Development and Validation of the Wall Boiling Model in ANSYS CFD

ANSYS

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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



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Introduction – Towards CFD for Flows through Nuclear Fuel Assemblies



ANSYS

- 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



CFD Simulation for Fuel Assemblies in Nuclear Reactors





Multiphase Flow Regimes for Boiling Water Flow





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

Mechanistic wall heat partioning model:



Grid Dependent Correlations



Quenching heat flux



Grid Dependent Correlations



- Evaporation heat flux
 - $\dot{q}_{E} = \dot{m} \cdot (h_{G} h_{L})$

 $\dot{m} = \frac{\pi d_W^3}{2} o f n$

- d_W bubble departure diameter
- n nucleation site density per m²
 - *f* bubble departure frequency

$$d_{W} = \min\left\{1.4mm, 0.6 \operatorname{mm} \cdot \exp\left(-\frac{T_{s}\left[\mathrm{K}\right] - T_{L}\left[\mathrm{K}\right]}{45\left[\mathrm{K}\right]}\right)\right\}$$

- small quenching & overestimated evaporation on fine grids
- wrong heat flux partitioning

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)

$$T^{+} = \Pr \cdot y^{+} e^{(-\Gamma)} + \left[2.12 \cdot \ln(y^{+}) + \beta \right] \cdot e^{(-1/\Gamma)}$$
$$y^{+} = \frac{\rho_{L} \cdot \Delta y \cdot u_{\tau}}{\mu}$$
definition of T+.

from definition of T⁺:

$$T^{+} = \frac{\rho \cdot c_{_{PL}} \cdot u_{_{\tau}}}{\dot{q}_{_{W}}} (T_{_{W}} - T_{_{L}})$$

 \rightarrow evaluating T⁺ at 2 different locations/wall distances y⁺

Revisited RPI Boiling Model



heat flux in boundary layer identical at both locations

$$\dot{q}_{W, y^{+}=first cell} = \frac{\rho \cdot c_{PL} \cdot u_{\tau}}{T_{y^{+}=first cell}^{+}} (T_{W} - T_{L})_{y^{+}=first cell}$$
 heat fluxes are equal

$$\dot{q}_{W, y^{+}=const} = \frac{\rho \cdot c_{PL} \cdot u_{\tau}}{T_{y^{+}=const}^{+}} (T_{W} - T_{L})_{y^{+}=const}$$
 heat fluxes are equal

$$T_{W} - T_{L}|_{y^{+}=const} = \frac{T_{y^{+}=const}^{+}}{T_{y^{+}=first cell}^{+}} \cdot \left(T_{W} - T_{L}|_{y^{+}=first cell}\right)$$

- additional factor in correlations for $d_{W_{e}} \dot{q}_{F_{e}} \dot{q}_{O}$
- assumption of y⁺_{const}=250; model parameter
- Replace (T_w-T_L) in submodel expressions with the above relation

RPI-Wall Boiling Model – Submodels for Model Closure



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:

 \rightarrow 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 Mod	el in the ANSYS
ANSYS CFX-Pre 12.0	
asic Settings Fluid Models Fluid Specific Models Fluid Pair Models Initialisation	Option RPI MuJel
- Mass Transfer	Fixed Yplus for Liquid Subcooling
	Line Price P
Dhase Change	Mass Source Under Relaxation
Phase Change Model	Mass Source Under Rel 0.:
Option Thermal Phase Change	Ruhhle Departure Dizmeter
Saturation Temperature	Tolubinski Kostanchuk
Saturation Temp. SaturTemper	Ref. Departure Diam. 0.6E 3 [m]
Wall Boiling Model	Max. Departure Diam. 1.4E-3 [m]
Option RPI Model	Liquid Subcooling Scale 45.0 [K]
Eixed Yolus for Liquid Subcooling	Wall Nucleation Site Density
Mass Source Linder Relaxation	_emmert Chawla
	Site Density 7.9354e5 [m ² -2]
	Ref. Wall Superheat 10.0 [K]
	Power Law Index 1.805
	Bubble Detachment Frequency
	Option Terminal Velocity over Departure Diameter
	Drag Coefficient 1.0
Bubble Diam. Influence Factor	E-
Max. Area Frac. of Bubble Influence	Option Propertional to Detachment Period
	Waiting Time Fraction 0.8
	□ Iquid Quenching Heat Transfer Coefficient □
	Option De Valle Kenning
Liquid Heat Transfer	Bubble Diam. Influence Factor
Option Ranz Marshall	Factor 2.0
VapourHeat Transfer	Max. Area Frac. of Bubble Influence
Option Zero Resistance	Max. Area Fraction U.5
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ANSYS Fluent 13.0 Wall Boiling Modeling



Wall boiling

- Based on same RPI nucleate boiling & heat flux partitioning model
- Non-equilibrium subcooled boiling
- Will support superheated vapor (convective heat flux to vapor)



Contours of vapor volume fraction in a heated rod bundle

ANSYS CFX R&D Development Work in Progress



Ongoing R&D and development:

- Provide more user interfaces to the RPI boiling model
- User defined area fractions A₁ and A₂
- 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

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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 = RPI 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
      LIOUID OUENCHING 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 = Lemmert Chawla
        Power Law Index = 1.805
        Reference Nucleation Site Density = 0.9922E+06*0.8 [m^-2]
        Reference Wall Superheat = 10.0 [K]
      END
    END
  END
END
```

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

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New capabilities: CFX5Pre GUI Extension



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Quenching Area a2	Automatic generation of default interfaces is not currently active. This fe editor in the outline tree.	eature can be activated via either the 'Edit > Options > CFX-Pre > General' editor or the 'Case Options > General'
Evaporative Area a2	In Analysis 'Flow Analysis 1' - Domain 'Default Domain': Please note tha	at the Grace Drag Force model is only valid for bubbly flows. This implies that the density of the particulate phase
	 Using custom file(s): 'RULES, CFXPrePhysics.ccl, CFXPreGui.ccl' from 	or the communds phase. I directory Votthome1/clifante/Software/FZD-BMBF-Energie-2020+/v2.0/gui'.
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Option = Two Resistance
FLUID1 INTERPHASE HEAT TRANSFER:
Option = Zero Resistance
END
FLUID2 INTERPHASE HEAT TRANSFER:
Option = Ranz 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
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 = RPI Model
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CCL & User Routine for 4th Wall Heat Partitioning Component

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 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



CFD-Post (on ottclifante2): /otthome1/clifante/Software/FZD-BMBF-Energie-2020+/v2.0/test/quser0 002.res _ 8 × File Edit Session Insert Tools Help 🔞 Location 🔹 🤹 🚳 📚 💉 🏚 🔢 🖓 ⊅ 🔘 🗶 🐻 💷 🖄 🙆 🕘 🛄 🏄 🖉 📾 🖂 😤 💥 🔩 🔟 🤌 👏 Outline Variables Expressions Calculators Turbo * \$ \$ \$ € € € @ □ - ?= 🗄 🝙 Cases View 1 🔻 🗄 💼 quser0_002 ANSYS 😑 🕣 Default Domain ☑]‡ Symme □ Symmetryaxis Wall □]‡ inlet **____**outlet + 🚱 Mesh Regions Variable Selector 2 D X B User Locations and Plots Default Transform Gas | Liquid.Evaporative Area ٠ Default Legend View 1 🖌 🗊 Wireframe Gas | Liquid.Fluid1 Heat Transfer Coefficient Report Gas | Liquid.Fluid2 Heat Transfer Coefficient **Fluid pair** ☑ 🏟 Title Page Gas | Liquid Heat Flux to Liquid + V A File Report Gas | Liquid.Heat Flux to Vapour Details of Symmetry Gas | Liquid.Interfacial Area Density Gas | Liquid.Nucleation Site Density Color Render View variables Gas | Liquid.Quenching Area Gas | Liquid.Saturation Temperature Mode Variable -Gas | Liquid.Surface Tension Coefficient Gas | Liquid.Temperature Superheating Variabl Pressure • Gas | Liquid.User Partitioning Term Range Global • Gas, Bubdia -0.0389534 [Pa] Min Gas.Conservative Volume Fraction Gas.Conservative Volume Fraction.Beta 3076.43 [Pa] Max Gas.Conservative Volume Fraction.Gradient Boundary Data Hybrid C Conservative Gas.Conservative Volume Fraction.Gradient X Gas.Conservative Volume Fraction.Gradient Y Color S Linear • Gas Conservative Volume Fraction Gradient Z Color M Default (Rainbow) - 🖪 Gas.Courant Number Gas.Density Undef. Gas.Density.Beta Gas.Density.Gradient Gas.Density.Gradient X Gas.Density.Gradient Y Gas.Density.Gradient Z Gas.Dynamic Viscosity Gas.Eddy Viscosity • OK Cancel 0.200 0.400 (m) 0 100 0.300 Apply Reset Defaults 3D Viewer Table Viewer Chart Viewer Comment Viewer Report Viewer

The Bartolomej et al. Testcase (1967,1982)



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The Bartolomej Test Case





Variable	Value
Ρ	4.5MPa
R	7.7 mm
G _{in}	900 kg/(s m2)
ġ	0.57MW/m2
Subcooling	58.2 K

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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

Inter-Phase Mass, Momentum and Energy Transfer

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

Numerical Grids



• Validation on mesh hierarchy with regular refinement factor of 4 (2d meshes)

Grid	Grid1	Grid2	Grid3
# Nodes (uniform)	20x150	40x300	80x600
Max y⁺	264	133	69
Δt [s]	10 ⁻²	10 ⁻³	5x10 ⁻⁴

Grid1











Grid 3





Comparison to Experimental Data ANSYS®





Comparison to Experimental Data ANSYS® - Parameter & Model Variation



None ---

X

-0.15

Exp Data 0.57 --- 0.38 ×

0.4

0.35

0.3

-0.25 Laction 0.2

9 0.15

0.1

0.05

0

-0.2

0.57

- Antal ----- Tomiyama \times Experimental Data

Exp Data 0.38

The Bartolomej et al. Testcase with Recondensation (Bartolomeij et al. (1980))



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Geometry & Flow Parameters



Geometry

- Pipe flow; axial symmetry
- Inner radius of pipe R = 6.015 mm
- Total pipe length L_T= 1.4 m
- Heated section length L_H= 1.0 m

Flow parameters

- Upward directed water flow
- Pressure @Inlet p_{in} = 6.89 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:

Experiment No.	q _{wall} [MW m^-2]	G _{in} [kg m^-2 s^-1]	T _{in} [K]
2	1.2	1500	495
3	0.8	1500	519
5	0.8	1000	503

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

 $Nu = 2 + 0.6 \text{ Re}^{0.5} \text{Pr}^{0.3}$ $0 \le \text{Re} \le 776.06$

 $Nu = 2 + 0.27 \text{ Re}^{0.5} \text{Pr}^{0.3}$ 776.06 \leq Re

– Tomiyama

 $Nu = 2 + 0.15 \text{ Re}^{0.8} \text{Pr}^{0.5}$

Interphase Heat Transfer Model (ANSYS)



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



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Lee et al. (2008) Experiment



- Axially symmetric circular annulus
- Radial dimensions
 - Inner radius of outer tube: R = 18.75 mm
 - Outer radius of inner tube: R₀ = 9.5 mm
 - Core radius: $R_c = 3/4 R_0$
 - 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 mm
- Radial Position: R_P
 - Dimensionless, radial distance from inner tube $(R_P = 0)$ to outer tube $(R_P = 1)$ across the annulus:

$$R_P = \frac{\left(r - R_0\right)}{\left(R - R_0\right)}$$



Investigated Geometry Configurations







Parameter comparison

Set No.*	q" [kW m^-2]	G [kg m^-2s]	T _{in} [°C]	P _{in} [kPa]
16	320.4	718.8	83.8	121.1
25	220.0	1057.2	90.1	134.4

Model Parameter Modifications in Comparison to PWR Conditions



Found that submodels need modifications for BWR **conditions** (see also Tu&Yeoh, Anglart et al., Krepper, Koncar):

- 1. Bulk bubble diameter
 - Kurul & Podowski \rightarrow modified d_B law \rightarrow
- d_{B.max}~1.5mm @ wall d_{B.max}~4.0mm @ wall
- 2. Bubble departure diameter Tolubinski & Kostanchuk const. bubble dept. diam. $\rightarrow d_w = 1 \text{ mm} - \frac{3 \text{ mm}}{3 \text{ mm}}$
 - \rightarrow d_w ~0.5mm max.
- 3. A₂ Wall area fraction influenced by steam bubbles default $\rightarrow 0.5$ increased up to 1.0

Modification for Bulk Bubble Diameter Correlation







Set25: Variation of Bubble Departure Diameter



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



Set25: Grid Independence



- Steam volume fraction on mesh1 mesh4
- Measurement cross section @ z = 1610 [mm]



The Lee et al. Testcase (ICONE-16, 2008) : Conjugate Heat Transfer



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 Specific energy source in solid material, Set25 (equiv. to q_{Wall}):

E_{Core}=8.23·10⁷ [W/m³]

 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 (Anglart & Nylund, 1967, 1996 & 1997)

ANSYS[®]

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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 kg m⁻² s⁻¹
- Pressure @Inlet p_{in} = 5 MPa



- Rod wall heat flux
 q_{Rod} = 0.522 MW m⁻²
- Liquid subcooling @Inlet
 T_{sub}= 4.5 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



Defintion 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



	Mesh01	Mesh02	Mesh03
No. Elements	699 x 150 (104 850)	2796 x 300 (838 800)	11184 x 600 (6 710 800)
No. Nodes	116 421	884 639	6 892 869
Max y+	180	94	51
Min Angle [deg]	51.9	50.4	49.64
Min Determinant	0.84	0.91	0.98
Numerical Effort	~ 90 minutes @ 6 CPU's	~ 17 hours @ 16 CPU's	~ 6 days @ 40 CPU's

FRIGG-6a Test Case Baseline Setup: SST

NSYS[®]





Two cross-sectional distributions of gas volume fraction (Mesh03,SST)

FRIGG-6a Test Case Baseline Setup: SST

NSYS[®]



Two cross-sectional distributions of liquid temperature (Mesh03,SST)

FRIGG-6a Test Case Mesh Comparison





FRIGG-6a Test Case Mesh Comparison





FRIGG-6a Test Case Mesh Comparison





Turbulence Modeling in Rod Bundles



- So far good comparison, but...
 - Wall friction in rod bundles leads to secondary flows
 - Anisotropic flow and turbulence
 - $-\operatorname{SST} \Rightarrow \operatorname{BSL}\operatorname{RSM}$
 - 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!



















SST model

BSL RSM model



Plot of gas volume fraction



• SST model \rightarrow NO secondary flows



Plot of gas volume fraction (Outlet)

Contour plot of gas volume fraction (Outlet)



• BSL RSM model \rightarrow secondary flows



Plot of gas volume fraction (Outlet)

Contour plot of gas volume fraction (Outlet)

ANSYS[®] **New R&D Consortium R&D** Initiative: ANSYS **"Modeling, Simulation &** Germany **Experiments for Boiling** Karlsruhe TUD, Dept. Inst. of Fluid **Processes in Fuel** Technology **Mechanics** (KIT) **Assemblies of PWR**" FZ TUM, Dept. Dresden/ TUD, Dept. Thermo-Nucl. Eng. **Rossen**dynamics dorf Univ. TUD Bochum, Medical Dept. Energy **Faculty** Systems Univ. Appl. Sciences Zittau/ Görlitz

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:



ANSYS, Inc. Proprietary
Modeling, Simulation & Experiments for Boiling Processes in Fuel Assemblies of PWR

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





