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:

\[ Q_W = f(\alpha_i) \cdot (Q_c + Q_q + Q_e) + (1 - f(\alpha_i)) \cdot Q_g \]

- \( Q_c \) : 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

Bubble Coalescence

Bubble Break-up

Condensation

Evaporation

Velocity Groups
Model Formulation for CFD Simulation of CHF
MUSIG + Wall Boiling

Homogeneous / Inhomogeneous MUSIG Model

Vapor Bubble Condensation

Bubble Coalescence

Heated Wall – predicted by CHT

Bubble Departure

Size Distr. $d_i$

Sauter diam

R

$\Delta > \Delta$
$\Delta - \Delta + \Delta - \Delta$
$\Delta - \Delta$
$\Delta < \Delta < \Delta$
$\Delta - \Delta$

Kurul & Podowski
## CFD Setup Characteristics – iMUSIG

### Extended RPI wall boiling model ↔ Inhomogeneous MUSIG ↔ CHT

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

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

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<th>Material</th>
<th>IAPWS IF97</th>
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<tr>
<td>Minimum Temperature</td>
<td>50 [C]</td>
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<tr>
<td>Maximum Temperature</td>
<td>400 [C]</td>
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<td>Minimum Absolute Pressure</td>
<td>0.8 [bar]</td>
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<td>Maximum Absolute Pressure</td>
<td>2 [bar]</td>
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<td>Number of Points</td>
<td>600</td>
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- 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 group
  - 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]
T80P1200M400
(Reference Case)
The COSMOS-L Test Facility (KIT)

T80P1200M400: CHF at $Q_{\text{wall}} = 850 \, [kW/m^2]$

- Cladding temperature excursion (mean domain temperatures are monitored)
- Previous simulation runs show restarts from:
  - $Q_{\text{wall}} = 400 \, [kW/m^2]$
    - $Q_{\text{wall}} = 550 \, [kW/m^2]$
    - $Q_{\text{wall}} = 700 \, [kW/m^2]$
    - $Q_{\text{wall}} = 850 \, [kW/m^2]$
- $Q_{\text{wall}} = 800 \, [kW/m^2]$ does not yet show this strong cladding temperature increase but behaves like the 700-er case with $T_{\text{wall}} \approx 408.2 \, [K]$
  - $\text{mean } T_{\text{wall}} \text{ increase by } \approx 50 \, [K]$
The COSMOS-L Test Facility (KIT) T80P1200M400: The Boiling Curve

Numerical results vs. Experimental data at T80P1200M400

Experiment: CHF @ 867 kW/m$^2$
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.
CHF at $Q_{\text{wall}} = 850$ [kW/m$^2$]

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

![Diagram showing the location of occurrence of CHF at the end of heater rod](image)
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

Calculated Boiling Curve
@ T80P2000M400

Experiment: CHF @ 1229 kW/m²

Wall Heat Flux [kW/m²]

Wall Superheat [K]

- IMUSIG-3-Size-Classes
- IMUSIG-6-Size-Classes
The COSMOS-L Test Facility (KIT)
T80P2000M400 Boiling Curve – Avg./Max. $T_{\text{Wall}}$

Calculated Boiling Curve
@ T80P2000M400

Experiment: CHF @ 1229 kW/m$^2$
The experimentally measured heat flux at which CHF occurs is about $1229 \text{ [kW/m}^2\text{]}$ with a standard deviation equal to $9 \text{ [kW/m}^2\text{]}$

- This is in good agreement with the ANSYS CFX results
  - Temperature excursion in the Zircalloy heater rod obtained @ approx. $1300 \text{ [kW/m}^2\text{]}$ in the simulations
  - Liquid cooling of ZircAlloy cladding breaks down at the very end of the heater rod
T80P2000M400: Temperature Distribution

Experimentally measured CHF value:

\[ Q_{\text{wall}} = 1229 \text{ [kW/m}^2\text{]} \]
T80P2000M600
(Reference Pressure and Fluid Mass Flow Rate Variation)
The COSMOS-L Test Facility (KIT) T80P2000M600 Boiling Curve – Avg./Max. $T_{\text{Wall}}$

Calculated Boiling Curve @ T80P2000M600

Experiment: CHF @ 1695 kW/m²
**T80P2000M600: Temperature Distribution**

- **$Q_{wall} = 1500 \text{ [kW/m}^2\text{]}$**
- **$Q_{wall} = 1700 \text{ [kW/m}^2\text{]}$**
- **$Q_{wall} = 1900 \text{ [kW/m}^2\text{]}$**

Experimentally measured CHF value:

$Q_{wall} = 1695 \text{ [kW/m}^2\text{]}$
T65P1200M400

(Fluid Subcooling Temperature Variation)
The COSMOS-L Test Facility (KIT)
**T65P1200M400 Boiling Curve – Avg./Max. $T_{\text{Wall}}$**

Calculated Boiling Curve
@ T65P1200M400

Wall Heat Flux [kW/m²] vs. Wall Superheat [K]

- **Area Averaged**
- **Maximum**
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].
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
  ⇒ 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 ⇔ Multiphase flow turbulence modeling
  – Extraordinary thin vapor layers at high liquid subcooling / high liquid mass flux
Acknowledgement

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