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Modeling of Wall-boiling Phenomena from Nucleate Subcooled Boiling up to CHF Conditions

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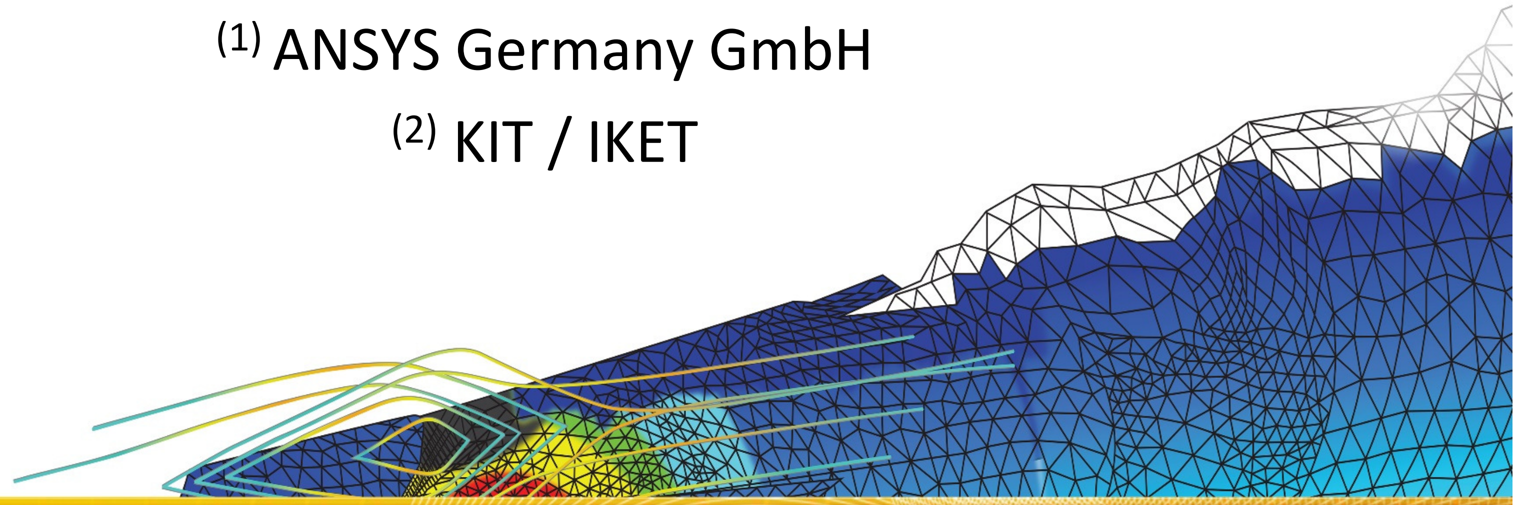
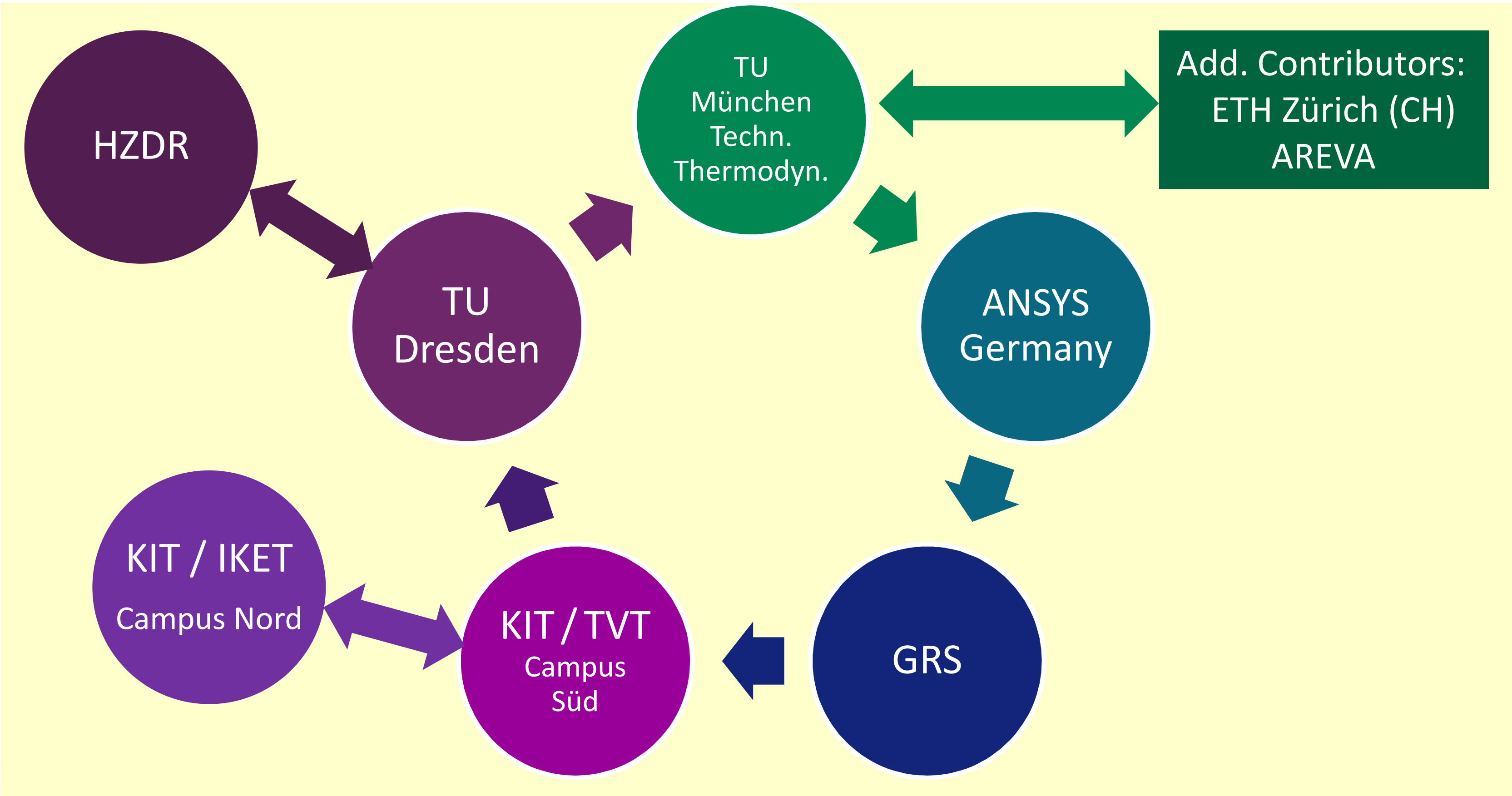


Outline

- 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 KIT COSMOS-L test facility
  - The test matrix
  - Wall boiling & CHF simulations
- Concluding remarks and outlook

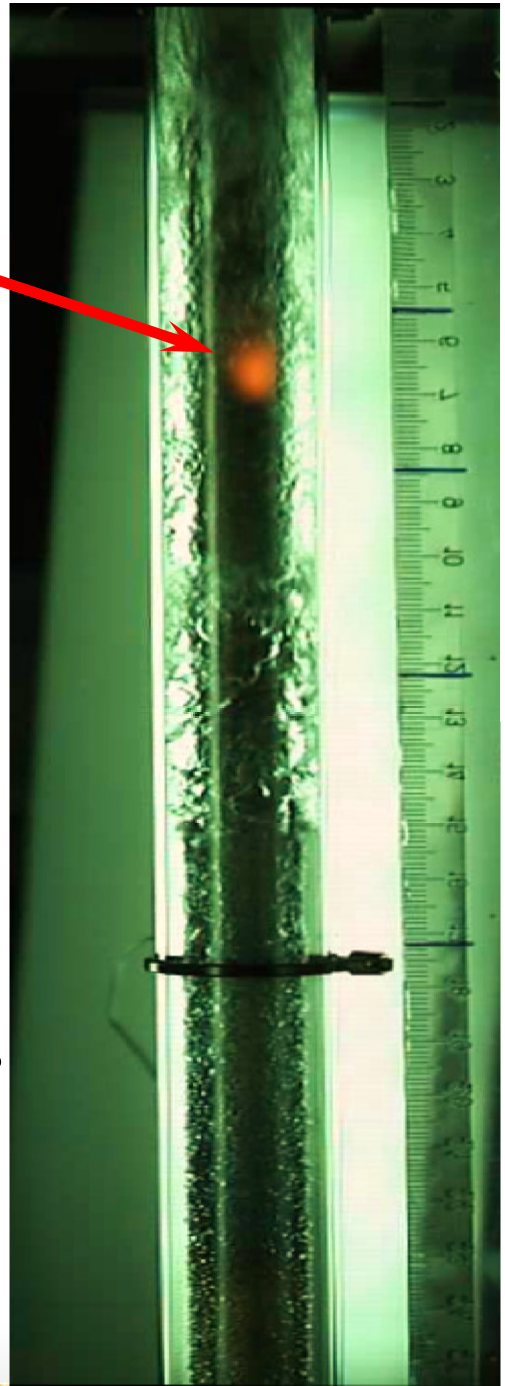
The NUBEKS R&D Consortium

- 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:

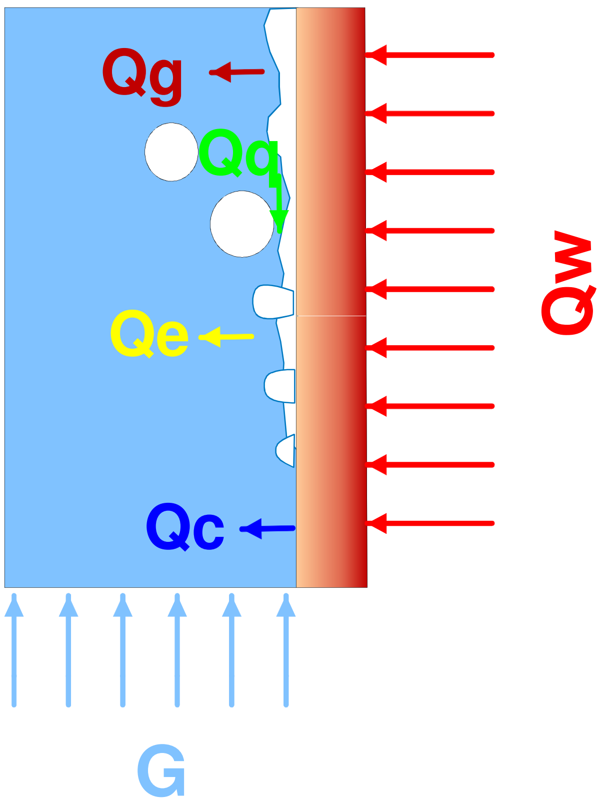
$$Q_W = f(\alpha_l) \cdot (Q_c + Q_q + Q_e) + (1 - f(\alpha_l)) \cdot Q_g$$

Q_c : single phase convection to liquid

Q_e : evaporation

Q_q : quenching

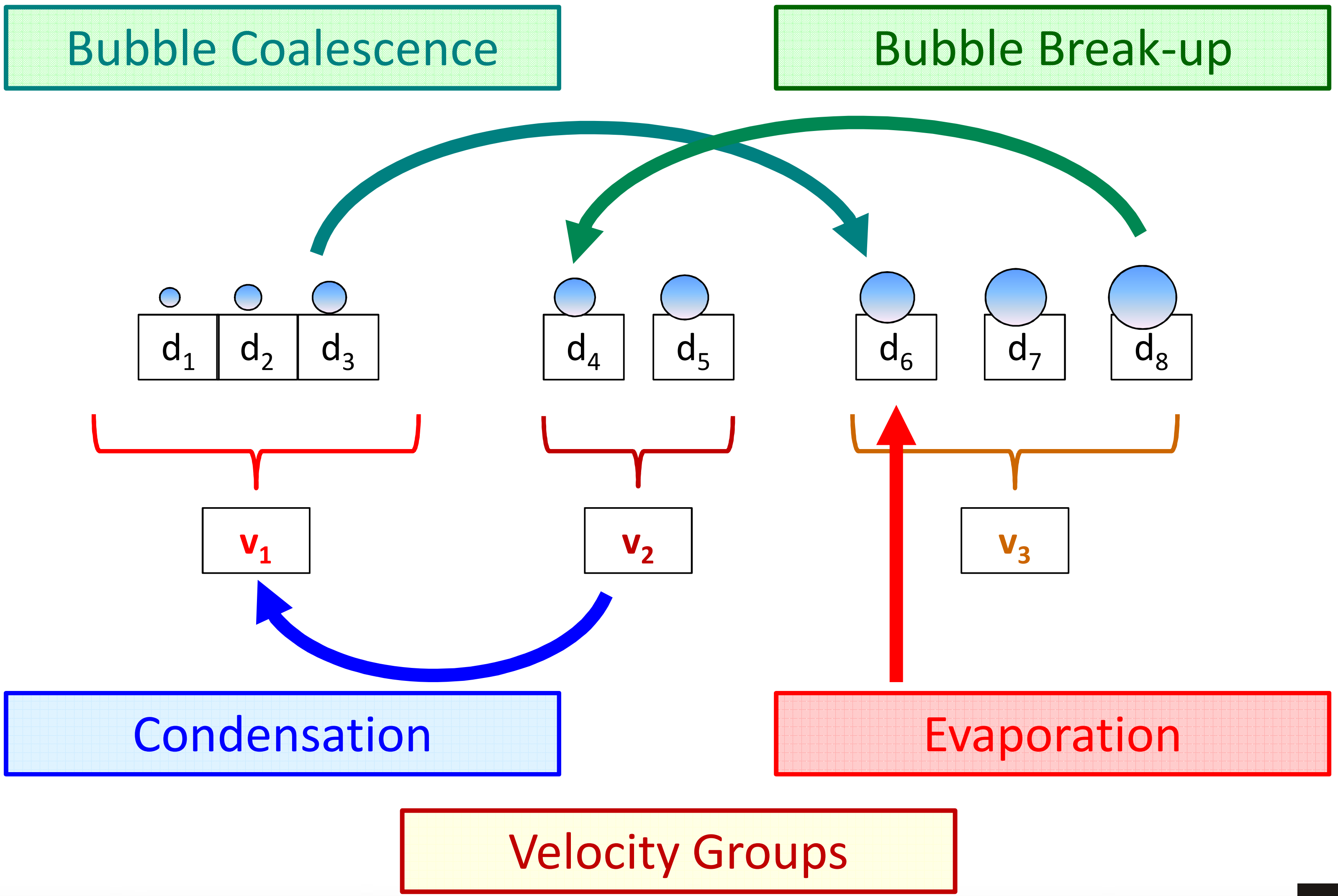
Q_g : single phase convection to gas



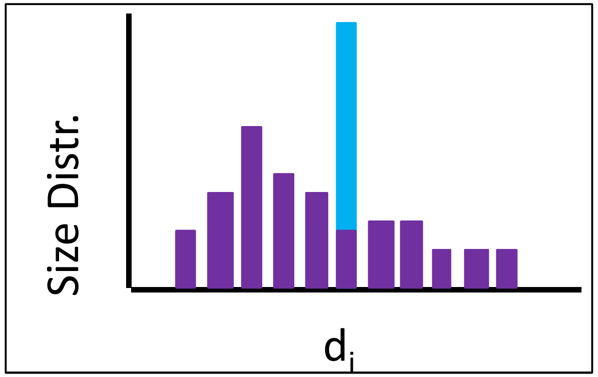
Model Formulation for CFD Simulation of CHF The MUSIG Model

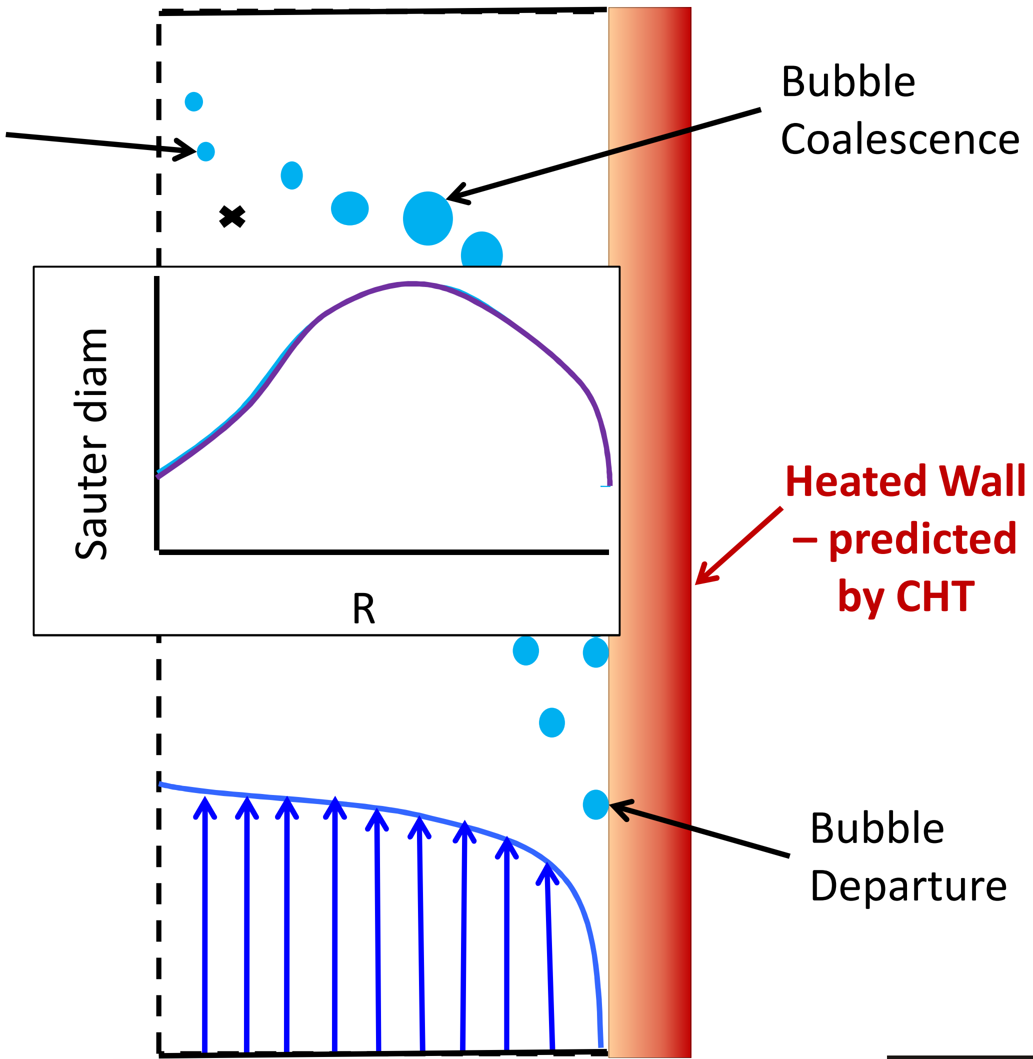
- MUSIG = Multiple Size Group Model
  - Discrete Population Balance Model for poly-dispersed flows
  - Particle size distribution is discretized by assigning bubbles to different 'size groups'
- Homogeneous MUSIG
  - Assumes single velocity field for all bubble classes (one dispersed phase)
  - Valid 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

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 turbulent dispersion 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	

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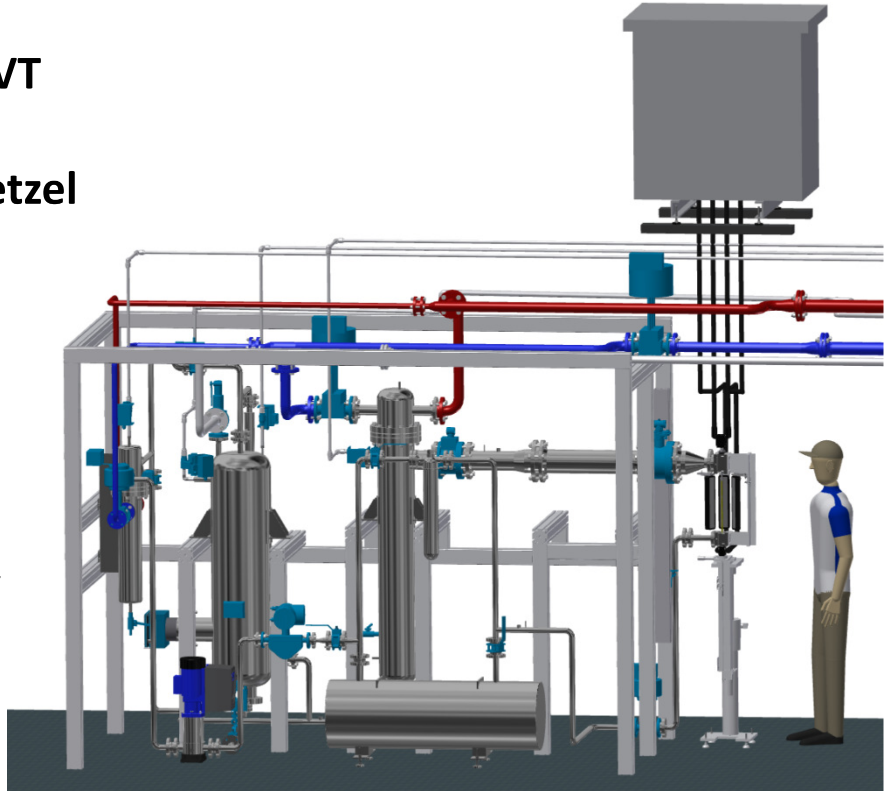
The COSMOS-L Test Facility (KIT/IKET)

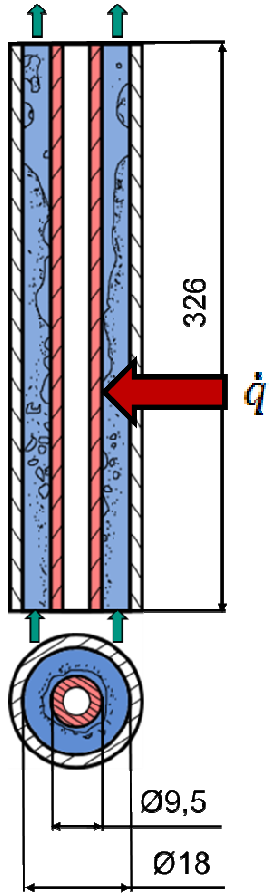
The COSMOS-L Test Facility (KIT)

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 .

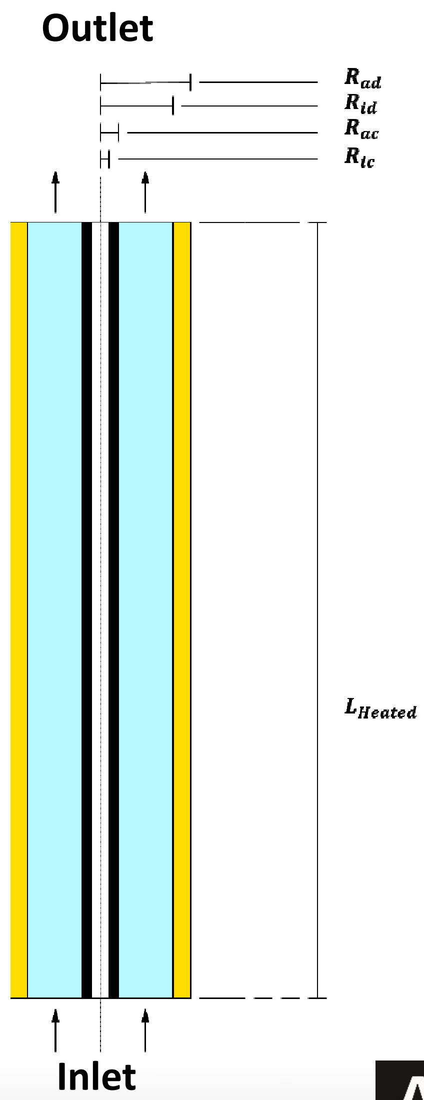


Images by courtesy of St. Gabriel & F. Kaiser (KIT)



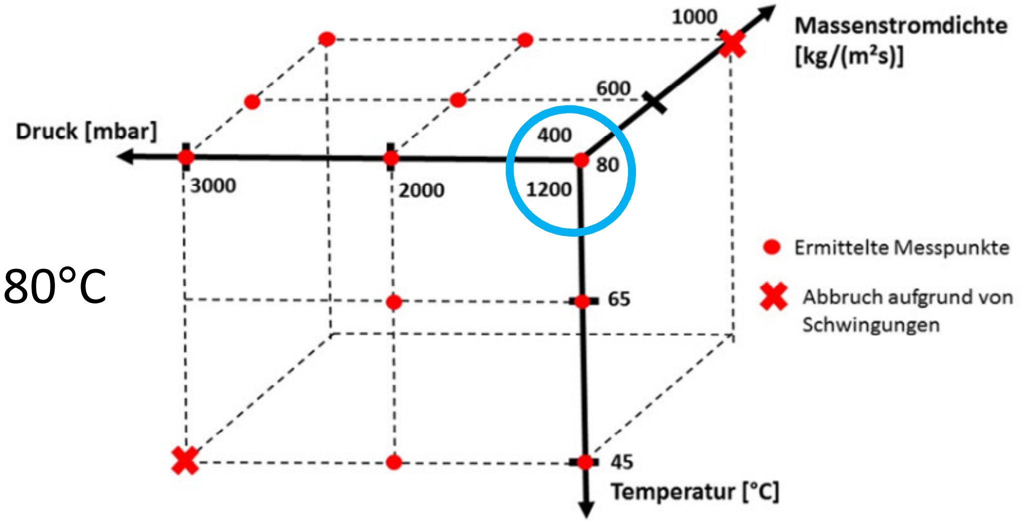
The COSMOS-L Test Facility (KIT)

- 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



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)

COSMOS-L: Polydispersed Fluid Resolution

- Two velocity groups with 26 size classes equidistantly distributed within each velocity groups
  - **20 size groups for the first velocity group**
    - Minimum diameter: 0.02 [mm]
    - The smallest observable bubble diameter been estimated by means of the provided HD videos to be around 0.1-0.2 [mm]
    - Bubble Departure Diameter (Lift-Off) according to Tolubinski et al. is approx. 0.4 mm
  - **6 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]

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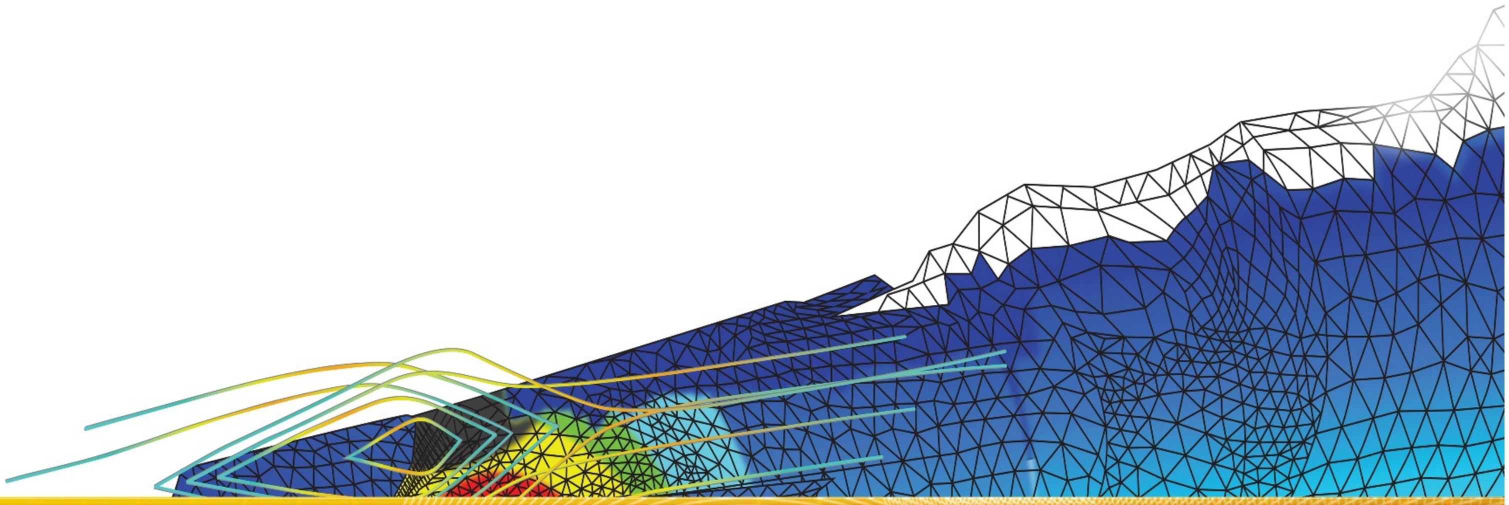
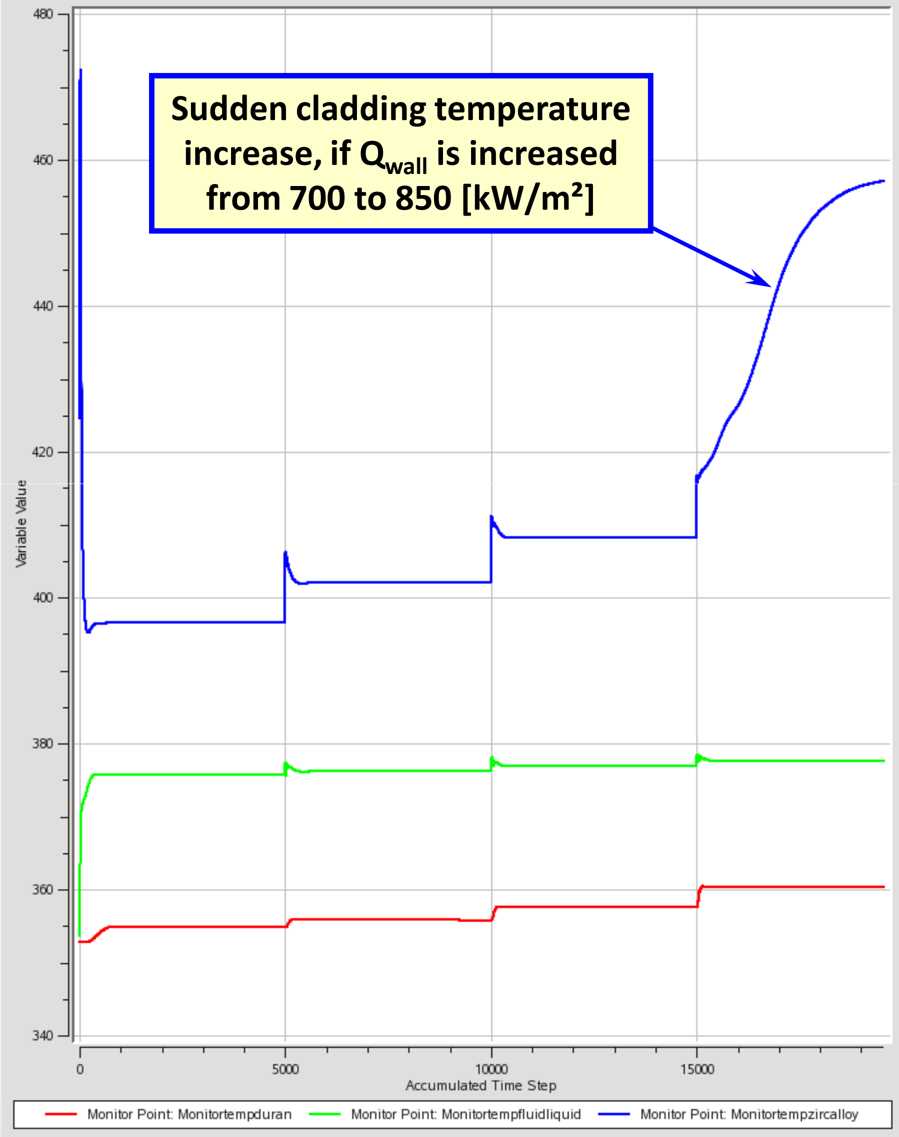
T80P1200M400

(Reference Case)

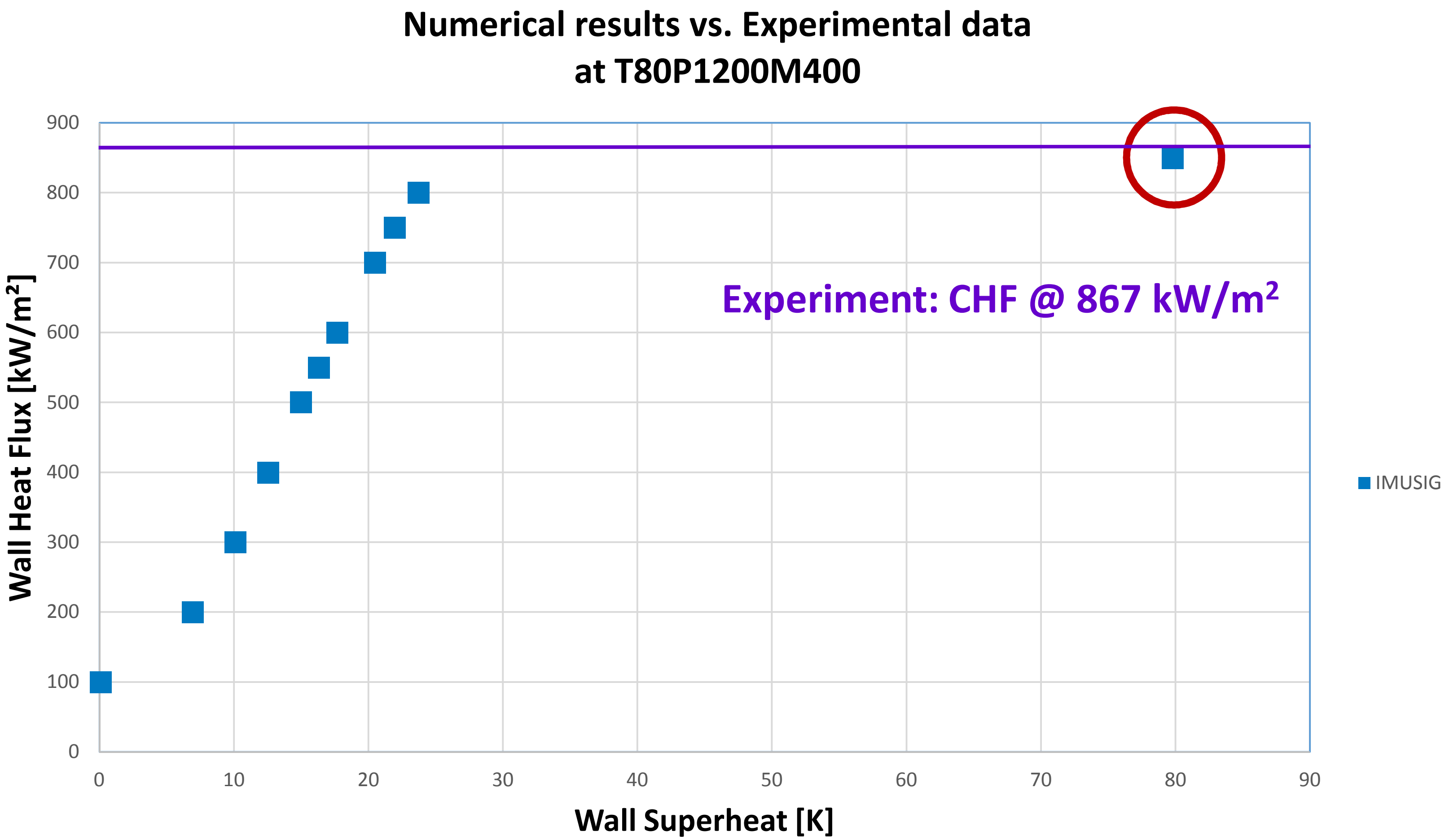


The COSMOS-L Test Facility (KIT)
T80P1200M400: CHF at Q_{wall} = 850 [kW/m²]

- 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]

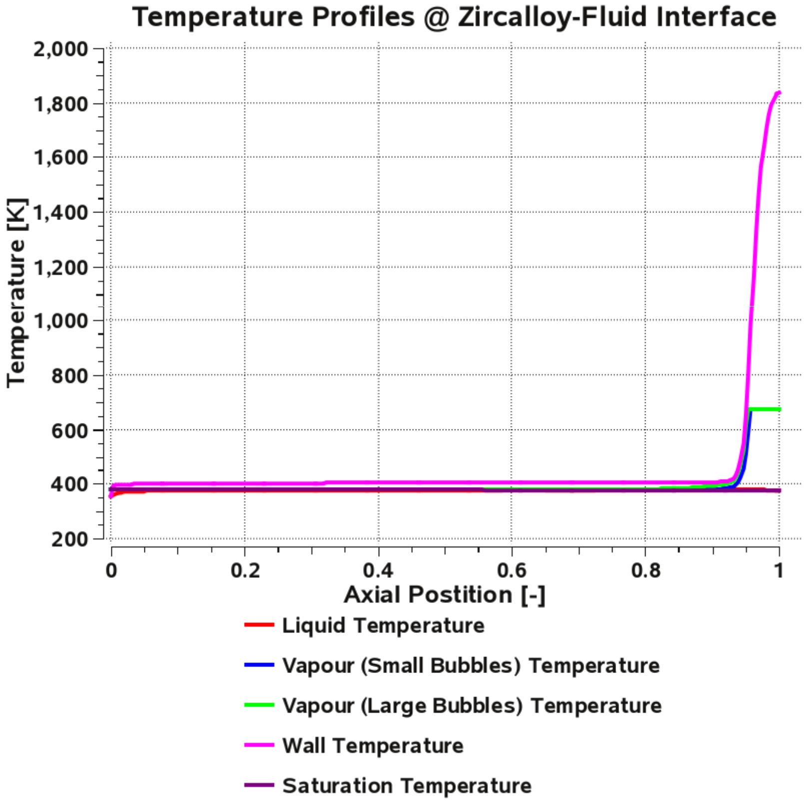


The COSMOS-L Test Facility (KIT)
T80P1200M400: The Boiling Curve



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

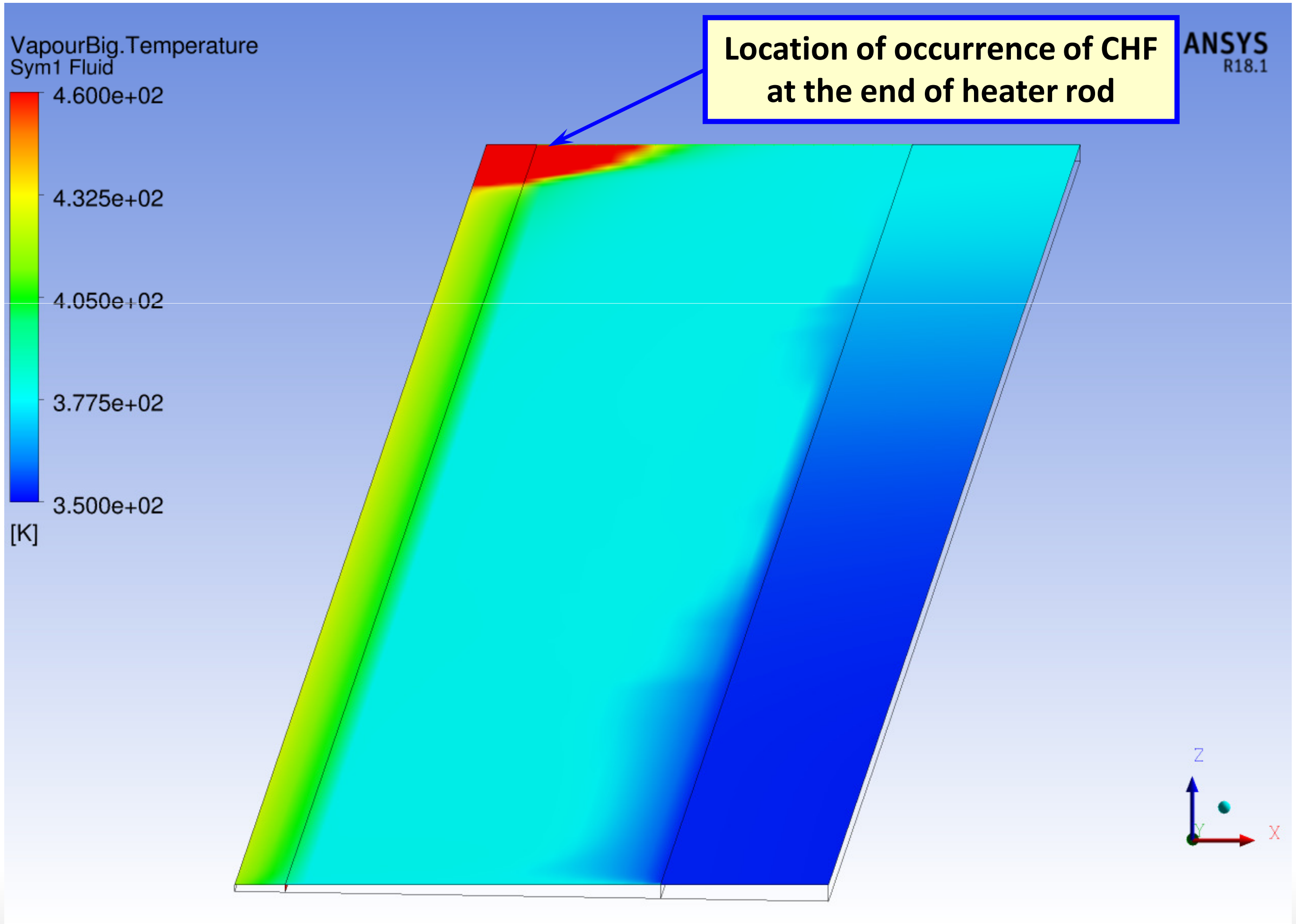
- The experimentally measured heat flux at which CHF occurs is about 867 [kW/m²] with a standard deviation equal to 16 [kW/m²]
- This is in good agreement with the ANSYS CFX results
  - Temperature excursion in the ZircAlloy heater rod obtained @ 850 [kW/m²] in the simulations
  - Liquid cooling of ZircAlloy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



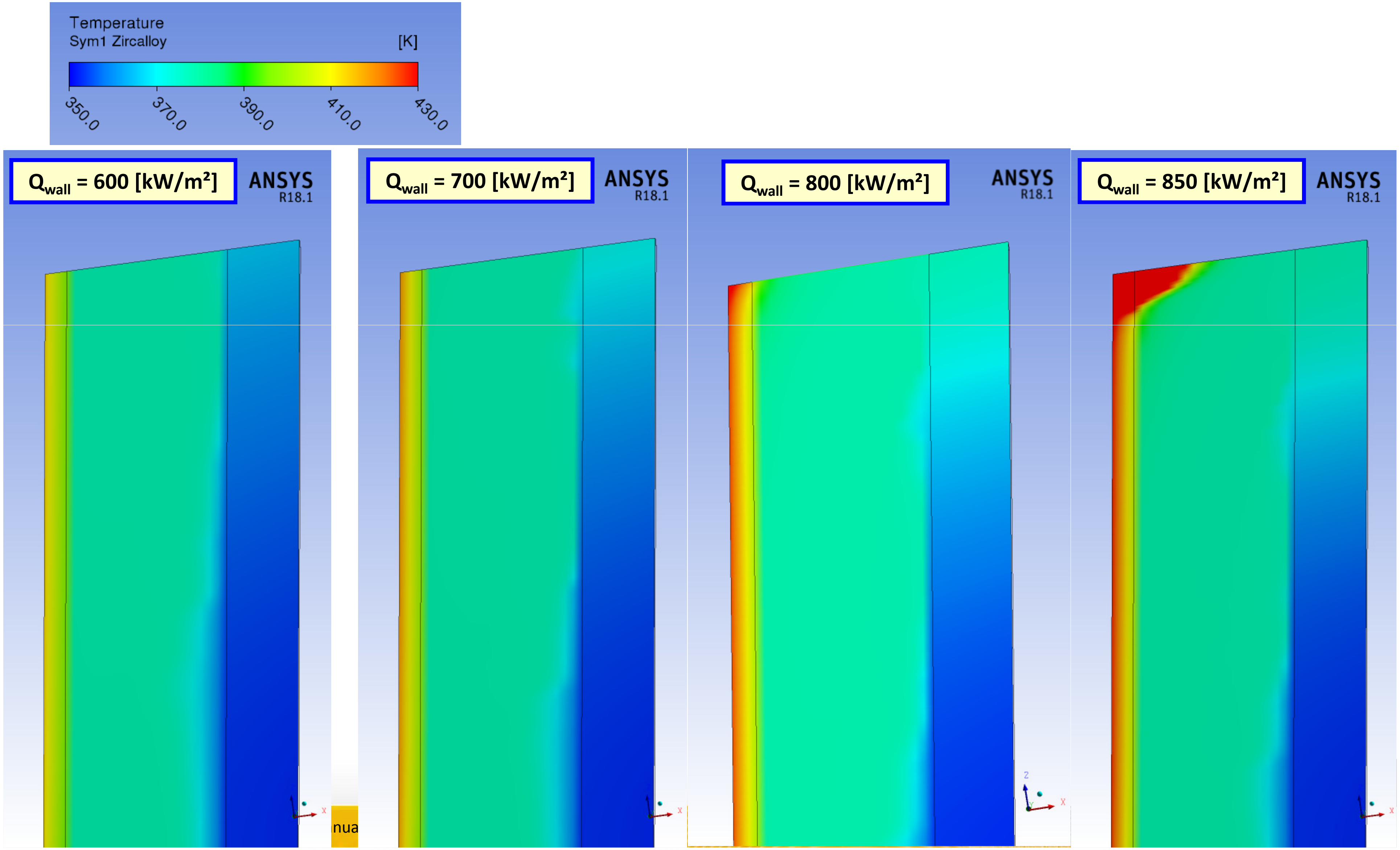
T80P1200M400
@ 850 [kW/m2]

CHF at Q_{wall} = 850 [kW/m²]

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

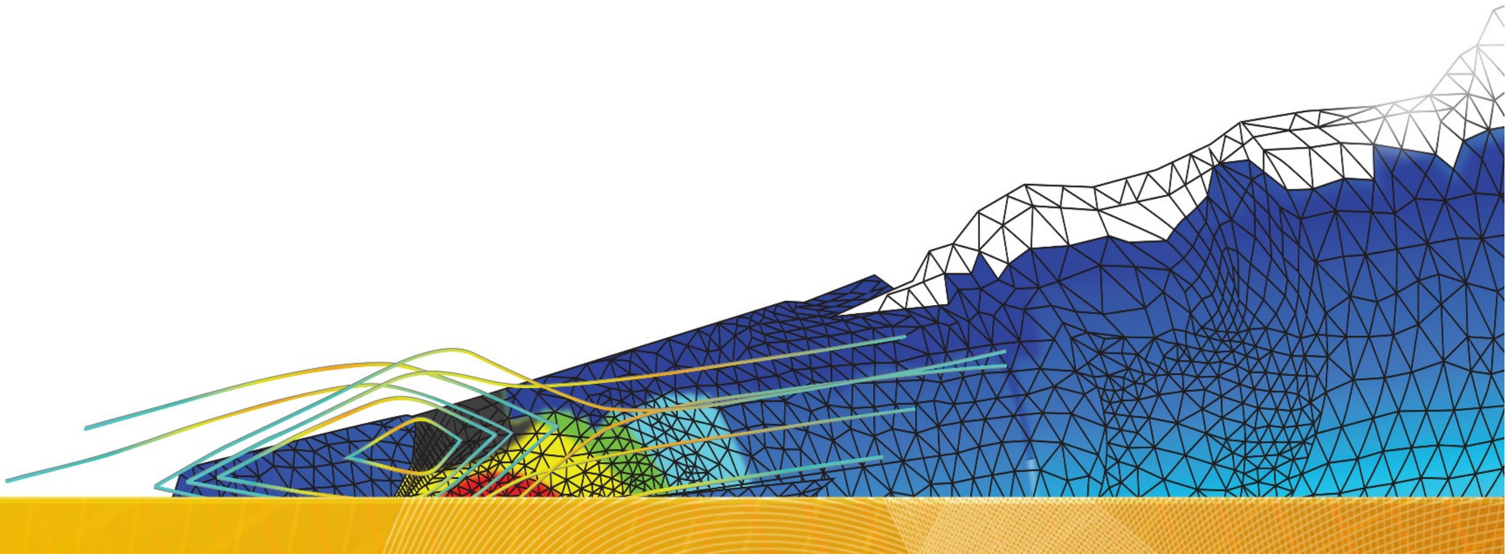


Temperature Distribution with Increased Wall Heat Flux : 600 [kW/m²] → 850 [kW/m²]

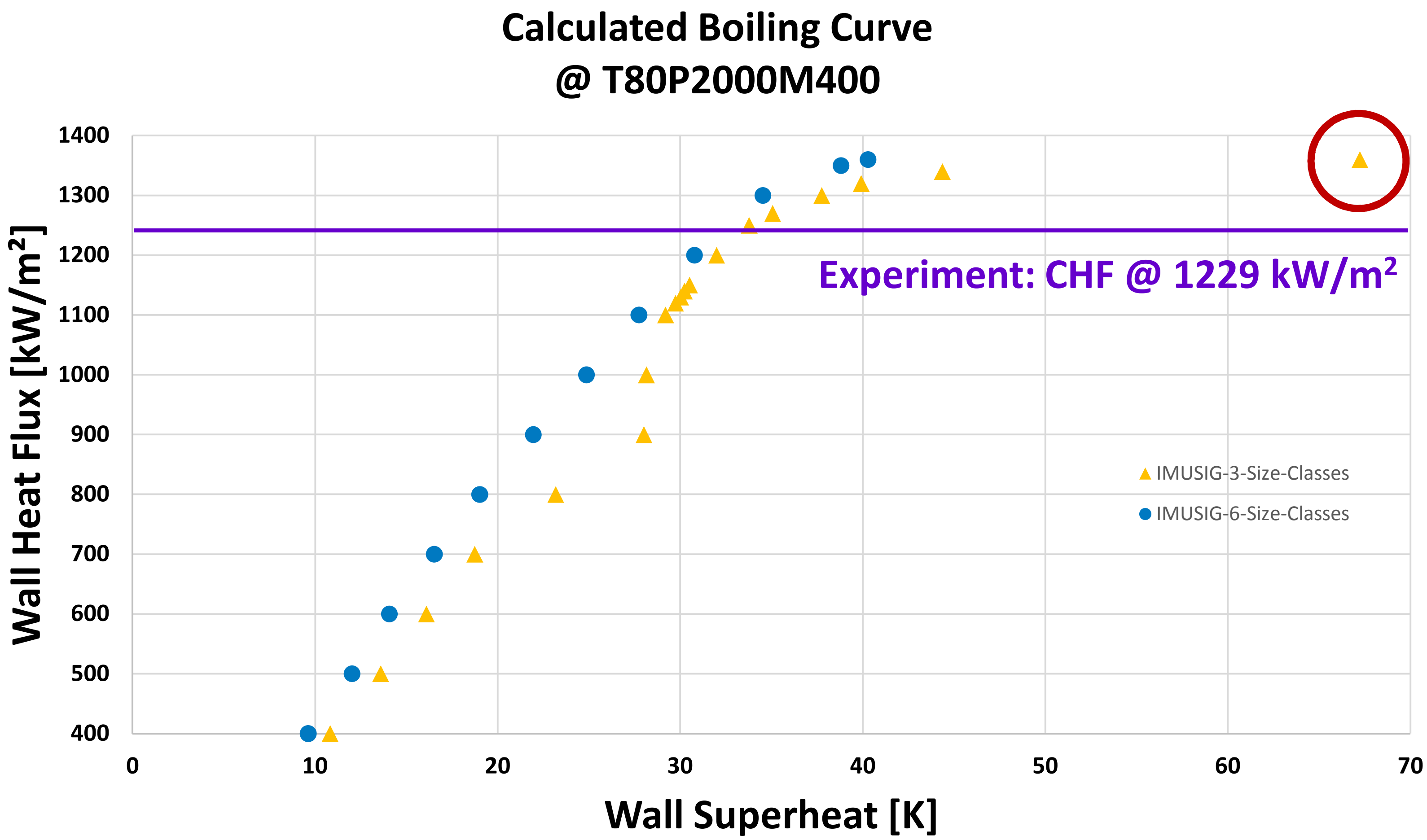


T80P2000M400

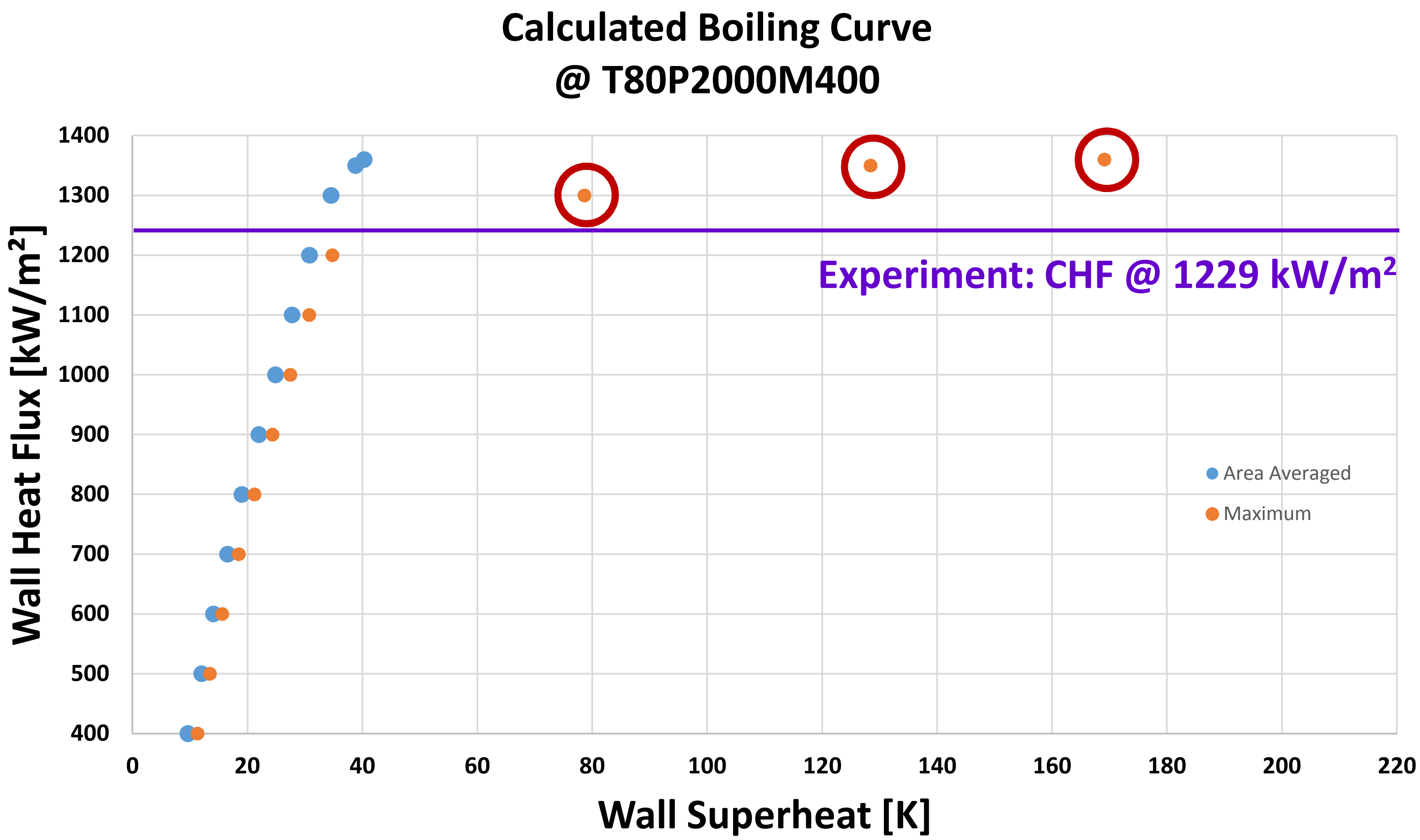
(Reference Pressure Variation)



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

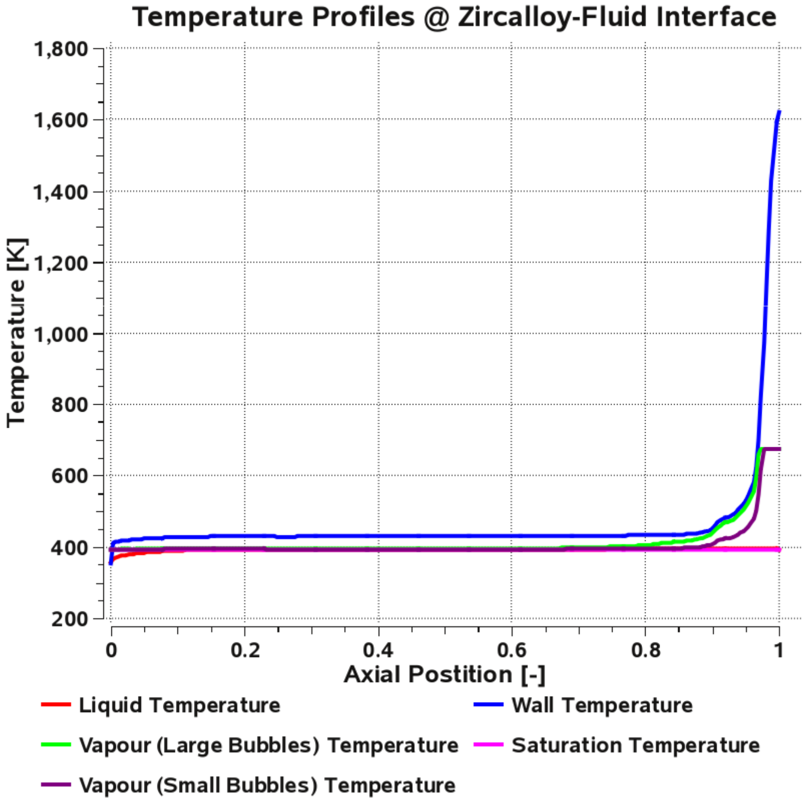


The COSMOS-L Test Facility (KIT)
T80P2000M400 Boiling Curve – Avg./Max. T_{Wall}



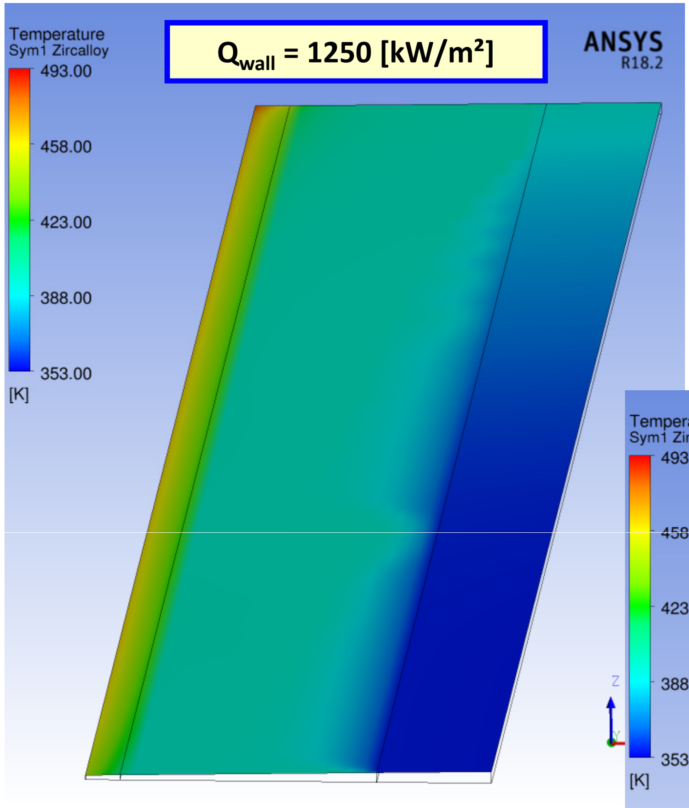
The COSMOS-L Test Facility (KIT)
T80P2000M400 - CHF Comparison

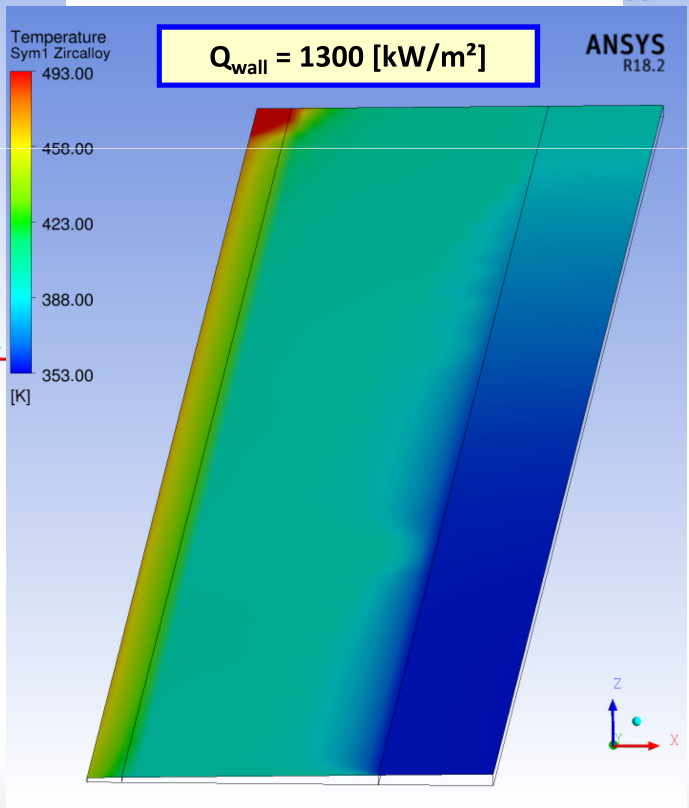
- The experimentaly measured heat flux at which CHF occurs is about 1229 [kW/m²] with a standard deviation equal to 9 [kW/m²]
- This is in good agreement with the ANSYS CFX results
  - Temperature excursion in the Zircalloy heater rod obtained @ approx. 1300 [kW/m²] in the simulations
  - Liquid cooling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

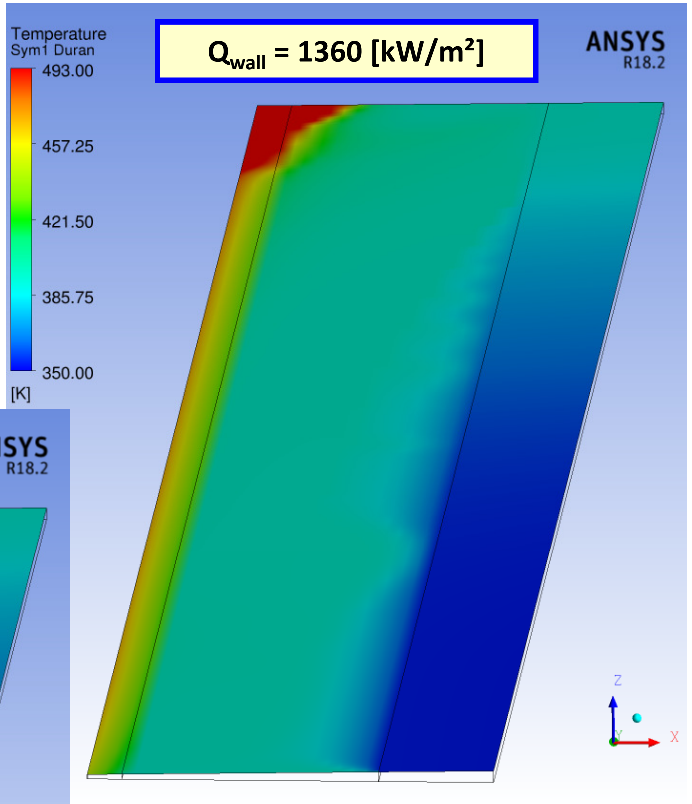


T80P2000M400
@ 1360 [kW/m2]

T80P2000M400: Temperature Distribution







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

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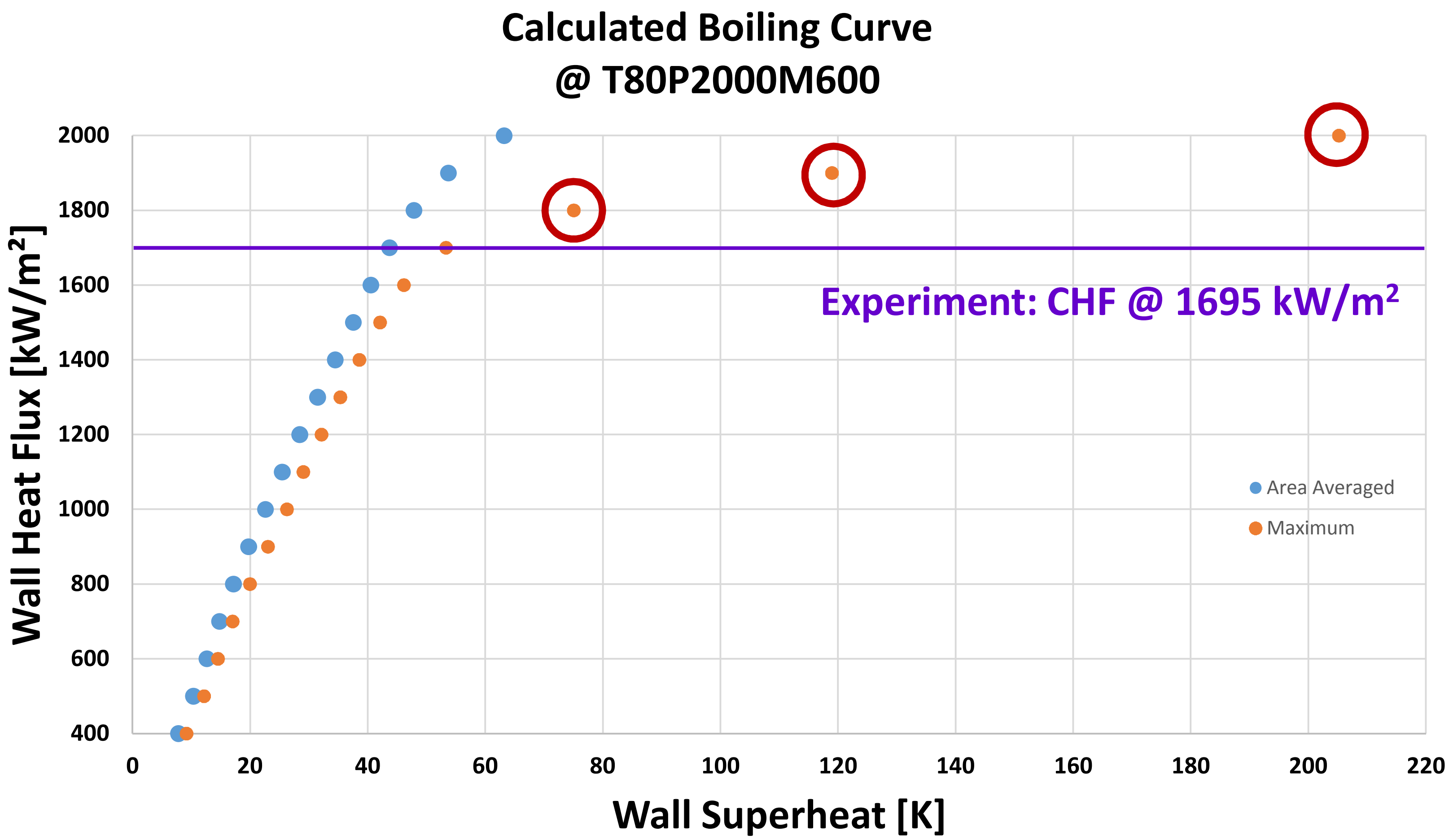
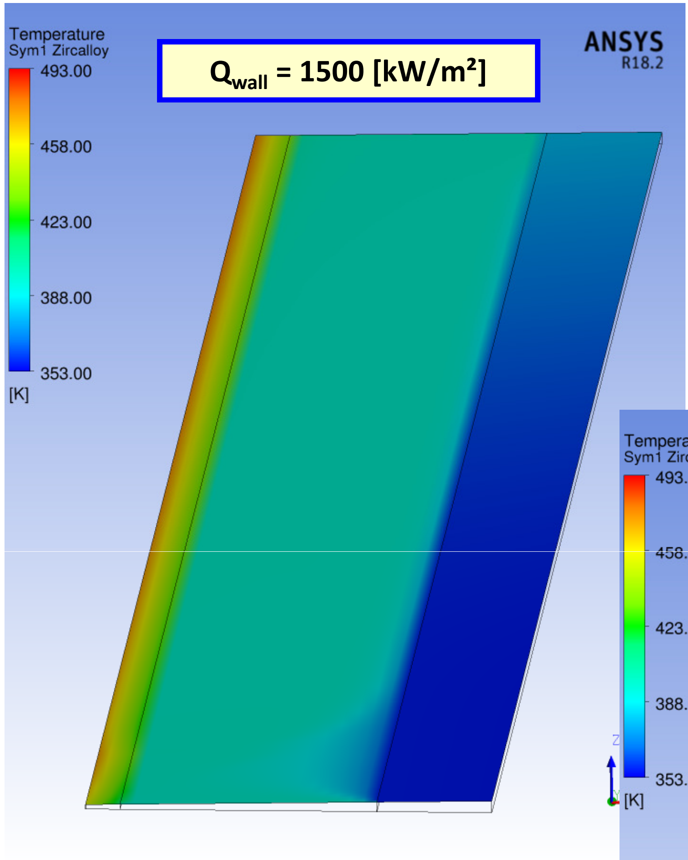
T80P2000M600

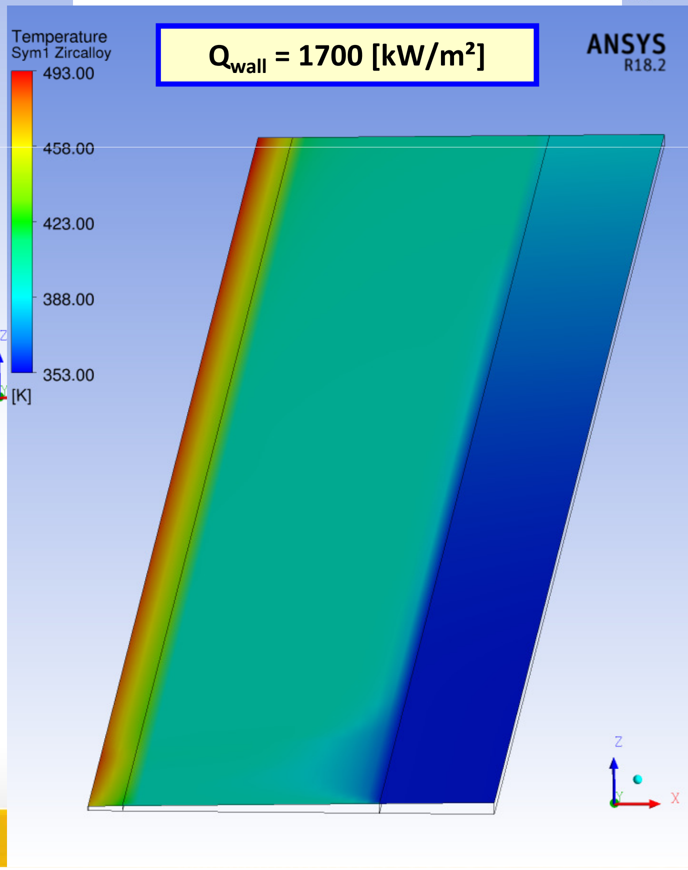
(Reference Pressure and
Fluid Mass Flow Rate Variation)

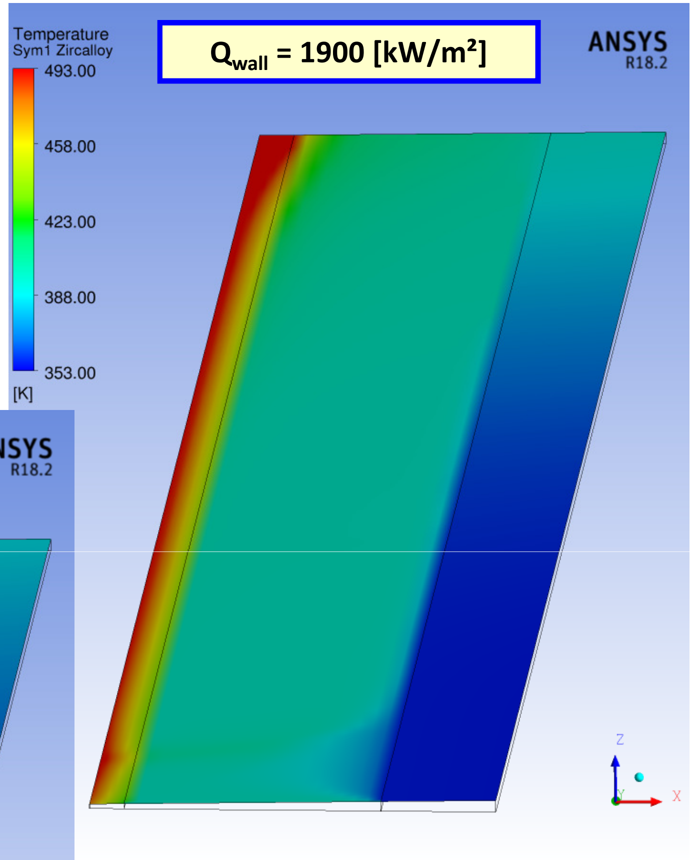
The COSMOS-L Test Facility (KIT)
T80P2000M600 Boiling Curve – Avg./Max. T_{Wall}



T80P2000M600: Temperature Distribution







Experimentally measured CHF value:
Q_{wall} = 1695 [kW/m²]

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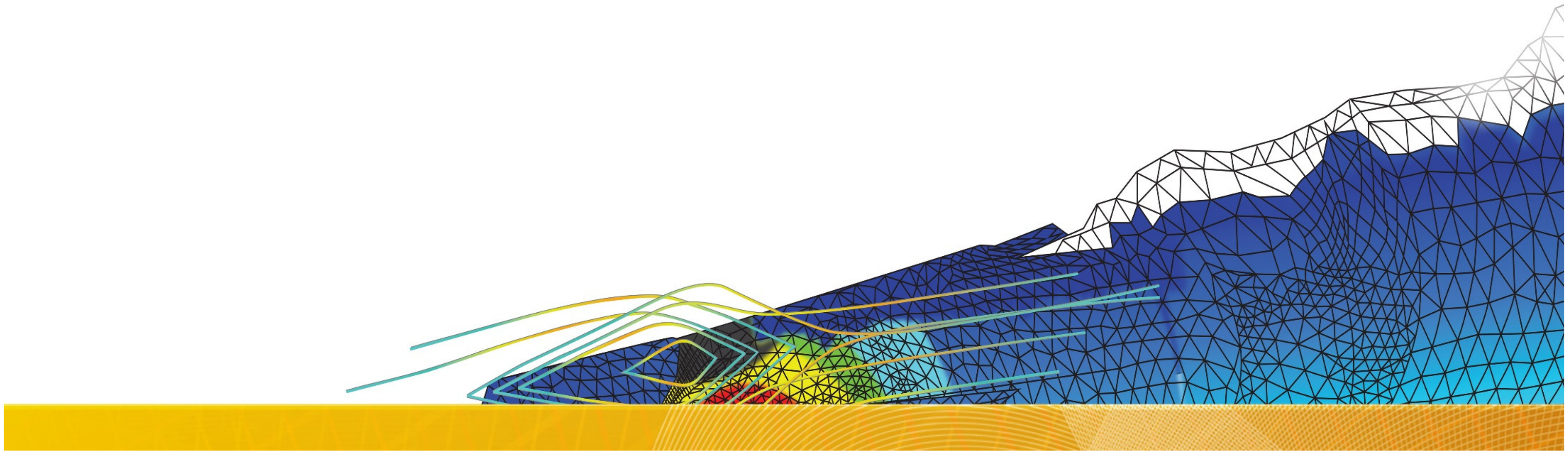
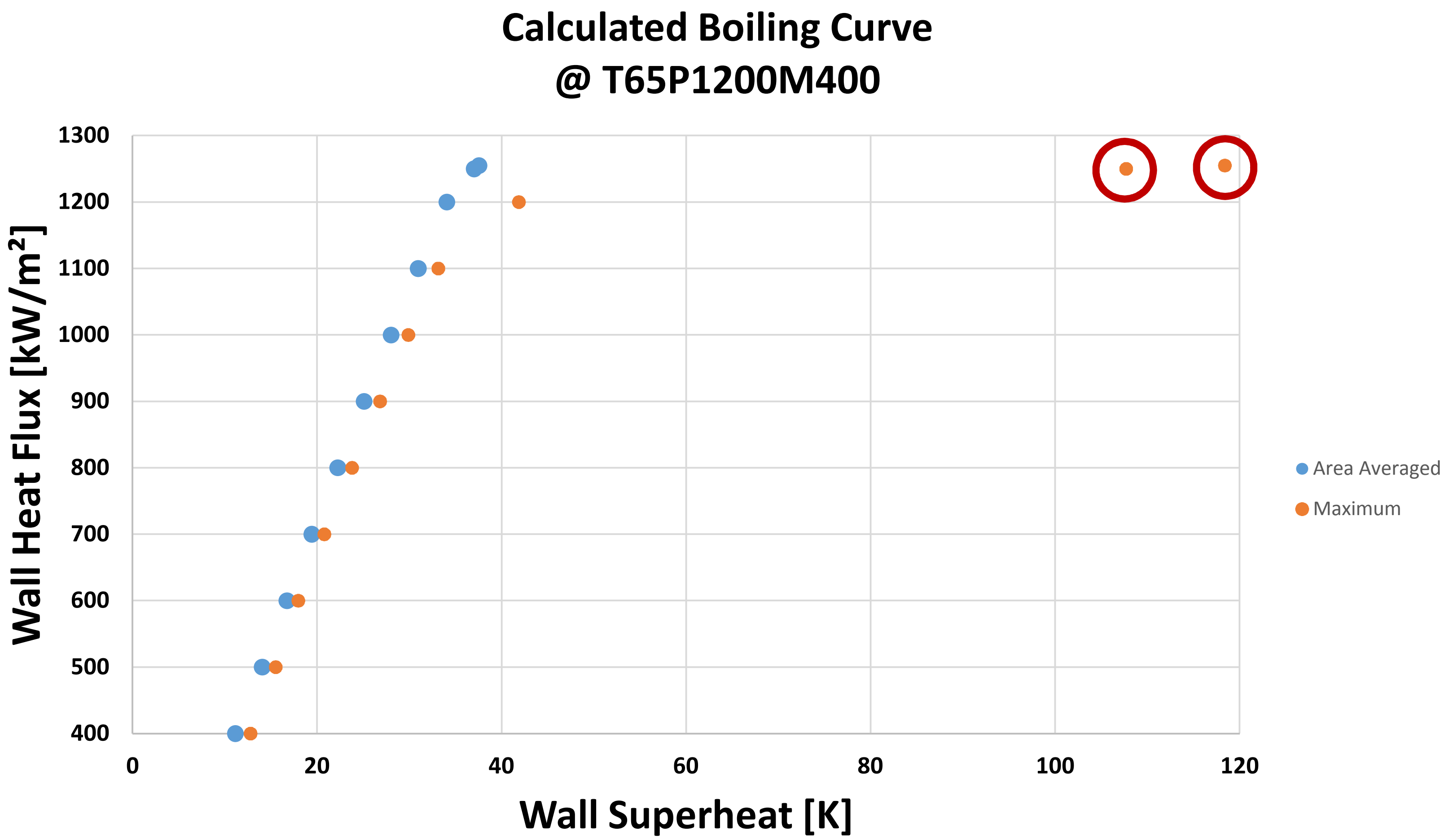
T65P1200M400

(Fluid Subcooling Temperature Variation)



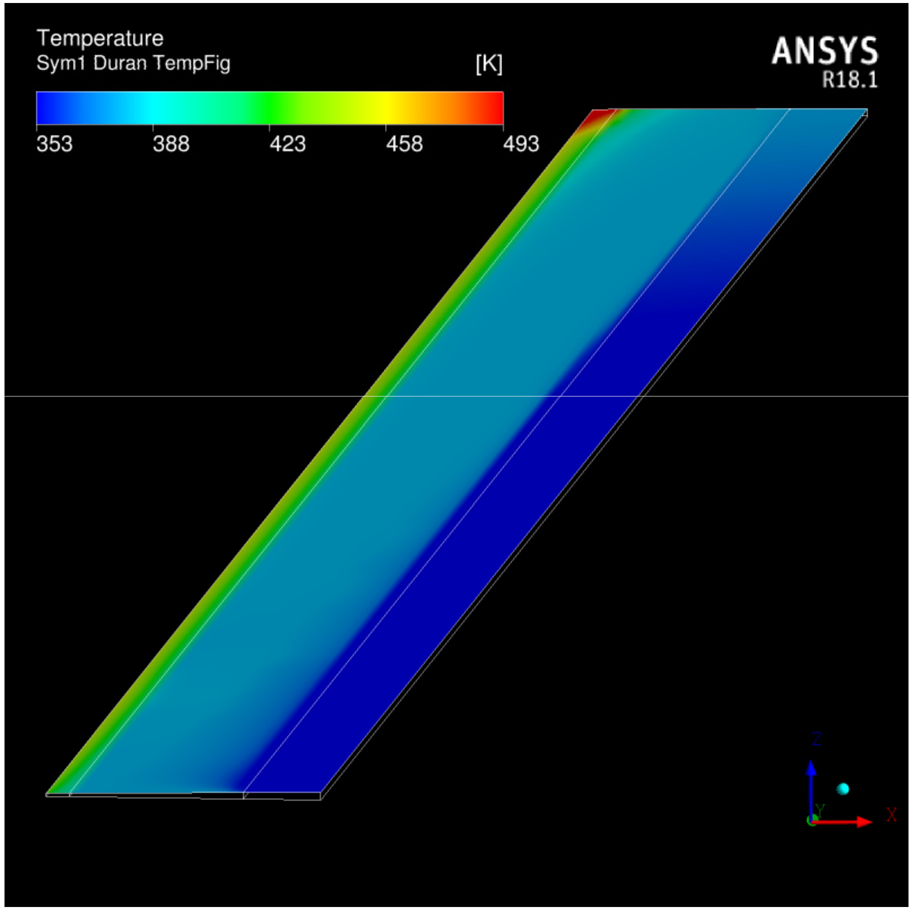
The COSMOS-L Test Facility (KIT)
T65P1200M400 Boiling Curve – Avg./Max. T_{Wall}



ANSYS

T65P1200M400 Temperature Distribution

- Due to the thinned vapor layer at the wall this case required the increase of the resolution of the number of classes for the velocity group of large bubbles from 3 to 6
- Maximum wall temperature is reached as in all other cases towards the outlet of the annular test section of COSMOS-L
- The wall and vapor temperature excursion was finally predicted for applied wall heat fluxes beyond 1255 [kW/m²]



T65P1200M400_H1255

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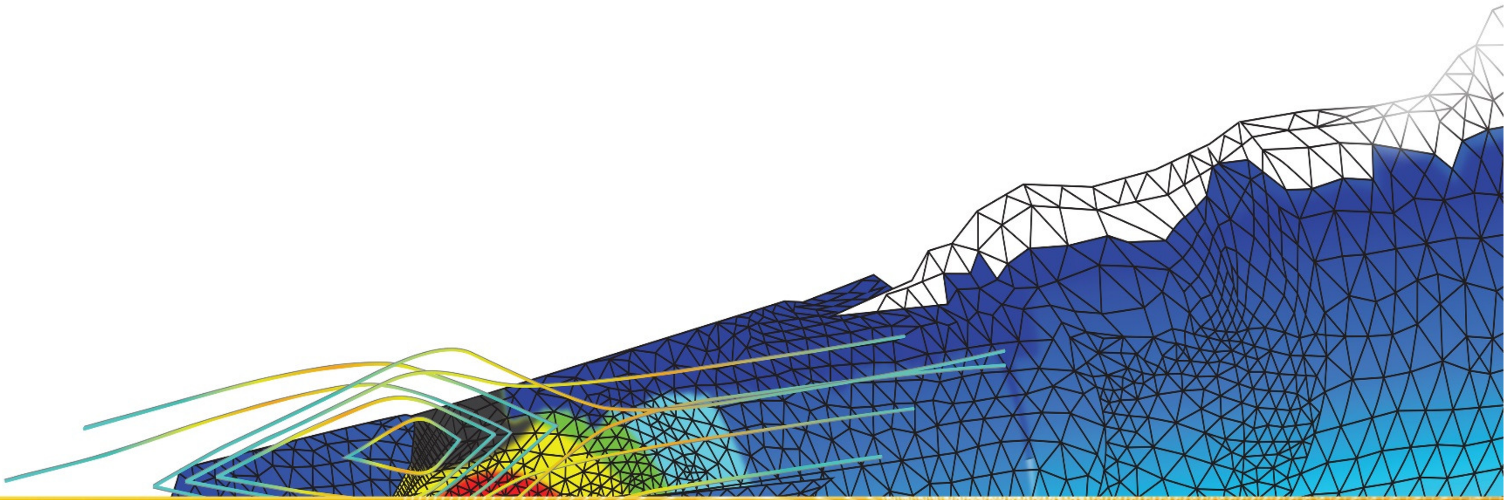

Concluding Remarks and Outlook

- 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 the boiling curve up to CHF for 4 experimental series from COSMOS-L (KIT) test facility
  $\Rightarrow$ CHF detection by temperature excursion in the heater CHT domain
- 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
  - Flow regime transition $\Leftrightarrow$ Multiphase flow turbulence modeling
  - Extraordinary thin vapor layers at high liquid subcooling / high liquid mass flux

Acknowledgement

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für Wirtschaft
und Technologie

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in the framework of the German CFD Network on Nuclear Reactor Safety Research and Alliance for Competence in Nuclear Technology, Germany.

ANSYS

