



**HAL**  
open science

# Simulation of flow reversal experiments with the code CATHARE

Francesco Occhiogrosso, Alberto Ghione

► **To cite this version:**

Francesco Occhiogrosso, Alberto Ghione. Simulation of flow reversal experiments with the code CATHARE. RRFM 2023 - European Research Reactor Conference, Apr 2023, Anvers, Belgium. cea-04191141

**HAL Id: cea-04191141**

**<https://cea.hal.science/cea-04191141>**

Submitted on 30 Aug 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# SIMULATION OF FLOW REVERSAL EXPERIMENTS WITH THE CODE CATHARE

F.OCCHIOGROSSO<sup>a,b</sup>, A. GHIONE<sup>a</sup>

<sup>a</sup> *Université Paris-Saclay, CEA, Service de Thermohydraulique et de Mécanique des Fluides 91191, Gif-sur-Yvette, France*

<sup>b</sup> *Politecnico di Bari, Via Edoardo Orabona 4, 70126 Bari, Italy*

## ABSTRACT

Flow reversal may occur in the core of research reactors with downward cooling. In case of accidental scenarios, the transition from forced to natural convection leads to an inversion of the coolant direction from downward to upward. During the transient, the two-phase flow may undergo high instabilities. Thus, it is important to prove that the simulation tools are capable to capture the phenomenon. In this paper, flow reversal experiments, performed at Brookhaven National Laboratory, have been simulated with the thermal-hydraulic system code CATHARE. The facility was scaled to reproduce the thermal-hydraulic loop of the High Flux Beam Reactor and the associated physical phenomena. The flow reversal was obtained with a linear coast-down of the circulating pump from nominal to zero flow. A CATHARE model has been realised. The results of the simulations show a very good agreement with the available experimental data. Several sensitivity analyses have been carried out.

## 1 Introduction

In order to ensure the high safety demand of nuclear reactors, thermal-hydraulic system codes have been employed all over the world as tools to simulate accidental scenarios. The French nuclear industry relies on the code called CATHARE [1], based on a transient 2-fluid 6-equation model, complemented by proper laws (or correlations) for single and two-phases flows. Its applicability has been also extended to research reactors where the cooling water flows in narrow rectangular channels. For this purpose new correlations have been implemented and existent ones have been tested and validated for such an application. [2, 3] The present paper is placed within this framework. The goal is to validate the CATHARE code against flow reversal experiments. This phenomenon may happen during accidental transients (e.g. loss of flow) in the core of research reactors that are cooled by a downward flow of water in nominal conditions. During the transient, the direction of the coolant in the core changes from downward to upward and a transition from forced to natural convection occurs. An experimental dataset of flow reversal tests conducted at Brookhaven National Laboratory (BNL) in the USA [4, 5] has been simulated with CATHARE. These tests have been carried out for the High Flux Beam Reactor, an American research reactor cooled in downward direction.

## 2 The flow reversal experiments

### 2.1 Experimental setups

Figure 1 displays the experimental setup in order to properly reproduce the flow reversal transient phenomenon in the HFBR. [4, 5] All the experiments were scaled to achieve similar thermal-hydraulic conditions compared to real reactor's ones. The most important part of the whole facility is the heated section, also called test section, since it is where the flow reversal takes place. Upward this component the inlet section and the upper plenum can be found. Downward the test section the lower plenum and the reflector channel are placed. Upper

plenum and reflector channel are linked with a bypass path in order to reproduce the alternative flow path when the flow reverses as in the real reactor. An orifice is placed in this path to imitate the flow choking provided by the valves of the real reactor. The loop is closed with a circulating pump. Heat exchangers provide the proper inlet conditions at the suction side of the pump. A screw pump is utilised as circulating pump. The pump coast-down is achieved via a pump speed control system. Demineralised water is used as working fluid.

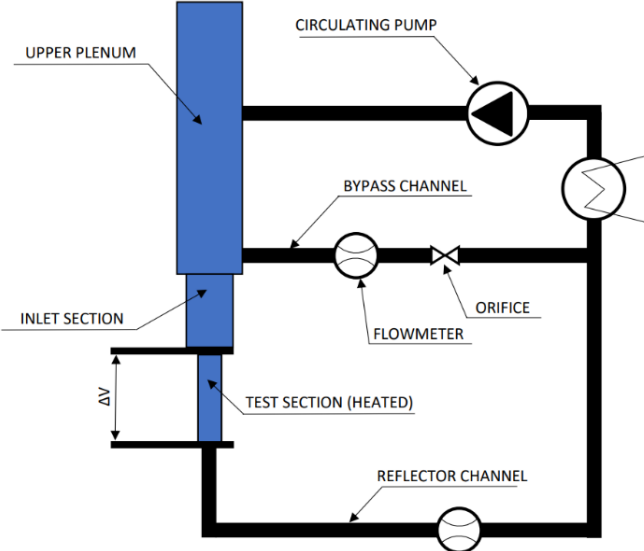


Figure 1: The experimental setup

A second experimental setup has been also realised. It includes several modifications if compared to the first one, in order to expand the experimental data base. The most important modification concerns the addition of a secondary bypass line, connecting the pump discharge to the line below the heated section. This secondary bypass line is intended to simulate the fact that the outlet core temperature is given by channels averaged power instead of the hottest channel power. Thus, such a secondary path injects cold water into the region below the heated section, to get closer to the real reactor conditions.

**2.2 Test section**

The test section consists of a narrow rectangular channel. It is electrically heated with a single-side plate. Figure 2 represents the cross sectional view of the test section, whereas Table 1 provides the test section dimensions. It is necessary to stress that a range of values is provided by the authors concerning the channel gap. This is due to the potential thermal expansion of the heated plate that gives a degree of uncertainty to this dimension. Some labels indicate the parts into which it is divided. In particular the white rectangle represents the transparent layer placed in order to visually observe the phenomenon. The two grey parts designate the two side rails (lateral guides in the figure). The red layer stands for the aluminium alloy heating plate and the remaining portion in yellow represents the thermal insulation.

| PARAMETER        | DIMENSION (mm) |
|------------------|----------------|
| Channel width    | 54.864         |
| Channel gap      | 2.54 – 2.8702  |
| Channel length   | 609.6          |
| Heater width     | 57.15          |
| Heater length    | 577.15         |
| Heater thickness | 1.27           |

Table 1: Test section dimensions

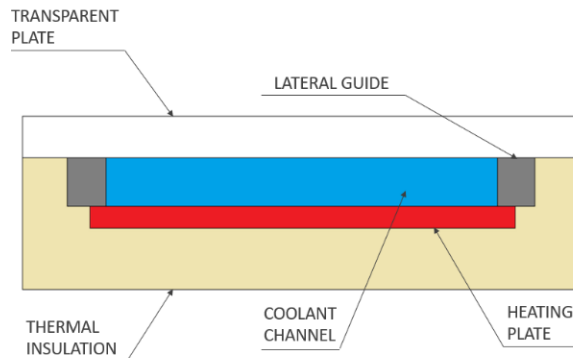


Figure 2: Test section cross-sectional view

### 2.3 Instrumentation

The time evolution of the following parameters are available for the tests: total loop flow rate, reflector channel flow rate, bypass channel flow rate, wall temperatures in the top, middle and bottom of the test section, coolant temperatures in test section inlet, outlet, upper plenum and reflector channel, electrical power and finally test section pressure drop.

The flow rates are recorded with turbine flowmeters, the coolant and wall temperatures with thermocouples, the pressures with differential pressure transducers and the electrical power is computed by voltage and current measurements.

It is worth to point out that limited information are given by the experimentalists on the exact placement of the instrumentation in the circuit, so often it was necessary to estimate their positions based on the available figures in the technical report.

### 2.4 Test procedure

The test procedure can be summarized and divided into three steps:

- Establishment of the steady state forced flow conditions. Sufficient time was conceded to stabilize the conditions and take steady-state measurements.
- After the stabilisation of steady state values, the test is initiated by linearly reducing the pump flow from nominal value to zero;
- The last step is associated to the full stop of the pump during which either a natural circulation is established or dry-out occurs. The test is ranked as successful flow reversal if the natural circulation is sustained for 30 seconds, otherwise it is considered as a dry-out outcome test. Dry-out is detected with two stopping criteria, either if the wall temperature exceeds the saturation temperature at the exit of test section by 4°C or if voltage trips of 10% above the initial operating voltage are detected.

### 2.5 Test conditions

The technical reports [4, 5] contain only the full results of 4 tests.

In this paper, we will focus on two of these tests with the experimental setup described in Subsection 3.1. The first one (B080394B) has as outcome a fully established flow reversal and the second one (B080394A) is stopped because the thermal crisis is reached in the channel.

Tables 2 and 3 show respectively the nominal conditions and the experimental results of the tests cited above.

For an overview of all simulations carried out, their nominal conditions and results, please refer to reference [4].

In order to study the influence of some parameters on system response (e.g. water level in upper plenum, coast-down time, inlet temperature, etc.), other tests have been performed on the experimental setup previously described. As mentioned above, no measurements are

available in the reports for these experiences, but their outcome is reported. The results of these additional experiments can be found in Table 4, including the experimental outcome (Flow Reversal or Dry-out) and the power levels.

|                                   |                            |
|-----------------------------------|----------------------------|
| Inlet flow rate                   | 0.000189 m <sup>3</sup> /s |
| Water level (above inlet section) | 4267.2 mm                  |
| Inlet temperature                 | 54.4 °C                    |
| Coast down time                   | 40 s                       |
| Bypass ratio                      | 1:2                        |

Table 2: Experimental nominal conditions

| TEST NUMBER | NOMINAL POWER | FLOW REVERSAL POWER | TRIP POWER | TEST OUTCOME  |
|-------------|---------------|---------------------|------------|---------------|
| B080394B    | 7.0 kW        | 7.4 kW              | -          | Flow reversal |
| B080394A    | 7.5 kW        | -                   | 8.0 kW     | Dry-out       |

Table 3: Experimental test results

### 3 CATHARE model

The whole pump coast down transients were simulated using the CATHARE-2 system code validated for research reactor applications, as described in [1]. The calculations were stopped either by reaching the end of the experimental time (with the establishment of the natural circulation) or by reaching the melting temperature of the heating plates (indicating the occurrence of the thermal crisis).

Figure 3 shows how the model of the circuit appears through GUIHARE graphical interface. Some label have been placed in the figure to distinguish the parts into which the input file is made up:

- **Label 1: Test section.** It is composed by the channel where the coolant flows (modelled as 1D CATHARE module), and the heating plate (modelled as plane WALL submodule).
- **Label 2: Inlet section.** 1D CATHARE module.
- **Label 5: Upper plenum.** It is itself divided into two parts (labels 5a and 5b), because in the real experimental setup it is composed by a circular section part followed by a rectangular section one. Both of them are modelled as 1D modules. In the pipe section of the upper plenum (5a) the first boundary condition inserted in the model can be seen, which sets the water inlet condition in the circuit.
- **Label 6: Ambient air volume.** A large volume module full of saturated steam simulating the ambient air conditions has been placed upstream the upper plenum. It is due to the fact that the upper plenum is open to the external environment in the real experiment. A boundary condition imposing the atmospheric pressure in the volume has been placed in order to close the circuit loop.
- **Label 4: Reflector channel.** 1D module. In its horizontal part a section shrinkage can be seen, where the first turbine flowmeter is placed in the real experiment. The reflector channel ends with the last boundary condition inserted in the model, which sets the water outlet condition, with a volumetric flow rate law equal and opposite to the inlet flow rate law, in order to well represent the two sides (suction and discharge) of the screw pump of the real experiment.
- **Label 3: Bypass channel.** The last 1D module. Two section shrinkages can be seen and they stands respectively for the second turbine flowmeter and the orifice placed in this path of the circuit. The bypass channel is joined to the rest of the circuit (Upper plenum and reflector channel) with TEE submodules on both its end sides.

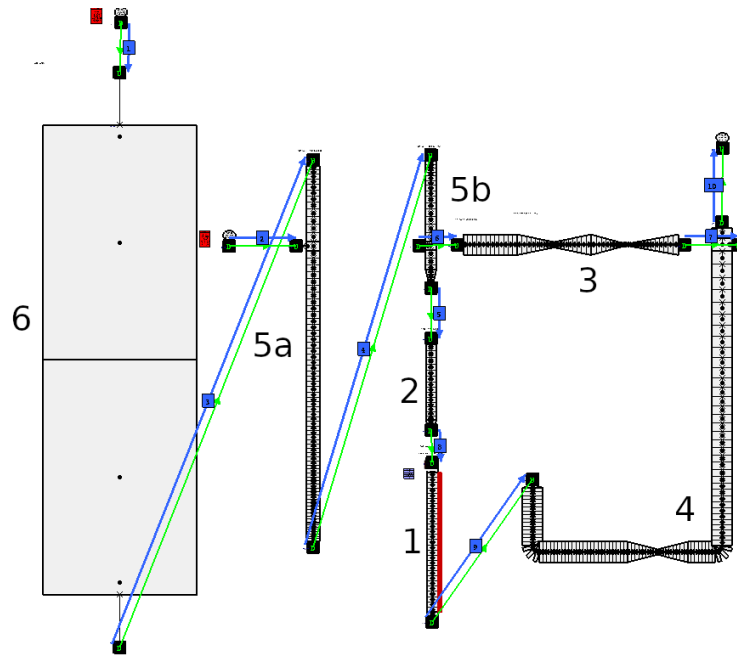


Figure 3: CATHARE model through GUTHARE graphical interface (not in scale)

The whole model is based on the following hypotheses:

- Heat losses calculated from experimental results and constant throughout the simulation;
- Calculation of an equivalent singular pressure drop coefficient for the pressure drops in the flowmeters;
- Manual calibration of the pressure drops in the orifice to obtain the experimental bypass ratio;
- Walls of the rest of the circuit adiabatic towards the outside and 3 mm thick (to model the thermal inertia of the system).

The geometrical dimensions are the same of the real experiments cited in Ref. [4, 5].

As reference value for the channel gap an averaged value between the two indicated in Table 1 has been chosen. More details can be found in [5].

## 4 Results

In this chapter, the results of the CATHARE-2 simulations are presented and compared to experimental evolutions.

All the flow reversal simulations are characterized by a transient with high amplitude and frequency oscillations due to the unstable two-phase flow. Usually these oscillations persist also when flow reversal is completely established, even if they are quite damped. Due to that, 3-second time averaged curves of CATHARE results are added to every chart, to better visualize the trends and so compare experimental and simulation outcomes.

### 4.1 Results of the flow reversal test B080394B

Figure 4 shows some simulation results concerning the test with a fully established flow reversal (i.e. B080394B). In particular, the coolant temperature above the test section and the reflector channel flow rate are displayed.

The CATHARE model behaves very well and good outcomes have been found. In fact, the tendencies are in accordance between experiments and simulation. As expected, negative values of the flow rate in the reflector channel are computed by the code once the flow reverses. Another remarkable result is that the simulation predicts exactly the moment in which flow reversal transient takes place. The only problem lies in the wall temperatures, which are overestimated of around 10-15 °C (not showed).

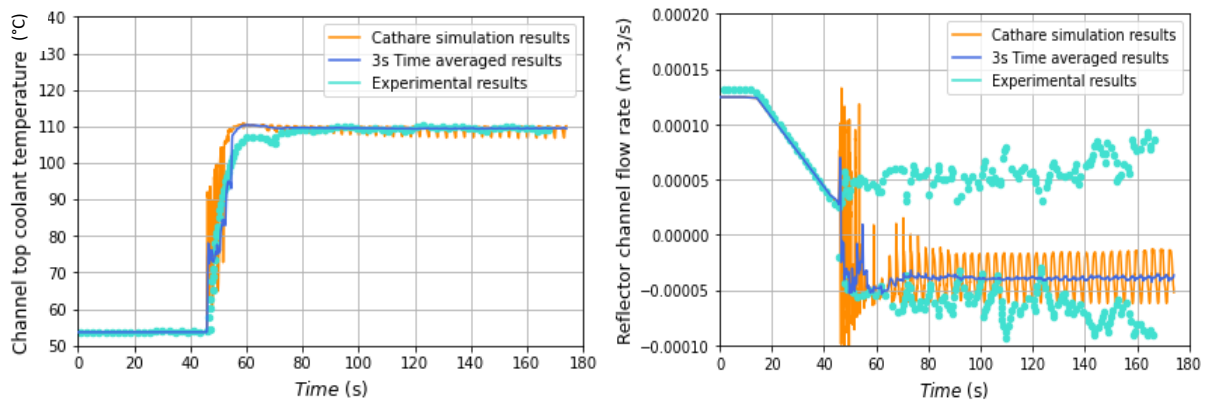


Figure 4: Comparison of experimental and calculated results for the flow reversal test B080394B

#### 4.2 Sensitivity analyses on flow reversal test

The sensitivity analyses carried out on flow reversal test B080394B lead to the following dependencies.

The simulation turns out to be almost independent of the gap size of the test section, of the CATHARE module chosen as upper plenum (1D vs 0D), of the single-phase turbulent flow wall heat transfer correlation ( $Re < 10000$ ) and of the singular pressure losses of the orifice and the flowmeters.

On the other hand, a strong dependence of the model on the thermal inertia of the piping walls (Figure 5) and on the interfacial friction correlation for bubbly-slug flows (Figure 6) has been detected. The thermal inertia is varied by changing the wall thickness of the piping in the circuit. Adding the thermal inertia to the simulation allows to reproduce correctly the temperature evolution in the system, especially during the flow reversal period.

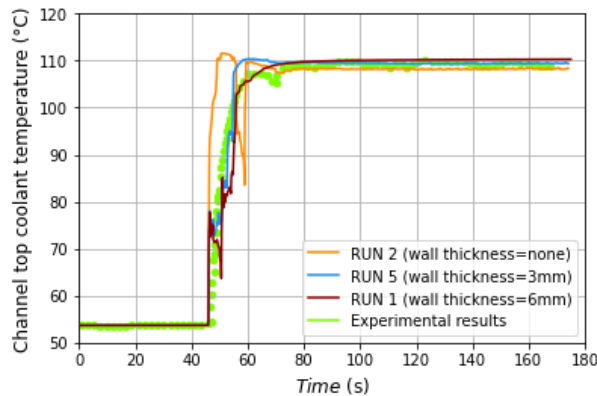


Figure 5: Thermal inertia sensitivity analysis

For a better understanding of Figure 6 it should be pointed out that the interfacial friction correlation for bubbly-slug flow validated for research reactors is activated in CATHARE via the keyword `RODBUNDL`. It can be seen, that without enabling this keyword, the simulation is quickly stopped because the thermal crisis is reached (the wall temperature rises rapidly during the transient). Using a proper interfacial correlation is therefore fundamental to predict correctly the flow reversal phenomenon in CATHARE.

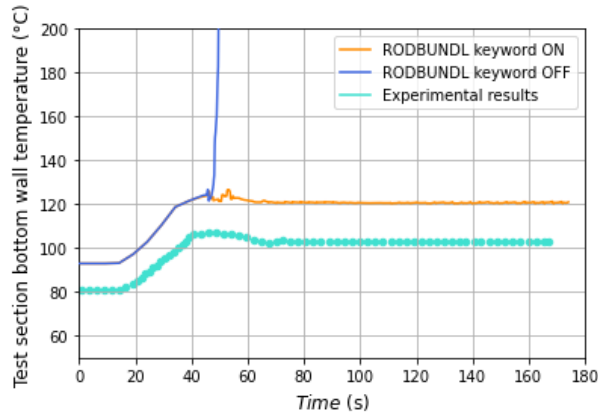


Figure 6: Interfacial friction correlation sensitivity analysis

### 4.3 Results of the Dry-out test B080394A

Figure 7 displays the coolant temperature above the test section and the reflector channel flow rate for the test with a dry-out outcome.

The simulation of this model configuration revealed that CATHARE was unable to predict dry-out setting the nominal heating power equal to 7.5 kW as in the experiment. Raising the nominal power up to 7.6 kW the code computes the overheating of the heating plate. Thus, the estimation of the dry-out is very satisfying. This is particularly true if we consider that the experimenters applied a quite conservative stopping criterion (4 °C above coolant saturation temperature for the heating plates) which could lead to a slight underestimation of the real dry-out condition.

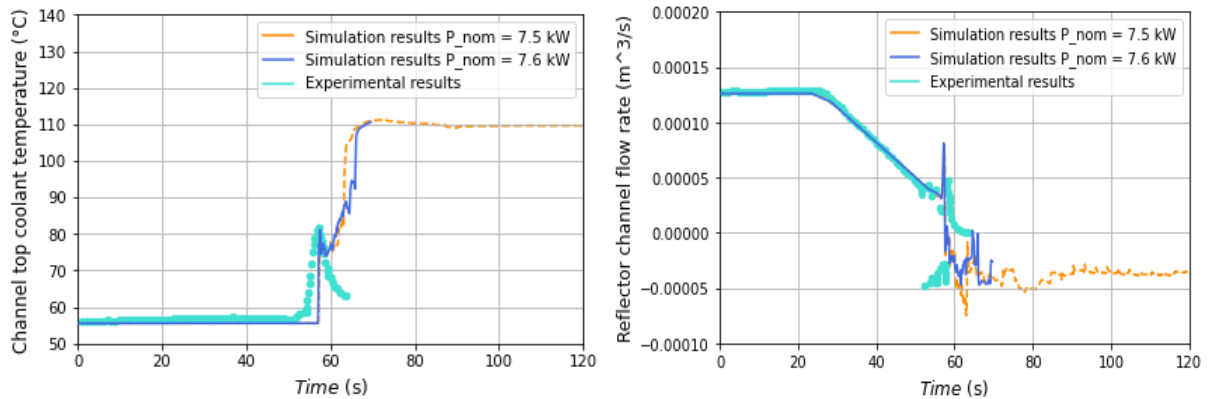


Figure 7: Comparison of experimental and calculated results for the dry-out test B080394A

### 4.4 Sensitivity analyses on the dry-out test

A sensitivity analysis on the piping walls thickness and on the flowmeters singular pressure losses has been performed on this test, in order to study their influence on the minimal heating power supplied to the system to reach dry-out conditions.

The best results have been obtained with more realistic hypothesis, i.e. adding to the model both the flowmeters losses and the walls of the remaining piping. In fact, dry-out has been reached setting a nominal power of 7.6 kW with walls 3 mm thick and 7.5 kW with a thickness of 6 mm. These values are quite similar to the nominal power imposed in the real experiment. Removing the pressure losses of the flowmeters, an augmentation of the nominal power is necessary to achieve dry-out. In this case, a nominal power of 8 kW without walls and of 8.2 kW with walls both 3 mm and 6 mm thick is necessary.



Finally, a diminution of the power has been detected by adding only the flowmeters singular pressure losses to the model (6.3 kW without walls).

These results can lead to the conclusion that the wall thickness of the piping has a small influence on the dry-out power threshold value, while the singular pressure losses massively influence the simulation.

#### 4.5 Results of the additional tests

In Table 4 an overview on the results obtained simulating the additional tests is shown. The symbolism of the table must be remarked: “FR” stands for a tests ended with a full established flow reversal, “Dry-out” for a test stopped because of the thermal crisis onset and “FR then dry-out” indicates a test where initially the flow reversal is sustained, but after that the system goes into thermal crisis.

The obtained simulation results can be considered very positive. In fact, CATHARE predicts the same outcomes as the experimental ones with a relative error on the dry-out power always below 9%.

| TEST NUMBER | NOMINAL POWER (EXP) | NOMINAL POWER (SIM) | EXPERIMENTAL RESULT | SIMULATION RESULT | POWER RELATIVE ERROR (%) |
|-------------|---------------------|---------------------|---------------------|-------------------|--------------------------|
| B021393F    | 7,0 kW              | 7,0 kW              | FR                  | FR                | -                        |
| B021393I    | 7,5 kW              | 7,5 kW              | FR                  | FR                | -                        |
| B021393K    | 8,0 kW              | 8,6 kW              | Dry-out             | FR then dry-out   | 7,5                      |
| B021393N    | 9,0 kW              | 9,0 kW              | FR                  | FR                | -                        |
| B021393P    | 10,0 kW             | 10,2 kW             | FR then dry-out     | FR then dry-out   | 2,0                      |
| B021393O    | 10,5 kW             | 10,5 kW             | FR then dry-out     | FR then dry-out   | 0,0                      |
| B021393Q    | 8,0 kW              | 8,0 kW              | FR then dry-out     | FR then dry-out   | 0,0                      |
| B021393R    | 9,0 kW              | 9,8 kW              | Dry-out             | Dry-out           | 8,9                      |
| B030493D    | 7,0 kW              | 7,0 kW              | FR                  | FR                | -                        |
| B033493E    | 7,5 kW              | 7,5 kW              | Dry-out             | Dry-out           | 0,0                      |

Table 4: Results of the additional tests

## 5 Conclusions

In the present work, a validation of the CATHARE code against flow reversal experiments has been performed. Some important results have been achieved:

- The simulation of flow reversal experiments with CATHARE is feasible and provides very good results. In particular, the code shows good performances in estimating the onset of the flow reversal and the fully established phenomenon. The prediction of the dry-out occurrence by CATHARE is also extremely satisfying, with code-experiment discrepancies on the power necessary to achieve dry-out of less than 9% for all available cases;

- The comparison between experimental results and simulation outcomes reveals only a mismatch in heating plate temperatures evaluation. Such a discrepancy occurs in all the simulations, and its values are between 13 and 27 °C. The experimental uncertainties associated to the wall temperature measurements may explain partially the differences;
- The sensitivity analyses carried out showed a strong dependency of the models on the following parameters: flowmeters and orifice pressure losses, thermal inertia of the piping in the circuit and interfacial friction correlation. On the other hand, the simulations are less dependent to the test section gap size, the upper plenum CATHARE module type (0D vs 1D) and the single-phase turbulent wall heat transfer correlation;
- The simulations confirm the same dependencies of the flow reversal phenomenon to the parameters varied in the experiments, e.g. the circuit inlet temperature, the pump coast-down timing and the water level in the upper plenum.

### Acknowledgments

The authors gratefully acknowledge the financial support of CEA (Commissariat à l'Énergie Atomique et aux Énergies Alternatives).

This work has been partially supported by the ENEN2plus project (HORIZON-EURATOM-2021-NRT-01-13 101061677) founded by the European Union.

### References

- [1] G. Geffraye, O. Antoni, G. Kadri, B. Laviaille e B. Rameau, «CATHARE 2 V2.5\_5: a single version for various applications.,» *Nuclear Engineering and Design*, vol. 241, pp. 4456-4463, 2011.
- [2] A. Ghione, «Assessment and improvements of thermal-hydraulic correlations and methods for the analysis of the Jules Horowitz Reactor,» PhD Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2017.
- [3] A. Ghione e F. Cochemé, «Qualification of the system code Cathare for nuclear research.,» in *12th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics*, Qingdao, China, 2018.
- [4] L. Cheng e P. Tichler, «Flow reversal power limit for the HFBR.,» Brookhaven National Laboratory Associated Universities, 1995.
- [5] L. Cheng e P. Tichler, «Flow reversal power limit for the HFBR,» Brookhaven National Laboratory, 1997.
- [6] F. Occhiogrosso, «International benchmark activity on the simulation of flow reversal experiments with the code Cathare.,» Master thesis, Politecnico di Bari, 2023.