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Investigation of heat transfer in a steam generator bayonet tube for the development of PbLi technology for EU DEMO fusion reactor

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In the frame of the EUROfusion roadmap for the development of the DEMO power plant, a research activity was carried out to develop a Lithium-Lead/water heat exchanger. The component should be capable to remove nuclear heat deposited in the liquid metal of the Dual Coolant Lithium Lead breeding blanket and feeding a steam turbine, ensuring an efficient thermal power conversion to electricity. One of the selected configurations is the steam generator bayonet tube. The HERO test section is an experimental mock-up in a relevant scale of this steam generator, consisting of a bundle of seven double-wall bayonet tubes with a leakage monitoring system. This test section, developed by ENEA at Brasimone Research Center and installed in the main vessel of the CIRCE pool facility, aims to investigate the thermal-hydraulic features of the system, providing a database for thermal-hydraulic system codes validation. An experimental campaign was carried out to demonstrate technological feasibility and performances of the prototypical heat exchanger, suitable as steam generator for the PbLi loop of the Dual Coolant Lithium Lead and Water Cooled Lithium Lead breeding blankets. A post-test analysis has been realized with RELAP5-3D and RELAP5/Mod3.3 codes in order to evaluate code capability in simulating heat transfer in liquid metal side.

Keywords: DEMO, RELAP5, heat transfer, PbLi loop

1. Introduction

The DEMOnstration (DEMO) fusion reactor [1] is a milestone to achieve the production of electricity from nuclear fusion reaction. The system devoted to extract the thermal heat from the breeding blanket is the Primary Conversion System (PCS) to convert it in electricity.

A research activity was carried out to develop a Lithium Lead (PbLi)/water Heat exchanger capable to remove nuclear heat deposited in the liquid metal of the Lithium Lead (PbLi) system of the Dual Coolant Lithium Lead (DCLL) [2] breeding blanket and feeding a steam turbine, ensuring an efficient thermal power conversion to electricity. One of the selected configurations is the Steam Generator Bayonet Tube (SGBT) [3][4].

The heat exchanger is prototypical, therefore experimental tests are required to demonstrate technological feasibility of the component. The test section selected to perform the experimental campaign is HERO (Heavy Liquid mEtal pRessurized water cOoled tubes) [5], which is an experimental mock-up in a relevant scale of the steam generator bayonet tube, consisting of a bundle of seven double-wall bayonet tubes with a leakage monitoring system. This test section, developed by ENEA at Brasimone R.C. and installed in the main vessel of the CIRCE (CIRColazione Eutettico) pool facility, aims at investigating the thermal-hydraulic behavior of the system, providing a database for codes validation.

A post-test analysis is carried out with RELAP5-3D code [6] in order to assess the code performances in predicting the heat transfer, and to characterize the heat transfer in liquid metal side, comparing the results with the experimental data. Preliminary validation of the modified version of RELAP5/Mod3.3[7][8] for fusion application is also reported.

Moreover, one of the features of the component is the reduced possibility of water-lead/lead-alloy interaction[9],[10],[11], thanks to a double physical separation between them and easier control of the leak occurrence by pressurizing the gap region with inert gas. Thanks to this safety features such design is also exploitable as heat exchanger in the PbLi loop of the Water Cooled Lithium Lead (WCLL) breeding blanket [12].

2. CIRCE-HERO layout

CIRCE is an integral effect facility set at ENEA Brasimone R.C. [13],[14]. Its main features, along with the implemented HERO SGBT geometry and instrumentation installed are reported in [5]. CIRCE consists in a cylindrical main vessel, having an internal diameter of 1170 mm, thickness of 15 mm and height of about 8500 mm, filled (up to 500 mm from the top flange) with about 70 tons of Lead-Bismuth Eutectic (LBE) with argon as cover gas maintained at about 0.2 bar_g, LBE heating and cooling systems, a storage tank, a transfer tank and auxiliary systems for LBE circulation and gas circulation.

The main flow path of the primary coolant inside the pool is reported in Fig. 1. The LBE flows upwards

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through the Fuel Pin Simulator (FPS) in red in Fig. 1 [15], it passes the Fitting Volume (green) and, flowing through the Riser (yellow), it enters into the Separator, in which the free level reaches about the middle height of the wall. An Argon injection device is located at the inlet section of the Riser, allowing to enhance the LBE mass flow rate. From this small pool, the LBE comes in the SGBT (blue) and starts its downwards flow, shell side. Then, LBE completes its loop into the pool bottom.

A once-though secondary loop has been realized to supply liquid water at the HERO SGBT unit [16]. The secondary loop is mainly composed of a demineralizer, 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, a manifold, a discharge line, thanks to which the steam produced in the HERO test section outflows in the environment, a bypass line used for the start-up phase and a helium line, for pressurizing the stainless steel powder gap of bayonet tubes at ~8 bar.

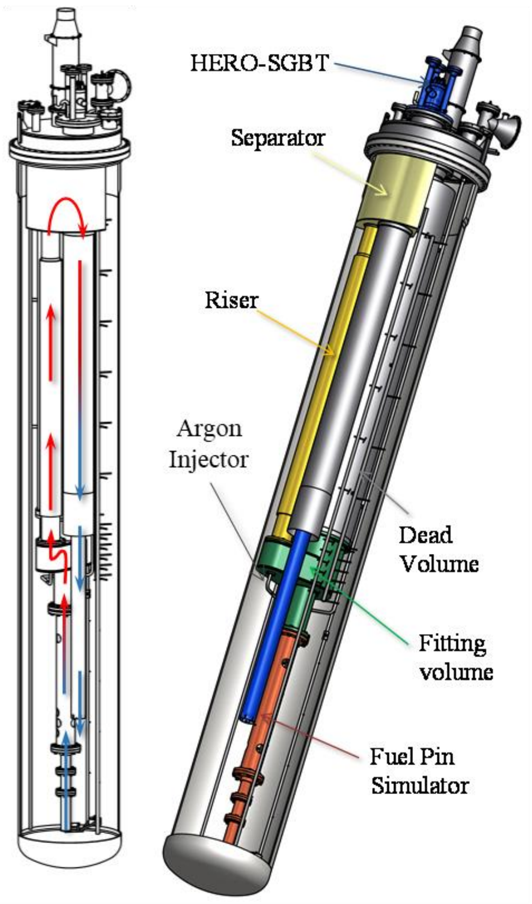

Fig. 1. General view of the CIRCE main vessel and HERO test section [15]

The HERO SGBT is mainly composed by a top flange with seven holes to accommodate the bayonet tubes and one hole for the instrumentation. The flange connects the SG bayonet tube unit to the CIRCE main vessel and it sustains the helium chamber, the steam chamber, the bayonet tubes and the hexagonal shroud (see Fig. 2).

The tube bundle is composed of 7 double wall bayonet tubes, with an active length of 6 m, arranged with a triangular pitch in a hexagonal shell (see Fig. 3). Each Bayonet Tube (BT) is composed of four coaxial tubes, for details see Ref. [5]: the feedwater enters from the top of the slave tube, 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 ~8 bar to detect any leakages, and maintaining a good heat exchange capability, thanks to the metallic powder. The detail of the BT geometry and the coolants flow paths are shown in Fig. 3. The LBE inlet is realized by six holes on the hexagonal shell, positioned 300 mm from the separator bottom. The steam produced is collected in the steam chamber and is discharged in the environment.

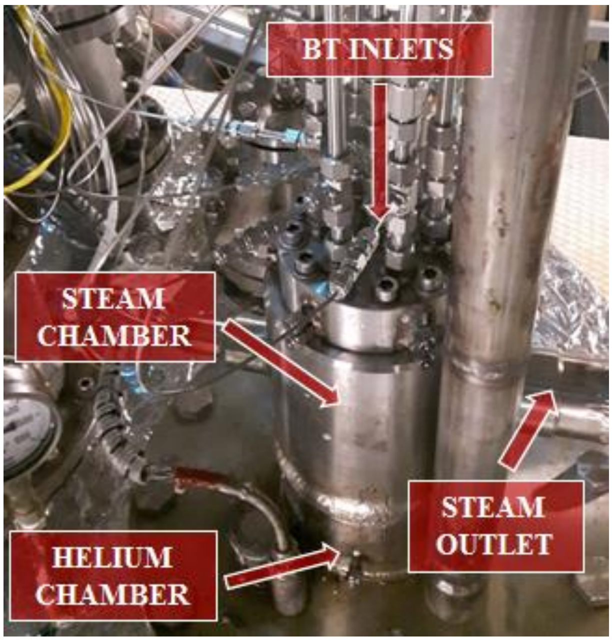

Fig. 2. View of HERO SGBT top flange. [15]

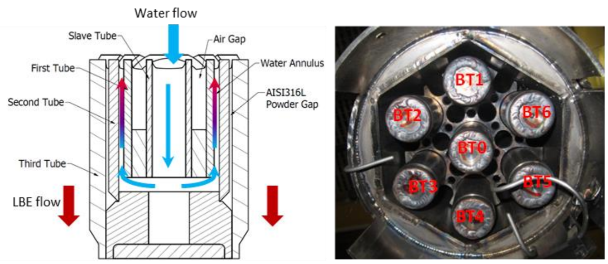

Fig. 3. Sketch of the hexagonal geometry (left) and detail of the bayonet tubes (right)

In the primary loop, the instrumentation installed in HERO test section is composed of an overall number of 170 thermocouples (TCs), 10 bubble tubes, 1 Venturi flow meter and 3 LBE level meters. Two pressure transmitters are set in S100 cover gas. Moreover, an argon flow meter measures the normal liters per second injected in the riser bottom, for gas lift occurrence.

A total of 39 TCs are set in the FPS, 3 TCs at riser inlet and 3 TCs at outlet section. A total of 119 TCs are distributed in the pool for mixing and stratification feedback, for details see Ref [5]. Five additional TCs are installed on the outer surface of the fitting volume, where large heat losses towards the pool are expected [17] [18].

The instrumentation installed in the secondary loop is composed of 30 K-type thermocouples, 9 relative pressure transmitters, 4 differential pressure transmitters, one Coriolis flow meter and 7 mini turbine flow meters (TFMs) [5].

Concerning the SG shell side, LBE temperature is measured at four different levels (+1500, +3000, +4200 and +6000 mm, assuming +0.0 mm as the SG outlet) in the three azimuthal positions of central BT (12 TCs), at lower three levels on outer surface of two outer BTs (6 TCs) and at the center of one central and three outer sub-channels 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. A scheme of the TCs is reported in Fig. 4. All the signals are acquired at 1 Hz.

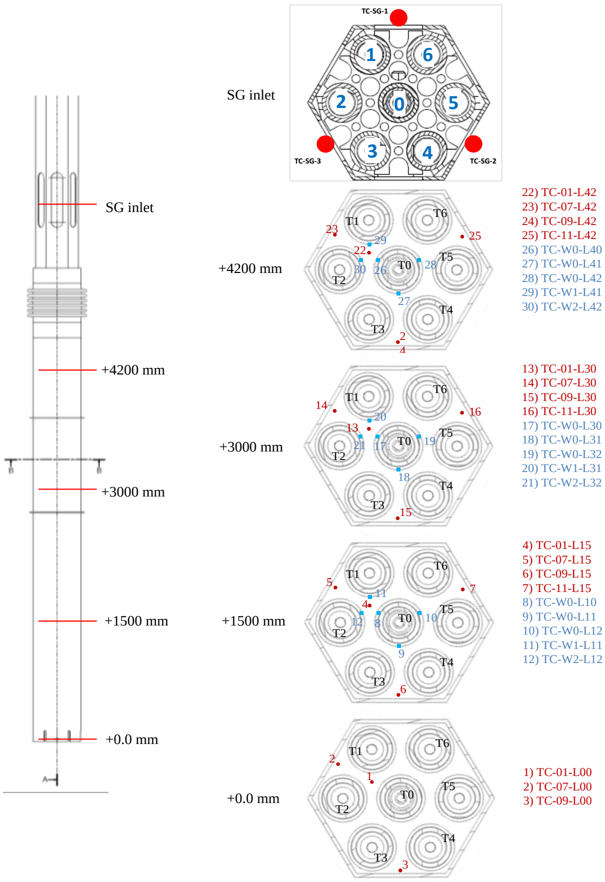

Fig. 4. Distribution of the thermocouples along the LBE side of the steam generator.

3. EUROfusion experimental campaign

A set of tests [4] has been designed for CIRCE facility in HERO configuration in order to achieve experimental data under working conditions relevant for the EU DEMO fusion reactor heat exchanger [3],[19]. The boundary conditions have been defined performing a preliminary numerical simulation activity using RELAP5-3D© Ver. 4.3.4 thermal-hydraulic system code [6],[19].

One of five tests has been selected and the results are hereinafter described and discussed. The selected test (EF-T1) is characterized by a secondary loop working pressure of 80 bar, a feedwater temperature of 280 °C and mass flow rate of ~0.31 kg/s. The feed water temperature of the secondary system, at the pre-heater outlet section has been set at 285°C, in order to achieve a water temperature at the SGBT inlet of ~280 °C. In the primary loop, the power supplied by the FPS has been regulated in order to assure a constant LBE inlet temperature in the HERO SGBT shell side of ~450 °C. The argon flow rate has been regulated in order to reproduce the values of LBE mass flow rate as close as possible to the designed conditions. The pressure of the helium line connected to the AISI316L powder gap has been maintained at ~8.0 bar. Tab. 1 reports the experimental boundary conditions, compared to the designed ones.

An experimental sensitivity analysis has been realized changing LBE mass flow rate. In particular staring from the initial value of ~38 kg/s (gas enhanced circulation regime), the LBE mass flow rate has been reduced in a total of 5 steps, managing the argon flow rate of the injection device, up to ~6/~8 kg/s (natural circulation regime), as reported in Tab. 1. During each step, all the working parameters are kept constant, achieving the steady state conditions, which are maintained for a time lapse of 20 minutes.

Table 1. EF-T1 boundary conditions: designed vs experimental

Parameter	Unit	Designed	Experimental
LBE m. flow rate	[kg/s]	40/33/27/ 20/10	37.5/31.5/ 26.0/20.0/9.0
LBE T_{in} SG	[°C]	450	454.2
H_2O m. flow rate	[kg/s]	0.31	0.33
H_2O T_{in} SG	[°C]	280	280.8
H_2O P_{out} SG	[MPa]	8.0	8.0

4. Experimental results

The LBE mass flow rate is measured by the Venturi Flow Meter located upstream the FPS and it is reported in Fig. 5. The initial value is about 37.5 kg/s, then the mass flow rate decreases reaching the values of 31.5 kg/s, 26.0 kg/s, 20.0 kg/s up to the final value of 9.0 kg/s, achieved in natural circulation regime, with the Ar gas injection system off. The maximum value of the LBE velocity is 0.48 m/s during the Steady State 1 (SS1), while the lowest is 0.12 m/s (SS5).

The experimental data of LBE temperatures in the HERO SGBT are reported in Fig. 6. At the inlet section the average temperature is about 454 °C. This value is evaluated averaging the temperature of two TCs (TC-SG-0X). At the SG outlet, the LBE temperature (TC-0X-L00) reaches the average value of 365 °C during SS1, then it decreases in the following steady states, accordingly with the reduction of the LBE mass flow rate, and reaching the final value of 306 °C. The average values of the outlet temperature are plotted for all SS as function of the mass flow rate in Fig. 7.

The complete LBE thermal field of the SG is reported in Fig. 8. The figure reports for each step the average values of the LBE experimental temperatures and the relative average value between temperatures measured by thermocouples. It is observed that, starting from SS1 to SS5, the temperatures are reduced due to the reduction of mass flow rate. The difference of temperature between inlet and outlet of the SG active length increases from SS1 (86.3 °C) to SS5 (148.7 °C).

The power removed by HERO is calculated through a thermal balance equation, considering the inlet mass flow rate measured by the Venturi Flow Meter and the difference of temperature between inlet and outlet section of the SG. The higher fraction of thermal power removed is achieved in SS1 (~465 kW), while the lower fraction is reached in SS5 (~200 kW). This implies that the power removed by each tube is in the range of 66.3 kW and 28.0 kW, at the specific test conditions with the secondary side set at 8.0 MPa.

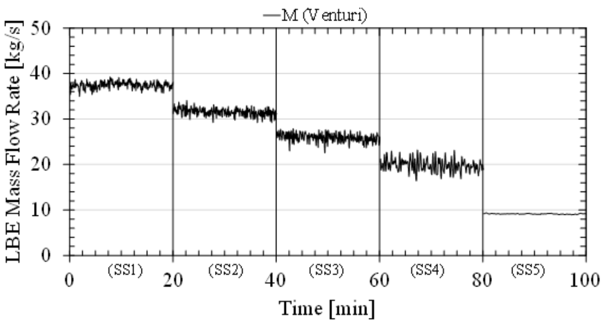

Fig. 5. EF-T1, LBE mass flow rate measured by Venturi flow meter.

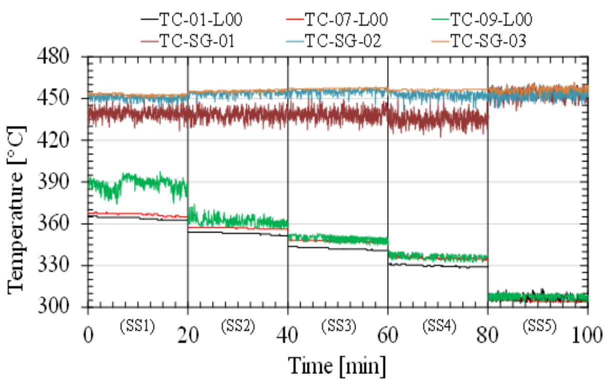

Fig. 6. EF-T1, LBE temperatures at the inlet section (TC-SG-0X) and outlet section (TC-0X-L00) of the Steam Generator

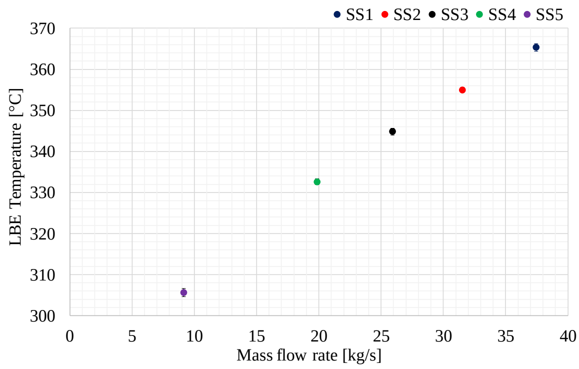

Fig. 7. EF-T1 LBE temperatures as function of mass flow rate for all Steady States

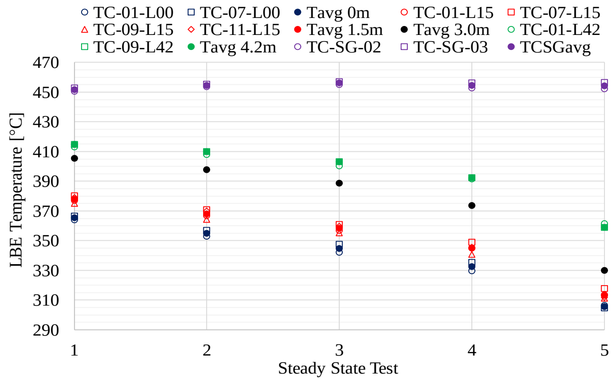

Fig. 8. EF-T1 LBE temperatures along the LBE side of the Steam Generator for all Steady States

5. Post-test analysis

A nodalization of the steam generator along with the secondary system has been realized using the System Thermal-Hydraulic (STH) code RELAP5-3D© v. 4.3.4, aiming at supporting the design and the realization of the secondary circuit and achieving information on the HERO SGBT performances [16]. The nodalization consists of a one-dimensional model with several pipes and junctions connected each other in such a way to build a truthful simulation of the different parts of the loop. The 7 double wall BTs are separately modelled. Each one is composed of one PIPE component, reproducing the descending slave tube, and of one ANNULUS component, simulating the annular region between first and second tubes.

A time dependent volume sets the water inlet conditions at the inlet section of the helical heater and a time dependent junction works instead of the pump setting the water mass flow rate. A time dependent volume defines the environment conditions of the air for the steam discharge at 10°C and atmospheric pressure. The LBE shell side of SGBT has been simulated with an equivalent PIPE; LBE inlet temperatures are set by a time dependent volume, while a time dependent junction fixes the LBE mass flow rate.

The division in volumes of the loop has been carried out in order to consider the correct position of the instrumentation located along the loop and the bulk and wall thermocouples in the HERO SGBT active length.

Concerning the heat structures, a thermal coupling has been simulated, between the annular riser of each bayonet tube and the equivalent LBE channel. The downcomer is assumed insulated with respect to the annulus and the manifold, and other pipelines are assumed insulated. A power source is introduced to simulate the water warm-up inside the helical heater, realizing a heating source set uniform along the pipe thickness and uniformly distributed along the pipe length. Standard RELAP5-3D liquid metals correlation is used for convective heat transfer for the bundle zone, see Ref. [20]. This correlation has been developed for fuel bundle of sodium fast reactor and has a range of applicability of the P/D from 1.05 to 1.4, where the best accuracy is up to 1.2. The P/D of HERO is equal to 1.42. This imply that the correlation tends to underestimate the convective heat transfer in the LBE side (about 20%).

The experimental data, reported in Tab.1, are assumed as initial conditions in the input deck for the simulation for each steady state test.

In order to evaluate the capability of RELAP5-3D code in simulating the thermal-hydraulic behavior of the HERO SGBT, the results of the numerical simulations have been compared with the experimental data, focusing on LBE side of the SG. In particular, Fig. 9 reports the average values of the temperatures measured by thermocouples during EF-T1 SS1 and the temperatures obtained with the numerical simulations. The figure is representative of the results achieved in all steady states of EF-T1. The results demonstrate that the code simulates correctly the thermal field of the LBE.

The experimental and numerical wall temperatures are reported in Fig. 10. It is observed that the code underestimates the wall temperatures: these discrepancies are probably due to the heat transfer correlations used by RELAP5-3D code. Moreover, as in the numerical model the LBE channel is simulated with an equivalent pipe, the resultant thermo-hydraulic behavior is the consequence of averaged values and do not reproduce the sub-channels effects. A further contribution to these differences could be found in the uncertainties related to the operative parameters during the test (e.g. water distribution among the 7 BTs, [21]), while the simulation assumes the same conditions at the inlet of the BTs.

Comparing Fig. 9 and Fig. 10 it is observed that, at +1500 mm and +3000 mm the wall temperature is ~10/20 °C lower than the LBE, as confirmed by numerical results. While, at +4200 there are two TCs (located on central tube) which measure a temperature similar to the LBE. This phenomenon could be justified by an unbalanced LBE flow distribution in the sub-channels.

The same simulation has been repeated, adopting the same thermal-hydraulic model and the same boundary conditions, using the modified version of RELAP5/Mod3.3 code [22][7], where fluid properties (i.e. Pb, LBE and PbLi) and related heat transfer correlations have been implemented. These are Ushakov and Mikytiuk correlations, which have been developed for heavy liquid metals as reported in [23].

The results of LBE and wall temperatures for test EF-T1 SS1 are reported in Table 2. The same table also reports the uncertainties (Exp. Un.) related to the performed measurements, calculated combining the standard deviations with the TCs uncertainties. The experimental values are compared with those obtained with RELAP5-3D.

The RELAP5/Mod3.3 code considers the LBE reference properties reported in [23], thus more accurate than those available in RELAP5-3D [6], moreover, the correlation used by the code for the heat transfer is suitable for the LBE.

Table 2. EF-T1 bulk and wall SG temperatures: experimental vs calculated

EF-T1 SS1	SG Length [mm]	Exp.	Exp. Un.	R5-3D	R5/Mod3.3
T LBE [°C]	+4200	414.9	±1.37	419.4	418.1
	+3000	405.3	±1.79	400.9	399.5
	+1500	377.8	±0.90	382.1	380.6
	Out	365.3	±1.71	367.0	365.5
T wall [°C]	+4200	405.9	±1.10	393.7	393.4
	+3000	390.4	±1.04	379.4	378.8
	+1500	367.6	±0.83	364.9	364.1

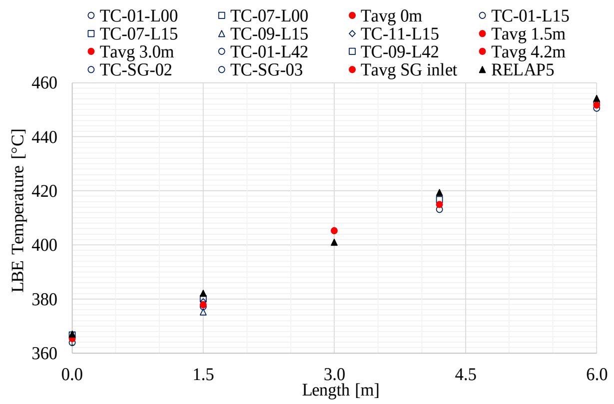

Fig. 9. EF-T1-SS1 LBE temperatures along LBE side of the SG: comparison between experimental data and R5-3D results.

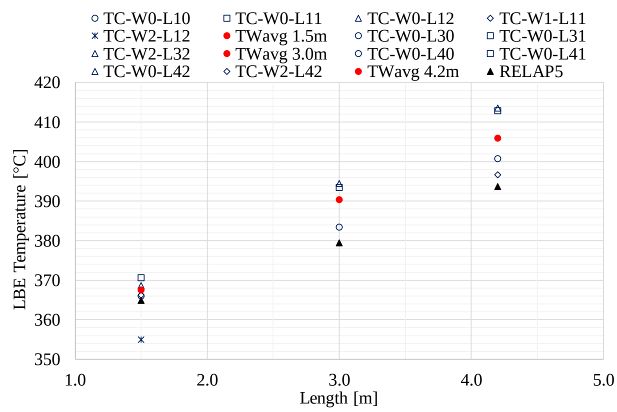

Fig. 10. EF-T1-SS1 wall temperatures: comparison between experimental data and R5-3D results.

6. PbLi as working fluid and comparisons with RELAP5-3D code results

The CIRCE experimental facility uses LBE as primary fluid. Heavy liquid metals (i.e. LBE, PbLi, Pb, etc.) rely on the same formulas of Nu number. This is also applicable in case of straight tubes bundle regions, such as HERO primary side geometry, where Mikityuk and Ushakov correlations are used. Therefore, the following it is possible to find a correspondence between the two fluids preserving the convective heat transfer (#1) and, both, the temperature difference and thermal power (#2).

Applying the method #2, the power and the temperature difference across the steam generator are preserved. In practice, the mass flow rate of the experiment is changed accounting for the thermo-physical differences between LBE and PbLi. The parameter considered in the transformation is the heat capacity. The re-calculated PbLi mass flow rate corresponding to the test data are 27.8, 24.2, 20.2, 15.2 and 7.0 kg/s. Results of the simulation are reported in Tab. 3. Absolute errors are in the range of 3.8 and 7.8 °C. Considering the differences between the thermo-physical proprieties of RELAP5-3D (i.e. c_p=180.5 J/kgK at 400°C) and the most up-dated values in Ref. [24] (i.e. c_p=187.8 J/kgK at 400°C), used for evaluating the equivalent PbLi mass flow rate, the differences expected in the code prediction of the outlet temperatures are in the range 4 - 6 °C. This implies that, if this contribution is neglected, the errors of code results become between -1.8 °C and 0.6 °C, consistent with the uncertainty of the experimental measurements.

Table 3. Experimental vs. RELAP5-3D results in case of PbLi applying the method #2

ID	W [kW]	MF_PbLi [kg/s]	Cp_PbLi [J/kgK]	Tin [°C]	EXP Tout [°C]	R5-3D Tout [°C]	Error [°C]
T1_SS1	464.4	27.8	187.8	454.2	*365.3*	360.1	**5.1**
T1_SS2	451.4	24.2	187.8	454.2	*355*	350.7	**4.2**
T1_SS3	414.8	20.2	187.8	454.2	*344.8*	340.9	**3.8**
T1_SS4	348.2	15.2	187.8	454.2	*332.6*	328.1	**4.4**
T1_SS5	196.1	7.0	187.8	454.2	*305.6*	297.7	**7.8**

7. Conclusions

In the frame of the EUROfusion BoP project, an experimental campaign was carried out to develop a PbLi/water heat exchanger capable to remove the nuclear heat deposited in the liquid metal of the DCLL BB. The test section selected for the experimental campaign is HERO SGBT developed by ENEA at Brasimone R.C. and installed in the main vessel of the CIRCE pool-type facility.

The aims of the research activity are: to investigate the thermal-hydraulic features of the system, improving the knowledge and the experience in terms of design and operations and providing a database for thermal-hydraulic system codes validation.

A set of five tests has been designed for CIRCE facility in order to achieve experimental data under working conditions relevant for the EU DEMO fusion reactor heat exchanger. One of the tests (EF-T1) has been selected and discussed in this paper.

During the experiment, the designed boundary conditions have been achieved, as well as the steady state conditions needed for testing the SG. In the primary side, the power supplied by the FPS to the LBE balanced the power removed by the SG and the heat losses from the CIRCE pool to the environment, maintaining the LBE SG inlet temperature as close as possible to the target values (discrepancy of ~4°C). The LBE mass flow rate in gas enhanced circulation regime has been performed thanks to the argon injection device, reaching the designed values in each SS. A small discrepancy can be found in SS1, where LBE mass flow rate achieved during the test is lower than the designed value (37.5 kg/s instead of 40 kg/s). In the secondary loop, the main components (i.e. volumetric pump, helical heater, regulation valves) have been managed in order to maintain the water conditions designed for the test.

The experimental results showed that the steam generator is capable to remove a high fraction of thermal power in gas enhanced circulation regime (~465 kW in SS1), as well as in natural circulation regime (~200 kW in SS5), providing an effective cooling of the CIRCE primary system. Considering the SGBT geometry, the power removed by each tube is in the range of 66.3 kW and 28.0 kW.

The experimental data were used to perform numerical post-test analyses using STH code RELAP5-3D© Ver. 4.3.4 and RELAP5/Mod3.3. The results demonstrate that the codes have the capability to simulate this kind of component. Slight discrepancies are observed between the two simulations. The results of RELAP5/Mod3.3 code are more accurate as it considers the reference LBE properties and the Ushakov convective heat transfer correlation.

It is possible to find a correspondence between LBE and PbLi preserving the temperature difference and thermal power. The differences expected in the code prediction of the outlet temperatures are in the range 4-6 °C, thus the errors of code results become between -1.8 °C and 0.6 °C.

Acknowledgments

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