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Development of a PbLi heat exchanger for EU DEMO fusion reactor: experimental test and system code assessment

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In the framework of the DEMO Work Package Balance of Plant of EUROfusion consortium, ENEA has been involved in experimental and numerical activities related to the development of a prototypical heat exchanger, suitable as steam generator for the lithium-lead loop of the Dual Coolant Lithium Lead and Water Cooled Lithium Lead breeding blankets. For this purpose, an experimental campaign has been executed on the pool-type liquid metal-cooled facility CIRCE at ENEA Brasimone Research Centre.

A dedicated test section named HERO has been designed and installed inside the main vessel of CIRCE. The innovative steam generator consists of a tube bundle with seven double walled bayonet tubes, fed with pressurized water. The selected configuration improves the plant safety, reducing the possibility of water-lead/lead-alloy interaction thanks to a double physical separation and allowing an easier control of eventual leakages from the coolant by pressurizing the separation region with inert gas.

A set of tests has been defined to demonstrate technological feasibility and performances of this prototypical steam generator, as well as the suitability of the component for the lithium-lead loop in DEMO. In particular, one of the performed tests is presented and discussed in this paper. The experiment is characterized by a secondary loop feedwater working pressure of 10 MPa and a steam generator inlet temperature of 300°C. On the primary side, the lead-bismuth eutectic has been used as working fluid with a steam generator inlet temperature of 480°C. During the test, an experimental sensitivity analysis on the primary coolant mass flow rate has been performed. Furthermore, the results of a post-test analysis realized with two versions of the system thermal-hydraulic code RELAP5 are presented, in order to evaluate their capability in simulating the performances of the component and to support the validation process of the codes for heavy liquid metal applications. The work is concluded presenting a scaling analysis to find the equivalence between LBE and PbLi, recalculating the available experimental data with RELAP5 code using PbLi as working fluid.

Keywords: DEMO, PbLi technologies, steam generator bayonet tube, RELAP5 code.

1. Introduction

Within the roadmap for the development of fusion technology, a significant effort has been undertaken for the realization of a DEMOnstration (DEMO) fusion reactor [1], having as final goal the production of electric power from nuclear fusion by the middle of this century [2].

In particular, within the frame of the DEMO Balance of Plant (BoP) tasks, a research activity has been addressed to the development of a Lithium Lead (PbLi)/water heat exchanger. The component has to be suitable for removing efficiently the thermal power from the PbLi system of the Dual Coolant Lithium Lead (DCLL) [3] Breeding Blanket (BB), generating at the same time superheated steam to feed the turbine for electricity production, as well as to be exploitable in the PbLi loop of the Water Cooled Lithium Lead (WCLL) BB [4].

For this purpose, the Steam Generator Bayonet Tube (SGBT) [5][6] has been selected as promising concept for the DCLL and WCLL PbLi systems. The key point of the SGBT is the enhanced safety, achieved thanks to the adoption of a double physical separation, by means of a double wall tube, between primary coolant (heavy liquid metal) and secondary coolant (water). This configuration allows to reduce the possibility of water-lead/lead-alloy interaction [7][8][9], as well as to make easier the detection and control of the leak occurrence by pressurizing with inert gas the gap region created inside the double wall tube.

In order to demonstrate the technological feasibility of the concept, a prototypical SGBT named HERO (Heavy Liquid mEtal pRessurized water cOoled tubes) [10] has been installed in a dedicated Test Section (TS) and implemented in the main vessel of the pool-type facility CIRCE (CIRColazione Eutettico) at the ENEA Brasimone Research Centre [10][11].

The HERO Steam Generator (SG) is an experimental mock-up, consisting of a bundle with seven double-wall bayonet tubes with a leakage monitoring system. The component has been involved in dedicated experimental campaigns aiming at investigating its thermal-hydraulic performances, as well as to create an experimental database suitable for the validation and verification process of numerical tools. One of the experimental tests executed is introduced and described in this paper. The HERO SG has been operated by a feedwater working pressure of 10 MPa and an inlet temperature of 300°C,

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accordingly with the DEMO SGBT operating conditions proposed in [12][13]. The PbLi thermal cycle foreseen for the DCLL BB SG is 535-300°C. In the CIRCE primary system, the SG inlet temperature of the Lead-Bismuth Eutectic (LBE), used as primary working fluid, was set at 480°C, corresponding to the maximum LBE temperature allowed. During the test, an experimental sensitivity analysis on the primary coolant mass flow rate has been performed.

A numerical post-test analysis has been carried out comparing the experimental data with a numerical simulation performed by means of a 1-D model of the HERO SG using two version of RELAP5: the RELAP5-3D© Ver. 4.3.4 code [14] and a modified version of RELAP5/Mod3.3 [15][16] which includes the heavy liquid metals as working fluids. The simulation aimed at evaluating the code capabilities in predicting thermal-hydraulic performances of the component, and to characterize the heat transfer in liquid metal side, supporting the validation process for fusion applications. Finally, a scaling analysis has been performed to find the equivalence between LBE and PbLi, recalculating the available experimental data with RELAP5 code using PbLi as working fluid.

2. HERO Steam Generator

HERO is an experimental mock-up devoted to investigate the thermal-hydraulic performances of a SGBT in nuclear applications involving heavy liquid metals as primary coolant. The component has been tested in a large range of operative conditions representative of the most-updated configurations of fission power plants (i.e. ALFRED, MYRRHA) [17][18] and fusion reactors (i.e. DEMO) [5][6]. The experimental results have been used also in support of validation activities for SYS-TH codes [19][20][21] and coupled SYS-TH/CFD codes [22].

The technical draw of HERO SGBT unit is depicted in Fig. 1, which also shows the bayonet tube bundle extracted from the hexagonal shell. The SGBT is composed of:

- a top flange, sustaining the helium chamber, the steam chamber, the bayonet tubes and the hexagonal shroud;
- the helium chamber, for pressurising the stainless steel powder gap with inert gas;
- the steam chamber, above the helium chamber, collecting the steam arising from the bayonet tubes;
- the tube bundle, composed by 7 bayonet tubes with an active length of 6000 mm, arranged in a hexagonal shell with a triangular pitch.

Each Bayonet Tube (BT) is composed of four coaxial tubes, as represented in Fig. 2: the feedwater flows downward through the slave tube, then it rises through the annular region between the first and second tube, where the steam is produced. A first gap between slave and first tube is filled by air as insulator in order to avoid steam condensation. The gap between second and third tube is pressurized with helium at ~8 bar to detect any leakages and it is filled by AISI316L powder to maintain a good heat exchange capability.

The HERO SG unit is fed by pressurized water (up to 18 MPa) by means of a dedicated once-though secondary loop [23]. Upward the BTs, the loop is equipped with a demineralizer, a volumetric pump, a helical heating system and a manifold. Downward, a discharge line allows the exit of the steam produced by the SG. Moreover, a bypass line is used for the start-up phase and a helium line, for pressurizing the stainless steel powder gap of bayonet tubes at ~8 bar.

The SGBT is hydraulically connected with the LBE circulating in the primary system by means of six holes on the SG hexagonal shell, allowing the primary coolant inlet. LBE flows downwards through shell side up to the SG outlet section about 6000 mm below. The LBE is heated up to the working temperature by means of an electrically heated Fuel Pin Simulator (FPS) and it flows in natural circulation, thanks to the different heights of the thermal barycenters of FPS and SGBT, or in gas-enhanced circulation promoted by a dedicated argon injection system. Further details on the CIRCE facility design can be found in [23].

Concerning the instrumentation, both primary and secondary systems are instrumented for monitoring and control of the facility operation, as well as to acquire the experimental data during the tests. Each component is instrumented with thermocouples located at the inlet and outlet sections (e.g. fitting volume, riser, separator). In particular, the FPS and the SGBT shell side are instrumented by bulk TCs and wall TCs, positioned at the inlet/outlet sections and at different elevations for a better monitoring of the temperatures along their active lengths [18]. For the purposes of this paper it is worth to recall in detail the instrumentation of the HERO SGBT, which is depicted in detail in Fig. 3 (shell side). On the secondary side, water temperature is monitored at the BTs inlet and outlet, as well as at the steam chamber exit, where three TCs are positioned to detect possible condensation and radial stratification.

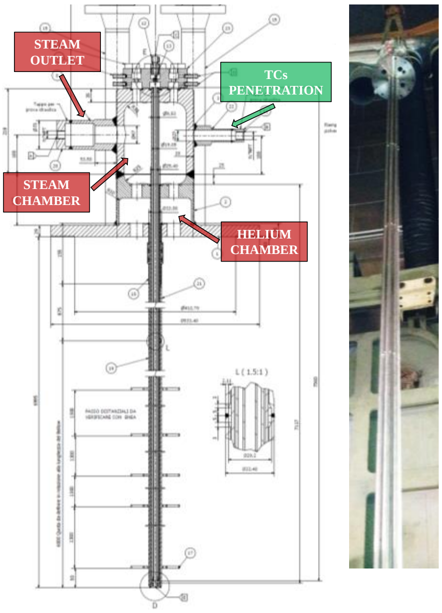

Fig. 1 – Technical drawing of HERO SGBT unit

The LBE mass flow rate is measured with a Venturi Flow Meter installed upstream the FPS, while the water mass flow rate is measured upstream the BTs with a Coriolis Flow Meter and with seven mini-turbine flow meters installed on each of the seven feeding tubes. Further details on the instrumentation installed on the primary and secondary systems are reported in [23].

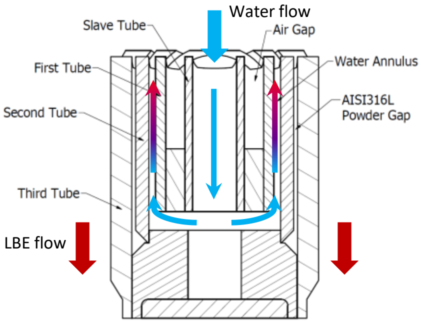

Fig. 2 – Bayonet tube geometry

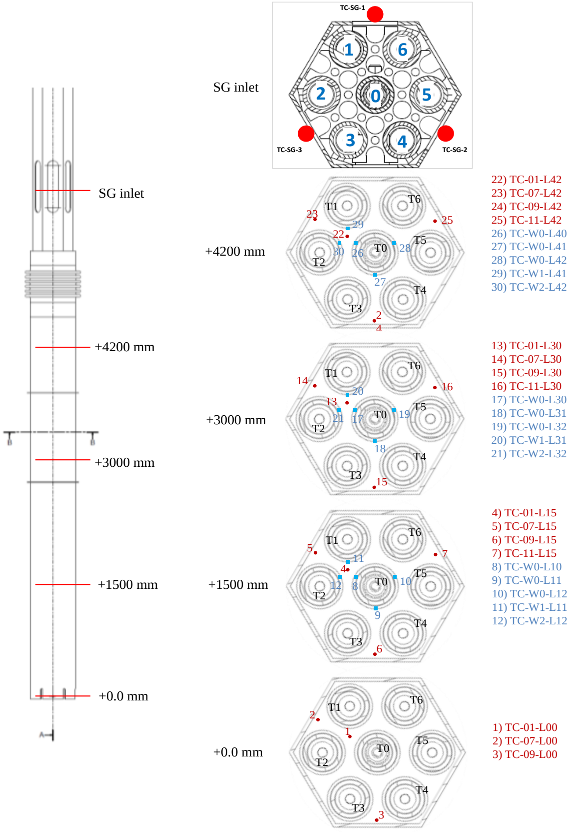

Fig. 3 – Distribution of the thermocouples along the LBE side of the steam generator

3. EUROfusion experimental test

3.1. Test description

An experimental campaign consisting of five tests has been designed for the CIRCE facility [6][24] in order to characterize from a thermal-hydraulic point of view the HERO SGBT under working conditions relevant for the EU DEMO fusion reactor heat exchanger. For this purpose, a numerical pre-test analysis has been performed using RELAP5-3D© Ver. 4.3.4 thermal-hydraulic system code, aiming at defining the boundary conditions of the experimental tests [12][13].

The present paper describes the results of the EUROfusion test 2 (EF-T2) [5]. The experiment is characterized by a secondary loop operative pressure of 10 MPa and a feedwater SG inlet temperature of ~295°C. The water mass flow rate is set at ~0.33 kg/s. On the primary side, the LBE enters the SG shell side at ~483°C. During the test an experimental sensitivity analysis changing LBE mass flow rate has been performed, regulating opportunely the argon injection. The mass flow rate is reduced in five steps, passing from the initial value of ~38 kg/s (gas enhanced circulation regime), up to ~8 kg/s (natural circulation regime), as reported in Tab. 1. The pressure of the helium line connected to the AISI316L powder gap has been maintained at ~8.0 bar. During each step, all the working parameters are kept constant, achieving the Steady State (SS) conditions, which are maintained for a time lapse of

20 min.

Parameter	Unit	Designed	Experiment
LBE m. flow rate	[kg/s]	40/33/27/ 20/10	38/32/28/ 21/8
LBE T_{in} SG	[°C]	480.0	483.0
H_2O flow rate	[kg/s]	0.31	0.33
H_2O T_{in} SG	[°C]	300.0	295.2
H_2O P_{out} SG	[MPa]	10.0	10.0

Tab. 1 – EF-T2 main parameters, designed vs experimental

3.2. Experimental results

In the following the experimental results are reported in terms of mass flow rates and temperatures across the HERO SG. The LBE mass flow rate, measured by the Venturi Flow Meter, is reported in Fig. 4 for each SS. The higher value is achieved in SS1 with 38 kg/s, then it decreases reaching the values of 32 kg/s (SS2), 28 kg/s (SS3), 21 kg/s (SS4) up to the final value of 8 kg/s in SS5, achieved in natural circulation regime (Ar gas injection system disabled). The corresponding LBE velocities across the SG shell side are in the range between 0.5 m/s (SS1) and 0.1 m/s (SS5), coherent with the PbLi velocities expected in the DCLL BB PbLi loop.

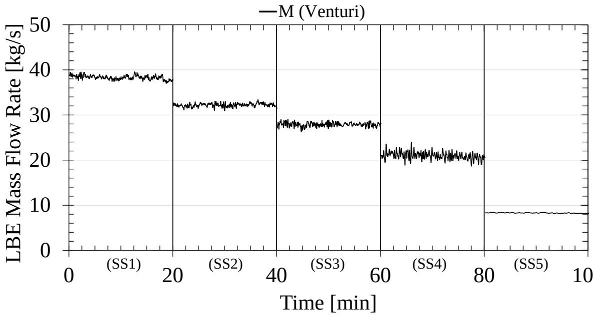

Fig. 4 – LBE mass flow rate achieved during EF-T2

Concerning the LBE temperatures, Fig. 5 shows their trends in the five SSs. At the inlet section the average temperature is kept constant at about 483 °C, obtained averaging the temperature of two TCs (TC-SG-02/03), while the temperature measured by TC-SG-01 is not considered, since it 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. At the SG outlet, the LBE temperature (TC-0X-L00) changes coherently with the LBE mass flow rate variations, passing from a maximum value of ~390°C in SS1 to a minimum of ~320°C in SS5.

Fig. 6 shows in detail the complete LBE thermal field in the SG shell side. For each SS, the LBE temperatures at different SG shell levels are reported. For each level, the values are obtained averaging the measurements of the TCs installed on the corresponding level, accordingly with the TCs distribution reported in Fig. 3. It can be observed that, starting from SS1 to SS5, the temperatures are reduced due to the decrease of the primary mass flow rate. The temperature difference between SG inlet and outlet sections increases from SS1 84.2 °C in SS1 to 162.5 °C in SS5.

Applying the thermal balance equation and referring to the most-updated LBE properties reported in [25], it is possible to calculate the thermal power removed by HERO, using the LBE mass flow rate and temperatures reported in Fig. 4 and Fig. 5. The higher fraction of thermal power removed is achieved in SS1 (~521 kW), while the lower fraction is reached in SS5 (~200 kW). The specific power removed by each tube is in the range of 74.4 kW and 28.5 kW.

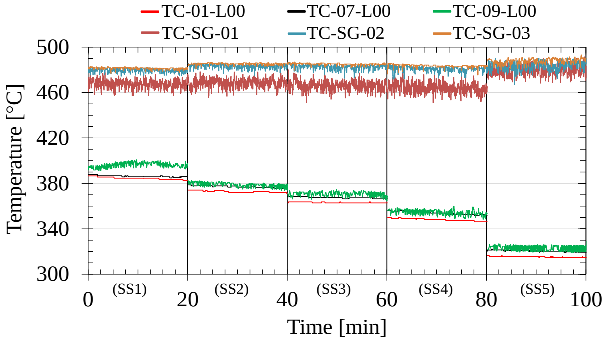

Fig. 5 – LBE SG inlet and outlet temperatures during EF-T2

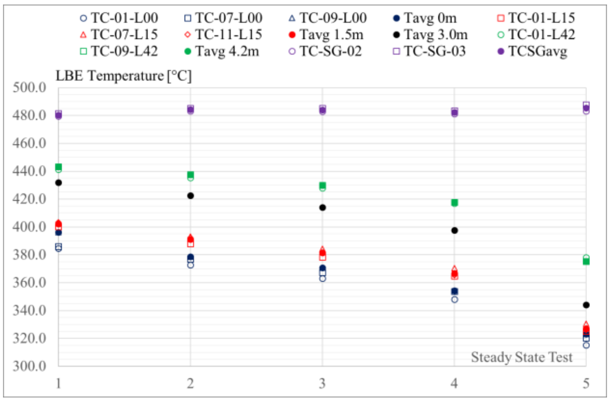

Fig. 6 – LBE temperatures along the LBE side of the SG during EF-T2.

Fig. 7 reports the water temperatures at the inlet section of the bayonet tubes (TC-TX-I) and at the outlet section of the steam chamber (TC-L3-X). The inlet temperature is maintained constant during each SS at about 295°C (small difference of ~1/~2°C) The temperature is almost constant also at the outlet temperature, reaching the value of ~311/~312°C, close to the saturation temperature at the working pressure of 10 MPa. This result proves that under the operating conditions defined above, the steam generator works producing steam close to the saturation conditions.

In a two-phase flow system, it is possible to evaluate the thermo-dynamic quality x_t based on a balance between the specific enthalpy of the liquid and of the steam, respectively, as shown in Eq. (1):

$$x_t = \frac{\bar{h}-h_l}{h_v-h_l} \qquad (1)$$

where $\bar{h}$ is the average specific enthalpy of the mixture liquid/steam, h_v is the enthalpy of the steam in saturation conditions at the pressure of the system and h_l is the enthalpy of the liquid water in saturation conditions at the pressure of the system. Since the feedwater inlet conditions (pressure and temperature) are measured during the experiment, h_l and h_v are known, while $\bar{h}$ can be calculated applying the thermal balance equation, considering the thermal power removed from LBE and the feedwater flow rate. The thermo-dynamic quality x_t is reported in Fig. 8. The higher values are achieved in SS1 and SS2, where x_t is slightly above 1.0, indicating the complete vaporization of the water, with a slight superheating. Also SS3 is characterized by a complete vaporization (x_t ~1.0), while in SS4 and SS5 the thermo-dynamic quality is ~0.85 and ~0.4, respectively.

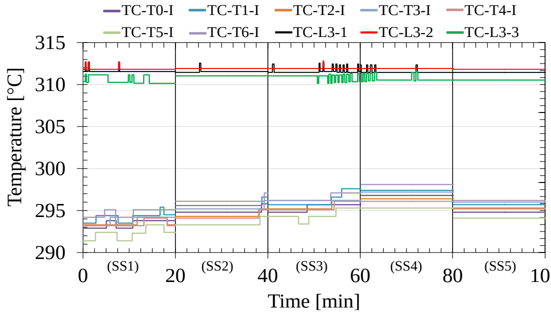

Fig. 7 – H2O temperatures at the inlet section of the bayonet tubes (TC-TX-I) and at the outlet section of the steam chamber (TC-L3-X) during EF-T2

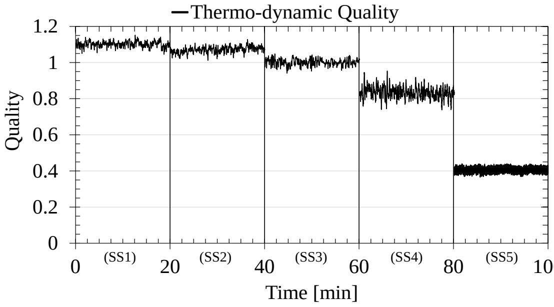

Fig. 8 – Thermo-dynamic quality of the steam produced at the outlet section of the HERO SGBT in EF-T2

4. Post-test analysis

4.1. RELAP5 model

The post-test analysis has been carried out by two versions of the RELAP5 thermal-hydraulic system code: the standard version of RELAP5-3D© Ver. 4.3.4 [14] and a modified version of RELAP5/Mod3.3 [26], which has implemented the fluid properties of Pb, LBE and PbLi and three heat transfer correlations for heavy liquid metals [27][28][15]: Seban-Shimazaki (used for non-bundle geometry) and Ushakov and Mikityuk (used for bundle geometries).

Fig. 9 shows the numerical 1-D model of the HERO SG, which has been extrapolated from the full nodalization of the CIRCE secondary loop [29]. The nodalization consists of 823 hydrodynamic volumes, 827 junctions, 287 heat structures and 3731 heat transfer nodes. The size of the hydrodynamic nodes is comprised between 0.15 m and 0.2 m. In particular, the main components reproduced are:

- the manifold, reported in red in Fig. 9, composed by pipe 214 and branch 218 simulating the distribution zone of the manifold with the seven pipes (from 219 to 225) connected to the SGBT tubes inlet (one for each SG inlet);
- the HERO steam generator bayonet tube, modelled tube by tube for a total 672 volumes. The 7 downcomers have been modelled with 7 pipe components while the 7 annular regions have been modelled with 7 annulus components;
- the discharge line consisting of: branch 150 which simulates the steam chamber, valve 166 for the pressure regulation along the secondary loop and the discharge pipeline (pipes 163, 165, 167).

The time dependent volume (TMDPVOL) 201 sets the water inlet conditions (taken from Tab. 1) upstream the manifold and the time dependent junction (TMDPJUN) 202 acts as a pump providing the mass flow rate, while TMDPVOL 171 defines the environment conditions of the air for the steam discharge (10°C and atmospheric pressure).

The LBE side has been simulated with an equivalent channel (pipe 403); the TMDPVOL 401 sets the LBE inlet temperature and TMDPJUN 402 fixes the LBE mass flow rate, while the TMDPVOL 405 represents the LBE outlet.

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 thermal structures, the seven downcomers of each bayonet tube have been assumed thermally insulated (adiabatic) respect to the annular region, such as the manifold and other pipelines. A thermal connection has been simulated between the annulus of each bayonet tube and the equivalent LBE channel by means of seven heat structures reproducing the second and third tube of the bayonet tubes, including the AISI316L+He stainless steel powder gap.

For the heat transfer in the shell side of the HERO tube bundle zone, the Westinghouse correlation [30][31] is used in RELAP5-3D, which is its standard convective heat transfer correlation for heavy liquid metals in vertical bundle geometry, while the Ushakov correlation is used in RELAP5/Mod3.3.

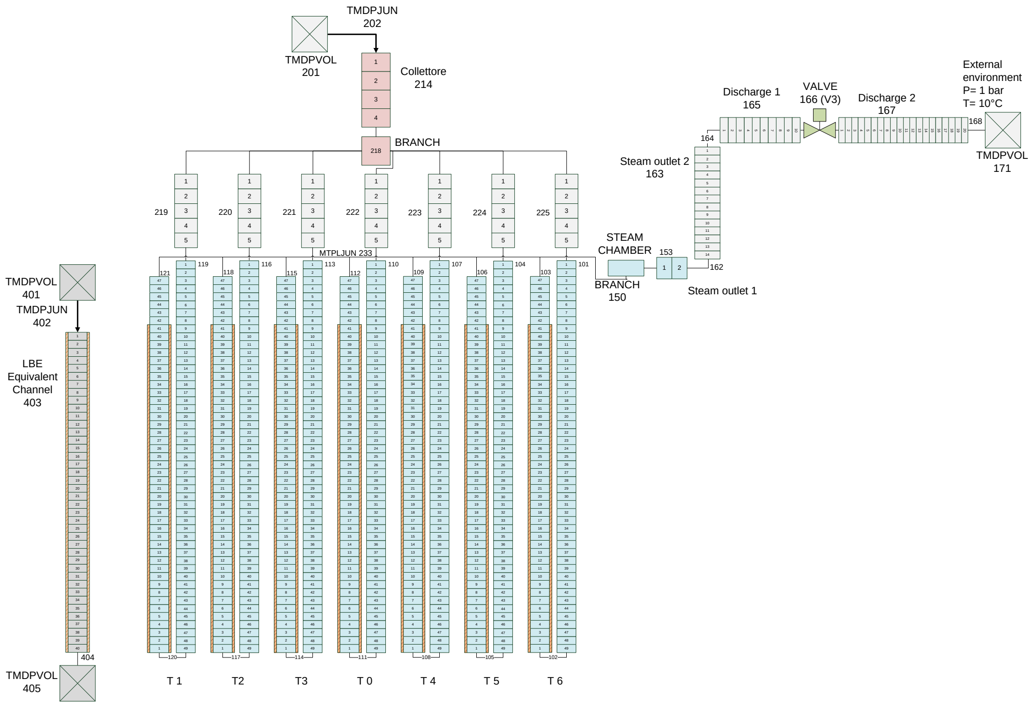

Fig. 9 – RELAP5 nodalization

4.2. RELAP5 results

The simulation results of the EF-T2 obtained with RELAP5-3D© Ver. 4.3.4 are reported in Fig. 10 and Fig. 11, in terms of LBE and tube wall temperatures during SS1. The same parameters are summarized, Tab. 2, comparing the experimental results with the numerical ones obtained with RELAP5-3D© Ver. 4.3.4 and RELAP5/Mod3.3. For completeness, the uncertainties (Exp. Un.) related to the experimental measurements are reported. The temperature average values are computed level by level, obtained averaging the measurements acquired by the TCs positioned at the same level, while the uncertainties related to the performed measurements, are calculated combining the standard deviation of the measured variable with the instrument uncertainty, according to the method reported in [32]:

$$\sigma^2_{X_i} = \hat{\sigma}^2_{X_i} + \sigma^2_{X_{i,Instr.}} \qquad (2)$$

where $\hat{\sigma}_{X_i}$ is the standard deviation of the variable X_i and $\sigma_{X_{i,Instr.}}$ is the uncertainty of the instrument. The results demonstrate that there is a good agreement between the two codes and with the experimental data, in particular as regard LBE bulk temperature (Fig. 10), proving that the codes simulates well the thermal field of the LBE. Small discrepancies of ~0.5°C/~1.5°C between codes can be observed, due to the different heat transfer correlations used and the fact that the RELAP5/Mod3.3 code considers the LBE reference properties reported in [25], which are updated respect to those available in RELAP5-3D [14].

As regard the experimental acquisitions of the wall temperatures (Fig. 11), at +1500 mm and +3000 mm they are ~10/~15°C lower than the LBE sub-channel temperatures. At the section +4200m there are two TCs (located on the central tube) which measure a wall temperature similar to the LBE sub-channel temperature. This behaviour could be due to an unbalanced LBE flow distribution in the sub-channels.

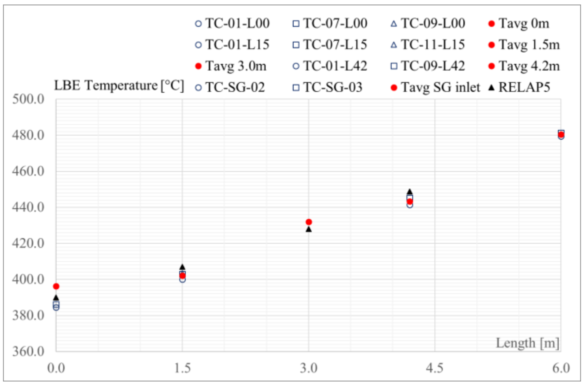

Fig. 10 – LBE temperatures along SG active length during EF-T2 SS1: simulation vs experiment

A difference between LBE bulk and wall temperatures is also predicted by the two codes, but it is observed that the wall temperatures are underestimated respect to the experimental ones. Such discrepancies could be addressed to the modelling approach which foresees the representation of the LBE channel by means of an equivalent pipe. The resultant thermo-hydraulic behaviour is the consequence of averaged values and it could not reproduce the sub-channels effects. Further contribution to the discrepancies could be due to the uncertainties of the operative parameters during the test (e.g. LBE flow rate distribution in the sub-channels, water distribution among the 7 BTs [20]).

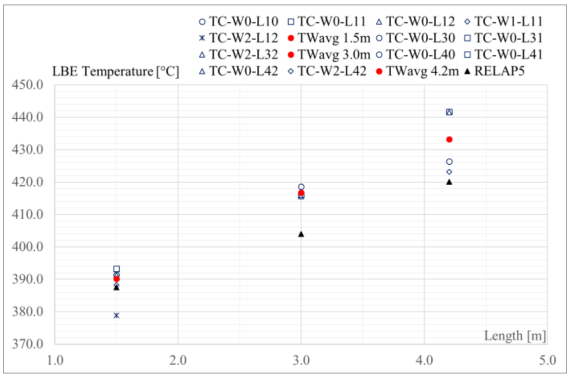

Fig. 11 – LBE temperatures along SG active length during EF-T2: simulation vs experiment

EF-T2 SS1	SG Length [mm]	Exp.	Exp. Un.	R5-3D	R5/Mod 3.3
T LBE [°C]	+4200	443.3	±1.42	448.9	448.3
	+3000	431.9	±2.17	428.1	427.1
	+1500	402.2	±1.13	407.0	405.7
	Out	389.0	±1.17	390.1	388.7
T wall [°C]	+4200	432.3	±1.44	420.1	420.3
	+3000	416.8	±1.21	404.0	403.8
	+1500	390.2	±0.89	387.6	387.1

Tab. 2 – Bulk and wall SG temperatures in EF-T2 SS1: experimental vs calculated

Uncertainty can be also found in the thermal conductivity of the HERO double wall gap filled with stainless steel powder + He. Dedicated experimental campaigns performed at ENEA Brasimone R.C. [33] highlighted that the steel powder thermal conductivity is a function of the temperature and it is influenced by different factors, i.e. the grain size and growth, powder compaction, thermal cycling. Experimental sensitivity analysis on such parameters has been performed and experimental correlations have been derived [34]. The correlations reported in [34] have been taken as reference for the simulations, since they have been the used during the design phase of the HERO SGBT.

Finally, there is the eventuality that LBE coolant might have formed compounds along the HERO tube bundle. These compounds attached to the external face of the tubes could cause an additional thermal resistance [35] which could enhance the differences between the experimental results and code simulations. Nevertheless, this hypothesis can be verified only during the next refurbishment of the facility, with the visual examination of the HERO tube bundle.

The results reported in Fig. 10, Fig. 11 and Tab. 2 are representative of the results achieved in all steady states of EF-T2.

Concerning the simulation of the secondary loop, Tab. 3 reports the comparison between the thermodynamic quality experimentally evaluated and the one calculated by the codes. It can be noticed that for all the SSs the numerical results are very close to the experimental ones.

EF-T2	Exp.	R5-3D	R5/Mod3.3
SS1	1.10	1.14	1.14
SS2	1.07	1.06	1.05
SS3	1.00	0.98	0.98
SS4	0.83	0.84	0.83
SS5	0.41	0.41	0.42

Tab. 3 – Thermo-dynamic quality of the steam produced: experimental vs. calculated

5. Scaling analysis in case of PbLi as working fluid

The experimental and numerical investigation reported above is completed with an analysis on the equivalence between the LBE (used in CIRCE) and the PbLi (foreseen in the PbLi loops of DCLL BB and WCLL BB). It is highlighted that both fluids (and heavy liquid metals in general) rely on the same formulations 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, it is possible to find a correspondence between the two fluids preserving the convective heat transfer (method #1) [5] and, both, the temperature difference and thermal power (method #2) [6].

In the following, the method #1 is applied. This method maintains the same conditions of convective heat transfer across the active length of the SG preserving the Nusselt number. This condition can be satisfied changing the experimental mass flow rate, taking into account the thermo-physical differences between LBE and PbLi. The reference parameter to apply this method is the Peclet number. First of all, the Peclet number has been evaluated from the available experimental data. In particular, the LBE density, heat capacity and thermal conductivity are calculated on the basis of the LBE average temperatures and accordingly with the correlations reported in [25]. The same parameters (density, heat capacity and thermal conductivity) are also calculated considering the PbLi as working fluid. Assuming the same values of Pe, it is possible to recalculate the equivalent theoretical PbLi mass flow rate as reported in Tab. 4.

A new RELAP5-3D run is set, using the same model described in Section 4.1 and running the calculation using the PbLi as working fluid. Results of the simulation are reported in Tab. 5, in which the experimental and R5-3D Nusselt number are compared. The Nu has been calculated with the heat transfer correlation used for liquid metals in a rod bundle (Kazimi and Carelli, 1976):

$$\mathrm{Nu} = 4.0 + 0.33(\mathrm{P/D})^{3.8}(\mathrm{Pe}/100)^{0.86} + 0.16(\mathrm{P/D})^{5} \qquad (2)$$

where P/D is the pitch-to-diameter ratio (in HERO geometry, p/d=1.42) of the rods and Pe is the Peclet number. From the comparison between the experimental and calculated values, it can be seen that the errors are in range of 24.1% and 38.2%. These discrepancies can be due to the uncertainty related to the use of Eq.(2) for the calculation of Nu and to the differences between the thermo-physical proprieties of RELAP5-3D (i.e. cp=180.5 J/kgK at 400°C) and the most up-dated values [36] (i.e. cp=187.8 J/kgK at 400°C). Neglecting the contribution of the fluid properties, the errors decrease in range of 15.7% and 28.7%.

ID EF-T2	mf LBE [kg/s]	v LBE [m/s]	Pe LBE	mf PbLi [kg/s]	v PbLi [m/s]
SS1	38	0.50	1367	32.0	0.43
SS2	32	0.41	1158	27.1	0.36
SS3	28	0.36	1019	23.8	0.32
SS4	21	0.27	770	18.0	0.24
SS5	8	0.10	299	7.0	0.09

Tab. 4 – Correspondence between LBE and PbLi according with Method 1

ID EF-T2	W [kW]	Mf PbLi [kg/s]	Pe PbLi	EXP Nu	R5-3D Nu	Error
SS1	521.0	32.0	1367	16.78	20.84	24.1%
SS2	504.7	27.1	1158	15.20	19.79	30.1%
SS3	474.2	23.8	1019	14.13	18.46	30.6%
SS4	395.3	18.0	770	12.16	16.04	31.8%
SS5	199.4	7.0	299	8.13	11.24	38.2%

Tab. 5 – Equivalence to PbLi, preserving the Peclet number and Nusselt number: experimental vs. RELAP5-3D results

6. Conclusions

Within the roadmap for the development of DEMO, a research activity has been addressed to the development of a PbLi/water heat exchanger capable to remove efficiently the thermal power from the DCLL BB and for the PbLi loop of the WCLL BB. An experimental and numerical investigation has been performed involving the HERO SGBT at ENEA Brasimone R.C. with the aim of investigating the thermal-hydraulic features of the component, improving the knowledge and the experience in terms of design and operations and providing a database for thermal-hydraulic system codes validation.

The paper describes one of the five characterization tests to which the HERO SGBT has been involved in the pool-type LBE-cooled facility CIRCE. During the experiment (EF-T2), the LBE conditions in the primary system and the water conditions in the secondary loop have been managed to be relevant for the EU DEMO fusion reactor heat exchanger: the SG has been fed with a water mass flow rate of ~0.33 kg/s, at 10 MPa and 295°C, while the LBE temperature at the SG inlet has been kept at about 483°C. The LBE mass flow rate has been changed opportunely in order to assume five different values during the test, from 38 kg/s (forced circulation) to 8 kg/s (natural circulation), achieving for each value a steady state condition in both primary and secondary systems.

The experiment showed that the component is capable to remove a relevant fraction of thermal power in gas enhanced circulation regime (~521 kW in SS1, 74.4 kW/tube), as well as in natural circulation regime (~200 kW in SS5, 28.5 kW/tube), producing high quality steam (SS1, SS2 and SS3) and proving that the SGBT concept is suitable for the DEMO purposes.

The analysis has been supported by numerical post-test using the thermal-hydraulic system codes RELAP5-3D© Ver. 4.3.4 and RELAP5/Mod3.3. The comparison of the results with the experimental data showed a good capability of the two codes to reproduce the thermal-hydraulic performances of the component. An underestimation has been observed for the SGBT wall temperatures calculated by the codes. Possible reasons of such discrepancies could be found in the model set-up which is not capable to reproduce the LBE sub-channel effects, as well as on the uncertainty related to the thermal conductivity assumed for the powder+He gap, which is influenced by different factors (i.e. the grain size and growth, powder compaction, thermal cycling) during the HERO SGBT operation. Furthermore, the eventual formation of LBE compounds around the external wall of HERO tubes and the consequent increase of thermal resistance has been also identified as possible reason of such discrepancies. Verification of this last hypothesis will be made when the HERO SGBT will be dismantled.

Finally, a correspondence between LBE and PbLi has been found, applying a scaling method which maintains the same conditions of convective heat transfer across the active length of the SG preserving the Nusselt number. The PbLi mass flow rates are re-calculated by scaling them from the LBE ones. Comparing the experimental and calculated values, it can be seen that the errors are in the range of 24.1% and 38.2%. These discrepancies can be due to the uncertainty related to the correlation used by RELAP5-3D for the calculation of Nu and to the differences between the thermo-physical proprieties of RELAP5-3D and the most up-dated ones. Neglecting this last contribution, the errors decrease in range of 15.7% and 28.7%. The analysis performed allows to make experimental data of heat transfer achievable in LBE also suitable for PbLi, since the two fluids rely to the same formulation of heat transfer correlations.

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References

[1] Boccaccini, L.V., et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Engineering and Design 109-111 (2016) 1199-1206. DOI 10.1016/j.fusengdes.2015.12.054.

[2] Donné, T., et al., European Research Roadmap to the Realisation of Fusion Energy, EUROfusion, 2018, ISBN 978-3-00-061152-0.

[3] Rapisarda, D., et al., Status of the engineering activities carried out on the European DCLL, Fusion Eng. Des., 124 (2017), pp. 876-881.

[4] Del Nevo, A., et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Engineering and Design, Volume 146, Part B, 2019, Pages 1805-1809, https://doi.org/10.1016/j.fusengdes.2019.03.040.

[5] Lorusso, P., et al., PbLi Heat Exchanger and fluid technology - As built PbLi/H2O HX test facility report, EUROfusion Internal Deliverable BOP-4.1.1-T002, Sept. 2019.

[6] Martelli, E., et al., Investigation of heat transfer in a steam generator bayonet tube for the development of PbLi technology for EU DEMO fusion reactor, Fusion Eng. Des. 159 (2020) 111772, https://doi.org/10.1016/j.fusengdes.2020.111772.

[7] Eboli, M., et al., Experimental activities for in-box LOCA of WCLL BB in LIFUS5/Mod3 facility, Fusion Eng. Des., 146 (2019), pp. 914-919. https://doi.org/10.1016/j.fusengdes.2019.01.113.

[8] Di Maio, P. A., et al., Thermal-hydraulic and thermo-mechanical simulations of Water-Heavy Liquid Metal interactions towards the DEMO WCLL Breeding Blanket design, Fusion Eng. Des., 146 (2019), pp. 2712-2716. https://doi.org/10.1016/j.fusengdes.2019.04.093.

[9] Eboli, M., et al., Simulation study of pressure trends in the case of loss of coolant accident in Water Cooled Lithium Lead blanket module, Fusion Eng. Des., 98–99 (2015), pp. 1763–1766. https://doi.org/10.1016/j.fusengdes.2015.05.034.

[10] Pesetti, A. et al., ENEA CIRCE-HERO test facility: geometry and instrumentation description, ENEA report CI-I-R-343, June 2018.

[11] Tarantino, M., et al., Fusion Technologies Development at ENEA Brasimone Research Centre: Status and Perspectives, Fusion Engineering and Design 160 (2020) 112008, https://doi.org/10.1016/j.fusengdes.2020.112008.

[12] E. Martelli, et al., DEMO BoP – LiPb heat exchanger and fluid technology, EUROfusion Internal Deliverable BOP-4.1.1-T001 (2019) April.

[13] Narcisi, V., et al., Steam Generator mock-up preliminary design suitable for Pb-Li technology demonstration and code assessment, Fusion Eng. Des 146 (2019) 1126–1130, https://doi.org/10.1016/j.fusengdes.2019.02.022.

[14] RELAP5-3D© Code Manual, The RELAP5-3D Code Development Team, INEEL-EXT-98-00834, 2013.

[15] Martelli, E., et al., Thermal-hydraulic modeling and analyses of the water-cooled EU DEMO using RELAP5 system code, Fusion Eng. Des., 146 (2019), pp. 1121-1125. https://doi.org/10.1016/j.fusengdes.2019.02.021.

[16] Martelli, E., et al., Study of EU DEMO WCLL breeding blanket and primary heat transfer system integration, Fusion Eng. Des., 136 (2018), pp. 828-833. https://doi.org/10.1016/j.fusengdes.2018.04.016.

[17] Lorusso P., et al., Experimental Analysis Of Stationary And Transient Scenarios Of ALFRED Steam Generator Bayonet Tube In CIRCE-HERO Facility, Nuclear Engineering and Design 352 (2019) 110169, https://doi.org/10.1016/j.nucengdes.2019.110169.

[18] Lorusso, P., et al., MYRRHA primary heat exchanger experimental simulations on CIRCE-HERO, Nuclear Engineering and Design 353 (2019) 110270, https://doi.org/10.1016/j.nucengdes.2019.110270.

[19] Castelliti, D., et al., H2020 MYRTE CIRCE-HERO experimental campaign post-test activity and code validation, 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-18), Portland, Oregon, August 18-23, 2019, 2-s2.0-85073733801.

[20] Narcisi, V., et al., Post-test simulation of a PLOFA transient test in the CIRCE-HERO facility, Nucl. Eng. Des 355 (2019) 110321, https://doi.org/10.1016/j.nucengdes.2019.110321.

[21] Lorusso, P., et al., Total Loss of Flow Benchmark in CIRCE-HERO integral test facility, Nuclear Engineering and Design 376 (2021) 111086, https://doi.org/10.1016/j.nucengdes.2021.111086.

[22] Galleni, F., et al., Simulation of operational conditions of HX-HERO in the CIRCE facility with CFD/STH coupled codes, Nuclear Eng. and Des. 361 (2020) 110552, https://doi.org/10.1016/j.nucengdes.2020.110552.

[23] Lorusso, P., et al., ALFRED steam generator assessment: design and pre-test analysis of HERO experiment, Proc. 26th Int. Conf. Nucl. Eng, (ICONE 2018), London, 2018, pp. 22–26 July.

[24] Lorusso, P., et al., Experimental Investigation on CIRCE-HERO for the EU DEMO PbLi/Water Heat Exchanger Development. Energies 2021, 14, 628. https://doi.org/10.3390/en14030628.

[25] OECD/NEA Nuclear Science Committee, Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, edition, Thermal-hydraulics and Technologies, 2015.

[26] RELAP5 Code Manual, RELAP5/Mod3.3 Code Manual Volume I: Code Structure, System Models, and Solution Methods, Nuclear Safety Analysis Division; Information Systems Laboratories, Idaho Falls, 2001.

[27] Oriolo, F., et al., Modifiche del Codice RELAP5 versione MOD3.2 per la Simulazione di Sistemi Refrigerati con leghe di Pb o Pb-Bi, RL 031/00, Università di Pisa, Novembre 2000.

[28] Tarantino, M., et al., Post Test Analysis of ICE Tests, Proc. of 20th Int. Conf. on Nuc. Eng. (ICONE20),

Anaheim, CA, USA, July 30–August 3, 2012, Paper No. ICONE20-54952, Vol. 2, pp. 703-712, 10 pages.

[29] Lorusso, P., et al., Protected loss of flow accident simulation in CIRCE-HERO facility: experimental test and system code assessment, Ibaraki, Proc. 27th Int. Conf. Nucl. Eng, (ICONE 2019), 19-24 2019 May.

[30] C.B. Davis, Applicability of RELAP5-3D for Thermal-Hydraulic Analyses of a Sodium-Cooled Actinide Burner Test Reactor, INL/EXT-06-11518, (2006).

[31] The RELAP5-3D Code Development Team, RELAP5-3D© Code Manual Vol. IV: Models and Correlations, INEEL-EXT-98-00834.

[32] Moffat, R.J., 1988. Describing the Uncertainties in Experimental Results, Experimental Thermal and Fluid Science, Volume 1, Issue 1, January 1988, Pages 3-17, https://doi.org/10.1016/0894-1777(88)90043-X.

[33] Rozzia, D., et al., Experimental investigation on powder conductivity for the application to double wall heat exchanger (NACIE-UP). Nucl. Eng. Des. 283, 100–113.

[34] Rozzia, D., et al., Experimental Investigation on Powder Conductivity for the Application to Double Wall Bayonet Tube Bundle Steam Generator, Proc. of the 24th Int. Conf. Nuc. En. for New Europe (NENE), Portoroz, Slovenia, Sept. 14-17, 2015. Paper 214, 9 pages. ISBN: 978-961-6207-38-6.

[35] Shin, Y., et al., Fouling effect of lead oxide crystallization on heat transfer in LBE, 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 2019, Pages 1346-1359, Portland, United States.

[36] Martelli, D., et al., Literature review of lead-lithium thermophysical properties, Fusion Eng. Des. 138 (2019) 183–195, https://doi.org/10.1016/j.fusengdes.2018.11.028.