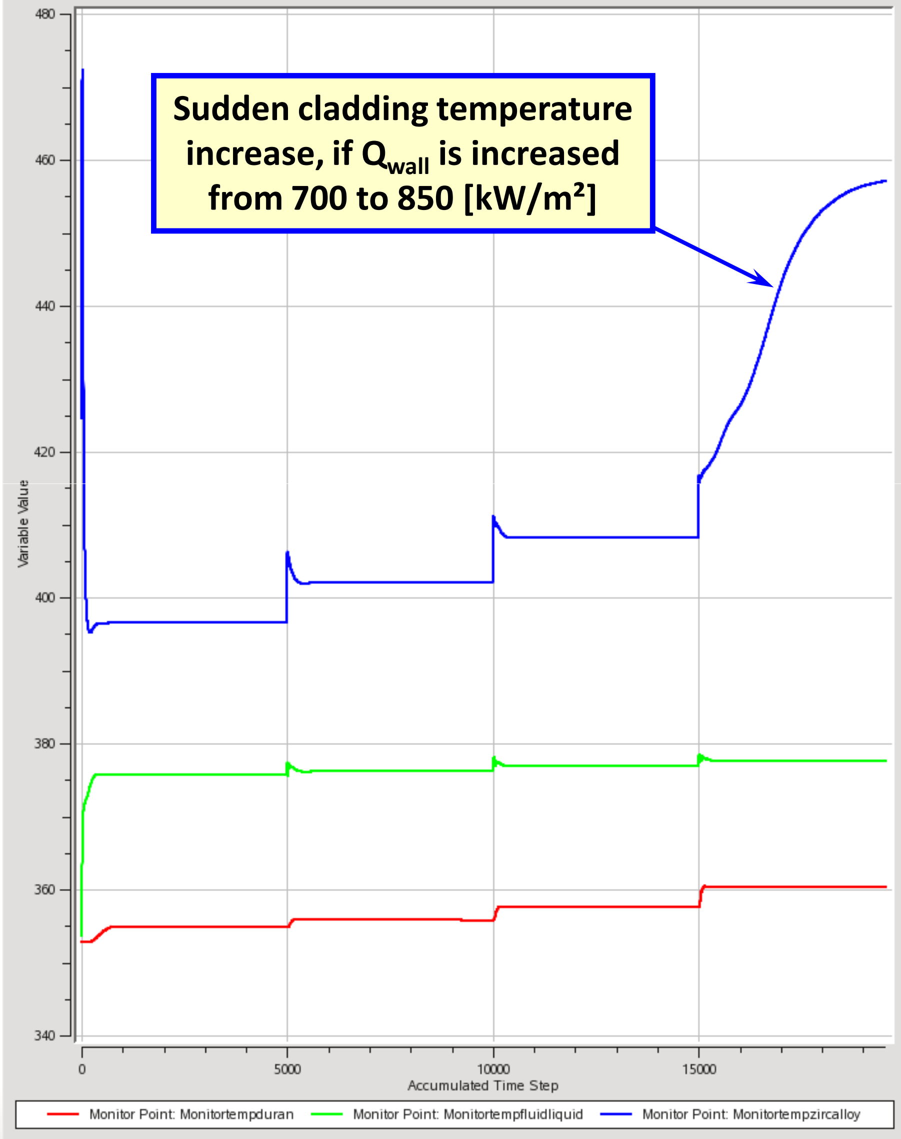
T80P1200M400

(Reference Case)

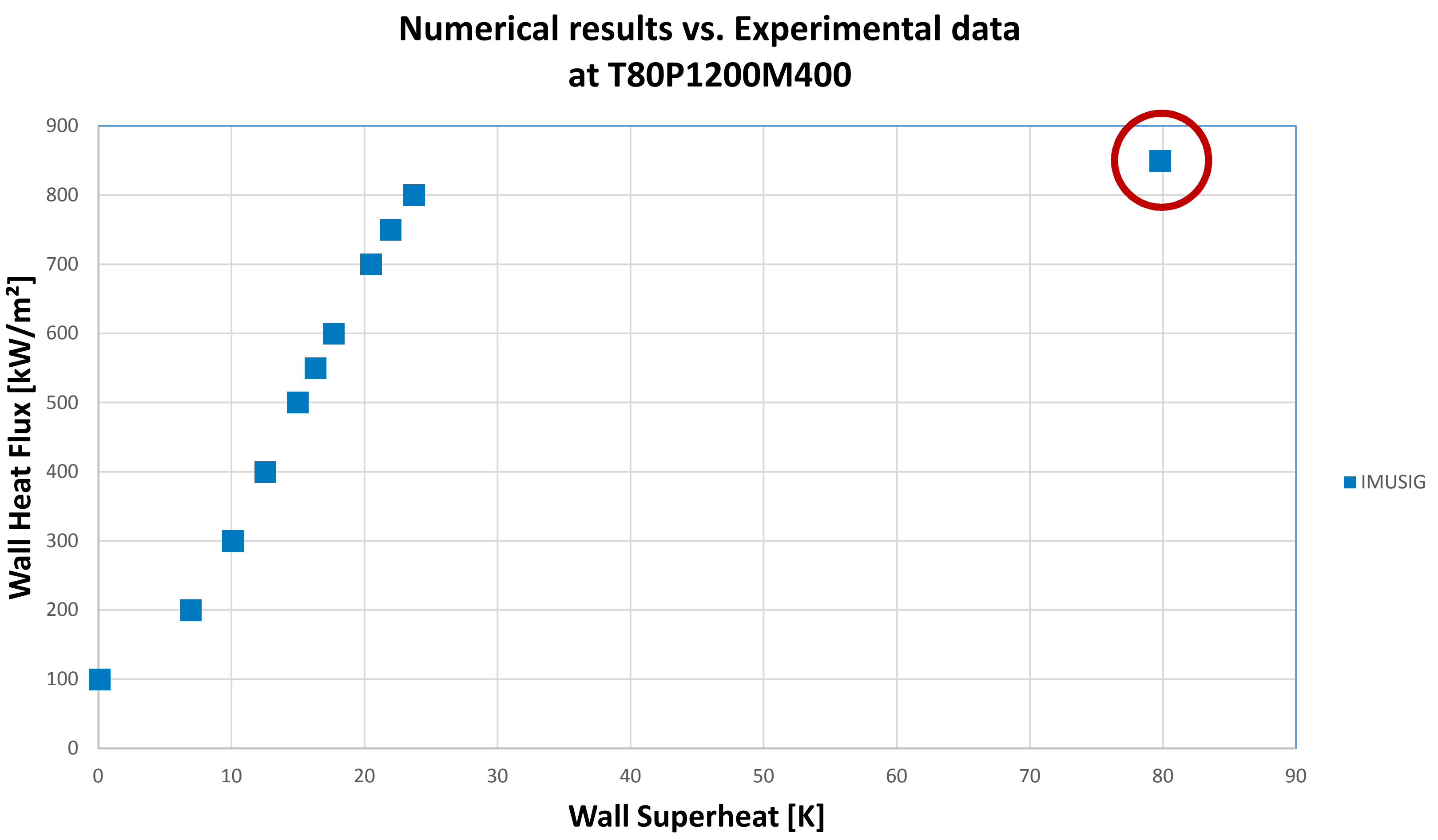


The COSMOS-L Test Facility (KIT)
T80P1200M400: CHF at Q_{wall} = 850 [kW/m²]

- Cladding temperature excursion (mean domain temperatures are monitored)
- Previous simulation runs show restarts from:
  Q_{wall} = 400 [kW/m²]
  → Q_{wall} = 550 [kW/m²]
  → Q_{wall} = 700 [kW/m²]
  → Q_{wall} = 850 [kW/m²]
- Q_{wall} = 800 [kW/m²] does not yet show this strong cladding temperature increase but behaves like the 700-er case with T_{wall}~408.2 [K]
  → mean T_{wall} increase by ~50 [K]

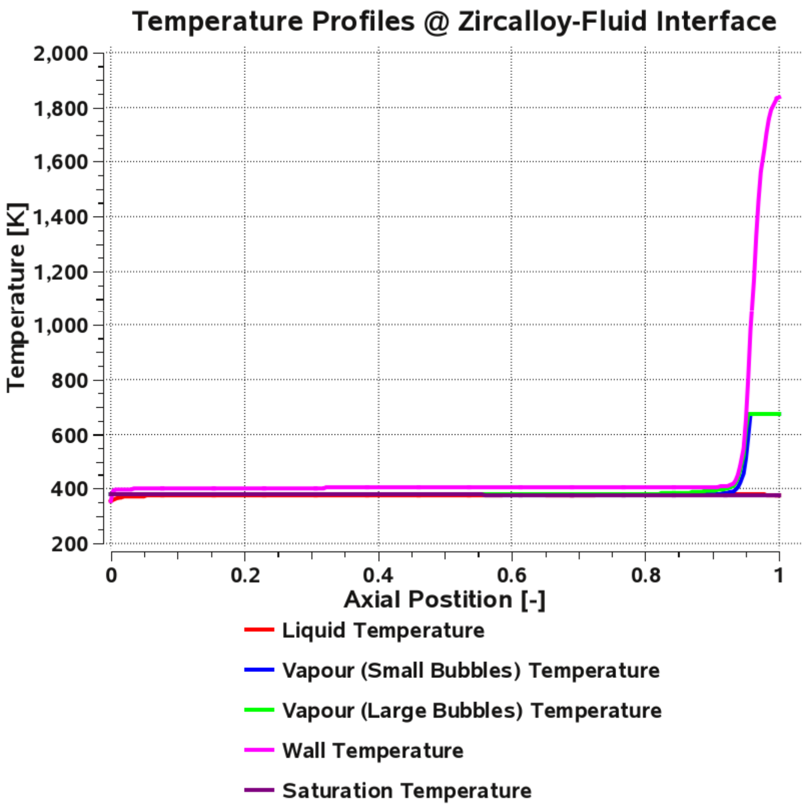


The COSMOS-L Test Facility (KIT)
T80P1200M400: The Boiling Curve



The COSMOS-L Test Facility (KIT) Reference Case T80P1200M400

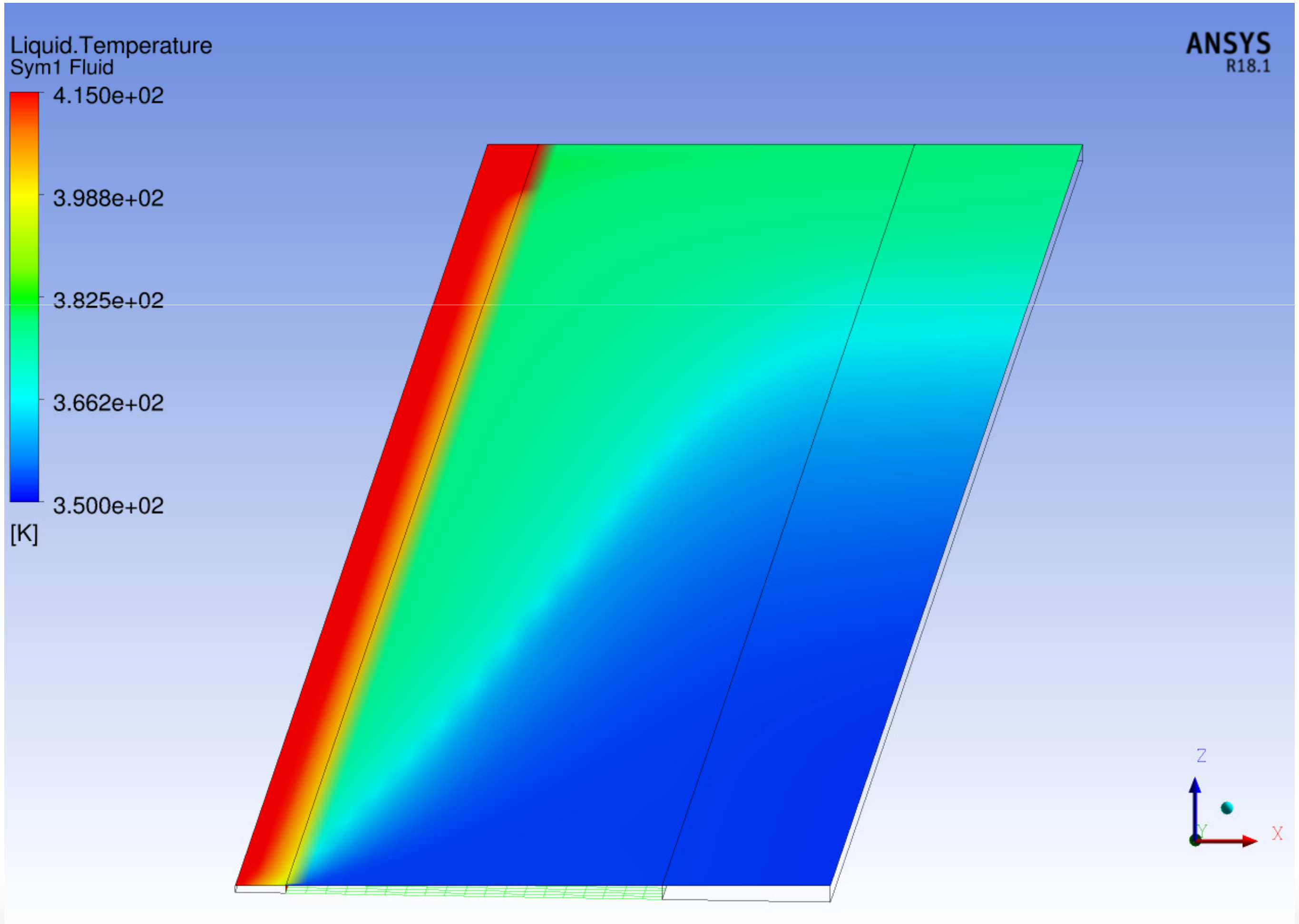
- The experimentally measured heat flux at which CHF occurs is about 867 [kW/m²] with a standard deviation equal to 16 [kW/m²]
- This is in good agreement with the ANSYS CFX results
  - Temperature excursion in the ZircAlloy heater rod obtained @ 850 [kW/m²] in the simulations
  - Liquid cooling of ZircAlloy cladding breaks down at the very end of the heater rod



T80P1200M400
@ 850 [kW/m2]

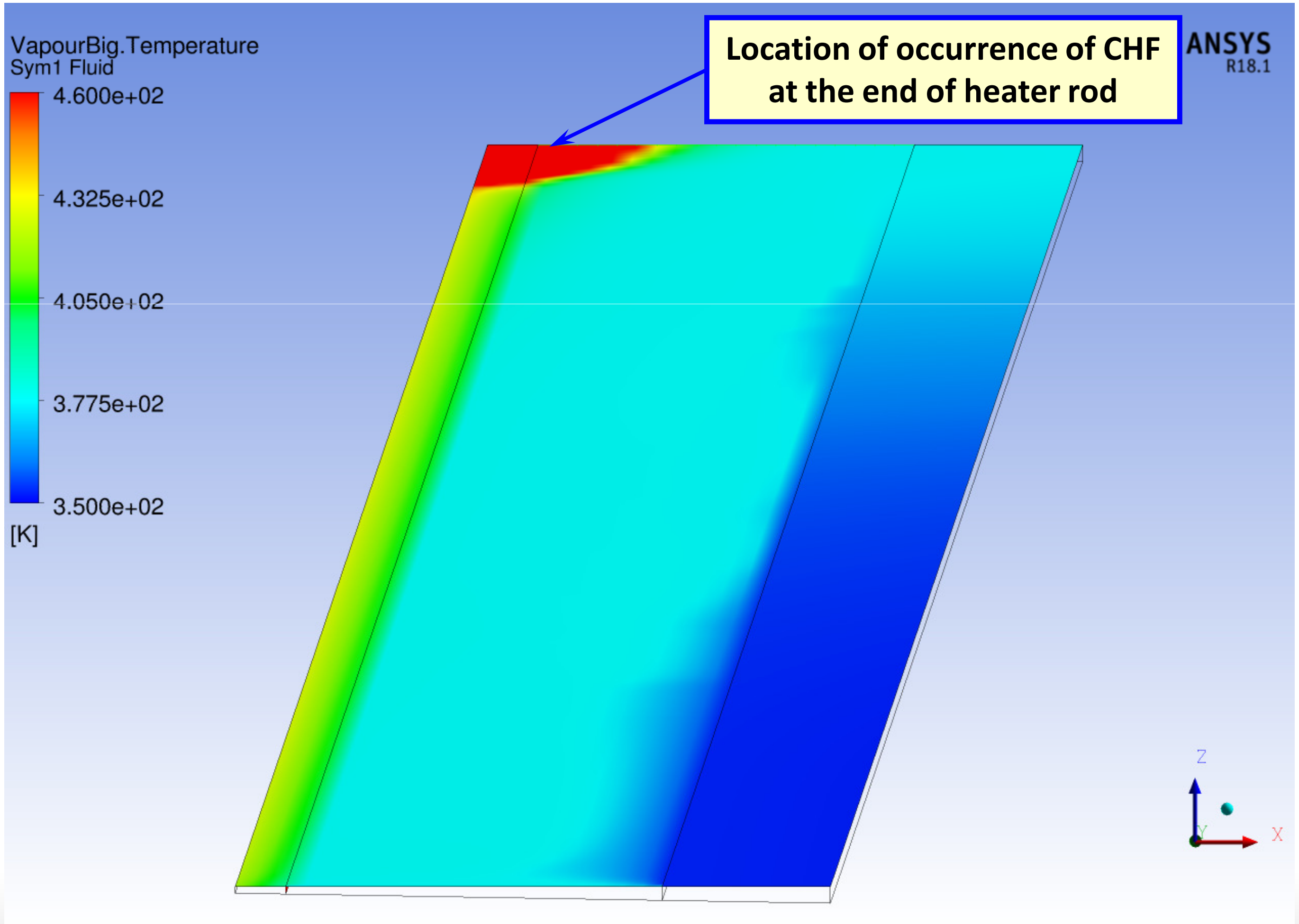
CHF at Q_{wall} = 850 [kW/m²]

- Liquid cooling of ZircAlloy cladding breaks down at the very end of the heater rod

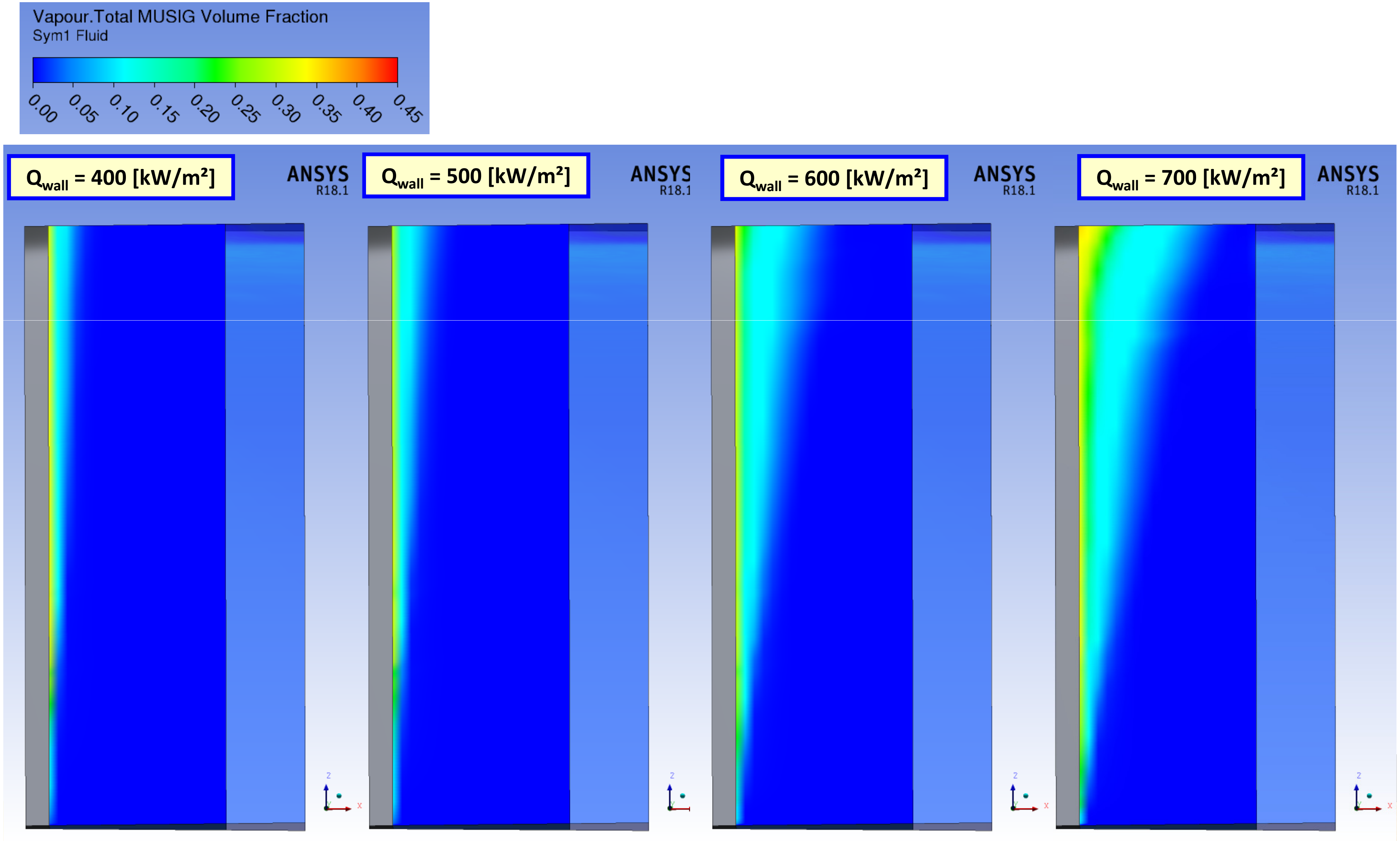


CHF at Q_{wall} = 850 [kW/m²]

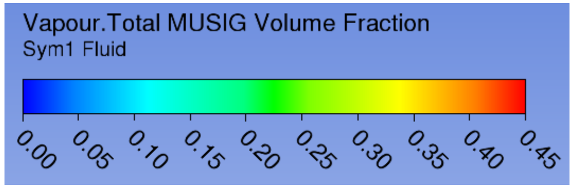
- CHF in the ZircAlloy cladding and highly superheated steam in both MUSIG velocity groups showing almost the same temperature

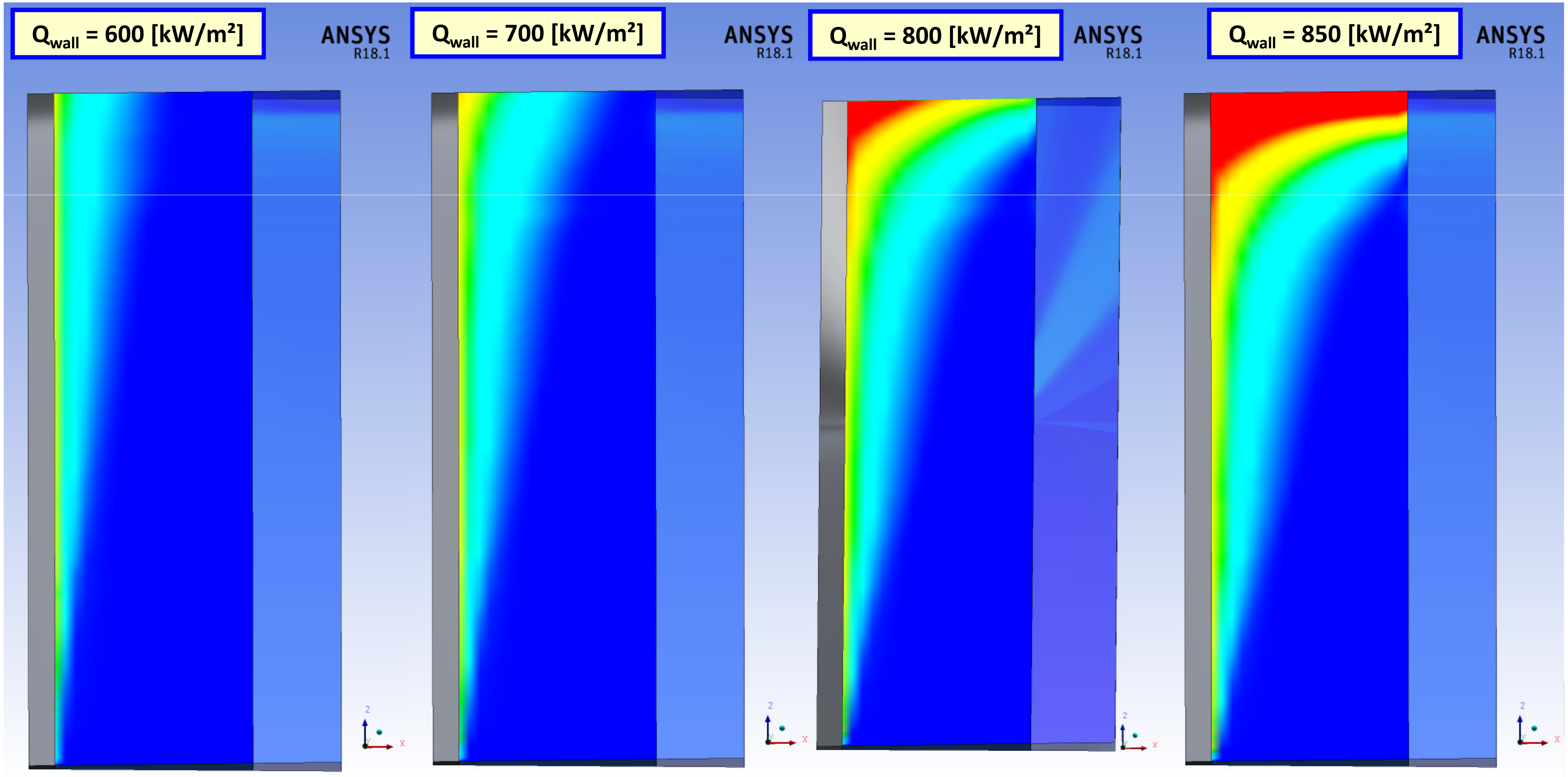


Total Vapour VF Distribution with Increased Wall Heat Flux : 400 [kW/m²] → 700 [kW/m²]

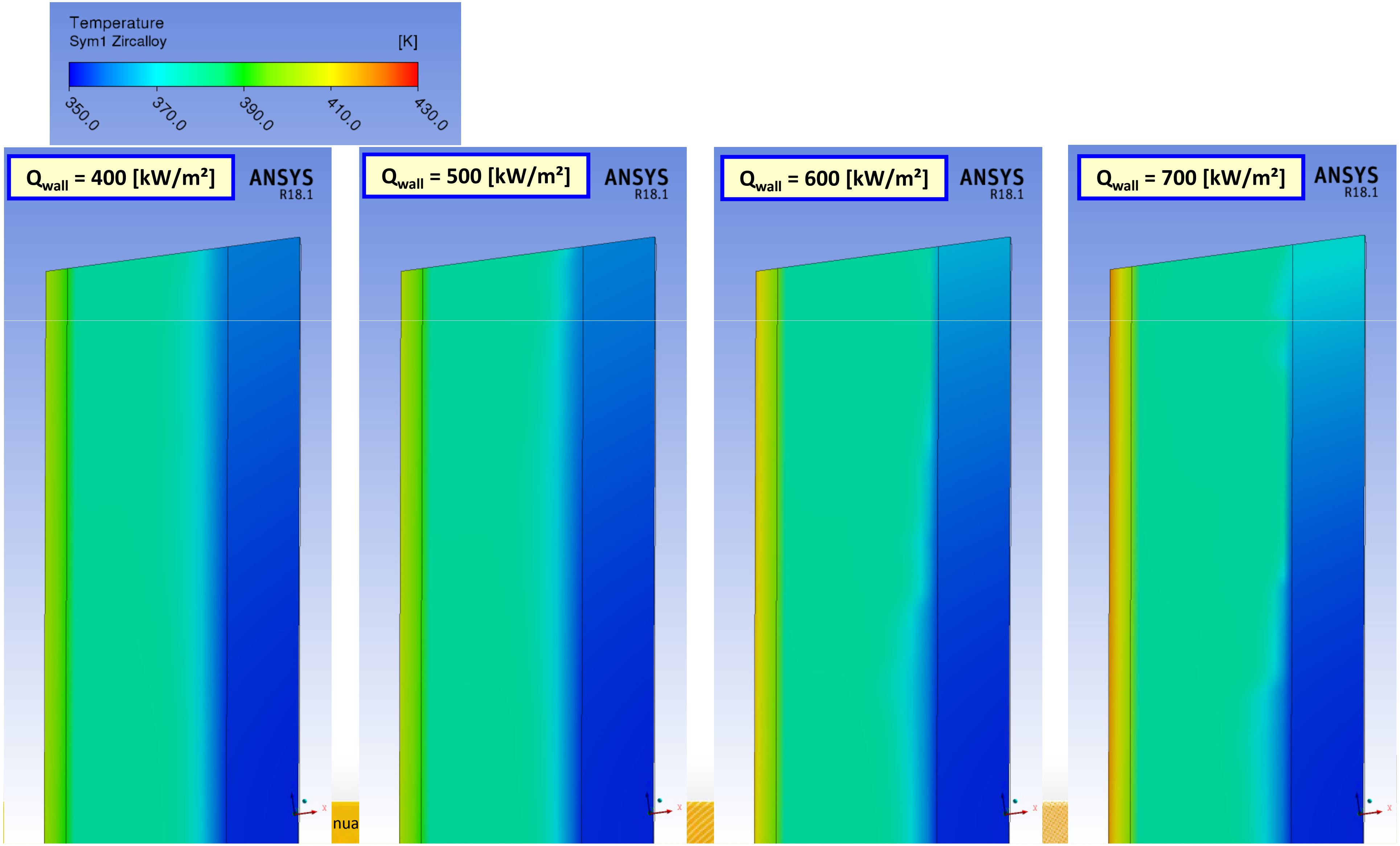


Temperature Distribution with Increased Wall Heat Flux : 600 [kW/m²] → 850 [kW/m²]

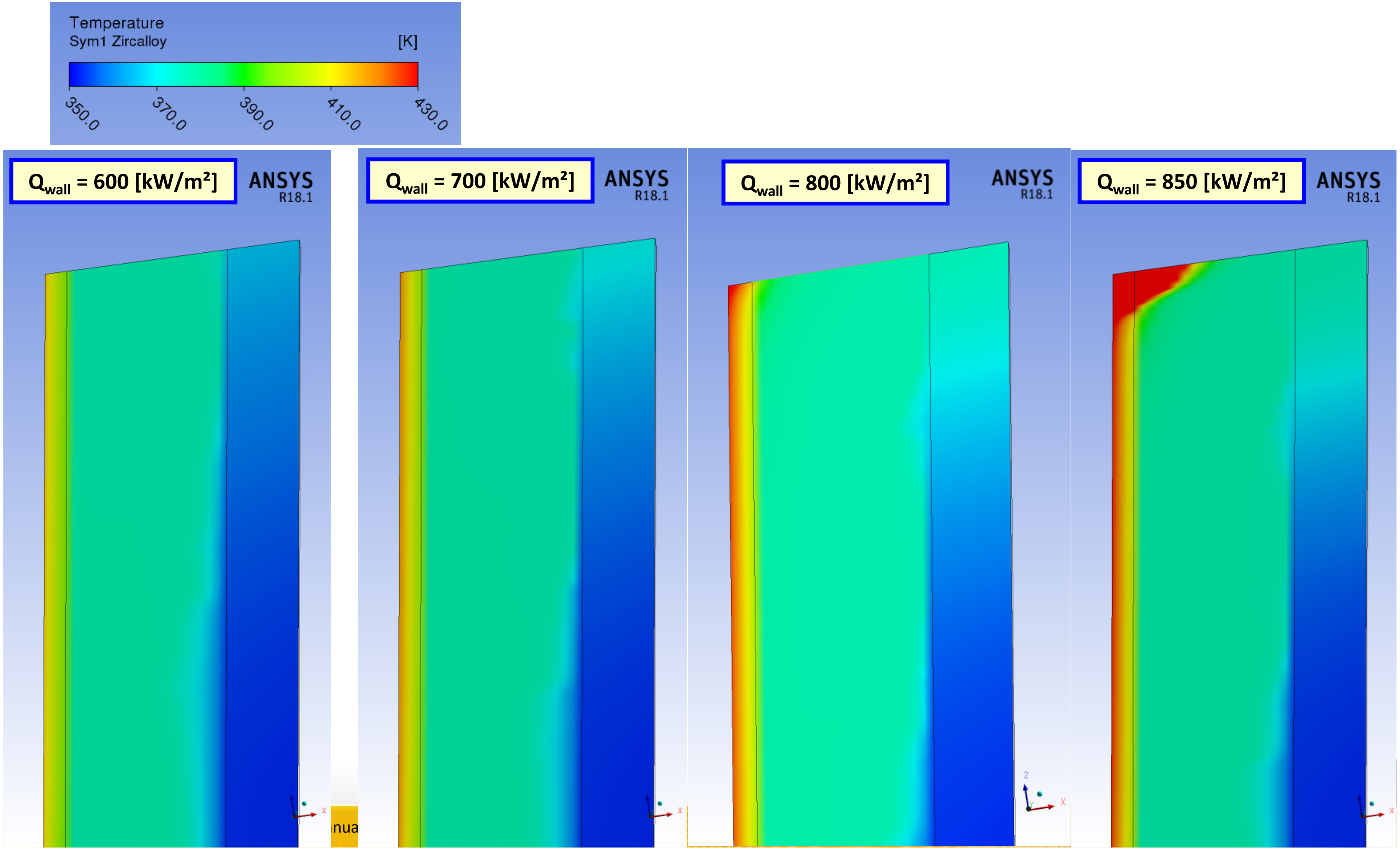




Temperature Distribution with Increased Wall Heat Flux : 400 [kW/m^2] → 700 [kW/m^2]

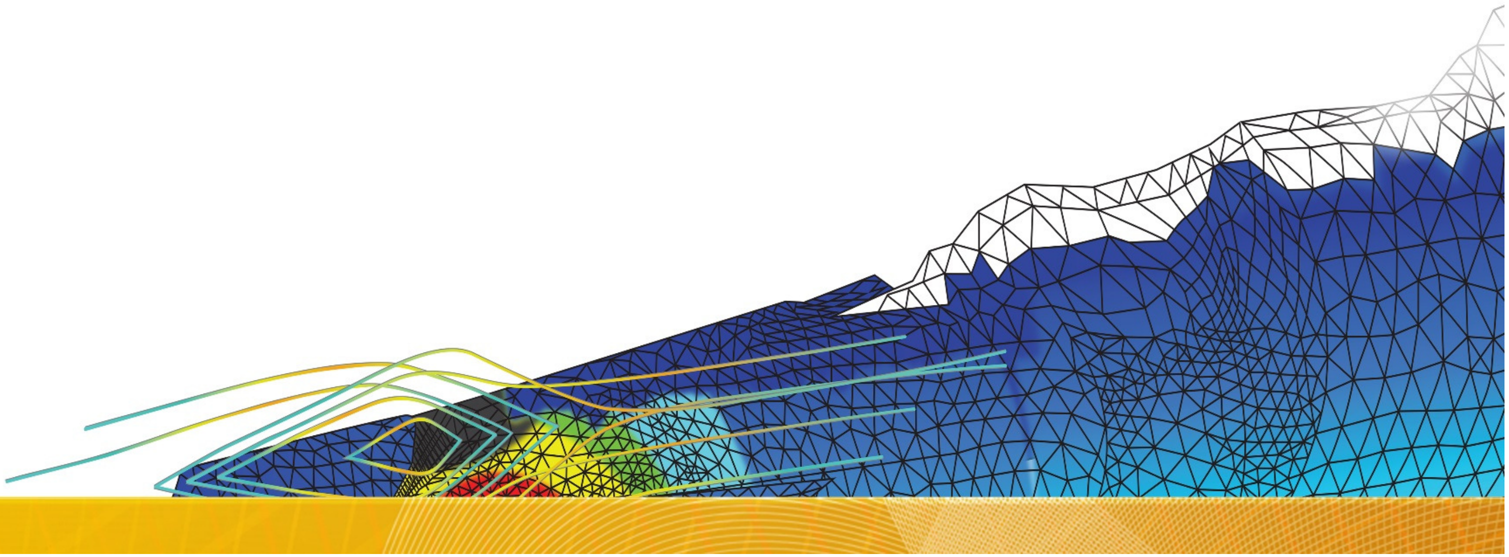


Temperature Distribution with Increased Wall Heat Flux : 600 [kW/m²] → 850 [kW/m²]

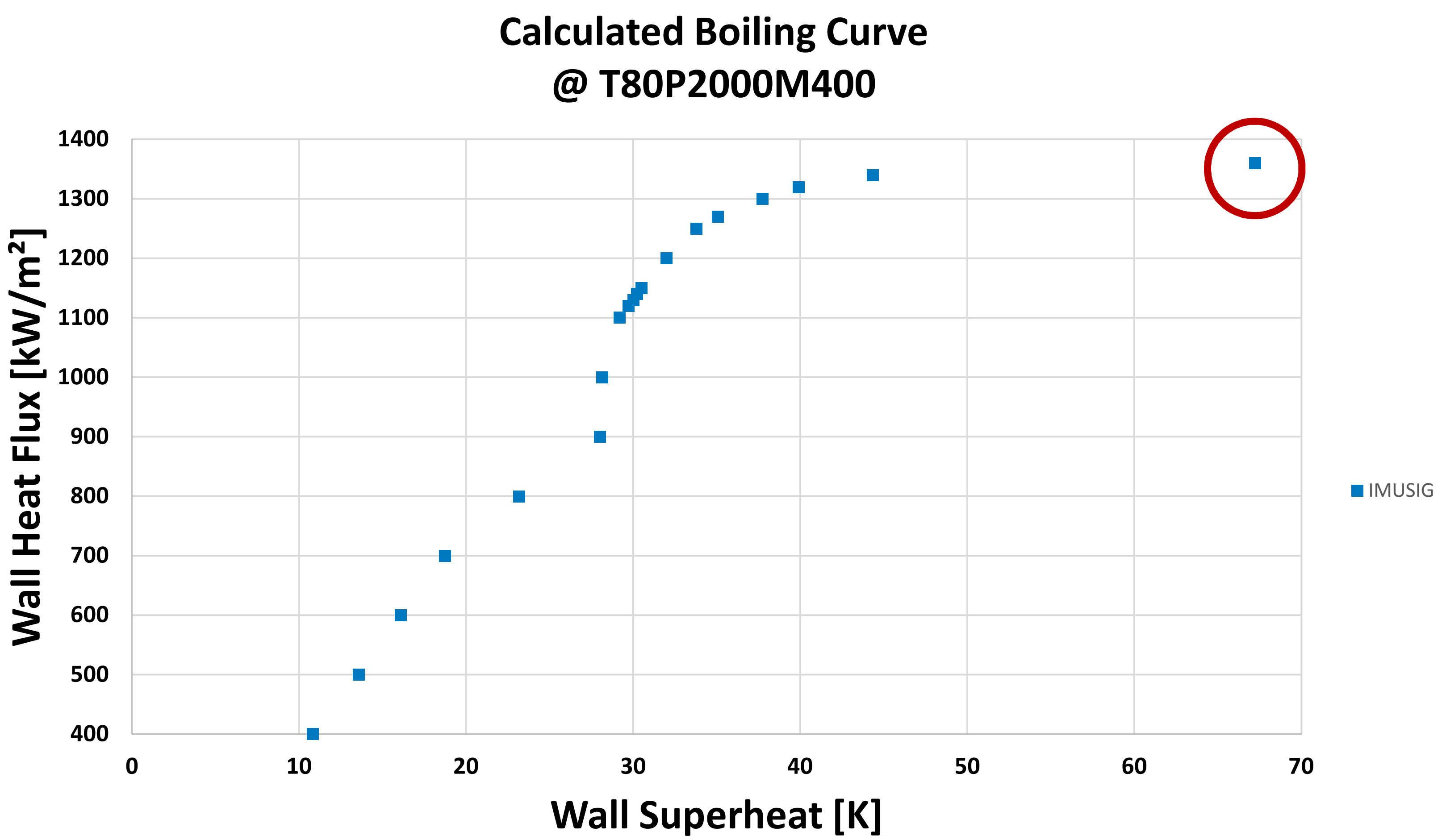


T80P2000M400

(Reference Pressure Variation)

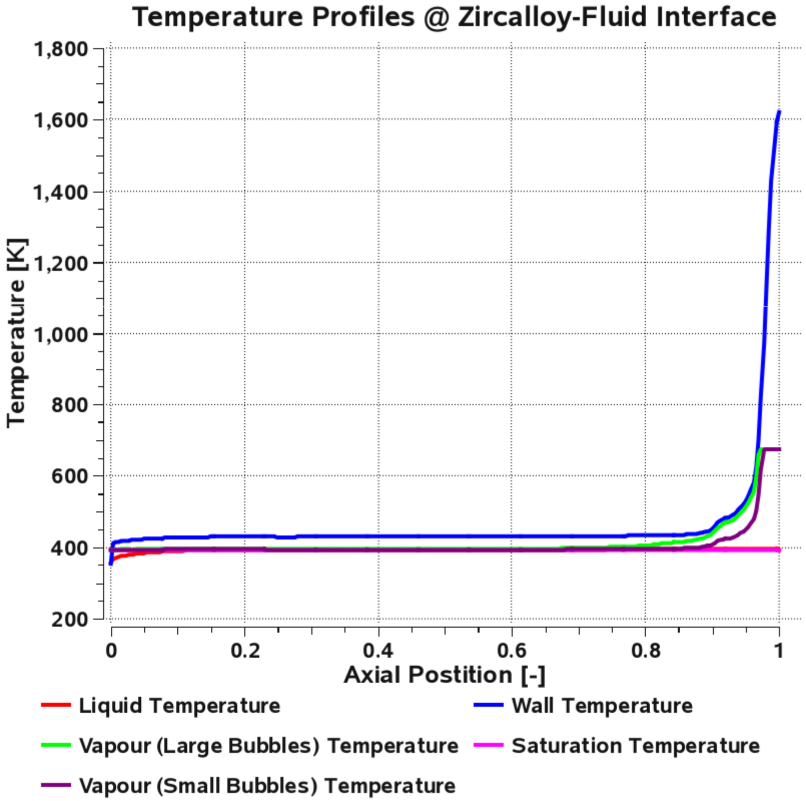


The COSMOS-L Test Facility (KIT)
T80P2000M400 Boiling Curve



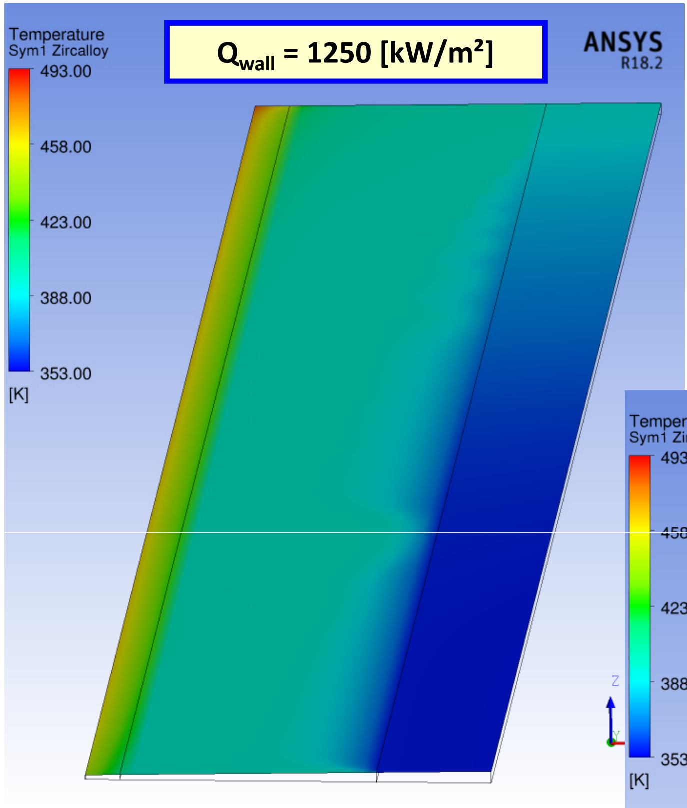
The COSMOS-L Test Facility (KIT) T80P2000M400 - CHF Comparison

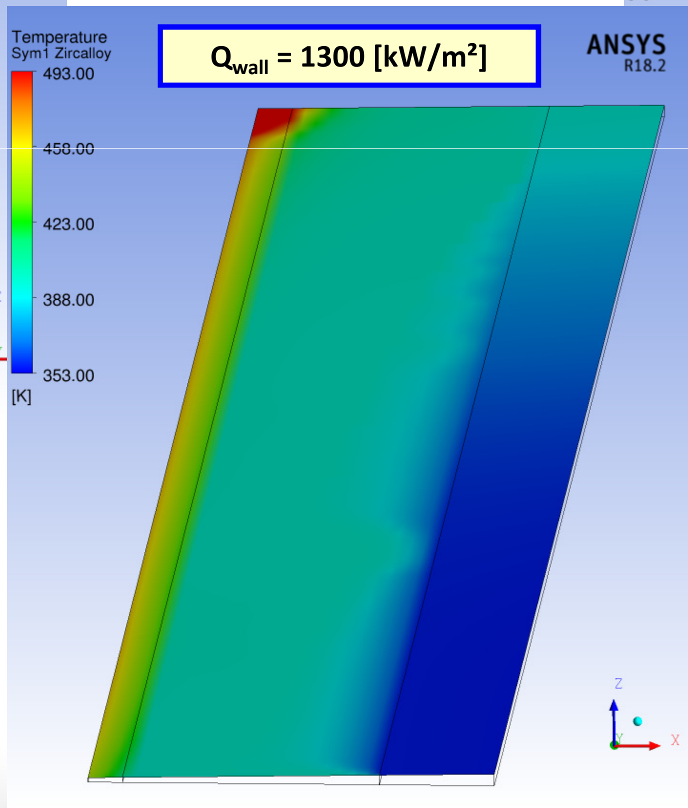
- The experimentaly measured heat flux at which CHF occurs is about 1229 [kW/m²] with a standard deviation equal to 9 [kW/m²]
- This is in good agreement with the ANSYS CFX results
  - Temperature excursion in the Zircalloy heater rod obtained @ approx. 1300 [kW/m²] in the simulations
  - Liquid cooling of ZircAlloy cladding breaks down at the very end of the heater rod

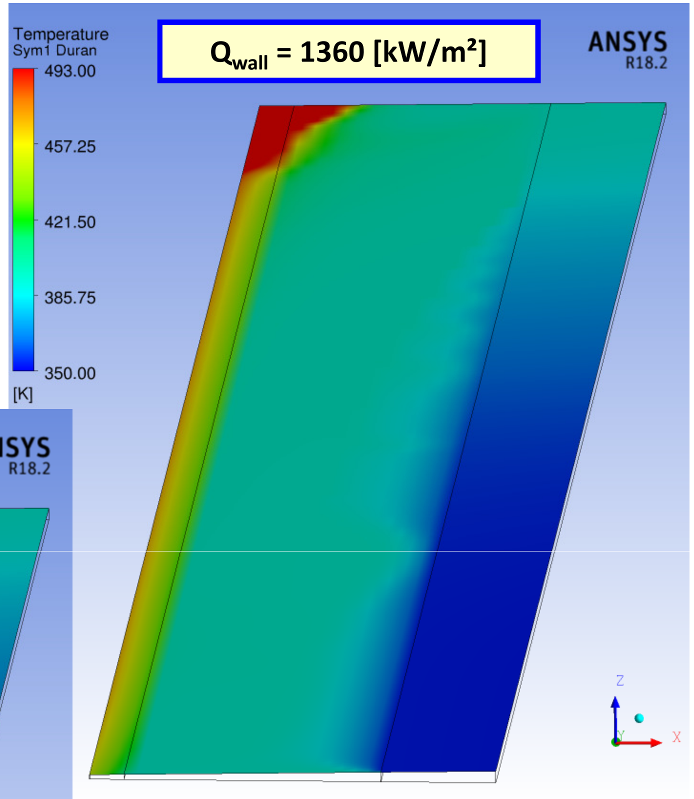


T80P2000M400
@ 1360 [kW/m2]

T80P2000M400: Temperature Distribution







Experimentally measured CHF value:
Q_{wall} = 1229 [kW/m²]

Concluding Remarks and Outlook

- Presented a short overview of the NUBEKS R&D project results obtained by ANSYS Germany for CFD modeling and simulation of Critical Heat Flux (CHF)
- Successfully predicted CHF for 3 experiments from TUM and COSMOS-L (KIT) test facilities
- Key ingredients:
  - ANSYS CFX 18.0 or newer
  - CHT for the heater material
  - Extended RPI wall boiling model
  - Inhomogeneous MUSIG model for the vapor phase IAD
- Some challenges and modeling uncertainties remain:
  - Nucleation site density specification
  - Break-up and coalescence modeling
  - Multiphase flow turbulence modeling for flow regime transition
  - Extraordinary thin vapor layers at high liquid subcooling / high liquid mass flux

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