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W-HYDRA: a new experimental platform for the Water-Cooled Lead Lithium Breeding Blanket

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Abstract

In the framework of the activities coordinated by the EUROfusion consortium, the Water thermal-HYDRAulic (W-HYDRA) experimental platform is being built at the ENEA Brasimone Research Centre in order to support the development of the Water-Cooled Lead Lithium (WCLL) Breeding Blanket (BB). In particular, this infrastructure will make possible the installation and testing of prototypical mock-ups under relevant working conditions, such as the First Wall (FW), the manifold and the Steam Generator (SG). Moreover, it will represent an integral test facility for the investigation of phenomena characteristic of WCLL BB concept, such as the PbLi/water interaction. Finally, the collection of data coming from the different planned experimental campaigns will allow to qualify and validate numerical models and codes currently adopted for the design of components, as well as for the modelling of complex phenomena typical of the WCLL BB. In order to come to a definitive design of the different facilities constituting the experimental platform, several design analyses assessing the thermal, hydraulic and structural performances of the different facilities and components are necessary. The paper reports a highlight of the W-HYDRA platform with a general description of the facilities. Some of the most relevant design studies carried out so far are reported as well, highlighting their impact on the evolution of the design.

Keywords: WCLL, breeding blanket, DEMO, experimental platform

(Some figures may appear in colour only in the online journal)

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1. Introduction

The design of the European DEMO is progressing towards its Conceptual phase, foreseen at the end of 2027 [1]. This phase will lead to the selection of a reference concept for the Breeding Blanket (BB). In this framework, ENEA is developing the Water-Cooled Lead Lithium (WCLL) BB concept [2, 3]. The achievement of such a goal depends on the maturity demonstration of some technology characteristics of this blanket concept. To pursue this objective, the Water thermal-HYDRAulic (W-HYDRA) experimental platform is being built at the ENEA Brasimone Research Centre. W-HYDRA platform is constituted of three different facilities, each of them focussed on a different aspect of the WCLL concept.

2. W-HYDRA experimental platform

The W-HYDRA experimental platform (figure 1) is constituted of three different experimental facilities, aimed at investigating features characteristic of the DEMO BB, the ITER Test Blanket Module (TBM) and the DEMO Balance of Plant (BoP) of the WCLL BB concept: the Water Loop (WL), the LIFUS5/Mod4 and STEAM facilities. WL and STEAM share the same supporting structure and some components, whereas the LIFUS5/Mod4 is segregated in a different hall.

The WL is a medium scale facility able to provide water at PWR (Pressurised Water Reactor) conditions (15.5 MPa, 295 °C–328 °C) for testing BB mock-ups and the ITER WCLL TBM, as well as being representative of the WCLL-TBM Water Cooling System (WCS) [4] to carry out experimental activities aimed at the validation of numerical codes and safety procedures. Being the WL design based on the ITER WCS, it is composed of three water circuits arranged on two different levels: the TBM test section is placed at the lowest level, while the rest of the main components (pressurizers, heat exchangers, etc) are located at the highest level.

Moreover, in order to reproduce the heat flux deposited on both the TBM and BB First Wall (FW) and study the related heat transfer phenomena, the WL will be connected with a Vacuum Chamber (VC) equipped with an 800 kW Electron Beam (EB) gun able to deliver high heat fluxes on selected mock-ups. The VC foreseen to be installed in the WL will be characterised by a length and a diameter of about 3 m. The EB gun will be installed on one of the two side flanges of the chamber, in order to allow the test of TBM-like components. Finally, the WL will be also connected with LIFUS5/Mod4 to reproduce the scenarios involving the interaction between water and PbLi. The three water circuits are characterised by different level of temperature and pressure:

— the primary circuit is an 8-shaped loop providing water (3.74 kg s^{-1}) at PWR conditions to the test sections (295 °C–328 °C at test section inlet and outlet). After passing through the test section, water flows through two delay tanks (inspired from those of the ITER WCS, necessary to preserve the total water inventory and transient time-evolution) and a further heat exchanger, to cede heat power to the secondary circuit and reaching the lowest circuit temperature of 110 °C. Then, an economizer and an electrical heater restore the required temperature at the inlet of the test section. A water-boiling pressurizer, equipped with a motorised and a safety valve, maintains the pressure of the circuit at the desired level;
— the secondary circuit is a simple O-circuit operating at the pressure of 2 MPa, 65 °C–128 °C as thermal range and with a mass flow rate of 4.3 kg s^{-1}. It has the main function of transferring the heat power to the final heat sink, represented by the tertiary circuit. A water-boiling pressurizer to regulate the pressure level is also included in the circuit;
— the tertiary circuit reproduces the function of the ITER Component Cooling Water System (CCWS). It receives the heat power from the heat exchanger with the secondary circuit and it finally rejects this thermal power to the environment by means of a cooling tower. As in the ITER CCWS, the thermal cycle of the tertiary circuit water ranges between 31 °C and 41 °C;
— finally, primary and secondary circuit pressurizers are connected with a Pressure Relief Tank (PRT) having the goal of collecting and condensing the vapour eventually released by the pressurizers.

STEAM is a water facility aimed at supporting and complementing the design of a WCLL BoP critical component, the Steam Generator (SG) of the BB Primary Heat Transfer System (PHTS) [5, 6]. Indeed, despite it adopts components of well-proven technology used in nuclear (fission) power plants, the ‘unconventional’ operation of DEMO, due to the pulsating plasma thermal power, poses unique challenges to the functional feasibility of this component in the reference BoP configuration considered (i.e. the WCLL BB BoP with direct coupling [7]), so that it can be considered ‘critical’ and needing accurate design and validation. In particular, the objective of water-water SG test campaign is to demonstrate the capability of the SG to perform as intended during the power phases of DEMO that, according to the present concept design assumption, consist of a 2 h pulse at full power followed by 10 min of dwell at low power (from 1% to 10% of the nominal full-power). It becomes then mandatory to assess the behaviour of the SG under both steady-state power regimes and during the transients among them.

This facility is mainly composed of two loops operating at different pressures and temperatures, thermally coupled by means of the test section (i.e. the Steam Generator) called Once Through Steam Generator (OTSG) [8], scaled down from the DEMO BB OTSG at beginning of life. The primary circuit operates at the same pressure and temperatures of the WL, thus representing a kind of high mass flow rate branch of the WL and sharing the pressurizer with it. A 3.1 MW electric heater ensures the temperature rise from 295 °C up to 328 °C, while a circulation pump ensures the nominal mass flow rate (16 kg s^{-1}) through the circuit. In order to maximise the STEAM primary circuit potentialities in terms of high

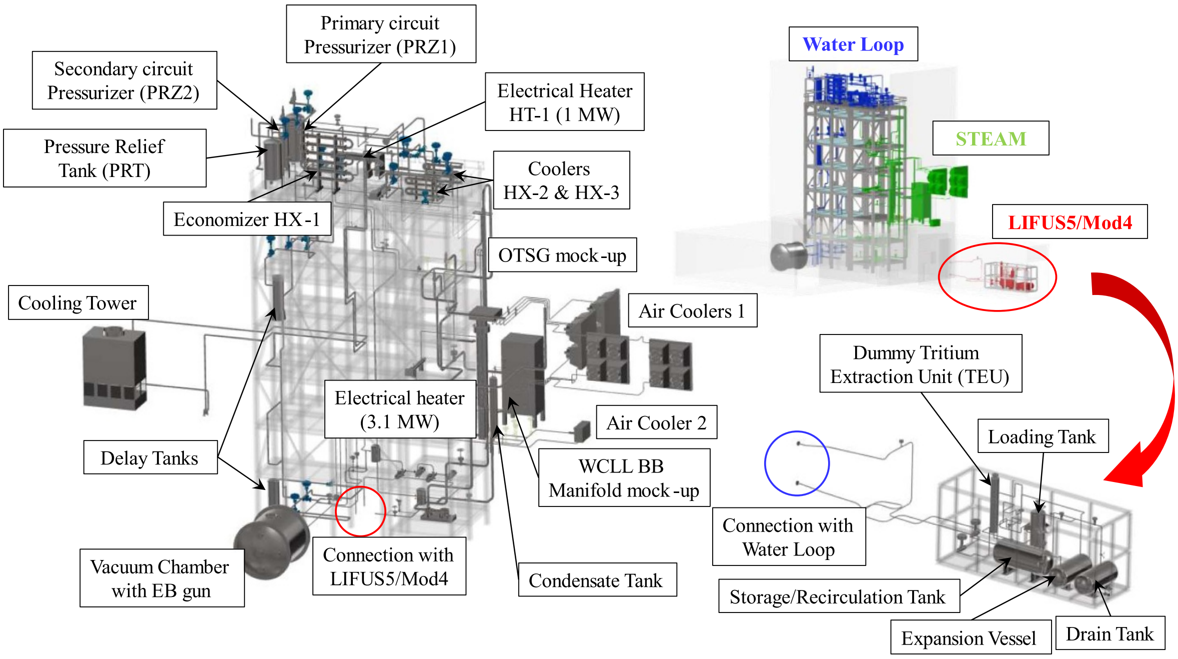

Figure 1. W-HYDRA platform with detail of the different components (top right figure: WL in blue, STEAM in green, and LIFUS5/Mod5 in red).

mass flow rate, it is foreseen to host a test section of the WCLL manifold, aiming at investigating the hydraulic behaviour of this component. The STEAM secondary circuit, working at 6.4/2.5 MPa, is constituted by the SG secondary side, a lamination valve performing the pressure reduction from 6.4 to 2.5 MPa, two sets of air coolers between which a condensate tank is installed to operate in saturation conditions, a filter, a loading pump and an electrical heater.

LIFUS5/Mod4 is a PbLi facility aimed at the investigation of the PbLi-water interaction [9] at TBM scale to validate numerical models and tools currently adopted for modelling this phenomenon [10]. Indeed, one of the main concerns in terms of safety of the WCLL BB/TBM is the occurrence of an in-box Loss Of Coolant Accident (LOCA) due to the rupture of a cooling tube dived in the PbLi. This kind of accident is characterised by different phenomena taking place at the same time, namely the injection of high pressure-high temperature water in a heavy liquid metal, the exothermic chemical reaction between water and the lithium fraction contained in the PbLi, as well as the production of hydrogen as a result of this last reaction. Thus, LIFUS5/Mod4 is designed to be as representative as possible to WCLL TBS PbLi loop [4] in terms of pipes length, elevation, pressure drops, and component volumes (Tritium Extraction Unit—TEU equivalent volume, recirculation and relief tanks), which are considered as the main loop together with a test section reproducing a WCLL-TBM elementary unit. The facility is operated at a pressure of 0.1 MPa and in isothermal conditions, with the possibility of ranging between 330 °C and 450 °C, whereas the design pressure is 18.5 MPa. Finally, since the test section is connected with the WL, LIFUS5/Mod4 represents an Integral Test Facility for the investigation of the in-box LOCA in the WCLL-TBM.

3. Design analyses

In order to properly design and size the different components, as well as integrate them, several thermal-hydraulic and thermo-mechanical analyses have been conducted on the different experimental facilities.

3.1. WL

The normal operational state at end-of-life conditions was assessed through a comparison of WL and WCLL-WCS numerical simulations done with RELAP5/Mod3.3 code. The capability to reproduce the normal operational state is the first step to ensure the achievement of the facility goals. For both circuits, a RELAP5/Mod3.3 model was created reproducing both the piping system and the main components. Components were surrounded with heat structures to mimic the tube thickness. These structures are composed by two layers, the innermost made of AISI 316 and the outermost made of an isolation material (Paroc). The end-of-life conditions have been chosen because of the tube plugging and fouling expected on the heat exchangers. A more comprehensive description of the model, including control logic and boundary conditions can be found in [11]. The normal operational state is a pulsed regime divided into 4 phases (see figure 2):

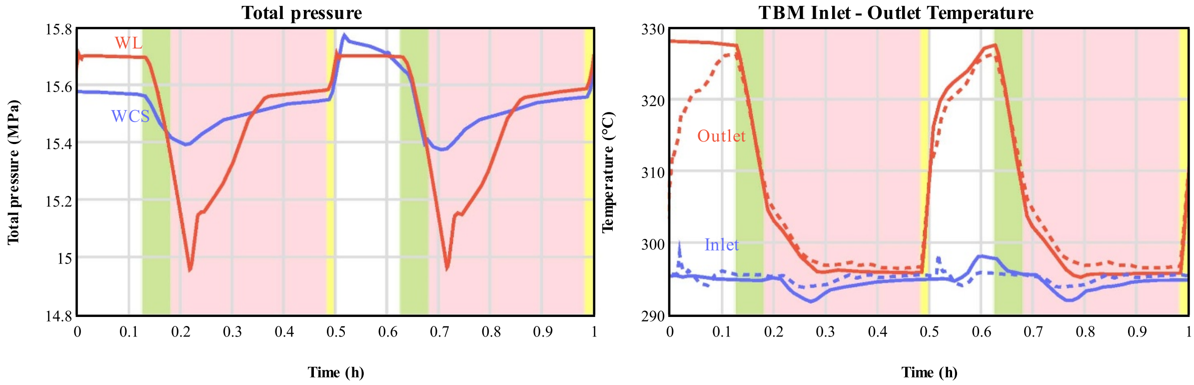

Figure 2. Normal operational state—primary loop results.

- — 60 s of ramp-up from zero to full plasma power (yellow area in figure 2);
- — 450 s of full plasma power (about 723 kW released in the WCLL TBM, 492 kW from nuclear heating, and 231 kW from FW heat flux). This phase is also called flat-top (white area in figure 2);
- — 200 s of ramp-down from full to zero plasma power (green area in figure 2);
- — 1090 s of dwell (zero plasma power—red area in figure 2).

This regime has been simulated in WL assuming a full WCLL TBM mock-up installed in the Vacuum Chamber under the foreseen 0.3 MW m^{-2} wall heat flux coming from the Electron Beam gun and a set of heating cables to mimic nuclear heating. During the dwell phase the electrical heater (HT-1) is switched on to control the TBM inlet temperature (295 °C). The absence of heat in the TBM (decay heat is about 1% of the flat-top power) leads to a decrease of the TBM outlet temperature, but this variation is compensated by the economizer (HX-1). This action avoids any temperature fluctuation on the primary loop cooler (HX-2) and the main coolant pump. The evolution of temperatures, at TBM inlet and outlet, and pressure showed an overall good agreement with the WCLL-WCS (figure 2, solid lines refer to WCS, dashed ones to WL). The pulsed regime has a detrimental effect on the stability of the primary loop pressure. During the dwell phase the 'hot' coolant after the TBM shrinks due to the reduction of its temperature leading to a sudden drop of the pressurizer level, and so to a decrease of the loop pressure. To overcome this phenomenon the electrical heater installed in the pressurizer is switched on and the pressure re-enters in the correct operational range in about 15 min. The opposite phenomenon occurs when the ramp-up phase starts: the coolant at TBM outlet swells leading to a pressurizer level increase, and so to a pressure spike. This spike is controlled activating the pressurizer spray system that allow the ingress of cold water. This cycle of under- and over-pressurization occurs for each pulse. The discrepancies shown for the total pressure when the two phenomena occur are due to the slightly different loop layout and the control logic adopted to activate the spray line. Instead, the discrepancies shown for all figure of merits in the first 0.12 h depend on the different simulation approach used to reproduce the first flat-top phase. Further details on this study can be found in [11].

3.1.1. WL fill & drain analysis. Ancillary operative analyses have been also performed with RELAP5/Mod3.3 to investigate the management of the WL facility. The first analysis carried out covered the filling procedure: the injection/filling line was placed before the pump of the primary circuit being lowest point of the system. This choice ensures the pushing of air toward the uppermost sections of the circuit. The injection was simulated with a time-dependent junction connected to a time-dependent volume aimed at imposing initial coolant conditions (1 bar, 27 °C). A time-dependent mass flow rate was adopted to overcome numerical instabilities in the code. The air initially contained is released toward the outer environment opening ad-hoc valves. The venting system was simulated as valve connected on the uppermost pipelines of the circuit and opening with a control logic based on the volume content (valve open if the liquid fraction is below 1.0). The analysis was carried out to discover and prevent the formation of air bubbles in the piping system, rather than set accurate values for the line diameter and flow rate to be used in a real procedure. The removal of air bubbles was achieved setting the inclination (1°) of the different pipes and installing air venting valves at the uppermost piping system point(s). Different pipe size areas were investigated for the injection line and the venting lines to find a suitable balance between contrasting requirements: minimize the time to conclude the filling procedure, keep low coolant velocities, minimize the number of venting lines, and minimize flow area to have a low as possible critical velocity in case of failure of an injection or vent line. The most suitable equilibrium was found adopting 2 vent lines and a single injection line (1/2″ each) for both circuits. The analysis also suggested the most efficient strategy to open/close bypass and isolation valves dispersed along the primary circuit.

The second analysis performed was the draining procedure: the coolant at atmospheric conditions in the loops is being routed to a discharge tank/sewer through ad-hoc lines. The aim of the analysis is to define the number of draining lines required to ensure the complete removal of the coolant. The

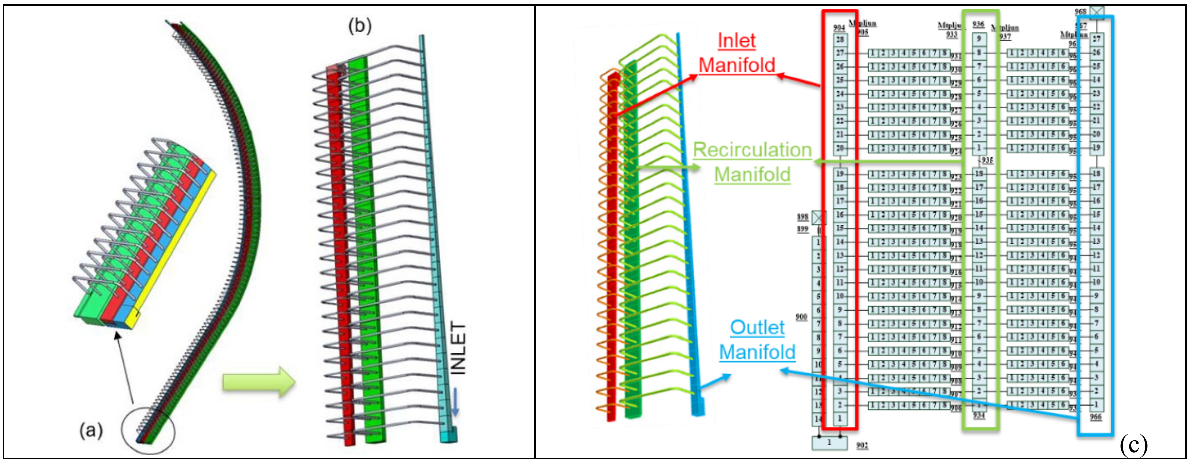

Figure 3. Schematic view of (*a*) the layout of the full-size OB manifolds, with the DWTs lumped in equivalent porous pipes, (*b*) of the test section under design and (*c*) the RELAP5/Mod3.3 input model.

valves used for air release in the filling procedure were used again to allow the ingress of air in the circuits. Two sensitivities were performed to investigate the time required to drain different loops only by gravity and with a pressurization of 1 bar. The analysis showed the necessity to install 8 draining lines in the primary loop and 5 in the secondary loop (1/2″ each), thus suggesting the need to modify the layout of the two circuits for both the WL facility and the WCLL-WCS. Moreover, a sensitivity study demonstrated that the pressurization of the loop is capable to half the time required to drain the loops, but the increased complexity of the facility and the overall acceptable duration obtained with only gravity (primary loop in less than 4 h, and secondary loop in less than 1 h) discourage the adoption of loop pressurization.

3.1.2. WCLL BB mock-ups: the manifold. Among the different mock-ups to be tested in the WL, a detailed study of that reproducing the WCLL BB manifold system is reported in following. To this purpose, between the different strategies investigated for the scaling down the WCLL BB water manifold serving the Breeder Zone of a WCLL BB segment [2], it was decided to keep the same velocity profile along the manifolds and scaling the mass flow rate and the cross-section area by the same scaling factor, equal to 4. To further simplify the manufacture of the test section, the curvature of the full-size manifold is discarded, and the pipes connecting the RECirculation (REC) to the Outlet Manifold (OM) are not nested within the pipes connecting the Inlet Manifold (IM) to the REC one, as shown in figures 3(*a*) and (*b*). The Double Wall Tubes (DWTs) of the full-scale design has been lumped in the mock-up in two equivalent pipes. Since the diameter of the pipes has been calibrated there to give the same cross section of the DWTs 1–7 (1″ sch. 160 pipe) connecting the IM to the REC and of the DWTs 8–11 (3/4″ sch. 160 pipe) connecting the REC to the OM, the same dimensions have been preserved here. The equivalent pipes are tuned in length or equipped with an orifice to give the same pressure drop at the nominal flow rate as the bundle of DWTs. Preliminary evaluations [12] show that the mass flow distribution among the equivalent DWTs is almost equivalent to the real scale component.

A further assessment is performed adopting RELAP5/Mod3.3 code to estimate the heat losses from the manifold test section. The scheme of the model input is reported in figure 3(*c*). The mass flow distribution inside the DWT pipes were calibrated according to the previous CFD results [12]. The thermal insulator thickness on the AISI 316 pipes and manifolds (i.e. ISOVER rockwool) ranges from 100 mm (Case 1) to 40 mm (Case 2) on the IM, REC and OM. In both cases a pressure of 15.5 MPa and a temperature equal to 313 °C was adopted for the internal surface of the manifold, whereas a temperature of 10 °C has been set for the environment. A natural convective heat transfer coefficient of 8 W m^{-2} °C has been considered on the external insulation surface, while radiation towards the environment has been neglected. The total heat loss for case 1 (100 mm) is about 5.1 kW to the environment equivalent to a temperature drop inside the test section of 0.1 °C. Adopting a lower insulator thickness (40 mm), the heat loss increases to about 7 kW with a temperature drop of about 0.2 °C, thus suggesting that the insulation thickness can be reduced without a big impact on the mock-up performances.

3.2. STEAM

3.2.1. CFD analysis of the OTSG mock-up. A numerical CFD investigation has been performed on the primary side of the OTSG component looking for the mass flow distribution of the fluid inside the 37 pipes. The CAD model (figure 4(*a*)) includes: the 180° U bend upstream the component, the inlet collector, the 37 pipes of the bundle, the outlet collector and 200 mm outlet pipe downstream. The CFD model is focused on the flow distribution region of the inlet collector enclosed by the red circle in figure 4(*a*), it includes only the fluid domain, and it is a purely hydraulic calculation (no thermal energy is considered). The OTSG mesh has 19.9 million nodes and 21.4 million elements. The CFD code adopted is ANSYS

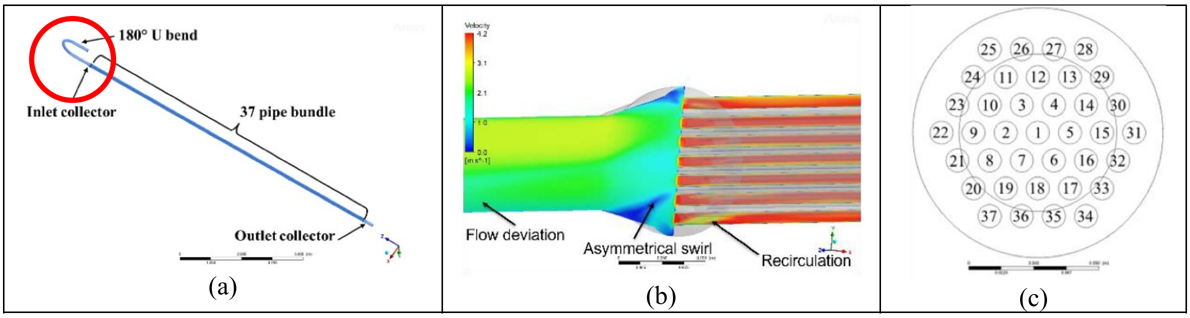

Figure 4. Sketch of the CAD model adopted for the CFD simulations (*a*), velocity contour at the inlet section of the OTSG (*b*) and nomenclature of the OTSG pipes view from the top (*c*).

Table 1. Fluid elastic stability check.

Section	Crossflow velocity (m s^{-1})	Critical velocity (m s^{-1})	Usage factor
Recirculation	6.00	7.61	1.27
Secondary fluid outlet	10.44	10.35	0.99

CFX R21.1 [13], water properties have been set as constant at 15.5 MPa and 310 °C while the turbulence model adopted is the SST k-omega model [14]. The CFD simulation is a stationary RANS with isothermal conditions, a mass flow of 16.05 kg s^{-1} is set on the inlet surface while a 0 Pa relative pressure is set on the outlet one. Mass flow rate is monitored during the simulation on all the 37 pipes. Full convergence is declared when all the residuals are lower than 10^{-5} and the mass flow monitoring points have reached a stable value.

The velocity contour on a central axial plane (figure 4(*b*)) highlights the presence of a flow deviation in the upstream pipe of the OTSG due to the U bend that give rise to asymmetric flow swirls in the inlet manifold and flow recirculation at the inlet section of one pipe of the bundle. Analysing in detail the mass flow distribution inside the bundle, as monitored in the simulation and fixing an average mass flow rate in the pipe of 0.4337 kg s^{-1}, some pipes show a flow rate lower or higher of 1% against the average value. In detail (figure 4(*c*)), three pipes (9, and 21) located under the asymmetrical swirl suffer a mass flow reduction ranging from 1.32% to 1.39% while on the opposite side four pipes (14, 15, 16 and 32) suffer an increased mass flow ranging from 0.6% to 0.88%. The mass flow distribution is found to be acceptable for the OTSG design. More details on this study on the model, loads, boundary conditions and results obtained can be found in [15].

3.2.2. Investigation of OTSG vibration-induced issues. In order to preliminarily investigate the potential onset of vibration-induced issues within the tubes at some critical regions of the OTSG mock-up, the procedure reported in [16] has been adopted, making use of proper assumptions where necessary. It has to be underlined that, as widely explained in literature, the methods and correlations commonly used to perform vibration studies are characterised by high margins of uncertainties, as they do not take into account the full set of phenomena potentially generating vibrations (some having a stochastic nature) and, moreover, being strongly dependent by the tubes lattice's parameters. However useful indications can be often obtained, establishing if vibration-induced issues in the tubes can be reasonably excluded (in case acceptance criteria are satisfied with large margin) or if they could represent a concrete concern, requiring more detailed studies (e.g. numerical analysis) and/or specific experiments.

Regarding the DEMO OTSG mock-up, three different sections have been identified as the most critical in terms of vibration-induced issues: the secondary fluid inlet section, at the lowest Z coordinate, where the inlet fluid has been considered as saturated liquid; the recirculation section, at $Z = 8.722$ m, where the secondary fluid has been considered as saturated steam and the secondary fluid outlet section, and at the highest Z coordinate, where the outlet fluid has been considered as superheated steam. In these sections, the fluid crossflow with respect to the tubes vertical orientation may originate non-negligible vibrations. In particular, in the lowest section, the fluid elastic stability check and the wake shedding check have been carried out. Instead, in the other two sections characterised by the presence of steam, the acoustic vibration and random excitation checks have been performed together with the fluid elastic stability check. Moreover, the vibrations potentially induced by the parallel flow has been checked too in all the three sections.

Results have shown a very good behaviour at the secondary fluid inlet section, where vibration-induced issues can be excluded at all. Conversely, some concerns may arise looking at the fluid elastic stability check in the other sections, whereas parallel flow, acoustic resonance and random excitation do not seem to be a problem. Indeed, as reported in table 1, the usage factor predicted for the fluid elastic stability check is slightly above the unity for the recirculation section. This means that the check here is passed even if with a little margin. Instead, as to the secondary fluid outlet section, the crossflow velocity (depending on the crossflow section and on the fluid thermodynamic conditions) is practically equal

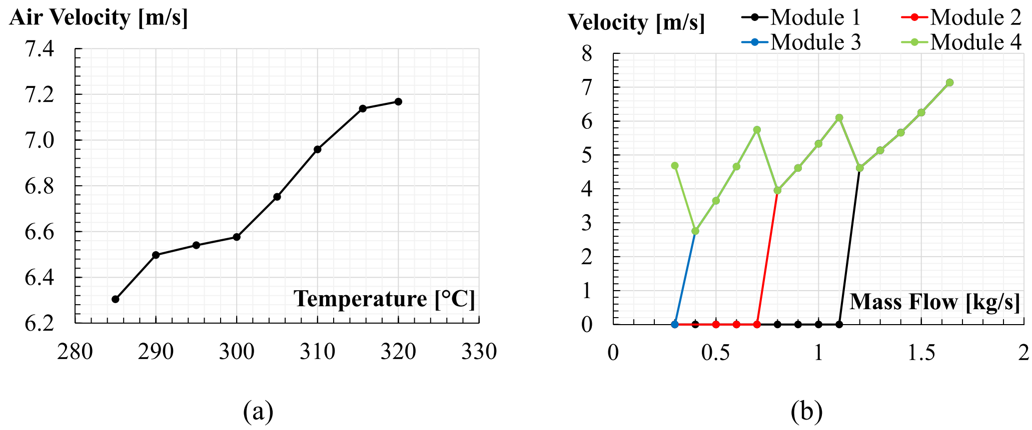

Figure 5. AC1 modules air velocity variation for different OTSG outlet temperature (*a*) and AC1 modules air velocity variation for different OTSG vapour mass flow (*b*).

to the critical value (function of the system natural frequency and of the pipe dimensions and material), giving rise to little concerns on the potential onset of vibration induced issues. In any case, as the other checks are widely passed, the possible effect of such a kind of phenomenon should not be particularly intense. Moreover, accelerometers and strain gauges are foreseen to be installed in the OTSG mock-up in order to measure vibrations and deformations in these areas, as well as to validate detailed dynamic models adopted for numerical calculations.

3.2.3. Detailed TH analysis of the air cooler system. The produced steam is condensed and subcooled through Air Coolers (ACs), which use air in forced convection to cool down the working fluid. The cooling process is divided into two separate components: the de-superheating and condensation air cooler (divided into four parallel modules to facilitate the low load operations), named in the following as AC1, and the sub-cooling module, named as AC2. The condensation capability of the AC1 has been object of dedicated analyses showing that no standard control logics can be used to regulate the air mass flow (that has been then determined after a sensitivity). In fact, operating in saturation, the outlet temperature is not an indicator of the fluid outlet thermo-dynamic conditions. The RELAP5/Mod3.3 detailed results of the AC1 in nominal conditions show an unbalanced mass flow distribution among the four modules, as a result of the different chain of pressure drops characterizing the lines reaching each module, due to geometrical asymmetries in the pipe paths. Consequently, even if the single modules operation differs from the nominal one, the fluid averaged conditions at the AC1 outlet fit the requirements with a very low margin.

Considering the extremely various power conditions that will be tested in STEAM, a set of sensitivity analyses has been performed to characterize the AC1 four modules condensation capabilities in different operative conditions, aiming at determining in each case the required air velocity. At first, OTSG outlet temperature has been varied from 285 °C to 320 °C keeping constant the nominal mass flow (figure 5(*a*)), then the vapour mass flow has been varied from 100% to 20% keeping the OTSG outlet temperature fixed and intercepting one module per each 25% decrease of the total mass flow (figure 5(*b*)). Results show that the presence of an inverter allowing the air velocity variation on all modules guarantees the correct operation of the system in the analysed scenarios with an error on the AC1 averaged outlet enthalpy lower than about 3%.

3.3. LIFUS5/Mod4

Considering the objectives stated in section 2, the LIFUS5/Mod4 facility aims at investigating the response of the WCLL-TBS both during nominal operation and in-box LOCA scenarios. Even though LIFUS5/Mod4 layout reproduces the ITER WCLL TBS PbLi loop, the main difference between the two circuits is the absence of the recirculation pump in the LIFUS5/Mod4 one. This is mainly due to the 'violence' of the experiment which will be tested in. This led to an additional secondary circuit for the PbLi load and drain, and in a change of some operating procedures which have been analysed during the design phase.

3.3.1. LIFUS5/Mod4 fill & drain analysis. The RELAP5/Mod3.3 nodalisation of LIFUS5/Mod4 facility has been set up in order to analyse selected operational scenarios including fill and drain procedures. The loading procedure is composed by the pre-heating phase, the loading of PbLi from the load tank to the recirculation tank and finally from the recirculation tank to the entire loop. The loading starts with a slight argon overpressure to prevent air entering the circuit. Then the pressure in the load tank starts to increase. The argon cover gas will push the alloy inside the Recirculation Tank. Then the third phase can start with the opening of valves between recirculation tank, TEU equivalent volume and test section mock-up. A first tentative procedure has been investigated using the upper region of TEU as a relief region and pressurizing the recirculation tank till the operation condition. The main result of this procedure is that the highest region of the facility will act as a trap for the non-condensable gases, with an accumulation of argon (figure 6). To avoid the above represented trap region,

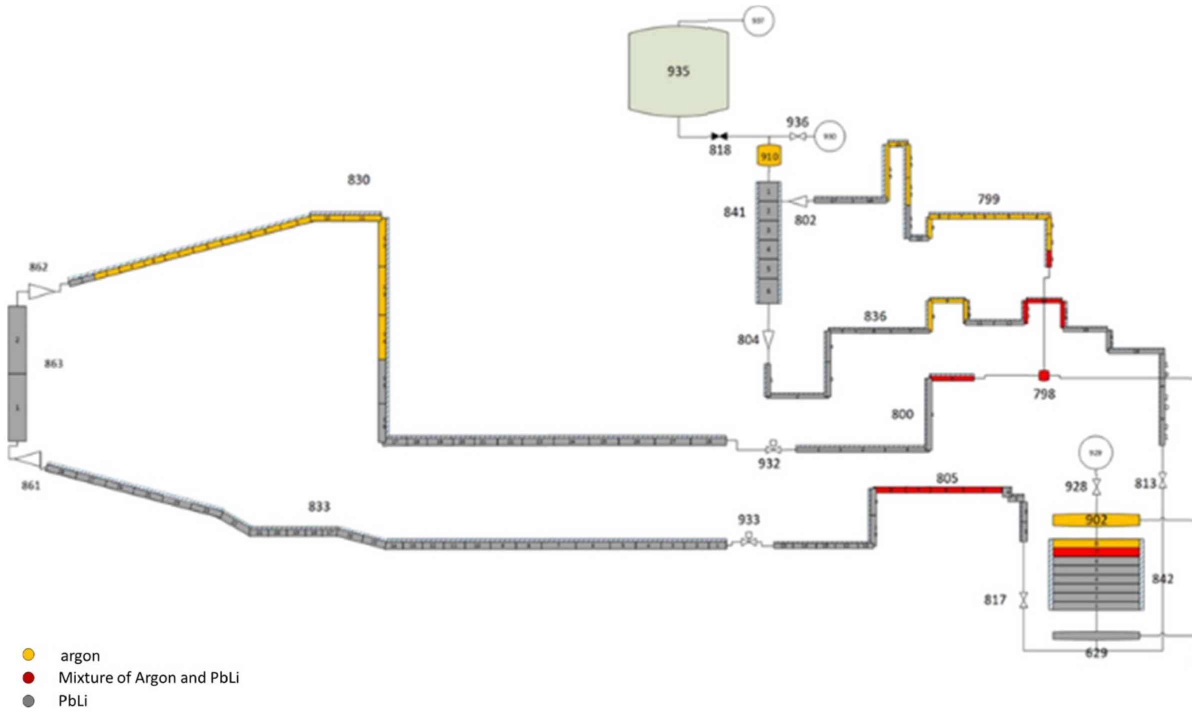

Figure 6. LIFUS5/Mod4 fill analysis.

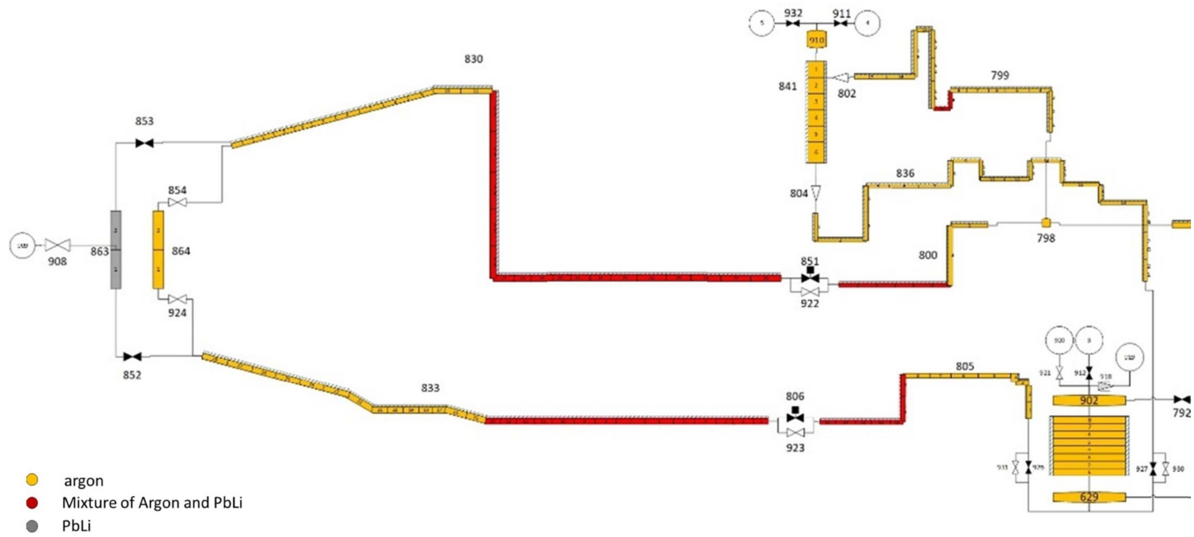

Figure 7. LIFUS5/Mod4 drain analysis.

a possible solution for the design is to increase the relative elevation of the TEU cover gas region and decrease the maximum elevation of the outlet pipe. An alternative procedure is now under investigation, creating void condition in the PbLi primary loop.

After the execution of the test, it is necessary to move the alloy from the main part of the facility to the secondary part (Drain Tank). Thus, the initial condition of the draining phase depends on evolution of the test. As first case, it is assumed that the isolation valves worked in the right way, i.e. avoiding the over-pressurization of the recirculation tank and the opening of the relief valve. So, at the end of the transient the mock-up and the piping will be at higher pressure in respect to the two tanks. Specified in this way the set of initial condition, the draining can start. It can be divided in different phases, in particular the Hydrogen analysis and depressurization of the main loop, the depressurization of the piping and test section, the opening of the link between recirculation and relief tanks, the opening of the isolation valves and finally the Argon pressurization of the circuit from the TEU moving the remain PbLi from the main circuit to the draining tank.

At the end of the procedure (figure 7) not all the alloy is moved to the draining tank. The parts in red have still a mixture of PbLi and argon due to both the pipes positioned at the same level of the bottom of the recirculation tank and the 'U' shape of the pipes. The results suggest the disposition of the recirculation tank in a lower position and to avoid the up and down path of the outer pipe before the TEU.

4. Conclusions and perspectives

The W-HYDRA experimental platform is being designed and built at ENEA Research Centre in Brasimone. It will represent a test bed devoted to host WCLL BB and TBM mock-ups to be tested under relevant operative conditions. The realisation of the W-HYDRA experimental platform is pivotal towards the achievement of a more mature status of water-related technologies to be adopted in the WCLL BB.

Concerning the WL, several design analyses involving filling, draining, heat-up operational phases, as well as nominal and accidental scenarios have been carried out. Thus, modifications to the layout have been performed to take into account the criticalities highlighted from the analyses. At the same time, the test matrices for the experiments to be performed on the BB prototypical mock-ups are being defined as well. The design of the facility is being finalised and the procurement of the main components is foreseen to take place in the very next future.

As far as STEAM is concerned, both detailed CFD and RELAP5/Mod3.3 analyses carried out so far have contributed to better define the operational procedures of the plant and a more detailed design of the components. Similarly to WL, the finalisation of the design phase is being reached and the procurement phase is approaching.

Finally, for what concern LIFUS5/Mod4 facility, detailed calculations of in-box LOCA events occurring in the test section are needed to progress and finalise the design activities, as well as pre-test analyses by means of the SIMMER-RELAP5/Mod3.3 coupling. As in the case of the BB prototypical mock-ups, a test matrix is going to be issued as well.

The construction of the W-HYDRA platform is foreseen to be achieved by the end of 2024, in order to start the commissioning procedure and first experimental tests in the first quarters of 2025.

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References

[1] Boccaccini L.V. *et al* 2022 Status of maturation of critical technologies and systems design: breeding blanket *Fusion Eng. Des.* **179** 113116
[2] Arena P. *et al* 2021 The DEMO water-cooled lead–lithium breeding blanket: design status at the end of the pre-conceptual design phase *Appl. Sci.* **11** 11592
[3] Arena P. *et al* 2023 Design and integration of the EU-DEMO water-cooled lead lithium breeding blanket *Energies* **16** 2069
[4] Tincani A. *et al* 2021 Conceptual design of the main ancillary systems of the ITER water cooled lithium lead test blanket system *Fusion Eng. Des.* **167** 112345
[5] Vannoni A. *et al* 2023 STEAM experimental facility: a step forward for the development of the EU DEMO BoP water coolant technology *Energies* **16** 7811
[6] Tincani A. *et al* 2023 Conceptual design of the steam generators for the EU DEMO WCLL reactor *Energies* **16** 2601
[7] Barucca L. *et al* 2022 Maturation of critical technologies for the DEMO balance of plant systems *Fusion Eng. Des.* **179** 113096
[8] Vannoni A., Lorusso P., Eboli M., Giannetti F., Ciurluini C., Tincani A., Marinari R., Tarallo A. and Del Nevo A. 2023 Development of a steam generator mock-up for EU DEMO fusion reactor: conceptual design and code assessment *Energies* **16** 3729
[9] Eboli M. *et al* 2023 PbLi/water reaction: experimental campaign and modelling advancements in WPBB EUROfusion project *Energies* **16** 7729
[10] Badodi N., Eboli M., Cammi A. and Del Nevo A. 2023 Status, features, and future development of the LIFUS5/Mod4 experimental facility design *Appl. Sci.* **13** 482
[11] Gonfiotti B. *et al* 2024 Assessment of the relevancy of ENEA water loop facility with respect to ITER WCLL TBS water cooling system by considering their thermal-hydraulic performances during selected transient conditions *Fusion Eng. Des.* **200** 114375
[12] Collaku A., Arena P., Del Nevo A., Marinari R. and Savoldi L. 2023 Design of a test section for the experimental investigation of the WCLL manifold hydraulic features *Energies* **16** 2246
[13] ANSYS INC 2019 *ANSYS User Manual, Version 19.2* (Ansys Inc)
[14] Menter F.R. 1994 Two-equation eddy-viscosity turbulence models for engineering applications *AIAA J.* **32** 269–89
[15] Vannoni A. *et al* The STEAM facility: design and analysis *Proc.* 20th *Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20)* (*Washington, D.C., USA, 20–25 August 2023*) (https://doi.org/10.13182/NURETH20-40567)
[16] Singh K.P. and Soler A.I. 1984 *Mechanical Design of Heat Exchangers and Pressure Vessel Components* 1st edn (Springer)