NACIE-UP: a HLM loop facility for natural circulation experiments

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Abstract. The NACIE-UP facility at ENEA-Brasimone R.C. is a large scale loop operating with Lead Bismuth Eutectic (LBE) in the range of 180-450°C in free and mixed convection. The difference in height between heat source and heat sink is about 4.5 m and allows the establishment of natural circulation regime inside the loop. Moreover, a gas-lift system provides the pressure head to enhance the circulation. The facility comprises also a secondary loop in pressurized water with air-cooler to cool the primary LBE. The primary side is instrumented with a prototypical thermal flow meter, a pressure transducer to measure pressure drops across the test section and several thermocouples.

A wire-spaced 19-pins fuel bundle simulator is actually installed inside the NACIE-UP loop. The pin bundle has a maximum wall heat flux of 1 MW/m^2 and is equipped with 67 thermocouples to monitor temperatures and analyze the heat transfer coefficient in different sub-channels and axial positions. Another test section has been designed in order to study the thermal-hydraulic behavior of a pin fuel bundle cooled by HLM in a flow blockage accident scenario. The bundle is composed of 19-pins with two spacer grids and is equipped with about 100 thermocouples in order to monitor pin wall temperatures both with and without flow blockage, the presence of hot spots and to evaluate the thermal mixing above the pin bundle. The experimental campaigns related to these two sections aim to study outstanding thermal-hydraulic phenomena such as the heat transfer during transient from forced to natural circulation flow and the flow blockage accident in a fuel assembly. These activities are in support of the front-end engineering design (FEED) of GEN. IV/ADS prototypes and demonstrators. Some experimental data on heat transfer coefficient obtained in mixed and natural circulation flow regime are also presented in the paper.

Key Words: Liquid Metal, Fast Reactor, Thermal-hydraulics, Fuel Pin Bundle.

1 Introduction

Lead-cooled fast reactors (LFRs) are one of the six nuclear energy systems identified and selected by the Generation IV International Forum (GIF). The six reactor projects have to fulfil well defined targets, related to efficient use of the fuel and a reduction of the waste production (sustainability), have to meet also stringent standards of safety, reliability and proliferation resistance [1]. The attractiveness of the LFRs relies on adequate physical and thermal properties of the heavy liquid metals (HLMs), on the possibility to work with fast neutron spectrum, to employ a closed fuel cycle with conversion of fertile uranium, and to be used as a actinide burners. Nevertheless, a proper understanding of thermal-hydraulic phenomena is one of the key issue for the design of innovative nuclear power plants. For instance, the study of heat transfer mechanisms in natural circulation regime is outstanding for its decay heat removal function in LFRs. More experimental data on heat transfer coefficient in rod bundles cooled by HLMs are desirable. Then, mixing and thermal stratification phenomena should be taken into account for safety analysis studies of Generation IV reactors.

In this context, intensive research activity is mandatory in order to comprehend the main issues related to the use of LFRs. In particular, experimental activities by facilities using HLMs as working fluid are preferable.

ENEA Brasimone R.C. (Italy) is strongly involved in research activities related to the HLM technology; several experimental facilities have been designed in order to perform integral circulation experiments, pool thermal-hydraulic investigation, heat transfer analysis in fuel rod bundles. NAtural CIrculation Experiment (NACIE) is one of the HLM facilities hosted at ENEA Brasimone R.C. The facility was designed in order to perform experiments in natural circulation regime thank to the difference in height between the heat source and the heat sink. In past works [2] the facility housed a fuel bundle simulator, made by three electrical heaters and a tube in tube heat exchanger. Afterward, other test sections were installed in the facility to perform preliminary studies of mixed convection in rod bundle, in support of the large-scale experiment ICE [3]. A “tube in tube” heat exchanger (HX), counter flow type, working with water at low pressure (about 1.5 bar) was also employed in this work. More recently, the facility underwent an upgrade, new components were installed and the facility in this new configuration is called NACIE-UP. The present configuration of NACIE-UP will be described in this paper, in Section 2. In particular, a detailed description of the Fuel Pin Simulator (FPS), a 19-pins wire-spaced fuel bundle, will be provided in Section 2.1, whereas a new test section, the ‘Blockage’ Fuel Pin bundle Simulator (BFPS), will be presented in Section 2.2. The experimental campaigns already carried out and foreseen in the next months, with the two mentioned test sections, will be explained in Section 3. The main conclusions will be presented in Section 4.

2 NACIE-UP facility

NACIE-UP is basically a rectangular loop which allows to perform experimental campaigns in the field of the thermal-hydraulics, fluid-dynamics, chemistry control, corrosion protection with full-scale components and test sections. The peculiarity of this facility is its huge height, which allows the achievement of natural circulation flow in the loop. The primary system of the facility is made of two vertical stainless steel (AISI 304) pipes (O.D. 2.5”), working as riser and downcomer, connected by two horizontal pipes (AISI 304 -O.D. 2.5”). The whole height of the facility is about 7.7 m, while the horizontal length is about 2.4 m. Several flanges allow to install the test sections and other components in the loop, usually a heat source in the lower part of the riser and a heat exchanger in the upper part of the downcomer. NACIE-UP is generally filled with lead-bismuth eutectic alloy (LBE) as working fluid (about 2000 kg, 200 l of capacity).The difference in height between the centre of the heating section and the centre of the heat exchanger is about 5.5 m and is essential for the onset of the natural circulation regime inside the loop. Furthermore, an argon gas injection device is placed inside the riser to provide the driving force to sustain forced convection in the loop. An expansion tank is located at the end of the riser and it is partially filled with Argon as cover gas to avoid oxidation and to accommodate the thermal expansion of the LBE. A schematic layout of the primary circuit is reported in *FIG. 1*. Its main components are:

- A prototypical wire-spaced Fuel Pin Simulator (19-pins) 235 kW maximum power, placed in the bottom of the riser (described in Section 2.1).
- A Shell and tube HX with two sections, operating at low power (5-30 kW) and high power (30-250 kW). It is placed in the higher part of the downcomer.
- An expansion tank in the upper part of the loop, partially filled with Argon as cover gas to control the pressure inside the primary circuit. Two level sensors are located inside the component.

- A regulation 2.5” ball valve placed downstream the FPS, which can be partially closed to regulate the mass flow rate through the loop, and an isolation 2.5” ball valve downstream the HX.
- A prototypical thermal flow meter placed in the lower horizontal pipe. This component has been designed by ENEA and Thermocoax and is characterized by very low pressure losses. A prototypical hydrodynamic housing (bulb) provides the power (few kW) to the fluid and a proper static mixer mixes the fluid downstream; two RTDs measure inlet and outlet temperatures. The mass flow meter has been tested [4], showing accurate measurements for the low and intermediate mass flow rates and a fast response to transients. The prototype design will be submitted for European patent.

The primary loop is instrumented with three bubble tubes to measure absolute pressure in the riser and several bulk thermocouples to monitor the LBE temperature in the loop.

The other systems of the facility are:

- The Secondary loop, filled with water at 16 bar, connected to the HX, shell side. It includes a pump, a pre-heater, an air-cooler, by-pass and isolation valves, and a pressurizer with cover gas. The two sections of the HX shell can be drained and filled separately. An ultrasonic flow meter allows to monitor the secondary water mass flow rate and several thermocouples monitor temperature in the loop.
- An ancillary gas system, to ensure a proper cover gas in the expansion tank and to manage the gas-lift system in the riser. The device for the injection of gas is a ½” O.D pipe 6135 mm long, inserted from the 2½” coupling flange in the upper part of the expansion tank. The gas finally flows out through 16 holes (1 mm diameter).
- A LBE draining section, with ½” pipes, isolation valves a filter and a storage tank.

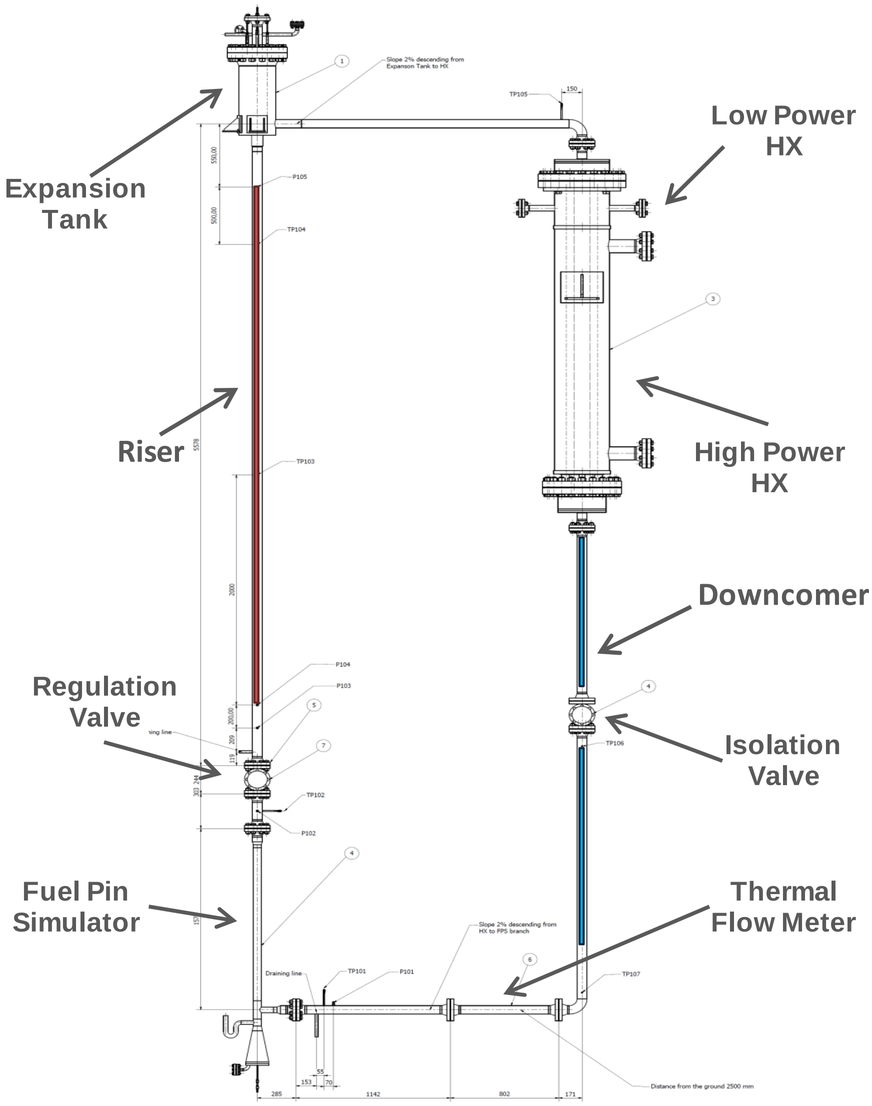

FIG. 1: Technical drawing and main components of the NACIE-UP loop.

2.1 The Fuel Pin bundle Simulator (FPS)

The Fuel Pin Simulator (FPS) is composed by 19 electrically heated pins with an active length of 600 mm. The total length of the test section (2000 mm) includes a non-active length (500 mm), in order to have a fully developed flow in the active region, and the electrical connectors. The 19 pins are arranged on a hexagonal lattice, spacer grids are avoided thank to the use of wires around the pins as spacers. The maximum power of the FPS is about 235 kW, corresponding to a maximum wall heat flux of 1 MW/m^2. The main dimensions of the bundle are reported in TABLE 1. A cross section of the bundle is represented in *FIG. 2*. The total flow area was conventionally divided into 54 sub-channels of three different ranks (S1-S6, S7-S24, S25-S54). The bundle is instrumented with a total of 67 thermocouples (TCs), all 'K' type: 52 are wall embedded TCs (0.35 mm thick) and 15 are sub-channel TCs (0.5 mm thick). Instrumented pins are depicted in red; instrumented sub-channels in orange, and wall TCs position in blue (see *FIG. 2*). Three different axial positions are instrumented: z = 38, 300, and 562 mm after the beginning of the active region (called respectively Section A, B and C), as illustrated in *FIG. 2*. The distance between two consecutive monitored sections is one wire pitch (262 mm).

TABLE 1: FUEL PIN SIMULATOR (FPS) AND BLOCKAGE FUEL PIN SIMULATOR (BFPS) MAIN DIMENSIONS.

Dimension	**Symbol**	**FPS**	**BFPS**
Number of pins	M	19	19
Pin outer diameter	D	6.55 *mm*	10 *mm*
Pitch	P	8.4 *mm*	14 *mm*
Pitch-to-diameter ratio	P/D	1.2824	1.4
Wire diameter	d	1.75 *mm*	-
Wire pitch	P_w	262 *mm*	-
Total length	L_{tot}	2000 *mm*	2000 *mm*
Active length	L_{active}	600 *mm*	600 *mm*
Total flow area	A	65.49 mm^2	1800 mm^2
Hydraulic diameter of the bundle	$D_{H,bdl}$	4.147 *mm*	9.052 *mm*
Hydraulic diameter of the equivalent infinite lattice	$D_{H,nom}$	3.836 *mm*	11.6 *mm*
Hexagonal wrapper apothem	a	19.67 *mm*	31 *mm*

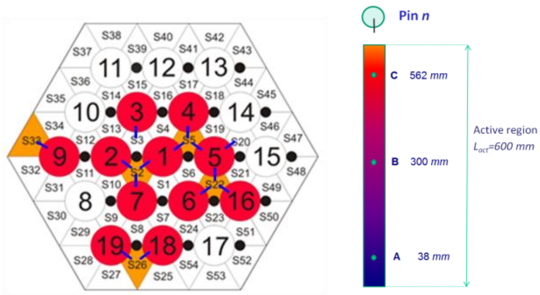

FIG. 2: Cross section of the FPS (left) and axial position of the instrumented sections (right).

2.2 The 'Blockage' Fuel Pin bundle Simulator (BFPS)

The Blockage Fuel Pin Simulator (BFPS) is composed by 19 electrically heated pins, placed on a hexagonal layout by a suitable wrapper. The pins diameter is 10 mm and the pitch to diameter ratio is 1.4. Other main hydraulic parameters of the test section are reported in TABLE 1. The maximum achievable wall heat flux is around 0.7 MW/m^2 and the total power of the pin fuel bundle is about 250 kW. Two spacer grids are employed to assure the pin bundle correct position. One is located at the beginning of the active region where a coupling flange is located as well. The blockage is achieved by opening the latter flange and obstructing the grid sub-channels with appropriate caps.
The test section will be instrumented with about 100 thermocouples. Most of them will be located in the region of the blockage. Referring to *FIG. 3*, pins 1, 2, 5, 15 will be instrumented with wall embedded thermocouples (0.35 mm thick) and sub-channel B2 with 0.5 mm bulk TCs. TCs will be disposed in sixteen axial positions (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500, 600 mm starting from the beginning of the active region). At z= 550 mm other pins will be also instrumented in order to characterize the heat transfer in the unblocked case (i.e. pins 1, 2, 4, 5, 7, 9, 14, 15; sub-channels B1, B2, B5, E1, E5, and the corner sub-channels across B5/C4 and E5/F4). In *FIG. 3*, instrumented pins are depicted in red, instrumented sub-channels are highlighted in orange, wall TCs positions are represented in light blue. Additional instrumentation (24 Resistance Temperature Detectors) will be placed in the mixing region, downstream the FPS.

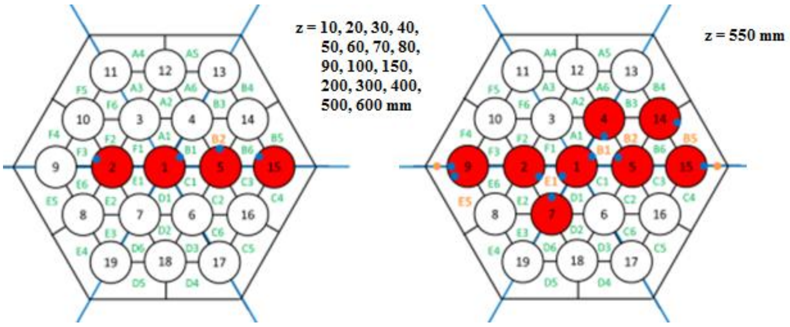

FIG. 3: Cross section of the BFPS and instrumentation position.

3 Experimental campaigns of LBE-cooled fuel pin simulator bundles

The last experimental campaign with NACIE-UP was performed in the frame of the SEARCH FP7 EU project and regarded the coolability of a wire-spaced fuel bundle in the natural convection regime [5]. A new experimental campaign with the same bundle have been performed across 2016 and 2017 in the frame of the HORIZON2020 project SESAME. Some obtained results are reported in Section 3.1. The experimental campaign with the BFPS will be performed at the end of 2017. The programmed tests are briefly described in Section 3.2.

3.1 Experimental campaigns with FPS test section

The first experimental campaign with FPS test section aimed to evaluate the heat transfer coefficient in a wire-spaced fuel bundle in the range of low and medium Péclet numbers. The campaign consisted in several steady state tests characterized by different power levels and LBE mass flow rates. Tests were performed in pure natural circulation regime or in gas enhanced circulation. The Nusselt numbers obtained experimentally have been compared with some correlations existing in literature, as shown in *FIG. 4* [5].

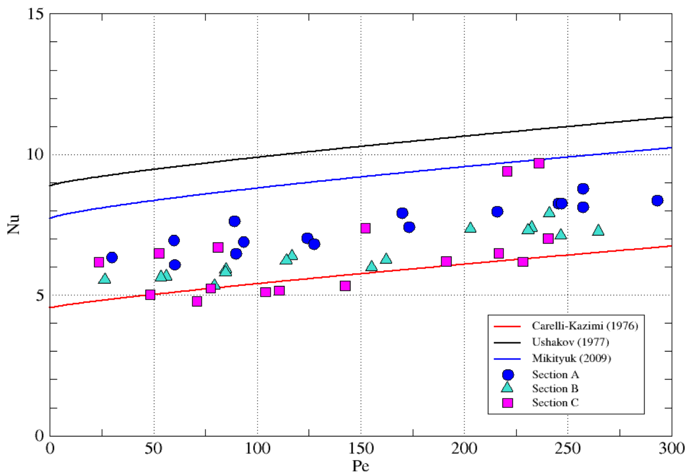

FIG. 4: Section-averaged Nusselt number compared with existing heat transfer correlations, ref [5].

The new experimental campaign focuses rather on transient tests, with power and/or mass flow transition. One of the test concerned the transition from natural circulation with nominal FPS power of 10 kW to natural circulation with nominal FPS power of 25 kW. The power level was switched after 1800 s of starting steady state. *FIG. 5* left shows the time trend of the nominal FPS power and the actual power released inside the active length, which was calculated through the energy balance. The difference is due to radial losses toward the environment and axial losses in the non-active part and in the cold tails. *FIG. 5* right displays the additional power source released in the loop for the thermal mass flow meter operation. The LBE mass flow rate achieved during the test is reported in *FIG. 6* left, whereas the main LBE temperatures inside the loop are shown in *FIG. 6* right. The LBE temperature at the FPS outlet suddenly increased after the power was switched to 25 kW, but then decreased due to the consequent increase of the mass flow rate. Further, TABLE 2 reports the main thermal-hydraulic parameters (mean values and standard deviation) at the starting and the final steady states of the natural circulation test. For the second steady state, the last 2000 s of the experiment have been considered.

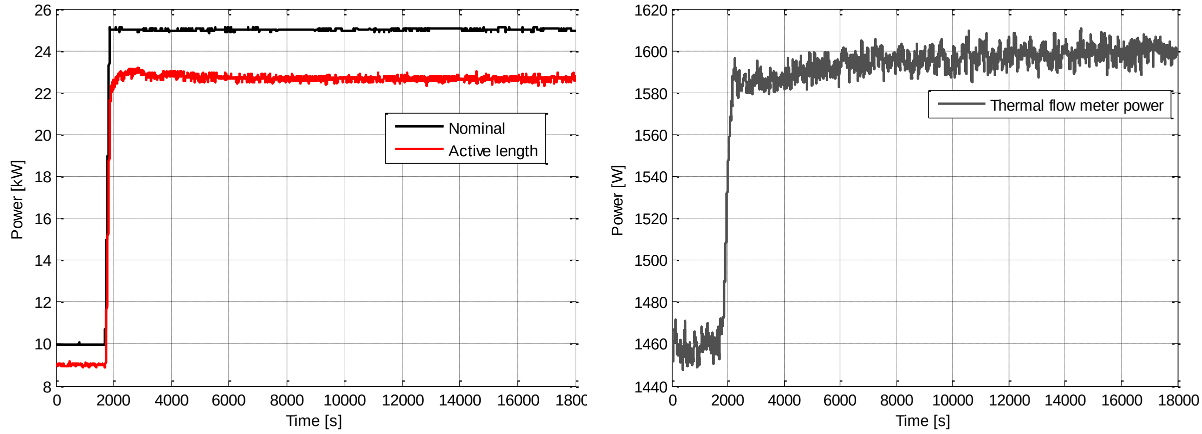

FIG. 5: Time trend of FPS power (left) and thermal flow meter power (right) for NC transition test.

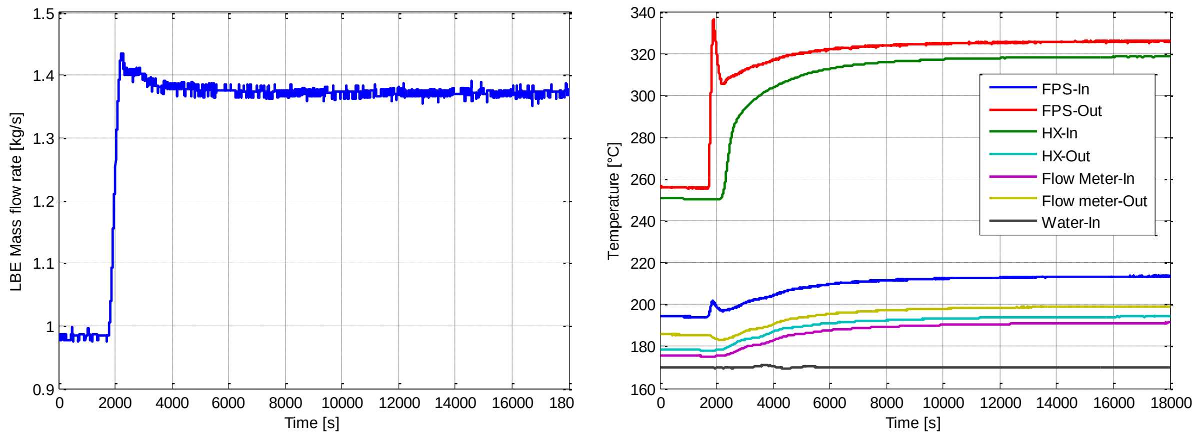

FIG. 6: Time trend of LBE mass flow (left) and LBE temperatures on the loop (right).

TABLE 2: MAIN THERMAL HYDRAULIC PARAMETERS OF NC TEST.

	Q [kW]	$Q_{FlowMeter}$ [W]	$\dot{m}$ [kg/s]	ΔT_{FPS} [°C]	Re_{FPS}	Pe_{FPS}
Steady state 1						
Average value	9.00	1458.3	0.98	61.7	2686	78
σ	1.53	5.0	0.03	0.3	208	9
Steady state 2						
Average value	22.52	1592.0	1.37	112.3	4360	100
σ	3.85	3.7	0.04	0.2	338	12

The FPS instrumentation allows to obtain detailed local data on the temperature distribution inside the bundle. For example, *FIG. 7* left shows the LBE temperature in sub-channels S2 (inner rank), S22 (intermediate rank) and S33 (external rank) at the three instrumented section (A, B and C). At section A, which is close to the beginning of the active length, no large difference is detectable among the three sub-channels, meaning that temperature profile is almost flat. At section B and C the temperature profile is more developed and a hotter region is evident in the inner region of the bundle. Wall temperatures were also monitored during the test. As an example, wall and sub-channel temperatures relative to sub-channel S2 are shown in *FIG. 7* right. The peak after the power transition is noticeable, with a sudden decrease due to re-wetting of the wall and the higher mass flow rate which establishes in the second part of the test. These local data become important for the analysis of heat transfer in such configuration and thermal-hydraulic conditions and allow the computation of Nusselt number in the single sub-channels, as well as the average value in the FPS section.

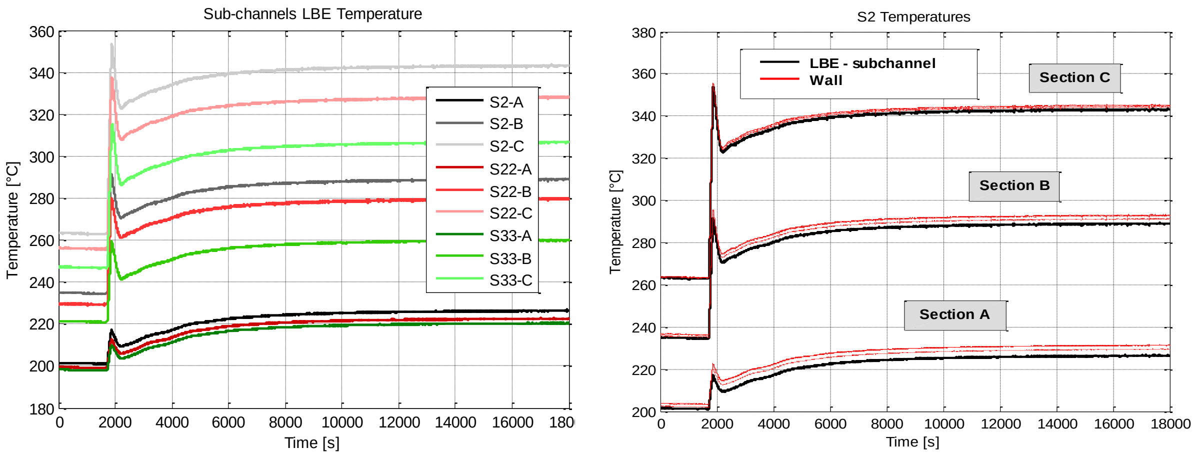

FIG. 7: Time trend of some sub-channel LBE temperature (left) and temperatures inside sub-channel S2 (right) at three axial positions.

3.2 Experimental campaign with BFPS test section

The Blockage Fuel Pin Simulator (BFPS) experiment was designed in order to investigate the local and bulk effects of an internal blockage in a LFR-like core. Indeed, the flow blockage in a Fuel Assembly (FA) is one of the key issues related to the LFR safety, since this event might lead to a damage of melting of a FA.
The objective of the experimental campaign with the BFPS test section is to analyze the effect of the partial blockage on cladding and coolant temperatures and pressure drops in the FA. Five kinds of blockages were initially individuated and are shown in *FIG. 8* (cases from 1 to 5). Case 0 is unblocked flow area, which allows to characterize the flow and the heat transfer in the test section in normal operation. The blocked part can have different extension and is located in different regions of the FA: central sub-channel blockage, corner sub-channel blockage, edge sub-channel blockage, one sector blockage, two sectors blockage. The blockage is made by means of stainless steel caps fixed to the grid spacer (in black in *FIG. 8*).

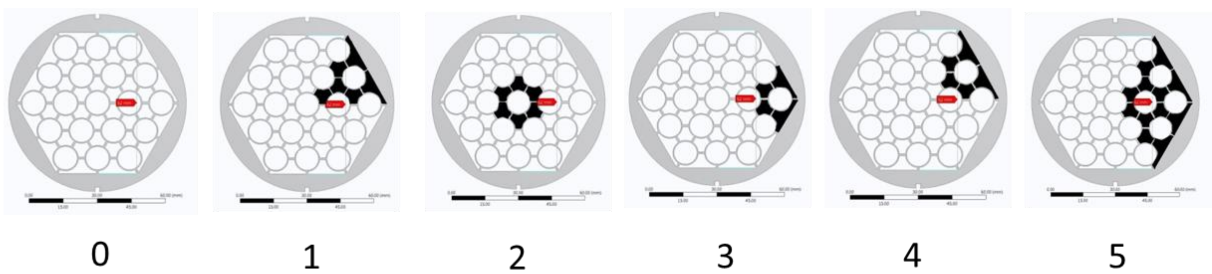

FIG. 8: Blockage types: (0) unblocked; (1) sector; (2) central; (3) corner; (4) edge; (5) two sectors.

A CFD pre-test matrix was prepared for defining the different blockage types at different mass flow rates. In the test cases presented in this paper the LBE mass flow rate is 16 kg/s, which is the maximum flow rate achievable in the NACIE-UP facility with this bundle. The power of the FPS was 94.2 kW in order to have an inlet-outlet temperature increase of 40°C. The inlet temperature is 200°C, to protect test section from damages during the experiments. The corresponding Reynolds number in the BFPS in these conditions is about 46700. The test cases differ for the blockage types of *FIG. 8*. *FIG. 9* (left) shows the clad temperature distribution in the region behind the blockage for blockage type 1, while *FIG. 9* (right) shows the LBE temperature in the stagnation region immediately after the blockage. A local temperature peak in the region 100 mm behind the blockage is clearly visible with a maximum temperature of about 360°C. The increase of local temperature due to the blockage is about 150°C with respect to the unblocked case. As evidenced in other computational and theoretical studies [6] [7], the reason for the local temperature peak is the vortex generated downstream by the obstacle. In particular, in the central stagnation point of the vortex, heat is exchanged only by conduction and the temperature increases. *FIG. 10* shows the maximum temperature profiles along the axial direction for all simulated cases, where the axial distance is measured starting from the beginning of the active region. Most of the cases have a similar maximum temperature behind the blockage around 360°C (about 150°C greater than the unblocked case). The region of influence behind the blockage is limited to 50-100 mm in most cases, and 200 mm for the larger two-sector blockage (case 5). This result is in line with previous studies and the region of influence is tied to the extension of the blocked area. Typically, an elongated recirculation vortex of aspect ratio 2-3 behind the blockage occurs.

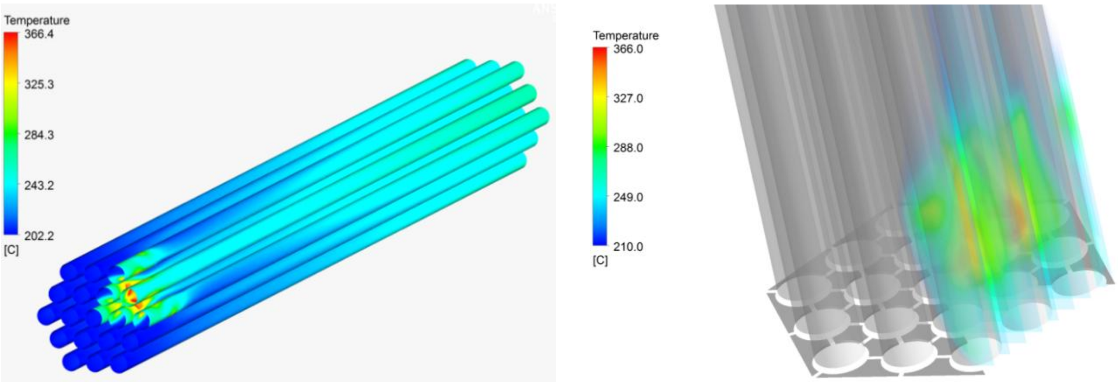

FIG. 9: Clad temperature (left) in the region behind the blockage and LBE temperature in the stagnation region (right) for blockage case 1.

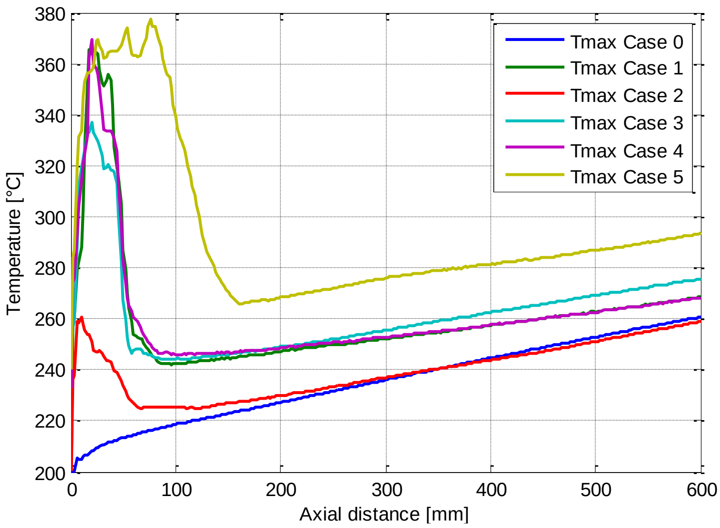

FIG. 10: Maximum temperature profile along the axial direction for the 6 cases investigated.

4 Conclusions

The facility NACIE-UP, located in Brasimone R.C. (Italy), is an experimental apparatus currently employed for investigations in the field of thermal-hydraulics, fluid-dynamics, chemistry control with the use of HLM as working fluid. In particular, its peculiar configuration permits the achievement of the natural circulation flow in the facility and to examine in depth phenomena involved in this flow regime. Recent work involved the installation of a prototypical fuel bundle simulator, made of 19 wire-spaced pins. The bundle was already employed for heat transfer analysis in steady state conditions in the range of low-medium Reynolds numbers. A new experimental campaign have been performed across 2016 and 2017, with the same bundle and new components in the loop, such as a prototypical thermal mass flow meter, designed and manufactured by ENEA and Thermocoax. The new campaign have been focusing on transient tests, especially transition from high power and forced circulation to natural circulation at low FPS power. The available instrumentation allows the detailed analysis of the heat transfer phenomena inside the bundle during transients and at steady state conditions. In the second part of 2017, the new test section (the Blockage Fuel Pin Simulator) will be installed in the facility for a new experimental campaign, addressed to the study of the effect of a flow blockage inside a fuel assembly. Some pre-test CFD analysis showed the clad and LBE temperature increase due to the blockage itself for different blocked configurations. This paper showed as the facility NACIE-UP is currently fully involved in research activities related to the use of HLMs as coolant in GEN IV nuclear reactors.

Acknowledgement

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