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Preliminary design of a helical coil steam generator mock-up for the CIRCE facility for the development of DEMO LiPb heat exchanger

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In the framework of the EU DEMO fusion reactor technology development, a new steam generator consisting in a helical tube bundle is currently under study for the lithium-lead loop of the Dual Coolant Lithium Lead (DCLL) and Water Cooled Lithium Lead (WCLL) breeding blankets. This solution turns out to be very interesting for high power plants, since the helical geometry is very compact and it assures a high thermal power exchanged, taking up the minimum amount of space.
In this framework, the ENEA Brasimone Research Centre supports the development of this innovative component by means of experimental activities, involving CIRCE, a large scale pool-type facility using Lead-Bismuth Eutectic as primary fluid and pressurized water as secondary fluid. The main components of a new test section named THETIS are: a Fuel Pin Simulator, acting as primary heating source, a vertical mechanical pump for the primary fluid circulation inside the main pool and a new prototypical helical coil steam generator mock-up, designed to be relevant for the DCLL and WCLL lithium-lead loop, acting as primary heat sink. In such configuration, the facility will be involved in a set of tests aiming at demonstrating the technological feasibility and thermal-hydraulic performances of this prototypical steam generator, as well as the suitability of the component for the lithium-lead loop in DEMO. The experiments will also provide a database for system thermal-hydraulic codes validation.
The aim of this paper is to present the main layout of the CIRCE facility, to describe the preliminary design of the test section and the main features of the helical coil steam generator mock-up. Furthermore, a preliminary test analysis carried out by the system thermal hydraulic code RELAP5/Mod3.3 is presented. A numerical 1-D model of the helical coil steam generator has been set-up in order to test the performance of the component from a thermal-hydraulic point of view. An additional 3D CFD analysis was performed for the flow field of the HCSG to assess the secondary flow behaviour in the component and the pressure losses.

Keywords: DEMO, LiPb technologies, helical coil steam generator, RELAP5 code.

1. Introduction

The technological development of the DEMOnstration (DEMO) fusion reactor [1] foresees the use of heavy liquid metals as breeder and/or coolant. In particular, the lithium-lead (LiPb) has been selected as breeder, coolant and tritium carrier for the Dual Coolant Lithium Lead (DCLL) [2] Breeding Blanket (BB) whereas it serves as breeder and tritium carrier for the Water Cooled Lithium Lead (WCLL) BB [3]. The use of LiPb as coolant makes necessary the execution of R&D activities focused on the investigation about the LiPb main issues [4][5] and the development of LiPb/water heat exchangers or steam generators suitable for such applications in fusion field. Currently, two configurations have been considered as candidate for the LiPb loops [6]: the Steam Generator Bayonet Tube (SGBT) and the Helical Coil Steam Generator (HCSG).

In this framework, research activities have been undertaken at ENEA Brasimone Research Centre to investigate the LiPb technology [7][8][9]. A dedicated task has been focused to support the development of a LiPb/water heat exchanger [10][11], investigating the two concepts proposed in order to demonstrate the technological feasibility and performances by means of experimental tests, as well as to assess the capability of numerical tools in providing reliable simulations of their thermal-hydraulic behaviour.

For this purpose, the Lead-Bismuth Eutectic (LBE) cooled pool-type facility CIRCE (CIRColazione Eutettico) at ENEA Brasimone R.C. is currently under refurbishment. A new Test Section (TS) named THETIS (Thermal-hydraulic HElical Tubes Innovative System) is under design and it includes a new mock-up of a prototypical HCSG. This solution is characterized by a very compact geometry and it assures a high power removed, taking up the minimum amount of space. The THETIS TS will replace the HERO (Heavy liquid mEtal – pRessurized water cOoled tube) TS which has been previously used to investigate on the technological feasibility and the thermal-hydraulic performances of a SGBT [11][12][13].

The new TS will be characterized by new features and some new components respect to the previous one. The TS will include: a Fuel Pin Simulator (FPS), acting as LBE heating source, a vertical mechanical pump for the primary fluid circulation inside the main pool and a new HCSG mock-up, acting as primary heat sink and fed by a dedicated secondary system designed to provide feedwater at high pressure and temperature.

The HCSG mock-up is designed to remove a maximum thermal power in a range of 400-450 kW, depending on the primary and secondary fluids

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conditions, and generating at the same time high temperature superheated steam, compatible with the conditions of the steam to be produced by the DCLL steam generator to feed the turbine for electricity production.

For the preliminary design of the component, numerical simulations are employed to support the design of the mock-up and to define the operating conditions of the experimental campaigns.

The present paper describes the features of the new TS under development for the CIRCE facility. The main components of the primary system are reported and the preliminary design of the HCSG mock-up is described, as well as the main operative parameters. The preliminary test analysis carried out by the system thermal hydraulic code RELAP5/Mod3.3 in support of the design phase is presented. The numerical 1-D model of the HCSG is introduced along with the calculations carried out to assess the thermal-hydraulic performances of the component. An additional 3D CFD analysis has been carried out to assess pressure losses and flow field on the LBE shell side and to support the design of the THETIS TS.

2. CIRCE facility and THETIS TS

CIRCE is a large scale pool-type facility using LBE as primary fluid set at ENEA Brasimone R.C. [14][15]. The facility has been widely involved in several experimental campaigns with integral tests [16] and component characterization tests [12][17] that make it a relevant experimental platform for the thermal-hydraulic analysis of system and components for nuclear applications (both fusion and fission Generation IV).

The main systems and components of CIRCE are:

- S100 main vessel, conceived to host the test sections. It has an inner diameter of 1170 mm, a thickness of 15 mm, and a height of about 8500 mm. It is partially filled with about 70 tons of LBE and argon as cover gas maintained in slight overpressure;
- S200 storage tank (Fig. 1), in which the LBE is stored during the periods of maintenance and refurbishment of the facility;
- S300 transfer tank (Fig. 1), used during the filling and draining phases of the main vessel;
- argon recirculation system, composed of a set of 5 compressors connected in parallel and an argon storage tank, acting as gas lung and directly connected to external gas tanks used for argon re-integration;
- Reactor Vessel Auxiliary Cooling System (RVACS), which allows the cooling of the external surface of the vessel by mean of air injection.

The main geometrical and operative parameters of CIRCE are summarized in Tab. 1.

The THETIS (Thermal-hydraulic HElical Tubes Innovative System) test section is currently under development at ENEA Brasimone R.C. and it will be mainly composed by the following components (see Fig.2 for reference):

- Fuel Pin Simulator (FPS), electrically heated for the LBE heating; it consists of a bundle composed by 37 electrically heated pins with a nominal thermal power of ~1 MW;
- Fitting Volume (FV) which collects the hot LBE rising from the FPS;
- riser connecting the FV to the pump suction;
- Main Circulation Pump (MCP) to perform LBE forced circulation;
- hot pool (separator) which will feed the HCSG;
- HCSG for the heat removal from the primary system; this component works in counterflow, with the LBE flowing shell side and the water flowing tube side;
- dead volume, which encloses and maintains insulated the power supply rods feeding the FPS.

The LBE can flow in forced circulation regime by means of the MCP or in natural circulation regime, thanks to the different heights of the thermal barycenters of FPS and HCSG.

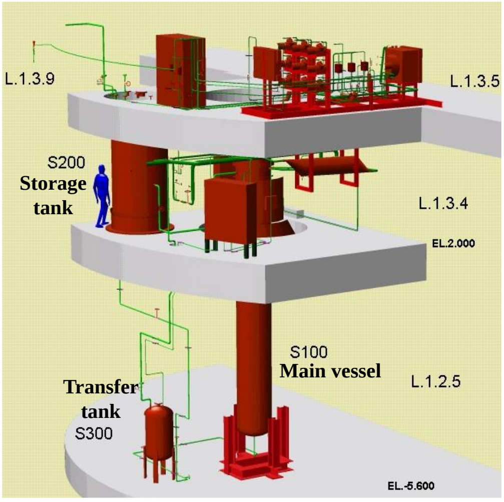

Fig. 1 – 3D view of the CIRCE facility

Parameter	Unit	Designed
Outer Diameter	[mm]	1200
Wall Thickness	[mm]	15
Vessel height	[mm]	8500
Material	----	AISI316L
Max LBE Inventory	[kg]	90000
Temperature Range	[°C]	200 to 500
Vessel design Pressure	[kPa]	160
Power installed	[MW]	1.0
MCP min/max FR	[m^3/h]	10/30

Tab. 1 – CIRCE main parameters

The HCGS is fed by pressurized water (up to 18 MPa) by means of a dedicated once-though secondary loop [18]. The loop is mainly composed of a demineralizer, a volumetric pump, a helical heating system, a manifold, a discharge line, through which the steam produced by the SG outflows in the environment, a bypass line used for the start-up phase.

Both primary and secondary systems will be deeply instrumented for monitoring and control of the facility operation, as well as to acquire the experimental data during the experiments.

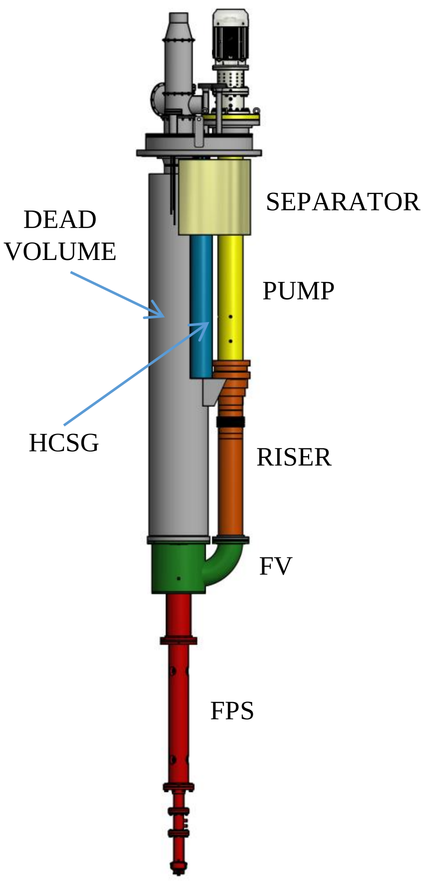

Fig. 2 – 3D view of the THETIS Test Section

3. Helical Coil Steam Generator design

A preliminary mock-up of the HCSG was previously performed on the basis of a geometrical scaling from the DEMO HCSG reference configuration [6]. However, considering the features of the CIRCE facility, the resulting mock-up was not representative for DEMO. For this reason, the approach followed to design the HCSG mock-up for CIRCE is to preserve the liquid metal velocities and the radial pitch to diameter ratio foreseen for the DEMO HCSG tube bundle.

The steam generator for the THETIS TS consists of a prototypical solution with a helical tube bundle, which assures a high power removed, taking up the minimum amount of space. The HCSG is conceived to work in counterflow, with LBE as primary fluid, flowing along the shell side, and pressurized water as the secondary fluid, flowing in the tubes side. This section focuses on the HCSG preliminary design, presenting the final layout achieved at the end of the design optimization process performed with the system thermal-hydraulic code RELAP5/Mod3.3. Details on the model set-up and calculations are reported in the next paragraphs.

The 3D view of the component is depicted in Fig. 3. The preliminary layout of the HCSG is composed of:

- a manifold (ex-vessel) for the feedwater distribution among the tubes;
- a straight tube downcomer bundle, having 15 tubes and a height of 1.5 m, which feeds the helical tube rising bundle;
- a helical tube rising bundle (in-vessel), with 15 tubes, having a height of 1.5 m, in which the vaporization occurs;
- a steam chamber in which the steam produced is collected (ex-vessel), connected to the discharge line;
- an inner double wall shell in which the straight tube downcomer bundle is enclosed (in-vessel);
- an outer double wall shell surrounding the helical tube riser bundle (in-vessel).

Each tube starts from the feedwater manifold on the top part of the HCSG and it goes down straight up to the bottom part, where it curves and rises with a helical shape up to the steam chamber. The coil inclination angle and the vertical pitch are managed in order to maintain constant the length of each helix. The horizontal pitch of the helical ranks is designed to avoid bypass zones for the LBE flow.

The helical tubes are arranged in three horizontal ranks: the inner rank is composed of 4 tubes, the intermediate one is composed of 5 tubes and the outer rank has 6 tubes. The minimum horizontal rank number of 3 is required, in order to assure the representativeness of the component respect to the systems of interest and to reproduce in a reliable way the main phenomena involved.

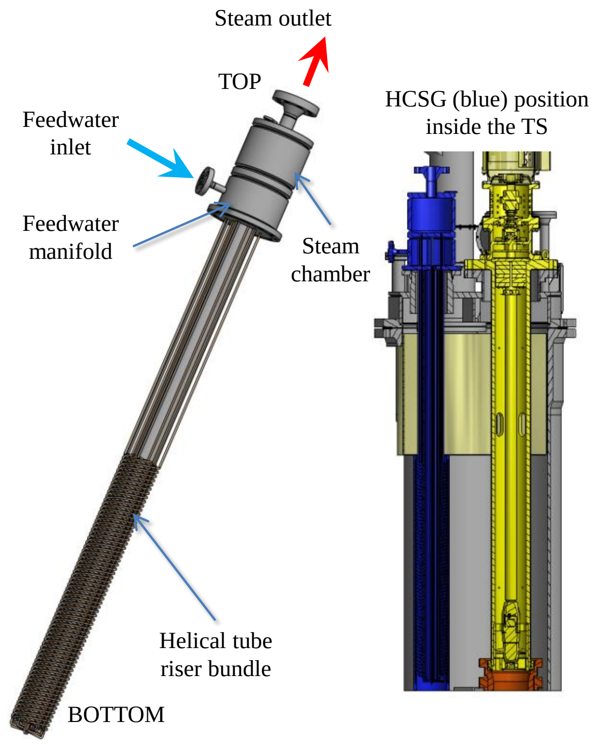

Fig. 3 – 3D view of the HCSG and position inside the TS

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The helical tube bundle is enclosed between a double wall outer shell and a double wall inner shell, as shown in Fig. 4. During the operation, the total LBE mass flow rate passes through the annular region formed between the two shells, allowing the heat exchange with the helical tube bundle only. The downcomer bundle is enclosed in a double wall inner shell (see Fig. 4), where the LBE is stagnant. This implies that the heat exchange between the descending feedwater and the stagnant LBE is strongly reduced since during the operation the two fluids reach almost the same temperature. In this way, the vaporization occurs in the ascending helical tubes only, avoiding eventual flow instabilities in the tubes during the HCSG operation.

The gap within the double wall of the two shells is filled by air acting as a thermal insulator. This allows to avoid the heat exchange from the hot LBE flowing in the annular region to the stagnant LBE inside the inner shell and the LBE in the main pool, enhancing in such a way the thermal-hydraulic performances of the component. In such a way, the HCSG can be considered insulated from the surrounding LBE pool.

Details on the geometrical data of the HCSG are reported in Tab. 2 and Tab. 3.

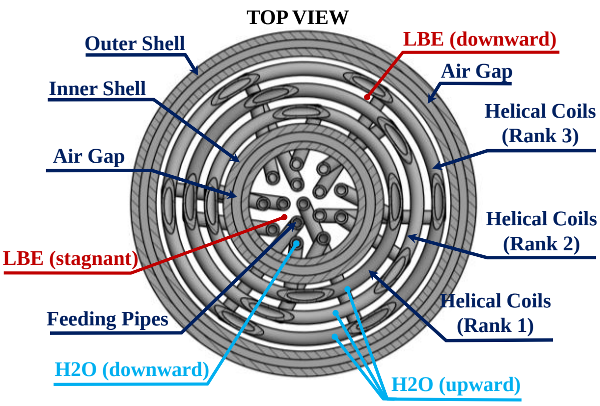

Fig. 4 – Top view of the HCSG

Parameter	Unit	I.D.	Thick.	O.D.
Double Wall Inner Shell				
Inner Tube	[mm]	77.92	5.49	88.9
Air Gap	[mm]	88.9	6.68	102.26
Outer Tube	[mm]	102.26	6.02	114.3
Double Wall Outer Shell				
Inner Tube	[mm]	210.27	6.0	222.27
Air Gap	[mm]	222.27	6.0	234.27
Outer Tube	[mm]	234.27	6.0	246.27

Tab. 2 – Summary of the HCSG shells geometrical data

4. Preliminary test matrix

The preliminary analysis to assess the main operative parameters of the facility is hereafter reported. The total power installed is used mainly for the LBE heating and feedwater pre-heating. The two power values are defined considering that the maximum electrical power available for the operation of the entire facility is about 1 MW and that, during the previous experiments, the power needed by the primary side for LBE heating (FPS) and by the secondary side for water pre-heating were comparable [16][23]. This implies that the power available to be supplied to the FPS can be assumed in the range of 450-500 kW. Assuming the presence of heat losses along the LBE flow path between FPS and steam generator (observed from previous experiments [16][23]), a power of 400-450 kW can be assumed as the thermal duty of the HCSG.

The thermal cycle to be performed in the primary side foresees the achievement of an LBE temperature difference inlet-outlet of the HCSG shell side of 480-400°C. Assuming a thermal power of 400 kW and applying the thermal balance equation referring to the most-updated LBE properties reported in [24], it is possible to calculate the LBE mass flow rate, equal to 35.2 kg/s.

Geometrical Data	Unit	Horizontal Rank N°1 (inner)	Horizontal Rank N°2 (middle)	Horizontal Rank N°3 (outer)
Height	[m]	1.5	1.5	1.5
Tubes I.D.	[m]	0.00622	0.00622	0.00622
Tubes O.D.	[m]	0.00952	0.00952	0.00952
N° of tubes (vertical ranks)	----	4	5	6
Horizontal P/D	----	1.6	1.6	1.6
D helix*	[m]	0.132	0.162	0.193
Coil Vertical P/D	----	10.08	12.61	15.13
Inclination angle	----	13.05°	13.24°	13.38°
L coil (active length)	[m]	6.642	6.547	6.484
Total length 1 tube*	[m]	8.142	8.047	7.984
Vertical P/D	----	2.521	2.521	2.521
L tot (active length)***	[m]	26.569	32.735	38.901

**Considering the tube axis*
***(L coil + 1.5 m) – lower and upper connections not included*
****lower connections not included*

Tab. 3 – Summary of the HCSG bundle geometrical data

On the secondary side, two water thermal cycles have been considered: a cycle at 9 MPa and HCSG inlet temperature of 300°C, and a cycle at 12 MPa and inlet temperature of 320°C. Since the HCSG is designed to produce steam with a good degree of superheating a preliminary value of 400°C has been considered for the steam outlet temperature. Assuming a thermal duty of 400 kW and applying the thermal balance equation, the water mass flow rate is 0.23 kg/s for the cycle at 9 MPa and 0.25 kg/s for the cycle at 12 MPa. This implies that the power needed for the water pre-heating is 291.6 kW for the case at 9 MPa and 353.5 kW for the case at 12 MPa. Assuming a FPS power of 450 kW and a MCP power of 15 kW, the total power needed for the facility operation is 756.6 in the first case (P=9 MPa) and 818.5 kW in the second case (P=12 MPa). In both cases, the total power is below the maximum power available of ~1 MW. The reference working conditions are reported in Tab. 4.

On the basis of the facility features and of numerical calculations, a preliminary test matrix can be proposed. The experiments aim at characterizing the HCSG from a thermal-hydraulic point of view in operating conditions consistent with the LiPb/water loops of the DCLL and WCLL. In particular, a test matrix of three tests is presented below. The tests have to be performed at different water pressures (i.e. two tests at 9 MPa and one at 12 MPa) and for each test an experimental sensitivity analysis is foreseen, changing the LBE mass flow rate in four steps (forced circulation at 70.5, 47.0, 35.2 kg/s and natural circulation regime). Considering the geometry presented in Section 3, in forced circulation, the LBE average velocities are in the range of 0.2-0.4 m/s, which is consistent with the velocity range expected for the DCLL BB LiPb/water heat exchangers. In natural circulation, the LBE velocity field is expected to be lower than 0.1 m/s, thus representative of the flow conditions of the WCLL LiPb loop.

It is worth to mention that, despite the different fluid used in CIRCE facility (LBE) respect to the one used in the DEMO WCLL and DCLL BB concepts (LiPb), both fluids rely on the same formulations of the Nusselt number. Therefore, it is possible to find a correspondence between LBE and PbLi, using two scaling methods [11][25], i.e. preserving the convective heat transfer (method #1) [13] and both the thermal power and temperature difference (method #2) [12]. Using such methods it is possible to make the tests carried out in LBE representative for systems operating with LiPb.

Parameter	Unit	Value
Tin LBE	[°C]	480
mfr LBE	[kg/s]	35.2
v LBE (avg)	[m/s]	0.18
P H2O	[MPa]	12
Tin H2O	[°C]	320
mfr H2O	[kg/s]	0.25
v H2O liq	[m/s]	0.61

Tab. 4 – Reference working conditions for the HCSG

Parameter	Unit	Test #1	Test #2	Test #3
LBE mfr	[kg/s]	70.5/47.0 /35.2/NC	70.5/47.0 /35.2/NC	70.5/47.0 /35.2/NC
T_{in} SG LBE	[°C]	480	450	480
T_{in} SG H_2O	[°C]	300	300	320
P_{out} SG H_2O	[MPa]	9.0	9.0	12.0
H_2O mfr	[kg/s]	0.23	0.23	0.25

Tab. 5 – Preliminary test matrix for the HCSG thermal-hydraulic characterization

5. RELAP5/Mod3.3 HCSG Simulation

In order to estimate the number of tubes of the helical bundle, the tube length and to optimize the overall design of the SG, a numerical model has been developed using RELAP5/Mod3.3 [19], modified by ENEA with the implementation of the properties of Pb, LBE and LiPb, along with some correlations for the heat transfer for heavy liquid metals [20][21][22]: Seban-Shimazaki (used for non-bundle geometry) and Ushakov and Mikityuk (used for bundle geometries).

Fig. 8 shows the numerical 1-D model realized for the simulation. The nodalization consists of 75 hydrodynamic volumes, 73 junctions, 40 heat structures and 520 heat transfer nodes. In particular, the main components reproduced are (see Fig. 8):

- the downcomer tube bundle, simulated by the equivalent PIPE 103, consisting of 20 volumes (non-active region);
- the helical riser bundle, simulated by the equivalent PIPE 105, consisting of 30 volumes. The volumes from 105-01 to 105-20 represent the active region, while the volumes from 105-21 to 105-30 reproduce the effects of the non-active length at the SG outlet;
- the LBE pool, simulated by an equivalent channel (PIPE 203).

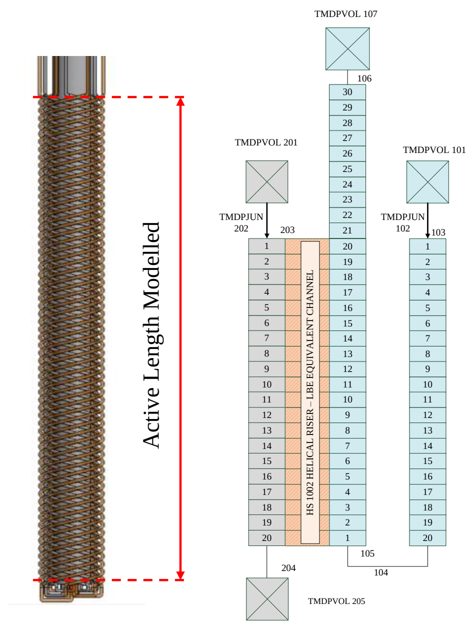

Fig. 5 – RELAP5/Mod3.3 Nodalization

The time dependent volume (TMDPVOL) 101 sets the water inlet conditions in the SG and the time dependent junction (TMDPJUN) 102 works as pump providing the water mass flow rate, while TMDPVOL 107 defines the conditions at the outlet section of the SG. In the same way, TMDPVOL 201 sets the LBE inlet temperature and TMDPJUN 202 fixes the LBE mass flow rate, while the TMDPVOL 205 represents the LBE outlet.

Concerning the heat structures, the downcomer tube bundle has been assumed thermally insulated (adiabatic), since it is immersed in stagnant LBE, while a thermal connection has been simulated between the equivalent PIPE 105 (helical riser bundle) and the equivalent LBE channel, reproducing the walls of the helical tubes, considering the properties of the AISI 316L stainless steel.

As a conservative assumption, the heat exchange between the tubes of the bundle and the LBE inside the separator has been neglected, such as the heat exchange between the LBE and the lower tube connections of the bundle between the downcomer tubes and riser tubes.

For the heat transfer in the helical tube bundle zone, the Seban-Shimazaki correlation is used. Since an appropriate convective heat transfer correlation for helical tube bundle is not implemented in the modified version of RELAP5, the Seban-Shimazaki correlation has been corrected with a multiplicative factor, calculated as the ratio between Seban-Shimazaki and Sherbakov correlation [26] which is used for liquid metal in helical coil bundle geometry.

The analysis has been developed on the basis of the geometrical data already presented in Tab. 3 and Tab. 2, assuming the initial conditions summarized in Tab. 4.

The results of the simulation are summarized in Tab. 6. The power removed by the HCSG from the LBE is about 421.7 kW, which is within the power range of 400-450 kW expected during the operation of the facility. In this condition, the LBE is cooled at about 396.6°C, while on the secondary side the superheated steam is produced at about 430°C, with thermodynamic conditions suitable for a steam turbine feeding. Details on the LBE and water temperature profiles along the HCSG active length are reported in Fig. 6.

R5/Mod3.3 results	Unit	Value
Power removed	[kW]	421.7
Power/tube	[kW/tube]	28.1
Tout LBE	[°C]	396.6
Tout H2O (steam)	[°C]	430.0
v H2O steam	[m/s]	12.6
Static quality outlet	----	1.0

Tab. 6 – Main outcomes of the RELAP5/Mod3.3 simulation

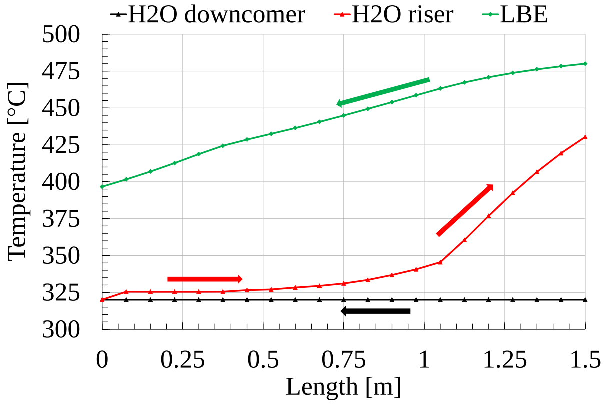

Fig. 6 – LBE and water temperature profiles along the HCSG active length

6. CFD analysis in reference conditions

A preliminary CFD analysis has been carried out on the LBE shell side of the HCSG to assess the fluid flow and the pressure losses in the component. These figures are important to characterize the behaviour of the HCSG and to design the height of the separator. The analysis considers the nominal flow rate of 35.2 kg/s (see Tab. 4). For the modelling and mesh, the exact geometry of the HCSG has been reproduced on the basis of the data reported in Tab. 3 and Tab. 2 and an unstructured mesh with inflation layer at the tube and shell walls has been built. The adopted inflation guarantees y^{+}=1 at the walls in nominal conditions and therefore the flow viscous sublayer and boundary layer were described explicitly without the use of wall functions or other approximations. The total number of nodes and elements was respectively 17 million and 48 million. Although a systematic mesh independence study was not conducted, y+=1 guarantees that 10 points in the viscous sublayer are present in the final computational mesh. Therefore, a strong influence of a further mesh refinement in the results is not expected. The turbulence model adopted was the SST k-omega and full convergence was achieved in the calculation with residuals at 10^{-5}-10^{-6}. The simulation required 1 day in a 24 Xeon parallel computer.

Fig. 7 shows the streamwise velocity distribution in the middle cross section of the HCSG. The maximum LBE velocity is about 0.3-0.4 m/s and is reached in a peripherals channels close to the tubes. A weak streamwise recirculation with positive velocities is evidenced in the intermediate rank. The average velocity in the section is about 0.18 m/s and is coherent with the RELAP5 analysis.

Fig. 8 shows the 3D streamlines in the domain. It can be noticed that the streamlines are not straight but they have a helical clockwise shape due to the fact that the pipes are helicoidally wrapped and two ranks have a clockwise direction which is dominant. Due to this feature, a strong secondary circulation is present and this will enhance heat transfer and increase pressure drop. This is shown in Fig. 9 were the secondary flow in the middle cross section is represented. The circulation is clockwise and it is particularly strong in the inner and in the outer ranks with a secondary velocity around 0.2 m/s, therefore of the same order of the streamwise main component. Finally, the computed pressure drop across the component is 13 kPa. This is the reference value to dimension the height of the separator in the THETIS TS.

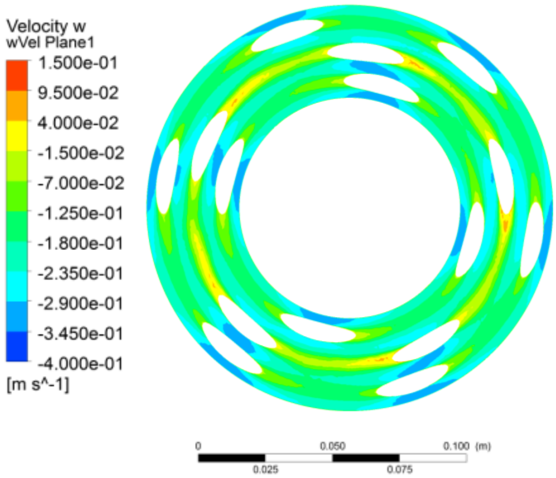

Fig. 7 – Streamwise velocity distribution in a cross section in the middle of HCSG

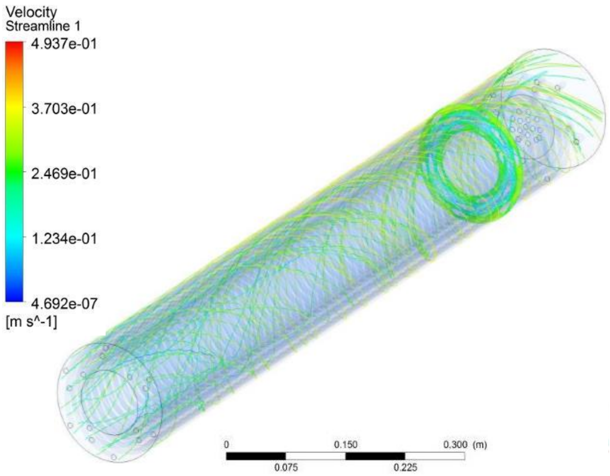

Fig. 8 – 3D streamline in the HCSG domain

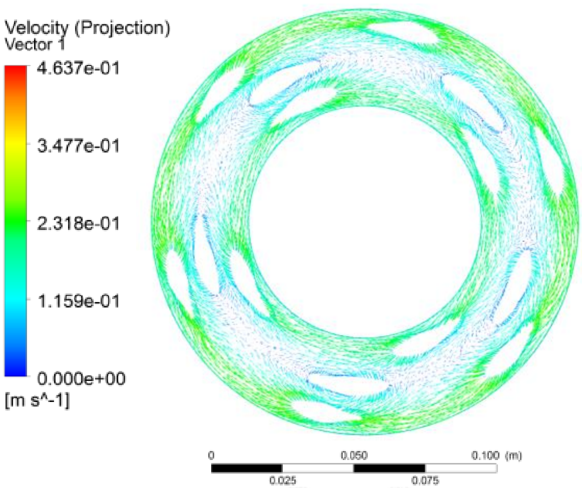

Fig. 9 – Secondary flow in the middle cross-section of the HCSG domain LBE side

7. Conclusions

In the framework of the DEMO Work Package Balance of Plant of EUROfusion consortium, a research activity has been addressed to the development of a LiPb/water heat exchanger capable to remove efficiently the thermal power from the DCLL BB and for the LiPb loop of the WCLL BB. In order to support this activity, an innovative mock-up of an HCSG has been developed at ENEA Brasimone R.C. and implemented in the new THETIS test section to be installed in the main vessel of the LBE-cooled CIRCE facility.

The paper describes the main features of the new test section, focusing the attention on the HCSG design. A preliminary analysis to define the operating conditions has been performed and a preliminary test matrix for the HCGS thermal-hydraulic characterization in operating conditions consistent with the LiPb/water loops of the DCLL and WCLL is proposed. The experimental data collected from the planned tests will be useful for the development of the LiPb/water heat exchanger making use of the scaling methods between LBE and LiPb [11][12]. Furthermore, the experimental outcomes could be used for a future experimental vs. numerical benchmark exercise for system thermal-hydraulic/CFD assessment.

The analysis is supported with a numerical calculation performed with a modified version of RELAP5/Mod3.3. The results showed that in the reference conditions, the HCSG in capable to remove a thermal power of 421.7 kW, producing high quality superheated steam at 430°C. Further numerical analysis will be performed during the engineering design phase of the component.

A CFD hydrodynamic analysis on the LBE shell side has been carried out to evidence flow features and compute the pressure drop in nominal conditions (mass flow rate 35.2 kg/s). Results showed the presence of a strong helical wrapped circulation determined by the geometry of the three ranks of tubes. The secondary circulation is of the same order of the main streamwise circulation with velocities around 0.2 m/s and it is expected that it could enhance heat transfer. The pressure drop in the HCSG has been computed as 13 kPa.

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