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Fusion Technologies Development at ENEA Brasimone Research Centre: Status and Perspectives

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In the European and international framework, ENEA coordinates the Italian fusion program, supported by linked third parties as universities, research institutes and industries. In this context, the Experimental Engineering Division (FSN-ING) is involved in experimental and numerical activities related to Breeding Blanket (BB) and Divertor technologies development.

This paper describes the scientific works presently ongoing at Brasimone R.C. enveloped in LLE, lithium, helium, tritium and pressurized water technologies, characterization of structural materials, analysis of materials corrosion rate and development and qualification of anti-permeation/corrosion barrier. The experimental activities conducted for the investigation of safety-relevant scenarios as In-Box LOCA (LLE-water interaction in the WCLL or shock waves propagation generated by helium injection in LLE in the HCLL/DCLL-BBs) are here reported.

Finally, new activities have been planned to support the Divertor Tokamak Test divertor characterization, the large-scale LLE-water interaction and a LLE components validation in relevant scale for WCLL-BB.

1. Introduction

The Experimental Engineering Division (FSN-ING) by the ENEA Brasimone Research Centre (R.C.) includes decades of scientific expertise in experimental and numerical research activities in supporting Fusion Technology development. More in detail, Brasimone R.C. together with the linked third parties (universities, research institutes and industries) collaborates for activities related to Breeding Blanket (BB) and Divertor technologies development, providing for design, safety analysis, material qualification and experimental validation, hosting several research infrastructures conceived and operated for this aim. Several activities are performed in support of BB technology and ancillary system development.

In particular, strong effort is devoted to the design of the Water-Cooled Lithium-Lead (WCLL) BB. This concept is featured by pressurized water as coolant and Lithium-Lead Eutectic (LLE) enriched at 90% in ^{6}Li as breeder, neutron multiplier and tritium carrier.

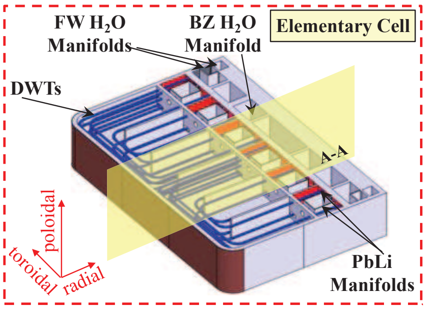

Figure 1: WCLL BB 2018v0 design: Isometric-View of the elementary cell

The design is based on DEMO2017 baseline [1], having 16 sectors. The single module segment approach has been selected, following design studies, such as thermo-mechanic analyses [[2]-[4]], neutronic [5], and magnetohydrodynamics (MHD) [[6]-[7]].

The Back Supporting Structure (BSS) has a thick of 100mm and it is in charge of connecting the breeding blanket segment to the vacuum vessel. Thermo-mechanical performances have been demonstrated considering the segment [3], [8] and the sector different load combinations: gravity, thermal and electro-magnetic [9]. Compliance with the rules prescribed by the safety codes was verified. Two water manifolds, First Wall (FW) and Breeding Zone (BZ), are integrated between the BSS and the LLE manifold. This design layout ensures an efficient cooling performance of the inboard BSS [10] as well as an optimized shielding of the vacuum vessel and magnets [5]. The water coolant temperatures are 295°C and 328°C at the inlet and outlet, respectively. The LLE manifolds are currently designed as coaxial square structures [11], delimited in radial direction by the water coolant manifold and the breeding zone. The LLE does not transport heat by design, thus its temperature is constant (330°C) at the inlet and outlet of the breeding zone. Functions and requirements make the design of the manifold challenging. Indeed, the LLE distribution in toroidal direction shall be uniform and ensure an efficient recirculation in the BZ; the maximum allowable pressure is set to 18.6 MPa, in accidental conditions; the risk of LLE water contact shall be minimized [12] and it shall contribute to the tritium breeding ratio performances. Horizontal and vertical stiffeners are placed in the BZ and are sized to withstand the thermo-mechanical and electro-magnetic loads postulated in normal, off normal and accidental

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conditions [12]. These constrains the LLE flow path, as well as affects the cooling system layout, which is based on 20 double wall tubes and square cooling channels, side 7mm and pitch of 13.5 mm [[13]-[15]]. The cooling system, at 15.5 MPa, is featured in order to keep the temperature of the structural material below 550°C and to deliver energy to the primary heat transport systems, i.e. FW and BZ [17]

Concerning the Work Package Balance of Plant (WPBoP) task in EUROfusion, the pool-type lead-bismuth eutectic cooled facility CIRCE (CIRcolazione Eutettico), has been involved in an experimental campaign, aiming at supporting the development of a LLE/water heat exchanger for DEMO primary heat transfer system of the Dual Coolant Lithium Lead (DCLL) BB [17] [18]. For this purpose, a dedicated test section named HERO (Heavy Liquid mEtal pRessurized water cOoled tubes) has been implemented in CIRCE. HERO is a mock-up in large scale of a Steam Generator (SG) consisting of seven double wall bayonet tubes arranged with a triangular pitch in a hexagonal shell, in a geometry consistent with the selected configurations for the DEMO heat exchanger. The double wall configuration increases the plant safety, reducing the occurrence of LLE-water interaction and it allows an easier detection of leakages thanks to the pressurization of the separation region by inert gas. The experimental thermal-hydraulic characterization of the steam generator has been realized performing a total of five tests at different water pressures (e.g. 6 MPa, 8 MPa, 12 MPa and two tests at 10 MPa) and for each test an experimental sensitivity analysis has been performed, changing the liquid metal mass flow rates in four tests (40, 33, 27, 20, 10 kg/s) and the SG feedwater flow rate in the repeated test at 10 MPa (primary side liquid metal mass flow rate 27 kg/s). The experimental results have demonstrated the technological feasibility of the prototypical steam generator bayonet tube, suitable for the LLE loop of the DCLL-BB.

Concerning the activities in support of the design of the Helium Cooled Lithium Lead (HCLL), Helium Cooled Pebble bed (HCPB) and DCLL, the thermalfluidynamic characterization of the main components and instrumentations up to scale 1:1 is performed with the support of HE-FUS3 facility [19]. The loop can perform the characterization of the TBS and BB in the following operation modes: i) long term isothermal cooling flow; ii) slow thermal cycling flow; iii) fast cold thermal shock flow; iv) Loss Of Coolant Accident (LOCA)/Loss OF Flow Accident (LOFA) simulation.

Moreover, experimental activities are performed for the study of tritium removal from the He flow. In particular, in the Coolant Purification System (CPS) of ITER HCPB/HCLL BB, the tritium removal is performed in two steps: oxidation of Q_2 (Q = H, D, tritium) into Q_2O and following removal of the generated Q_2O from the helium flow. The CPS also has the scope to transform the removed tritium in a suitable form for the downstream tritium processing systems. The oxidation of Q_2 considers the use of a catalyst consisting of copper oxide. For the removal of Q_2O, micro-porous materials, called molecular sieves, are taken into account. Reducing Beds (RBs), based on use of metallic alloys, are the reference technology to transform the trapped Q_2O in Q_2, which will be directed to the downstream tritium processing systems. The molecular sieve beds, for the Q_2O removal, and the RBs, for the transformation of Q_2O into Q_2, are also included in the Tritium Extraction System (TES) of the HCPB Breeding Blanket concept. HYDREX (HYDRogen EXtraction) is the experimental facility having the scope to test processes, components and materials considered for the CPS and TES of HCPB/HCLL Breeding Blankets. HYDREX, uses hydrogen instead of the radioactive tritium and it can compare the performances of different types of molecular sieves, also in conditions characterized by a strong difference of temperature and pressure between the purification and regeneration phases, as for the CPS. The facility includes oxidizing beds using copper oxide for hydrogen oxidation, but different oxidizing materials can be tested. During the regeneration of the molecular sieves, the trapped water is released and directed to a RB, in which the performances of a selected metallic alloy can be studied.

In the frame of the Broader Approach, under the umbrella of the IFMIF/EVEDA activities, great interest was dedicated to the study of erosion/corrosion phenomena on relevant structural material (EUROFER97 and F82H) under pure lithium flowing conditions. To this aim LIFUS6 facility was realized at ENEA and erosion/corrosion tests were conducted reproducing the working conditions expected in the Li loop and in the target assembly of IFMIF-DONES plant under in term of Li temperature, flow velocity and impurity content, adopting appropriate hot and cold traps for impurities like nitrogen, carbon, and oxygen. The results on the long tests performed on EUROFER during the first experimental campaign (from 1222 h to 4000 h) have shown a good resistance behavior of the material, characterized by corrosion rates lower than 0.2 μm/year, very few and isolated corrosion items and only a small chromium and tungsten depletion in the alloy composition at the surface [20].

Another relevant research line pursued at Brasimone R.C. deals with the remote handling and maintenance procedure for nuclear components. In particular, the divertor refurbishment platform facility was established at ENEA Brasimone R.C. since 1995. It was aimed at testing and validating the refurbishment operations to be performed on the ITER Divertor cassettes. More than 2500 hours of Remote Handling (RH) operations were performed on several prototypes of different Divertor cassette concepts. However, the DRP was conceived to be general enough to host several types of RH activities. Since 2002 it was used for the qualification of the maintenance tasks for the Li target assembly of IFMIF and today it is the reference facility in support to the EUROfusion project known as DEMO-Oriented Neutron Source (DONES).

Within the WP Early Neutron Source (WPENS) of EUROfusion, Brasimone R.C. is committed in the engineering design of the target system of DONES, aimed at producing a high intensity neutron flux with fusion-like spectrum to irradiate candidate materials to be used in DEMO and future fusion reactors. The work covers several aspects including analytical and numerical analyses as well as experimental validation activities.

2. LLE Technologies Development

Experimental activities on instrumentation and components for flowing LLE are carried out aiming at supporting the WCLL TBS (Test Blanket System). In particular, absolute and differential pressure transducers, flow meters and level meters were tested in IELLLO facility [19]. These instruments were then used to assess the performances of heat exchangers and of a permanent magnet pump.

IELLLO is an eight-shaped loop in which LLE circulates at a maximum mass flow rate of about 2.5 kg/s and can reach a temperature of 550°C in the hot side, while the cold side is kept below 350°C to protect the pump and the Coriolis flow meter. With respect to the loop described in [19], IELLLO underwent a few modifications in 2015 and in 2018. In 2015, the original mechanical pump was substituted with a permanent magnet pump, while new instruments to be tested were added in 2018. LLE is circulated by the permanent magnet pump and increases its temperature going through the economizer, a counter-current pipe in pipe regenerative heat exchanger. Then, the alloy can pass through a 40 kW electrical heater or it can maintain its temperature constant in a bypass line. Regardless of the path chosen for the operation, LLE passes through the test section and it cools down in the economizer and in the air cooler, before returning to the pump.

The results summarized in the next sections 2.1 and 2.2 are described in detail in [21], [22].

2.1 Instrumentation

Commercial measurement devices are not currently designed to work with LLE. In particular, reliable instruments to control key operative parameters, such as pressure, flow rate and LLE level, are still under development. ENEA Brasimone R.C. tested and contributed to improve the performances of absolute and differential pressure transducers, flow meters and level meters.

A GEFRAN piezoresistive absolute pressure transducer was compared with an already-qualified Barskdale transducer installed in gas phase, revealing a maximum discrepancy of about 0.5% of the full scale output. This comparison, performed at several working temperatures, allowed also correcting a temperature drift by implementing an empirical formula in the control software. The GEFRAN absolute pressure transducers were installed with threaded connections in IELLLO facility and with flanged connections in THALLIUM test section [23] The threaded connection was not the proper choice for this instrument as LLE was leaking through it after few hours of operation (at about 350°C and 6 bar). Instead, the flanged connections used in THALLIUM guaranteed no leakages over two experimental campaigns and with pressures up to 52 bar (along with about 400°C).

Guided-microwave level meter was tested against a graduated cylinder, revealing an accuracy of ± 2 mm (consistent with the accuracy declared by the supplier). Then, the instrument was installed in the expansion tank of THALLIUM test section, where it produced repeatable results over 11 tests (with maximum pressure of 52 bar and temperature of 400°C). The same instrument was installed on the storage tank of TRIEX-II facility that was successfully tested and validated in the former TRIEX [24], [25] , further verifying its reliability for LLE.

Three flow meters were tested and compared with each other at different flow rates. The thermal flow meter (TFM) was considered the most reliable of the three as:

- the principle of operation of the TFM is the simplest one, thus unpredicted phenomena that can hinder the correct working can be excluded;
- the Coriolis should measure the density, but it did not: a discussion with the supplier led to the possible conclusion that LLE density is out of the measuring range (i.e. 10,000 kg/m^3);
- the Vortex flow meter is not completely reliable as LLE density and viscosity could affect the correct formation of eddies, that constitute the working principle of this instrument (LLE viscosity lies between 1-3·10^{-3} Pa·s).

As a drawback, this design of the thermal flow meter has a lower working limit of 0.5 kg/s. Thus, if the thermal mass flow meter should be installed elsewhere, it is suggested to carefully select the correct design and then to test the instrument at the particular conditions in which it would work, consequently adapting the settings (particular attention must be paid to the safeguard on the temperature gradient at the inlet of the instrument).

As far as differential pressure transducers are concerned, five of them were installed and tested. They were firstly tested with stagnant LLE, checking the hydrostatic pressures and then used to assess the pump head and the pressure drops of Coriolis and thermal mass flow meters, of the air cooler and of the economizer. The experiments show that they can successfully be used in LLE, but with two warnings:

- their temperature working range is small, as their membrane cannot work above 400°C, while the melting point of LLE is about 234°C;
- particular attention must be paid to their installation not only to avoid LLE freezing or membrane damages, but also to assure LLE-membrane contact.

They were used to measure the pressure drops across the Coriolis and thermal mass flow meters. Both instruments produce very small pressure drops, with maxima of about 0.025 and 0.03 bar at about 2.5 kg/s.

2.2 Components

The instrumentation, after the experimental validation and assessment on liquid metal loops, was used to characterize the performances of the economizer, the air cooler and the permanent magnetic pump, which are three components that are relevant for the LLE loops of the WCLL TBS and BB.

Thanks the use of the qualified thermal mass meter, the efficiency of the economizer and of the air cooler at lower flow rate has been addressed, comparing the results with those gained in [21], based on the use of a Vortex flow meter. As far as the economizer is concerned, the gained experimental data shown that its efficiency decreases at higher flow rates, while it slightly increases with the maximum temperature of the loop. The highest efficiency is about 87.5% when the mass flow rate is about 0.5 kg/s and the maximum temperature of the loop is 500°C. The lowest efficiency is about 65% when the mass flow rate is about 2.5 kg/s and the maximum temperature of the loop is 400°C. According to that, it is expected an higher efficiency for this component if used for the WCLL TBS, where assumed mass flow rates are lower than those used in these tests (0.5-2.5 kg/s).

Regarding the air cooler, its capability to cool-down the liquid metal in the cold part of the loop at the desired temperature (usually below 350°C) was verified, even in the most demanding situation. Forced convection was successfully tested at the highest liquid metal flow rates (above 2.15 kg/s).

The differential pressure transducers allowed measuring the pressure drops across the air cooler and the economizer. The air cooler has the larger impact on the total pressure drops of the loop (about 11% of the total), while the economizer is less significant (about 3% of the total).

As far as the permanent magnet pump is concerned, it was reliably used in two experimental campaigns, characterizing its pressure head at different flow rates. Its operation was very stable over the speed range, with an exception below 10% of the rotational speed.

2.3 Numerical Tools

RELAP5-3D was used to simulate the tests carried out in IELLLO, highlighting small discrepancies both in the economizer efficiency (average discrepancy of about 3 percentage points) and in the air cooler performances (average discrepancy of 3°C).

RELAP5/mod3.3 was modified to include the LLE thermophysical properties [26] (using the ones proposed in [27]) and then used to simulate the experimental campaigns of THALLIUM test section. As the property library for LLE in RELAP5-3D has an upper threshold of 40 bar, it was not possible to directly use this version of the code. The numerical simulations confirmed that the modified version of the RELAP5 code was able to accurately predict the pressure trends of an In-box LOCA occurring in the HCLL TBM (Test Blanket Module), with an average discrepancy of about 3 bar (over a maximum experimental pressure of about 52 bar) [28].

3 Tritium Technologies

3.1 Tritium Permeation Investigation

The tritium balance in DEMO Reactor is a key factor for the successful of the energy production. Three of the four BB concepts candidates for DEMO use LLE enriched at 90% in 6Li as breeder, i.e. WCLL, DCLL and HCLL BBs. Therefore, the investigation of LLE tritium transport parameters, as Sievert's constant, tritium diffusivity, etc are fundamental for the development of a tritium transport model of the all systems. In fact, the inventory of tritium in fusion reactors blankets and the permeation of tritium into the blanket coolant, with the consequent leaks toward the environment, are strongly depending on its solubility and diffusivity in the LLE.

HYPERQUARK (Hydrogen Permeation Quartz Chamber) facility installed at Brasimone R.C., with Quartz test section and connections, will be used to measure the tritium solubility and diffusivity in LLE in the range of temperature 300–550°C and it will be operated with hydrogen partial pressure in the range 10–200 Pa [29]. The facility can work with desorption and absorption technique. The apparatus has been designed to allow the testing of H/D concentration sensors in LLE in operative conditions relevant to the WCLL–TBM and the characterization of hydrogen permeation barrier, which are required in order to reduce the tritium inventory inside the tritium building and the tritium release in the coolant inside the BBs.

3.2 Tritium Extraction Technologies

For the self-sufficiency of the fusion reactor and for the minimization of tritium release towards the external environment a tritium extraction and removal system from LLE with high efficiency is a critical issue towards the DEMO development. Different types of tritium extractors from the liquid LLE have been considered: Gas-Liquid Contactors (GLCs), among which the most promising technology is the packed-column, Permeation Against Vacuum (PAVs) and vacuum droplet towers. These technologies have been studied from both theoretical and experimental point of view with the support of the experimental facility TRItium Extraction (TRIEX) [24], [25] and in the up-graded facility named TRIEX-II. A mock-up of GLC, 1:1 ITER TBM scale, was characterized in TRIEX-II at 400 and 450°C in the liquid metal flow between 0.2 and 1.2kg/s. The facility can supply a maximum LLE flow to the test section of 6kg/s in the temperature range between 300 and 530°C. The LLE is pumped in the facility with a permanent magnet pump and is sent to the test section, the hydrogen isotopes extractor, the mass flow is controlled with the support of the pump inverter and two regulation valves. The Q_2 is solubilized inside the LLE with a GLC saturator, where the Q_2 is injected inside the saturator through a gas injector system, in a mixture with helium. The saturator allows the alloy to reach the desired hydrogen or deuterium concentration, which simulates the WCLL-TBM/BB outlet composition of LLE. The main characteristic of the facility is the instrumentation installed that allow to measure the tritium extraction efficiency:

- thermal flow meter to measure LLE flow rate in the test section
- differential pressure meter to measure pressure drops in the test section and TRIEX-II pressure head
- hydrogen isotopes permeation sensor to measure Q partial pressure in LLE
- mass spectrometer able to detect deuterium in helium stripping gas.
- LLE level sensor

Figure 2: TRIEX-II facility installed at C.R. Brasimone.

The experimental characterisation of the GLC carried out with helium as stripping gas and helium plus hydrogen, with deuterium solubilised in LLE to simulate tritium, has shown as efficiency up to 44%. The hydrogen permeation sensors used in TRIEX and TRIEX-II were qualified in HYPERQUARK facility.

On the basis of experimental and numerical results obtained the TER system of DEMO based on GLC technology will be design. GLC is the reference solution for ITER LLE system and the back-up solution for the WCLL/DCLL tritium extraction system of DEMO reactor, while the reference technology is PAV designed to reduce the tritium concentration at the outlet of the system of 90%. The system was design taking into account that the tritium partial pressure in the lead alloy is in the range between 10 and 200Pa.

4 Structural Materials and Coating Development

4.1 Structural Materials

The development and mechanical characterization of structural materials able to withstand the harsh operation conditions expected in DEMO, in particular the materials compatibility with the coolant and the LLE is mandatory for the design of the reactor. Several efforts were dedicated to upgrade and characterized the structural material, with particular reference to the advanced EUROFER steel [30]:

- shift of ductile to brittle transition temperature under irradiation (displacement cascade and helium generation) at low temperature
- thermo-mechanical treatments to improve the high temperature properties

The improved materials are qualified in mechanical laboratory to obtain data on their behavior under relevant conditions. slow strain rate, creep, creep-fatigue, tensile, fatigue, low cycle fatigue, fracture toughness, are tests carried out in order to perform a complete thermo-mechanical characterization of such materials.

4.2 Coating

To reduce the tritium permeation from LLE to the coolant and in the environment through the LLE pipes/components walls at high temperature, the application of a protective coating on the blanket walls is mandatory. The coating will minimize also the corrosive effect of EUROFER material and the release of corrosion product outside the vacuum vessel. In this context, Al-based coatings are considered as reference for barriers thanks to their good chemical compatibility with the LLE alloy and their capability to reduce permeation. Two coating technologies were developed in the frame of the EUROfusion project by ENEA/IIT: Pulsed Laser Deposition (PLD) and Atomic Layer Deposition (ALD) coating. An upscale of PLD and ALD system were completed in order to demonstrate the capability to coat a relevant mock-up of WCLL BB. The coating was characterised from the point of view of chemical compatibility with LLE (corrosion process), permeability with the support of PERI II facility and thermal test to evaluate coating adhesion.

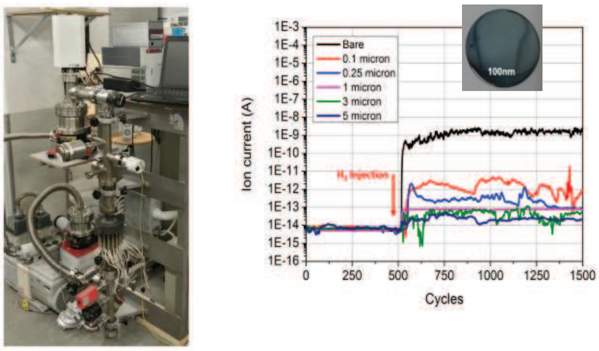

Figure 3. (Left) PERI-II facility used to characterize permeation factor of materials. (Right) QMS spectrum of hydrogen detection after thermal cycle (500 cycles), hydrogen is injected at 100mBar at 550°C

PERI-II facility allows characterising the Permeation Reduction Factor (PRF) of material and coating in the temperature range between 200 and 700°C with hydrogen and deuterium. A PRF of 1000 was obtained with PLD coating on EUROFER substrate at 550°C with 2μm of thickness. The performance of the coating does not change after thermal cycle tests.

PLD and ALD coating were characterised in stagnant LLE at 550°C in Alumina crucibles for 8000h, performing metallographic examination with SEM and EDX, showing as these techniques allow to create efficient anti-corrosion barrier against LLE environment.

To demonstrate the scale-up of the PLD and ALD technologies from laboratory scale to industrial scale a ALD machine able to realize the coating inside a WCLL mock-up of 0.5x1x1m is under construction at Brasimone R.C.; the preliminary characterisation was carried out successfully on 0.3x0.2x0.2 chamber

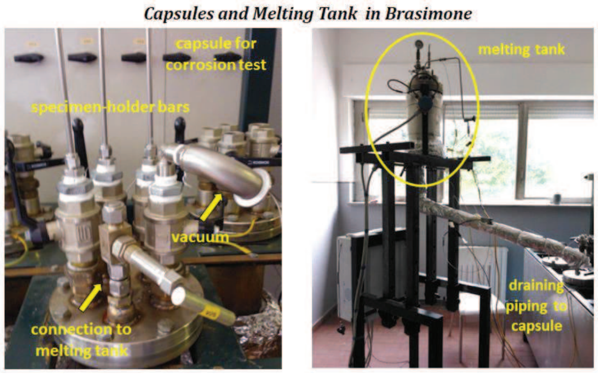

Figure 4: Corrosion device at ENEA Brasimone

Packed cementation and detonation gun Al_2O_3 coating were developed to coat internal part of experimental facility [31]. The coating manufactured with pack cementation was developed to coat internal part of pipes and vessel in order to protect the steel from corrosion by LLE working at high temperature and velocity. D-gun spray process is a thermal spray coating process, which gives an extremely good adhesive strength, low porosity and coating surface with compressive residual stresses. The coating manufactured can be applied on complex geometry.

Al2O3 coating manufactured on stainless steels substrates shows no crack, the mechanical fatigue tests shows good adhesion after the test at 500°C acting also as an electrical isolator.

4.3 Corrosion on RAFMS materials

The implementation of Reduced Activation Ferritic/Martensitic Steel (RAFMS) in flowing LLE and in a temperature range relevant for BB applications (450-550°C) requires further characterizations. Indeed, available corrosion rate of bare F/M steels in flowing LLE shows a spread of hundred micrometers per year (~20-900 μm/yr [32]). In addition, the behavior of coating materials in flowing LLE (such as Al_2O_3 based coating) needs to be investigated. To this end, a new LLE experimental loop, named LIFUS-II, was designed to investigate corrosion on bared and coated specimen at 550°C and at three different velocities (1.0, 0.1, 0.01 m/s) and different exposure time [33], [34] (1000, 2000, 4000, 8000 h). The loop has an eight shape with an economizer connecting the hot (550°C) and the cold (400°C) legs. Piping and components installed in the hot leg are internally coated by an aluminide diffusion coating with the aims to reduce the source of impurities generated by the corrosion of the structural material. Moreover, a cold trap system is designed to maintain the impurities concentration below the saturation concentration. Preliminary investigation on the aluminide diffusion coating was performed in stagnant condition with LLE at 550°C. samples after the coating were characterized by means of SEM-EDX analysis After 1000 h of exposition to stagnant LLE, the surface of the coating was mostly conserved and no signs of dissolution were detected. The only modification on the surface was related to the formation of dark islands made of Al_2O_3, commonly promoted in LLE environment with beneficial effects in protecting the aluminide diffusion layer from long-term dissolution.

5 Safety-relevant Activities

5.1 LLE-Water interaction

WCLL BB [35] in-box LOCA accidental condition involves the interaction/reaction of Water and LLE [12] following the double wall tube rupture inside the module. This is a relevant safety issue to be analyzed from the point of view of thermo-fluid dynamics, pressure transient, and chemical reaction.

Research activities are ongoing to master phenomena and processes occurring during the postulated accident enhancing the predictive capability and reliability of numerical tools. With this aim, the Verification and Validation activity [36], [37] requires to apply a standard methodology to experimental data with reproducible and defined initial and boundary conditions. In parallel, a numerical simulation activity is ongoing [38], [39] performed by the modified version of SIMMER-III code, which implements the LLE/water chemical reaction [40]. Experimental results will also constitute a useful database for the support of new system thermal-hydraulic/2D coupling calculation tool [41], [42].

In view of this, the new separate effect test facility LIFUS5/Mod3 [43] has been commissioned and the Series D experimental campaign is in progress [44]. The installed instrumentation and dedicated data acquisition system at 10 kHz provides meaningful and reliable data such as pressure wave propagation in LLE, increase of temperature due to the chemical reaction, and hydrogen production. The Series-D experimental campaign focuses on the chemical interaction between LLE and water, in particular on the validation of the implemented chemical model in SIMMER code. Therefore, relevance is given to parameter ranges of WCLL BB as well as to parameter ranges suitable for the reliable quantification of the test data. Five tests are scheduled, and partially performed with fresh LLE, varying the temperature of the water, the temperature of the LLE and the amount of injected water.

The analysis of the gained experimental results led to a comprehensive knowledge of the phenomena occurring during the test, as well as obtaining well-known initial and boundary conditions. Data obtained by pressure transducers and strain gages permitted to investigate the dynamic effects of energy release on the structures. Indeed, PTs recorded pressure waves propagation evidenced by successive pressure peaks at which correspond a damping effect on the structure recorded by strain peaks. Data recorded by TCs permitted to analyze the effect of the interaction/reaction between LLE and water. Firstly, a cooling effect was highlighted closer to the injector, then, at the jet expansion interface, the chemical reaction occurred. Finally, the quantification of the hydrogen produced by the reaction confirmed the theoretical stoichiometric evaluation of the hydrogen produced considering 50 g of water. Moreover, this data will serve for SIMMER code validation and of the coupled RELAP5/SIMMER approach.

5.2 In-box LOCA in the HCLL TBM

A critical accidental scenario for HCLL TBS is represented by the in-box LOCA: injection of helium at high pressure (about 80 bar) into the TBM box due to the rupture of a cooling and/or stiffening plate. THALLIUM test section was designed and built to simulate the LLE loop of the HCLL TBS and consists of a TBM mock-up and an expansion tank (with a protection system), connected by two pipes: the lower leg and the upper leg with its bypass [23]. The experiments simulated the rupture of the stiffening plate of the HCLL TBM and the resulting injection of He from the helium cooling system. A mitigation strategy, based on the action of a rupture disk and on the pressure relief from the expansion tank, was evaluated and tested in these experimental activities.

Eleven tests were carried out, varying the injection duration, the injection area ($9.5\cdot10^{-5}$ m^2 and $1.3\cdot10^{-5}$ m^2), the He pressure, the actuation of the isolation valves and the opening pressure of the rupture disk. Further details on the two experimental campaigns can be found in [28], [45].

The tests performed highlighted that the maximum value of all pressure peaks is significantly lower than the injection pressure. As THALLIUM was designed to be relevant for the LLE loop of the HCLL TBS, the behavior of the pressure trends allow to give some hints on the design of that system.

6 Future Activities

Apart the R&D activities above described, ENEA Brasimone R.C. is committed in supporting the design and the experimental validation of components for the Divertor Tokamak Test facility (DTT) [46]. According to the European Road Map, the DTT experiment should start its operation in 2025. To be coherent with this plan, the realization of the device will cover a time of around 7 years, starting from the first tender (during 2018) up to full commissioning and the first plasma (during 2025). The operations should then cover a period of more than 20 years, up to the initial phases of the DEMO realization.

The R.C. will also remain committed on the WCLL-BB, increasing the devoted efforts. In the development of the WCLL-BB as well as in the design activities of the WCLL TBM, a key issue is the modelling of the water coolant and LLE systems in normal operation, off-normal and accidental conditions [12], including water-LLE interaction (in-box-LOCA). Concerning the water-LLE interaction (see Section 51.), a chemical model has been implemented by ENEA in SIMMER codes [40]. After the verification phase, a procedure for code validation has been set-up and the validation activity is in progress using the experimental data of the Separate Effect Test Facility LIFUS5/Mod3 [39]. In parallel, a modified version of RELAP5/Mod3.3 code has been developed. The enhanced capabilities are oriented to the water coolant LLE breeding blanked and connected systems [47]. Finally, a chain of codes for the deterministic safety approach of the “in-box-LOCA” postulated accident will be set-up and applied. This will include coupling techniques [41], [42] and the use of thermo-mechanics codes [48]. These numerical tools will be used for supporting the design and the safety analyses of the WCLL TBM and BB. Moreover, an Integral Test Facility [49] will be built and operated aimed at demonstrating the consequences and the technical feasibility of mitigation strategies in case of “in-box-LOCA”, and at generating reference databases to qualify the codes selected for the licensing process. The design phase of this experimental infrastructure (so far called “LIFUS5/Mod4”) is starting at the end of 2019, whereas the construction is planned to start in 2021. The LLE water reaction/interaction will occur in a mock-up representative of the TBM of ITER where the consequences of the fluids interaction and the chemical reaction will be recorded in terms of pressure, temperature and strain transients. The water coolant loop and the LLE loop will represent the correspondent systems of the TBM in scale 1 to 1. This will include the control and safety systems for a correct representation of the pressure wave propagation and of mitigation strategy. The objective of the facility is to provide experimental data applicable to full-scale WCLL TBM system conditions, thanks full representative geometry and initial conditions of the experiments. In a second phase, the infrastructure can be used as integral test facility to investigate the operation, the transients and postulated accidents involving the WCLL TBM set, its water coolant system and with some extent the LLE loop. On the other side, the experimental data of the test matrix will be fundamental for demonstrating the reliability of computer codes in simulating the behavior of transient, as it is a regulatory requirement.

In parallel, the characterization at relevant scale of the technologies developed for the DEMO LLE loop is planned in order to validate the engineering design carried out. In particular, it is under proposal the design, erection and operation of a large scale LLE loop able to characterize i) TER system at relevant scale, ii) DEMO LLE pumping system integrated in the expansion tank designed to remove helium bubble solubilized in the coolant, iii) characterize the thermalfluidynamic performance of WCLL BB with flowing LLE, water and heat flux under relevant magnetic field.

Finally, a multipurpose test facility is scheduled at Brasimone R.C. to support the R&D of the water coolant components. This will be a water loop suitable for hydraulic and thermal-hydraulic testing of the main components of the WCLL BB and TBM, including their connected coolant systems. R&D will be focus on the steam generator connected with the water primary heat transfer system of DEMO. Indeed, the pulsed operation makes challenging their operation. Sample questions to be addressed are: how to control the component for ensuring the control of the primary water coolant temperature and how the transition pulsed dwell and vice-versa will be managed and optimized [50]. Experimental data will be used to set-up numerical models and to qualify system codes. The preliminary main design parameters are identified as: power = 2.0 MW; pump mass flow = 7 kg/s; pump head = 800 kPa; coolant pressure = 18.5 MPa; coolant temperature = 350 °C. This implies that the facility has in principle the capability to execute the hydraulic testing for the qualification of the full scaled TBM set and of scaled mock-up of the BB segment. The design activity will start in 2021 in order to start the experimental tests by 2023.

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