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Heavy Liquid Metal Natural Circulation in a One - Dimensional Loop

G. Coccoluto, P. Gaggini, V. Labanti, M. Tarantino

ENEA Brasimone, 40032 Camugnano (BO), Italy
Tel. +39-0534-801262, Fax +39-0534-801250, email mariano.tarantino@enea.it

W. Ambrosini, N. Forgione, A. Napoli, F. Oriolo

Università degli Studi di Pisa, Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione
Via Diotisalvi, 2 - 56126 Pisa, Italy, Tel. +39-050-836657, Fax +39-050-836665

ABSTRACT

The ENEA Brasimone Research Centre since 1999 is strongly involved in the national and European research programmes performed in the field of heavy liquid metal technology aiming at the development of critical (LFR) and subcritical (ADS) nuclear systems.

In particular, in the frame of the IP-EUROTRANS, (6th Framework Program EU), ENEA assumed the commitment to perform an integral experiment with the aim to reproduce the primary flow path of a HLM pool-type nuclear reactor, cooled by Lead Bismuth Eutectics (LBE). This new experimental activity, named ICE "Integral Circulation Experiment", will be performed by an appropriate test section designed to be installed in the CIRCE facility.

In order to support the ICE activity, as well as characterise the natural and gas enhanced circulation flow regimes in a HLM loop, qualify test procedures, components nuclear relevant, a new facility was designed and built up by Brasimone Research Centre, named NACIE "NAtural CIrculation Experiment".

The paper reports a detailed description of the loop and the main experimental results carried out from the natural circulation tests already performed on the NACIE loop.

Numerical simulations have been performed in collaboration with the University of Pisa, adopting the RELAP5/Mod3.3 system code modified to allow for LBE as a cooling fluid.

The aim of the performed post-test calculations is to compare the code response with the experimental results under the natural circulation flow regime, allowing to qualify the adopted nodalisation as well as the performance of the code when employed on HLM loop.

INTRODUCTION

In the last years, wide importance is given to the activities in support of the development of systems for the transmutation of radioactive waste, as can be noticed from the European Union (EU) projects EUROTRANS [1] (EUROpean research programme for the TRANSmutation of high level nuclear waste in Accelerator Driven Systems), which concurs to demonstrate the feasibility of an ADS-type dedicated transmuter. Other activities are ongoing with the aim to develop a Generation IV LFR concept [**2**], like ELSY [**3**] (European Lead-Cooled System) project, aimed at showing the possibility of realization and operation of a safe and competitive fast lead-cooled critical reactor.

In parallel, project dedicated to address specific issues have been and still are carried out, as, for example, considering the EU framework programmes, TECLA (TEChnologies for Lead Alloys), dedicated to lead technologies, aimed at assessing the use of lead alloys both as a spallation target and as a coolant for an ADS, VELLA [**4**] (Virtual European Lead LAboratory), aimed at integrating the existing European HLM infrastructures, developing synergies and complementarities among the laboratories and the research groups across the EU

In this framework, several R&D priorities (and planned efforts) have been defined, focusing on system design, fuels development, HLM technology, materials, component development, demonstration [**5**,**6**,**7**].

In particular large-scale integral tests to characterise the behaviour of the main systems are necessary especially for the licensing process.

An integral system experiment is foreseen in ENEA, where the circulation of a sector of the primary lead coolant in the reactor pool will be reproduced. The normal steady state conditions operating transients (e.g. pumping system start-up and core power changes) and incidental transients (e.g. transient from forced to natural circulation) will be experimented.

This experimental activity, named "INTEGRAL CIRCULATION TEST", ICE, will be performed by the ENEA C.R. Brasimone, where an appropriate test section has been designed to be installed in the CIRCE facility.

The ICE activity will allow getting detailed information about different topics, as to evaluate the thermal-hydraulics behaviour of a HLM pool system by the analysis of the coupling between an appropriate heat source and a cold sink placed inside it, to investigate the behaviour of representative components (i.e. prototypical heat exchangers) for the LFR/ADS concepts, to characterize the natural circulation flow regime in a HLM pool system.

In this frame, the NACIE loop facility has built up to carry out experimental tests needed to characterize the natural and gas enhanced circulation flow regimes, and to qualify components for HLM applications, especially in support of the ICE activities .

In fact, since the heat source designed for the ICE activity, named Fuel Pin Simulator FPS, is based on the use of prototypical electrical heaters, a preliminary characterization of their thermal and electrical performance is required; this characterization will be accomplished by the NACIE loop.

NACIE Loop Description

As already mentioned, the aim of NACIE loop is to set up a support facility able to qualify and characterize components, systems and procedures relevant for HLM nuclear technologies.

Moreover, by this facility it will be possible to perform several experimental campaigns in the field of the thermal-hydraulics, fluid-dynamics, chemistry control, corrosion protection and heat transfer, allowing to obtain correlations essential for the design of the nuclear power plant cooled by heavy liquid metal.

Finally, the possibility to test four prototypical pin simulators as well as all their ancillary systems and mechanical connections is mandatory in order to confirm the design of the ICE test section.

For this reason the NACIE loop is prepared to house a bundle made with four prototypical pin simulators in full scale to the ones which will be manufactured for the ICE test section.

NACIE is a HLM rectangular loop which basically consists of two vertical pipes (O.D. 2,5") working as riser and downcomer, connected by means of two horizontal branches (O.D. 2,5").

The adopted material is stainless steel (AISI 304) and the total inventory of LBE is about 1000 kg; the design temperature and pressure are 550 °C and 10 bar respectively.

In the bottom part of the riser a heat source is installed through an appropriate flange, while the upper part of the downcomer is connected to an heat exchanger.

The difference in level between the thermal centre of the heat source and the one of the heat sink was fixed to reproduce the same height that characterises the ICE test section (H = 4.5 m).

The loop is completed by an expansion vessel, installed on the top part of the loop, coaxially to the riser.

The general layout of the loop is depicted in figure ***1***, while the geometrical data which characterize the NACIE facility are reported in table *1*.

Total Vertical Length [mm]	9231
Horizontal Length [mm]	1000
Pipe Inner Diameter [mm]	62.7
Pipe Thickness [mm]	5.16
Expansion Vessel Height [mm]	765
Expansion Vessel Inner Diameter [mm]	254.5
Heat Exchanger Length [mm]	1500
Heat Source Active Length [mm]	1000

Table 1 NACIE Main Geometrical Data

For the NACIE activity two different bundles are foreseen, named "high flux bundle" and "low flux bundle".

High Flux Bundle

The high flux bundle consists of four prototypical pins; the characteristics of the bundle are reported in table *2* .

The pins are arranged in a triangular lattice with a pitch to diameter ratio of 1.8, as envisaged for the ICE bundle. The total installed power is 100 kW, even if during the tests only one pin will be active. In figure *2*, a sketch of the high flux bundle is reported.

The aim of the tests planned using the high flux bundle is to characterize the pins, in term of performance of the active length as well as cold length, reliability and thermal fatigue.

The results carried out should allow choosing the more suitable technical solution for the pins to adopt in the ICE bundle.

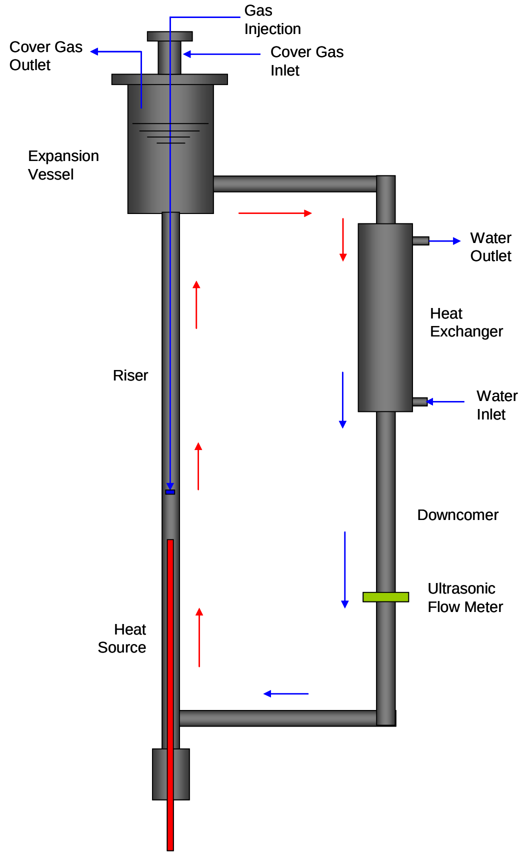

Figure 1. NACIE loop layout

A-type Prototypical Pin	
Number	2
Diameter [mm]	8.2
Active Length [mm]	1000
Total Length [mm]	2760
Heat Flux [W/cm^2]	100
Flux Distribution	Uniform
Thermal Power [kW]	25
B-type Prototypical Pin	
Number	2
Diameter [mm]	8.2
Active Length [mm]	1000
Total Length [mm]	8380
Heat Flux [W/cm^2]	100
Flux Distribution	Not-uniform
Thermal Power [kW]	25

Table 2 . High Flux Bundle Characteristics

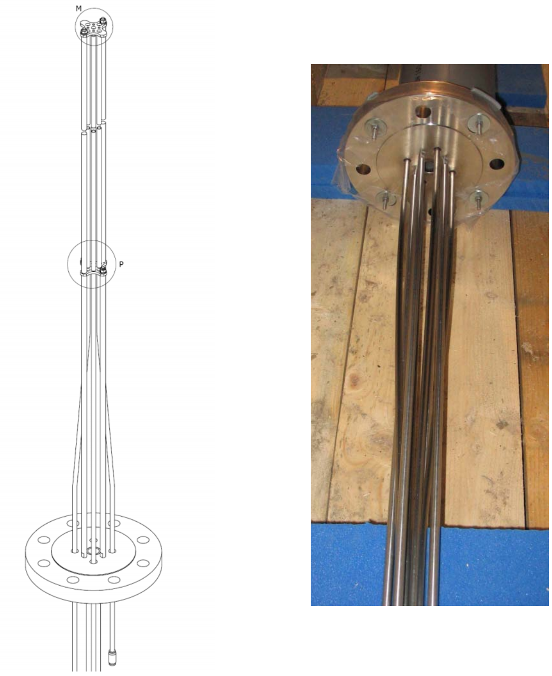

Figure 2. View of the High Flux Bundle

Low Flux Bundle

The low flux bundle consists of three electrical cartridges placed on triangular lattice with a pitch to diameter ratio of 1.4; the total thermal power installed is 30 kW.
The main parameters of the low flux bundle are reported in the table *3*.

The low flux bundle will be instrumented to allow HTC measurement under natural circulation flow regime as well as under gas-injection enhanced circulation.

Number	3
Diameter [mm]	19.05
Active Length [mm]	1000
Total Length [mm]	2380
Heat Flux [W/cm^2]	16.8
Flux Distribution	Uniform
Thermal Power [kW]	10

Table 3 Low Flux Bundle Characteristics

Pumping System

To promote the LBE circulation along the loop, a gas lift technique will be adopted [8,9,10, 11].

A pipe having inner diameter of 10 mm is housed inside the riser, connected through the top flange of the expansion tank to the argon feeding system.

At the other end of the pipe the injection nozzle is mounted, located just downstream the heating section. The gas will be injected in the riser through the nozzle, enhancing the liquid metal circulation. In the expansion tank the separation between the phases will take place.

In this way the possibility to have a two phase mixture flowing through the heat source is avoided.

The gas injection system is able to supply Argon flow rate in the range [1-75 Nl/min] with a maximum injection pressure of 5.5 bar.

Heat Exchanger

The Heat Exchanger (HX) designed for the NACIE loop is a “tube in tube”, counter flow type; the secondary fluid is water at low pressure (about 1.5 bar). The HX is made by three coaxial tubes with different thicknesses; the dimensions of tubes are reported in table *4*.

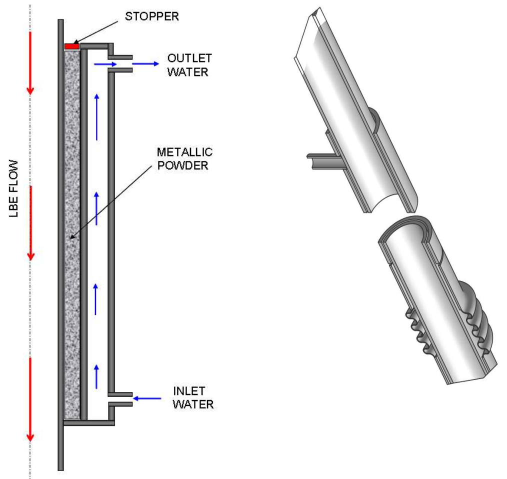

Figure 3 . Scheme of the HX and view of the expansion joint

	Inner Pipe	Middle Pipe	External Pipe
Inner Diameter [mm]	62.68	84.9	102.3
Outer Diameter [mm]	73	88.9	114.3
Thickness [mm]	5.16	2.0	6.02
Length [mm]	1500	1500	1500
Material	AISI 304	AISI 304	AISI 304

Table 4 . NACIE HX Pipes Dimension

LBE flows downward into the internal pipe, while water flows upwards into the annulus between the middle and external pipes (see figure 3).

The annulus created by the internal and middle pipe, that has a width of 5.95 mm, is filled by stainless steel powder. The aim of this powder gap is to guarantee the thermal flux towards water, since it has a good thermal conductivity, mitigating at the same time the thermal stresses on the pipes due to the differential thermal expansion along the axis during the operation. In fact, the three pipes are welded together in the lower part by a plate, while in the upper part only the middle and external pipe are constrained together. In this way the internal pipe has no axial constraints with the HX and axial expansion is allowed.

The annulus containing the powder is closed on the top by a "stopper" made by graphite, in order to avoid the powder leakage.

Finally, on the external pipe an axial expansion joint is installed to compensate the different axial expansion between the middle and external pipe (see figure 3)

Moreover, the powder gap allows reducing the thermal gradient through the thickness of the pipes; in fact, its thermal resistance is about the 30-50% of the overall one.

The NACIE HX has been designed assuming a thermal duty of 30 kW; it is the case of the low flux bundle under the natural circulation flow regime.

RELAP NODALIZATION

The scheme of the nodalization adopted for RELAP5 is reported in figure 4. It consists of several pipe, branch and single junction components aiming at the simulation of the different parts of the loop.

The heater power, generated by the prototypical pins, has been imposed in heating rods. Heat losses have been also introduced in the analyses and have been adjusted according to the information coming from the experiments; in this aim, appropriate heat transfer coefficient and fluid temperature are imposed outside the pipe walls, also taking into account the pipe thermal insulation.

Whenever possible, a node each 10 cm of pipe length is introduced throughout the nodalization.

The time dependent volume 60 and the time dependent junction 55 are considered to allow the simulation of the tests with the assisted circulation through the injection of the argon in the riser. In this work, the injected argon flow rate is maintained equal to zero.

The time dependent junction 305 is used to fix the right water flow rate. The time dependent volume 300 impose the temperature of the water at the inlet section of the HX secondary side, while the time dependent volume 330 impose the outlet pressure.

In order to simulate the effect of the heating cables present on the external pipe surface along the loop, used to avoid the solidification of the LBE when the heater power is off, it is been imposed an high HTC between pipes and the external environment.

The powder gap thermal conductivity was chosen as 12.5% of the stainless steel theoretical value, in order to have a good agreement between calculated and experimental LBE temperature time trends.

PERFORMED TESTS

The experimental activity performed up to now with NACIE facility included four different tests concerning natural circulation. In particular, the tests have been performed with only one pin activated, type B, inside the heating section, with a nominal power of 25 kW.

The differences in the heater power for the four tests can be observed in figure *5*. As it can be noted, the electrical power effectively supplied to the system is about 23.5 kW for tests n. 1, 2 and 4, nearly 95% of the nominal power, while in the test n. 4 the power is very near the nominal value.

Different boundary conditions are instead applied for the water temperature at the inlet section of the HX secondary side and mass flow rate. In particular, in tests n. 1 and 2 the inlet temperature of the water has been started at around 65 °C and the decreased to about 25 °C when an average temperature of LBE of about 350°C is achieved along the heat source.

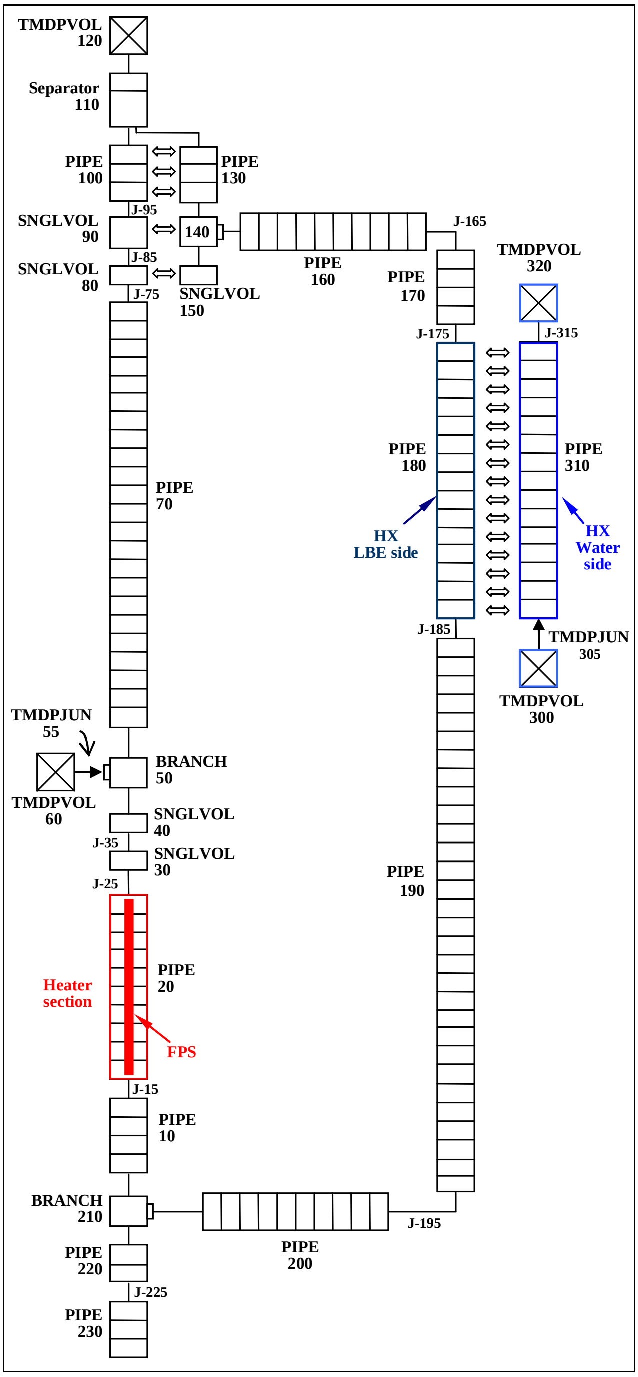

Figure 4 . RELAP5 Nodalization for the NACIE loop

This behaviour is due to the start of air cooler installed in the secondary loop. In the case of tests n. 3 and 4 the inlet temperature of the water is maintained to about 80°C during all the time. During the transient the secondary pump is active, to avoid the boiling of water inside the heat exchanger, even if the flow rate is set at a value much lower than the nominal one (see figure *6*).

Though the ultrasonic flow meter is not yet installed along the NACIE loop, an estimation of the LBE flow rate under steady state condition could be made applying an energy balance across the heat source, as in the following:

$$W = \frac{\dot{Q}_{HS}}{c_{p,LBE}\,\Delta T_{HS}}$$

As it can be noted in figure *7*, the estimated flow rate in the steady state conditions is about 5.5 kg/s.

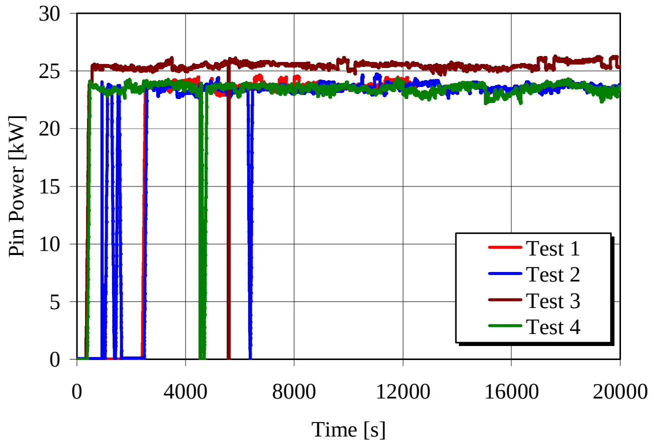

Figure 5 . Electrical power supplied to the loop, by the pin type-B.

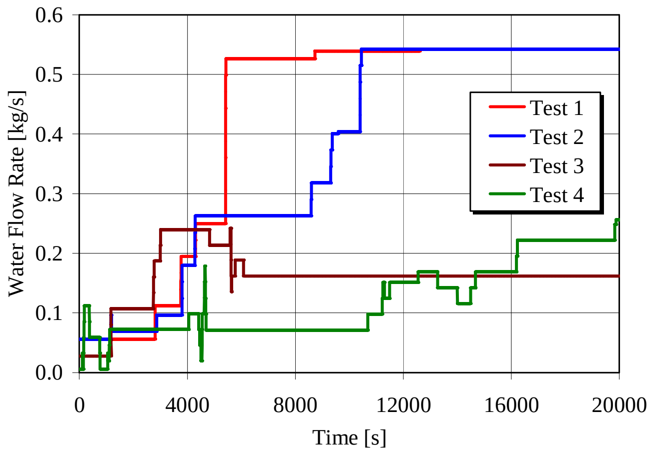

Figure 6 .Time evolution of the water flow rate in the HX secondary side.

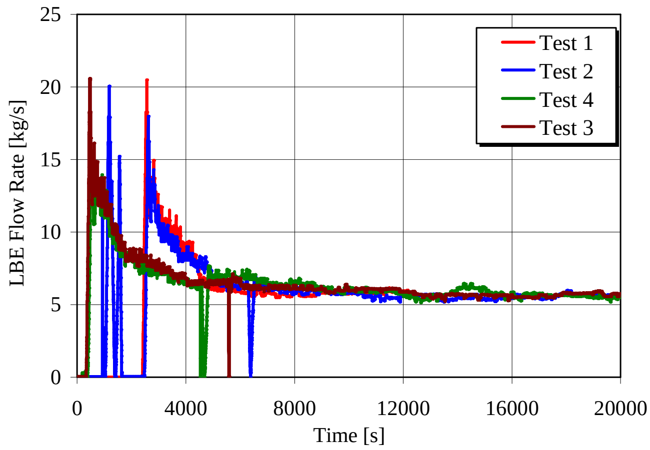

Figure 7 . LBE flow rate calculated by an energy balance through the HS

RESULTS

The fluid dynamic behaviour of the system has been simulated by a version of the RELAP5/Mod3.3 code, modified in order to take into account the LBE fluid properties.

In figures *8* and *9* are reported the time trends of the calculated and energy balance flow rate, respectively for the test n. 1 and n. 4. There is a very good agreement between calculated and experimental trends, mainly in the last part of the transient, with relationships closely matching with each other. The figures show that in the first phase of the transient the flow rate evaluated by the energy balance through the heat source is considerably higher than that obtained from the calculations. This behaviour is due to the fact that the energy balance is based on the assumption of steady state conditions.

In the calculation results can be observed that the LBE flow rate, when the heater power is off (first phase of the transient), is not equal to zero. This because, before the start of the heating power in the HS the temperature along the loop is maintained constant with the heating cables. In the same time water circulate in the secondary side of the heat exchanger causing a not negligible heat exchange between primary and secondary loops.

The presence of LBE circulation in the loop during the first phase of the transient is confirmed by the experimental trend of the inlet and outlet HX temperatures, reported in figures *10* and *11*. In fact, both calculations and measures show a temperature difference of the LBE between inlet and outlet HX section also in the first phase of the analysed transient, when the electrical power applied to the heater section is zero, though we will aspect that the flow rate is slightly overestimated by the code.

There is a very good agreement between calculated and experimental trends with relationships closely matching with each other for both the time trends in the HX and in the HS, as shown in the figures *12* and *13*.

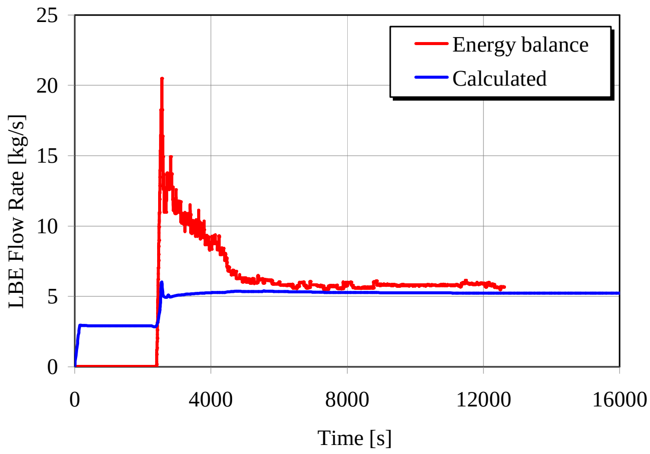

Figure 8 . Comparison between calculated and "energy balance" LBE flow rate for the test n. 1.

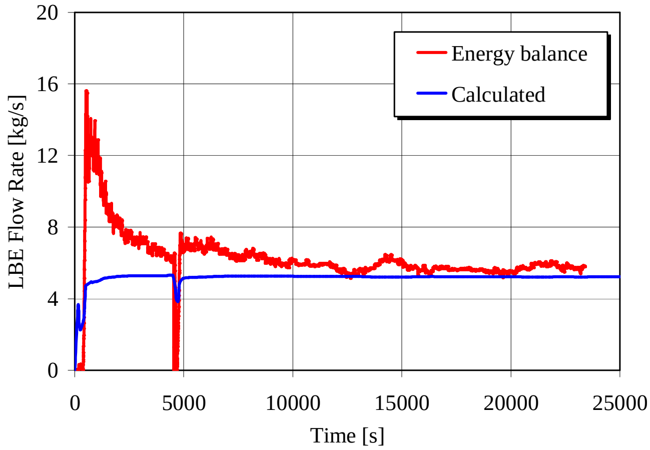

Figure 9 . Comparison between calculated and "energy balance" LBE flow rate for the test n. 4.

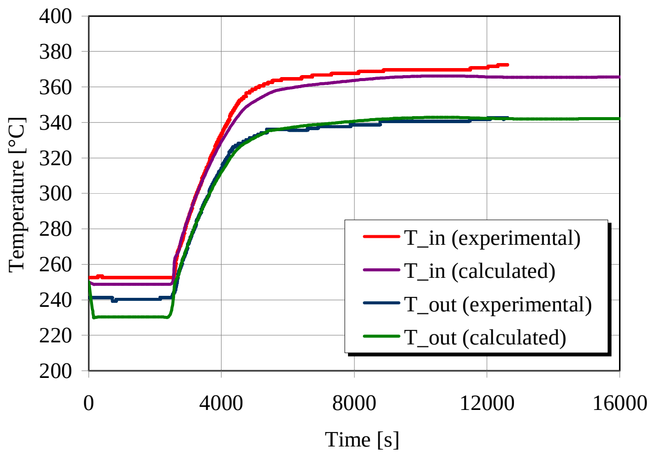

Figure 10 . Comparison between calculated and measured temperatures in the inlet and outlet HX sections for the test n. 1.

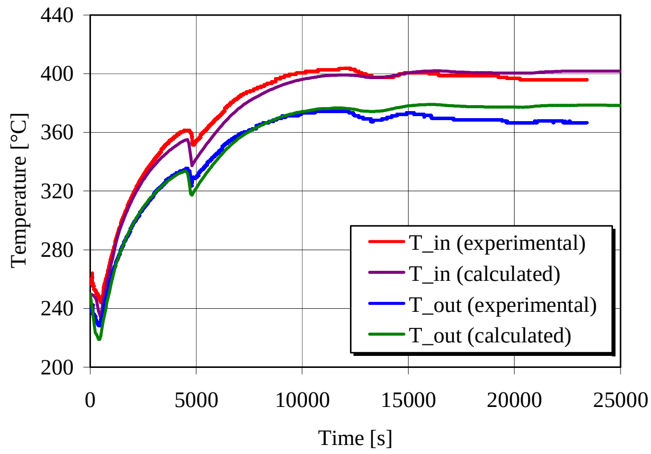

Figure 11 . Comparison between calculated and measured temperatures in the inlet and outlet HX sections for the test n. 4.

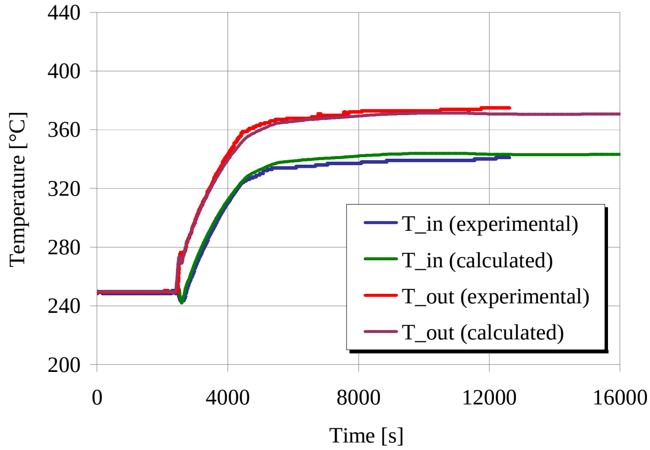

Figure 12 . Comparison between calculated and measured temperatures in the inlet and outlet HS sections for the test n. 1.

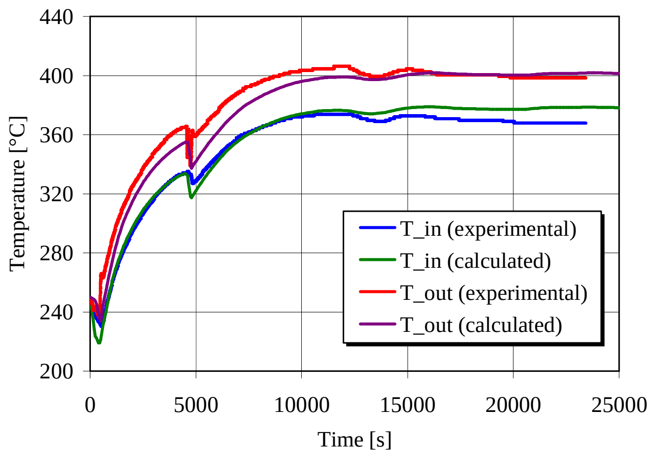

Figure 13 . Comparison between calculated and measured temperatures in the inlet and outlet HS sections for the test n. 4.

CONCLUSIONS

The NACIE heavy liquid metal loop was designed and built-up by the Brasimone Research Centre to support the ICE test section design.

In fact, due to the high thermal performance required for the ICE Heat Source, prototypical pin elements have been realized adopting two different technological solution.

The aim of the NACIE loop is to house a high flux bundle, made by four prototypical pins and to test and qualify the elements in order to define which will be the adopted element for the ICE bundle.

Preliminary experimental tests have been performed by the NACIE loop, testing the Data Acquisition System, the Power Supply System and starting the thermal characterization of the prototypical pins. In particular, feeding only one pin, steady state natural circulation tests have been run with a thermal power of 25 kW.

The preliminary results show that the NACIE loop behaviour agrees with the design specifications and that the thermal behaviour of the prototypical pin matches with the numerical simulations performed by the supplier.

After the high flux bundle qualification tests, a low flux bundle will be installed on the NACIE loop and a new experimental campaign will start. Its aim is to characterize the natural circulation and gas enhanced circulation flow regimes in a HLM loop. Several experimental data on natural circulation heat transfer coefficient in a rod bundle assembly will be available, covering the knowledge gap existing in this field. Finally, several operational and accidental transients will be simulated, allowing to establish a reference experiment for the benchmark of commercial codes when employed in HLM loop.

Concerning the simulations, RELAP code provide good results for the LBE flow rate and LBE temperatures inside the loop. Taking correctly into account inertia of the thermal structures, the RELAP code is also able to reproduce in a good way the transient of the flow rate in the circuit. As soon as the flow meter will be installed in NACIE loop, better comparison will be possible particularly in the initial transient phase of the tests.

The performed activity encourages further developments. In particular, assisted circulation test, with argon injections, will be conducted and experimental data analysed with the same RELAP5 nodalization.

NOMENCLATURE

Roman Letters

C_p	specific heat [J/(kgK)]
D	diameter [m]
f	friction factor
g	gravity (m/s^2)
q''	heat flux [W/m^2]
$\dot{Q}$	heating power [W]
T	Temperature [°C]
w	fluid velocity [m/s]
W	mass flow rate [kg/s]

Subscripts

HS	Heat source
LBE	Lead Bismuth Eutectic

Abbreviations

ADS	Accelerator Driven System
ICE	Integral Circulation Experiment
FPS	Fuel Pin Simulator
HLM	Heavy Liquid Metal
LFR	Lead Fast Reactor

Acronyms

CIRCE	Circolazione Eutettico
EUROTRANS	EUROpean research programme for the TRANSmutation of high level nuclear waste in Accelerator Driven Systems
ELSY	European Lead-Cooled System
NACIE	Natural Circulation Experiment
TECLA	Technologies for Lead Alloys
VELLA	Virtual European Lead Laboratory

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