USE OF CFD FOR IVR STUDIES

C. Le Guennic, K. Atkhen, M. Guingo, J. Laviéville

Technical Meeting on Phenomenology and Technologies Relevant to In-vessel Melt Retention and Ex-vessel Corium Cooling

Shanghai, 18/10/2016

SOMMAIRE

1. **INTRODUCTION AND SCOPE OF THE PRESENTATION**

2. **ADDED VALUE OF CFD**

3. **CORIUM POOL BEHAVIOR**
   3.1. BIBLIOGRAPHIC REVIEW
   3.2. THIN LAYER
   3.3. HOMOGENEOUS POOLS

4. **EXTERNAL COOLING**
   4.1. BIBLIOGRAPHIC REVIEW
   4.2. VALIDATION DATA

5. **PERSPECTIVES**

1. INTRODUCTION AND SCOPE OF THE PRESENTATION

- **In-vessel retention (IVR) is one of the possible SA mitigation strategies**
  ⇒ already implemented in several reactors currently operating (VVER440) or under construction (AP1000, APR1400, CPR1000+…)

- **In Europe, the feasibility of IVR for high power reactors still needs to be demonstrated**
  - Uncertainties regarding corium behaviour
  - Penalizing hypotheses lead to an **over conservative assessment** of the thermal loads

- **The IVMR project was launched to "improve the methodology by reducing the degree of conservatism in order to derive more realistic safety margins".**
  ⇒ extensive program covering experimental faculties and integral codes, but also the **possible uses of CFD**.

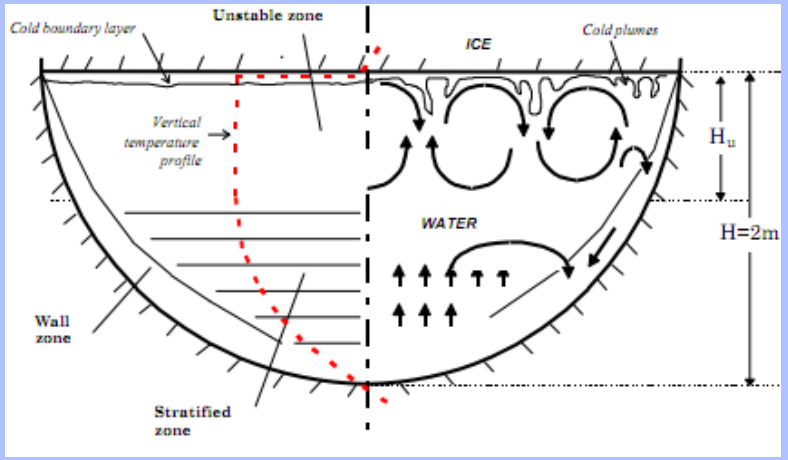
- **This presentation will focus on the work performed at EDF, partly in the frame of the IVMR project, using the NEPTUNE_CFD software.**

2. ADDED VALUE OF CFD

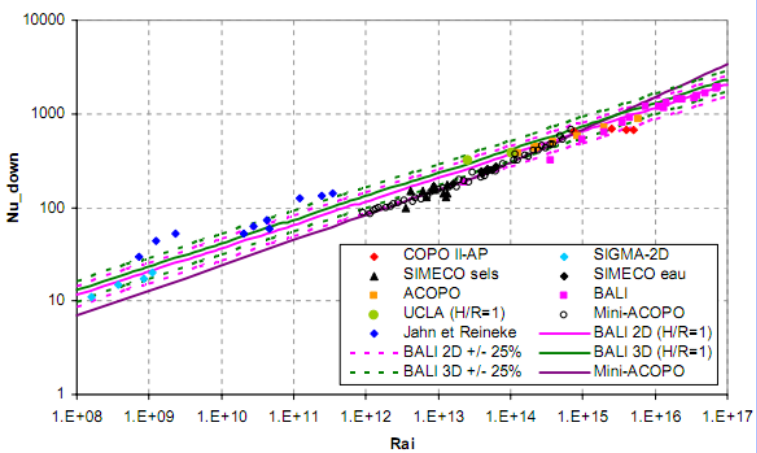
- **Some SA-relevant phenomena cannot be studied experimentally, because of:**
  - Technological barriers, especially for instrumentation or heating technology.
  - Costs.
- **Knowledge about these phenomena could be improved through the use of CFD**
  - Wide range of possible applications, fast, flexible and cost efficient, but needs to be validated for SA applications.
  - Results could be used to **refine existing assumptions** and correlations.
  - Potential **safety margins** have been identified.
- **We will discuss the 2 following issues:**
  - In-vessel **corium pool** behaviour (relevant for transient thermal loads)
  - **External vessel cooling** (affects the coolability limits).
- **What is out of scope for now?**
  - thermochemical phenomena
  - crust behaviour, freezing/melting of the pool (although some softwares can handle it)

3.1. BIBLIOGRAPHIC REVIEW ON CORIUM POOLS 1/3: EXPERIMENTS

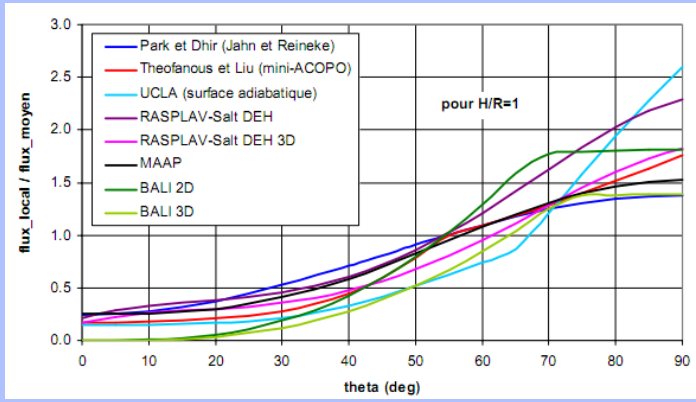
- **Homogeneous pools**
  - Many **simulant based** experiments of varying geometries and scales (from 1/16th to full-scale).
  - Mostly 2D, but some scaled 3D experiments as well: ACOPO (without heating), LIVE, SIGMA.
- **Key results**
  - Heat flux **correlations**: mean upward heat flux, mean downward heat flux, local lateral heat flux.
  - **Flow structure** and heat transfer mechanism in the upper part (Bernaz, et al., 2001).
  - Main focus on heat transfer at the pool boundaries: the **thermalhydraulics** have only been investigated by a few experiments (Jahn & Reineke, BALI).



BALI tests: flow structure



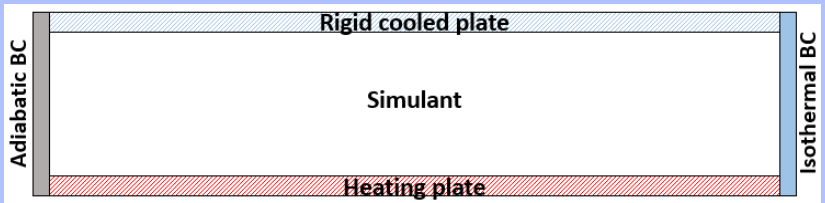
(Tourniaire, et al., 2008): Nu_{dn} as a function of Ra_i



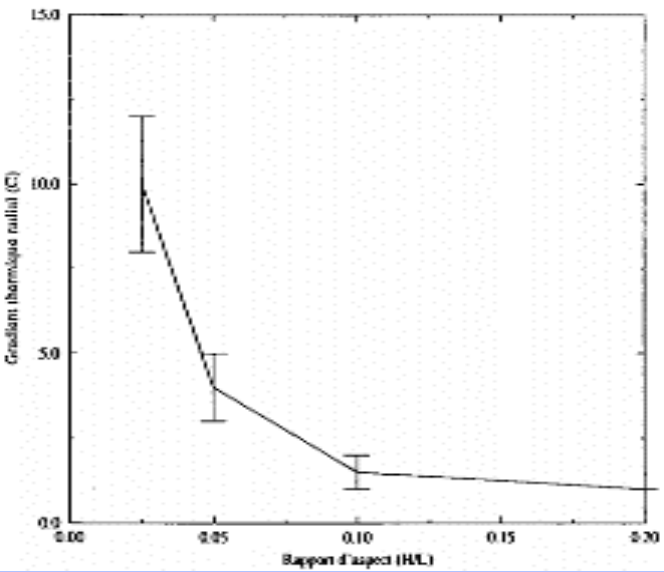
(Tourniaire, et al., 2008): Normalized lateral heat flux profile

3.1. BIBLIOGRAPHIC REVIEW ON CORIUM POOLS 2/3: EXPERIMENTS

- **Thin metallic layer behavior: 2 specific experiments with similar principle**
  - MELAD (UCSB)
  - BALI-Metal (CEA)
- **Key results:**
  - Observation of a **radial temperature gradient** that increases with diminishing aspect ratio
  - **Periodic alternance** between two flow regimes: monocellular and split cell
  - Clear **confirmation of the focusing effect**: the $\varphi_{lat}/\varphi_{in}$ ratio increases when the aspect ratio decreases.
- **Bénard-Marangoni convection is not accounted for**
  - Increases upward heat transfer.
  - Significant impact for layer depths of 3-4 cm.



Principle of the MELAD and BALI-Metal installations



(Villermaux, 1999): radial temperature gradient in the BALI-Metal tests

H	P_{lat}	P_{sup}
0,05	15%	85%
0,10	25%	75%
0,20	45%	55%
0,40	60%	40%

(Villermaux, 1999): BALI-Metal power split as a function of height

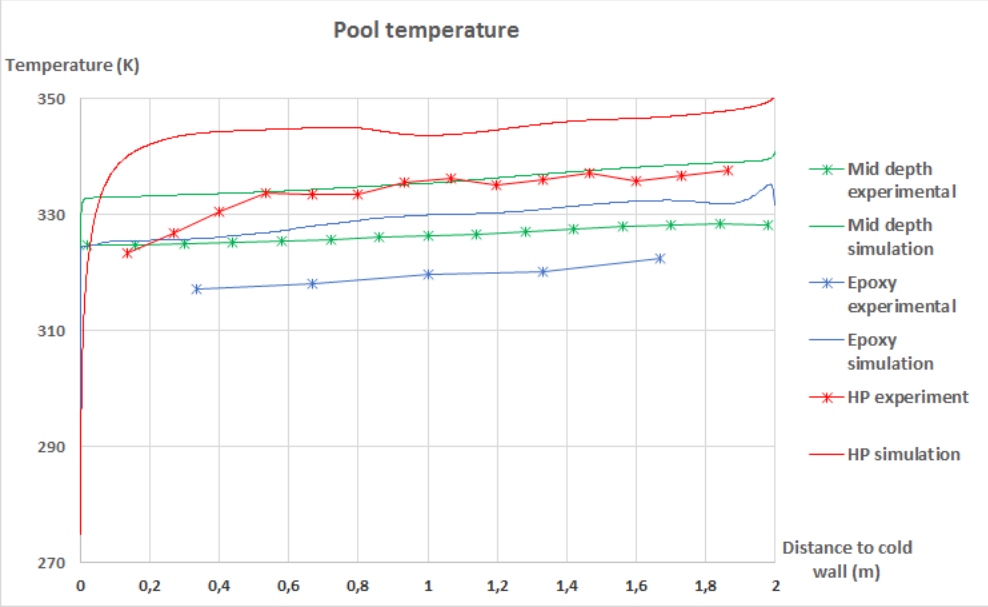
3.1. BIBLIOGRAPHIC REVIEW ON CORIUM POOLS 3/3: MODELING

- **Integral codes use closure laws based on stationary Nusselt number correlations to evaluate the heat transfers in stratified pools:**
  - For internally heated fluids, the Nusselt number is correlated with the internal Rayleigh number; the correlations are drawn from specific simulant materials experiment (BALI, COPO, ACOPO, LIVE…)
  - For metallic layers without internal heating, the Nusselt number is correlated with the external Rayleigh number; the correlations are drawn from **separate effect** tests using simulants.

- **This modelling has several known issues:**
  - The correlations are based on steady-state results, and may not be suited to study the **transient evolution** of the pool;
  - The **scattering** of the correlations for high Rayleigh numbers produces significant discrepancies between codes;
  - The correlations for the thin metallic layer are not validated for low aspect ratios, and have been found to overestimate the lateral heat flux for thin layers.

3.2. THIN METALLIC LAYER 1/2

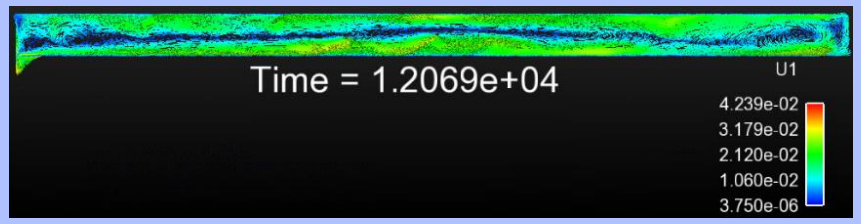
- **Objective: to assess the accuracy of current correlations for low aspect ratios and account for the effect of Bénard-Marangoni convection.**
- **Validation data: BALI-Métal tests (Villermaux, 1999)**
  - Well-known simulant, geometry, boundary conditions;
  - Valuable data on the **flow structure**.
  - Aspect ratios as low as 1/40th.
- **Simulations through a RANS approach, using a RSM turbulence model.**
- **First approach: pseudo-2D simulation**
  - Conservative but satisfactory power split (**30/70** instead of 25/75 experimentally).
  - **Adimensional numbers** within the right order of magnitude.
  - Good agreement of the **temperature profiles**.
  - Only the monocellular regime is observed ⇒ expected from the bibliographic data on natural convection in enclosures (Viskanta & al., 1987).



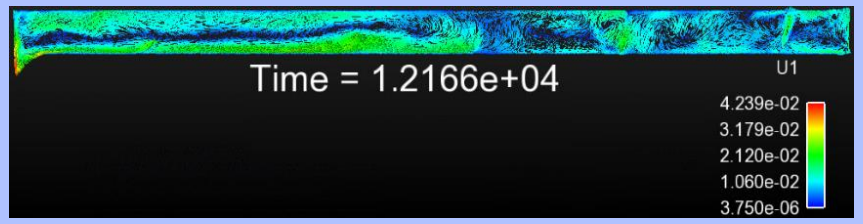
	Ra_{up}	Nu_{up}	Ra_{lat}	Nu_{lat}	Ra_{dn}	Nu_{dn}
Experiment	$4{,}95 \times 10^7$	68	$1{,}23 \times 10^9$	162	$6{,}60 \times 10^7$	65
Simulation	$6{,}63 \times 10^7$	58	$1{,}62 \times 10^9$	125	$8{,}47 \times 10^7$	65

3.2. THIN METALLIC LAYER 2/2

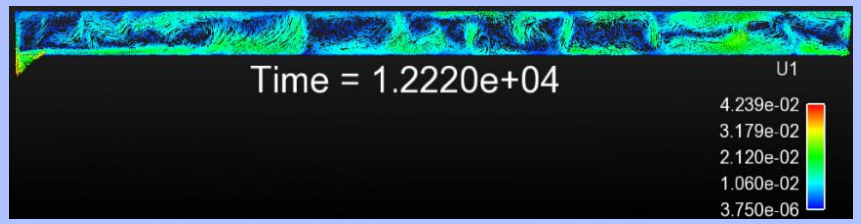
- **2nd approach: 3D simulation**
  - No significant impact on the power split or the temperature profiles.
  - The **flow alternance** is observed, and the global period of about 300 s seems to be correctly reproduced.



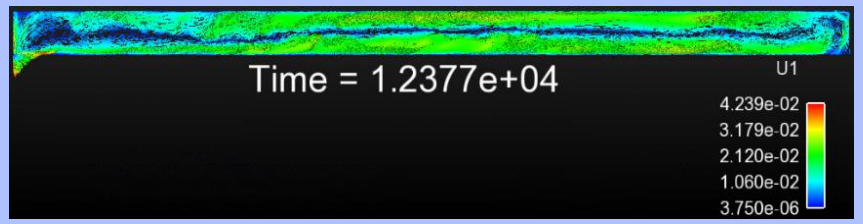
1) Established monocellular regime



2) Disruption of the monocell



3) Split flow



4) Return of the monocell

- **Questions remain regarding the applicability of these results to the prototypical case.**

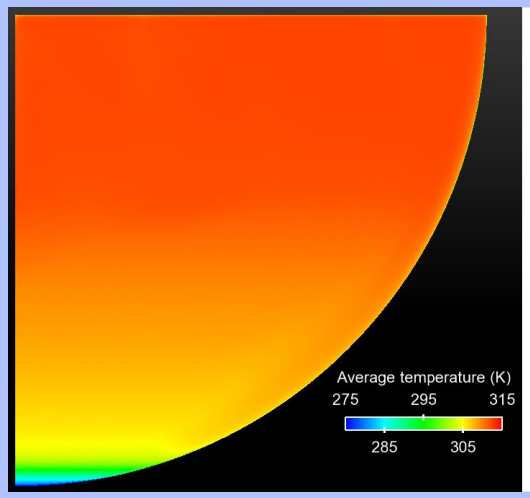
  ⇒ effect of the Prandtl number.

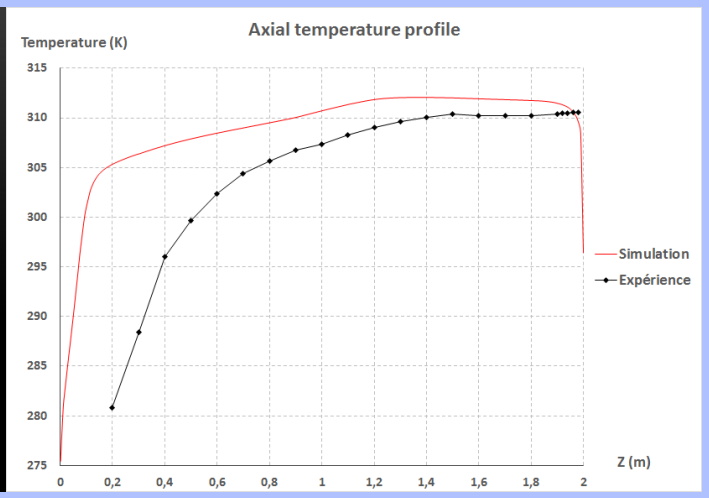
3.3. HOMOGENEOUS POOLS 1/2

- **Objective: to correctly reproduce the pool velocity field and power split before proceeding to the study of layer entrainment in stratified pools.**

- **Validation data: BALI tests (Bonnet & Seiler, 1999)**
  - Well-known simulant, geometry, boundary conditions;
  - Valuable data on the flow structure at prototypical Rayleigh numbers.
  - CFD computations have already been performed with encouraging results (Fukasawa & al., 2008).

- **3D RANS simulation using RSM turbulence models:**
  - Underestimation of the stratified zone thickness, leading to a more uniform axial temperature profile.
  - The adimensional numbers are all **within 15 %** of the experimental data.



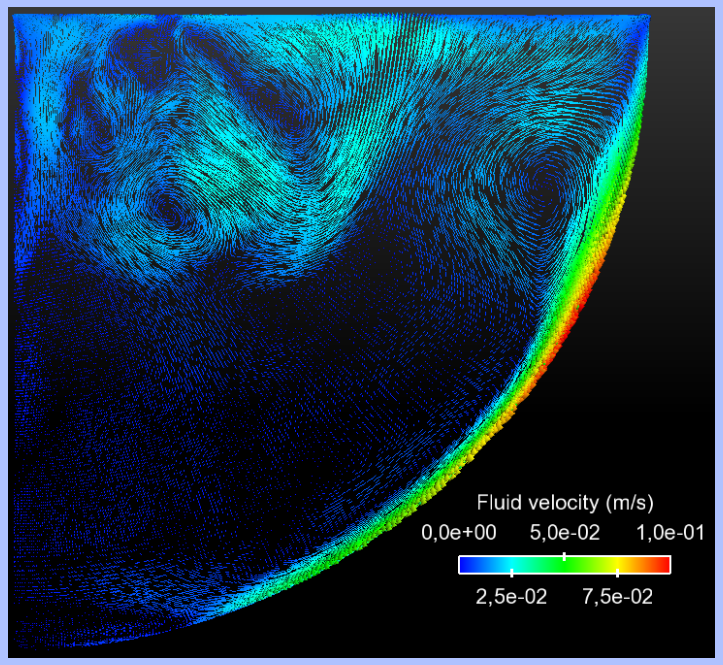


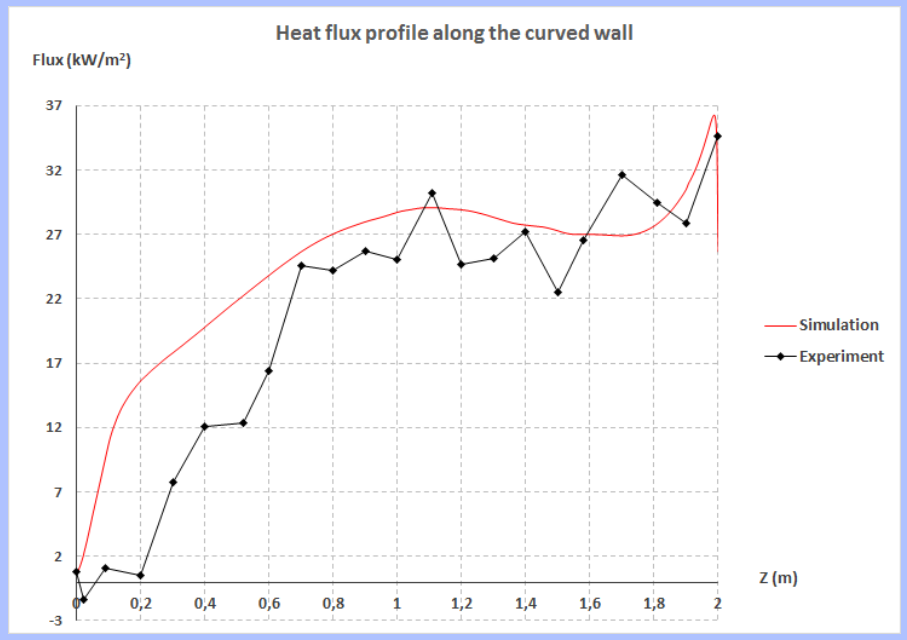
	Ra_i	Ra_e	Nu_{up}	Nu_{dn}
Experiment	$2{,}27 \times 10^{16}$	$3{,}75 \times 10^{12}$	2550	1430
Simulation	$2{,}37 \times 10^{16}$	$4{,}13 \times 10^{12}$	2260	1627

3.3. HOMOGENEOUS POOLS 2/2

- **Simulation results, continued:**
  - Good reproduction of the **general flow structure**; velocities seem to be underestimated in the descending boundary layer (up to 10 cm/s instead of “a few tens of cm/s” mentioned in reports).
  - The **power repartition** between the upper and lateral walls is satisfying: 43,4% up – 56,6% lat, compared to 43,0% up – 47,3% lat experimentally (the missing 10% in the experimental case can be attributed to heat losses and/or uncertainties).
  - The **lateral heat flux** profile compares well to the experimental data.

- **The applicability of these results to the prototypical case must be investigated.**





4.1. BIBLIOGRAPHIC REVIEW ON ERVC 1/2

- **The coolability limits are defined by the critical heat flux (CHF), whose values are strongly dependent on the local subcooling level, the superficial fluid velocity and the heated wall material.**

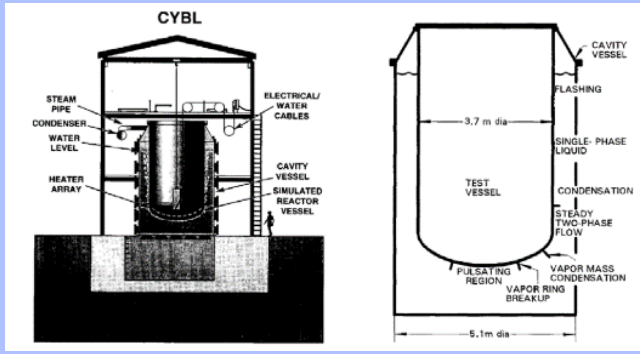
- **Certification processes generally rely on 2D-loops with full-scale height:**
  - Thanks to the prototypical gravity head, the experimental thermosiphon that takes place around the thermal insulator is:
    - Directly transposable to reactor situation when using a sector geometry.
    - Transposable after some corrections on the thermal load distribution when using a slice geometry.
  - Due to the **axisymmetric assumption**, the deviation of the streamlines caused by the discrete gap exits cannot be reproduced in a 2D experiment.

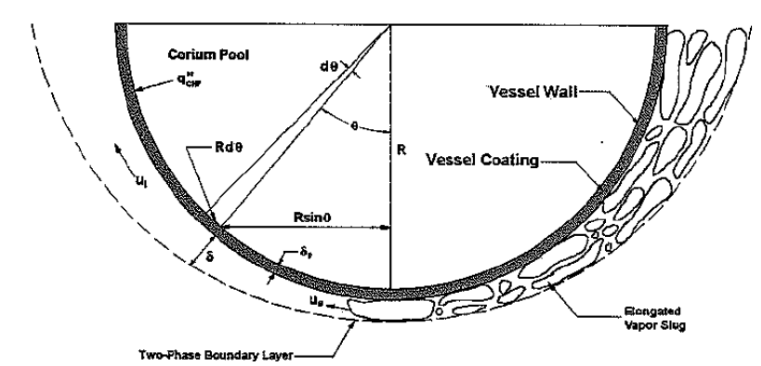
- **Tests with a simplified geometry also exist to develop a CHF correlation independent of a specific reactor geometry: SULTAN, MIT…**

Loop (host)	ULPU V (UCSB)	CERES (KFKI)	IVR loop (CNPRI)	REPEC_II (SJTU)	RESCUE-2 (CEA)
Reactor	AP1000	VVER440	CPR1000+	CAP1400	Low power reactor
Geometry	2D axi slice (1/84)	2D axi slice (1/40)	2D axi slice (1/80)	2D axi slice (1/80)	2D axi sector (1/40)
Heated wall material	Copper	Copper	Copper	Vessel steel	Vessel steel
Coolant	DI or tap water	DI water	DI water	DI water + BA + TSP	DI water

4.1. BIBLIOGRAPHIC REVIEW ON ERVC 2/2

- Very few **3D circulation loops** are available
  - CYBL experiment at SNL (1:1 scale) investigated the initial steam bubble growth at the bottom of the vessel.
  - A 3D 1:5 scale loop at CNPRI is under construction. If well instrumented, it may be a good opportunity to improve CFD code validation.

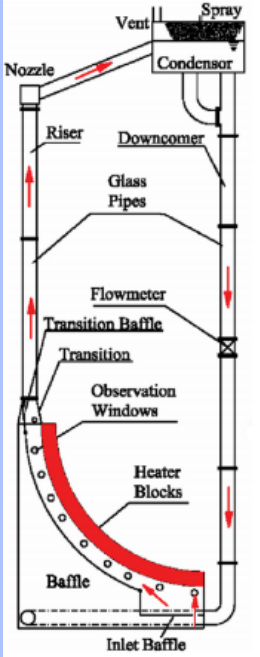




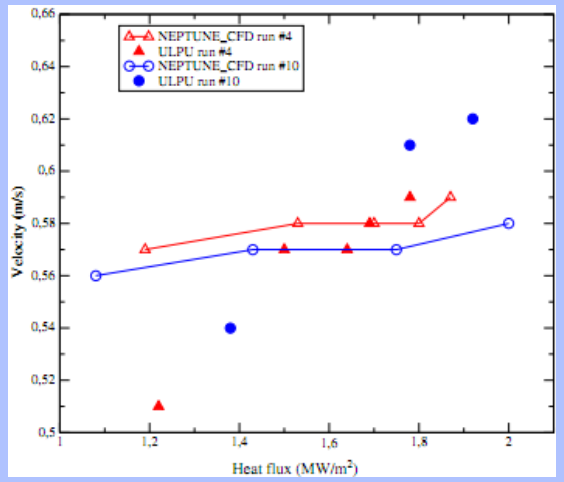
- **The use of sufficiently validated CFD tools can be useful:**
  - To explore **3D effects** in the upper part of the thermosiphon
    - Because of the low gravity head, this area is critical as some **flashing phenomena** may occurs, affecting the flow stability.
  - To assess overall coolability for a given configuration
    - A CHF correlation can be used in **post-treatment of CFD results**. Such a correlation should be made using prototypical vessel wall material and representative water chemistry (MIT-EDF collaboration).

4.2. VALIDATION DATA: ULPU EXPERIMENTS 1/2

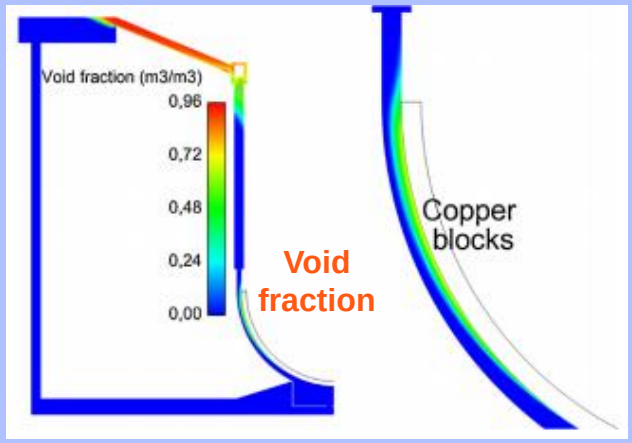
- **For natural circulation boiling flows at low pressures, validation of CFD codes is poor.**
- **The Neptune_CFD code has been validated on ULPU tests (Jamet & al, 2015)**
  - Good agreement on the superficial velocity (**<10%** discrepancy); the velocities do not exhibit the same sensitivity to the heat flux as in the experiment.
  - The differential pressures are generally well reproduced.
  - The void fraction evolution is conform to expectations.



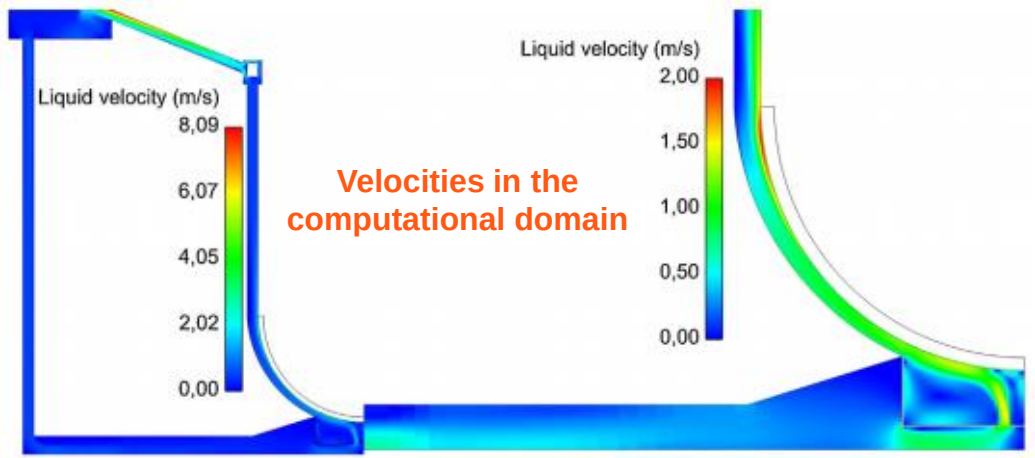
ULPU-V test section



Velocities in the downcomer



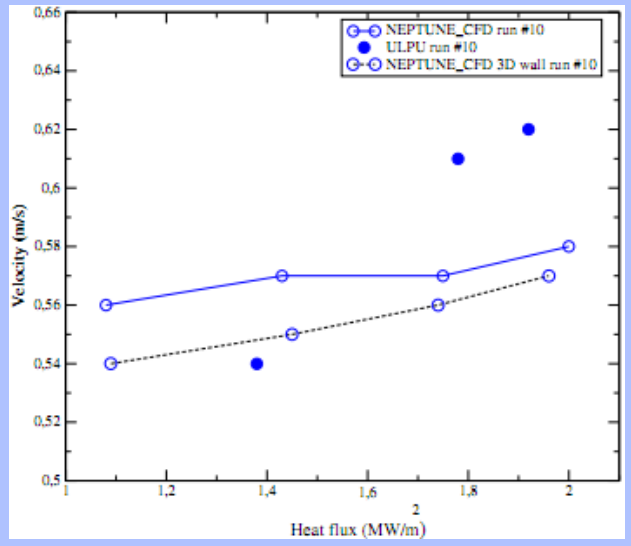
Void fraction



Velocities in the computational domain

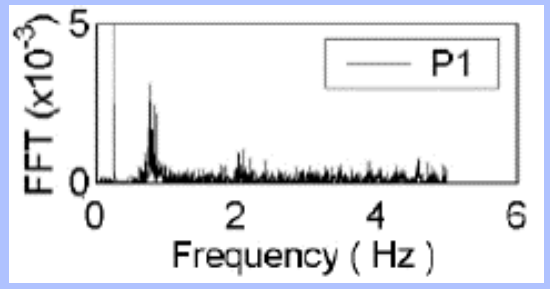
4.2. VALIDATION DATA: ULPU EXPERIMENTS 2/2

- 3D computations: few difference to 2D computations; the additional head losses lead to a reduction of the velocity.
- **Flow oscillations** can be reproduced through instationary computations.
- These results show:
  - a **mainly monophasic flow** (<50% void fraction) in the lower part of the loop;
    ⇒ the current physical modeling should be able to accurately reproduce the flow in this part.
  - a possible **flashing phenomenon** in the upper part of the loop
    ⇒ need for additional work to develop a model that can handle the transition between small bubbles, slug flow and stratified steam/water flow).

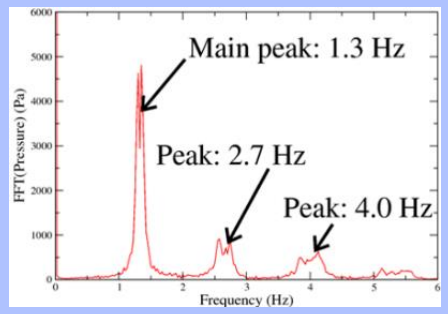


Impact of 3D meshing on the velocities in the downcomer

- **The results compare well to the available data, but the lack of local measurements (local void fraction, interfacial area density…) limits the validation.**



Experimental flow oscillations



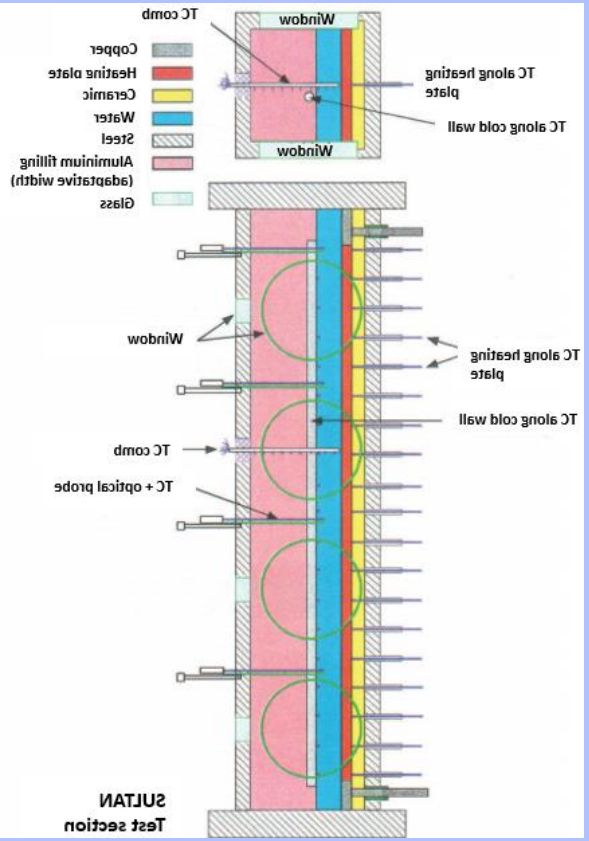
Simulated flow oscillations

4.2. VALIDATION DATA: SULTAN EXPERIMENTS

- **The SULTAN tests (Rougé, 1997) were chosen as validation data**
  ⇒ local measurement of the void fraction and fluid temperature.

- **First conclusions:**
  - A 3D simulation is necessary to account for the head losses caused by the front and back wall.
  - The 4-flux wall heat transfer model needs to be **re-calibrated for low pressures**; for the time being, the steam production is significantly overestimated.
  - A **thermal coupling** with a solid conduction code improves the stability and avoids unphysical temperature discontinuities along the heated wall.
  - Significant impact of the outlet boundary condition: can cause **recirculation** and disturb the temperature and void fraction profile.

- **Further code developments may be necessary.**



SULTAN test section

5. PERSPECTIVES 1/2

- **Beyond the scope of single-phase corium pool calculations:**
  - **mid-term perspectives:** multiphase CFD simulations for **layer entrainment** in a stratified pool with NEPTUNE_CFD;
    - First computations performed in April/May, with reasonable stability.
    - LM/oxide configuration in a full-scale 2D slice: typical PWR corium (properties assessed using MAAP) and pure iron as an approximation for the metallic layer.
    - Further computations are performed at EDF R&D Beijing to move towards more representative boundary conditions.
  - **long-term perspectives:** multiphase CFD simulations accounting for **thermochemical phenomena** (stratification inversion, crust formation, …)
    - will require specific CFD-compatible modelling developments
    - ongoing work at CEA regarding stratification kinetics.

- **External cooling:**
  - Continue CFD code validation on such flows, and work to better predict and compute the transition between bubbly flows and large steam slugs
    - Additional validation on the **SULTAN tests**
    - Relevant analytical tests are needed, provided they are equipped with **relevant instrumentation** (local void fraction, local phase velocities...)
  - Perform exploratory sensitivity calculations to try to **optimize the natural circulation loop** for a given geometry (ensure high stability and maximum superficial velocities).

5. PERSPECTIVES 2/2

- **Additional R&D is necessary to obtain relevant data**
  - Determination of corium properties is a prerequisite for future prototypic computations
    - IVMR project: VITI tests will be performed to measure the **viscosity and surface tension** of the light metallic layer.
    - SAFEST project: tests have been proposed at the FLF facility to gain information on the **spectral emissivity** of the metallic layer under an **oxidizing atmosphere**.
      - so far, tests have only been performed under an **inert atmosphere**.
      - **important dispersion** on this parameter between various integral codes.
  - Behaviour of stratified pools
    - KTH/KIT tests to be performed at the SIMECO and LIVE facilities
      - main focus on **heat transfer between layers**.
      - data could eventually be used for further CFD code validation
    - Ongoing technological R&D at XJTU on layer entrainment in stratified pools
      - main focus on **thermalhydraulics and phase entrainment**.
      - If the preliminary study yields positive results, simulant based stratified pool tests could be performed at the COPRA facility.

6. CONCLUSION

- **Models implemented in current SA codes are very conservative for in-vessel pools.**
  ⇒ demonstrating the feasibility of IVR for high power reactors may require gaining some margins.

- **CFD tools could bring additional insights (transient behaviour, coolability limits) and help for optimization, but need to be validated first.**

- **The first results on simulant experiments are rather encouraging, especially for corium pools.**

- **Additional data will be needed for future prototypic computations:**
  - input data, both experimental and from integral computations
  - validation data from new or as yet unexploited experiments.

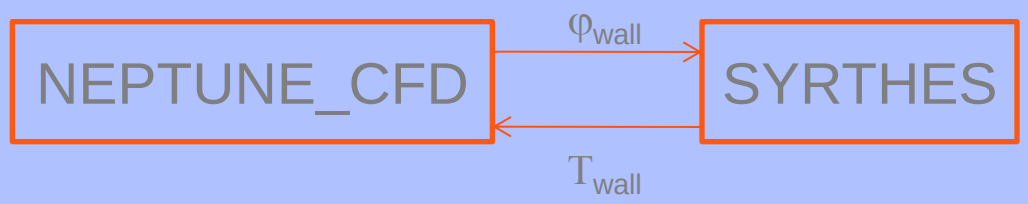
- **Satisfying progress has been made in the past year, opening up interesting prospects for future applications.**

- **The transition to prototypic materials remains the key difficulty.**

Thank you for your attention. Questions?

REFERENCES

- Bernaz, L., Bonnet, J.M., Seiler, J.M., 2001. “ Investigation of natural convection heat transfer to the cooled top boundary of a heated pool ”, *Nuclear Engineering and Design, vol. 204, pp 413-427*.
- Bonnet, J.M., Seiler, J.M., 1999. “ Thermal hydraulic phenomena in corium pools: the BALI experiment ”, *Proceedings of the 7th International Conference on Nuclear Engineering (ICONE 7), Tokyo, Japan*.
- Fukasawa, M., Hayakawa, S., Saito, M., 2008. “ Thermal-Hydraulic analysis for inversely stratified molten corium in lower vessel ”, *Journal of Nuclear Science and Technology, vol. 45, pp 873-888*.
- Jamet, M., Laviéville, J., Atkhen, K., Mechitoua, N., 2015. « Validation of NEPTUNE_CFD on ULPU-V experiments », *Nuclear Engineering and Design, vol. 293, pp 468-475*.
- Rougé, S., 1997. “SULTAN test facility for large-scale vessel coolability in natural convection at low pressure”, *Nuclear Engineering and Design, vol. 169, pp 185-195*.
- Tourniaire, B., Dufour, E., Ratel, G., Spindler, B., 2009. “ Synthèse sur la thermohydraulique des bains de corium pour les configurations en cuve ” (Synthesis on corium pool thermalhydraulics for in-vessel configurations), *CEA technical document CEA/DEN/GRE/SE2T/LITA/NT2009-006/0*.
- C. Villermaux, 1999. “ Physical and numerical modelling of natural convection in a low aspect ratio fluid layer in the frame of severe accident studies for pressurized water reactors ”, PhD thesis (in French), Institut National Polytechnique de Grenoble.
- Viskanta, R., Kim, D.M., Gau, C., 1986. “Three-dimensional natural convection heat transfer of a liquid metal in a cavity”, *International journal of Heat and Mass Transfer, vol. 29, pp. 475-485*.

PRESENTATION OF THE NEPTUNE_CFD CODE

- **3D-local CFD code developed since 2001 in the framework of the NEPTUNE project with support from EDF, CEA, IRSN and AREVA**
- **Initially developed and validated for nuclear applications such as pressurized thermal shock and departure from nucleate boiling, with two major sets of models: bubbly flow and free surface flow**
- **Based on a multi-fluid, one-pressure formulation; the solver ensures mass, momentum and energy conservation for each phase**
- **Possibility of coupling at each time step with the SYRTHES code for the resolution of thermal transient in solid materials**