Experimental Fuel Pin Bundle characterization in the NACIE-UP HLM facility

I. Di Piazza
ENEA C.R. Brasimone
Camugnano, 40032, Brasimone, Italy
ivan.dipiazza@enea.it

M.Angelucci, N. Forgione, R. Marinari,
UNIPI
UNIPI DICI, Largo Lucio Lazzarino 2 – 56122 Pisa, Italy

G. Polazzi, V.Sermenghi, L. Laffi, D. Giannotti, M. Tarantino
ENEA C.R. Brasimone
Camugnano, 40032, Brasimone, Italy

ABSTRACT

In the context of the studies on GEN. IV/ADS nuclear systems, the correct evaluations of the temperature distribution in the fuel pin bundle is of central interest. In particular, the use of lead or lead-bismuth eutectic (LBE) as coolant for the new generation fast reactors is one of the most promising choices. Due to the high density and high conductivity of lead or LBE, a detailed analysis of the thermo-fluid dynamic behavior of the heavy liquid metal (HLM) inside the sub-channels of a fuel rod bundle is necessary in order to support the front-end engineering design (FEED) of GEN. IV/ADS prototypes and demonstrators. At ENEA-Brasimone R.C., large experimental facilities exist to study HLM free, forced and mixed convection in loops and pools: e.g. NACIE-UP is a large scale LBE loop for mixed convection experiments with a secondary side in pressurized water. In the context of the SEARCH FP7 project, an experiment was performed in the NACIE-UP facility to assess the coolability of a 19-pin wire-wrapped electrical bundle (Fuel Pin Simulator, FPS), with heat flux up to 1 MW/m^2. The bundle is representative of the one adopted in the MYRRHA concept, and it is instrumented with 67 thermocouples to monitor bulk and wall temperatures in the different ranks of subchannels at different heights. The mass flow rate in the loop is measured by an induction flow meter and by thermal balance in stationary conditions.

A large experimental test matrix has to be carried out in order to characterize the coolability of MYRRHA Fuel Sub-Assembly. Results in terms of wall and bulk temperatures, heat transfer coefficients and pin azimuthal temperature distribution are available at different mass flow rates in the range 0-7 kg/s, i.e. up to 1 m/s in the subchannel, half of the MYRRHA FA nominal velocity.

The first experimental tests with FPS are provided in the paper. Those are the first data on HLM-cooled wire-wrapped Fuel Assembly reproducing the MYRRHA FA. Post-test analysis and error propagation study on derived quantities is also provided.

KEYWORDS

Liquid Metal, Fast Reactor, Thermal-hydraulics

1. INTRODUCTION

In the context of the studies on GEN. IV/ADS nuclear systems, the correct evaluations of the convective heat transfer in the core is of central interest. For the GEN IV fast reactors, the use of Lead or Lead-Bismuth Eutectic (LBE) as coolant is one of the most promising choices, due to their attractive thermal-physical properties (e.g. high density, high conductivity, high boiling temperature). Nevertheless, a

detailed analysis of the convective thermo-fluid dynamic behavior of the Heavy Liquid Metal (HLM) is necessary. One of the key aspect is the comprehension of the mechanisms of heat transfer inside the sub-channels of a fuel rod bundle in normal operation and during transients.
In this frame, at the ENEA-Brasimone Research Centre, NACIE-UP facility, an upgraded configuration of the NACIE (NAtural Circulation Experiment) was manufactured. It is a large scale LBE rectangular loop meant for mixed convection [1] which allows to perform experimental campaigns in the fields of the thermal-hydraulics, fluid-dynamics, heat transfer, and also chemistry control, corrosion protection.
Moreover, in the frame of the research activities planned to support the development of the MYRRHA irradiation facility (SCK-CEN) [2], ENEA assumed the commitment to run experimental tests to simulate the thermal-hydraulic behavior of a wire-spaced fuel pin bundle cooled by heavy liquid metal. These activities are performed in the context of the European FP7 SEARCH Project.
For this purpose, an electrically heated rod bundle was specifically designed and manufactured as test section for the facility, with the aim to simulate the fuel pins . The Fuel Pin Simulator (FPS) is 19-pin wire wrapped bundle and it is representative of the one adopted in the MYRRHA concept. It is instrumented with 67 thermocouples to monitor bulk and wall temperatures in the different ranks of subchannels at different heights.
The experimental campaign has been intended in order to describe the thermal-hydraulic behavior of the MYRRHA FA during a Loss of Flow Accident (LOFA) with the coast-down of the main circulation pump. Heat transfer during a LOFA is driven by the inertia of the fluid during the pump coast-down and the onset of natural circulation due to the difference in height between the heat source and the heat sink. The aim of the experimental campaign planned on the NACIE-UP facility is to obtain primarily stationary conditions in the facility corresponding to some test cases foreseen and to characterize each stationary condition with respect to the local heat transfer measurements in the bundle, the mass flow rate, the pressure drop. These part of the experimental campaign will assess the coolability of the FA. The data available with the FPS bundle regard: the measurement of the pin cladding temperature by embedded thermocouples; the measurement of the sub-channels temperature; Heat Transfer Coefficient (HTC) evaluation; the check of hot spots and peak temperatures; the evaluation of the axial thermal stratification entrance length along the sub-channels. Data will be also the base for post-test CFD validation.
The first experimental test was already achieved and a large experimental test matrix has to be carried out soon to characterize the heat transfer in the wire-wrapped bundle cooled by a heavy liquid metal and its coolability during transients. These are unique data on HLM-cooled wire-wrapped Fuel Assembly reproducing the MYRRHA FA. A similar experiment, but with higher mass flow rates, will be performed at KIT within the same research project [3].
In Section 2, the description of the NACIE-UP facility is provided. It is focused on the overall configuration and subsystems ,the experimental test section and the instrumentation of the Fuel Pin Simulator. In Section 3, some details of the experimental data are shown, post processing methods and results are described. Finally in section 4 some conclusive remarks are presented.

2. THE NACIE-UP EXPERIMENTAL LOOP

2.1 General framework

NACIE-UP is a rectangular loop which consists of two vertical pipes (O.D. 2.5”), working as riser and downcomer, connected by two horizontal pipes (O.D. 2.5”). The whole height of the facility is around 8 meters, while the horizontal length is 2.4 meters.
In the bottom of the riser a prototypical wire-spaced fuel pin bundle simulator (FPS), with a maximum power of 235 kW, is installed. A heat exchanger will be placed in the upper part of the downcomer for the heat removal from the LBE.

NACIE-UP is made in stainless steel (AISI 304) and it can be operated both with lead and eutectic alloy LBE as working fluid (about 2200 *kg*, 220 *l* in the updated configuration). It has been designed to work up to 550°C and 10 bar. A simplified scheme of the facility and a picture are sketched in Figure 2.1.

a) Conceptual scheme of NACIE-UP b) Picture of NACIE-UP

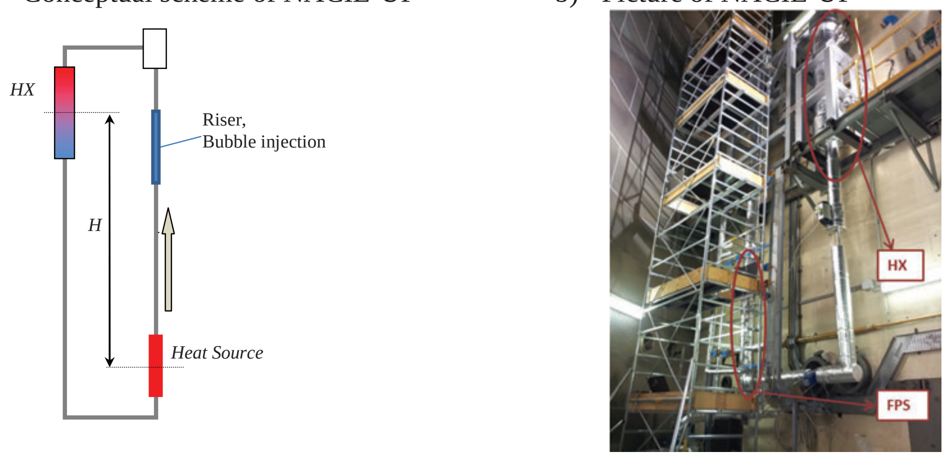

Figure 2.1: Configuration of the NACIE-UP facility

The difference in height *'H'* between the center of the heating section and the center of the heat exchanger, crucial for the natural circulation driving force, is about 5 meters. Further, an argon gas injection device is set in the riser to ensure a driving force to sustain forced convection in the loop.
Moreover, the facility consist of an ancillary gas system (cover gas) and a pressurized water (16 *bar*) secondary side for the normal operation and transient analysis. A fill&drain system is installed to allow the right operation of the loop too.
The reference for the piping and instrumentation is reported in Figure 2.2, where all the instrumentation, components and pipes are listed and logically represented. Its schematic layout is reported in Figure 2.3.

The facility is assembled by:

- A Primary side, filled with LBE, made by several components, pipes and coupling flanges. Pipes T101, T103, T104, T105 are austenitic SS AISI304 2.5″S40, I.D. 62.68 *mm*;

- A Fuel Pin Simulator (19-pins) 250 kW maximum power;
- A Shell and tube HX with two sections, operating at low power (5-50 kW) and high power (50-250 kW);
- A high mass flow rate induction flow meter (3-15 kg/s) FM102;
- 5 bubble tubes to measure the pressure drops across the main components and the pipes and the gas-lift pressure head;
- Several bulk thermocouples to monitor the temperature along the flow path in the loop;
- The Secondary side, filled with water at 16 bar, connected to the HX, shell side. It includes a pump, an air-cooler, by-pass and isolation valves, and a pressurizer (S201) with cover gas;
- An ancillary gas system, to ensure a proper cover gas in the expansion tank and to provide gas-lift enhanced circulation;
- A LBE draining section, with ½″ pipes, isolation valves and a storage tank (S300);
- A gas-lift circulation system in the riser ensures about 0.6 bar of driving force allowing the accomplishment of mass flow rates up to ~7 *kg/s*.
- The ancillary gas system has the function to ensure the cover gas in S101 and to manage the gas-lift system in the riser (T103) for enhanced circulation regime.

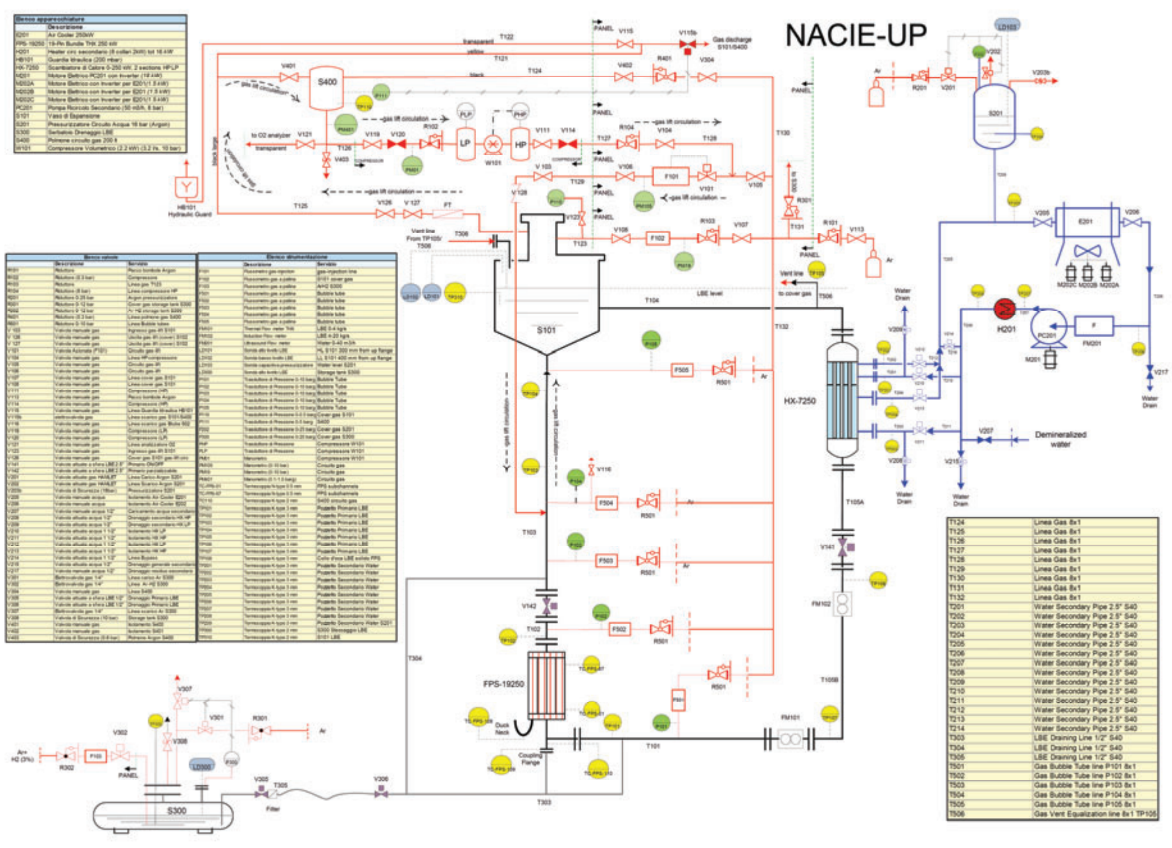

Figure 2.2: Piping and Instrumentation Diagram (P&ID) of the NACIE-UP facility.

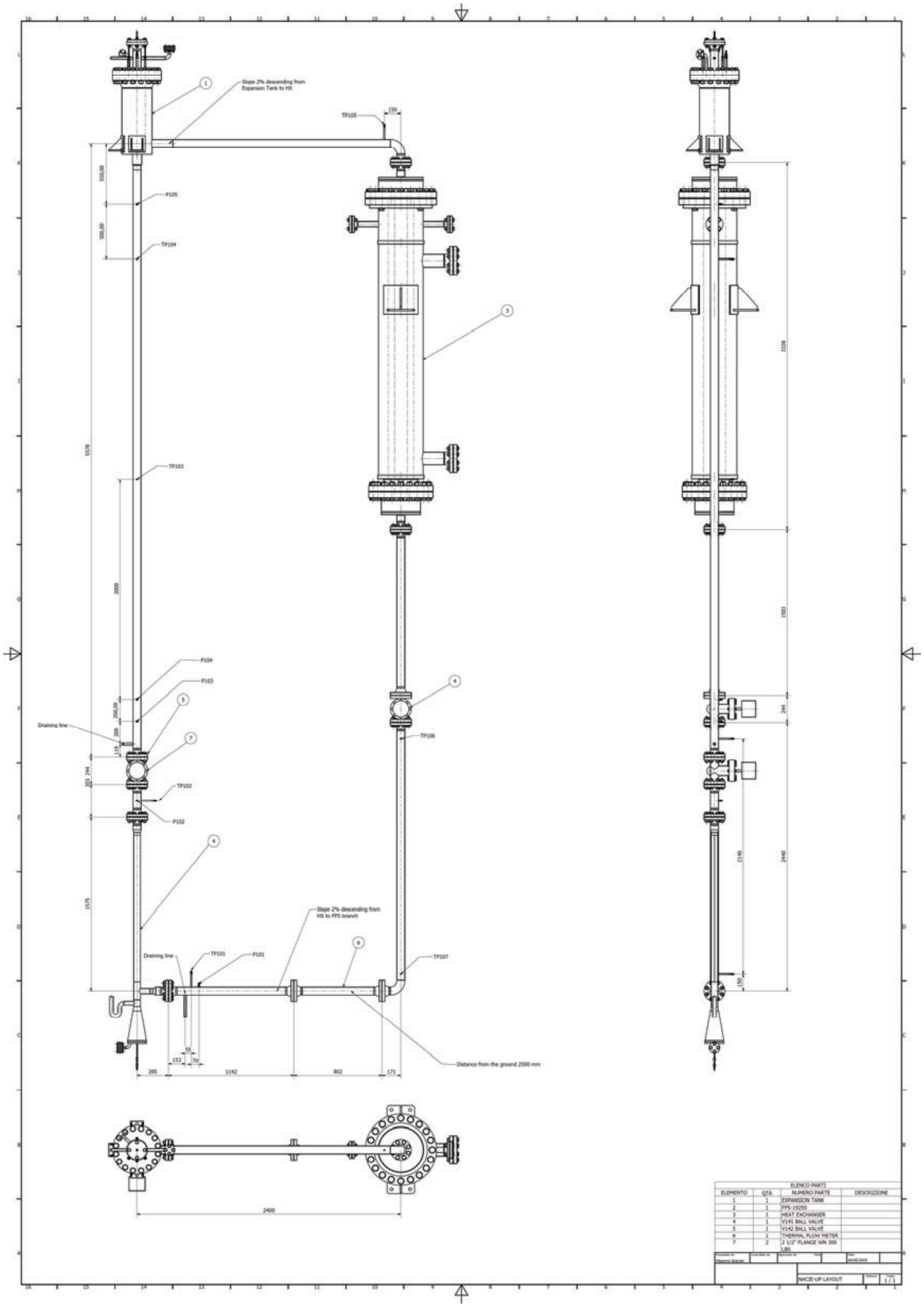

Figure 2.3: Schematic layout of the NACIE-UP facility: primary loop.

2.2 The fuel pin simulator(FPS) experimental test section

The FPS consists of 19-pin electrical heated rod bundle specifically designed and provided by THERMOCOAX SAS for this purpose. The active length is L_{active} = 600 *mm*. The whole length (L_{total} = 2000 *mm)* includes the *non-active* length and the electrical connectors region. The pin have a diameter D= 6.55 *mm*, and the maximum wall heat flux will be close to 1 MW/m^2. The pins will be placed on an hexagonal lattice by a suitable wrapper, while spacer grids will be avoided thanks to the wire spacer. The maximum power of the fuel pin bundle is ~ 235 kW.

With respect to the MYRRHA bundle some differences occur. First, the number of ranks and pins: 7 ranks and 127 pins for MYRRHA against 3 ranks and 19 pins for NACIE-UP. This difference in the number of pins is not relevant for the convective heat transfer in the subchannels because side, corner and central subchannels can be monitored in the 19 pin bundle and basic phenomenology is the same as in the MYRRHA bundle.

The inlet temperature was fixed to T_{inlet}=200 °C for all cases, being the thermal-fluid dynamic behavior of the bundle independent by T_{inlet}. The reference quantities for each test are the average subchannel velocity u_{sc} [*m/s*], which characterize the flow from an hydraulic point of view, and the average linear power in a single pin Q_{lin} [*kW/m*], which defines the heat transfer boundary conditions.

The subchannel velocity u_{sc} determines, on the base of the geometry of the bundle and on the fluid properties, the LBE mass flow rate in the MYRRHA FA $\dot{m}_{FA}\ [kg/s]$, and the LBE mass flow rate in the NACIE-UP bundle $\dot{m}_{NACIE}\ [kg/s]$. On the other side, the linear power density Q_{lin} [*kW/m*] fixes the total power of the NACIE-UP 19-pin bundle Q[*kW*].

A schematic representation of the cross-section of the pin bundle is shown in Figure 2.4. The total flow area can be divided into 54 sub-channels of different ranks (S1-S54). The sub-channels and the relative pins that will be instrumented are also indicated. Wires are helicoidally twisted around each pin.

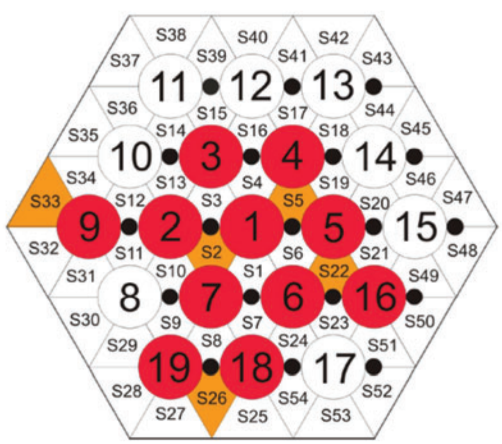

Figure 2.4: Sketch of a section of the new fuel pin bundle simulator for the NACIE-UP facility. Instrumented pins in red; instrumented subchannels in orange, wire in black.

The main geometrical dimensions to be considered for a thermal-hydraulic assessment of the FA are:

- The rod diameter D=6.55 mm;
- The wire diameter d=1.75 mm;
- The pitch to diameter ratio x=P/D ≈1.28;
- The streamwise wire pitch Pw=262 mm;
- The regular lattice is triangular/hexagonal staggered;
- The resulting flat to flat distance of the hexagonal wrap is 39.34 mm;
- The equivalent hydraulic diameter of the infinite lattice bundle is D_{eq}=3.836 mm;

The three pin ranks of the bundle are representative of all the sub-channels in the MYRRHA FA. In fact, it is well known from the literature [4] that for wire-wrapped bundles of similar geometry, the influence of the wall is considered important for the external rank N and for the N-1 rank of pins, while the other ranks are not so much influenced by the wrap wall. The fuel pin bundle simulator (FPS) consists of the hexagonal wrap and additional parts and flanges to connect the bundle to the NACIE-UP facility. A developing non-heated wire-wrapped region of 2.5 wire pitch is present in order to allow the flow to be fully developed at the beginning of the active region. The wire is wrapped anticlockwise, if viewed from the top.

2.3 Bundle Instrumentation

The bulk and wall temperatures in the FPS will be monitored in three different cross sections in the active region. The total number of bulk thermocouples (ϕ=0.5 mm) is 15, while the total number of wall embedded thermocouples (ϕ=0.35 mm) is 52. As already pointed out, Figure 2.4 represents a section, viewed from the top, of the bundle with pins and subchannels that must be instrumented. Pins 2, 4, 6, 7, 9, 16, 18, 19 will be equipped with wall embedded thermocouples on a generatrix parallel to the pin axis, as shown. Three different levels will be considered: z= 38, 300, 562 *mm* starting from the beginning of the active region of the pins (connector side), as shown in Figure 2.5 *a*. Conventionally, measurement sections at z=38, 300 and 562 *mm* will be called respectively sections *A*, *B* and *C*. The reference section in **Errore. L'origine riferimento non è stata trovata.** *b* is referred at the section *A*, z=38 mm, and the other measurement sections chosen *B*, *C* (i.e. z=300, 562 *mm*) are exactly in the same configuration, being the wire pitch P_w=262 *mm*= 300-38 *mm*= 562-300 *mm*.

a) Axial location b) Azimuthal orientation

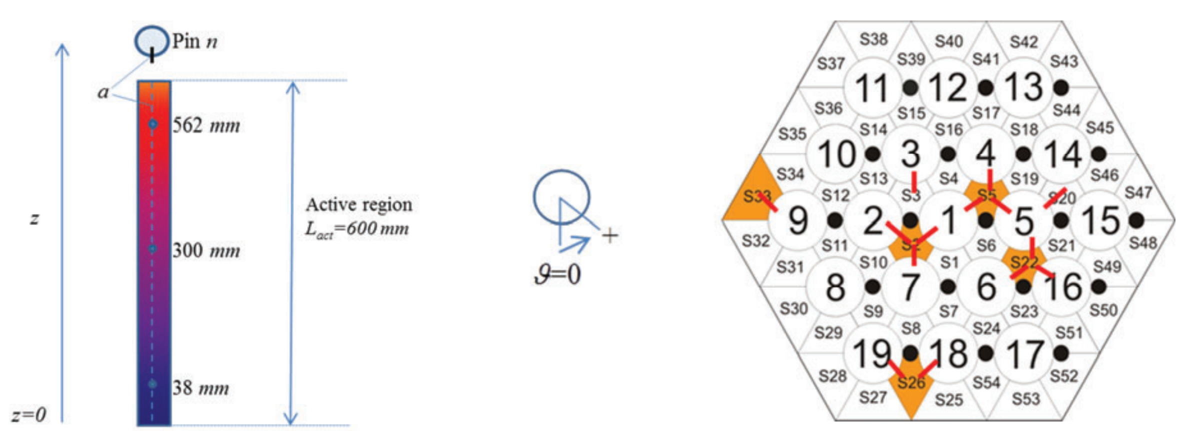

Figure 2.5 Wall Embedded TCs locations for pins n. 2,4,6,7,9,16,18,19.

Therefore this choice allows to have three independent measurements of heat transfer referred to the same relative position of wire and pins and this feature minimize systematic errors.
Pin 1 will be instrumented with wall embedded thermocouples on two generatrices *a* and *b*, located 180° each other, parallel to the pin axis; pin n. 5 will be instrumented along three generatices *a*, *c*, *d*, located at 120° each other.
Subchannels S2, S5, S22, S26, S33 will be instrumented with bulk thermocouples 0.5 *mm* thickness at the 3 measurement sections A, B and C, i.e. at levels z=38, 300, 562 *mm*. The generic measurement section, with wall thermocouples and subchannels instrumented, is shown in a schematic view in Figure 2.4.
Pin number 3 will be instrumented along a generatrix with 13 wall embedded thermocouples along the active length, placed every $P_w/6$=43.66 mm starting from z=38 mm.; the azimuthal orientation of the groove is ϑ=0.
Thermocouples are K-type high accuracy, with a declared uncertainty by manufacturer of 0.1 °C.

For further details on the FPS test section and the NACIE-UP facility, see the paper presented in the HLMC-2013 International Conference in Russia [6].

3. EXPERIMENTAL RESULTS

A first experimental test was accomplished with the NACIE-UP facility for the evaluation of the heat transfer coefficient and the temperature distribution in the FPS. Moreover, the test was a general check to assess the correct behavior of all the systems of the facility.
In this test, a nearly steady-state condition was reached. Some light difficulties were found in the operation of the secondary system, in order to reach a stationary situation by removing heat finally through the air-cooler. Nevertheless, both the LBE temperature at the inlet and at the outlet of the FPS are almost constant with a deviation of less than 1 °C. The trend is shown in Figure 3.1.

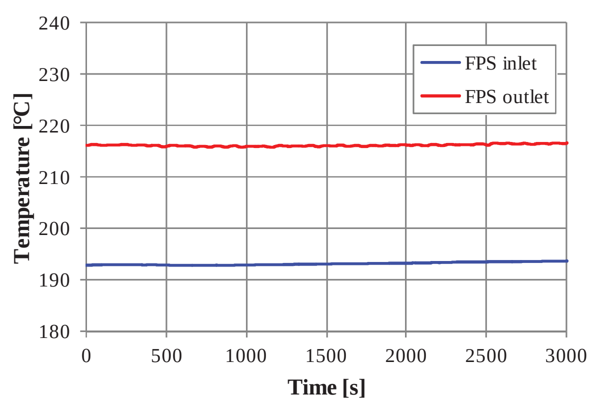

Figure 3.1: LBE temperature across the FPS

This test were characterized by a power level equal to 9 kW and the injection of the gas was turned on to a set point of 10 Nl/min in order to enhance the circulation of the LBE. The secondary side was operated with a mass flow rate of about 4.5 m^3/h. Temperature across the heat exchanger and the mass flow rate were checked and finally the FPS heat was removed by the air-cooler in the pressurized water secondary side.

In Figure 3.2, the set point and the measure of gas injected flow rate in the riser above the FPS are shown [Nl/min].

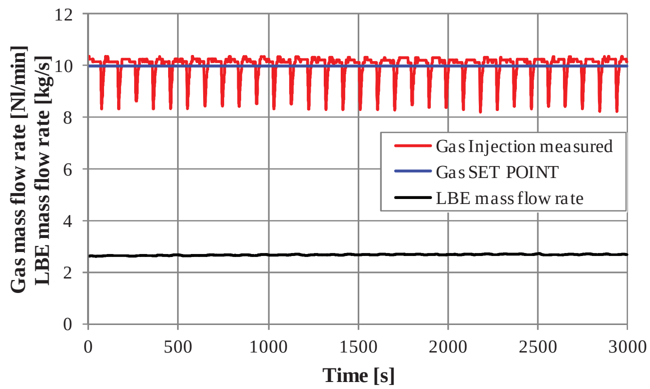

Figure 3.2: LBE and gas injection mass flow rates.

The stable condition allowed to compute the LBE mass flow rate in the loop trough the energy balance equation:

$$Q = \dot{m}\, c_p\, \Delta T$$

In Figure 3.2 the trend over of LBE mass flow rate is also depicted. The average value of the LBE mass flow rate was calculated as the average value of the trend as 2.67 ± 0.22 kg/s.
In this first work this simple method is used to compute mass flow rate at this stage. By refining the post-processing method, a more accurate and consistent way to measure inlet temperature and mass flow rate was developed [5].
Afterwards the averaged values for all the measured parameters were computed: LBE temperatures inside the loop, wall and bulk temperature inside the FPS, pressures, power. These parameters were used to compute derived parameters and non-dimensional quantities.

3.1. Post Processing results

The post-processing of the results was carried out by applying the error propagation theory including in the computation the instrumentation error. Practically, a random flat instrumentation error was added to the primitive data (e.g. thermocouples) and then the derived quantities were computed. Then the average and standard deviation were computed on the samples by capturing in this way the overall uncertainty. This procedure was implemented in Matlab routines on the raw data. A complete description of the method with further enhancements are described in [5].

The characterization of the heat transfer is accomplished through the calculation of non-dimensional numbers in each of the three monitored sections of the bundle (e.g. *A*, *B*, *C*). The averaged in time value of the average temperature among the 5 bulk thermocouples for each section and the relative properties to calculate the Reynolds, Prandtl and Peclet numbers for the entire section were considered, see Table 3.1. A more sophisticated weight-averaged method was used in the final stage of post-processing [5]. At this early stage a simple arithmetic average was used. In any case, the consistency with the heat balance was checked. Then, the Nusselt numbers were calculated locally for each subchannel of the section ,through the averaged-in-time value of the average among the wall temperatures related to the subchannel

considered. The bulk temperature for each local Nusselt number is the central channel temperature of the bulk thermocouple. The conductivity is taken at the average section bulk temperature. The results are shown in Table 3.2. The irregular axial trend of the local Nusselt numbers needs further investigation.
The relative error of the experimental data vary between 6.5% and 15%. It includes the statistical oscillation, the instrument errors, the approximation error in the evaluation of the LBE properties and their propagation in the calculation of the derived parameters.

Table 3.1: Reynolds, Prandtl and Peclet numbers computed for the test in the different sections.

Section	Re	Pr	Pe
A (z=38mm)	7881±937	0.034	267±32
B (z=300mm)	8172±970	0.032	262±31
C (z=562mm)	8437±970	0.031	257±31

Table 3.2: Experimental Nusselt Number in the FPS in the instrumented subchannels shown in Figure 2.5.

Section	**Nu S2**	**Nu S5**	**Nu S22**	**Nu S26**	**Nu S33**
A (z=38mm)	8.205±0.7644	6.103±0.4543	11.43±1.299	7.806±0.7438	6.186±0.5275
B (z=300mm)	8.066±0.7238	8.231±0.7796	8.998±1.118	4.353±0.2921	4.271±0.3205
C (z=562mm)	12.19±1.778	7.807±0.7076	8.378±1.052	4.759±0.3713	8.477±1.072

The experimental results can be compared with the Nusselt number calculated by the correlation in literature. The correlation of Mikityuk [7] and Ushakov [8] was used for this purpose and reported below:

- Mikityuk correlation: $Nu = 0.047\left(1 - e^{-3.8(x-1)}\right)(Pe^{0.77} + 250)$
- Ushakov correlation: $Nu = 7.55x - \frac{20}{x^{13}} + \frac{0.041}{x^2}Pe^{0.8-0.024x}$

The Nusselt numbers for the experimental data, obtained from Mikityuk and Ushakov correlation are reported in Table 3.3

Table 3.3: Nusselt number calculated with correlation for the experimental test.

Section	**Mikityuk**	**Ushakov**
A (z=38mm)	10.02	11.12
B (z=300mm)	9.98	11.08
C (z=562mm)	9.95	11.05

The experimental data agree well with the correlations considered although local differences must still fully analyzed and understood. Few values are quite smaller with respect to the reference. However, these values are related to peripheral subchannel, where the heat transfer is affected by the hexagonal wrap. Further definitions and effort are needed to have a more precise and extended comparison among experimental data, and this is out of the scope of the present work.

Further, it should be mentioned that the test was characterized by a relative low power and high mass flow rate with respect to the typical values expected in the natural circulation cases. For this reason, the average differences between wall and bulk temperature inside the bundle is very low, $\Delta T \sim 1.0 - 2.0\ °C$. It can lead to larger relative errors in the calculation of the heat transfer coefficient with respect to the cases with higher ΔT between wall and bulk, which are expected in the planned experimental test matrix. The lower is the ΔT measured, the more the measure is affected by the instrument error, which is

σ_{TC}= 0.1 °C. As a consequence ,higher relative errors are expected for the derived parameters. Nevertheless, the temperature measurements also at low power can be considered well esteemed and very satisfying. The time behavior of the difference between space averaged-wall and bulk temperature for the subchannel S2 at three axial sections is shown in Figure 3.3 as example.

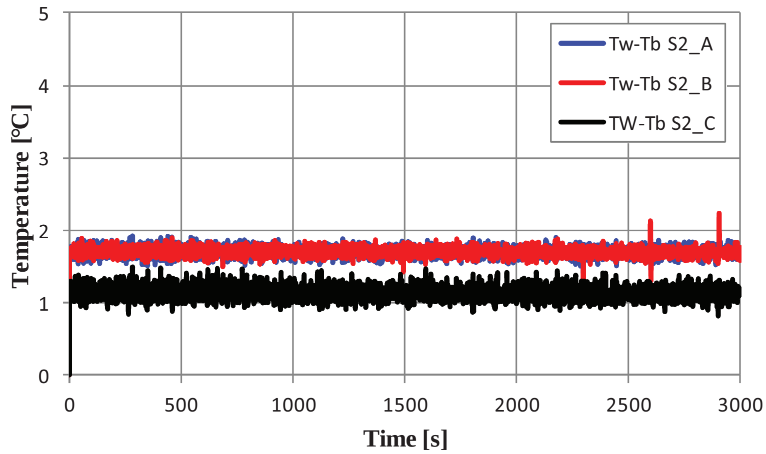

Figure 3.3: Temperature differences between wall and bulk temperatures for the S2 subchannel at the three different sections.

Finally, Figure 3.4 shows the time-averaged axial temperature distribution along pin 3, with a linear behavior typical of a constant wall heat flux in rod bundles.

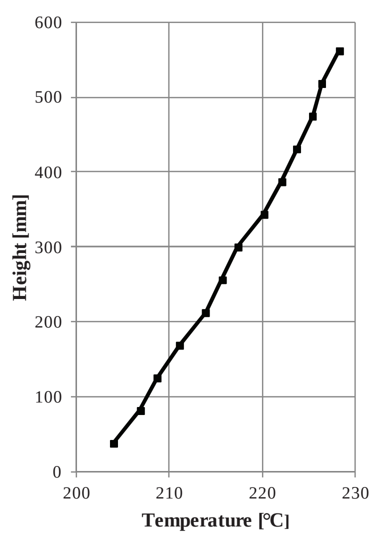

Figure 3.4: Axial wall temperature in the pin 3.

4. CONCLUSIONS

At ENEA-Brasimone R.C., large experimental facilities exist to study HLM free, forced and mixed convection in loops and pools: e.g. NACIE-UP is a large scale LBE loop for mixed convection experiments with a secondary side in pressurized water. In the context of the SEARCH FP7 project, an experiment was performed in the NACIE-UP facility to assess the coolability of a 19-pin wire-wrapped electrical bundle (Fuel Pin Simulator, FPS), with heat flux up to 1 MW/m^2. The bundle is representative of the one adopted in the MYRRHA concept, and it is instrumented with 67 thermocouples to monitor bulk and wall temperatures in the different ranks of subchannels at different heights. The mass flow rate in the loop is measured by an induction flow meter and by thermal balance in stationary conditions.

A large experimental test matrix has to be carried out in order to characterize the coolability of MYRRHA Fuel Sub-Assembly. Results in terms of wall and bulk temperatures, heat transfer coefficients and pin azimuthal temperature distribution are available at different mass flow rates in the range 0-7 kg/s, i.e. up to 1 m/s in the subchannel, half of the MYRRHA FA nominal velocity.

A first experimental test with FPS is provided in the paper. Those are the first data on HLM-cooled wire-wrapped Fuel Assembly reproducing the MYRRHA FA. Post-test analysis and error propagation study on derived quantities is also provided.

Stationary conditions were obtained with a mass flow rate of 2.7 kg/s and a FPS power of 9 kW, in the middle of the experimental range.

Results show that, with the expected wall-bulk temperature difference of 1 K, HTC and Nusselt numbers can be derived and computed with an acceptable error less than 15%. Results agree well with existing correlations for rod bundles in liquid metals. This test assesses the quality of the test section, able to measure HTC even with a very low wall-bulk temperature drop around 1 K. The experimental test matrix cases will be with a higher temperature drop and therefore the experimental uncertainty will be low in any condition.

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