

020

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

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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



Fuel Assemblies



Wall Boiling Modeling

Why special modeling for wall boiling?

- For subcooled flows with superheated walls, standard thermal phase change models for bulk boiling/condensation will <u>underpredict</u> 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
 A convective heat transfer
 - → convective heat transfer, evaporation, quenching
- Empirical submodels required for closure
- Available for different BC's: prescribed T_{wall} or q_{wall}, CHT walls
- Activated per boundary patch with individual T_{wall} or q_{wall}





Multiphase Flow Regimes for Boiling Water Flow





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



Mechanistic wall heat partioning model:



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:
 → 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

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Basic Settings Fluid Mod	dels 📔 Fluid Specific Models	Fluid Pair Models	Initialisation	
Mass Transfer	\frown			
Option	Phase Change			
Phase Change Model-	\sim			
Option	Thermal Phase Change		-	
Saturation Tempe	erature			
Saturation Temp.	SaturTemper			
Wall Boiling Mode				ר
Option	RPI Model		•	
Fixed Yplus for I	Liquid Subcooling		±	
Mass Source Un	der Relaxation			
🗌 🗖 Bubble Departu	re Diameter		Ŧ	
- Wall Nucleation	Site Density			Ц
Bubble Detachm	nent Frequency			'
Bubble Waiting	Time			
Liquid Quenchin	g Heat Transfer Coefficient —			
Bubble Diam. In	fluence Factor			
Max. Area Frac	. of Bubble Influence			
Heat Transfer				
Option	Two Resistance		-	
Liquid Heat Transfer				
Option	Ranz Marshall		•	
- Vapour Heat Transfer-				
Option	Zero Resistance			

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_		
✓ Wall Boiling Model		
Option	RPI Model	–
- 🔽 Fixed Yplus for Liq	uid Subcooling	E
Fixed Yplus	250.0	
- 🔽 Mass Source Unde	r Relaxation	E
Mass Source Under Re	0.1	
- 🔽 Bubble Departure	Diameter	———Е
Option	Tolubinski Kostanchuk	•
Ref. Departure Diam.	0.6E-3 [m]	
Max. Departure Diam.	1.4E-3 [m]	
Liquid Subcooling Scale	45.0 [K]	
- 🔽 Wall Nucleation Sit	e Density	E
Option	Lemmert Chawla	•
Site Density	7.9384e5 [m^-2]	
Ref. Wall Superheat	10.0 [K]	
Power Law Index	1.805	
- 🔽 Bubble Detachmer	t Frequency	E
Option	Terminal Velocity over Departure Diameter	•
Drag Coefficient	1.0	
- 🔽 Bubble Waiting Tin	1e	E
Option	Proportional to Detachment Period	•
Waiting Time Fraction	0.8	
- 🔽 Liquid Quenching H	leat Transfer Coefficient	E
Option	Del Valle Kenning	▼
🔽 Bubble Diam. Influ	ence Factor	E
Factor	2.0	
Max. Area Frac. o	f Bubble Influence	E
Max. Area Fraction	0.5	
Apply	Close	S, Inc. Proprie

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ANSYS Fluent 13.0 Wall Boiling Modeling



- 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 Volume fraction (vapor)

Apr 15, 2010 ANSYS FLUENT 13.0 (3d, dp, pbns, eulerian, rngke)

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 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

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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
     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 = 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

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New capabilities: CFX5Pre GUI Extension

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CCL & User Routine for 4th Wall Heat Partitioning Component



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 = 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 Option = RPI Model User Partitioning Term = 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.HLV) 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 = al Evaporative Area = 0.0 Option = User Defined Quenching Area = a2 END

 Introduction of 4th component of the wall heat flux partitioning via CCL or User Fortran

CCL & User Routine for 4th Wall Heat Partitioning Component



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	Option Thermal Phase Change	-
	☐ Heat Transfer Coefficient Under Relaxation Factor —	
	₩ Wall Boiling Model	
	Option RPI Model -	1
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 Customization of CFX5Pre for the extension of the RPI wall heat flux
 partitioning algorithm
 → 4th component of the wall heat flux splitting

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Extended CFX5Post Output

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Inc. Proprietary

Coupling of RPI Wall Boiling Model with Homog./Inhomg. MUSIG



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CFX5Pre Customization: Inhomogeneous MUSIG & RPI



GEX-Pre (on ottclifante2): rpi_musig_inh_red	CFX-Pre (on ottolifante2): rpi_musig_inh_red CFX-Pre (on ottolifante2): rpi_musig_inh_red File Edit Session Insert Tesls Halp
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Wall Boiling Model	
Option RPI Model	Option RPI Model
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Liquid Subcooling Sra IMod WaBo BDebD ToluKosta LidSubScale	
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Investigated Boiling Testcases





Bartolomei with recondensation



• OECD NEA PSBT subchannel benchmark (1987-1995, 2009)



• Lee et al. (ICONE-16, 2008)





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

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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 & Flow Parameters





- 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)





Experiment No. 3 (Mesh02)





Experiment No. 3 (Mesh03)





Experiment No. 3 (Mesh04)





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

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

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

– Tomiyama

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

Interphase Heat Transfer Model







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





FRIGG-6a Test Case Baseline Setup: SST





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

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 turbulence
 - SST \Rightarrow BSL RSM
 - Does not influence so much cross-sectional averaged flow properties
 - Secondary flows affect steam & temperature distributions on wall surfaces
 → Can be relevant for safety!







SST model

BSL RSM model



Plot of gas volume fraction

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SST model → NO secondary flows



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• BSL RSM model \rightarrow secondary flows





DEBORA Testcase: RPI & MUSIG

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dashed lines $- d_B = f(T_{sat} - T_L)$; solid lines $- d_B$ as mean Sauter diam. from MUSIG group



R&D Consortium





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 ANSYS, Inc. Proprietary

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

Acknowledgement





Bundesministerium für Bildung und Forschung



This research has been supported by the

German Ministry of Education & Research (BMBF)

under the contract number 02NUK010G in the project:

"Modeling, Simulation and Experiments for Boiling Processes in Fuel Assemblies of Pressurized Water Reactors (PWR)"

in the framework of the German CFD Network on Nuclear Reactor Safety Research and Alliance for Competence in Nuclear Technology, Germany and the BMBF funding framework for basic research Energy-2020+.





