Nuclear Engineering and Design 353C (2019) 110270, https://doi.org/10.1016/j.nucengdes.2019.110270

MYRRHA PRIMARY HEAT EXCHANGER EXPERIMENTAL SIMULATIONS ON CIRCE-HERO

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ABSTRACT

In the frame of the MYRRHA ADS technological development, an intense research effort has been undertaken by European Commission, in particular for the Heavy Liquid Metal technology assessment. In this scenario, EURATOM HORIZON2020 funded the SESAME & MYRTE projects, coordinating a series of thermal hydraulics experiments and simulations for the safety assessment of liquid metal fast reactors. In particular, in the MYRTE project, a dedicated activity has been defined, consisting of a low pressure experimental campaign realized at the ENEA Brasimone Research Centre and concerning a double wall Steam Generator Bayonet Tube (SGBT), aiming at supporting the development of the Primary Heat Exchanger (PHX) of MYRRHA.

The CIRCE (CIRColazione Eutettico) pool facility hosts a devoted Test Section (TS) named HERO (Heavy liquid mEtal pRessurized water cOoled tubes). HERO consists of seven double wall bayonet tubes, with an active length of 6 m, arranged in a hexagonal geometry. This solution aims at improving the plant safety reducing the possibility of water-lead/lead-alloy interaction thanks to a double physical separation between them and allowing an easier control of potential leakages of the coolant by pressurizing the separation region with inert gas.

The experimental campaign in CIRCE-HERO has been supported by a pre-test analysis using system thermal-hydraulic codes (i.e. RELAP5). A sensitivity analysis has been performed considering the mass flow rate and HERO inlet temperature for both the water and LBE, fixing the operating pressure at 16 bar.

A test matrix, as produced as output of the sensitivity analysis and aimed at reproducing as faithfully as possible the thermal-hydraulic behaviour of the MYRRHA PHX under different operating conditions, is here presented. The experimental results collected from the low pressure tests on HERO test section are reported and discussed.

HIGHLIGHTS

- ✓ Experimental campaign on Lead-Bismuth Eutectic thermal-hydraulics in the CIRCE-HERO pool-type facility.
- ✓ Experimental tests on CIRCE-HERO facility in support of MYRRHA primary heat exchanger.
- ✓ Double Wall Bayonet tube Steam Generator.
- ✓ CIRCE-HERO experimental tests on Heavy Liquid Metal flow in gas-enhanced circulation regime.

1 INTRODUCTION

In the framework of the HORIZON2020 MYRTE (MYRRHA Research and Transmutation Endeavour) European project (MYRTE Project, EURATOM H2020, 2015), a dedicated experimental activity has been defined and realized at the ENEA Brasimone Research Centre, providing support to the development of MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications, MYRRHA Team, 2011) and acquiring thermo-dynamic feedbacks of the MYRRHA Primary Heat Exchanger (PHX) behaviour.

For this purpose, the large LBE (Lead-Bismuth Eutectic) pool integral effect CIRCE facility at CR ENEA Brasimone, implementing the HERO Test Section (Rozzia et al., 2017), has been involved in a low pressure secondary side (~16 bar) experimental campaign. The secondary loop for the HERO SGBT unit has been designed and realized for the SESAME experimental campaign, in support of the development of the ALFRED design (Frignani et al., 2017), and both the primary and secondary systems have been instrumented. On the basis of the final layout of the secondary circuit, a numerical model has been developed with the System Thermal-Hydraulic (STH) code RELAP5 in order to carry out a pre-test analysis for the setup of the low pressure tests experimental campaign. The preliminary numerical results obtained have been used to define the tests to be included in the experimental test matrix. The tests are characterized by an operating pressure of ~16 bar, maintained constant at the SGBT outlet, and a water inlet temperature of ~198°C in order to assure few degrees of sub-cooling at the HERO inlet.

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The present document reports the experimental tests performed, in terms of mass flow rates and temperature for both primary and secondary system, providing the details of the boundary conditions of each test and showing the experimental data achieved.

2 CIRCE-HERO REVIEW

The LBE pool CIRCE is an integral effect facility set at ENEA CR Brasimone (Lorusso et al., 2018a). Its main features, along with the implemented HERO test section geometry and installed instrumentation are detailed in Pesetti et al., 2018 and Lorusso, et al., 2018b. CIRCE consists of a cylindrical main vessel 8.5 m high filled with about 70 tons of LBE with argon as cover gas, LBE heating and cooling systems, a storage tank, a transfer tank and auxiliary systems for LBE circulation and the gas recirculation. The HERO test section is obtained from the previous Integral Circulation Experiments (ICE) test section (Tarantino et al., 2015), replacing the heat exchanger with a new SGBT. The CIRCE main vessel and the main components of the TS are shown in Figure 1. The main components of the TS are: the Fuel Pin Simulator (FPS) on the bottom part (in red in Figure 1) and consisting of an electrical bundle with 37 pins, the fitting volume (in green), the riser (in yellow), the separator on the top and the SGBT unit (in blue in Figure 1).

During the operating conditions, the LBE is heated inside the FPS and is driven through the riser up to the separator component, where the hot LBE is collected and from which it comes down, passing through the shell side of the HERO SGBT, closing in such a way the LBE loop into the bottom part of CIRCE main vessel. A dedicated argon injection device is located at the inlet section of the riser, for performing enhanced circulation of the primary coolant (gas lift). The gas injected flows up along the riser and it is separated from the LBE at the separator.

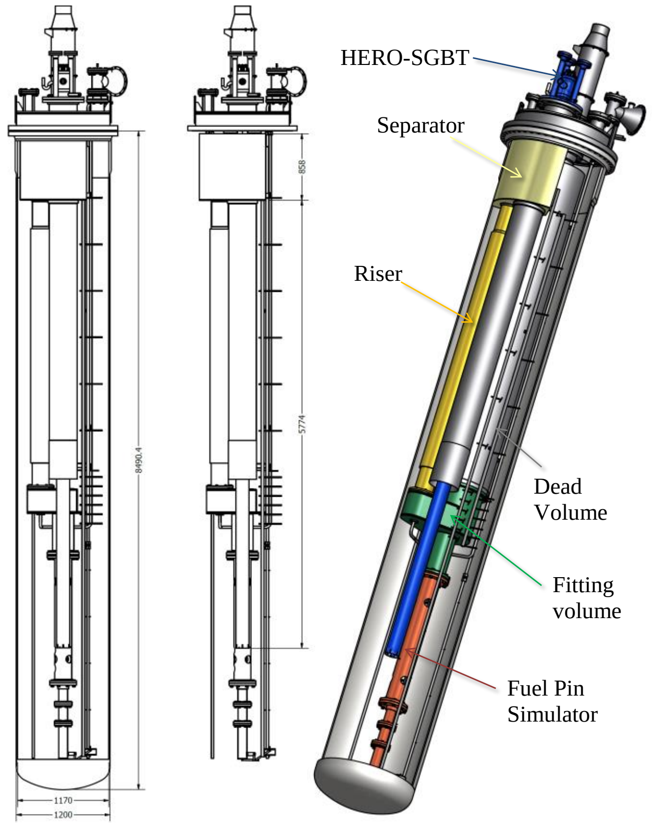

Figure 1 CIRCE-HERO Primary Loop (main vessel and HERO Test Section)

The 7 bayonet tubes of the steam generator are composed of four coaxial tubes, as represented in Figure 2: the feedwater enters in the slave tube from the top of the SGBT unit (see Figure 3), flowing downward and then rising through the annular riser between the first and second tube, where the steam is produced. The gap between slave and first tube is filled by air (slight vacuum) as insulator in order to avoid steam condensation. The gap between second and third tube is filled with AISI316L powder and slightly pressurized helium at ~10 bar to detect any leakages, and maintaining a good heat exchange capability, thanks to the metallic powder. The LBE inlet inside the SG is realized by six holes on the hexagonal shroud (right in Figure 2), positioned 300 mm from the separator bottom. The tubes have an active length of 6 m, arranged in a hexagonal shell (Figure 2) with a triangular pitch. The hexagonal shell is then contained in a cylindrical shroud (in blue in Figure 1).

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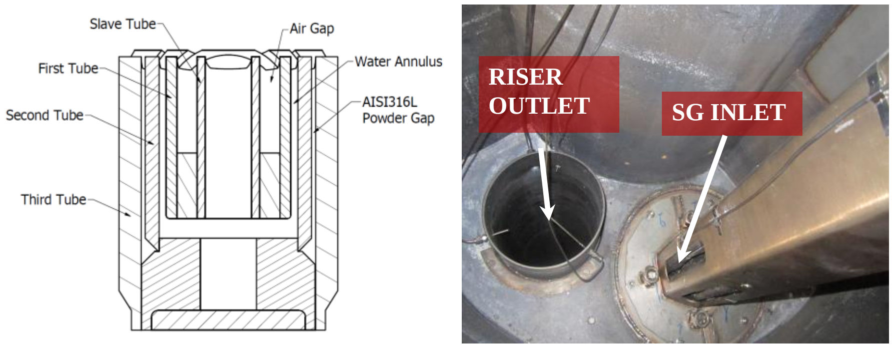

Figure 2 Bayonet Tube geometry (left) and internal view of the separator (right)

A once-through secondary loop has been realized (Lorusso et al., 2018b) to supply liquid water at the HERO SGBT unit. At the nominal working conditions, realized during the SESAME experimental campaign (Lorusso et al., 2019a), the water is injected in the bayonet tubes at ~335°C, producing superheated steam at ~172 bar at the SGBT outlet. A view of the secondary loop is shown in Figure 3. The main components are:

- a demineraliser;
- a volumetric pump regulated by a bypass valve and inverter and equipped with a 40 bar accumulator and a check valve;
- a helical heating system (HEATER in Figure 3);
- a manifold with seven outlet ½" tubes connected to the inlet of the bayonet tubes (Figure 3);
- a 3” discharge line, thanks to which the steam produced in the HERO test section outflows in the environment; the pressure along the loop is maintained at the operating pressure through the regulation of valve V3 (Figure 3);
- a ¾" bypass line used for the start-up phases, equipped with the regulation of valve V2 (Figure 3);
- a helium line, for pressurizing the stainless steel powder gap of bayonet tubes at ~10 bar.

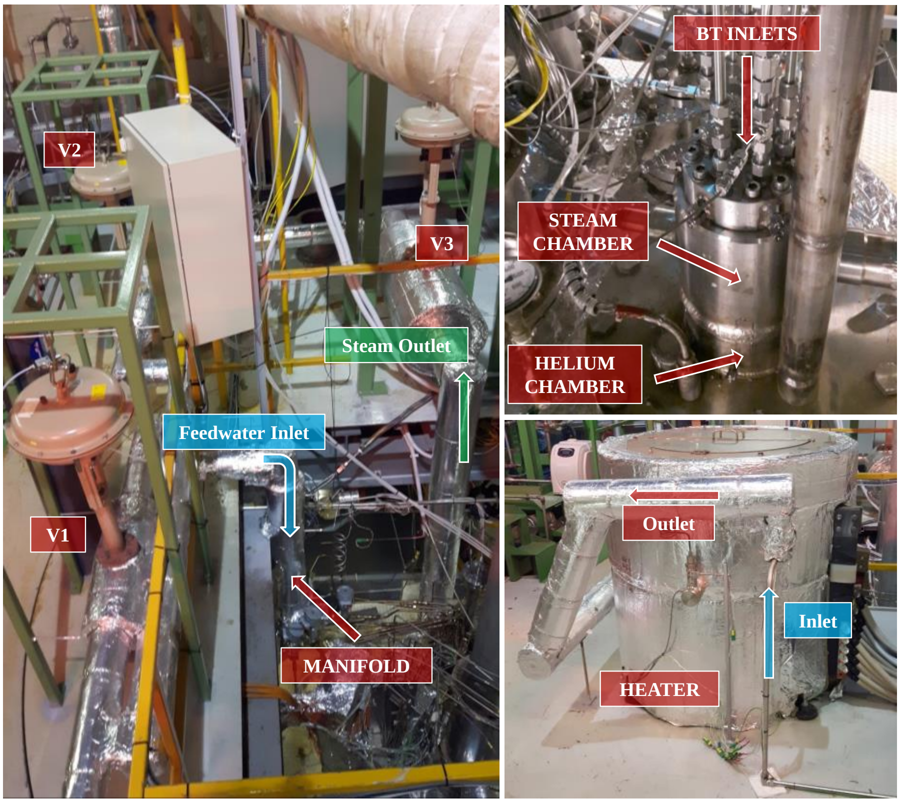

Figure 3 View of the secondary loop (left), the SGBT top flange (top, right) and the HEATER component (bottom, right)

The instrumentation in the primary system of the CIRCE facility is composed by an overall number of about 170 thermocouples (TCs), 10 bubble tubes, 1 Venturi flow meter and 3 LBE level meters. Two pressure transmitters are set in S100 cover gas. The argon flow rate injected for performing the LBE enhanced circulation is measured by an argon flow meter (FE400).

A total of 39 TCs are set in the fuel pin simulator, 3 TCs at riser inlet and 3 TCs at outlet section and 119 TCs distributed in the pool (see Figure 4) for mixing and stratification feedback, maintained in the same position of ICE TS (Pesetti et al., 2018, Narcisi et al., 2019). Five TCs are positioned on the outer surface of the fitting volume for evaluating thermal losses towards the pool. Three additional TCs were set for increasing measurement points of thermal stratification in the pool (Figure 4), accordingly with the expected thermal stratification level, obtained with a pre-test analysis realized by the RELAP5-3D© STH code (Narcisi et al., 2018).

In the CIRCE main vessel, bubble tubes have been installed, consisting in tubes injecting argon below the molten metal level (Ambrosini et al., 2004). Concerning the bubble tubes position, 6 are connected to 3 differential pressure transmitters for measuring ΔP: in the Venturi flow meter (inlet and throat section), between LBE free level in the pool and separator and across the lower spacer grid of the FPS. Remaining 4 bubble tubes are acquired by 4 absolute pressure transmitters, for measuring time trends inside the fitting volume, along the riser (inlet and outlet section) and in the pool cover gas.

The secondary loop is equipped with 9 relative and 4 differential pressure transmitters which characterize single and two-phases pressure losses across 4 BTs. The water mass flow rate is measured with 7 mini Turbine Flow Meters TFMs installed upstream each BT. An overall of 30 K-type thermocouples (TCs) are installed along the secondary loop. The water pressure and temperature are monitored at inlet and outlet sections of the heater, manifold and BTs, as well as downstream V3. Three thermocouples set at the steam chamber exit aim to detect possible condensation and radial stratification.

An overall number of 12 TCs, having a diameter of 0.5 mm, was positioned in the annular gap of the central BT (5 TCs, for characterising water evaporation) and at the exit of each BTs gap (7 TCS). LBE temperature is measured at four different levels (+1500, +3000, +4200 and +6000 mm) on three azimuthal positions of the central BT (12 TCs) and at three lower levels on outer surface of two outer BTs (6 TCs). Other measurement points are located at the centre of one central and three outer subchannels at three lower levels (12 TCs), besides 3 TCs at BT-SG outlet section (+0 mm). Three TCs are set at middle height of LBE inlet windows, about 150 mm from the separator bottom. All the signals are acquired at 1 Hz. For a detailed description of the secondary loop instrumentation see Lorusso et al., 2018b.

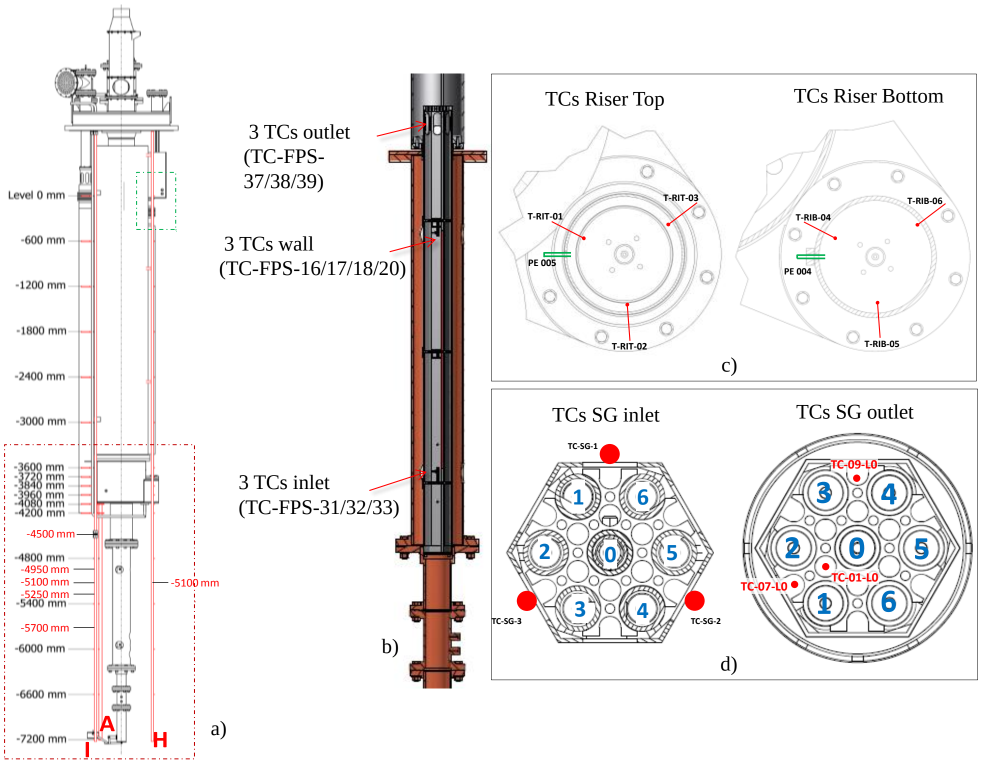

***Figure 4** Thermocouples installed in the primary system: a) in the LBE pool for mixing and stratification monitoring, b) along the FPS, c) at the inlet/outlet sections of the riser, d) at the inlet/outlet sections of the steam generator*

3 MYRTE EXPERIMENTAL CAMPAIGN

In the framework of the MYRTE Project, a set of tests has been foreseen for CIRCE facility in HERO configuration in order to achieve experimental data relevant for MYRRHA PHX. In the following, a test matrix consisting of 9 tests is presented and the results of the experimental campaign are described (Lorusso et al., 2019b).

The boundary conditions of the tests have been defined performing a preliminary simulation activity by STH codes RELAP5. The preliminary numerical results obtained have been used to define the tests to be included in the experimental test matrix. The tests are characterized by an operating pressure of 16 bar (set at the HERO outlet section) and a water inlet temperature of ~198°C (few degrees below the saturation temperature at ~16 bar). These conditions have been defined for the experiment to be as most representative as possible of the MYRRHA PHX operating conditions (De Bruyn et al., 2018).

A test reference has been set, assuming on the primary side the LBE mass flow rate 30 kg/s and the LBE inlet temperature in the shell side of the steam generator maintained at 235°C. In the secondary loop, the water mass flow rate is assumed constant at ~0.17 kg/s, corresponding to the 50% of the HERO nominal water mass flow rate (0.33 kg/s), in order to keep low pressure drops along the bayonet tubes. Starting from the conditions of the test reference, a sensitivity has been carried out changing one parameter at a time as shown in Table 1: a difference of +/-30% has been assumed for the LBE mass flow rate (Tests #3 and #4) and for the water mass flow rate (Tests #7 and #8), while a difference of +/-20°C has been assumed for the LBE temperature (Tests #1 and #2) and for the water temperature (Tests #5 and #6). It can be noticed that for Test #5 the water inlet pressure has been set to 23 bar instead of 16 bar because of the higher temperature assumed for water (at 23 bar Tsat=219.56°C).

The conditions assumed for the tests are reported in Table 1. During the experiments, each test has been performed after 1 h of steady state stabilization on the conditions of the Test Reference, in order to assure in such a way the repeatability of the tests.

Table 1 MYRTE Test Matrix, designed boundary condition

Parameter	Unit	Test ref.	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8
LBE T_{in}	°C	235	255 (+20°C)	215 (-20°C)	235	235	235	235	235	235
LBE mass flow rate	kg/s	30	30	30	39 (+30%)	21 (-30%)	30	30	30	30
H2O T_{in}	°C	198.0	198.0	198.0	198.0	198.0	218.0 (+20°C)	178.0 (-20°C)	198.0	198.0
H2O mass flow rate	kg/s	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.21 (+30%)	0.12 (-30%)
H2O P_{outlet}	bar	~16	~16	~16	~16	~16	~23	~16	~16	~16

3.1 Preliminary Analysis

As introduced in the previous paragraph, a preliminary test analysis is carried out using the STH code RELAP5. A numerical 1-D model of the HERO SG and the secondary loop has been realized in order to test the loop layout and its main components from a thermal-hydraulic point of view and to carry out a sensitivity analysis to define the test matrix for the low pressure experimental campaign (Tarantino et al, 2019). In particular, a RELAP5-3D© Ver. 4.3.4 has been used by the University of Rome "La Sapienza" and a modified version of RELAP5/Mod3.3 including the thermophysical LBE properties (Barone G. et al, 2013) has been used by University of Pisa. A further numerical model has been developed by SCK•CEN using RELAP5-3D© Ver. 4.3.4.

A general overview of the main numerical results for each test in terms of water pressure drops, power removed and steam mass fraction produced, is reported in Table 2, for both RELAP5-3D© Ver. 4.3.4 and RELAP5/Mod3.3 system codes. The highest value of the power removed is reached in Test #1 where the LBE inlet temperature has been increased of 20°C up to 255°C, while the Test #2, characterized by the reduction of the LBE inlet temperature up to 215°C, represents the case with the lowest power removed.

Test #1 also reports the highest steam mass fraction produced, and consequently it is the case with the highest pressure drops, while the lower values are reached in Test #2 (1.6 bar of pressure drops and 13% of steam mass fraction) and Test #5 (1.4 bar of pressure drops and 15% of steam mass fraction).

Table 2 Sensitivity analysis: main numerical results

Parameter	---	T ref.	T #1	T #2	T #3	T #4	T #5	T #6	T #7	T #8
H2O ΔP [bar]	UniRoma1	3.4	4.6	1.6	3.8	2.6	1.4	2.9	4.2	2
	UniPi	3.4	5.2	1.6	3.9	2.4	1.4	2.6	4.7	1.8
	SCK•CEN	2.4	3.1	1.5	2.5	2.1	0.9	2.1	2.9	1.7
Steam Mass Fraction	UniRoma1	34%	53%	13%	39%	27%	15%	30%	27%	46%
	UniPi	34%	53%	13%	41%	26%	15%	30%	29%	47%
	SCK•CEN	29%	44%	15%	32%	25%	10%	26%	22%	42%
Power Removed by HERO [kW]	UniRoma1	102	164	41	118	81	45	106	103	100
	UniPi	104	168	43	122	84	46	109	106	105
	SCK•CEN	92	141	45	101	78	32	97	89	96

4 MYRTE EXPERIMENTAL RESULTS

This paragraph shows the main results of the experimental tests performed, in terms of flow rates and temperature trends for both primary and secondary systems. In particular, a comparison between Test Reference, Test #1 and Test #2 is presented, while the experimental results achieved in the other tests are summarized in Table 3.

The boundary conditions achieved for the Test Reference, Test #1 and Test #2 are reported in Figure 5 for the power supplied by the FPS and Figure 6 for the argon flow rate injected. The tests were ended after 1 h of steady-state. The power of the FPS has been set to ~90 kW in Test Ref., 140 kW in Test #1 and ~25 kW in Test #2, in order to compensate the power removed by the steam generator and the heat losses to the environment. The argon gas injection has been set at 1 Nl/s in order to reach the designed LBE mass flow rate) of 30 kg/s (see Figure 6).

Concerning the secondary loop, the water mass flow rate supplied by the volumetric pump is measured by the mini-turbine flow meters installed upstream the inlet section of each bayonet tube. The measured mass flow rates for the entire duration of the Test Ref., Test #1 and Test #2 are reported in Figure 7. The total water mass flow rate measured is about ~0.163 kg/s, assuming a water density of ~867 kg/m^3 (P_{H2O} = 16 bar, T_{H2O} = 198°C). It can be noticed from Figure 7 that the water flow rate is equally distributed among the tubes, except for the tube 6, in which the value measured by the TFM-T6 is ~50% lower than the flow rates measured by the other TFMs. This unbalanced distribution in tube 6 has been investigated replacing the TFM-T6 with TFM-T5, obtaining the same discrepancy in the flow rate measure and concluding that it is not related to a fault of the instrumentation, but it is most probably related to the actual geometry of the BT itself (e.g. tolerances of manufacturing). A further investigation will be carried out during the next refurbishment of the facility.

An additional evaluation of the water flow rate can be carried out applying the thermal balance equation on the HEATER component:

$$\dot{m}_{H2O} = \frac{\dot{Q}_{H2O}}{hout - hin} \qquad (1)$$

where:

Q_{H2O} is the electrical power supplied to the water by the HEATER;
h_{in} is the water enthalpy at the inlet section of the HEATER;
h_{out} is the water enthalpy at the outlet section of the HEATER.

achieving a value of ~0.16 kg/s, very close to the measured one.

The water temperature at the inlet section of the BTs is maintained at ~198°C, managing the power of the HEATER component. The pressure of the helium line in the AISI316L powder gap has been maintained at 8.0 bar.

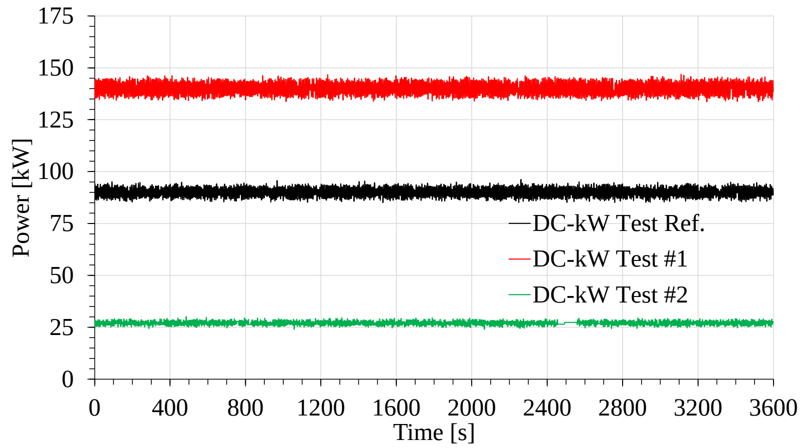

Figure 5 Electrical power supplied by the FPS during Test Ref., Test #1 and Test #2

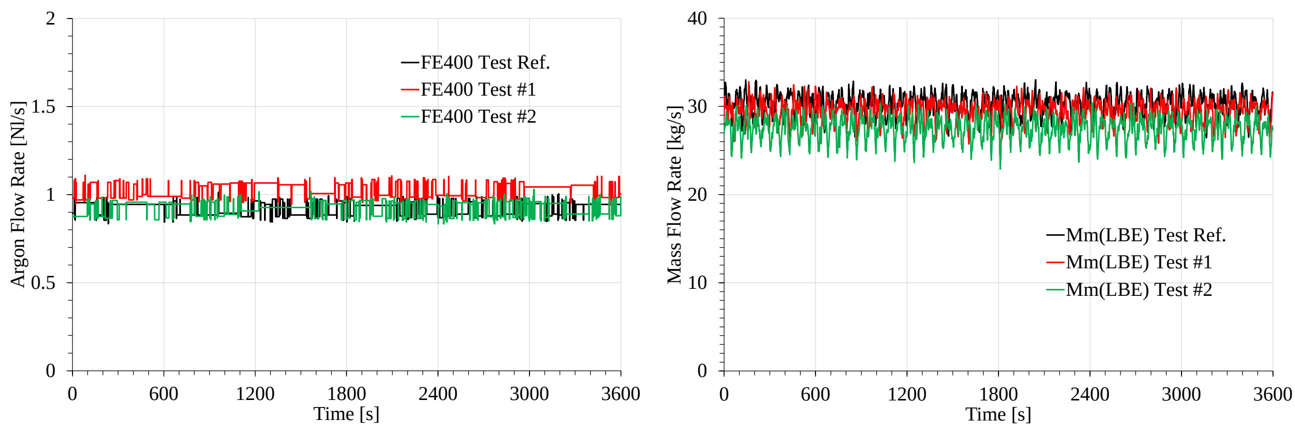

Figure 6 Argon flow rate injected (left) and LBE mass flow rate achieved in the primary loop (right) during Test Ref., Test #1 and Test #2

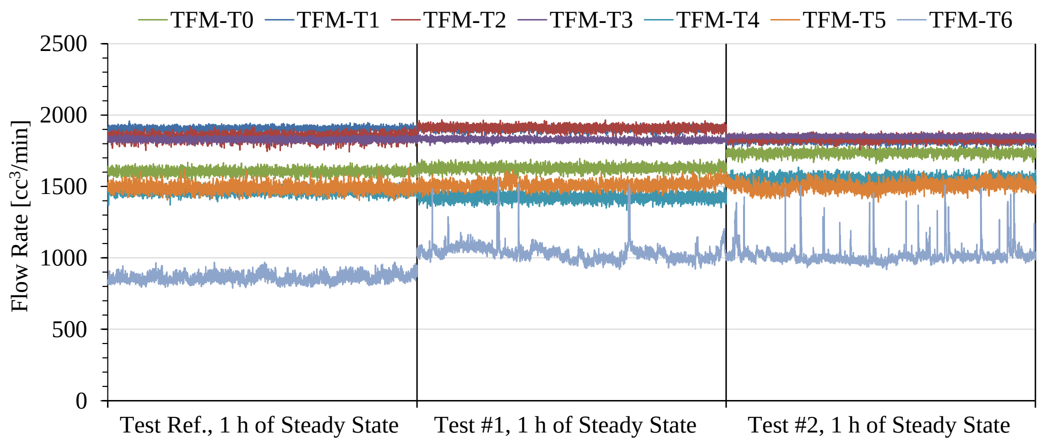

Figure 7 Water flow rate supplied by the volumetric pump during Test Ref., Test #1 and Test #2

Figure 8 reports the temperature of the coolant inside the FPS, in correspondence of the inlet and outlet sections, during Test Ref., Test #1 and Test #2, respectively, when the steady state conditions are reached in the primary loop.

The LBE temperature at the FPS inlet in Test Ref. is ~222°C, while the outlet temperature is ~240°C, with a ΔT along the active length of about 18°C. The Test #1 is characterized by the highest temperature range, with a LBE temperature of about 232°C achieved at the inlet section of the FPS and ~263°C at the FPS outlet section, with a ΔT of ~31°C. Contrariwise, the LBE temperatures achieved in Test #2 are the lowest reached, compared to all the other tests: the FPS inlet/outlet temperatures are 207°C/214°C, achieving a ΔT along the active length of ~7 °C. These differences in temperature range of Test #1 and Test #2 are consistent with the different power supplied during the two tests.

Arising from the bottom part of the riser up to the separator, the LBE temperature is subjected to a slight decrease of few degrees, due to the heat losses along the riser length, as can be noticed in Figure 9 which reports the LBE temperatures at the inlet and outlet sections of the HERO SGBT. The temperature decrease from the FPS outlet to the SG inlet is more pronounced in Test #1, due to the high temperatures of the primary coolant, with an overall reduction of 5 °C, while in Test Ref. and Test #2 the temperature decreases of ~3°C and ~1°C, respectively.

Figure 9 also reports the outlet temperature of the SG, giving information concerning the thermal-hydraulic performance of the HERO unit during the tests. During the Test Ref. the temperature at the SG inlet section is about 238°C, while after the cooling it is about 221°C. In these conditions it is possible to evaluate the power removed by HERO, assuming an average c_p for the LBE of 146 kJ/(kg*K), the average LBE mass flow rate of 30 kg/s and the ΔT of 17.3°C, obtaining from the thermal balance equation the average value of ~77 kW. In Test #1, the LBE temperature achieved at the SG inlet is ~258°C, with a temperature at the outlet section of ~232°C and a power removed by HERO, applying the thermal balance equation, of about 125 kW. Finally, concerning the Test #2, the LBE at the SG inlet and outlet sections reaches the temperatures of 213 °C and 209 °C respectively. The power removed by HERO in these conditions is very low, about 20 kW, due to the low LBE temperature at the SG inlet and, thus, to the small temperature differences between the primary and secondary coolants.

It can be noticed from Figure 9 that the temperature measured at the inlet by TC-SG-01 suffers an instability respect to the other two TCs, because of its position in the separator. In fact, this TC is directly exposed to the rising LBE, mixed to the argon injected at the bottom of the riser and this turbulence affects the measure acquired.

Figure 10 shows the temperatures measured by the 119 TCs placed in the LBE pool as function of their vertical position on the supporting bars (A-I), after 1 h of steady state in the designed conditions for Test Ref., Test #1 and Test #2, respectively. In all the tests performed, the stratification in the pool occurs between the positions at 5000 mm and 6000 mm (assuming 0 mm the bottom part of the separator, see Pesetti et al., 2018), corresponding to the outlet zone of the steam generator. The Test Ref. is characterized by a maximum temperature reached of ~235°C, in the upper part of the pool (in correspondence of the separator), while the lowest value is ~221°C in the lower part of the pool. The pool stratification during Test #1 is more pronounced; the temperature range is higher than the Test Reference and comprised between ~255°C and ~231°C, while the temperature profile achieved in Test #2 is only slightly visible, passing from a temperature of 210 °C to 207°C between 5000 mm and 6000 mm, as a consequence of the restricted temperature field reached in the test.

Finally, it can be noticed from Figure 10 that the thermal stratification in the LBE pool occurs in vertical direction only, with uniformity along the horizontal planes. Figure 11 reports a detail of the LBE temperatures measured by TCs of rod H for Test Ref., Test #1 and Test #2, showing a steady state condition achieved in the LBE pool during the tests.

Figure 12 and Figure 13 show the BT inlet and outlet water temperatures, and the pressure drops along the bayonet tubes, respectively. The water is injected in the steam generator at about 198-200°C (Figure 12) and the temperature is maintained constant for the entire duration of the tests. At the steam generator outlet, a two-phase flow with liquid/steam mixture is obtained, with an outlet temperature of ~202°C, corresponding to the saturation temperature at the operative pressure of ~16 bar. The low water outlet temperature of TC-T1-I reported in Figure 12 during the Test Ref. is due to a malfunction of its acquisition channel of the DACS and it is not related to the instrument.

About the pressure drops in the bayonet tubes (Figure 13), the differential pressure measurements are realized between the BTs inlet (downstream the orifices, see Pesetti et al., 2018) and immediately downstream the steam chamber outlet. The pressure drops in Test Ref. are about 0.8 bar, value acquired by each differential pressure transmitter installed, which demonstrates that the thermal hydraulic performances of each BT are almost the same.

Test #1 shows higher pressure drops (~1.4 bar) than Test Ref., while Test #2 is characterized by a very low value (~0.1 bar). In Test #1 the difference is due to the higher power removed (higher LBE temperatures) which caused the higher steam mass fraction produced in the BT annular region. In Test #2 it is due to the lower thermal field of the primary coolant, which leads to a low fraction of power removed and a small steam mass fraction produced.

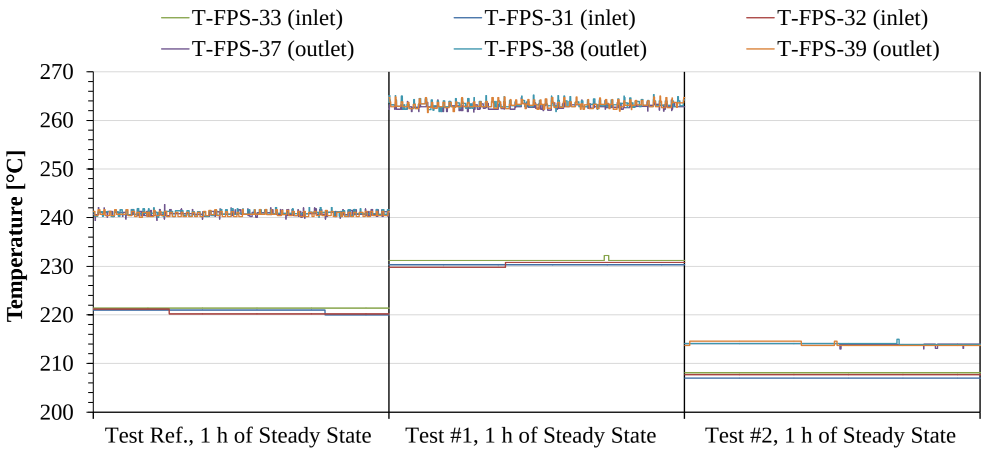

Figure 8 LBE temperature trends at the FPS inlet-outlet during Test Ref., Test #1 and Test #2

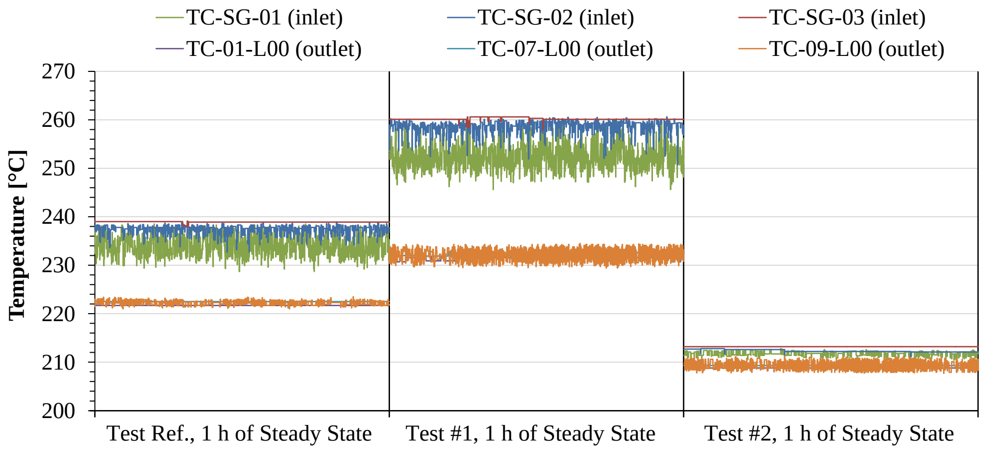

Figure 9 LBE temperature trends at the SG inlet-outlet during Test Ref., Test #1 and Test #2

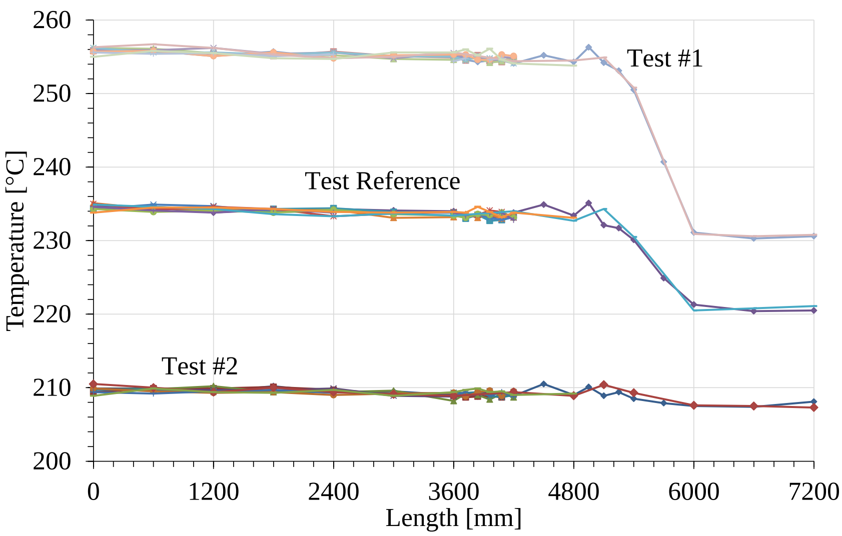

Figure 10 Axial temperature profile of the LBE inside the main vessel during Test Ref., Test #1 and Test #2

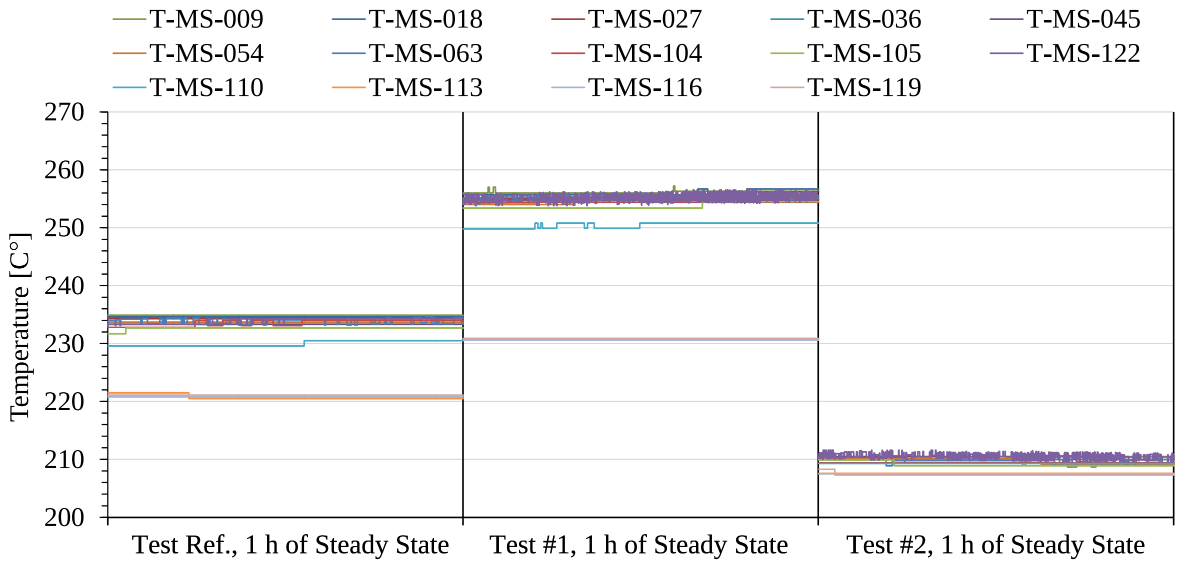

Figure 11 Temperature measured on supporting rod H during Test Ref., Test #1 and Test #2

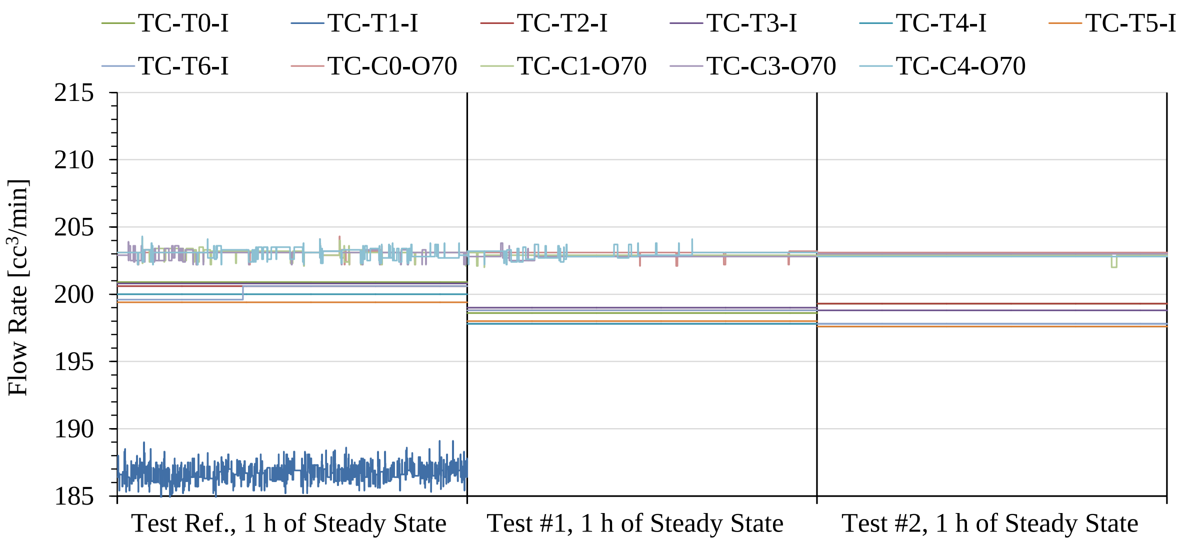

Figure 12 Water temperature trends at the BTs inlet-outlet during Test Ref., Test #1 and Test #2

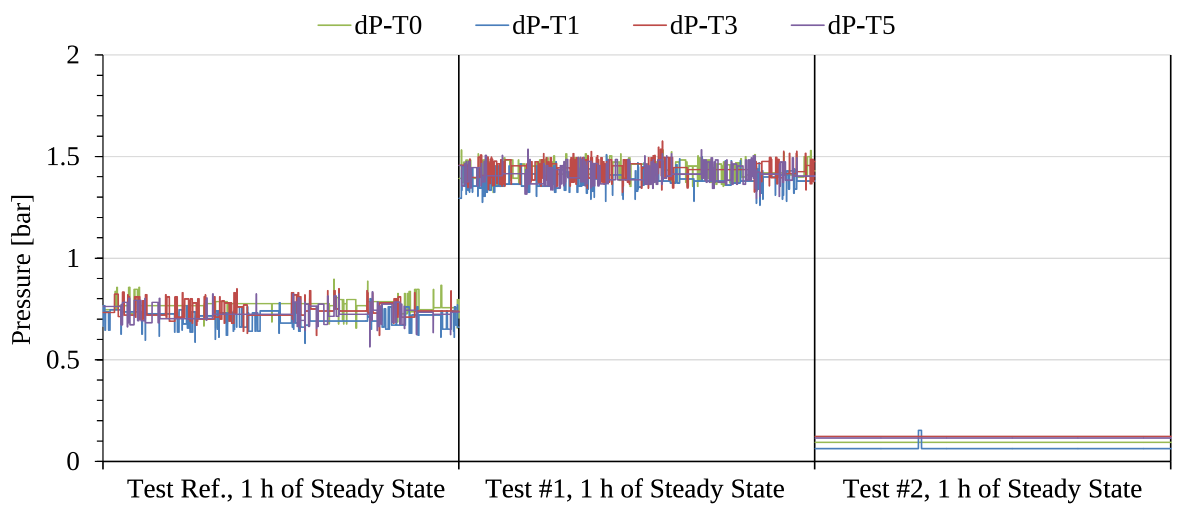

Figure 13 Water pressure drops between BTs inlet-outlet during Test Ref., Test #1 and Test #2

A summary of the experimental results of the three tests already described above and of the other six tests performed is reported in Table 3. In all the tests, the LBE mass flow rate achieved with the argon injection is comprised in the range of 28-30 kg/s, except for Test #3 and Test #4, characterized by a LBE mass flow rate of 38 kg/s and 20 kg/s, respectively. The LBE SG inlet temperature achieved in Test #1 and Test #2 is 258°C and 213°C, very close to the boundary conditions defined in Table 1. In the other tests the LBE temperature at the SG inlet is kept constant at ~239°C, about 4°C higher than the designed values of Table 1, while in Test #4 it reaches ~244°C. Concerning the secondary loop parameters, both the water mass flow rates and the feedwater inlet temperatures achieved in the nine tests are very close to the target values defined in Table 1.

The comparison shows that the thermal-hydraulic performances of the facility in the operating conditions defined in Test Reference, Test #3, Test #4, Test #6, Test #7 and Test #8 are very similar. In fact, in these tests, the power removed by HERO is almost the same, and comprised in the range of 70-80 kW. The highest value of power removed by HERO has been achieved in Test #1 (~125 kW) characterised by the highest LBE SG inlet temperature, while the lowest power has been achieved in Test #2 (~20 kW) characterised by the lowest LBE SG inlet temperature. The experimental sensitivity carried out on the thermal-hydraulic parameters shows that the LBE temperature in the primary system is the most influent parameter, which determines the performances of the system in terms of power exchanged. A low power removed is also achieved in Test #5 (~25 kW), where the HERO water inlet temperature has been increased from 198°C to 218°C, reducing in such a way the temperature difference between the primary and secondary coolants, and consequently reducing the overall performances of the steam generator.

Table 3 also shows that Test Reference, Test #3, Test #4, Test #6 and Test #8 have a similar behaviour concerning the pressure drops along the bayonet tubes, with a ΔP achieved between the inlet section of the BTs and the outlet section of the steam chamber comprised between 0.5 bar and 0.8 bar. As seen for the power, also the pressure drops have achieved the maximum and minimum values in Test #1 and Test #2, respectively: in the first case (ΔP ~1.4 bar) it is due to the higher power removed (higher LBE temperatures) which caused the higher steam mass fraction produced, in the second case (ΔP ~0.1 bar) the opposite situation occurred, with a lower steam mass fraction produced (lower power removed) due to the lower LBE temperature.

Test #7 is also characterized by high pressure drops, due to the higher water mass flow rate, while Test #5, in which the secondary loop pressure was increased from 16 bar to 23 bar, reports an overall BTs pressure drops of ~0.15 bar.

Table 3 MYRTE experimental results

Parameter	*Unit*	*Test Ref.*	*Test #1*	*Test #2*	*Test #3*	*Test #4*	*Test #5*	*Test #6*	*Test #7*	*Test #8*
LBE mass flow rate	[kg/s]	30	29.5	28	38	20	28.5	29.5	29.5	29.5
LBE FPS T_{in}	[°C]	222	232	207	222	218	229	219	220	221
LBE FPS T_{out}	[°C]	240	263	214	237	248	238	239	241	241
LBE SG T_{in}	[°C]	238	258	213	235	244	236	236	238	237
LBE SG T_{out}	[°C]	221	232	209	222	219	230	220	222	222
SG power removed (thermal balance)	[kW]	77	125	20	70	75	25	75	75	80
H2O mass flow rate	[kg/s]	0.163	0.159	0.162	0.163	0.162	0.168	0.158	0.219	0.125
H2O SG T_{in}	[°C]	200	198	198	198	198	217	178	199	197
H2O SG T_{out}	[°C]	202	202	202	202	202	219	202	202	202
H2O BT ΔP	[bar]	0.8	1.4	0.1	0.75	0.65	0.15	0.5	1.25	0.5

5 CONCLUSIONS

The CIRCE facility, implementing HERO TS, has been involved in a low-pressure experimental campaign in the framework of the HORIZON2020 MYRTE European project. A test matrix consisting of nine low-pressure experimental tests in steady state conditions has been designed and performed. The tests realized allowed to evaluate the thermal-hydraulic performance of the HERO SG in working conditions relevant for the MYRRHA PHX.

A preliminary analysis has been carried out using STH codes RELAP5 in support of the secondary side low pressure test experimental campaign. A reference test has been set assuming an LBE inlet temperature of 235°C and mass flow rate of 30 kg/s and a water injection in the HERO SGBT at 198°C and 16 bar, with a total mass flow rate ~0.17 kg/s. A sensitivity analysis for each of these parameters has been performed in order to see the influence of their variations on the results. Furthermore, a preliminary code-to-code comparison between two versions of RELAP5 has been carried out showing a good consistency among them.

During the steady-state tests, it has been possible to evaluate the supplied power to the FPS aiming at balancing the power removed by the SG, maintaining the LBE SG inlet temperature as close as possible to the target values foreseen for each test. The stationary conditions of the LBE mass flow rate in each test in gas enhanced circulation regime have been successfully achieved, thanks to the argon injection device. In the same way, the main components of the secondary loop (i.e. volumetric pump, helical heater, regulation valves) have been managed in order to maintain the water conditions designed for each test.

The experimental sensitivity showed a similar general behaviour for Test Reference, Test #3, Test #4, Test #6, Test #7 and Test #8. The most important differences have been achieved in Test #1, characterised by the highest LBE SG inlet temperature, and Test #2, characterised by the lowest LBE SG inlet temperature, highlighting that the parameters which mostly influence the thermal-hydraulic performances of the system are the feedwater temperature and the temperature field inside the LBE pool. Test #5 also reports relevant differences, due to the increased water inlet temperature and the consequent reduction of the temperature difference between the primary and secondary coolants.

ACKNOWLEDGMENT

This work was performed in the framework of H2020 MYRTE project. This project was funded by the European Commission under grant agreement No 662186.

The authors wish to thank all the ENEA's technicians involved in the implementation and operation of the CIRCE-HERO experimental facility.

NOMENCLATURE

Q	Electric Power	W
h	Enthalpy	kJ/kg

ABBREVIATIONS

ADS	Accelerator Driven System
ALFRED	Advanced Lead cooled Fast Reactor European Demonstrator
BT	Bayonet Tube
CIRCE	CIRColazione Eutettico
DACS	Data Acquisition and Control System
FPS	Fuel Pin Simulator
HERO	Heavy liquid mEtal pRessurized water cOoled tubes
LBE	Lead-Bismuth Eutectic
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
MYRTE	MYRRHA Research and Transmutation Endeavour
PHX	Primary Heat Exchanger
SESAME	Simulations and Experiments for the Safety Assessment of MEtal cooled reactors
SG	Steam Generator
SGBT	Steam Generator Bayonet Tube
STH	System Thermal-Hydraulic
TC	Thermocouple
TFM	Turbine Flow Meter
TS	Test Section

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