Fusion Engineering and Design 192 (2023) 113753

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Design of a scaled mockup of the WCLL TBM for MHD experiments in liquid metal manifolds and breeder units

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A R T I C L E I N F O

Keywords:
Water-cooled lead lithium (WCLL) blanket
Test blanket module (TBM)
Magnetohydrodynamics (MHD)

The current reference concept for a European liquid metal test blanket module (TBM) for ITER is a water-cooled lead lithium (WCLL) blanket. The liquid alloy lead-lithium (PbLi) is used as breeder, neutron multiplier, and heat carrier. Pressurized water cools the blanket structure and the breeding zone by a large number of cooling pipes immersed in the liquid metal. The spatial distribution of these pipes interfering the breeding zone and manifolds is a critical issue. Efficient heat removal from the liquid metal has to be ensured to avoid local hotspots in the fluid or in blanket walls. The highest liquid metal velocities occur in the feeding and draining manifolds, which represent quite complex geometrical structures. It is expected that the magnetohydrodynamic (MHD) flow of PbLi in the manifolds generates the major fraction of pressure drop. Moreover, the design of the manifolds has a decisive influence on the flow partitioning in the blanket, and their contribution to the overall performance of the module is significant.

In order to investigate the MHD impact on the liquid metal flow, a scaled mockup of the WCLL TBM has been designed with focus on detailed measurements of flow quantities in the manifolds. The geometry of the mockup has been derived from the ITER TBM design. It takes into account internal solid obstacles such as cooling pipes, which block parts of the fluid volume and force the flow to complex 3D meandering paths. The present paper gives an overview of the WCLL mockup design, fabrication and measurement system. This information could be quite useful for engineers who are planning future experiments to see how some technical problems have been solved here. The mockup has been integrated in the liquid metal loop of the MEKKA facility of the Karlsruhe Institute of Technology for MHD experiments. Results will improve the current understanding of MHD flows in WCLL manifolds and help to improve and optimize the design of WCLL blankets.

1. Introduction

1.1. Overview and objectives of the work

One of the proposed concepts for an ITER test blanket module (TBM) is the water cooled lead lithium (WCLL) blanket [1]. Liquid eutectic alloy lead lithium (PbLi) is employed as tritium breeder and neutron multiplier, pressurized water is used as coolant for the first wall (FW) and breeding zone (BZ), and EUROFER steel as structural material [2]. The design of the WCLL TBM consists of 16 breeder units (BU) arranged in two columns with a complex structure of PbLi and water manifolds and distributors (see Fig. 1). A flow of pressurized water in the cooling channel system inside the first wall and side walls is used to remove heat and cool the blanket structure. A 3D system of double-walled water-cooled pipes placed inside the breeder zones (BZ) and PbLi manifolds is used to remove the heat generated in the liquid metal. These water pipes as well as the stiffening plates crossing the PbLi manifolds occupy a significant fraction of the manifold cross section narrowing and redirecting the PbLi flow. The modified tortuous and narrowed flow path will further increase the PbLi velocity in the manifold, which results in a quite complicated 3D flow path.

3D liquid metal flow in strong magnetic fields is known to cause significant magnetohydrodynamic (MHD) effects due to additional 3D electric currents and increased Lorentz forces, resulting in additional MHD pressure drop. Previous MHD experiments using a scaled mockup for a helium cooled lead lithium (HCLL) TBM have shown that the major fraction of pressure drop arises from the liquid metal flow in the manifolds, while the pressure drop along the BUs remains relatively small [3]. This is caused by the fact that the velocity in the BUs is very small. The cross-sections in the manifolds, however, are much smaller than those in the BUs and therefore velocities are higher. Moreover, one manifold has to feed liquid metal to up to 8 BUs and another one has to

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https://doi.org/10.1016/j.fusengdes.2023.113753
Received 5 October 2022; Received in revised form 12 April 2023; Accepted 13 April 2023
Available online 19 April 2023

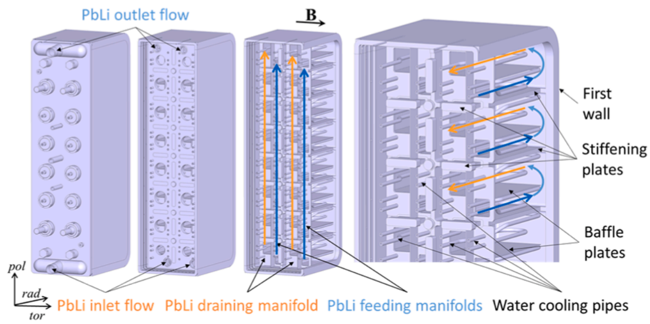

Fig. 1. Original CAD design of the WCLL TBM geometry as provided by CEA. View from outside and internal details such as liquid metal manifolds, water pipes, breeder units, separating and stiffening plates.

collect those flows during continuous operation of the TBM. This requires higher manifold velocity, and therefore the pressure drop in manifolds is significantly larger than the one in single breeder units.14FUSION113753

Objective of the planned experiments is to achieve knowledge about the pressure distribution in the TBM of a WCLL blanket module and to determine the distribution of the liquid metal flow from the manifold into the breeder units.

With the aim to investigate experimentally the liquid metal flow in a blanket geometry that is most realistic and comparable to the original concept foreseen for ITER, a scaled MHD mockup has been designed on basis of the WCLL TBM design provided by CEA as input documents for the present work.

The flow in the TBM is dominated by electromagnetic forces that are much stronger than viscous or inertia forces. Such flows are characterized by very high Hartmann numbers

$$Ha = BL\sqrt{\frac{\sigma}{\rho\nu}},$$

where Ha^2 denotes the ratio of electromagnetic to viscous force. Here $B\sim 4$T is the strength of the magnetic field in ITER at the position of the TBM, $L = 0.097$ m is a typical Hartmann length measured in BUs along magnetic field lines (half of the toroidal length), σ, ρ, ν stand for electric conductivity, density and kinematic viscosity of PbLi [4] taken for the estimate of Ha at a reference temperature of 580 K. As a result, we expect for the ITER TBM$Ha_{TBM} \approx 8000$. In order to approach experimentally fusion-relevant Hartmann numbers, the mockup geometry should be as large as possible while the mockup has to fit into the gap of the magnet available at the MEKKA facility. To keep the geometry as large as possible, it has been decided to consider only one column of 8 BUs with distributing and collecting manifolds. With a scale of 1:2.5 such a model geometry fits well into the magnet, and with NaK at 40 °C as a model fluid [5] and a maximum laboratory magnetic field of 2.1T, it should be possible to achieve experimental conditions with $Ha_{mockup} \approx 4900$.

From the original WCLL TBM design as shown in Fig. 1, a scaled mockup (1:2.5 scale) with 8 BUs has been derived. Fig. 2 shows an isometric view of the mockup with the main dimensions, and a transparent view for visualization of the liquid metal flow path (bottom; inlet: blue, outlet: orange). For the experiments, the mockup is embedded with horizontal orientation into the magnet and connected to the existing liquid metal loop. The main dimensions of the scaled mockup are 668.4 $\times$ 222.6 $\times$ 102 mm^3, which fits well into the gap of the magnet in the MEKKA laboratory. The liquid metal is distributed and collected by two poloidal manifolds into and out of the BUs. Each BU is fed through small windows in the back wall of the manifolds. The liquid metal flow is redirected at the first wall and guided back into the outlet manifold. The liquid metal is fed into the mock up and removed from it through circular pipes. A number of small pipes is foreseen as pressure taps for pressure measurements and for venting and draining of the BUs and

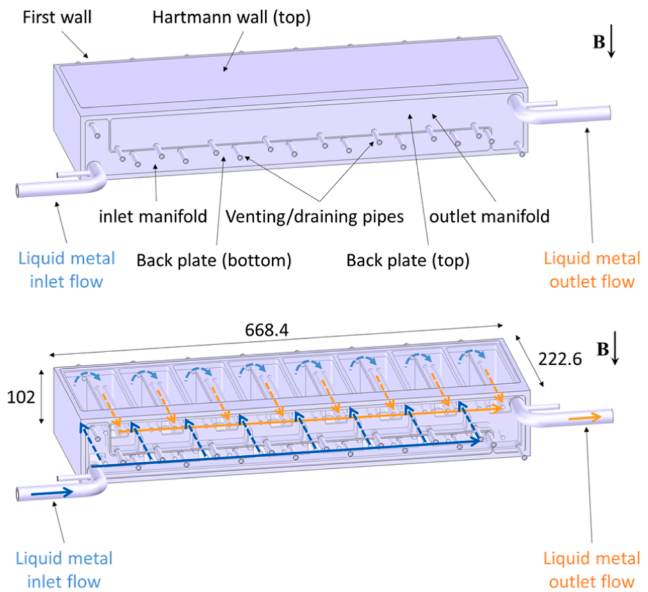

Fig. 2. Design of the WCLL MHD mockup; Isometric view with pipes for feeding, venting and draining and pressure measurements (top), liquid metal flow path inside WCLL TBM mockup (bottom).

manifolds.

The mockup design has been simplified in terms of manufacturing issues and fabrication costs. Details concerning the water channels in the blanket walls and BZs have been omitted since it is expected that water channels might affect the liquid metal flow only in a very narrow vicinity close to the walls [6] with little influence on the global flow at some distance from the wall. However, water channels inside the walls have been taken into account by using in the experiment solid walls, which have the same amount of steel as in the original design. This has been achieved by reducing the wall thickness accordingly in order to guarantee a comparable overall electric conductance of model and original wall, which is important for realistic MHD experiments. This has been done before downscaling. The difference in electrical conductivity of stainless steel and EUREOFER has not been taken into account. This can be considered later by upscaling experimental results from NaK-stainless steel experiments to PbLi-EUROFER behavior in the TBM.

Water pipes, representing a partial blockage for the liquid metal flow in the manifolds are all present in the mockup. They are modelled as solid dummies to represent the correct plugging ratio of the liquid metal cross section. Cooling pipes inside the BZs are not fully complete near the first wall (short toroidal parts are missing) to simplify manufacturing of the mockup. This seems justified since the focus of the present experiments is on the liquid metal flow in the manifolds where the geometry is complete. The mockup has also been designed with the objective to reduce the number of parts and therefore the number of welds, respectively. An optimized number of well-placed welds minimizes the risk of welding distortions and ensures good handling of the mockup in the limited space of eroding and welding machines available in the mechanical workshop. The design and fabrication of components has been a good compromise regarding its high geometric similarity with the original blanket design and having all functionality required for MHD experiments in the MEKKA laboratory.

A 3D view on the mockup design indicating flow paths in manifolds and BUs is shown in Fig. 2 and dimensions and further geometric details may be seen from Fig. 3, which should ensure reproducibility of future results, also performed with numerical methods.

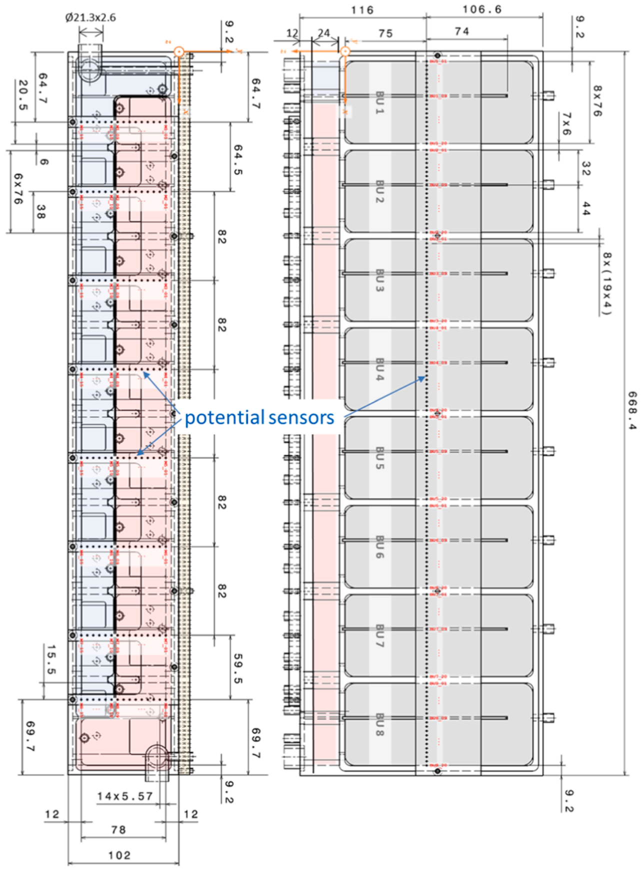

Fig. 3. Drawing showing dimensions of the mockup, wall thickness, and size of inlet and outlet pipes. Small dots indicate potential sensors; 160 on the Hartmann wall along poloidal direction and 8 × 15 across the manifolds.

1.2. Liquid metal loop

Experiments with the WCLL TBM mockup will be performed in the MEKKA-facility at KIT. The liquid metal alloy NaK is used as experimental fluid so that experiments can be performed at room temperature. The total amount of NaK in the loop is about 200 liters and the liquid metal flow can be driven by an electromagnetic pump (to be used at high temperatures), or by a mechanical pump that gives flow rates up to 25 m^3/h and maximum pressure heads of 9.5 bars. The magnetic gap in the dipole magnet used for the experiments has a rectangular cross-section and within a volume of 800 × 480 × 168mm^3 the magnetic field is homogeneous with deviations from the core value smaller than 1%.

The loop can be operated also at elevated temperatures, which is necessary during the initial stage of experimental campaigns, when newly fabricated test-sections are inserted and electrical wetting of walls has to be achieved. Perfect electrical contact is essential since the occurrence of contact resistances at the fluid-wall interface would lead to results difficult to be interpreted due to unpredictable MHD conditions [7,8]. At high temperatures above 300 °C, oxides and impurities dissolve in the liquid metal. The test-section and pipe connection has to be prepared for this procedure by adding a thick thermal insulation. For the high-temperature wetting a purification loop is operated in a bypass for removing the impurities from the liquid metal (see Fig. 4). The purification circuit consists mainly of a cold trap with thermostat and electromagnetic flow meter. In the cold trap, oxides and impurities precipitate on a wire mesh and separate from the NaK. The separation process takes advantage of the weaker solubility of the dissolved species in NaK at low temperatures. For this purpose, the NaK in the cold trap is cooled by a thermostat to temperatures between 30 and 50 °C. After finishing the wetting procedure, the thermal insulation on the test-section was removed and the instrumentation for electric potential measurements installed on the mockup.

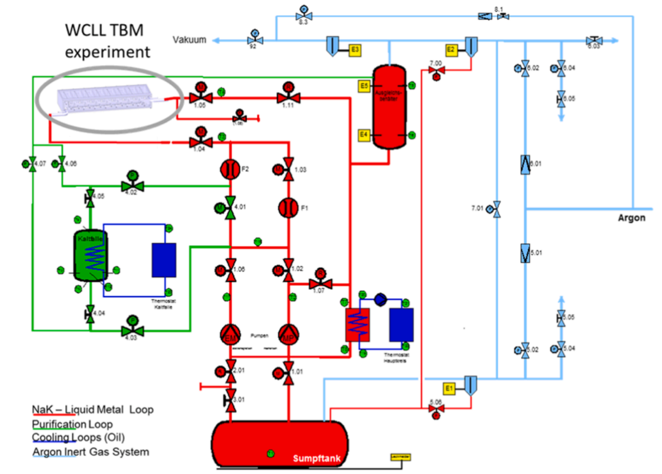

Fig. 4. Sketch of the liquid metal NaK loop in the MEKKA laboratory. Colors indicate different parts of the system. Red: liquid metal loop; green: purification circuit; blue: oil cooling loops; light blue: inert gas system.

The mockup and the liquid metal loop are depicted in Fig. 4. Filling of the loop is achieved by applying argon pressure to the dump volume in order to push the liquid metal into the loop. Draining of the loop after operation and in case of an emergency is performed by gravity.

1.3. Mockup fabrication

The entire assembly of the fabricated mockup is shown in Fig. 5. To fit into the gap of the magnet, the pressure taps were bent before installation and assembling with the liquid metal loop in the MEKKA laboratory. The main body consists of a single piece, which forms the walls of all BUs, including first wall, stiffening plates, back plate and walls separating the two inlet and outlet manifolds for the liquid metal flow. The breeder units are closed from both sides by two Hartmann walls (perpendicular to the magnetic field, top and bottom) and the manifolds are closed by two back plates. The geometry of water pipes is simulated by dummy parts of solid material. All parts are made of 1.4571 austenitic steel that has good compatibility with the used model fluid NaK,. With this design, only four plates have to be welded: the Hartmann walls located in the figure at the top and bottom and the two manifold covers respectively back plates. This was be done by electron

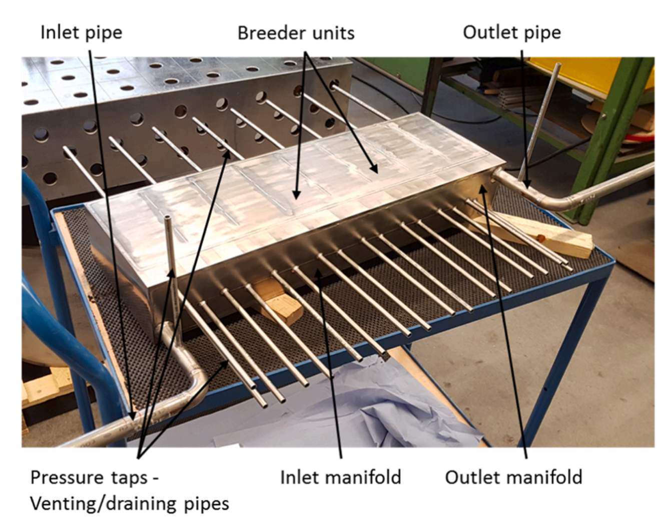

Fig. 5. WCLL TBM mockup assembly.

beam (EB) welding to minimize welding distortions. With only these few parts, costs for welds are minimized. This design has emerged as the most favorable after clarifying details of fabrication and welding possibilities.

Pressure differences between numerous points of the mockup will be measured using a piping system between the pressure taps and the pressure transducers which are located outside of the magnet (for more details see §0). To avoid additional pipes for draining and venting during the filling and emptying process, both functions are combined in only one set of pipes at the mockup, further called pressure taps. Draining of the inlet manifold is ensured by the main PbLi inlet pipe, venting of the outlet manifold is ensured by the main PbLi outlet pipe. The positions of these pipes are chosen at the lowest and highest points of the manifold. Venting and draining of manifolds for BU1 and BU8, respectively is achieved by shifting the pressure taps to the top and bottom of the manifolds for BU1 and BU8. This should not be a problem for pressure measurements since usually in strong magnetic fields the pressure is constant along magnetic field lines. Therefore, it does not matter, if the pressure is measured in a central axial flow position or (as indicated in Fig. 7) on top or bottom of the cavities. The pressure taps for BUs 2–7 have been placed with the same purpose of draining and venting at lowest respectively highest positions in the manifolds. They are arranged such that their inner perimeter just touches the separation wall between the two manifolds. Additional venting pipes respectively pressure taps are placed at the first wall on top of each BU.

1.4. Radiographic and hydraulic pressure test of the mockup

Complying with the European code 2014/68/EU and national pressure equipment directive (AD 2000) the mockup has been designed, fabricated and tested in agreement with standard rules. Radiographic testing of all welds has been performed without observing defects. After the radiographic testing, a hydraulic pressure test has been performed. A pressure of 12 bar has been applied to the pipe using demineralized water for several hours without noticing any pressure loss. The pressure test has been attended and documented by the Technical Inspection Authority (TÜV) and an approved test certificate has been issued. After the pressure test, the test-section has been drained, opened and carefully dried by a hot air stream (250 °C at entrance) for more than one day to remove residual humidity from the pipe.

2. Installation of the WCLL TBM mockup in MEKKA

2.1. Connecting the mockup with the liquid metal loop

After final assembly and inspection, the mockup was positioned inside the magnetic gap of the MEKKA facility and moved to the final position. The first step consisted of connecting the mockup with the liquid metal loop. The main inlet/outlet pipes of the mockup with a size of DN15 had to be adapted to a size of DN40 to match with the main flanges of the liquid metal loop. Additionally, the horizontal and vertical offset of all pipe axes, first the main inlet pipe of the mockup to the NaK loop, and the main outlet pipe of the mockup to the return pipe of the NaK loop, had to be three-dimensionally aligned. Therefore, pipe reductions are welded to the DN15 pipes of the mockup, followed by DN40 pipes, which are sized to correct lengths and bent to meet the axial and radial connection points of the liquid metal loop. Fig. 6 shows the mockup installed in the magnetic gap before and after connected main pipes. After the installation of the mockup in the liquid metal loop was completed, and all pressure taps were connected with the pressure transducers, the loop and the test-section were pressurized with argon inert gas. The pressure test performed over several days confirmed tightness of all connections.

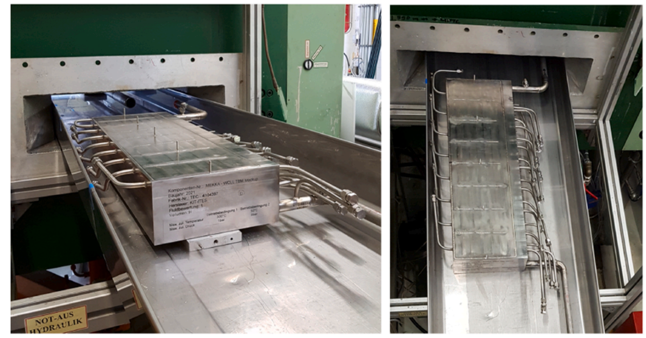

Fig. 6. Installation of the mockup: before (left) and after (right) connecting the main inlet and outlet pipes.

3. Instrumentation

3.1. Pressure distribution

In the experimental campaign, pressure differences are recorded between various points on the mockup (see Fig. 7) via five capacitive pressure transducers located outside of the magnet. All pressure taps of the mockup are connected to these pressure transducers by a piping and valve system. The measurement principle of a capacitive pressure transducer is simple. Its membranes are deformed when a pressure difference exists, which leads to a change in electric capacity. This capacity change is transformed in a current that can be measured by a data acquisition system. The accuracy of the pressure transducers used for the experiments is ±0.5% of the maximum value of the chosen measurement range. The transducers are mounted in series, i.e. they are all measuring the same pressure difference, but they have different ranges of sensitivity that overlap to avoid reading errors near the end of the spans. The final value that is then considered as the actual measurement is obtained by weighting the reading of each transducer depending on their precision for the recorded quantity. The system is designed to measure a positive pressure difference between two lines, one with high pressure H_i and another line with lower value L_k. Fig. 8 shows schematically the connection of pressure taps with the pressure transducers and Fig. 9 displays a photograph of the pressure transducers and some of the valves.

All pressure tap pipes are cut and bent to the correct length (see Fig. 10) connecting the mockup (top) with the valve system (bottom).

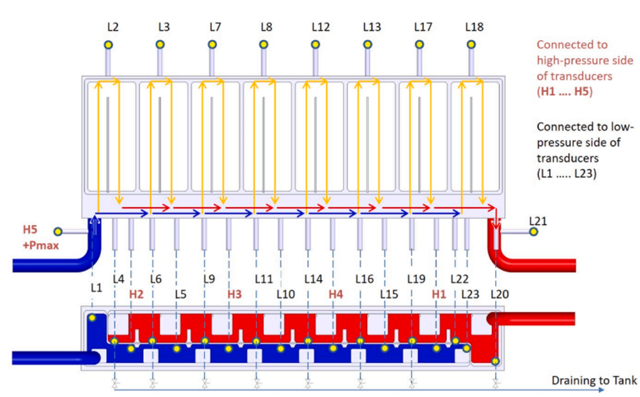

Fig. 7. Scheme showing nomenclature of pressure taps H1 …. L21 on the mockup. The first pressure tap H5 is connected in addition with the safety system of the MEKKA facility for automatic shutdown of pumps in case of unacceptably high system pressure.

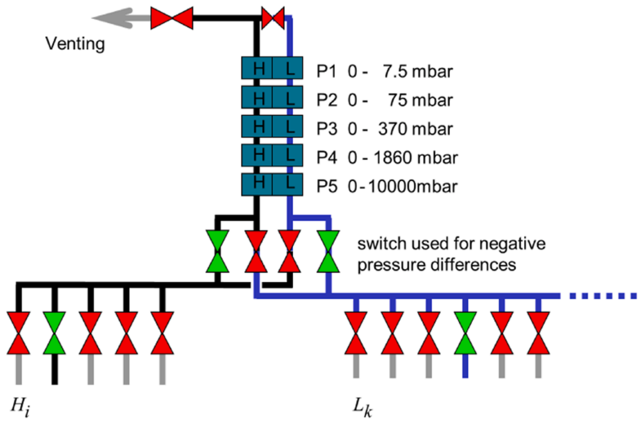

Fig. 8. Connection of pressure taps with pressure transducers. Venting into expansion tank is established via valves at the highest position.

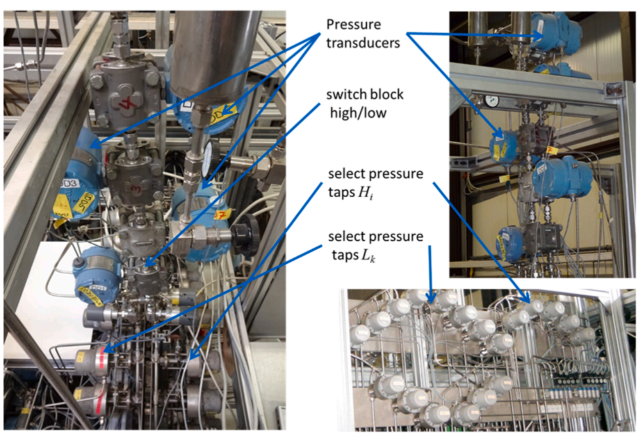

Fig. 9. Valve system for switching pressure taps and pressure transducers.

3.2. Potential differences on the external surface of walls

After the high-temperature wetting of the test-section at 300 °C had been completed, insulating plates with potential sensors have been installed. The potential gradient may be directly interpreted as a velocity signal since, according to the dimensionless Ohm's law, $\mathbf{j} = -\nabla\phi + \mathbf{v}\times\mathbf{B}$, with a magnetic field $\mathbf{B} = \widehat{\mathbf{y}}$, velocity components may be determined as

$$u \approx \frac{\partial\phi}{\partial z} \text{ and } w = -\frac{\partial\phi}{\partial x}.$$

In order to record the potential distribution on the surface of the mockup, two insulating Peek plates are fabricated. They were instrumented with spring-loaded potential probes. One of these plates has been fixed across the back plates of the manifolds and the one on top the mockup in a central position of the BUs. The electrical potential distribution is recorded at in the middle of the Hartmann wall at 160 positions and at 8 × 15 positions across the manifolds. Cables are connected with a multiplexer that switches packages of 15 signals to a digital multichannel nano-voltmeter, which resolves electric potential differences with errors smaller than ±0.1μV. The multiplexer and the nanovoltmeter are controlled by a computer. Fig. 11 shows the set-up for electrical potential measurements on the mockup with the designed plates (see also Fig. 3). The manufactured and instrumented plates can be seen in Fig. 12.

Fig. 10. Pressure tap pipes from the mockup (top) to the valve system (bottom).

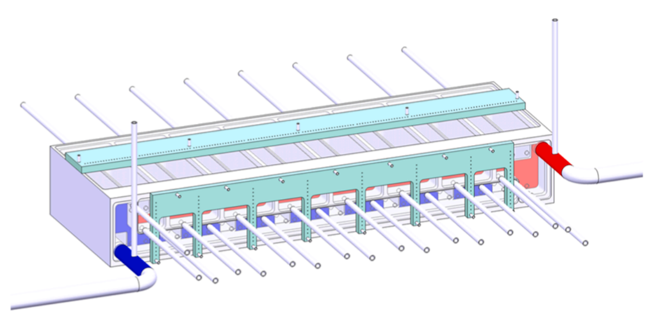

Fig. 11. Set-up for the electrical potential sensors on the mockup. For more details, see also Fig. 3.

4. Conclusions

A scaled mockup of the WCLL TBM for ITER has been designed, fabricated and installed in the liquid metal NaK loop of the MEKKA facility at KIT. The mockup exhibits many geometric details such as for instance water cooling pipes that occupy a considerable fraction of the liquid metal manifolds. They are made as solid dummy obstacles to mimic the geometric constraints for the liquid metal flow. A number of

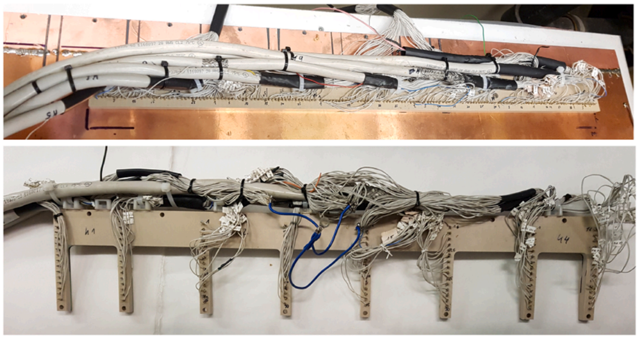

Fig. 12. Manufactured and instrumented plates for electrical potential measurements.

pressure taps is available such that pressure differences between numerous positions on the text section can be recorded. Venting and draining of specific parts of the mockup is also achieved through these pressure lines. Potential probes on the upper Hartmann wall are foreseen for determining flow partitioning and velocity in BUs. This mockup offers the possibility for performing relevant MHD experiments in strong magnetic fields with Hartmann numbers up to Ha=4500. It is ready for measuring pressure drop along both liquid metal manifolds. Pressure differences along BUs and potential data will allow determining the flow distribution in breeder zones.

The connection of the mockup with the liquid metal loop has been finished and tightness has been confirmed. Results of the upcoming experiments will determine how the ITER TBM will perform under fusion relevant conditions in terms of MHD pressure drop and flow distribution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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