Extension of CFD Codes to Two-Phase Flow Safety Problems

By

D. Bestion (CEA, France)

OECD-WGAMA
CFD WG3:

D. Lucas, (FZD, Germany)
H. Anglart (RIT, Sweden),
B.L. Smith, M. Andreani, (PSI,Switzerland)
J. Mahaffy (PSU, USA),
G. Zigh (US-NRC)
C.H.Song, (KAERI, Corea)
E. Komen (NRG, Netherland),
P. Mühlbauer (NRI, Czech Rep),
M Scheuerer (GRS, Germany)
T. Morii, F. Kasahara (JNES, Japan)
T. Watanabe (JAEA, Japan)
F. Moretti (U.Pisa, Italy)

Objectives and Content of Work

The objective is to give orientations for the future development and assessment of two-phase CFD tools to be used in Nuclear Reactor Safety (NRS) problems

Phase 1:

- A classification of NRS problems requiring 2 phase CFD use
- A classification of different modelling approaches
- The specification and analysis of needs in terms of physical & numerical assessment,

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Phase 2:

- Selection of a limited number of NRS issues having a high priority and for which two-phase CFD has a reasonable chance to be successful in a reasonable period of time.
- Identification of the remaining gaps in the existing approaches for the selected issues.
- Identification of some verification, demonstration and validation test cases of special interest for each selected NRS issue. Proposal of benchmark exercises.
- Establish the foundation of Best Practice Guidelines for two-phase CFD application to the selected NRS issues

Final report to be completed by end 2008

Identification of NRS problems where extension of CFD capabilities to two-phase flow may bring real benefit

	NRS problem	Maturity of present CFD tools
1	**DNB, dry out and CHF investigations**	M
2	Subcooled boiling	M
3	**Two-phase pressurized thermal shock**	M
4	Direct contact condensation: steam discharge in a pool	M
5	Pool heat exchangers: thermal stratification and mixing problems	H
6	Corrosion Erosion deposition	L
7	Containment thermal-hydraulics	H
8	Two-phase flow in valves, safety valves	L
9	ECC bypass and downcomer penetration during refill	L
10	Two phase flow features in BWR cores	M
11	Atmospheric transport of aerosols outside containment	M
12	DBA reflooding	M
13	Reflooding of a debris bed	L
14	Steam generator tube vibration	L
15	Upper plenum injection	L
16	Local 3-D effects in singular geometries	L
17	Phase distribution in inlet and outlet headers of steam generators	L
18	Condensation induced waterhammer	L
19	Components with complex geometry	L
20	Pipe Flow with Cavitation	M
21	External reactor pressure vessel cooling	M
22	Behaviour of gas-liquid interfaces	M
23	Two-phase pump behaviour	L
24	Pipe Break-In vessel mechanical load	M
25	Specific features in Passive reactors	M

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Porous body or open medium approaches

	NRS problem	Open 3D	Porous 3D	Open 3D for Porous or for 1D
1	DNB, dry out and CHF investigations	O		O ⇒ P
2	Sucooled boiling	O		O ⇒ P
3	Two-phase Pressurized Thermal Shock	O		
4	Direct contact condensation: steam discharge in a pool	O		
5	Pool heat exchangers: thermal stratification and mixing problems	O	P	
6	Erosion, corrosion, deposition	O		
7	Containment thermal-hydraulics	O		
8	Two-phase flow in valves, safety valves	O		
9	ECC bypass and downcomer penetration during refill phase of a LBLOCA	0	P	O ⇒ P
10	Two phase flow features in BWR core		P	O ⇒ P
11	Atmospheric transport of aerosols outside containment	O		
12	DBA reflooding		P	O ⇒ P
13	Reflooding of a debris bed		P	O ⇒ P
14	Steam generator tube vibration			O ⇒ P
15	Upper plenum injection		P	
16	Local 3-D effects in singular geometries	O		
17	Phase distribution in inlet and outlet headers of steam generators	O		O ⇒ P
18	Condensation induced water hammer	O		
19	Components with complex geometry- separators, dryers			O ⇒ P
20	Pipe flow with cavitation	O		
21	External reactor pressure vessel cooling	O		
22	Behaviour of gas liquid interfaces	O		
23	Two-phase pump behaviour	O		
24	Pipe break-in vessel mechanical load	O	P	
25	Specific features in advanced PWR	O		

NRS problems where extension of CFD capabilities to two-phase flow may bring real benefit

For each NRS problem:

- Description of the issue
- Why extension of CFD to two-phase flow may bring real benefit
- Degree of maturity of present two-phase CFD tools to treat the problem
  - 'High' maturity was applied to the case in which sufficient information was available, all related phenomena were identified well, and models were developed for each phenomenon, improvements may be welcome for some of them.
  - "Medium" maturity was applied when a publicised background exists, most basic phenomena are supposed to be well identified and some models exist which require improvements and validation.
  - 'Low' maturity was applied to the case in which no trusted information was available on the validity of existing models.
- References

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Classification of Two-phase CFD approaches

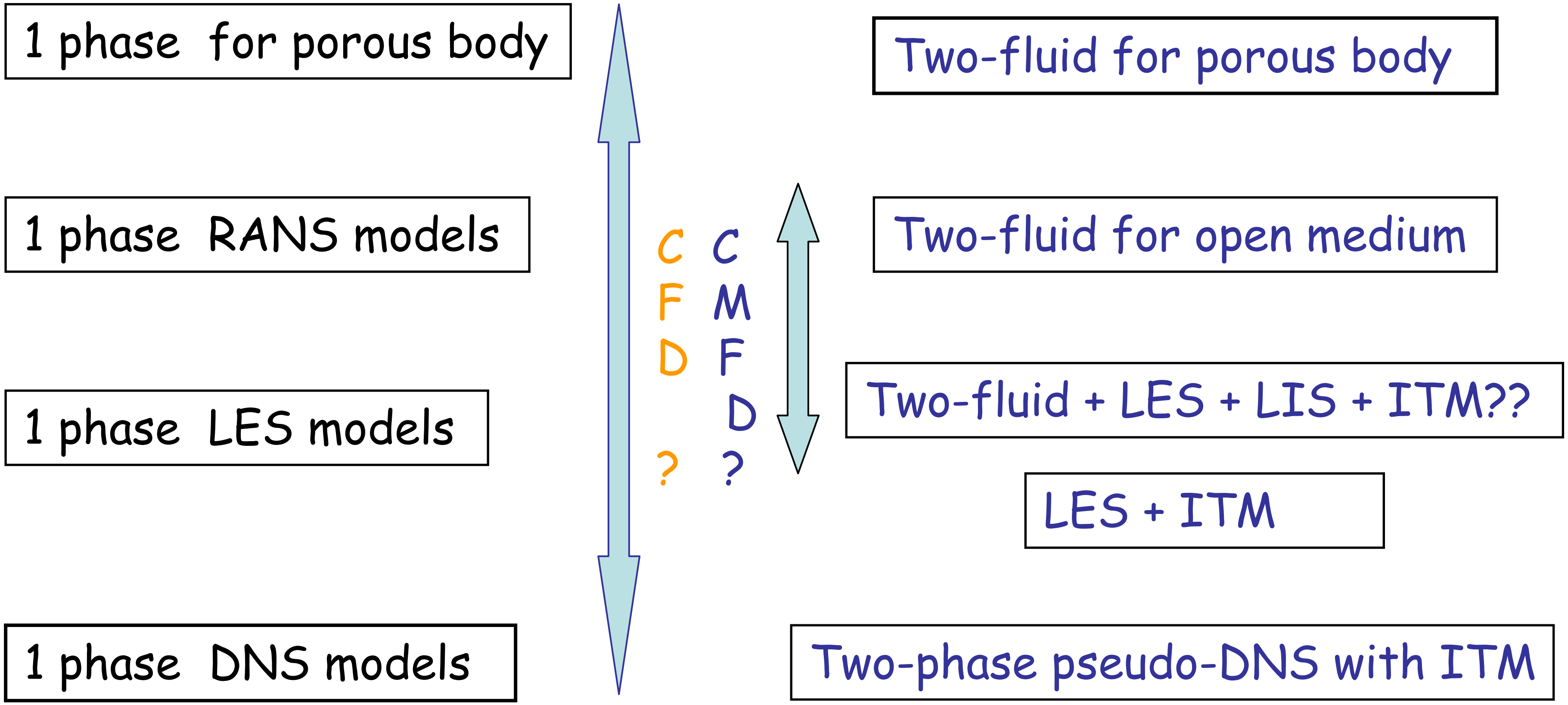
Classification with respect to the averaging of basic equations:

- ❑ Space averaging :
  - ➢ 3D model for porous medium
  - ➢ 3D model for open medium
- ❑ Filtering turbulent scales and two-phase intermittency scales:
  - ➢ All turbulent scales are filtered (RANS models)
  - ➢ Only some scales are filtered (two-phase LES)
  - ➢ All turbulent scales are predicted (DNS)
- ❑ Phase averaging or field averaging:
  - ➢ Homogeneous for a two-phase mixture
  - ➢ Two-fluid model
  - ➢ Multi-field models
- ❑ Additional transport equations, which are used:
  - ➢ Transport or turbulent quantities: k-ε, Rij-ε,
  - ➢ Transport of interfacial area or particle number density,…
- ❑ Use of Interface Tracking/Capturing Technique

Classification with respect to :

- ➢ Eulerian-Eulerian method
- ➢ Eulerian-Lagrangian method

Classification of 3D CFD models



Single -Phase

Two -Phase

1 phase for porous body

1 phase RANS models

1 phase LES models

1 phase DNS models

Two-fluid for porous body

Two-fluid for open medium

Two-fluid + LES + LIS + ITM??

LES + ITM

Two-phase pseudo-DNS with ITM

Proposed multi-step methodology for using two-phase CFD to NRS issues

1. *Identification of all important flow processes*: PIRT analysis.
2. *Selecting a Basic model*: one–fluid model, two-fluid model, multi-field models…
3. *Filtering turbulent scales and two-phase intermittency scales*: averaging or filtering of basic equations: ensemble averaging, time averaging, space averaging, or combined averaging, space and time filtering of Turbulent scales and two-phase intermittency scales . RANS, LES, LIS, …
4. *Identification of Local Interface structure*: ITM?, statistical description with void fraction, interfacial area density, polydispersion, MUSIG, MSM ?
5. *Modelling interfacial transfers*: mass momentum and energy interfacial transfers have to be modelled depending on the modelling choices and validated on available SETs.
6. *Modelling Turbulent transfers*: turbulent transfers have to be modelled depending on the modelling choices and validated on available SETs.
7. *Modelling Wall transfers*: momentum and energy wall transfers have to be modelled (wall functions) and validated on available (SETs).
8. *Matrix of Validation tests and Demonstration tests.*
9. *Numerical Verification*: pure numerical benchmarks.

Then :

10. *Evaluation of uncertainty (when physical modelling will be mature enough)*
11. *Precise BPG for a CFD use by non specialists*

Selection of a limited number of NRS issues (Phase 2)

Selected issues:

- DNB investigations
- Dry-out investigations
- Pressurised Thermal Shock
- Steam discharge in a pool
- Pool Heat Exchanger
- Fire analysis

Selection criteria

- High priority issues with respect to nuclear safety
- Chance to be successful
- Covering generation 2 and 3 water reactors
- Covering all flow regimes
- Existence of a sufficient data base

Structure of the final report

- ☐ SELECTION OF A LIMITED NUMBER OF NRS ISSUES
    - THE DRY-OUT INVESTIGATIONS
    - THE DEPARTURE FROM NUCLEATE BOILING
    - THE PRESSURIZED THERMAL SHOCK
    - THE POOL HEAT EXCHANGERS
    - THE STEAM DISCHARGE IN A POOL
    - FIRE ANALYSIS

- ☐ VERIFICATION TEST CASES OF SPECIAL INTEREST FOR THE SELECTED ISSUES

- ☐ PROPOSAL OF BENCHMARKS RELATIVE TO THE SELECTED ISSUES

- ☐ BEST PRACTICE GUIDELINES

Pool heat exchangers: thermal stratification and mixing problems

Examples of pool HX

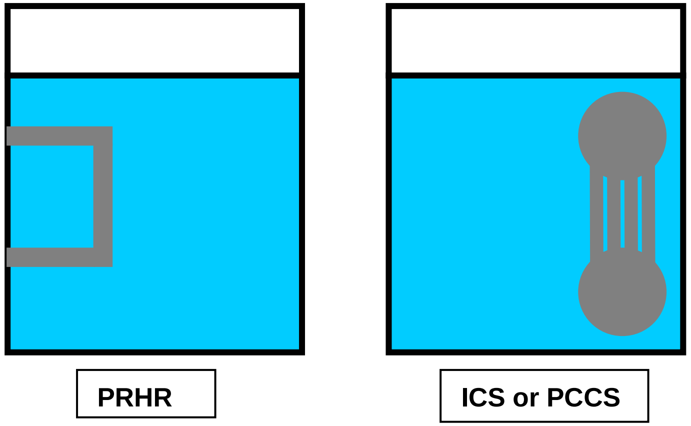
- PRHR (AP1000): RHR + cooling in LOCA before gravity draining from the IRWST
- ISC : BWR heat sink when normal steam flow is disrupted
- PCCS (ESBWR)

Problems to solve:

- can they remove the power & how long they will function? before outside intervention
- Predict the condensation rates in the tubes and
- Predict the heat transfer rate (boiling) on the pool side
- single phase & two phase buoyancy driven natural circulation
- thermal stratification

What benefit CFD may bring?

- Simulation of accidental transients with system codes do not represent correctly 3D effects in the pool (long-term cooling phase)
- in SA conditions, presence of hydrogen leads to complex conditions in the multi-tube geometry, with possibility of flow reversal in several of the tubes, and strongly inhomogeneous deposition of aerosols.
- evaluate the reliability and the efficiency of HX in a wide spectrum of accident conditions
- helping an economically competitive design



Direct contact condensation: steam discharge in a pool

Steam discharge in a pool with DCC is encountered in:

- BWR suppression pool.
- passive safety systems of new reactor designs, **ADS**

Associated phenomena

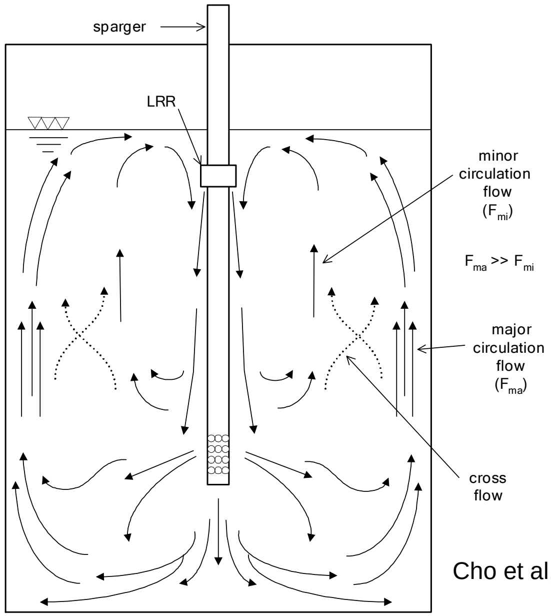
- Bubble detachment, break up, turbulence production
- low submergence and large flows result in possible steam by-pass
- DCC with instability & pressure fluctuations may occur (effect of the design)
- thermal mixing in the pool
- gas bubbles resulting from the injection of steam-gas mixtures may have an impact on other systems, e.g., ECCS

Difficulties

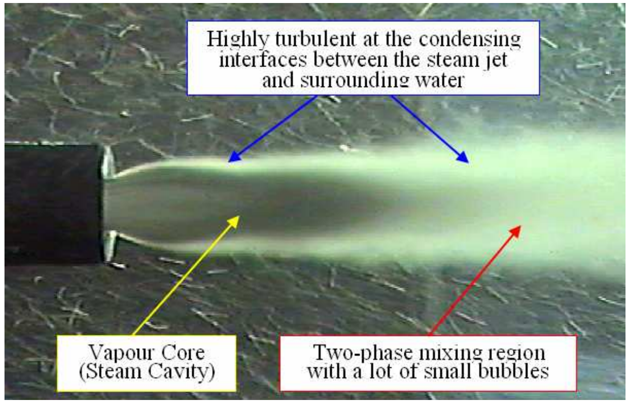
- Strong thermo-mechanical coupling.
- DCC regimes & transition criteria: chugging, subsonic and sonic jetting , condensation oscillations,…
- DCC regime and efficiency sensitive to geometry of vent nozzle
- Design can only be based on costly experiments

What benefit CFD may bring?

- A better understanding of coupled phenomena
- Help design
- Predict behaviour: DCC, thermal mixing, steam bypass



Cho et al, 2002



Song et al. 1998

References

Cho et al. Characteristic of thermal mixing and pressure load during continuous steam discharging phase, Proc. KNS Spring Conf KNS 2002

Song et al., Characterization of DCCof steam jets discjharging into subcooled water, IAEA technical committee meeting, PSI, Villingen, Sept 14, 1998

Dry Out investigations

Identification of all important flow processes for Dry Out

Droplet diameter:

- *turbulence-particle interactions*
- *drop break-up*
- *coalescence*

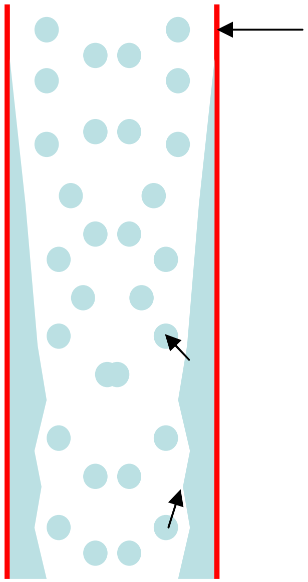
Deposition

- *drop dispersion in turbulent flow*
- *interactions with eddies of various scales (ratio of the particle response time to the eddy characteristic time)*

Entrainment

- *steam flow generates waves on the film surface, with droplets being entrained from the crests of these waves.*
- *splashing associated with drop deposition,*
- *nucleate boiling in the film, split of bubble liquid film*

Film Thickness



Mechanisms for dryout (Hewitt, 1982):

- Entrainment + evaporation > deposition
- Formation of a dry patch within the liquid film,
- Vapour film formation under the liquid film (DNB)

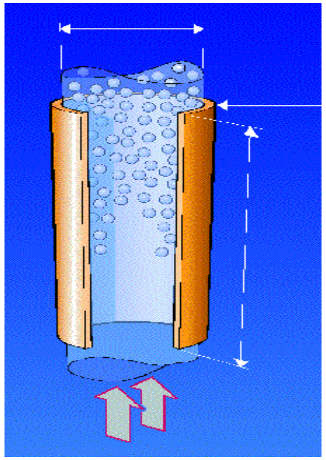
Data sources for Dry-Out investigations

Data source	**Würtz, 1978**	**Andreussi, 1983**	**Govan et al., 1989**	**Cousins & Hewitt, 1968**	**Adamsson & Anglart, 2005**	**Okawa et al., 2005**	**Fore & al., 2002**	**Fore & Dukler, 1995**	**Andreussi, 1983**
Geometry	**Tube** Di =10 mm **Annulus** Di=17 mm, De=26 mm,	**Tube** Di= 24 mm	**Tube** Di=31.8 mm	**Tube** Di: 9.52 mm	**Tube** Di: 13.9 mm	**Tube** Di: 5 mm	**Tube** Di: 9.67 mm	**Tube** Di: 50.8 mm	**Tube** Di: 24 mm
Fluid Heating	Steam-water Adiabatic & diabatic	Air-water Adiabatic	Air-water Adiabatic	Air-water Adiabatic	Steam-water Diabatic	Air-water Adiabatic	N2-water Adiabatic	Air-water Air-water+glycerine Adiabatic	Air-water Adiabatic
ΔP	**X**	**X**	**X**						
Q_{film}	**X**			**X**	**X**				
E				**X**		**X**			**X**
Q_{dep}			**X**			**X**			
Drop size distribution							**X**	**X**	
Other measurements	δ_f f_w C_w:	τw τl	C_w						**Rate of liquid interchange**

DNB investigations

Present industrial methods for predicting CHF in PWR (DNB) and BWR (Dry-out) rely on:

- pure empirical methods which require costly experimental testing in real geometry with real fluid real flow conditions and real rod power
- subchannel analysis with prediction of P,G,X averaged in the subchannel



DNB occurrence depends on phenomena at various scales:

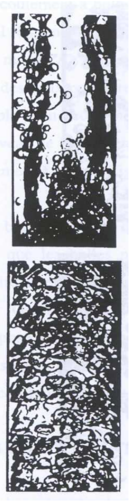
- Macro-Scale (order of about 1 cm)
    - Mixing between sub-channels, cross-flows , turbulence
    - Grid spacers effects on averaged flow parameters P, G, Xth
- Meso-scale (order of about 1 mm)
    - Bubble transport and dispersion growing, collapse, coalescence and break up
    - Turbulents transfers of heat and momentum
    - Local grid spacers effects
- Micro scale (order of 1 μm or less)
    - activation of nucleation sites, growing of attached bubbles
    - sliding of attached bubbles along wall, coalescence of attached bubbles,
    - bubble detachement, wall rewetting after detachement

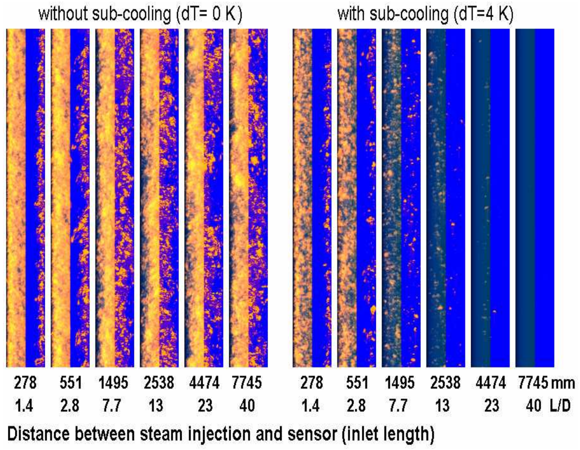
CFD may bring:

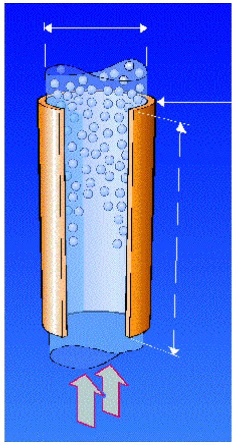
- A better understanding of meso-scale effects on CHF occurrence
- Help new fuel bundle design
- Allow a « local predictive approach »

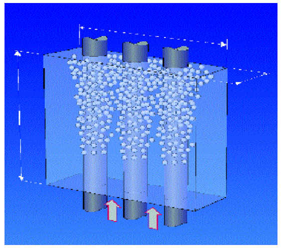
Data sources for DNB investigations

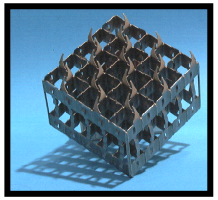
Phenomena	DEDALE	TOPFLOW	DEBORA	ASU	PURDUE boiling	KAERI boiling	DEBORA Promoter	AGATE (&AGATE-promoter)	BFBT	LWL
Geometry	Tube L=6 m D=0.0381 m	Tube D=195.3mm	Tube D=0.0192 m	Annulus Di=15.78mm De=38.02m	Annulus Di=19.1m De=38.1m	Annulus Di=19mm De=37.5mm	Tube + promoter	Rod bundle (tube+promoter)	Rod bundle	Rod bundle
Fluid / flow conditions	Air-water adiabatic	Air-water and Steam-water	R12	R113	Steam-water	Steam-water	R12	water	Steam/ water	Steam/ water
Local measurements	α, Ai, δ_b, F_δ, V_{lz}, v'_{lz}, V_{bz} at Z/D = 8, 55 & 155	α, δ_b, V_{bz}, F_δ	α, Ai, T_l, T_w , δ_b, V_{bz},	α, V_{lz}, v'_{lz}, v'_{lx} , V_{bz}, T_w, T'_w, turbulent heat fluxes	α, Ai, δ_b, V_{bz} at z/D=52.6 + visual observations	α, Ai, δ_b, V_{lz}, V_{bz}	α, Ai, T_l, T_w , δ_b, V_{bz},	V_{lz}, v'_{lz} V_{lx}, v'_{lx}	α ϕ_{crit}	ϕ_{crit}











Correspondence between data sources and basic phenomena for DNB investigations

Phenomena	DEDALE	DEBORA	DEBORA Promoter	AGATE (&AGATE-promoter)	ASU	PURDUE boiling	KAERI boiling	TOPFLOW	BFBT	LWL
Wall to fluid heat transfer		P			P	P	P	P	P	P
Bubbles transport & dispersion	v	V			V	V	V	V	V	P
Vaporization - condensation		V			V	V	V	V	V	P
Coalescence & break up of bubbles	V	V			V	V	V	V	P	P
Turbulent Transfers of heat & momentum	V	V	V	V	V	V	V	V	P	P
Effects of polydispersion		V						V	P	P
Effects of grids			V	V						
Combined effects in real geometry									BWR	PWR WWER

V: allows validation
P: the phenomenon is present (but does not allow separate effect validation)

State of the Art in modeling boiling flow for DNB investigations

Identification of flow processes:

Macroscale & Meso-scale phenomena are identified
Micro-scale : the DNB mechanism(s) not yet identified

Basic model:

The 2-fluid model is OK (+polydispersion)

Averaging or filtering equations:

RANS is OK with
2-phase LES may help to modelling bubble dispersion

Identification of Local Interface structure:

Statistical description of bubbles with TIA + polydispersion (MUSIG, MSM)
Close to DNB, a criterion is necessary for identifying the steam layer appearance

Interfacial transfers:

Some more effort required for both lift and turbulent dispersion forces.
Interfacial energy transfers require a modelling of polydispersion effects

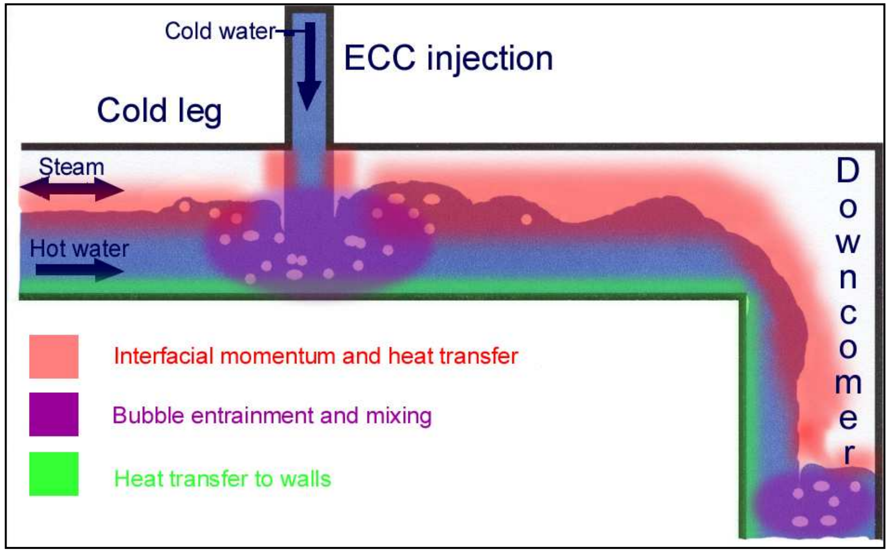
Turbulent transfers:

The k-epsilon or SST method were used with some success
RST better in swirls behind grids.

Wall transfers:

Improvements of wall function for momentum obtained & validated on ASU tests
Specific wall functions have to be developed for boiling flow for energy equations.

Two-Phase Pressurised Thermal SHOCK



Scenarios leading to PTS

- During a LOCA, cold ECCS water is injected into the cold leg of a PWR
- Depending on the transient, the cold leg can be either single phase or in two-phase conditions.
- The ECCS water mixes with saturated water or exchanges heat with steam
- Depending on the temperature, the cold leg and PV wall might be subjected to a thermal shock, which has to be withstood without brittle fracture risk.
- For an ageing reactor more precision is required for the liquid temperature evolution during the SI injection in order to justify a greater life span of the vessel.

Why extension of CFD to two phase flow may bring real benefit ?

- System codes are only able to predict an average Tl while CFD predicts the minimum local temperature
- The coupling of system and CFD codes is required for a complete answer to the reactor case.

Main phenomena to be addressed by CFD:

- Condensation on the jet itself before mixing
- Turbulence production below the jet, in wall shear layers & in interfacial shear layer
- Effect of condensation upon interfacial structure and wave structure
- Effects of turbulent diffusion upon condensation
- Interfacial transfer of momentum , heat & mass with condensation
- Interface configuration in top of downcomer & flow separation or not in dowcomer at cold leg nozzle
- Heat transfers with cold leg and RPV walls

Validation tests for two-phase PTS

EXPERIMENTS	**Validation Demonstration**	**Type**	**Main interest of simulation**
MASHEK Water sloshing	V D	Air-water Cylindrical tank	Capability to predict free surface movements
FABRE et al. data: air/water flow in rectangular channel"	V	Air-water Rectangular channel	SET on momentum transfers at free surface Turbulent transfers
THORPE experiment: KH instability	V	Liquid-liquid Rectangular box	SET on interfacial transfers in stratified flow with K-H instability
HAWAC	V	Air-water Rectangular channel	SET on interfacial transfers in stratified flow with K-H instability
HYBISCUS	V	Air-water-salted water Cold Leg- Donwcomer	SET on density stratification
LAOKOON data	V	Steam-water Rectangular channel	SET on condensation in stratified flow
LIM et al data	V	Steam-water Rectangular channel	SET on condensation in stratified flow
COSI data	V D	Steam-water Scaled Cold Leg	Condensation in scaled Cold leg geometry
PMK condensation induced waterhammer	V D	Steam-water Pipe	Condensation induced K-H instability
UPTF-TRAM data	V D	Scale 1 Reactor	Reactor geometry
BONETO-LAHEY data:	V	Air-water Cylindrical tank	Jet induced bubble entrainment below free surface
IGUCHI et al. data	V	Air-water Cylindrical tank	Validation on turbulence below a plunging jet
TOPPFLOW-PTS	V	Steam-water Scaled Cold Leg + downcomer	Mixed effects in scaled geometry
ROSA IV-LSTF	V	Scale1/48 Reactor	Mixed effects : system effects

Correspondence between data sources and basic phenomena for PTS investigations

PHENOMENA	MASHEK	FABRE	THORPE	HAWAC	HYBISCUS	LAOKOON	LIM	COSI	PMK	UPTF	BONETO	IGUCHI	TOPFLOW	ROSA
Instabilities of jet														P
Condensation on the jet													V	P
Entrainment of bubbles								P			v	P	V	P
Turbulence production by the jet												V	V	P
Free surface movement	V	P	V	V	P	P	P	P	P	P	P	P	P	P
momentum transfer at free surface	V	V	V	V	P	P			P				P	P
heat & mass transfer at free surface						V	V	V	P				V	V
Turbulence production in wall & interfacial shear layers		V											V?	P
Effects of turbulent diffusion upon condensation						P	P	P	P	P			PV?	P
Interactions between waves , turbulence & condensation							V	P					PV?	P
Effects of T° stratification					PV?	P	P	P		P			PV?	P
Influence of NC gases														P
Heat transfers with cold leg and RPV walls													PV	P
Flow separation or not in dowcomer													V	V

Proposed benchmarks

- Dry-Out: Jepson et al. Okawa et al. (2005) Fore et al. (2002) Wurtz (1978) data to validate entrainment, deposition, drop size and film thickness
- DNB: 1 ASU test (velocity and turbulence) + 1 DEBORA test (bubble diameter and size distribution)
- PTS: TOPFLOW (SET) and ROSA (IET)
- Pool HX: LINX test: bubble plume with recirculation cell and free surface
- Steam injection in a pool: GIRLS test (KAERI) : Velocity and turbulence measurements around the steam jet
- Fire analysis: ICMFP benchmark exercise # 3 (400-2300Watt, $V=580m^3$ $H=3.8m$)

Foundations of BPG

Some BPG taken from single phase CFD are applicable to 2-phase and will be reported

- Strategies to Reduce Numerical Errors
- Strategies to Reduce Model Errors
- Strategies to Reduce User Errors (required expertise)
- Strategies to Reduce Software Errors (Verification tests)
- Strategies to Reduce Application Uncertainties

Some recommendations are based on the general methodology for applying two-phase CFD to NRS

And… most of the work has still to be done as long as 2-phase CFD will be developed assessed, applied