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

Th. Frank, C. Lifante, F. Reiterer
ANSYS Germany
Thomas.Frank@ansys.com
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

Steam Generators

Process Technology

Steam Condensers

Engine cooling water jackets

Fuel Assemblies
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 $T_{\text{wall}}$ or $q_{\text{wall}}$, CHT walls.
- Activated per boundary patch with individual $T_{\text{wall}}$ or $q_{\text{wall}}$. 

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Flows with Subcooled Boiling (DNB) – RPI-Wall Boiling Model

Mechanistic wall heat partitioning model:

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

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

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

- **Evaporation heat flux**
  \[ \dot{q}_E = \dot{m} \cdot (h_G - h_L) \]
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

Phase Change Model
Option: Thermal Phase Change

Saturation Temperature

Wall Boiling Model
Option: RPI Model

Heat Transfer
Option: Two Resistance

Liquid Heat Transfer
Option: R-CM Model

Vapor Heat Transfer
Option: Zero Resistance

OK
- ANSYS Fluent 13.0:
  - Based on same RPI nucleate boiling & heat flux partitioning model
  - Non-equilibrium subcooled boiling
  - Supports superheated vapor (convective heat flux to vapor)

Contours of vapor volume fraction in a heated rod bundle
• 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 = CRN 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 = Lemnert Chaula
Power Law Index = 1.805
Reference nucleation site density = 0.9922u*0.6*0.0 [m^-2]
Reference Wall Superheat = 10.0 [K]

END

END

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New capabilities:
CFX5Pre GUI Extension
Introduction of 4th component of the wall heat flux partitioning via CCL or User Fortran

Option = Fluid Dependent
END
END
FLUID PAIR: Gas | Liquid
INTERPHASE HEAT TRANSFER:
  Option = Two Resistance
PLUID1 INTERPHASE HEAT TRANSFER:
  Option = Tarn Resistance
END
PLUID2 INTERPHASE HEAT TRANSFER:
  Option = Ranz Marshall
END
END
INTERPHASE TRANSFER MODEL:
  Interfacial Area Density = AreaDensity
  Maximum Volume Fraction for Area Density = MaxAVforArea
  Minimum Volume Fraction for Area Density = MinAVforArea
  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 Vplugs for Liquid Subcooling = 250.0
  Maximum Area Fraction to Insert Influence = 1.0
  Option = RPF Model
  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,HU)
END
BUBBLE DEPARTURE DIAMETER:
  Liquid Subcooling Scale = 45.0 [K]
  Maximum Departure Diameter = 1.4x-3 [m]
  Option = Tolubinski Kostanchuk
  Reference Departure Diameter = 0.6x-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 Keoning
END
PARTITIONING AREA FRACTIONS:
  Convective Area = a1
  Evaporative Area = 0.0
  Option = User Defined
  Quenching Area = a2
END
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./Inhomog. MUSIG

Future model extensions:
- 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)
  - $G_n=900 \text{ kg/(s m}^2\text{)}$
  - $q=0.57 \text{ MW/m}^2$
  - $R=7.7 \text{ mm}$
  - $Z=2 \text{ m}$

- Bartolomei with recondensation (1980)

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

– Model Validation –

*Testcase with Recondensation*

(Bartolomei 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**
  - 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>$q_{Wall}$ [MW m$^{-2}$]</th>
<th>$G_{in}$ [kg m$^{-2}$ s$^{-1}$]</th>
<th>$T_{in}$ [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
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
    \[ Nu = 2 + 0.6 \, Re^{0.5} \, Pr^{0.3} \quad 0 \leq Re \leq 776.06 \]
    \[ Nu = 2 + 0.27 \, Re^{0.5} \, Pr^{0.3} \quad 776.06 \leq Re \]
  - Tomiyama
    \[ Nu = 2 + 0.15 \, Re^{0.8} \, Pr^{0.5} \]
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 mm)
• Zone2 (14.6 mm < r < 28.6 mm)
• Zone3 (r > 28.6 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>
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)
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
    $\Rightarrow$ Can be relevant for safety!
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 $\rightarrow$ secondary flows

![Plot of gas volume fraction (Outlet)](image1)

![Contour plot of gas volume fraction (Outlet)](image2)
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 & Coalescence
• RPI

By courtesy of E. Krepper, FZD
R&D Initiative:
“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:

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
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Thank You!