Hydraulic design and validated calculation tool of the Jules Horowitz Reactor (JHR) Reflector

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Abstract. Optimisations of Research Reactors hydraulic design have to be performed on major components such as core or reflector in order to reach neutronic performances while limiting reactor cost. Validated calculation tools are developed for these components in order to support design and produce operating and safety studies.

TechnicAtome is in charge of both the design and construction management of the 100 MW Jules Horowitz Reactor on behalf of CEA. This modular Material Testing Reactor will show capabilities of radioisotope production and material testing. The JHR reflector outside the primary loop is composed of non-similar beryllium blocks arranged all around the core in 9 independent sectors cooled by one downward flow open pool circuit. Its design is now completed and this paper is dealing with the process that lead to the hydraulic design of the reflector, tests which have been performed on dedicated hydraulic loops and all the actions which lead to provide validated calculation tools as STAR-CCM+ (PLM Software) for 3D computations and CATHARE (CEA) for circuits modelling.

JHR specifications led to a complex design especially for reflector beryllium blocks with heterogeneous gamma heating according to the presence of gamma shield. Taking into account the need to load and unload experimental devices while reactor is under operation, thermal-hydraulic design had to manage these cooling constraints whereas a downward flow cooling circuit limits the maximum mass flow and its head losses.

To dispatch the flow between structures of the reflectors (beryllium reflector blocks, aluminium structures or zircaloy shields) and experimental devices, each sector of the reflector has a water box with diaphragms located at the input. A torus water box collects these flows and makes a balance of the head losses. The JHR reflector hydraulic design can be compared with an organ where each family of channels is set to use the only necessary mass flow.

A coupled approach based on experimental hydraulic tests and computer codes simulations is performed. The first head losses characterization of beryllium blocks and water boxes are based on hydraulic loops tests with a Reynolds similitude to cover the operating and accidental domain. Whereas there are approximately 20 different types of beryllium blocks and 9 sectors due to core design, a predictive methodology is developed (based on a 1D calculation approach for beryllium blocks and a 3D calculation approach for water boxes) to limit the number of hydraulic experiments. This coupled approach (hydraulic tests/calculations) makes possible the extrapolation to different beryllium blocks and water boxes designs by calculations only. Calculation tools are operational to finalize the cooling sizing of the reflector and to simulate various configurations of the JHR reflector.

1. Introduction

The Jules Horowitz Reactor (JHR) is a Material Testing Reactor under construction at CEA Cadarache in France. It will represent a major research infrastructure for scientific studies dealing with material and fuel behaviour under irradiation [1].

Experimental devices will be placed in every part of the reactor, in the core area and in the reflector area at the same time. There are designed to reach the highest flux and heating requirements of such experimental devices.

JHR requirements led to a complex design especially for reflector as explained in section 2. As a consequence, the JHR reflector thermal-hydraulic sizing is restricted by antagonist constraints due to the design options as presented in section 3. For this, the calculation tools used in this sizing have to be validated and applied to the JHR reflector geometry.

This paper focuses on the methodology employed for calculation tools validation.

After a short description of the flows inside reflector in section 4, the calculation tools are presented in section 5. Then in section 6, the general process adopted for their validations and the main experimental approaches are presented. Conclusions are summarized in section 7.

2. JHR reflector requirements

The JHR reflector enables to improve the neutronic performances and to allow a wide range of experiments.
Operators of the reactor should have a strong flexibility on the experimental load and should be able to load and unload devices when the reactor is at power.

The main design drivers of the JHR reflector which result from design option selected at early stage of the project, are as follows:

- High performance and accurate power ramps on high burn up fuel samples achieved by the mean of displacement systems,
- Capability to load and unload experimental devices during normal operating conditions,
- Irradiation locations with flexibility of use in order to cover a wide range of neutron fluxes and spectra.

As a consequence of these requirements, the following design options have been frozen at the early stage of the project:

- Beryllium Modular reflector is installed outside the circular shaped core housing especially to get a lot of irradiation locations and also to comply with flux performances purposes,
- Zircaloy shields between the core and the reflector are set partially around core to reduce gamma heating,
- Reflector structures and irradiation devices such as capsules or some isotopes production rigs are cooled by an open pool cooling circuit. It has been chosen to enable operators to have a direct view on the experimental load and to handle it if required.
- A downward cooling flow is adopted, when the reactor is operating, in order to facilitate the devices handling and to prevent the ejection risk. So, Flow reversal at the onset of natural convection cooling is occurred when the reactor is at shutdown.

3. Constraints on JHR reflector thermal-hydraulic sizing

The JHR reflector and experimental devices are exposed to a high energy deposit due to the proximity with the core.
Due to the design options, they are cooled by an open pool cooling circuit with a downward forced flow during normal operating conditions. The pool cooling circuit architecture integrates a redundant pump, plate based heat exchanger and redundant flaps to manage the transient from downward forced flow to upward natural circulation. The reflector is located at the pump suction.

Due to this cooling circuit architecture, the hydraulic operating domain is restricted by several antagonist constraints as shown in the ***Figure 1***.

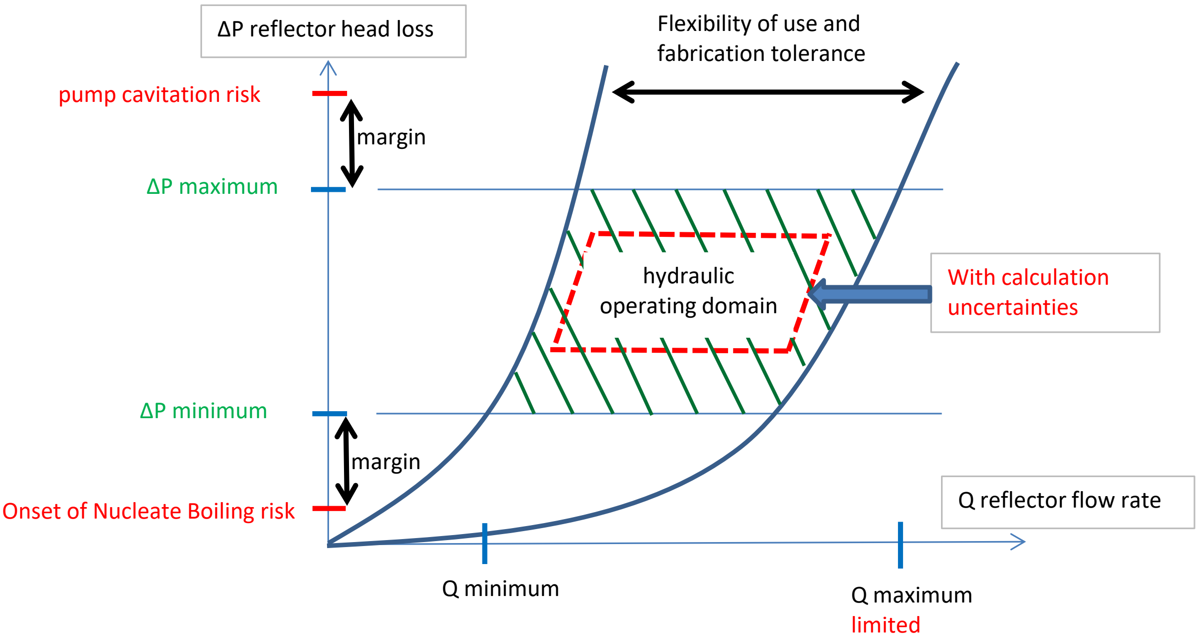

***Figure 1**: Hydraulic operating domain of JHR reflector*

Hydraulic operating domain of the JHR reflector is limited by those following constraints:

- The expected flexibility of use (irradiation locations possibilities, load and unload experimental devices) and the fabrication tolerance of reflector are delimited by two extreme flow rate - head loss curves during normal operating conditions.

- The minimum head loss is determined to satisfy the reflector cooling which limits the cooling flow rate. Some margins are taken into account to avoid the Onset of Nucleate Boiling risk.

- The maximum head loss is determined in accordance with the NPSH of the pump. Some margins are taken to prevent the pump cavitation risk. So, the maximum cooling flow rate is limited. As a consequence, it leads to manage adequately the cooling flow rate crossing each structure and experimental devices.

A preliminary thermal hydraulic sizing has been performed with generic calculation models. The hydraulic operating domain determined was strongly reduced by the calculation uncertainties and by the margins to be considered.
For the final sizing, it is important to define with accuracy this hydraulic operating domain. For this need, two actions are undertaken:

- Reduce the calculation uncertainties by using experiment on some reflector mock ups,
- Adjust the necessary cooling flow rate crossing reflector structures and irradiation devices.

For this, the calculation tools used in this sizing have to be validated and applied to the JHR reflector geometry.

4. Hydraulic description of the reflector

Figure 2 : JHR reflector general description - Sectors name is given in red and the different elements are identified

The JHR reflector is divided into 9 sectors (as shown in ***Figure 2***) separated by the aluminum plates. Each sector is composed of different elements to be cooled:

- Beryllium blocks installed everywhere in the reflector,
- Zircaloy gamma shields (excepted for C2, C3 and C4 sectors),
- Experimental devices are inserted in guiding tubes which are introduced in some beryllium blocks. Guiding tube is made in Aluminum.

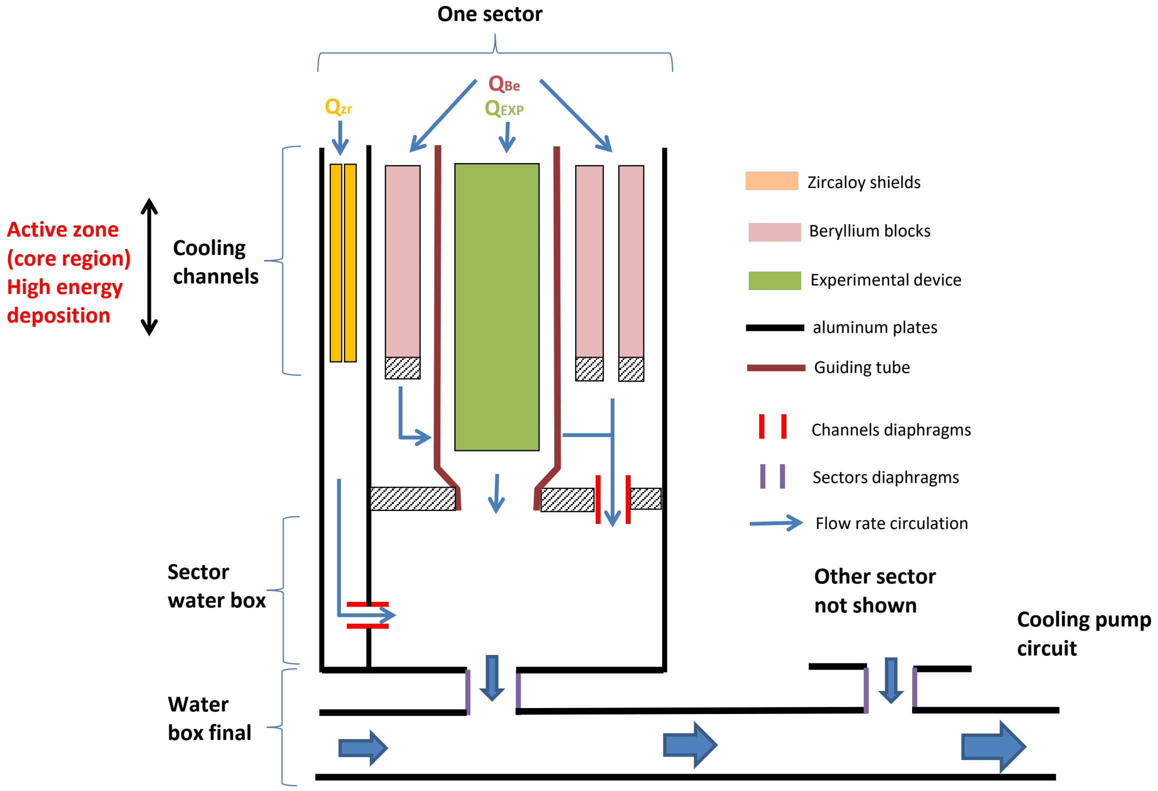

Figure 3 : schematic of internal flows circulation in the reflector (axial view)

Each element is designed to cover more than the active zone of the core.

The reflector geometry can be viewed in three hydraulic regions axially (*Figure **3***):

- The first region concerns water channels in each sector. The pool water flows in first in the elements of each sector. The cooling flow rates crossing the elements absorb the thermal energy deposited in the structures. Then, the outlet flow rates are gathered in a specific water box of the sector representing the second region.

- Each flow rate going in the sector water box is adjusted by a diaphragm located at the inlet represented in red in this graph. So, the main functions of the sector water box are to adjust the cooling flowrate of each element and to collect the total flowrate crossing the sector.

- The outlet flow rates of each sector joint together in a last water box called water box final representing the third region. The water box final is located at the bottom of the reflector. This water box has a torus form. Each flow rate coming from above is adjusted by a diaphragm located at its inlet. The main goal of the water box final is to adjust the cooling flow rate crossing each sector and to collect the total flow rate of the reflector.

5. Calculation tools

In this section, the calculation tools for thermal hydraulic sizing are presented. The application of each calculation tool is also presented.

5.1 CATHARE Code

5.1.1 Presentation

CATHARE is developed by CEA, EDF, IRSN and AREVA. The verification and validation process is managed by the CEA.

CATHARE code (Code for Analysis of Thermal-hydraulic during an Accident of Reactor and Safety Evaluation) was developed to perform best-estimate calculations of pressurised water reactor accidents, but specific modules and set of correlations have also been implemented to allow modelling of other reactors like boiling water reactors, gas cooled reactors, sodium cooled reactor, and pool or tank in pool research reactors.

A specific set of laws of CATHARE is dedicated to MTR core thermal hydraulics. Its validation, focused on two phases flow instabilities and critical heat flux evaluations, is based on experimental data compiled since the sixties. Other capabilities used for MTR design are derived from its PWR validation (primary and secondary circuit, pool and containment/confinement).

Thermal-hydraulics studies of pool cooling circuit are performed with HORUS3D/Sys [1] (Horowitz Reactor simulation Unified System/System). HORUS3D/Sys contains a specific set of laws dedicated to thermal-hydraulic of JHR reactor using CATHARE code.

5.1.2 Application

The JHR reflector model has been developed in CATHARE code (***Figure 4***) and follows the description given in section 4:

- First region: several cooling channels modelled by 1D modules in parallel,
- Second region: 9 sector water boxes modelled by 0D modules to collect the outlet flowrate of cooling channels,
- Third region: the water box final modelled by a 0D module to collect the outlet flow rate of the 9 sector water boxes.

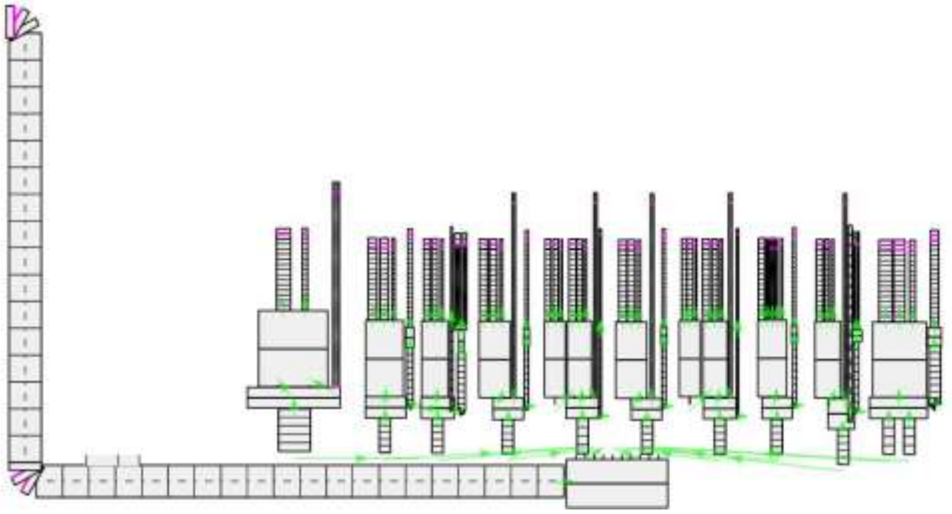

Figure 4 : CATHARE nodalisation of the reflector cooling circuit

A preliminary thermal-hydraulic sizing has been performed to define the cooling flow rate for reflector structures and irradiation devices. This cooling need has been determined in a conservative way, considering the following configuration:

- A maximum power deposit in structures, based on the 100 MW thermal power of the reactor and a maximal unbalance of the neutronic flux in the reflector,
- A maximum load of experimental devices, considering 300 kW of thermal power extracted by the pool cooling circuit for each device,
- A limitation of the cooling area in order to maximise neutronic performances.

However, the preliminary thermal-hydraulic sizing has been performed considering several hypotheses about modelling parameters:

- Friction coefficient evaluated for smooth surface (without surface roughness effect),
- Singular coefficients determined with literature correlations (cf. Idelchik [3]),
- Local phenomena inducing 3D effects (mixing flow in water boxes, fluid jet through diaphragms) evaluated by a singular term.

Those hypotheses have to be evaluated and verified by experimental hydraulic tests on some representative reflector mock-ups in order to validate the final sizing. The approach adopted is presented in section 6.

5.2 STAR CCM+ code

5.2.1 Presentation

STAR CCM+ code developed by Siemens is a Computational Fluid Dynamic code widely used in many applications to design and to study more precisely multi-physics behaviors. It is usually used for designing some components.
TechnicAtome considers STAR CCM+ as a reference CFD code. For this, SATR CCM+ is retained to characterize the hydraulic flows in the reflector water box and to design all the diaphragms.

5.2.2 Application

As described in section 4, the JHR reflector is composed of several water channels related to the different elements (beryllium reflector blocks, zircaloy shields, aluminium structures and experimental devices):

- Each water channel has a specific hydraulic characteristic (regular and singular head losses) due to the optimisation of the cooling area,
- In order to maintain a reasonably low mass flow rate in the pool cooling circuit while keeping versatile experimentations (so a high mass flow rate in experiments channels), the flow rate crossing the different water channels is optimized for the needs of each structure (see section 4),
- The highest pressure drop in the reflector is imposed by the experimental devices, which combine the highest power deposits and the longest wet surfaces.

The diaphragms designs in reflector are defined to satisfy the experimental device cooling releasing the highest heat.

This reference experimental device has the following features:

- Maximum heat power: 300 kW,
- Maximum device diameter: 97 mm inducing a water channel width of 2.5mm,
- Maximum device length: 2 m.

This reference experimental device has the highest requirements in terms of cooling:

- Maximum cooling flow rate allocated to all experimental devices,
- Maximum head loss among all cooling channels in JHR reflector.

All the flows in the adjacent cooling channels present a lower head loss than the reference experimental device head loss. So, the diaphragms in reflector are defined to bring the additional head loss as explained by the following formula:

$$\Delta P_{EXP}(Q_{EXP}) = (\Delta P_{chan} + \Delta P_{Diaph})(Q_{chan})$$

With
Q_{EXP} : Cooling flow rate of the reference experimental device
ΔP_{EXP} : Head loss of the reference experimental device evaluated for Q_{EXP} flow rate
Q_{chan} : Cooling flow rate crossing the channels (specific to each reflector element)
ΔP_{chan} : Head loss along the cooling channel corresponding to Q_{chan} flow rate
ΔP_{Diaph} : Head loss of diaphragm corresponding to Q_{chan} flow rate

Hence, the diaphragms are designed to reach a reference hydraulic characteristic:

- The cooling flow rate determined by thermal-hydraulic studies,
- A similar head loss for the reference experimental device and all the adjacent cooling channels equipped with their diaphragms.

6. Process for calculation tools validation

6.1 General process for calculation tools validation

The general process for the calculation tools validation is illustrated in the ***Figure 5***.

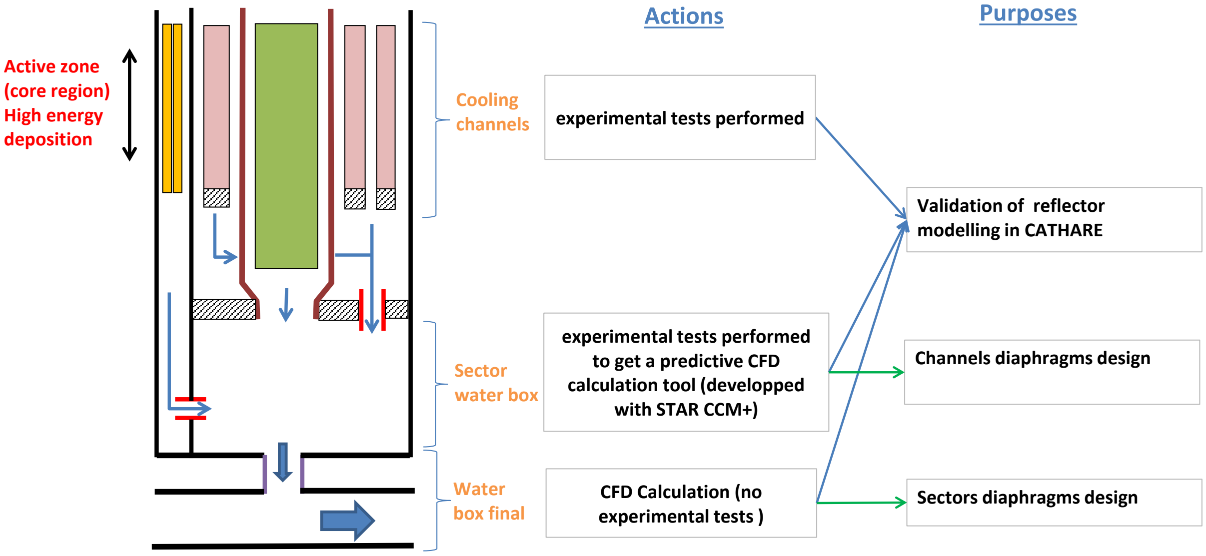

Figure 5: Mains actions and purposes for calculation tools validation

The actions undertaken have 2 goals.

- The first one is to validate a reflector model developed in CATHARE code used for the thermal-hydraulic sizing,
- The second is to validate a CFD calculation scheme developed in STAR CCM+ code used for designing the different diaphragms and for validating the water boxes modelling in CATHARE code.

Each hydraulic region is analyzed separately because each one represents a specific hydraulic step in the reflector.

The two first hydraulic regions (cooling channels and sectors water boxes) present a strongly heterogeneous geometry and amount to both about 90% of the reflector head loss. For those reasons, these regions are analyzed by comparison of the results between experimental hydraulic tests and computer codes simulation.

The water box final behaves conversely:
It presents a low rate of reflector head loss and it has a simpler geometry (torus form) which can be quantified only by calculation with higher uncertainties.

In the next sections, it is presented the experimental process retained to analyze the hydraulic flow in the cooling channels and in the sector water boxes.

6.2 Experimental process for the hydraulic qualification of cooling channels

For flows in cooling channels, experimental hydraulic tests were performed on scale 1 mock-up representative of different elements types (beryllium blocks, zircaloy shields, guiding tube).
Each mock-up is inserted in a closed loop where the flow rate is imposed by a pump.
Several differential pressure sensors are connected in the cooling channels to quantify the resistance to flow, friction and singular terms.
The hydraulic tests were performed in Reynolds' similitude covering the reflector's operating conditions.

In the ***Figure 6***, you can see one beryllium block mock-up in aluminum with a hexagonal shape and its testing loop.

Figure 6 : Beryllium block mock-up (hexagonal shape)

Those hydraulic tests allowed the assessment of parameters impacting the hydraulic resistance in the water channels.

- The friction coefficients have been determined for all type of channel shapes. In the 1D model, corrective factor are applied to the standard correlations of the code to take into account the results of the hydraulic tests.
- The singular coefficients (input and output of elements, seal rings…) are evaluated and introduced in the 1D model.
- The surface roughness effect has been evaluated in the fabrication tolerance limit,
- The misalignment effect of elements induces the local reduction of a water channel thickness.

Each mock-up has been controlled by metrological measurements in order to be more accurate on the results and analysis.
All those results feed a database to qualify 1D modelling prediction with CATHARE.

6.3 Experimental process for the hydraulic qualification of sector water boxes

For flows in sector water boxes, the qualification process of CFD calculation scheme developed in STAR CCM+ code is based on 2 steps:

The aim of the first step is to determine the mesh rules and turbulence models in order to simulate the flows in all the sector water boxes with the best accuracy.
For this, a scale 1 mock-up representative of the most constraining sector water box due to it geometry has been chosen to tune the CFD modelling and to quantify low calculation uncertainties. This mock-up made in Plexiglas is presented on the ***Figure 7***.
It is inserted in a closed loop. Each water inlet contents a diaphragm and the flow rates are imposed by a pump. Several differential pressure sensors are connected everywhere on the mock-up to get the best prediction with the CFD calculation scheme.
The hydraulic tests were performed in Reynolds' similitude covering the reflector's operating conditions.

Figure 7 : C4 sector water box mock-up (in Plexiglas)

Several configurations have been tested to increase the applicability domain of CFD calculation scheme:

- It was tested different diaphragm diameters in each water inlet.
- Different experimental positions have also been tested to characterize at best the loop.

The aim of the second step is to validate the mesh rules and turbulence models determined in the first step performing a blind test.
For this, it was considered another mock-up with a completely opposite geometry than the first one. This mock-up was modelled respecting the CFD rules. Its results were compared to measurements on a second mock-up which validated the uncertainties of the CFD tool. Thus, the 7 other water boxes were computed.

One of the CFD calculation results are shown in the ***Figure 8***. These correspond to two experimental device positions showing the velocity magnitude in the C4 sector water box. Its results were compared to experimental hydraulic tests results.

We can see that the velocity field in the water box is dependent of the fluid jet going out of water inlets and its positions. As a consequence, the diaphragm head loss taken between water inlet and inside water box cannot be considered for it dimensioning.

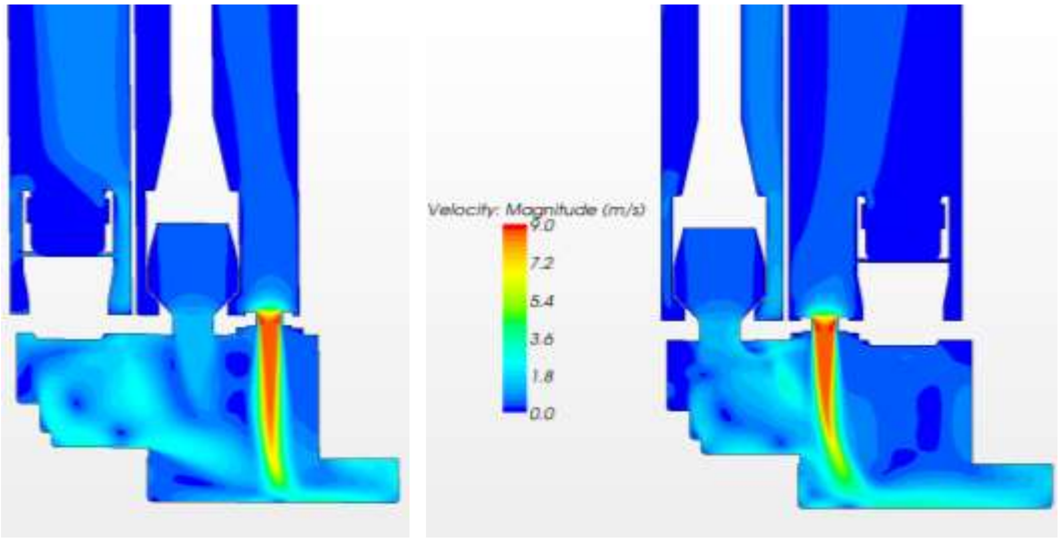

Figure 8: Velocity magnitude for 2 positions of experimental devices in sector C4

However, it was noted that the total head loss of the water box between each inlet and it outlet remains almost the same whatever the experimental device position. Indeed, the sector water boxes are large enough to get a homogeneous velocity field in outlet. So, each diaphragm is defined considering the total head loss of the sector water box seen by each water inlet.

Finally, those hydraulic tests allow to get a CFD code predictive which can be applied for the sector water boxes geometry.
Hence, all the diaphragms are designed with a maximum uncertainty less than 8% on the target head loss with this CFD code.

7. Conclusions

JHR reflector is an important component, especially, for the expected experiments in the JHR project. For this, several design options have been selected at the early stage of the JHR project. Those design options led to a complex geometry of the JHR reflector. Several configurations of use have to be analysed and taken into account in the thermal hydraulic sizing. The challenge of the JHR reflector thermal hydraulic sizing is to ensure the reflector cooling with the expected flexibility. For this, calculation tools are used to perform this sizing. At the end of the reflector design, it is important to define with accuracy the hydraulic operating domain.

This paper shows the method employed by TechnicAtome to validate the calculation tools used in the final sizing. In current state, the hydraulic qualification of the JHR reflector is finished.

All the actions undertaken for calculation tools validation led to:

- reduce significantly the calculation uncertainties allowing to validate and to increase the hydraulic operating domain,

- finalize the reflector design. All the diaphragms in the reflector have been determined by CFD calculation with the best accuracy.

7. References

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