ACCEPTED MANUSCRIPT available at https://doi.org/10.1016/j.fusengdes.2019.02.045
DOI 10.1016/j.fusengdes.2019.02.045

The CIEMAT LiPb Loop Permeation Experiment

B. Garcinuño[a,b], D. Rapisarda[a], I. Fernández-Berceruelo[a], E. Carella[a], J. Sanz[b]

[a]*CIEMAT-LNF, Av. Complutense 40, 28040 Madrid, Spain*
[b]*UNED, Dept. of Energy Engineering, C/ Juan del Rosal 12, 28040 Madrid, Spain*

A new facility, CLIPPER, is being constructed at CIEMAT to investigate tritium extraction from PbLi. It consists in a forced circulation loop with the main objective of validating the technique of permeation against vacuum. Originally, CLIPPER was designed with two zones operating at different temperatures and connected through a recuperator, which gives most of the required thermal jump. In the cold leg the PbLi circulated at 300 ºC to have the PbLi in liquid phase, but high enough for avoiding cold points. The hot leg would increase PbLi temperature up to the experimental necessities (500 ºC). After a careful evaluation of the preliminary design, and considering the limitations of the laboratory in terms of power and available space, it was decided to change the approach to a simpler and cheaper facility.

The new CLIPPER consists in a unique isothermal loop operating at 500 ºC. The main advantages are the lower PbLi inventory and the suppression of a very complex and expensive heat exchanger. In CLIPPER, the PbLi is heated, melted and cleaned outside the loop, in a tank integrated in a dedicated glove box under argon atmosphere. The test section includes a prototype of permeator (TRITON) and its auxiliary systems, such as its associated vacuum system and instrumentation. TRITON consists of a rectangular multi-channel component with vanadium membranes. A novel gas injection system specifically designed for CLIPPER is used to introduce the gases that must be extracted through the permeator (hydrogen isotopes). This system, based on a multi-tube component with permeable niobium membranes, is able to solubilize the hydrogen in the PbLi up to the required concentration.

The final design of CLIPPER is presented together with the integration of its main components, including a thermomechanical assessment of the loop.

Keywords:

1. Introduction

Future fusion reactors will look for the production of electrical power by fusing two deuterium/tritium nuclei and, at the same time, for the achievement of tritium self-sufficiency. The latter has been recognized as one of the main missions in the path towards the consecution of fusion electricity, otherwise there will not be enough fuel to operate the fusion reactor [1], [2].

To deal with the question of tritium breeding, the reactor incorporates a key component, the breeding blanket, which has to provide a Tritium Breeding Ratio higher than unity to assure a constant fuel injection despite of the losses in the system. Within the EUROfusion programme, those blankets concepts based on a liquid breeder (Helium Cooled Lithium Lead – HCLL, Water Cooled Lithium Lead – WCLL and Dual Coolant Lithium Lead – DCLL) use the eutectic alloy of lead-lithium (PbLi) as breeder and neutron multiplier [3].

Once the tritium is re-generated in the blanket the crucial point is its recovery from the PbLi. For this aim, an indispensable element in the power plant is the Tritium Extraction and Removal System (TERS) which is connected to the breeding blanket through a loop that circulates the PbLi. There, the tritium is recovered and routed to the Tritium Plant to be finally re-injected into the plasma closing the tritium cycle. Among the different techniques proposed in EUROfusion for tritium extraction from PbLi, the Permeation Against Vacuum (PAV) technology has been selected as baseline due to its high expectative in terms of efficiency, fabrication, design and operational mode [4]. A complete design of the TERS based on PAV technology has been recently developed for a DCLL based DEMO reactor [5]. Its objective is to operate at a minimum 80% efficiency under DCLL conditions in terms of PbLi mass flow and temperature which are conditioned by the need of achieving a TBR>1.10 and extracting the heat power [6]. The experimental validation of this approach is fundamental, since there are no results at the moment. For this aim, a small scale prototype of PAV (TRITON) has been designed and fabricated [7][6][5]. A PbLi facility for its testing under PbLi flow is under construction in CIEMAT. CLIPPER (Ciemat Lithium-lead loop for Permeation exPERiments), is a forced circulation loop originally designed with two zones operating at different temperatures and connected through a recuperator, which gives most of the required thermal jump. In the cold leg the PbLi circulated at 300 ºC to have the PbLi in liquid phase, but high enough for avoiding cold points. The hot leg would increase PbLi temperature up to the experimental necessities (500 ºC). After a careful evaluation of the preliminary design, and considering the limitations of the laboratory in terms of power and available space, it was decided to change the approach to a simpler and cheaper facility. The final design, consisting on an isothermal loop, minimizes the PbLi inventory by the suppression of a very complex and expensive heat exchanger. Since the PAV technique has not been demonstrated, the loop has been designed to cover a wide operational range to fully characterize their behaviour under different experimental conditions.

The present work provides the design of the PbLi loop devoted to experimentally validate the PAV technology. A description of the PbLi loop main objectives and operational parameters is presented in Section 2; the loop P&ID and a complete dimensioned layout are shown in Section 3; the main components are described in Section 4; structural calculations and main issues are presented in Section 5. Finally, a summary is drawn in Section 6.

2. CLIPPER objectives and operational parameters

The loop, called CLIPPER (Ciemat Lithium-lead loop for Permeation exPERiments), is firstly aimed to validate the permeation against vacuum technique as a feasible and efficient system for tritium extraction from PbLi. Following this task, the detailed objectives are:

-Test hydrogen/deuterium permeation in flowing PbLi. Since the management of tritium is of high risk and special installations are required, the technology would be tested using deuterium and hydrogen. Since the three gases are isotopes it is possible to extrapolate the results obtained to those of the expected from tritium.

-Test the extraction under DCLL conditions. The PbLi loop should allow to work under conditions of temperature, velocity and tritium partial pressure following the design of the TERS for a DCLL-DEMO to validate the prototype of PAV.

-Test different permeator concepts or configurations for efficiency assessment. The PbLi loop should be designed in that way that it could be adapted to different configurations of PAV. In this sense, the PbLi mass flow must operate in a wide range; the temperature of operation should be variable.

The operational parameters of the loop are fixed to cover all the objectives listed. The requirements are here presented:

PbLi mass flow rate. The amplitude of mass flow is chosen in order to cover a high range. First, high velocities are reached, in order to assure a relevant operation for DCLL. Secondly, the variable range allows working under different PbLi velocities to evaluate the recovery dependence. In this sense it is possible to obtain results also relevant for the other liquid blanket concepts which work at low velocities. Moreover, if there are changes on the test section, the loop should be able to adapt the operation.

PbLi temperature. Since the characteristic temperature of a DCLL breeding blanket is about 550 ºC, the loop should reach those conditions to validate the technology. Taking into account the dependence of the efficiency of the extractor with the temperature, different measurements should be performed to confirm the behaviour. Furthermore, for other liquid based blanket concepts, the operational temperature is about 300 ºC, therefore, the loop will be able to cover the specifications of the three considered blanket concepts.

PbLi velocity. Since there is a high corrosion rate caused by the liquid metal on the piping system, and it is dependent on the velocity, the loop will be designed in order to work under 3 m/s for the highest mass flow specified.

Table 1 summarizes the main parameters of the loop.

Table 1: PbLi loop main parameters

Parameter	Value
Temperature	300-550 ºC
PbLi mass flow rate	2-39 kg/s
PbLi velocity in pipes	<3 m/s
PbLi velocity in test section	<1 m/s

3. Description of the facility: CLIPPER layout

The objectives of the loop are focused on the validation of the technique based on permeation against vacuum for hydrogen extraction from PbLi, although other techniques could be also validated in future. The design of the loop will allow the experiments to be performed at different temperatures and PbLi flow rates, but mainly to test the technology at DCLL relevant conditions of PbLi temperature, velocity and tritium concentration.

The Process and Instrumentation Diagram (P&ID) is presented in Figure 1. All heaters, thermocouples and pressure sensors are included together with the gas line, valves and components.

The PbLi is heated and melted in a dedicated tank. A glove box installed at the top of the melting tank, and operated under argon atmosphere, will allow the access to the liquid metal to remove impurities during the melting process and other operations. The glove box will be connected to a vacuum system and to an argon system. Once the PbLi is melted, it will be routed through a pipe to the filling tank located at a lower height to facilitate the process. There are two tanks in the loop circuit, S101 and S102, named filling and expansion tanks, respectively. Each one owns various PbLi level indicators (LI-01 to LI-06) and is connected to the gas line in order to assure an inert atmosphere, absorb volume expansions of the liquid and help to the filling/draining process. The expansion tank (S102) is located on the highest part of the loop and is opened to the circulation of PbLi while the filling tank is isolated once the loop is filled. Both tanks are heated thanks to heating elements named HT-01 and HT-02.

There are three valves in the liquid line: two (V-02 and V-03) connecting the filling tank (S101) to the melting tank located in the glove box; one connects the tank S101 to the whole loop (V-01). This last valve is automated in order to assure a safety operation and to be opened for an emergency drain of the loop in case of necessity. Furthermore, each valve has its own heating element, named from HV-01 to HV-03. The PbLi circulates thanks to the permanent magnets pump (P-101) which is connected to the flowmeter (FIC) to establish the velocity of the liquid metal. Two pressure sensors located before and after the PMP indicate the pressure drop caused by the circulation through the whole loop (PDI-101). As it is of high importance to avoid freezing the PbLi inside the PMP channel, three temperature sensors are installed along the PMP (TI-102 to TI-104) and two heaters are positioned in the pipe section out of the magnet zone (H-06 and H-07).

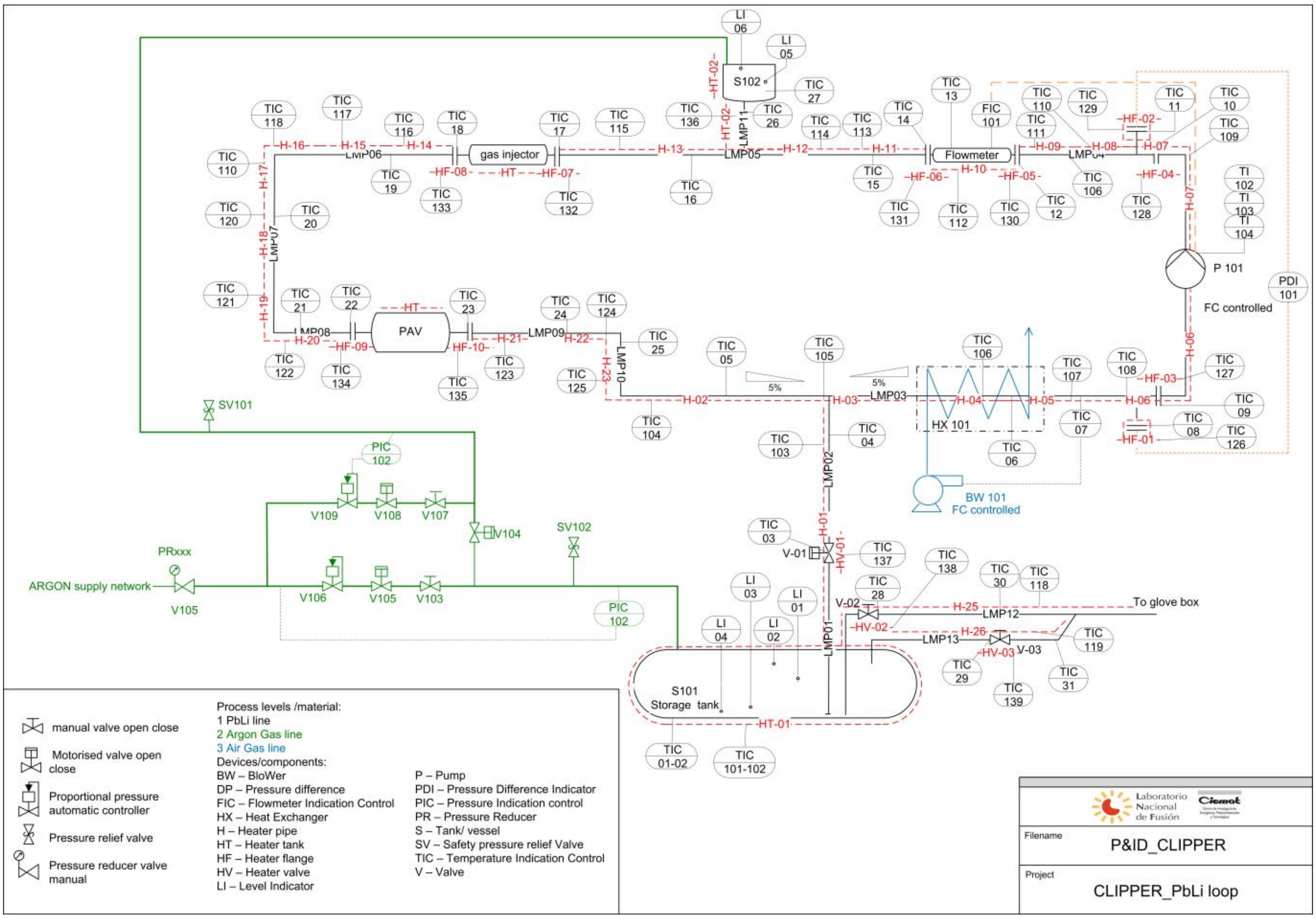

Fig. 1. CLIPPER P&ID

A cooler of blower type is installed before the PMP entrance (BW-101) to cool down the PbLi temperature when necessary. It is connected to a thermocouple located at the exit (TIC-07) to control the on/off operation.

The loop will be designed with stainless Steel 316 pipes of 1.5 inch diameter. The piping trams are named from LMP-01 to LMP-13. A slope of 5% in the horizontal sections will ease the draining of the PbLi when required. Thermal expansion of the pipelines will be balanced by a careful circuit layout. As seen in the P&ID, the LMP-09, LMP-10 and LMP-03 connection is a Z-shaped zone to absorb possible expansions of the system. All piping trams are heated with a series of heating elements named from H-01 to H-26 which possess their own control thermocouples to assure they are within the operation limits (TIC-103 to TIC-125).

Each component (pump, heat exchanger, etc.) is connected to the piping line through DN-CF40 flanges. These elements have their own heating element to avoid cold zones within the circuit (HF-01 to HF-10).

Being the locations of the inlet and outlet connections of the PMP at a distance of 0.5 m in the vertical direction, the loop is developed both in vertical and horizontal directions, Figure 2. In the upper part of the loop, after the PMP, the flowmeter is installed followed by the expansion tank. The gas injection system is integrated before the turn down of the pipe-route. Then the PbLi circulates through the PAV and finally it reaches the cooler before entering into the PMP.

A description of the components of the loop is presented:

3.1. Permeator Against Vacuum

The extraction of hydrogen by means of the permeation against vacuum technique is based on the concentration gradient generated between both sides of a permeable membrane. The gas is solved in the PbLi which is in contact with one of the sides of the membrane while vacuum is performed in the other side to force the diffusion of the gas. This procedure allows the extraction of the pure gas in a one-step facilitating its management within the tritium cycle in the reactor. Following the design performed for a DCLL-DEMO of the tritium extraction and removal system [8], a small prototype has been developed [7] and constructed. It is based on vanadium membranes of 1 mm thickness stacked on a supporting structure of stainless steel AISI410 to conform 7 channels for flowing PbLi and 8 alternated vacuum channels to extract the hydrogen solved in the PbLi (Fig. 3). The main structure is closed on the laterals to perform vacuum. The total length of the prototype is 1.5 m and counts with CF connections to the loop circuit, to vacuum system, pressure and temperature sensors and heating system.

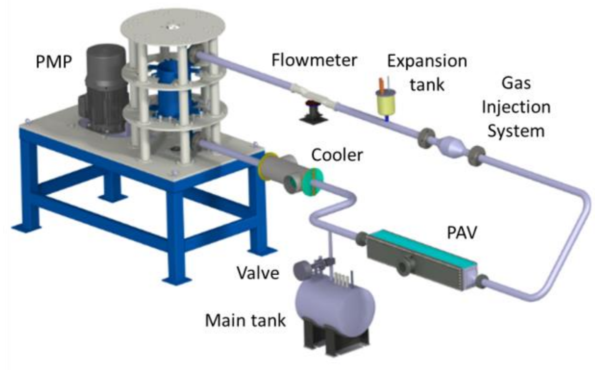

Fig. 2.3D design of CLIPPER showing all the components

3.2. Gas Injection System

In a fusion reactor, tritium is generated by the neutrons incident on the lithium in the breeding blanket. At laboratory scale, this reaction is not possible and it is needed a way to solubilize tritium into the PbLi at desired and known concentration for its further extraction in the PAV. This task is accomplished by a gas injection system. A tube-in-tube design based on forced permeation has been developed. Here a membrane permeable to hydrogen contains the flowing liquid metal and a pressure of gas is applied from the outside, forcing the gas injection. In this way it is able to solubilize the gas in the PbLi procuring a uniform distribution, avoiding the formation of bubbles and enhancing the solubilisation since isotopes are injected in atomic form. The design, based on a 5-niobium-tube system of 1 inch diameter and 20 cm length, is connected in line with the PbLi flow (Fig. 4). It counts with a cover case that contains pressurized hydrogen/deuterium and is able to inject gas at the same rate it is extracted in the PAV in the range of operation of CLIPPER (Table 1).

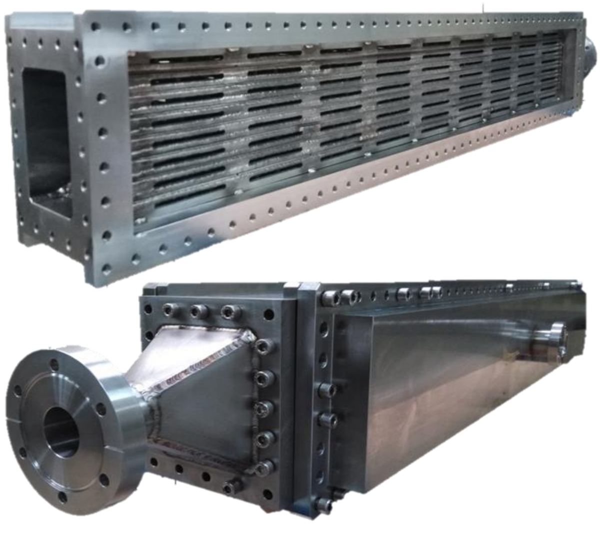

Fig. 3. TRITON Permeator Against Vacuum

3.3. Glove box

A glove box connected to a vacuum system and to an argon gas line will allow the manipulation of the ingots in the melting tank and the removal of impurities during the melting process. It owns a custom-made tank in where the PbLi is melted. The glove box, manufactured by Jacomex (Fig. 5**¡Error! No se encuentra el origen de la referencia.**), is made on stainless steel and counts with a gas purification system to keep oxygen and water levels inside below 1 ppm to not contaminate the PbLi, air conditioner and a vacuum pre-chamber for the introduction of the material. The dimensions of the glove box are: 2080 mm length and 1050 mm height. A custom made supporting structure is fabricated in order to give an extra support for the tank and adjust the height. This is because the tank should be located at higher position with respect to the filling tank of the loop (S101) to allow the PbLi transport by gravity.

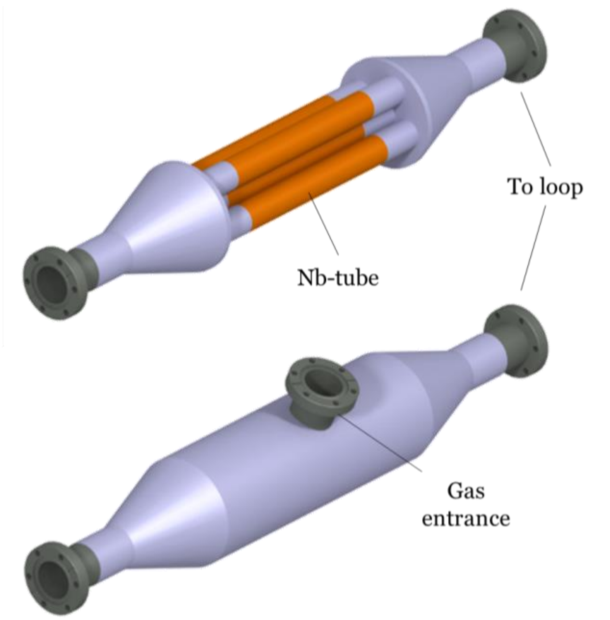

Fig. 4. 3D design of the gas injection system

3.4. Tanks

The melting tank is the container where the PbLi ingots will be melted. It will be installed at the bottom of the glove box (Fig. 5). It is built of stainless steel 316L. Its capacity will be enough to contain all the ingots and at the same time, to compensate the thermal changes of the liquid metal volume. It is estimated the PbLi volume in the whole loop will be around 25 litres; therefore the dimensions of the tank are 28 cm inner diameter, 5 mm wall thickness and a total length of 50 cm. The installation in the glove box is made with a series of Viton-gaskets to assure a proper sealing of the chamber. It incorporates a cover to close when the PbLi is being melted in order to avoid heat loses.

The filling tank (S101) will be located at a lower height with respect to the melting tank. It is devoted to fill/drain the loop, therefore its design takes into account the total amount of PbLi estimated inside the circuit. The dimensions are 30 cm diameter and 50 cm length providing a volume of 35 litres. It will be connected to the loop through a pipe line (LMP-01) of one inch diameter and 2 mm thickness with an automatized valve. The end of the pipe is located at the bottom of the tank to allow the filling of the loop by applying pressure of argon. Four level indicators (LI-01 to LI-04) are located at different deepness to measure the PbLi level.

Moreover, a 10 mm diameter pipe inlet of argon gas is included in order to pressurize the liquid metal for filling the loop. Two piping lines of half inch diameter and 1 mm thickness, with their own valves, connect the tank with the melting tank (LMP-12 and LMP-13). One line is immersed at deeper location for sending the liquid metal back to the melting tank when necessary, with the help of argon gas pressurized.

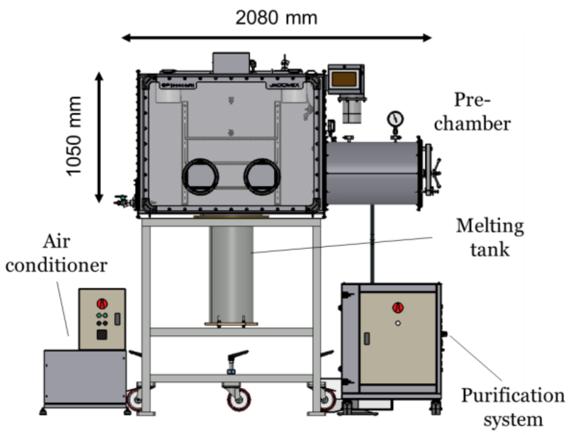

Fig. 5. Glove box by Jacomex with melting tank

The expansion tank (S102) is located in the highest part of the loop to control the expansion of the fluid. It will own a pressure release valve in the gas line. There are two level indicators (LI-05 and LI-06) and the whole volume is 2 litres.

3.5. Pump

The chosen solution is a permanent magnets electromagnetic pump (PMP), manufactured by SAAS GmbH. It is a rotor-type pump with separate supporting bearing and flexible coupling to the motor, which develops an electrical power of 18 kW. The diameter of the rotor is 350 mm and the magnets are made of SmCo. This kind of pump offers several advantages for this application: no problems related to the reliability of propellers and seals; simpler construction; high efficiency. It covers a mass flow rate between 2 and 39 kg/s.

3.6. Cooler

A forced cooling system will be located prior the PMP to assure a PbLi temperature low enough to enter the pump. Its design is based on a controllable heat exchanger that can perform 1.25 kW to adjust the thermal balance of the loop.

3.7. Auxiliaries

The heating system to increase the PbLi temperature up to the operational conditions will be based on electrical trace heating around the pipes and equipment. Heating cables HSQ by Horst are employed for the pipes. They are insulated with quartz yarn and provide a power up to 370W. Their flexibility allows the use for small winding radii. Heating mats by Horst, are used for those elements with complex geometry (flanges, valves). They are flexible and for the temperature regulation, each heating mat is equipped with a NiCr-Ni temperature sensor providing a power up to 500W. For the tanks, the mineral insulated band barrel from Watlow is applied which gives a power of 700W. All heated components will be insulated with Superwool Plus fibre by Morgan Advanced Materials. This material with 128 kg/m^3 withstands temperatures up to 1200ºC and has a thermal conductivity of 0.11 W/m·K at 500ºC.

An electromagnetic flowmeter of flywheel type would be implemented in the loop to control the PbLi mass flow rate and give the input to the PMP. It is provided by SAAS GmbH. The magnets are made of SmCo alloy and it owns a support of high precision lubricated with air. The required pressure of compressed air is 3 bar. As the liquid metal flows, the magnet system rotates, being the rotation speed proportional to the flow rate. The calibration of the device is based on the thermal balance of the loop, for that aim the loop should be adjusted into a stationary thermic state. The diameter of the disk is 120 mm providing a measurement range up to 2 m/s.

Temperature measurements will be performed through Type K (NiCrNi) thermocouples located at different points in the system (see P&ID). The process is based on a redundant system to make the measure more accurate. It consists on a three point measurement inside the pipe at different depths to obtain the average value. The thermocouples are inserted in the pipe through a vain.

Inside the tanks there would be installed various level sensors for the monitoring of the liquid metal level. It would be based on commercial spark plugs connected to conducting probes that will be inserted at different depths that will indicate the level. It is a yes/no sensor which determines if there is PbLi in contact with the sensing part or not because the electrical circuit is closed/open taking advantage of the PbLi property as an electrical conductor liquid

For pressure control the Cerabar T pressure transducer by Endress+Hauser will be used. This kind of sensor is based on a piezoresistive measuring cell and metallic process isolating diaphragm for absolute and gauge pressure applications. The measuring ranges go from 0 to 1 bar up to 0 to 400 bar. The process pressure acting upon the metallic process isolating diaphragm of the sensor is transmitted to a resistance bridge via a fluid.

5. Thermomechanical assessment

A preliminary thermomechanical analysis has been performed to assess the behavior of the loop structure under the highest operational temperature foreseen for the experiments (500ºC). Since the interest of the analysis is focused on the thermal stresses produced on the piping elements, the geometry of some loop components has been simplified. Specifically, the PAV has been substituted by a beam-type connection which simulates its linear expansion. Besides, just the parts of the pump closest to the PbLi channel have been represented as solid bodies, whereas most of its structure has been replaced with beam-type connections. Furthermore, as no other loads like weight or PbLi pressure are considered here, gravity supports have been not included in the analysis. Excepting the body-ground connections constraining the pump, no other displacement boundary conditions are taken into account and the structure is allowed to freely expand, fully subjected to a thermal condition of 500ºC. This is equivalent to assume frictionless joints between the circuit and the gravity supports, as well as an ideal thermal insulation of the circuit elements. Additionally, the central bodies which join the fins in the cooler are considered as bonded to the pipe external surface, instead of being maintained together by means of bolted unions. Regarding materials, temperature-independent properties of SS-316 have been assigned for the whole circuit elements.

As a result, the maximum deformation of the loop exceeds 5.5 cm, whereas the maximum deformation along the Y-axis almost reaches 4 cm. Excepting the parts of the pump connected to the ground by beams, the resulting stress level is certainly low (1-50 MPa).

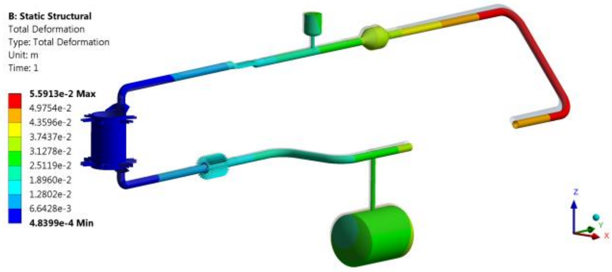

Fig. 6. CLIPPER total deformation (m)

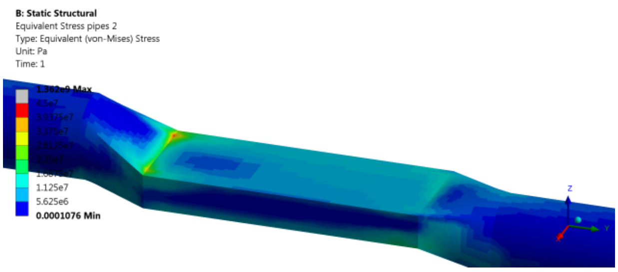

Fig. 7. Equivalent Von Mises stress (Pa) in the flowmeter channel

6. Summary

The design of a PbLi loop to perform experiments on hydrogen extraction from the liquid metal is presented. It is firstly aimed to demonstrate the validity of the permeation against vacuum technique for tritium extraction from PbLi and its application in future fusion power plants.

This isothermal loop, CLIPPER, counts with a permeator against vacuum as extraction system, a system able to inject the gas into the liquid, an electromagnetic pump to circulate the PbLi, filling and expansion tanks and a separated glove box with an integrated tank to melt the PbLi under inert conditions. All these components have been designed to cover the specifications in terms of PbLi temperature and velocity to be representative of those of a breeding blanket.

The integration of all the components is presented in a P&ID which includes the heating tracing system, the gas line and temperature and pressure sensors. Then, the description of the main characteristics of these components and the auxiliaries is following.

Finally the thermomechanical evaluation of the loop is addressed. It is shown that the design of the loop causes a relatively low stress level (1-50 MPa).

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has been partially funded by the MINECO Ministry under project ENE2013-43650-R. B. Garcinuño acknowledges a pre-PhD contract of the Spanish MICINN.

References

[1] B. Bornschein et al., "Tritium management and safety issues in ITER and DEMO breeding blankets", Fusion Eng. Des. 88 (2013) 466-471

[2] T. Tanabe, "Tritium fuel cycle in ITER and DEMO: Issues in handling large amount of fuel", J. Nucl. Mater. 438 (2013) S19-S26

[3] L. V. Boccaccini et al., "Objectives and status of EUROfusion DEMO blanket studies", Fusion Eng. Des. 109-111 (2016) 1199-1206

[4] D. Demange et al., "Tritium extraction technologies and DEMO requirements", Fusion Eng. Des. 109-111 (2016) 912-916

[5] B. Garcinuño et al., "The Tritium Extraction and Removal System for the DCLL-DEMO fusion reactor" Nuclear Fusion 58 (2018) 095002

[6] D. Rapisarda et al., "Conceptual Design of the EU-DEMO Dual Coolant Lithium Lead Equatorial Module", IEEE Trans. Plasma Sci. 44 (2016) 1603-1612

[7] B. Garcinuño et al., "Design and fabrication of a Permeation Against Vacuum prototype for small scale testing at lead-lithium facility", Fusion Eng. Des. 124 (2017) 871-875

[8] B. Garcinuño et al., "Design of a permeator against vacuum for tritium extraction from eutectic lithium-lead in a DCLL DEMO", Fusion Eng. Des. 117 (2017) 226-231