EXPERIMENTAL RESULTS FROM A WATER SCALE MODEL FOR THE THERMAL-HYDRAULIC ANALYSIS OF A HLM REACTOR

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ABSTRACT

The thermal-hydraulics challenges of a nuclear reactor are numerous and crucial to be investigated for the design and safety of new reactors. Numerical simulation through computational fluid dynamics codes or system codes can address a lot of the different challenges, nevertheless the use of water modeling for the study and validation of the thermal-hydraulic behavior of a new primary circuit design remains a very valuable tool. A water model of the heavy liquid metal (HLM) cooled MYRRHA reactor was developed at the von Karman Institute in collaboration with SCK•CEN and has been named MYRRHABELLE. It is a full Plexiglas model at a geometrical scale 1/5 of primary system (design version 1.2) of MYRRHA. The scaling was performed by respecting the Richardson and the Euler similarity with the HLM reactor. A detailed description of the model and of the scaling procedure is provided in this paper. A transparent water model allows the application of non-intrusive optical measurement techniques for the flow characterization like Particle Image Velocimetry (PIV) for velocity and turbulence intensity measurements. The first results of PIV performed at the outlet of the ACB (Above Core Barrel) provide the flow pattern and the turbulence intensity map at the different outlet holes. Thermal measurements using thermocouples characterize the temperature profile at the outlet of the ACB and show the influence of the Richardson number. The thermal-hydraulic behavior of MYRRHABELLE is also simulated with CFD. The measurements performed inside the water model provide first input to a database for validation of CFD codes.

KEYWORDS
MYRRHA, water modeling, Richardson number, PIV, validation

1. INTRODUCTION

The thermal-hydraulics challenges in the design of innovative nuclear reactors are still numerous. The attendance and the number of publications of the bi-annual NURETH conferences show that it remains a hot topic [1]. It is obvious that thermal-hydraulics is a key point for the design and safety of reactors. The use of system codes or computational fluid dynamics (CFD) tools can address a lot of the different challenges and the capabilities of CFD codes to simulate multi-physics phenomena continuously increase but nevertheless, the use of water modeling for the study and validation of the thermal-hydraulic behavior of the primary circuit remains a very valuable tool. Some complex physical phenomena might be discarded in CFD simulations and therefore a physical model is needed to provide the required information and also the necessary validation data for CFD codes. We present hereunder a bibliographic review of water modeling of innovative nuclear reactors. Afterwards, we review the main scaling criteria when dealing with water modeling of heavy liquid metal (HLM) reactors and we present the water model that has been built to investigate the flow of the primary circuit of the lead-bismuth cooled MYRRHA reactor [2]. Thermal-hydraulic results are presented in the second part of the paper, mainly focused on the outlet of the Above Core Barrel (ACB). To our knowledge, it is the first time that the PIV technique is used to characterize the flow field inside the upper plenum of a pool-type primary circuit. Temperature results obtained with thermocouples complete the thermal-hydraulic characterization at the outlet of the ACB.

2. WATER MODELING OF LIQUID METAL COOLED NUCLEAR REACTORS

Water modeling of the primary circuit of nuclear reactors has been used to study the thermal-hydraulic challenges faced when developing new reactors [3, 4, 5]. Water modeling studies focused on the global thermal-hydraulic behavior in the upper plenum and lower plenum were performed for the development of Sodium cooled Reactor in France, Germany, India and in Japan:
-The water models COLCHIX (scale 1/8) and JESSICA (scale 1/3) have been built by the CEA [4] to study the flow field in the above core region under steady-state condition and in transient regimes. Temperature evolutions in the above core were measured at the same time as the upper plenum temperature evolution. In the transient regime, where buoyancy plays an important role, the Richardson number in the water model had to correspond to the value of the reactor. A separate water model, named COCO (scale 1/10) was used for the study of the thermal-hydraulics in the lower plenum.
-A water model of the Japan Sodium-cooled Fast Reactor (JSFR) at scale 1/10 has been built to study natural circulation decay heat removal [5]. The model was built to address issues in natural circulation operating conditions identified by performing first simulation tests.
- The RAMONA & NEPTUN water facilities (scale 1/20 and scale 1/5 respectively) have been developed in Germany to simulate sodium flows. The two different scaling has allowed the study of scaling effects.
- A recent theoretical and numerical study performed by X.N. Chen [6] showed that it is possible to hold Reynolds and Richardson similarities with water modeling of LBE flow, by choosing the appropriate inlet and outlet temperature of the water model. However, temperatures above 100°C are needed, leading to a pressurized water model.

A lot of thermalhydraulic challenges can be addressed by using water modeling of the upper plenum and lower plenum of a HLM reactor.
In the upper plenum, the global velocity field and temperature distribution can be measured in nominal conditions but also in accidental scenarios. By measuring velocity profiles and temperature profiles at different locations, it is possible to identify the presence of flow unsteadiness and thermal stratification. Water model tests can also be used to detect free surface oscillations which might induce thermal fatigue on the different structures immerged in the upper plenum. The behavior of bubbles or particles escaping from the core of the reactor can be investigated and used to validate CFD simulations of accidental scenarios. Finally the flow patterns in non-symmetric situations can be measured and investigated.
In the lower plenum, the water model provides important data on the dissipation of the swirl created by the rotating pumps. The tri-dimensional flow patterns can be measured and used to validate or fine-tune CFD simulations. Stagnation regions of low velocity but high turbulence can also be identified easily and the flow patterns in non-symmetric situations can be investigated. Bubbles and particles (lighter or heavier than water) can also be injected to study the flotation or decantation in case of an accident.

2.1. Scaling criteria

A water model of a HLM reactor with the foreseen dimensions of MYRRHA needs to be scaled down. They are some evident scaling requirements but the main scaling criteria are based on dimensionless numbers, which allows the extension of the results to the full HLM reactor.

Major scaling requirements

The major scaling requirements are the following;

- The overall behavior in the prototype plant should be preserved (geometrical scaling).
- The major thermal-hydraulic phenomena should be reproduced.
- The scale of the water model must be sufficiently high to be able to represent the detailed features of the reactor.
- The balance between buoyancy fore and pressure losses must be preserved when studying natural convection.
- The balance between heat generation and heat cooling must be preserved.
- The water model should be built at a reasonable cost.

Two modes of operation have been considered for the water model:

- Simulation of the nominal operating condition (full power).
- Simulation of the natural convection in reduced power (decay heat removal after reactor shut-down).

Dimensionless numbers

The adimensional analysis and the scaling for the nominal conditions have been performed following the criteria presented in the different reference papers of S. Grewal [3], R. Kiang [7] and M. Ishii [8].
Hydrodynamic scaling requires that the geometry of the scaled model is similar, the boundary conditions are similar and that the Richardson number, the Euler number and the Reynolds number are the same. These last three numbers can be found in the dimensionless form of the momentum equation from the Navier-Stokes equations [8].

The geometric and boundary conditions similarity will be accomplished by appropriate facility design. The similarity of the Reynolds number is of second order. The flow regime should however be similar (turbulent flow), which can be achieved for Reynolds numbers higher than 10.000. The two important parameters remaining are the Richardson number and the Euler number.

The Richardson number is a measure of the significance of the fluid buoyancy relative to its inertia Eq.(1). The Richardson number, Eq.(4), can be expressed in terms of material properties and variables that describe the experimental facility: the length scale L (diameter of the core), the power Q and the mass flow rate M.

$$Ri = \frac{\beta \cdot \Delta T \cdot g \cdot L}{U^2} = \frac{Gr}{\mathrm{Re}^2} \qquad (1)$$

$$U = \frac{M}{\rho \cdot L^2} \qquad (2)$$

$$\Delta T = \frac{Q}{M \cdot Cp} \qquad (3)$$

$$Ri = \left(\frac{g \cdot \beta \cdot \rho^2}{Cp}\right) \cdot \left(\frac{Q \cdot L^5}{M^3}\right) \tag{4}$$

When the contribution of buoyancy to the flow is important, the Richardson number in the water model should be equivalent to the one of the HLM reactor.

Two additional criteria have been taken into account in the design of the water model:

1- The maximum power density that can be tolerated in the water test is determined from the requirement that there should be no boiling.

2- The velocities in the water experiment should be measurable within acceptable accuracy limits. Therefore, it is advisable to maximize the flow rate.

The Euler number is a measure of the significance of the pressure losses of the fluid relative to its inertia. The pressure losses include contributions from friction from the viscous flow in channels and from form losses due to orifices, obstructions and contractions. In a scaled water model, this number should be matched for the entire hydraulic circuit. This will be fulfilled by adapting form loss coefficients to compensate for changes in friction loss terms.
The main pressure losses in the HLM reactor are located in the core, in the heat exchanger and in the above core region. In the water model at the nominal condition, the velocity will be smaller (reduction by a factor 6.5) and the density will be 10 times lower; meaning that the dynamic pressure will be reduced by a factor close to 500. Therefore, the pressure loss inside the hydraulic circuit of the water model should be largely reduced. Special care has been taken during the design of the water model.

The non-dimensional equation for the transport of energy highlights the importance of the Péclet number in similarity rules. The Péclet number represents the ratio of the convective to conductive transport of energy. A reduction in scale is favorable for keeping the Péclet number; when using water to simulate lead-bismuth. It is even possible to satisfy fully the Péclet number similarity by reducing the operating velocity of the water model.

The adimensional analysis and scaling for the natural convection investigation has been performed following the criteria of Y. Eguchi [9]. The parameters which are allowed to change are the heating rate in the core and the cooling rate of the heat exchanger. However the balance between heat generation and heat cooling should be conserved. The requirements for Euler, Richardson and Heat Source number are automatically satisfied by setting the ratios of representative velocity and temperature difference.

The ratios of velocity and temperature are then given by relations Eq.(5) and Eq.(6). Time will also be scaled according to the ratio given by Eq.(7) which correspond to t=L/U.

$$U_r = \left(\frac{Q \cdot \beta \cdot g}{\rho \cdot C_p \cdot L}\right)_r^{\frac{1}{3}} \tag{5}$$

$$\Delta T_r = \left(\frac{Q^2}{\beta \cdot g \cdot \rho^2 \cdot C_p{}^2 \cdot L^5}\right)_r^{\frac{1}{3}} \tag{6}$$

$$t_r = \left(\frac{Q \cdot \beta \cdot g}{\rho \cdot C_p \cdot L^4} \right)_r^{\frac{1}{3}} \quad (7)$$

The ratio of the representative velocity can also be found by comparing the modified Grashof numbers [4].

3. MYRRHABELLE water model

3.1. Description

The water model designed and constructed at VKI, in collaboration with SCK•CEN, is a full Plexiglas model at a scale 1/5 of the primary circuit (design version 1.2) of MYRRHA. It has been named **MYRRHABELLE** for **MYRRHA B**asic S**E**t-up for **L**iquid F**L**ow **E**xperiments [10]. The model follows the in-vessel design and combines the lower plenum and the upper plenum with the diaphragm separating the two plenums (figure 1 and figure 2). It is equipped with 16 electrical heaters to simulate the core (maximum heating capacity of 48 kW), with two pumps immersed like in the MYRRHA design and with four water-cooled heat exchangers located in the upper plenum (nominal cooling capacity of 12 kW each). The free surface of the water model is at atmospheric pressure.

The water model is designated for a nominal water flow rate of 5.6 l/s but the flow rate can be increased to 10 l/s. The model is mainly built in Plexiglas for optical access. The maximum ΔT that is allowed during the tests is limited to 30°C (constraint on the Plexiglas). Based on these values, it is possible to simulate a Richardson number between 0.1 and 70 when performing water experiments.

The Reynolds number characterizing the water model is smaller than the Reynolds number of the real lead-bismuth reactor (factor 200), whereas the Péclet number is of the same order of magnitude (factor 2) when performing experiments respecting the Richardson number.

In natural convection, assuming a decay power of 5 MW in the real HLM reactor, the ratio of velocity between MYRRHA and MYRRHABELLE (Eq. (5)) is estimated to be equal to a value of 3. The ratio of temperature (Eq. (6)) is equal to 4, and the ratio of time scale is equal to 0.6, meaning that frequencies measured on the water model should be multiplied by 1.66 for extrapolation to the full-scale HLM reactor.

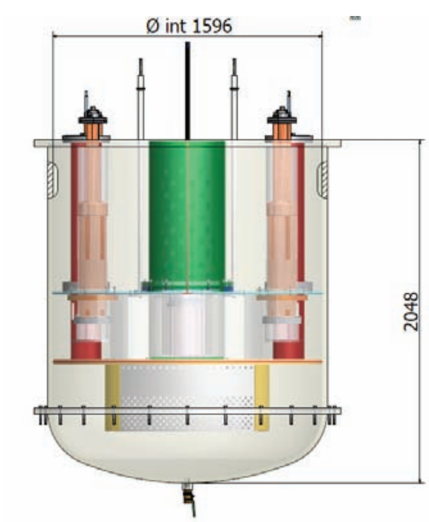

Figure 1. Overall dimensions of the model

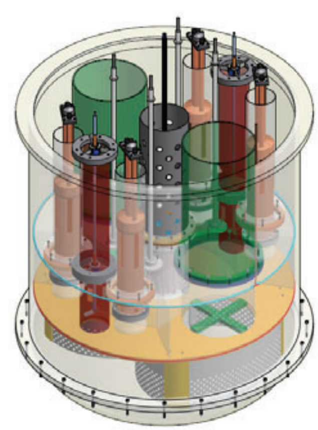

Figure 2. 3D view of the model

Figure 3 shows a picture of the water model representing the upper plenum illuminated by a Laser sheet for flow visualization. The heating elements used to simulate the heat source at the core level can be seen in the background, with the feeding electrical cables leaving slightly in zigzag the model at the level of the free surface. The electrical cable is inside the ACB and is the only obstacle above the heating zone (core). The different holes of the ACB can be identified in the figure.
One copper heat exchanger is clearly visible in the frontal part of the picture. One the left side of it, we can distinguish partially the immersed pump.

3.2. Operating conditions

The Richardson similarity can be achieved by adjusting the water flow rate (figure 4) for a specific power to obtain a similar Richardson value than in the different operating conditions for MYRRHA. Results are presented for two values of Richardson number (Richardson = 0.46 and Richardson = 3.7).

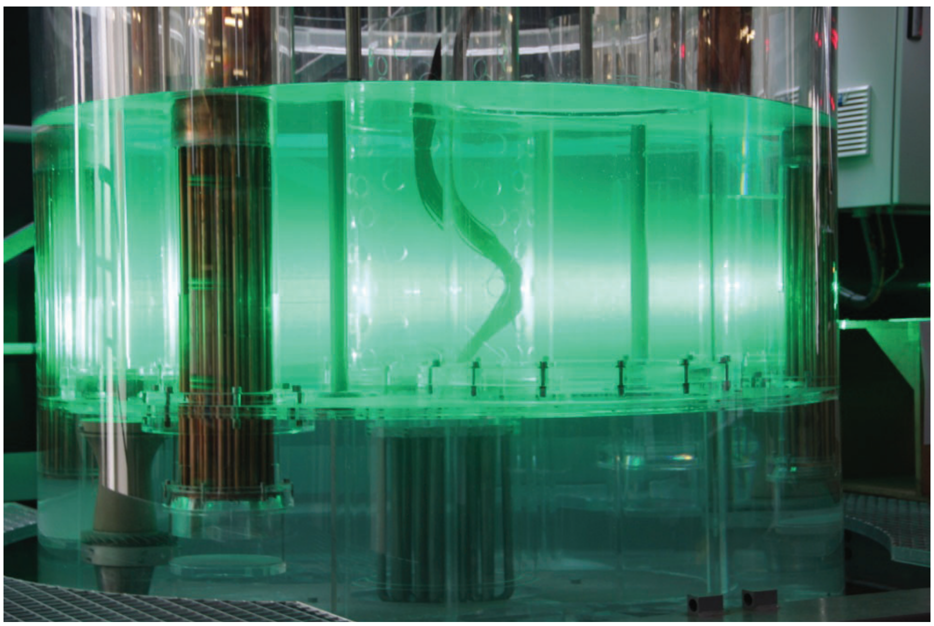

Figure 3. MYRRHABELLE water model

The Euler number has been respected by measuring the overall pressure loss of the loop and by adding an obstruction at the level of the core outlet to satisfy the global Euler similarity, taking into account the pressure losses of the heat exchangers and the core region. The flow through the by-pass of the core can be controlled with a sliding gate which allows the opening of the by-pass area to vary from 0% (no bypass flow) to 30 %. Depending of the opening of this by-pass, different Euler numbers characterizing the pressure loss at the core level of the water model can be obtained as shown in table 1. To expand the range of possible Euler numbers and obtain a better correspondence with MYRRHA, additional orifice plates at the core outlet are foreseen for future experiments.

Table 1. Core Euler number based on the pressure loss at the core level of the water model

	opening of by-pass			
	0%	9%	18%	30%
Euler number	181	174	160	132

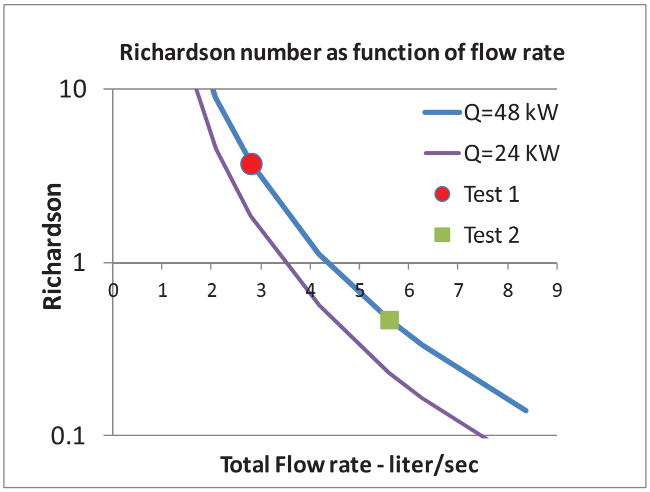

Figure 4. Richardson number as function of the water flow rate

3.3. PIV results

The flow field inside the upper plenum is measured using the PIV technique. 2D measurements have been performed in different planes. Results obtained in the plane shown in figure 5 are presented hereafter. The Laser sheet is created above the free surface by an optical bench and is illuminating the upper plenum from top to bottom (figure 6). The camera is placed on the side of the water model. Before recording the images, a calibration plate is positioned at the level of the measurement plane for an accurate computation of the image distortion and an appropriate spatial calibration.

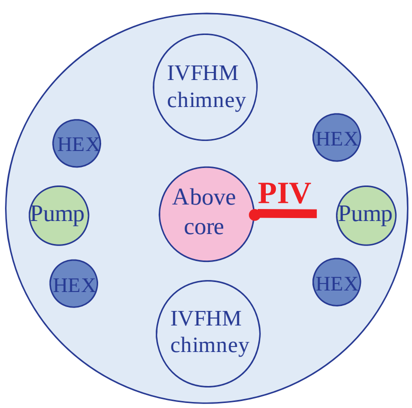

Figure 5. Position of the PIV measurement plane in the Upper Plenum

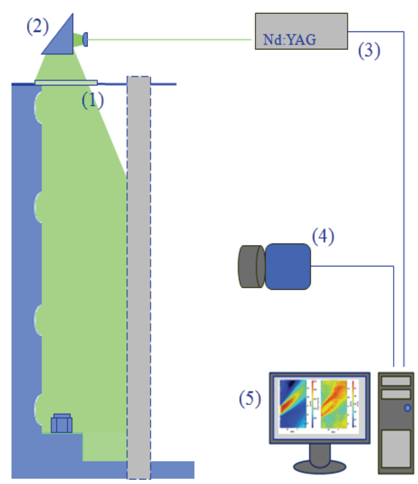

Figure 6. Schematic of PIV measurements system: (1) Optical access, (2) Optics, (3) Double pulsed Laser, (4) Double exposure CCD camera, (5) Synchronization and acquisition software

The water is seeded with a proper concentration of hollow glass spheres having a diameter between 40 µm and 50 µm. The uniform mixing of the seeding particles with the water was assured by running the pumps when introducing the particle solution to the water. Every recording consist of a couple of images obtained by the double exposure CCD camera. At every opening of the CCD, a Laser pulse illuminates the test section. The particles scatter the Laser light that is impressed in the images. The software Davis 8 was used for the synchronization of camera exposures and the Laser pulses. The best delay time in between every exposure was calculated before every test by the same software. The double pulse Laser allows short separations between two pulses, in order to respect the optimal particle displacements from one frame to the other. The data are processed by using Davis PIV software.

PIV measurements have been performed for different Richardson numbers and for the natural convection case. The velocity magnitude and the RMS of this velocity at the outlet of the ACB for Richardson = 0.46 and 18% opening of the by-pass are shown in figure 7. Measurements were performed in the symmetry plane passing through the pump axis. The flow field distribution through the four holes is measured inside the same image, giving a good overall view of the flow structure, the velocity distribution and quantitative information on the turbulence level, but with a low resolution. However, we can clearly indentify the different jets at the outlet of the Above Core Barrel. The mass flow and the exit angle of the jets can be extracted from these measurements. The flow rate through the first hole is much smaller than the one of the second and third hole. The jet angle of the second and third hole is quite similar while the flow escaping through the hole close to the free surface is almost horizontal.

A zoom at the outlet of the third hole was made with a smaller PIV window to get a higher resolution and the results are presented in figure 8. High values of RMS of the velocity are measured not only at the edges of the jet (shear region) but also in the centre, with a value of turbulence intensity close to 30% in the middle of jet. The flow field exiting the ACB is highly turbulent. We also measured a high RMS value in the stagnant zone surrounding the jet, with turbulence intensity close to 100%. The high RMS value measured in the bottom right of figure 8 comes from the jet below (exit n°2).

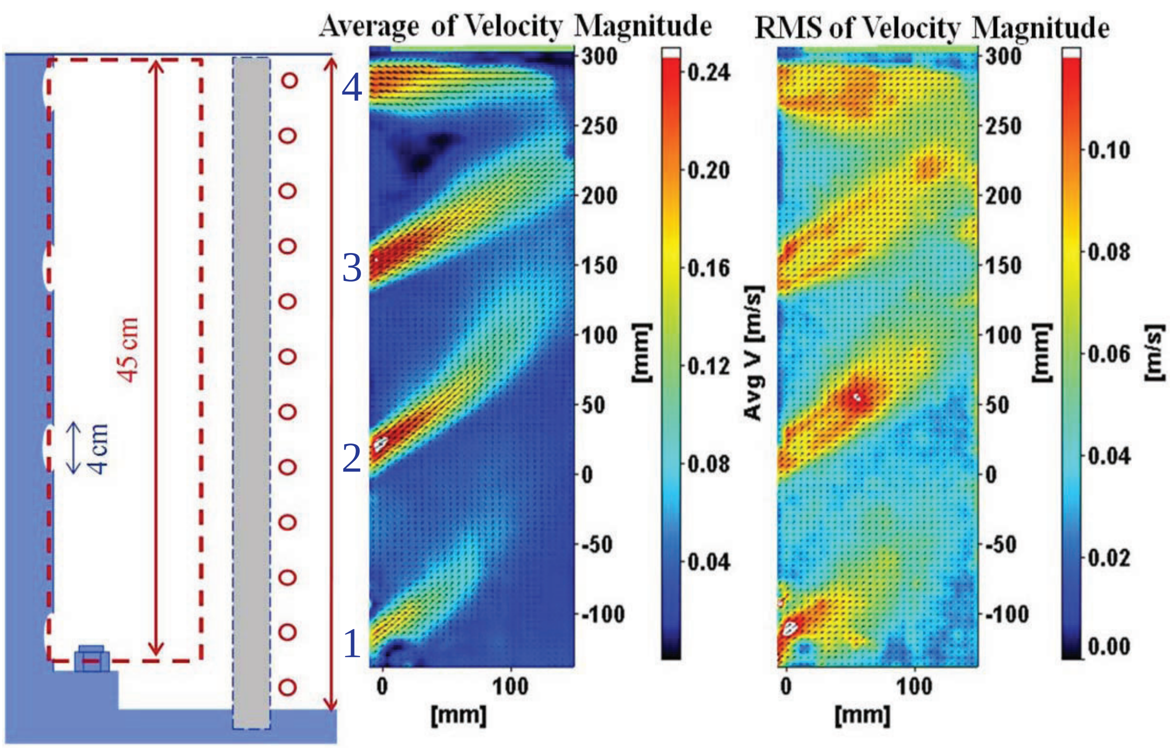

Figure 7. PIV results at the outlet of the ACS – Richardson = 0.46

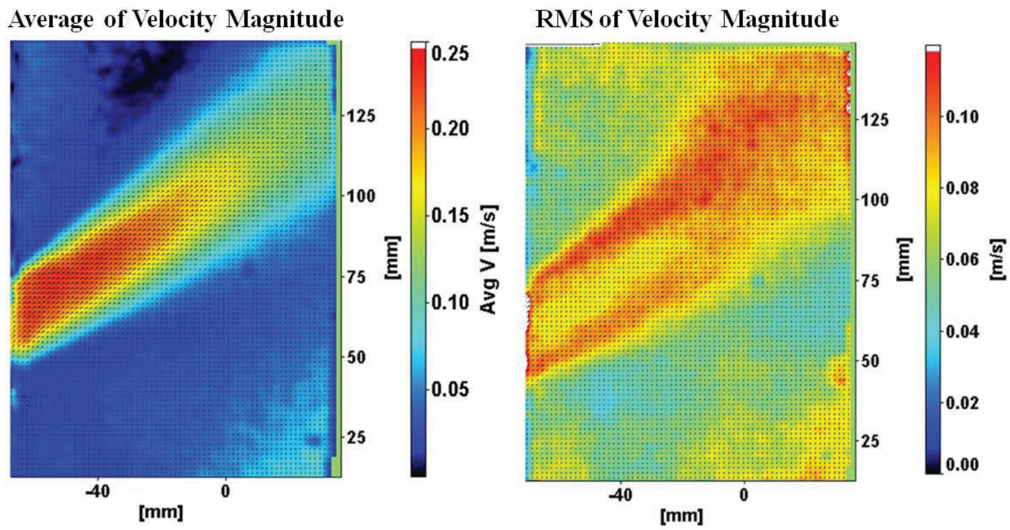

Figure 8. PIV measurements at the outlet of the hole n°3 of the ACS – Richardson=0.46

In natural convection with a 9% opening of the by-pass, the flow at the outlet of the four holes reaches a pseudo-stationary regime after 30 minutes, as illustrated in Figure 9. The flow through the bottom hole is entering inside the above core barrel (reverse flow), while the flow rate exiting the ACB is increasing from exit n°2 to exit n°4. The velocities measured are lower than in the nominal operating conditions with a reduction of magnitude by a factor of +/- 5.

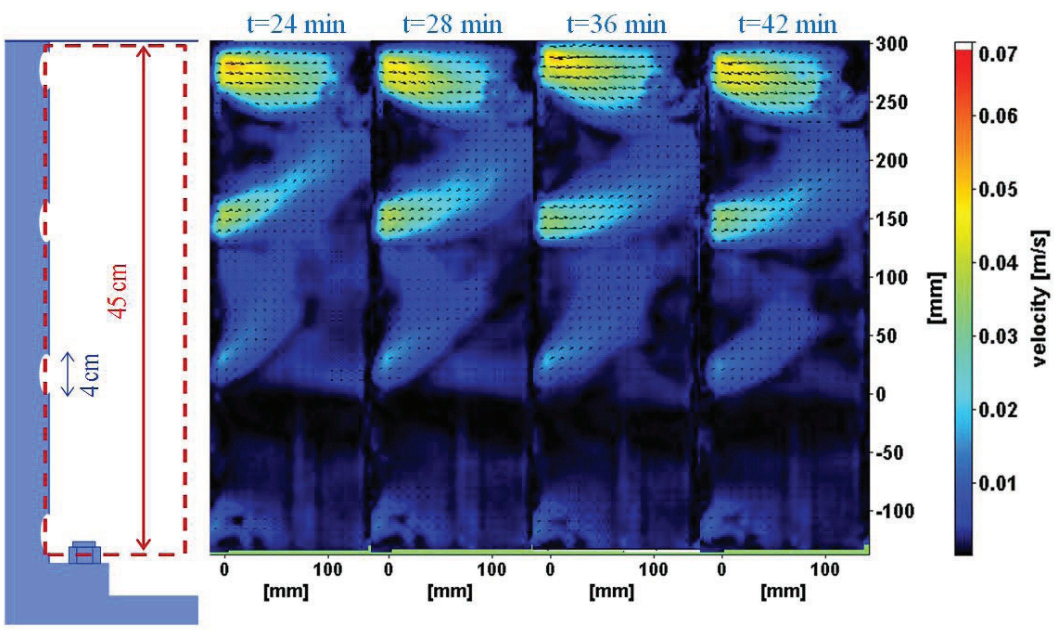

Figure 9. PIV results at the outlet of the ACS – Natural convection

The flow field measured here above gives important information for the temperature measurements presented in the next paragraph.

3.4. Thermal analysis

The MYRRHABELLE facility is equipped with thermocouples for temperature characterization. Rakes of 16 thermocouples can be immersed in the upper plenum to measure vertical temperature profiles at any position. In order to understand the thermal field at the outlet of the ACB, two rakes of thermocouples have been placed just at the outlet of the 3 holes in one vertical line A and at the outlet of 4 holes in one vertical line B of the ACB (figure 10 and figure11). Thermocouples are also located above the heating zone, at the outlet of the pumps and at the bottom of the lower plenum. A special calibration procedure for the thermocouples has been established using the water model at different uniform temperature to ensure a good accuracy on the temperature measurement.

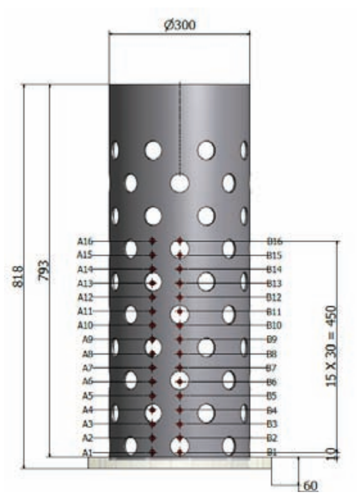

Figure 10. Position of the thermocouples

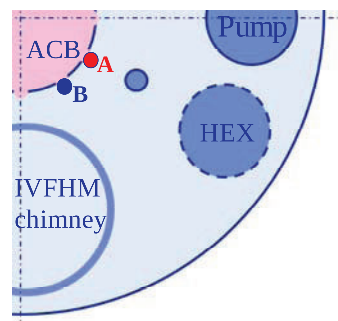

Figure 11. Top view of ¼ of the upper plenum

Temperature profiles measured on rake A are presented at different time instants in figure 12 for a Richardson number equal to 3.7, with a by-pass opening of 9%. The ΔT plotted corresponds to the difference in temperature between the measured temperature and the temperature of thermocouple A1 (thermocouple of reference) at the end of the test. Figure 12 shows clearly the imprint of the three exit holes from the ACB inside the upper plenum. The temperature of the flow exiting from the first hole is lower than the upper plenum temperature (negative ΔT). It corresponds to the cold flow coming from the lower plenum and passing through the core by-pass next to the heating zone.

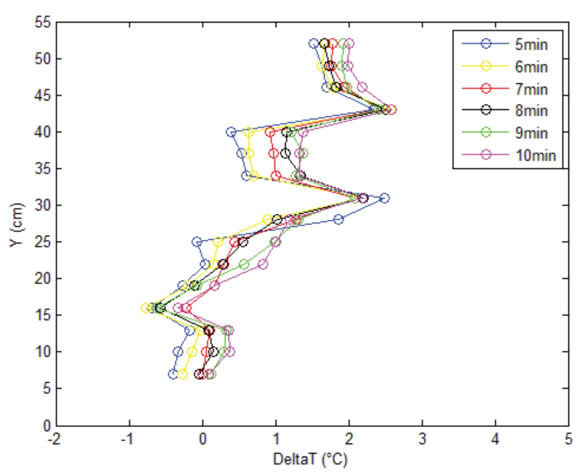

Figure 12. Temperature profile – Richardson = 3.7 – rake A

Figure 13 shows the temperature profile on line B. The flow passing through the core by-pass is responsible for the low temperature imprint measured at the level of the first and second exit. The imprint of the third and fourth exits (high temperature) can clearly be identified. The maximum ΔT measured between the coldest and warmest temperature measurements reaches 3°C for Richardson equal to 3.7.

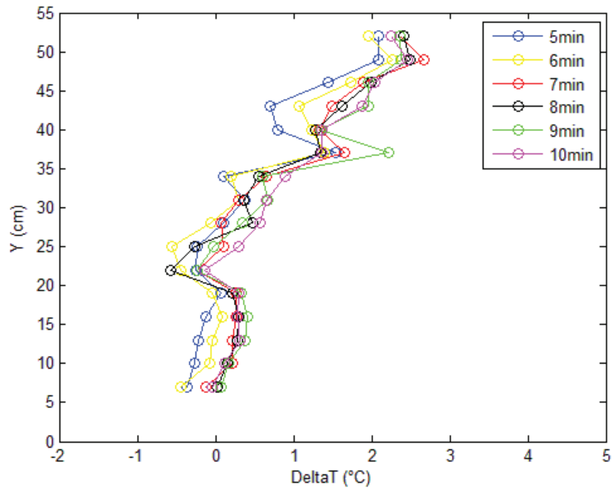

Figure 13. Temperature profile – Richardson = 3.7 – rake B

Figure 12 and figure 13 show mean temperature profiles at different instants. When analyzing the time evolution of the different temperatures as represented in figure 14, we observe temperature variations, especially at the level of the thermocouples in front of the jet exits (for example thermocouple 11). These oscillations are the result of the unsteadiness (high turbulence intensity) of the jet coming from exit n°3 as presented previously in the PIV measurements.

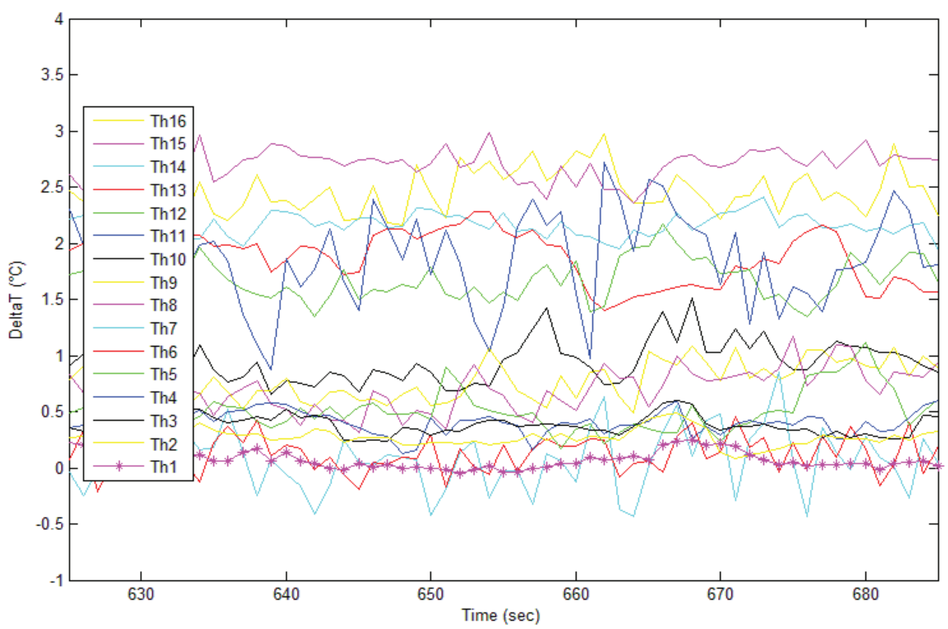

Figure 14. Time variation of the thermocouples located on rake B (Richardson =3.7)

Figure 15 shows the temperature profile on line B for a lower Richardson number of 0.46. During the measurements, the temperature was still increasing, but the shape of the temperature profile is quite similar at different instants. The imprint of the second exits (cold flow with negative ΔT) and the third and fourth exits are clearly identified. The maximum ΔT measured between the coldest and warmest temperature measurement reaches 1.5°C.

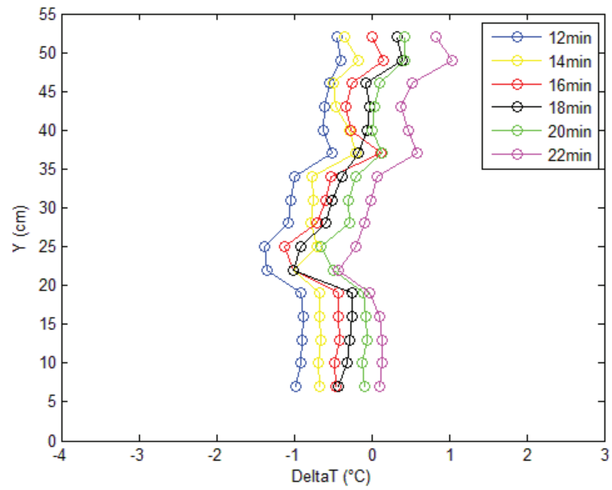

Figure 15. Temperature profile – Richardson =0.46 – rake B

A temperature gradient of 4°C is measured at the level of the outlet of the ACB when the water model facility is running in natural convection (figure 16). A cold zone in the lower part of the upper plenum (1/3 of the height) and an almost uniform warm zone in the upper part (2/3 of the height) are clearly identified. This indicates the presence of a stratified flow region.

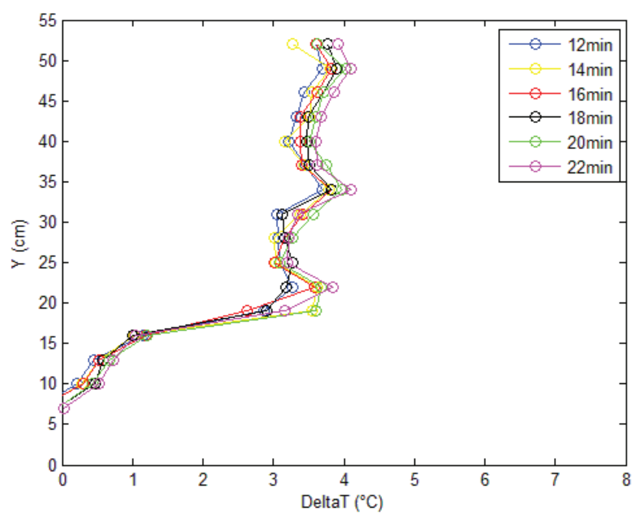

Figure 16. Temperature profile – Natural convection – rake B

4. CFD simulations

The water model experiments are simulated in parallel with the open source OpenFOAM simulation platform. The CAD file used for the construction of the experimental facility has been imported directly in snappyHexMesh to avoid geometrical mismatches. The full geometry of the heat exchanger (90 tubes per heat exchanger) and the full geometry of the heating zone (16 electrical resistances) are taken into account. The velocity magnitude in a vertical plane is represented in figure 17. The amplitude of the velocity magnitude at the outlet of the ACB matches the amplitude measured by PIV.
The turbulence intensity in the above core region and also at the outlet of the different holes of the ACB is represented in figure 18. Values of turbulence intensity at the outlet of the different holes are lower than the one measured experimentally (figure 6). The pattern of turbulence intensity is also different than the one measured with PIV (high levels of RMS on the edges of the jets). Further investigations are on-going to understand this discrepancy.

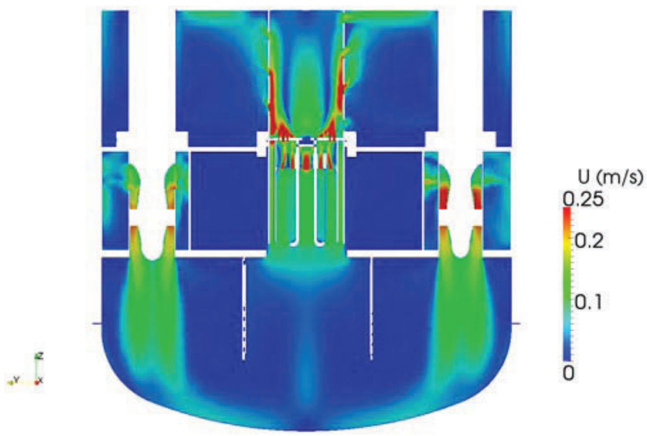

Figure 17. Velocity magnitude – Richardson =0.46

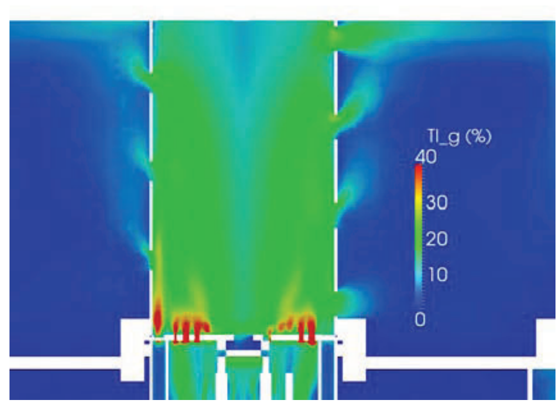

Figure 18. Turbulence intensity – Richardson =0.46

5. CONCLUSIONS

A thermal-hydraulic water scale model of the MYRRHA reactor was built at VKI and is now used to characterize the thermal-hydraulic behavior of the reactor. Results of velocity measurements using the PIV technique and temperature measurements using thermocouples have been presented. In this paper, we have focused the presentation on the results at the outlet of the ACB (Above Core Barrel).

Velocity measurements have provided useful information of the flow repartition through the different holes of the ACB. High turbulence intensities were measured at the jet exits. Temperature profiles at the outlet of the ACB for two different Richardson numbers and for the natural convection case have provided the temperature gradient. The analysis of the temperature fluctuations has shown large variations due to jet oscillations.

The water model facility provides useful results in nominal and accidental scenarios that can be extrapolated to a real size HLM reactor using appropriate similarity rules. An experimental database is constructed for the validation of CFD codes. The MYRRHABELLE facility continues to be used to address the thermal-hydraulic challenges of liquid metal cooled reactors [11].

NOMENCLATURE

ACB Above Core Barrel
CFD Computational Fluid Dynamics
PIV Particle Image Velocimetry

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