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Steam Generator mock-up preliminary design suitable for Pb-Li technology demonstration and code assessment

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The Power Conversion System (PCS) is designed to remove heat from PHTSs and to ensure an efficient thermal power conversion to electricity. The Dual Coolant Lithium Lead (DCLL) breeding blanket concept is based on two coolant fluids flowing into two independent circuits: a helium circuit, cooling first wall, and a PbLi circuit, removing heat generated in the breeding zone (BZ). The steam generator connected to PbLi system is prototypical, therefore experimental tests are required to demonstrate technological feasibility, performances and to assess capability of codes in providing reliable simulations of the behavior. The objective of the activity is to support the design of a PbLi/water steam generator and the experimental campaign defining test matrix and expected outcomes. Two steam generator configurations are analyzed using a modified version of RELAP5/Mod3.3 (R5): the Steam Generator Bayonet Tube (SGBT) and the Helical Coil Steam Generator (HCSG). The experimental mock-up of these configurations will be tested in CIRCE facility at ENEA Brasimone RC, which is currently the largest and most powerful heavy liquid metal facility in operation. Finally, numerical simulations are employed to support the design of the mock-ups and the experimental campaign.

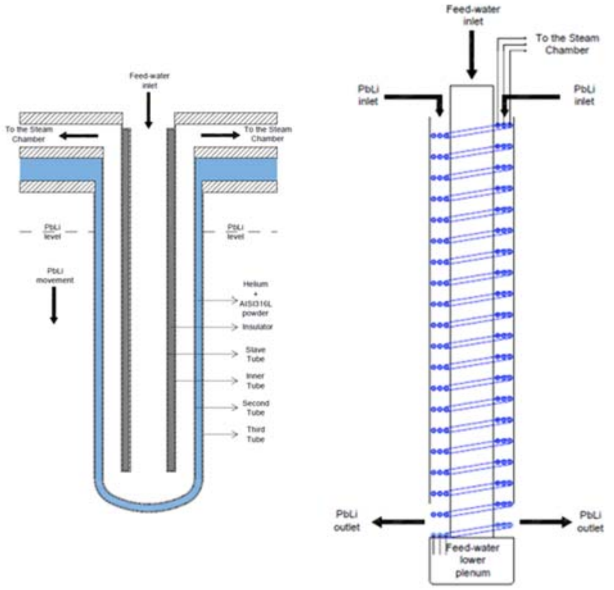
Keywords: DEMO, DCLL, CIRCE-HERO, LiPb, Steam Generator Bayonet Tube, Helical Coil Steam Generator

1. Introductory remarks

The heat transfer between PbLi and water plays an important role in fusion technology because three out of four candidate EU breeding blankets [1] rely on this heavy liquid metal (HLM) as breeder and/or coolant [2][3][4]. The PbLi/water heat exchangers or steam generators are envisaged in the PbLi loop, where the PbLi main issues are investigated [5]. The DCLL breeding blanket, using liquid metal as breeder and cooling, requires a steam generator capable to remove nuclear heat deposited in the liquid metal and to feed a steam turbine.

For the preliminary design of the PbLi PHTS, two steam generators (SG) configurations are considered as candidate: the Steam Generator Bayonet Tube (SGBT), featured by enhanced safety characteristics thanks the double wall tubes separating the PbLi and the water and the leakage detection capability (Fig. 1a), and the Helical Coil Steam Generator (HCSG), characterized by excellent heat transfer performances and by a more compact geometry (Fig. 1b).

The objective is to support the design of a PbLi Heat Exchanger, executing an experimental campaign, according with the following rationale: 1) developing two conceptual designs of SG for the DCLL PbLi PHTS, supported by numerical simulations, using R5 code, extended version set-up with the implementation of the PbLi fluid properties [6]; 2) selecting an experimental facility suitable for testing of the SG mock-up; 3) selecting the mock-up features, identifying scaling distortions and designing the experiments by means of numerical simulations.



(a) SGBT (b) HCSG

Fig. 1. Steam generators schematic view

2. Steam Generator configurations: description and sizing

The DCLL PHTS and the PCS conceptual design is developed on the basis of DCLL breeding blanket design [7]. The data referred to DEMO2015 parameters [8]. The power exchanged between the BZ PHTS and the PCS is 1116.5 MW_{th}; considering the PbLi temperature drop across the BZ PHTS (300-535°C), the liquid metal mass flow rate is 25138 kg/s. The thermal power is transferred from the BZ PHTS to the PCS through SG with water as secondary fluid.

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2.1 Steam Generator Bayonet Tube

The design is constituted by a bundle of Double Wall Bayonet Tube (DWBT). The concept was proposed in the frame of Lead-cooled Fast Reactor (LFR) technology R&D [9] allowing enhancement of safety performance and reducing probability of steam generator tube rapture occurrence. The DWBT, presented in Fig. 1a, is composed of four concentric tubes (Tab. 1).

Table 1. DWBT main data.

	Outer diameter (mm)	**Thickness (mm)**
Slave tube	9.52	1.07
Inner tube	19.05	1.88
Second tube	25.40	1.88
Third tube	31.37	2.11

The feed-water enters the unit on the top edge flowing, downward inside the slave tube and then, upward in the annular riser between inner and second tubes, in countercurrent with PbLi. Second and third tubes constitute the double physical separation between primary and secondary fluid; the annular volume is filled with pressurized helium, to detect possible leakages, and a high thermal conductivity AISI316L powder to obtain good thermal efficiency.

The sizing of the SGBT has been carried out considering 2, 4 and 6 SGs composed of a bundle of DWBT, arranged in a triangular lattice (p/d=1.422) with active length of 6 m, according to the current LFR design. Tube dimensions and p/d are assumed to ensure PbLi velocity between 0.2-0.8 m/s, considering corrosion and erosion issues, and outlet steam velocity <30 m/s. The SG design has been investigated developing and using the extended version RELAP5/Mod3.3 code, using Ushakov correlation [10] for the evaluation of the heat transfer coefficient (HTC) for PbLi in bundle geometry. Considering that PbLi primary system parameters are fixed, SG performances have been evaluated based on secondary side pressure, feed water inlet temperature and DWBT length. A preliminary analysis has been carried out in order to evaluate the feasible SG operating parameters, highlighting some constraints: an acceptable value of the SG housing inner diameter lower than 3 m, corresponding to about a maximum number of tubes per SG lower than 3000, and a PbLi coolant velocity in the range of 0.15-0.8 m/s. Being PbLi outlet temperature equal to 300°C a requirement, only few low velocity cases (around 0.15 m/s) were acceptable assuming the DWBT length of 6 m (see Fig. 2 and 3). The number of acceptable cases increased assuming an active length of 10 m (i.e. 0.15-0.31 m/s) (see Fig. 4 and 5). Considering that low PbLi velocity involves low HTC, the SGBT with an active length of 10 m and PbLi velocity equal to 0.31m/s has been selected as reference case. Indeed, it satisfies most of the outlet requirements. Shorter active length equal to 6 m would be considered if the thermodynamic cycle of the primary fluid is modified, reducing the ΔT. A sensitivity analysis has been performed assuming steam pressure between 6 and 10 MPa. The relevant parameters are reported in Tab. 2 and the No. 4 is selected as the reference case.

2.2 Helical Coil Steam Generator

Six HCSG are supposed to remove the total power of 1116.5 MW, in order to limit the SG diameter below 3 m. In the helical coil concept (see Fig.1b), feed-water moves upward inside helical tubes and PbLi flows downward on shell side, maintaining velocity in the range of 0.3-0.5 m/s to limit corrosion effects. A R5 model has been developed to investigate the HCSG design. Due to the lack of an appropriate HTC correlation in R5, a multiplicative factor, calculated as the ratio between Sherbakov [11] and Seban&Shimazaki [12] correlation, has been introduced to better reproduce the HTC for PbLi in HC geometry.

A preliminary analysis has been carried out to individuate HCSG geometrical parameters (Tab. 3). Considering these assumptions, a HCSG height of 3.75 m (average tube length: 21 m) and 21 coils, a first analysis has been performed to investigate the influence of radial p/d, changed in the range 1.35-1.55. This parameter has limited influence on PbLi outlet temperature (close to 300°C) but it affects HLM velocity (Fig. 6); the radial p/d must assume a value between 1.4 and 1.55 to obtain acceptable PbLi velocity. Calculations have been repeated increasing the number of coils to 22 and 23, individuating the reference configuration (Tab. 4). Fig. 7 shows that increasing the steam pressure, steam velocity and outlet temperature decrease, instead PbLi outlet conditions are not affected.

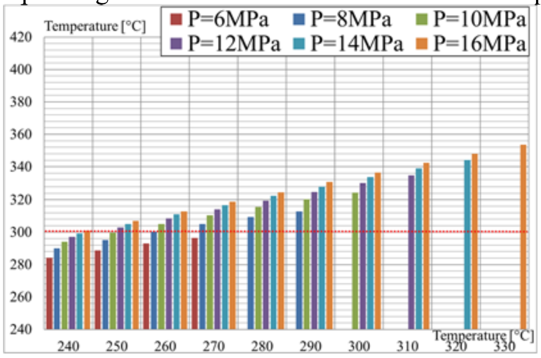

Fig. 2. Active length: 6 m; PbLi velocity: 0.15 m/s

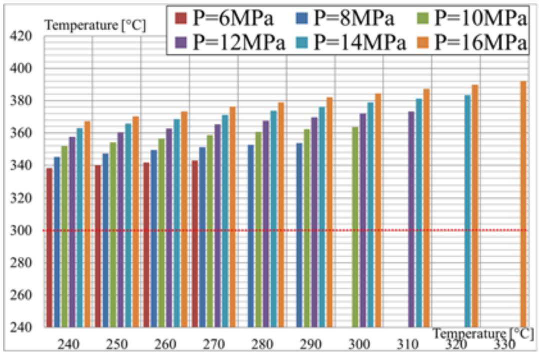

Fig. 3. Active length: 6 m; PbLi velocity: 0.31 m/s

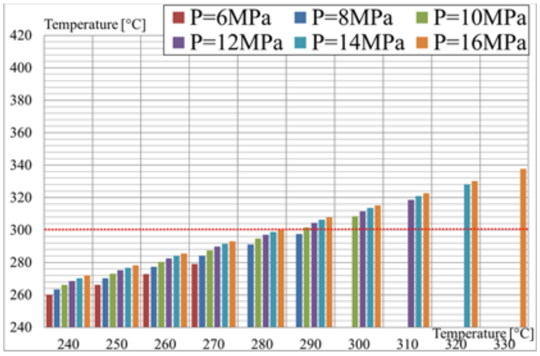

Fig. 4. Active length: 10 m; PbLi velocity: 0.15 m/s

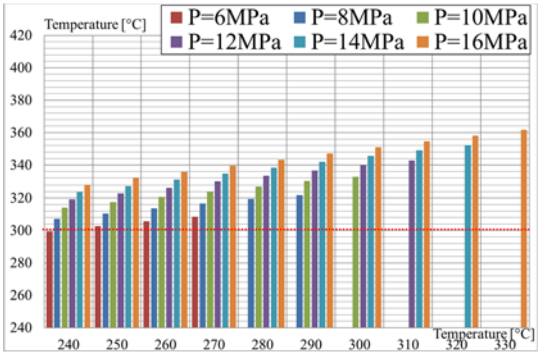

Fig. 5. Active length: 10 m; PbLi velocity: 0.31 m/s

Table 2. Relevant parameter for selected cases.

Case	PbLi mass flow per tube (kg/s)	PbLi velocity (m/s)	Steam pressure (MPa)	Feed-water inlet T (K)	No tubes 2 SG	No tubes 4 SG	No tubes 6 SG
1	2.52	0.26	6	270	5007	2504	1669
2	2.84	0.30	6	250	4415	2208	1472
3	2.39	0.25	8	260	5255	2627	1752
4	2.37	0.25	10	250	5320	2660	1773

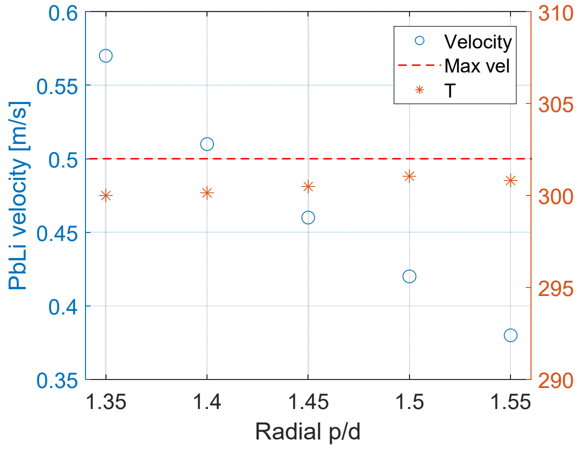

Fig. 6. PbLi v and T_{out} v.s. p/d.

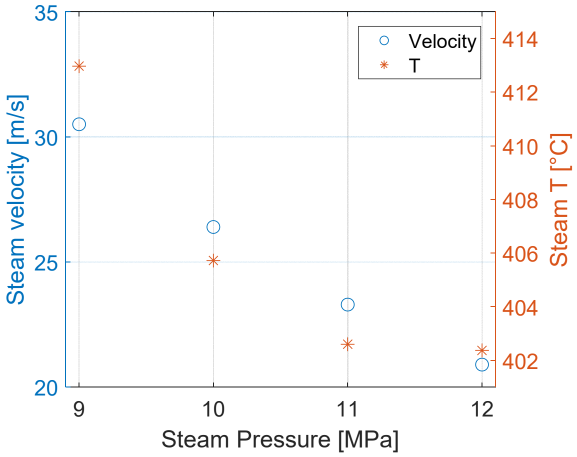

Fig. 7. PbLi v and T_{out} v.s. steam p.

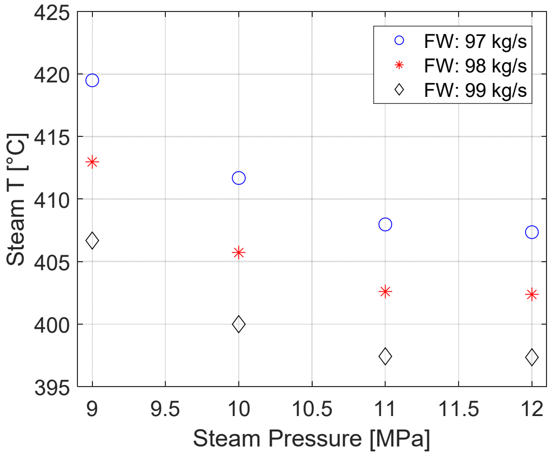

Fig. 8. Steam T v.s. steam p

The effect of feed-water mass flow rate increase is depicted in Fig.8 which highlights a decrease of the steam temperature. The PbLi outlet conditions are influenced by feed-water subcooling inlet T; a sensitivity analysis has highlighted a significant increase of the HLM outlet *T* due to the decrease of feed-water subcooling *T*. The last analysis concerns the SG height, fixed to 3.75 m for reference case. The SG height has been increased to 4.5 and 5.75 m (tube length: 26 and 30 m). It allows higher steam pressure than reference configuration and a decrease of feed-water subcooling temperature at the SG inlet, but the steam velocity is limited to 22 m/s.

Table 3. HCSG: fixed parameters.

Parameter	Value
Tube OD (mm)	15.9
Tube thickness (mm)	2.41
Average tube inclination (°)	10
Vertical p/d	1.5

Table 4. HCSG: reference configuration.

Parameter	Value
No tubes	1009
No coils	23
Radial p/d	1.45
SG diameter (m)	2.27

PbLi outlet T (°C)	300.5
PbLi maximum velocity (m/s)	0.46
Power per tube (MW)	1.106
Steam outlet T (°C)	413.0
Steam velocity	30.5

3. Mock-up design

To support PbLi heat exchangers design, an experimental campaign is promoted by ENEA Brasimone Research Center. CIRCE facility has been selected for the experimental campaign. CIRCE is a LBE pool facility characterized by height of 8 m and an installed power of 1 MW_e [13]. The maximum height and the thermal power of the facility require a scaling approach for SG mock-up design. The use of LBE rather than PbLi must also be considered in scaling analysis. Two scaling approaches have been proposed. The first one consists in maintaining same heat transfer conditions using LBE rather than PbLi. The dimensionless Peclet number (Pe), defined as $Pe = Re \cdot Pr$, provides information on heat transfer conditions. The approach is to evaluate mock-up LBE velocity to offset Pr variation with Re, maintaining a constant Pe. In the operative range, the thermo-physical properties of the two liquid metals present similar trends, maintaining the ratio between LBE and PbLi in a limited range. The LBE velocity can be obtained as:

$$v_{LBE} = Pe_{PbLi} \left(\frac{k}{\rho\, c_p}\right)_{LBE} \frac{1}{D_h}$$

Assuming same geometry, the ratio between LBE and PbLi velocity is in the range of 1.072-1.146, with an average value of 1.122. Combining the variation of density and velocity, the LBE mass flow rate is obtained as $\Gamma_{LBE} = 1.176\, \Gamma_{PbLi}$, and the LBE SG temperature drop (ΔT) as $\Delta T_{LBE} = 1.125\, \Delta T_{PbLi}$. The second approach consists in maintaining the same ΔT on the primary side, and the same thermal power ($\dot{Q}$) removed by the SG. Set the ΔT and the $\dot{Q}$, the Γ_{LBE} only depend on the specific heat ratio, obtaining: $\Gamma_{LBE} = 1.323\, \Gamma_{PbLi}$.

HERO is selected as the SGBT mock-up. The test section consists of a bundle of 7 DWBTs characterized by the geometrical parameter summarized in Tab. 1 and a p/d of 1.422 [9] [14] (Fig. 9). The tubes have an active length of 6 m; for this reason, the analysis will be divided in different ΔT ranges. The maximum temperature allowed by CIRCE facility is 500°C that limits the maximum temperature for the experimental campaign, assumed to 480°C. The whole temperature drop (480-300°C) is investigate in different ΔT ranges, changing the LBE inlet temperature in the range of 480-400°C with a step of 20°C. Considering the case 4 of Tab. 2, the Γ_{LBE} will be 19.5 kg/s for the first scaling approach, and 22.9 for the second one. The experimental campaign will consist in three tests based on stepwise "quasi" steady state operative conditions. The test matrix is summarized in Tab. 5.

Fig. 9. HERO Test Section

Table 5. CIRCE-HERO: test matrix.

Parameter	Test 01	Test 02	Test 03
Steam p (MPa)	10	10	10
PbLi T_{in} (°C)	480-400	480-400	480-400
PbLi MF (kg/s)	19.5	19.5	19.5
PbLi v (m/s)	0.24	0.24	0.24
Feed-water T_{in} (K)	300	300	300
Feed-water MF (kg/s)	0.070	0.063	0.054

The HCSG mock-up is supposed to be a full scale in length of the SG conceptual design. The main constraint is the power installed in CIRCE. The actual electrical power of 1 MW would be enough for only one tube; this solution could be not representative for the HCSG. An increase of the nominal thermal power of the facility could allow the construction of a mock-up composed of 3 helical tubes (1:1 in length) that will be more representative; in this case, the Γ_{LBE} will be 14.7 kg/s for the first scaling approach, and 16.5 for the second one. The costs assessment for increasing the electrical power to 2 MW_e is currently under evaluation. The second solution would be to reduce the mock-up active length,dividing the analysis in different ΔT ranges.

4. Conclusions

The activity supports the design of PbLi/water SG, analyzing the performance by a modified version of R5 and testing the design through prototype mock-up. Two configurations are analyzed: the SBGT and the HCSG. The experimental campaigns will be performed in CIRCE facility. The first one aims to demonstrate SGBT capability through HERO test section; the second one will investigate HCSG capability through an experimental mock-up discussed in this paper. This campaign will be performed after the electrical power upgrade of the facility, the installation of a centrifugal pump instead the gas-enhanced circulation system and the procurement of the mock-up.

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