NEPTUNE_CFD
Multi-phase local CFD
Outline

- Local two-phase thermal-hydraulics challenges
- Development framework: NEPTUNE project
- Overview of NEPTUNE_CFD
- Some applications
- Perspectives
Local two-phase TH challenges

- Nuclear thermal-hydraulics
  - Involved in many design, competitiveness and safety issues of NPP

- Component and system scales
  - Improved models and closure terms, validation against new experiments
  - Extension of 3D and coupling capabilities (e.g. CATHARE 3)

- The advent of CMFD
  - Improved knowledge of local flow phenomena is a key issue for numerous design and safety issues
    - Fuel efficiency: with respect to Critical Heat Flux, design of spacer grids, CHF occurrence itself (thermal mixing, wall-to-fluid transfer, CHF prediction)
    - Pressurized Thermal Shock, involved in plant life-extension (mixing in stratified two-phase flow)
    - Many others: SG Tube vibrations, CRUD deposition, cavitation,…
Major challenges: CHF in PWR

- **Critical Heat Flux**: value of heat flux leading to fuel rod damage
  - DNB occurs: Departure from Nucleate Boiling
  - A vapour film isolates the fuel from the water: the fuel heats up sharply and suddenly

**Heat Flux**

![Heat Flux Diagram](diagram)

- Basic physical mechanisms not yet really understood
- → Get reliable CFD simulations for boiling bubbly flows in fuel assemblies
Major challenges: PTS in PWR

Overview of PTS (Pressurized Thermal Shock) issue

- In case of a LOCA, safety injections feeds cold legs and vessel downcomer with (really) cold water
- The induced thermal shock is a risk for vessel mechanical resistance, increased by material ageing (fluence)
- Local temperature evolution in the pressure vessel wall is a key parameter for the structural analysis
The NEPTUNE project: EDF/CEA/IRSN/AREVA-NP joint development programme since 2001

- To meet the industrial needs in the field of nuclear thermal-hydraulics
- By preparing the new generation of industrial two-phase flow codes

The objective of the software platform is to address:

- The whole range of modelling scales
- Multi-scale and multi-disciplinary calculations
- Industrial studies as well as R&D work

WP structure

- Software development
- R&D: models and numerical methods
- Experimental programmes: validation
The NEPTUNE project

Resources

- ~25 men.year per year (2/3 CEA, 1/3 EDF), 5 PhD, 5 sites
- 2011 Funding shares: 50 % EDF, 30 % CEA, 10 % IRSN, 10 % AREVA NP

3 complementary axes for a qualified software
Overview of NEPTUNE_CFD

- Development team: EDF and CEA
  - Development, validation, maintenance, installation, training, hot-line

- Users (~50)
  - EDF, CEA, IRSN, AREVA-NP
  - Academic collaboration (IMFT)
  - European projects partners (NURISP)

- Main features
  - 3D and local two-phase flow analysis
  - Generalized multi-field model
  - Physical models
    - Turbulence (k-ε and RSM)
    - Interfacial area and polydispersion models
    - Set of models for boiling bubbly flows
    - Set of models for stratified steam-water flows
    - Conjugate heat transfer
  - Numerics
    - 3D fully unstructured cell center Finite Volume
    - Iterative coupling of equations
    - Parallel by distributed memory (domain splitting)
Verification & Validation strategy

- Physical and numerical benchmarks
  - Definition of tests cases and acceptability criteria
  - Classical benchmark and more complex cases

- Physical validation for boiling bubbly flows (for DNB)
  - Existing data for adiabatic and boiling bubbly flows
  - New comprehensive experimental programs
    - Adiabatic bubbly flow tube
    - Adiabatic bubbly flow bundle+grid
    - Condensation tube
    - Convective boiling flow tube
    - Global tube
    - Global bundle+grid

- Physical validation for PTS-related models
  - Validation on existing experiments
  - New dedicated international program (TOPFLOW-PTS)
Application to mixing grid analysis

- **Objectives**
  - Gain knowledge about the two-phase boiling flow through a spacer grid with mixing vanes
  - Assess the impact of turbulence models on the target variables supposed to be related to DNB (max void fraction at the wall, max wall temperature, mixing efficiency, ...)
  - Impact of vane orientation on the target variables

- **Configuration**
  - 2x2 bundle, simple grid
  - PWR core conditions penalised to cause boiling
    - 155 bar; 330 °C; 3000 kg/m²/s; 1.6 MW/m²
    - Vapor fraction up to 70%
  - Meshes: 1.5 to 7.6 Mcells

![spatial grid with mixing vanes](image)
Application to mixing grid analysis

- Void fraction and liquid velocity
  - Downstream mixing vanes

Visualization of the “anti-void” effect of the vanes

Difference between the 2 turbulence models results
- Strong underestimation of rotation by k-ε
- Void fraction slightly higher with RSM
- Temperature gradient higher with RSM
Application to mixing grid analysis

Future work

- Full length 5x5 bundle with detailed grid
Application to PTS analysis

- In incidental transients such as LOCA, cold water is injected into the cold leg ➔ potential Pressurized Thermal Shock

- Compared to (1D) correlations approaches, validated (3D) CFD codes + conjugate heat transfer shall provide
  - Improved precision
  - Reduced conservatisms

- Methodology
  - System scale (CATHARE) one way coupling
  - 3D CFD + conjugate heat transfer
  - Structural analysis

- Objective: extend the methodology to two-phase configurations
Application to PTS analysis

- Complex CFD modelling with steam & water in the hot leg
  - Free surface + Friction + Turbulence
  - Jet + Bubble entrainment + Turbulence
  - Condensation + Turbulence

- Need for validation
  - Start with existing COSI experiment (cold leg 1:5, downcomer 1:100 in volume)
    - Two-phase flow with cold jet and direct condensation
    - Liquid temperature and global condensation
Application to PTS analysis

- **UPTF experiment** (full scale 1300 Konvoi; air / water: no condensation)
  - Thermal mixing with free surface
  - Conjugate heat transfer (SYRTHES)

- **New integral experiment with all the physics**: TOPFLOW-PTS (HZDR, EDF, CEA, IRSN, AREVA, PSI, ETHZ)
  - Pre-test NEPTUNE_CFD computations used to adjust the test matrix
Application to PTS analysis

First test of full scale two-phase scenario (2005): 900 MWe CPY 2” LOCA) with

- System scale (CATHARE) one way coupling; 3D CFD + conjugate heat transfer; Condensation
Some other applications in progress

- Containment
  - Spray modeling
  - Wall condensation
  - Gas mixing

- Cavitation and valve qualification
  - Pressure constraints
  - Thermal shocks
  - Cavitation

- High fluxes device (fusion)
  - Very high-heat fluxes
  - Special CHF-increasing designs

Some profitable contributions to NEPTUNE_CFD:

- The European Project NURESIM: 01/02/2005 – 31/12/2008
  - 18 partners: EDF, CEA, FZD, GRS, UCL, JSI, KFKI-AEKI, NRI, U-Pisa, VTT, LUT, PSI, ASCOMP, KTH, UNI-KA, TU-Delft, UP-Madrid, INRNE

- 13 partners using NEPTUNE_CFD (Thermal-Hydraulics WP)
  - Some contributions to NEPTUNE_CFD
  - Verification: NURESIM enables to increase the quality of NEPTUNE_CFD
    - Eg.: corrections thanks to comparisons by KFKI (VVER)
  - Benchmark and validation
    - Numerous comparisons on various test-cases
  - First developments in NEPTUNE_CFD, very early in NURESIM
    - Eg.: wall functions, surface tension, …
  - Framework to better know the partners and exchange technically
    - Eg.: technical exchanges with JSI and UCL
  - NEPTUNE_CFD supports the comparison to FLUENT/CFX
    - Eg.: 3 users (UCL, PSI, JSI) mention the good numerical performance of NEPTUNE_CFD compared to FLUENT and CFX
...Thank you for your attention...

Reference (general)


NEPTUNE_CFD balance equations

- Basis: classical two-fluid one pressure approach, including mass, momentum and energy balances for each phase, extended to \( m \) phases:

Two mass balance equations:

\[
\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k V_k) = \Gamma_k
\]

Two momentum balance equations:

\[
\frac{\partial \alpha_k \rho_k V_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k V_k V_k) = -\alpha_k \nabla p + M_k + \alpha_k \rho_k g + \nabla \cdot \left[ \alpha_k \left( \sum_k + R_k \right) \right],
\]

Two total enthalpy balance equations:

\[
\frac{\partial}{\partial t} \left[ \alpha_k \rho_k \left( h_k + \frac{V_k^2}{2} \right) \right] + \nabla \cdot \left[ \alpha_k \rho_k \left( h_k + \frac{V_k^2}{2} \right) V_k \right] = \alpha_k \frac{\partial p}{\partial t} + \alpha_k \rho_k g V_k
\]

Wall transfer model for nucleate boiling

Reynolds stress tensor

The interfacial transfer terms of mass, momentum and heat.

turbulent heat flux