Experimental and numerical investigation of double wall bayonet tubes performances in pool type integral test facility

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ABSTRACT

ENEA has designed and manufactured an experimental mock-up (called Heavy liquid mEtal – pRessurized water cOoled tube – HERO) with seven instrumented full scale double walled bayonet tubes installed in CIRCE facility in order to provide integral test experiments which are representative of the ALFRED Steam Generator. The present paper summarizes the activities performed in support to the experimental campaigns in the HERO-CIRCE facility. In particular, preliminary calculations by means of RELAP-5 and pretest-experimental campaigns are given in this document.

1. INTRODUCTION

GEN-IV Heavy liquid metal (HLM) cooled fast reactors rely on Steam Generators (or heat exchangers) located inside the primary vessel [1]. This plant layout is simple, but it implies the possibility that the secondary side coolant (i.e. water) interacts with the primary coolant in case of tube rupture (SGTR), being a potential initiator event which can lead to severe consequences on the plant integrity. Prototype double wall bayonet tubes have been designed to reduce the probability that a SGTR occurs for the ALFRED reactor [2], in the framework of the LEADER project. The double wall bayonet tube is constituted by three concentric tubes: in the smallest one, the coolant (i.e. water) enters in down flow and turns in the second concentric tube where it rises up removing the heat from a hot fluid (i.e. lead) located into the HX shell side. The largest tube is placed between the second tube and the hot fluid to double separate it from the coolant. This design increases the safety margin of the unit by reducing the probability of interaction coolant-hot fluid and allowing the possibility to monitor eventual leakages from the coolant or from the hot fluid by pressurizing the separation region. On the other hand, if it is required to monitor the leakages and get high thermal performance of the unit, the annular space that separates the fluids should be filled with a porous heat transfer enhancer (i.e. SS powder). Since this configuration has never been used in the nuclear technology as SG, experimental activities are needed to test this component, its thermal-hydraulic performances and to validate numerical tools adopted in the design and safety analysis. ENEA has designed and manufactured an experimental mock-up (called Heavy liquid mEtal – pRessurized water cOoled tube – HERO) with seven instrumented full scale double walled bayonet tubes in CIRCE facility in order to provide integral test experiments which are representative of the ALFRED SG [3]. The tubes are equipped with intermediate porous medium pressurized by helium (in the lead – steam double wall annular region) and vacuum (in the feed-water – steam double wall annular region) in order to enhance their thermal efficiency and to reveal leakages from the water side as well as from the lead side. HERO-CIRCE is expected to be operated at 172 bar and to generate superheated steam at about 400°C. The overall configuration of the facility includes the electrically heated fuel core simulator, a steam generator/heat exchanger (HERO) representative of ALFRED reactor design (bayonet tubes, scaled one to one), the enhanced circulation system, the DHR and the secondary pre-heating and pressurization feed-water and steam lines.

2. DESCRIPTION OF THE HERO-CIRCE FACILITY

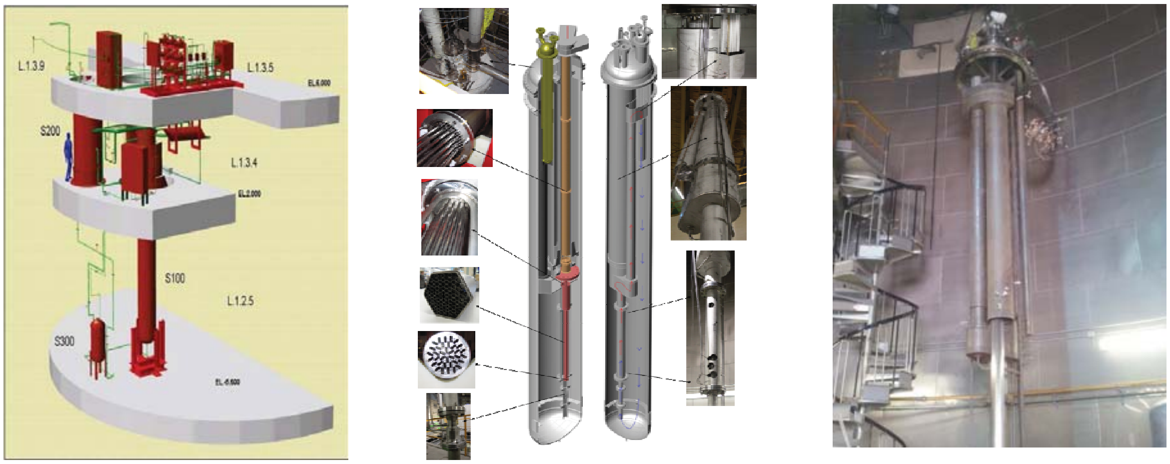
CIRCE basically consists of a cylindrical vessel (Main Vessel S100) filled with about 70 tons of molten Lead-Bismuth Eutectic (LBE) with argon cover gas and recirculation system, LBE heating and cooling system, several test sections welded to and hung from bolted vessel heads for separate-effect and integral testing, and auxiliary equipment for eutectic gas enhanced circulation [4]. Its main components are the above mentioned vessel S100, the storage tank S200 and the intermediate vessel S300, this later one being used during the handling of the LBE between the two other vessels, Figure 1. During the loading operations, the LBE is gradually transferred from the storage tank to the S300 vessel. In this way, step by step, S100 is gradually filled from the bottom. This main vessel consists of a vertical vessel which is 8500mm in height, connected by gates to the other systems, from both the LBE and gas sides. It is equipped with electrical heating cables, installed on its bottom and lateral surface. This heating system allows operating in a temperature range of 200÷450 °C. The HERO test section consists of an open loop fed by demineralized service water pressurized by an axial pump (with oscillation reducer) which works coupled to a steam pressurization valve (V-8), Figure 2. During normal operation, the water flows at 0.331 kg/s and 180 bar into the pre-heater. This component is a spiral tube of 30m in length that supplies about 450kW to the water by electrical heating. The fluid leaves it at 335°C to enter in the collector and then the 7 bayonet tubes. The super-heated steam is generated into the HERO Steam Generator Bayonet Tubes unit (SGBT) by means of the power supplied by CIRCE (about 440 kW in nominal conditions), is collected into the SGBT steam chamber and finally released to the environment by V-8. The line includes a bypass that acts as heating-pressurization system during the start up at cold conditions (20°C, 1 bar water), Figure 2, and Table 1. The SGBT bundle is given in Figure 3, it is composed of:

- A top flange with seven holes to accommodate the bayonet tubes and one hole for the instrumentation. It connects the SGBT to the CIRCE S-100 component and sustains the helium chamber, the steam chamber, the bayonet tubes and the hexagonal shroud. This flange is Φ356 mm with a thickness of 30 mm and is made of AISI-304.
- Welded above the top flange (and therefore located outside CIRCE), there is the Helium chamber. It is constituted by a AISI-304 tube 6” sch.40 with an integral roof. The helium chamber have appropriate holes to accommodate the bayonet tubes. These have been fixed to the holes by sealing joints to guarantee no helium leakages up to 5 bars.
- On the top of the helium chamber there is the steam chamber that accommodates the superheated steam and contains the feed-water tubes (sealed by joints that are capable to sustain superheated steam at 180 bar).
- The SGBT is contained into a double wall wrap. It consists of an hexagonal wrap with spacers (to keep a given meatus between the wrap and the external shroud). Six fissures

180mm x 40mm are realized in the wrap at the top of the active length. The fissures are designed to be placed inside the cylindrical distributor of CIRCE being totally submerged by the LBE that feed the SGBT unit. A cylindrical external shroud is located below the fissures concentric to the hexagonal wrap. It is sealed at the bottom and at the top in order to provide a meatus which is filled by air to avoid heat exchange between the pool of CIRCE and the SGBT unit.

- The bayonet tube dimensions are reported in Table 2. They are kept in position by means of five hexagonal spacer grids.

The SGBT unit is instrumented with 65 thermocouples (TCs), 21 differential pressure transducers, 2 absolute pressure transducers and 8 flow meters. The central tube (labeled as tube 0) is instrumented with 31 thermocouples, Figure 4, the remaining tubes (labeled as tube 1 to 6) are instrumented with 18 TCs. The equivalent LBE sub-channel bounded by tube 0, tube 1 and tube 2 is monitored at its periphery at three axial elevations by the TCs located at the outer surface of these tubes and at its center by means of three TCs, Figure 5. Three boundary sub-channels bounded by tubes 1-2, tubes 3-4, and tubes 5-6 are monitored by 3 center-bulk TCs at three axial elevations (totally 9 TCs). Finally, four TCs are located in the steam plenum. The differential pressure transducers allow to measure, per each tube, the pressure drop across the orifice, the total pressure drop along the tube (feed-water tube and annular riser), the descended pressure drop (feed-water tube only) and the ascendant pressure drop (annular riser only).



a) CIRCE isometric view b) CIRCE main components c) HERO-CIRCE test section

Figure 1 - CIRCE overview.

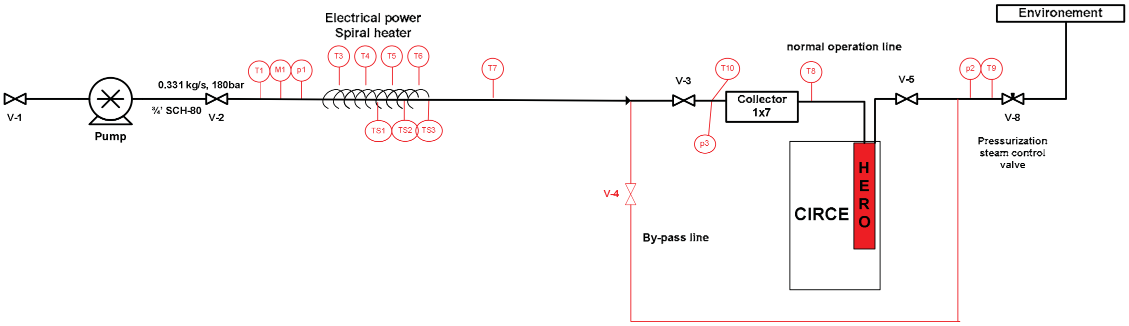
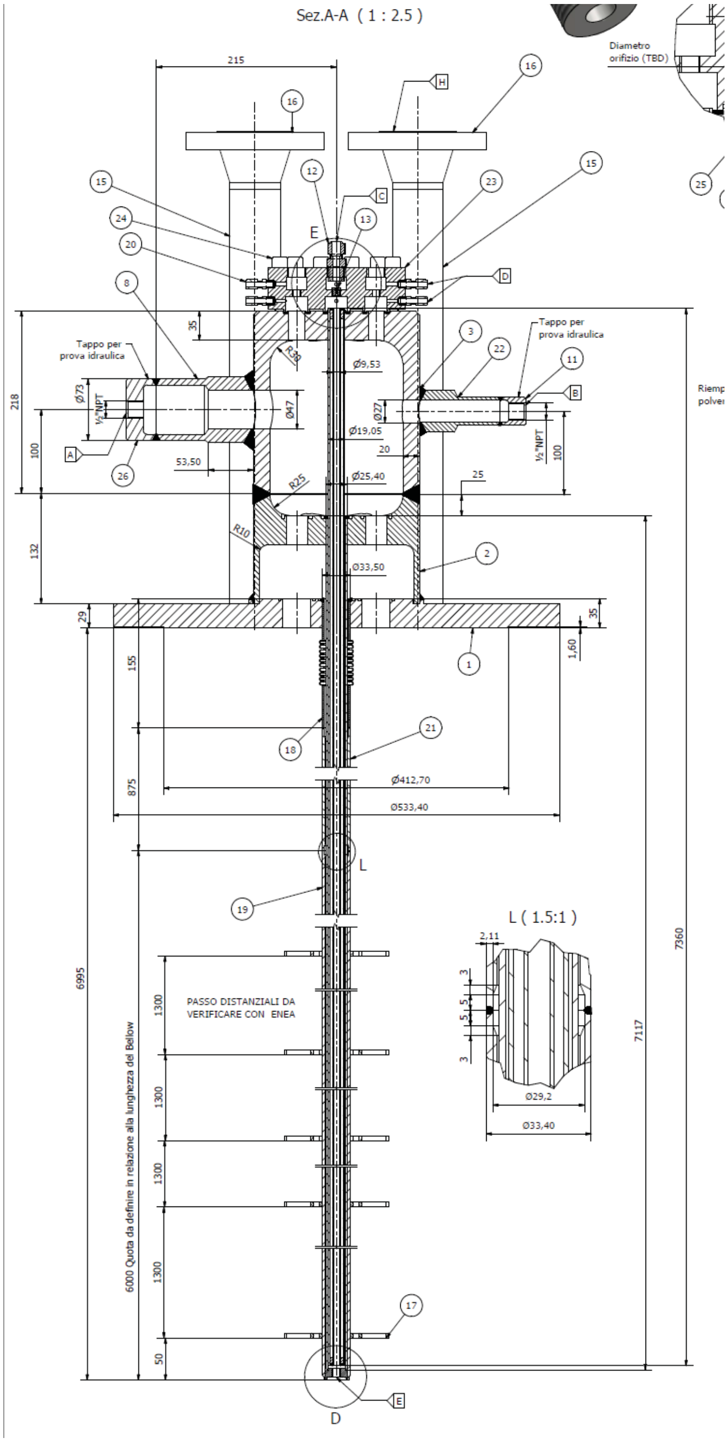


Figure 2 – Simplified scheme of the HERO open loop.



Position	N°	Description
1	1	Flange to S-100
2	1	Helium chamber
3	1	Steam chamber
4	7	Second tube Φ25.4mm s 2.11mm
5	7	Inner tube Φ19.05mm s 1.65mm
6	7	Slave tube Φ9.53mm s 1.22mm
7	14	Ring spacer
8	1	Steam outlet
9	2	Swagelok SS-6MO-1-2W
10	1	Thermocouple outlet
11	2	Threaded plug case
12	7	Swagelok SS-10MO-1-8
13	7	Orifice 1/8 “
14	7	End cap 25.4mm
15	3	Oxygen sensor tube
16	3	Flange
17	5	Grid spacer
18	7	Thermal stress accommodator
19	7	Third tube Φ33.4mm s 3.38mm
20	14	Swagelok SS-6MO-1-2
21	1	Third tube Φ33.4mm 1000mm
22	1	Steam thermocouples casing
23	1	Water flange
24	12	UNI 5931 M12 x 70
25	7	Seal
26	1	Plug

Figure 3 - HERO-CIRCE SGBT unit: main overview.

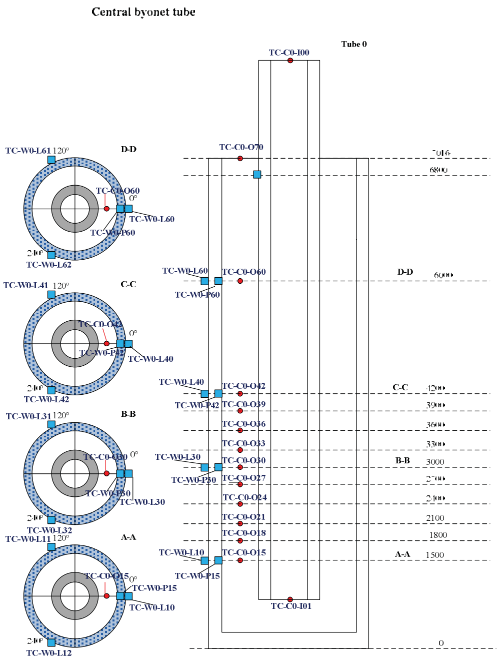


Figure 4 - HERO-CIRCE SGBT central tube instrumentation (TCs).

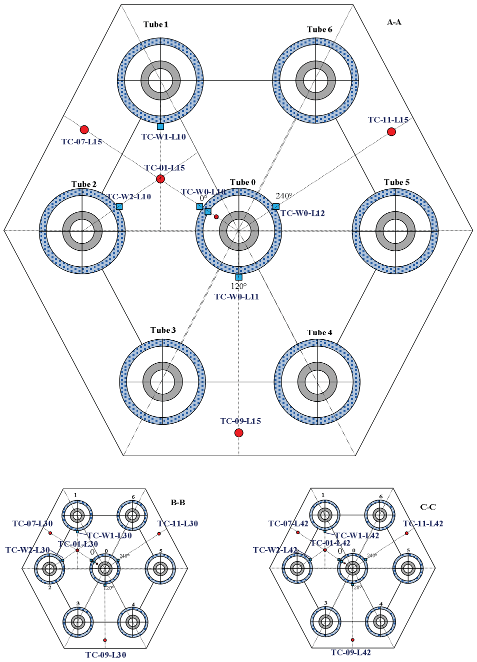


Figure 5 - HERO-CIRCE SGBT lead channel instrumentation (TCs).

Description	**Unit**	**Steam line**	**Helium line**	**LBE side**
Fluid	--	Water - steam	Helium	LBE
Circulation mechanism	--	Axial pump + accumulator	Storage tank for leakage refilling	Gas enhanced
Main components	--	7 bayonet tubes, steam chamber	Helium chamber	SGBT unit shell
Bundle type and P/D	-	Triangular	--	Shell
Operating inlet temperature	°C	335	--	480
Operating mass flow	kg/s	0.330785	stagnant	44.573529
Design pressure	bar	172	5.0	As CIRCE
Operating pressure	bar	170	4.5	Hydraulic head
Test pressure	bar	180	--	--
Design temperature	°C	432	432	As CIRCE
Volume	m^3	0.0083	0.0054	--

Table 1: HERO-CIRCE SGBT unit, main data.

Label	**ID [mm]**	**OD [mm]**	**Thickness [mm]**	**Material**
Feed-water slave tube	7.09	9.53	1.22	AISI-304
Feed-water tube gap	9.53	15.75	3.11	Slight vacuum
Feed-water outer tube	15.75	19.05	1.65	AISI-304
Annular riser gap	19.05	21.18	1.07	Water-steam
Second tube	21.18	25.40	2.11	AISI-304
Annular gap	25.40	26.64	0.62	AISI 316 powder
Third tube	26.64	33.40	3.38	AISI-304

Table 2: HERO-CIRCE SGBT, tube design.

3. MODELING OF HERO TEST SECTION

The SGBT unit has been modeled by means of RELAP version 5.3.3 [5]. A schematic overview of the nodalization adopted is reported in Figure 6. The model includes: one single tube that represents seven tubes. In particular, the following main hydrodynamic components are considered: the feed-water tube (pipe 100), the annular steam riser (pipe 110), the equivalent lead channel (pipe 140), the steam plenum (branch 111) and the argon zone (branch 136). The analysis has been developed on the basis of the following assumptions:

- The heat exchange between the annular steam riser and the Argon zone has been neglected, that means adiabatic behavior of the non-active outer-side tube surface region.
- The materials and the geometry are according to the design of HERO.
- The powder (AISI-316) conductivity is according to the experimental finding achieved in to a facility designed constructed and operated by ENEA Brasimone specifically to measure thermal conductivity of porous media: the Tubes for Powder Facility (*Eq. 1*) [6].
- The heat transfer between the lead side and the annular riser is modeled according to the Mikityuk correlation that has been developed for fuel rod bundle.
- The hexagonal wrap has been considered in the model.
- The spacer grids are modeled as concentrated pressure drops.
- CIRCE facility is not simulated, it is assumed as boundary condition (nominal lead mass flow rate at nominal inlet temperature of ALFRED)

$$C_{He-4bar} = 5*10^{-6}T^{2} + 8*10^{-4}T + 1.3198 \qquad Eq.\ 1$$

(where $C_{He-4bar}$ is conductivity under pressurized Helium atmosphere 4bar [W/mK] and T is temperature)

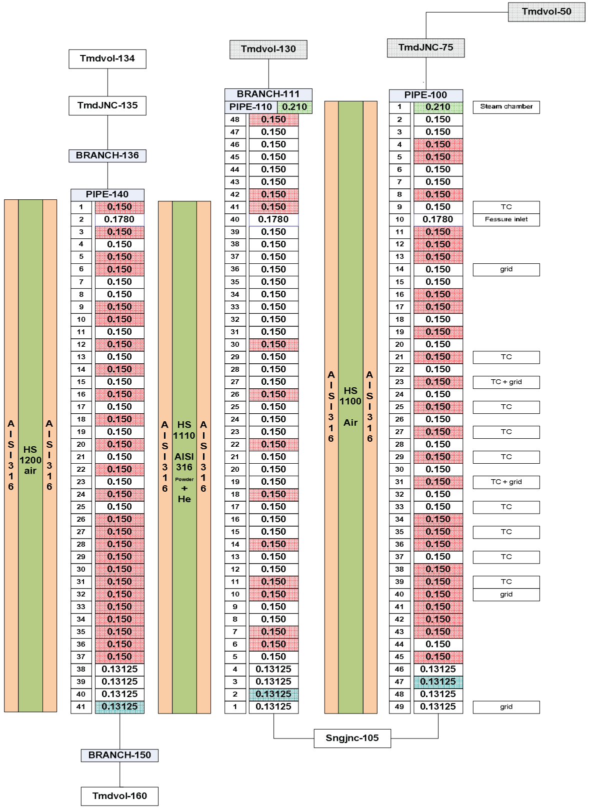


Figure 6 - HERO-CIRCE SGBT unit modeling: nodalization scheme.

4. ANALYSIS OF THE HERO TEST SECTION

4.1 Assessment by RELAP - 5

The results of the simulations are summarized in Figure 7 and Table 3. Figure 7 reports: the feed-water tube fluid temperature as function, the annular riser temperature, the lead channel temperature and the void fraction of the annular riser as functions of the tube length. Superheated steam is generated at about 400°C being the boiling height located into the first 4 meters of the annular riser. Compared to ALFRED SG, it is 50°C below its requirements and this is due to two main issues: the first is the porous heat transfer enhancer (modeled as a fictitious material which has 55 times the conductivity of helium in the ALFRED SG calculations and here assumed based on experimental data AISI 316 powder), the second is related to the selection of the tubes material (AISI-304 instead of T91 which means less conductivity and higher tube thicknesses). Despite of this, this result is considered acceptable for a SG prototype, even if design improvement is required to fulfill the ALFRED SG goal. The lead temperature drop is close to 70°C which corresponds to 438 kW of removed power. The steam-water pressure drop is concentrated in the boiling region, it is 1.15 bar. The pressure drop in the LBE channel is predicted 1.08 bar.

A parametric analysis has been conducted for the development of the experimental test matrix. Different boundary conditions have been analyzed for this purpose mainly on the key parameters that can be switched during the experiments such as the feed-water and LBE inlet temperatures and mass flow rates, they are summarized in Table 4. The reduction of the feed-water inlet temperature tends to improve the heat exchange and therefore the removed power (up to 19.5 kW) with a relatively limited decrease of the outlet steam temperature (up to 8.2 °C). The reduction of the feed-water flow rate causes an increase of the steam out-let temperature (up to 74.7 °C) with an obviously large decrease of removed power (up to about one half of the nominal power). The variation of the LBE mass flow rate highlights an impact similar to the variation of the feed-water flow rate. The LBE inlet temperature appears crucial for the achievement of superheated steam: at least 450°C are required to generate it.

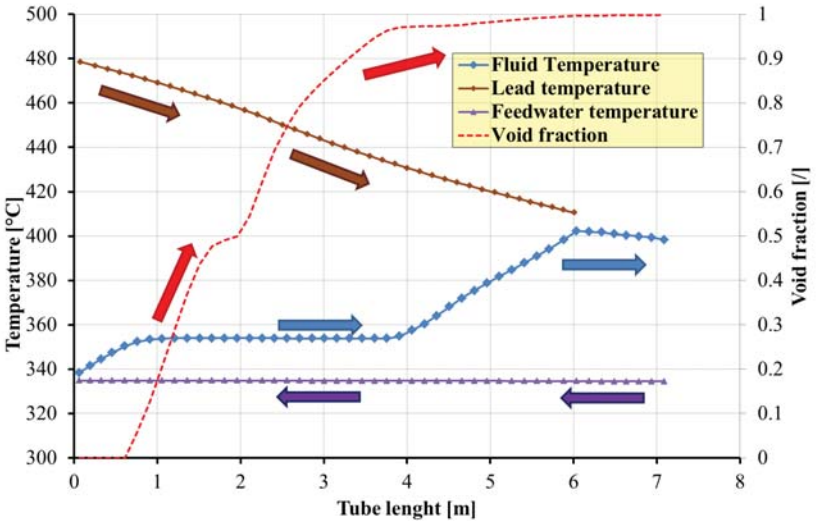


Figure 7 - HERO-CIRCE SGBT RELAP-5 model, nominal operating conditions.

Parameter	**Quantity**
Water mass flow rate [kg/s]	*0.330785*
Lead mass flow rate	*44.5735*
T water inlet [°C]	*334.9*
T steam outlet [°C]	*398.3*
Submerged height steam temperature [°C]	*402.3*
T lead inlet [°C]	*478.5*
T lead outlet [°C]	*410.5*
Lead velocity [m/s]	*0.56*
Pressure drop in the annular riser [bar]	*1.15 (friction only)*
Pressure drop in the feed-water tube [bar]	*0.21 (friction only)*
LBE total pressure drop [bar]	*1.08 (friction only)*
Total power exchanged [kW]	*438.4*

Table 3: HERO test section, reference simulation: TH performances.

#	**Description**	**Outlet steam temperature *[°C]***	**Removed power *[kW]***
0	Reference calculation	***398.3***	***438.4***
1	Feed-water inlet temperature 315°C	390.5	457.7
2	Feed-water inlet temperature 325°C	393.6	447.1
3	Feed-water inlet temperature 345°C	405.3	427.5
4	Feed-water mass flow 50%	473.0	271.2
5	Feed-water mass flow 70%	453.7	364.0
6	Feed-water mass flow 80%	433.5	395.6
7	Feed-water mass flow 90%	414.5	420.0
8	Feed-water mass flow 120%	380.3	461.9
9	LBE mass flow 50%	365.0	333.8
10	LBE mass flow 70%	382.3	391.1
11	LBE mass flow 80%	386.5	409.8
12	LBE mass flow 90%	393.2	425.0
13	LBE mass flow 120%	407.9	456.2
14	LBE inlet temperature 400°C	357.0 (still in 2 phase)	163.1
15	LBE inlet temperature 415°C	357.2 (still in 2 phase)	224.3
16	LBE inlet temperature 430°C	357.2 (still in 2 phase)	282.2
17	LBE inlet temperature 450°C	370.5	356.6

Table 4: HERO test section, parametric analysis.

4.2 Preliminary experimental campaign

The preliminary experimental campaigns consisted of eight different tests aimed to assess the thermal hydraulic performance of CIRCE – HERO test section. In these tests HERO is not fed by water and the power is removed by the DHR. Both natural circulation and gas enhanced circulation tests have been conducted at different power levels (constant in order to get isothermal conditions inside the LBE pool). TEST 28-2 proved that the LBE mass flow rate at the fissure inlet is consistent with the requirements of HERO (about 44 kg/s) by using gas enhanced circulation inside the capabilities of the facility (1.55 Nl/s of Argon).

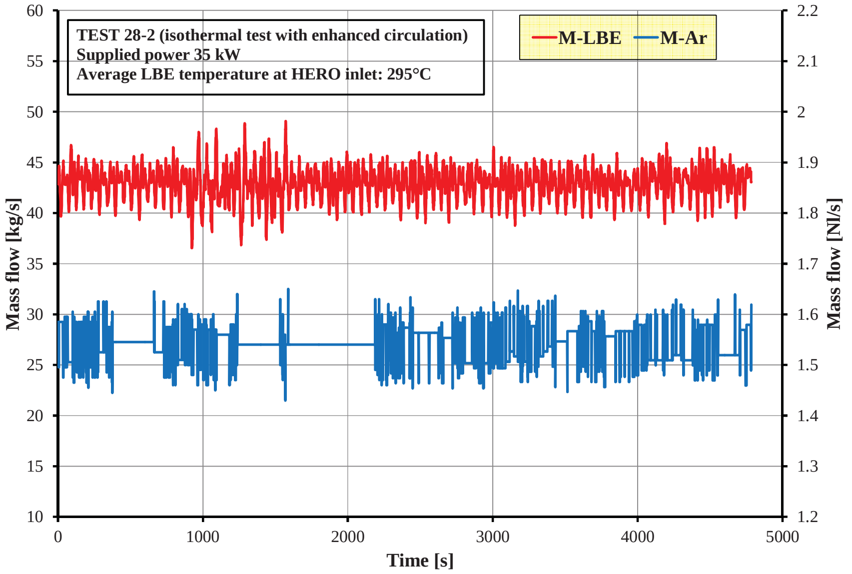


Figure 8 - HERO-CIRCE preliminary experimental campaign TEST 28-2.

Data from	**TEST 28-2** **h 9.50 to 11.10, 9-12-2014**
Average fuel bundle power	35 kW
Average LBE temperature at HERO inlet	295 °C
Ar mass flow rate	1.51 – 1.58 Nl/s
LBE mass flow rate at HERO inlet	40 – 46 kg/s
Average power removed by DHR	5 kW

Table 5: HERO-CIRCE preliminary experimental campaign TEST 28-2.

5. CONCLUSIONS

The Heavy liquid mEtal – pRessurized water cOoled tube (HERO) is an experimental test section of CIRCE designed and constructed by ENEA CR Brasimone to simulate the ALFRED SG. It consists of an hexagonal bundle of seven instrumented full scale double walled bayonet tubes (triangular pitch) and it aims to provide integral test experiments suitable for code validation and design optimization. The HERO SG bundle has been installed in CIRCE and the secondary line is actually under commissioning.

The SGBT unit has been modeled by RELAP-5 and the analysis highlights the achievement of superheated steam at about 400°C under nominal conditions (which are the same of ALFRED SG). This result is considered acceptable for a SG prototype, even if it 50°C below the ALFRED SG goal. A parametric analysis has been conducted for the development of the experimental test matrix mainly on the key parameters that can be switched during the experiments such as the feed-water and LBE inlet temperatures and mass flow rates. Among them, the LBE inlet temperature appears crucial for the achievement of superheated steam: at least 450°C are required to generate it.

Eight different isothermal tests aimed to assess the thermal hydraulic performance of CIRCE – HERO test section has been conducted. In these tests, HERO is not fed by water and the power is removed by the CIRCE-DHR. TEST 28-2 proved that the LBE mass flow rate at the fissure inlet is consistent with the requirements of HERO (about 44 kg/s) by using gas enhanced circulation inside the capabilities of the facility (1.55 Nl/s of Argon).

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6. ABBREVIATIONS

ADP	Accordo Di Programma National Programme
ALFRED	Advanced LFR European Demonstrator
CIRCE	CIRColazione Eutettico facility
DHR	Decay Heat Removal system
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia, e lo sviluppo economico sostenibile
HERO	Heavy liquid mEtal – pRessurized water cOoled tube
HX	Heat eXchanger
HLM	Heavy Liquid Metal
LBE	Lead Bismuth Eutectic
LEADER	Lead cooled European Advanced DEmonstration Reactor
LFR	Lead cooled Fast Reactor
SG	Steam Generator
SGBT	SG Bayonet Tubes unit
SGTR	SG Tube Rupture
UNIPI	University of Pisa