Development and Validation of the Wall Boiling Model in ANSYS CFD

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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

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CFD Simulation for Fuel Assemblies in Nuclear Reactors

- Material Properties
- Wall Boiling & Bulk Condensation
- Conjugate Heat Transfer (CHT)
- FSI: Stresses & Deformations
- Multiphase Flow Modeling
- Turbulence

Validation against Experiments
Multiphase Flow Regimes for Boiling Water Flow

- subcooled flow
- bubbly flow
- slug flow
- annular flow
- spray flow

ONB OSB

T

T_{\text{sat}}

wall temperature

mean fluid temperature

subcooled boiling

nucleate boiling (saturated boiling)
Mechanistic wall heat partitioning model:

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

- **Convective heat flux**
  \[ \dot{q}_F = A_1 \cdot \dot{h}_F \cdot (T_W - T_L) \]

- **Quenching heat flux**
  \[ \dot{q}_Q = A_2 \cdot \dot{h}_Q \cdot (T_W - T_L) \]

- **Evaporation heat flux**
  \[ \dot{q}_E = \dot{m} \cdot (h_G - h_L) \]
• 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
  \[
  \dot{q}_E = \dot{m} \cdot (h_G - h_L)
  \]
  \[
  \dot{m} = \frac{\pi d_W^3}{6} \rho_G f n
  \]
  \[
  d_W = \min \left\{ 1.4 \text{mm}, 0.6 \text{mm} \cdot \exp \left( - \frac{T_s [\text{K}] - T_L [\text{K}]}{45 [\text{K}]} \right) \right\}
  \]
  
- small quenching & overestimated evaporation on fine grids
- wrong heat flux partitioning

\[\rightarrow\] 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

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

• additional factor in correlations for \( d_W, \dot{q}_F, \dot{q}_Q \)

• assumption of \( y^+_{\text{const}} = 250 \); model parameter

• Replace \( (T_W - T_L) \) in submodel expressions with the above relation
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

#### Mass Transfer
- **Option:** Phase Change
- **Saturation Temperature:** [SatTemper]
- **Wall Boiling Model:** RPI Model
- **Fixed Value for Liquid Subcooling** (optional)
- **Mass Source Under Relaxation** (optional)
- **Bubble Departure Diameter** (optional)
- **Wall Nucleation Site Density** (optional)
- **Bubble Detachment Frequency** (optional)
- **Bubble Waiting Time** (optional)
- **Liquid Quenching Heat Transfer Coefficient** (optional)
- **Bubble Diam. Influence Factor** (optional)
- **Max. Area Frac. of Bubble Influence** (optional)

#### Heat Transfer
- **Option:** Two Resistance
- **Liquid Heat Transfer:** Ranz Marshall
- **Vapour Heat Transfer:** Zero Resistance

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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)
• 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

- 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
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 = Han 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
END
MASSTransfer:
Option = Phase Change
PHASE CHANGE MODEL:
Option = Thermal Phase Change
END
WALL BOILING MODEL:
Bubble Diameter Influence Factor = 2.0
Fixed Volus for Liquid Subcooling = 250.0
Minimum Area Fraction of Dambo Influence = 1.0
Option = RPI Model
END
END
BUBBLE DEPARTURE DIAMETER:
Liquid Subcooling Scale = 45.8 [K]
Maximum Departure Diameter = 1.4E-3 [m]
Option = Tolubinski Kostanchuk
Reference Departure Diameter = 8.6E-3 [m]
END
END
BUBBLE DETACHMENT FREQUENCY:
Drag Coefficient = 1
Option = Terminal Velocity over Departure Diameter
END
END
BUBBLE WITTING TIME:
Option = Proportional to Detachment Period
Waiting Time Fraction = 0.8
END
END
LIQUID QUENCHING HEAT TRANSFER COEFFICIENT:
Option = Del Valle Kenning
END
PARTITIONING AREA FRACTIONS:
Convective Area = a1
Evaporative Area = 0.8
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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>4.5 MPa</td>
</tr>
<tr>
<td>R</td>
<td>7.7 mm</td>
</tr>
<tr>
<td>$G_{in}$</td>
<td>900 kg/(s m²)</td>
</tr>
<tr>
<td>$\dot{q}$</td>
<td>0.57 MW/m²</td>
</tr>
<tr>
<td>Subcooling</td>
<td>58.2 K</td>
</tr>
</tbody>
</table>

$R = 7.7$ mm

$G_{in} = 900$ kg/(s m²)

$q = 0.57$ MW/m²
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
• **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
• Validation on mesh hierarchy with regular refinement factor of 4 (2d meshes)

<table>
<thead>
<tr>
<th>Grid</th>
<th>Grid1</th>
<th>Grid2</th>
<th>Grid3</th>
</tr>
</thead>
<tbody>
<tr>
<td># Nodes (uniform)</td>
<td>20x150</td>
<td>40x300</td>
<td>80x600</td>
</tr>
<tr>
<td>Max $y^+$</td>
<td>264</td>
<td>133</td>
<td>69</td>
</tr>
<tr>
<td>$\Delta t$ [s]</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$5\times10^{-4}$</td>
</tr>
</tbody>
</table>
Grid 2

Liquid Temperature
Plane 1

Gas Volume Fraction
Plane 1

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ANSYS, Inc. Proprietary
Grid 3

Liquid Temperature
Plane 1
- 5.300e+02
- 5.150e+02
- 5.000e+02
- 4.850e+02
- 4.700e+02
[K]

Gas Volume Fraction
Plane 1
- 5.000e-01
- 3.750e-01
- 2.500e-01
- 1.250e-01
- 0.000e+00
Comparison to Experimental Data

Mean Temperature

Void Fraction

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Comparison to Experimental Data - Parameter & Model Variation

Influence of wall heat flux:

Influence of wall lubrication force model:

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The Bartolomej et al. Testcase with Recondensation (Bartolomeij et al. (1980))
• **Geometry**
  - Pipe flow; axial symmetry
  - Inner radius of pipe $R = 6.015 \text{ mm}$
  - Total pipe length $L_T = 1.4 \text{ m}$
  - Heated section length $L_H = 1.0 \text{ m}$

• **Flow parameters**
  - Upward directed water flow
  - Pressure @Inlet $p_{in} = 6.89 \text{ Mpa}$
  - 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:

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>$q_{\text{Wall}}$ [MW m$^{-2}$]</th>
<th>$G_{\text{in}}$ [kg m$^{-2}$ s$^{-1}$]</th>
<th>$T_{\text{in}}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.2</td>
<td>1500</td>
<td>495</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>1500</td>
<td>519</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>1000</td>
<td>503</td>
</tr>
</tbody>
</table>
Experiment No. 3 (Mesh01)

- Distribution of water temperature and steam volume fraction
Experiment No. 3 (Mesh02)

- Distribution of water temperature and steam volume fraction

![Liquid Temperature Plane 1]

- Liquid Temperature Plane 1:
  - 5.590e+02
  - 5.490e+02
  - 5.390e+02
  - 5.290e+02
  - 5.190e+02

![Gas Volume Fraction Plane 1]

- Gas Volume Fraction Plane 1:
  - 4.800e-01
  - 3.600e-01
  - 2.400e-01
  - 1.200e-01
  - 0.000e+00
Experiment No. 3 (Mesh03)

- Distribution of water temperature and steam volume fraction

![Graph of Liquid Temperature and Gas Volume Fraction](image-url)
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)
    \[ \text{Nu} = 2 + 0.6 \text{Re}^{0.5} \text{Pr}^{0.3} \]
  - Hughmark
    \[ \text{Nu} = 2 + 0.6 \text{Re}^{0.5} \text{Pr}^{0.3} \quad 0 \leq \text{Re} \leq 776.06 \]
    \[ \text{Nu} = 2 + 0.27 \text{Re}^{0.5} \text{Pr}^{0.3} \quad 776.06 \leq \text{Re} \]
  - Tomiyama
    \[ \text{Nu} = 2 + 0.15 \text{Re}^{0.8} \text{Pr}^{0.5} \]
Experiment 3 on Mesh02

Void Fraction [-]

Z [m]

Ranz Marshall  Hughmark  Tomiyama  Experiment
The Lee et al. Testcase (ICONE-16, 2008)
Lee et al. (2008) Experiment

- **Axially symmetric circular annulus**
- **Radial dimensions**
  - Inner radius of outer tube: \( R = 18.75 \text{ mm} \)
  - Outer radius of inner tube: \( R_0 = 9.5 \text{ mm} \)
  - Core radius: \( R_C = \frac{3}{4} R_0 \)
  - Annulus width: 9.25 mm
- **Axial dimensions**
  - Total heating section height: \( L_T = 1670 \text{ mm} \)
  - Distance between inlet and measuring plane: \( L_M = 1610 \text{ mm} \)
- **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

<table>
<thead>
<tr>
<th>Set No.*</th>
<th>$q''$ [kW m^{-2}]</th>
<th>G [kg m^{-2}s]</th>
<th>$T_{in}$ [$^\circ$C]</th>
<th>$P_{in}$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>320.4</td>
<td>718.8</td>
<td>83.8</td>
<td>121.1</td>
</tr>
<tr>
<td>25</td>
<td>220.0</td>
<td>1057.2</td>
<td>90.1</td>
<td>134.4</td>
</tr>
</tbody>
</table>
Found that submodels need modifications for BWR conditions (see also Tu&Yeoh, Anglart et al., Krepper, Koncar):

1. **Bulk bubble diameter**
   Kurul & Podowski $\rightarrow d_{B,\text{max}} \approx 1.5\text{mm} @ \text{wall}$
   modified $d_B$ law $\rightarrow d_{B,\text{max}} \approx 4.0\text{mm} @ \text{wall}$

2. **Bubble departure diameter**
   Tolubinski & Kostanchuk $\rightarrow d_w \approx 0.5\text{mm} \text{ max.}$
   const. bubble dept. diam. $\rightarrow d_w = 1\text{mm} - 3\text{mm}$

3. **$A_2$ - Wall area fraction influenced by steam bubbles**
   default $\rightarrow 0.5$
   increased up to **1.0**
Modification for Bulk Bubble Diameter Correlation

- Modified Kurul & Podowski (1991) law:

\[ d_B = \frac{d_{B1} (T_{sub} - T_{sub,2}) + d_{B2} (T_{sub,1} - T_{sub})}{T_{sub,1} - T_{sub,2}} \]
Set25: Variation of Bubble Departure Diameter

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

![Graph showing variation of bubble departure diameter](image)
Set25: Grid Independence

- Steam volume fraction on mesh1 - mesh4
- Measurement cross section $@ z = 1610 \text{ [mm]}$
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 $q_{\text{Wall}}$):

$$E_{\text{Core}} = 8.23 \cdot 10^7 \text{ [W/m}^3\text{]}$$

- Temperature and Steam VF distribution in vertical plane
Set25 & CHT: Grid independence for temperature distribution @ z=1610[mm]; 1:1 mesh interface
Set25 & CHT: Vapour VF distribution @ z=1610[mm]
1:1 mesh interface
Comparison of temperature distributions for conforming vs. non-conforming mesh, 1:1 vs. GGI
FRIGG-6a Test Case
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
    \[ G_{in} = 1163 \text{ kg m}^{-2} \text{ s}^{-1} \]
  – Pressure @Inlet
    \[ p_{in} = 5 \text{ MPa} \]
  – Rod wall heat flux
    \[ q_{Rod} = 0.522 \text{ MW m}^{-2} \]
  – Liquid subcooling @Inlet
    \[ T_{sub} = 4.5 \text{ K} \]
**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

**Definition of Zones:**
- Zone1 \( (r < 14.6 \text{ mm}) \)
- Zone2 \( (14.6 \text{ mm} < r < 28.6 \text{ mm}) \)
- Zone3 \( (r > 28.6 \text{ mm}) \)
# FRIGG-6a Test Case
## Mesh Refinement Hierarchy

<table>
<thead>
<tr>
<th></th>
<th>Mesh01</th>
<th>Mesh02</th>
<th>Mesh03</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. Elements</strong></td>
<td>699 x 150</td>
<td>2796 x 300</td>
<td>11184 x 600</td>
</tr>
<tr>
<td></td>
<td>(104 850)</td>
<td>(838 800)</td>
<td>(6 710 800)</td>
</tr>
<tr>
<td><strong>No. Nodes</strong></td>
<td>116 421</td>
<td>884 639</td>
<td>6 892 869</td>
</tr>
<tr>
<td><strong>Max y⁺</strong></td>
<td>180</td>
<td>94</td>
<td>51</td>
</tr>
<tr>
<td><strong>Min Angle [deg]</strong></td>
<td>51.9</td>
<td>50.4</td>
<td>49.64</td>
</tr>
<tr>
<td><strong>Min Determinant</strong></td>
<td>0.84</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>Numerical Effort</strong></td>
<td>~ 90 minutes @ 6 CPU’s</td>
<td>~ 17 hours @ 16 CPU’s</td>
<td>~ 6 days @ 40 CPU’s</td>
</tr>
</tbody>
</table>
Two cross-sectional distributions of gas volume fraction (Mesh03, SST)

Plot of gas volume fraction (Mesh03, 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

Zone2

Gas Volume Fraction [-]

z [m]

Mesh01  Mesh02  Mesh03  Experiment

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FRIGG-6a Test Case
Mesh Comparison
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
  $\Rightarrow$ Can be relevant for safety!
FRIGG-6a Test Case
Turbulence Model Comparison

Zone 1 (Mesh02)

Gas Volume Fraction [\(\cdot\)]

\( Z [m] \)

- SST
- k-epsilon
- BSL RSM (Mesh01)
- Experiment

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Gas Volume Fraction @Line1 (z=1.94m, Mesh02)
FRIGG-6a Test Case
Turbulence Model Comparison

SST model

Outlet

BSL RSM model

Outlet

Plot of gas volume fraction
• SST model → NO secondary flows
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)
R&D Initiative:
“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:
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
  \( \rightarrow \) number of uncertainties remaining for further investigations \( \rightarrow \) 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
Thank You!