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Design of a test section to analyze magneto-convection effects in WCLL blankets

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Abstract - The water-cooled lead lithium (WCLL) blanket is one of the European concepts for a DEMOnstration nuclear fusion reactor. The spatial distribution of the water cooling pipes inside the liquid metal blanket breeder zone is a critical issue, since an efficient heat removal from the liquid metal has to be ensured, avoiding local hotspots in the fluid or in blanket walls. The convective motion, driven by density gradients due to volumetric heat sources in the liquid breeder and heat removal by cooling pipes, is affected by magnetohydrodynamic interactions of the electrically conducting lead lithium with the external magnetic field. For the recent complex design of the DEMO WCLL blanket, a prediction of the liquid metal flow is quite difficult. In order to determine the flow distribution resulting from the combined interaction of electromagnetic forces, buoyancy and pressure, preliminary numerical and experimental studies are necessary. A test section based on a simplified model geometry supported by preliminary numerical simulations has been designed for experiments in the MEKKA laboratory at the Karlsruhe Institute of Technology (KIT) and is presented in this paper.

Keywords - WCLL, blanket, fusion, MHD, magneto convection

1 Introduction

One of the European liquid metal blanket concepts considered for a DEMOnstration nuclear fusion reactor is the water-cooled lead lithium (WCLL) breeding blanket [1]. The liquid metal alloy lead lithium PbLi is used as breeder, neutron multiplier and as heat carrier. Pressurized water flows through a large number of cooling pipes immersed in the liquid metal and in the blanket structure and cools the walls and breeding zone (see Figure 1).

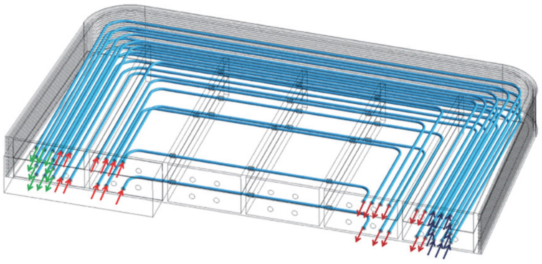

Figure 1 WCLL blanket design (ENEA [2]), equatorial section in a blanket module with cooling pipes.

The distribution of the water cooling pipes in the breeding zone is a critical issue. Efficient heat removal from the liquid metal has to be ensured, avoiding occurrence of local hotspots. In order to get first insight in the flow distribution resulting from the combined interaction of electromagnetic forces, buoyancy and pressure, preliminary numerical and experimental studies of buoyant magnetohydrodynamic (MHD) flows are foreseen. For being relevant for applications in WCLL blankets, these investigations should cover liquid metal heat transfer and magneto-convective flow in a geometry with internal obstacles simulating the cooling pipes in the blanket.

A simplified model geometry will be used for these studies. The test section consists of a liquid-metal-filled box, in which a heated pipe simulates neutron heating while a cooled pipe removes the heat from the liquid metal. The magneto-convective flow is driven by buoyancy, when heat is exchanged between liquid metal and the cooling and heating pipes. The dimensions of the box have been chosen such that the experiment fits into the gap of the dipole magnet available in the MEKKA laboratory at the Karlsruhe Institute of Technology (KIT), where a quite uniform magnetic field is achieved in a domain of $800 \times 480 \times 168\mathrm{mm}^3$ [3]. The design of the experimental test section is presented in this paper. Results of the experiments and numerical simulations will improve the understanding of magneto-convective flows and help to optimize the design of the cooling system in the breeding zone and to demonstrate the feasibility of the proposed WCLL DEMO design.

2 Preliminary numerical simulations

Preliminary numerical simulations have been performed for buoyant flow in a model geometry with volumetric heating. The heat was removed by a single cooling pipe in a rectangular channel. The simulations predict the liquid metal flow and heat transfer in strong magnetic fields, where thin layers develop along magnetic field lines, tangential to the cooling pipe [4], [5].

In order to support the design of the present experiment with some theoretical data, numerical simulations have been performed, in which the driving temperature difference between heated and cooled pipe has been set to ΔT=T2-T1=40K. The strength of the magnetic field is measured in terms of the nondimensional Hartmann number $Ha = BL\sqrt{\sigma / \rho\nu}$, where B is the magnetic field, L the half length of the box in field direction, σ, ρ, ν stand for electric conductivity, density and kinematic viscosity of the fluid. All walls are electrically insulating and adiabatic.

Some results of numerical simulations are shown in Figure 2 for different strengths of the magnetic fields, i.e. for different Hartmann numbers. The figures in the left column show contours of fluid temperature. Flow streamlines indicate that there are convective cells present in the center between the two pipes and the maximum velocity occurs near the walls of the tubes. For a small Ha=50 the liquid metal flow and the convective heat transport is strong enough to influence temperature distribution. Hot fluid is transported towards the cold pipe and vice versa. When increasing the magnetic field, the intensity of the convective motion reduces significantly and temperature and velocity distributions became symmetric with respect to the vertical mid plane. For Ha=1000 the maximum velocity is localized in thin layers parallel to the magnetic field and tangent to pipes. The fluid velocity in the rest of the box is remains quite small. It should be mentioned that in the numerical simulations it is assumed that the box is long enough that the flow reaches fully developed thermal and hydrodynamic conditions normal to the considered plane. Consequently, no axial electric potential difference builds up and electric currents induced in the liquid metal circulate exclusively in axial direction. Since the experiment will have finite axial length, it is expected that 3D phenomena with measurable potential differences will occur near the end walls. Corresponding 3D numerical simulations are ongoing.

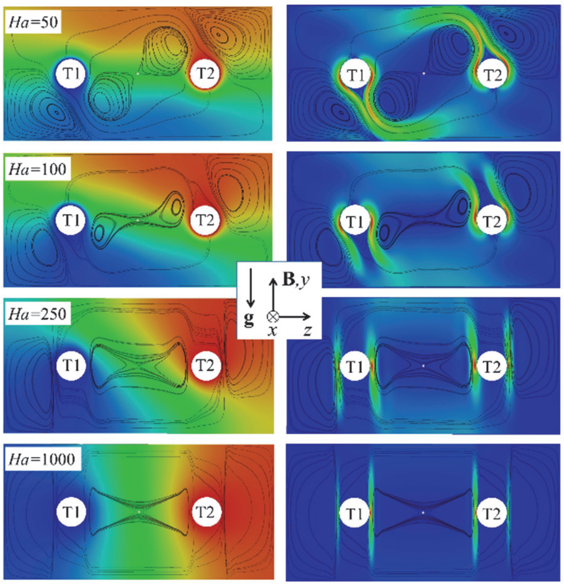

Figure 2 Contours of temperature (left) and magnitude of velocity (right) on a cross-section of the geometry. Streamlines in black. Magneto-convective flow for ΔT=T2-T1=40K.

According to these numerical results, suitable positions for measuring temperature are along magnetic field lines. Interesting velocity data is expected in tangent layers, and electric potential differences might be seen only on the end walls of the box, where electric currents have to close in thin viscous layers.

3 Design and instrumentation

3.1 Test section

Figure 3 shows two transparent views of the experimental WCLL test section design in an isometric and top view. It consists of a rectangular box made of Peek plates. Peek can be used for higher temperatures and it is compatible with the model fluid GaInSn. Peek plates are designed to form a leak-tight rectangular box. They are assembled with screws as well as a thin layer of silicon flat seal and a one-component adhesive based on silicon. All lead-ins into the box, for the thermocouple probe or UDV sensors, are closed with circular caps sealed by O-rings and fixed with screws. For draining and venting of the mockup two small access pipes are attached to the front plate.

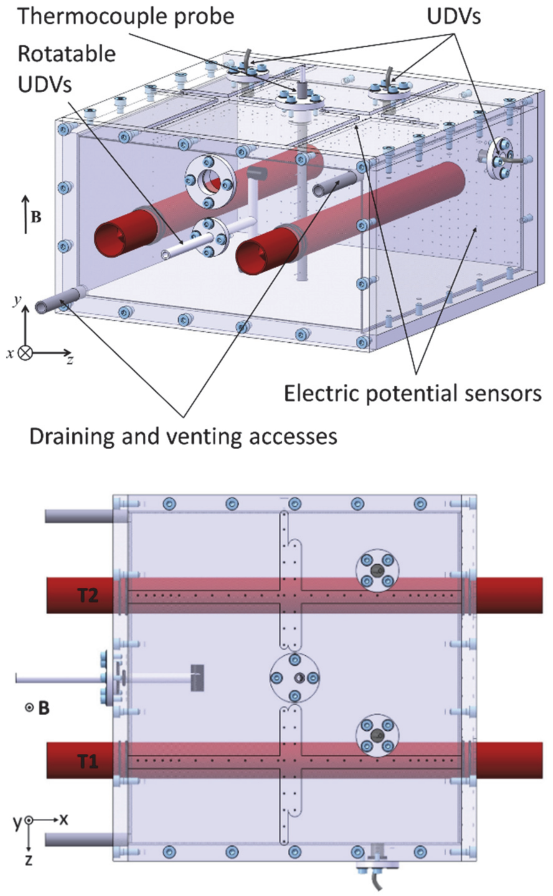

Figure 3 Design of the experimental test section in isometric (top) and top view (bottom).

All parts of the box have been fabricated in the workshops of KIT. Figure 4 shows the fabricated and assembled parts before instrumentation.

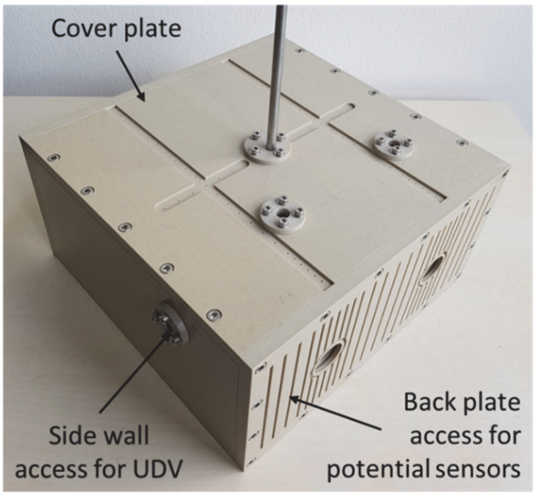

Figure 4 WCLL mockup without instrumentation.

Two parallel copper pipes are placed inside the box and sealed with two O-rings at the front and back plate. The outer surface of the pipes has been coated with a 2µm thin silicon carbide layer (SiC-Silcor). The coating is thin enough for a good thermal conductivity, but provides sufficient protection against corrosion attack. The pipes are kept at constant temperature difference ΔT=T2-T1 during the experiments by internal water cooling or heating. For that reason, each pipe is connected to a temperature-controlled water circuit, which allows establishing the desired temperature difference in the box. Copper has been used as pipe material due to its good thermal conductivity. The pipes are supplied with copper cores for achieving as good as possible isothermal conditions (Figure 5).

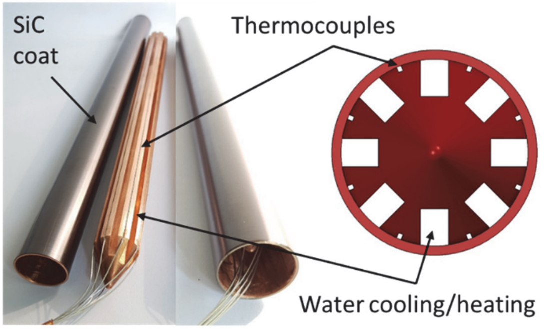

Figure 5 Copper pipe and core with inserted thermocouples (left), front view of design (right).

The copper cores have been designed to have 8 channels circumferentially distributed, where the tempered water cools or heats the pipes. There are another 8 small grooves were thermocouples are placed at different axial and circumferential positions. Thereby, the temperature can be monitored during the experiments near the inlet, outlet and at the center of the pipes.

3.2 Instrumentation of the test section

The aim of the experiments is measuring simultaneously several physical quantities such as liquid metal velocity, electric potential on the surface of the box and temperature distribution at numerous points within the fluid. For measuring the vertical temperature distribution in the center of the test section, a temperature probe has been fabricated, which has 11 thermocouples equidistantly distributed over the height. Installation of the probe is possible via an O-ring-sealed flange on the upper wall. Figure 6 shows the temperature probe with thermocouples assembled in the test section.

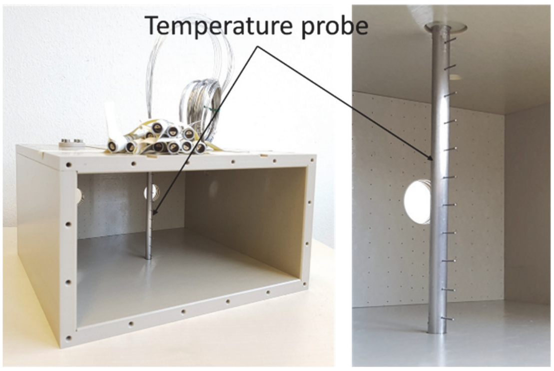

Figure 6 Temperature probe inside the mockup.

In addition, the temperature on the walls of the box is monitored in more than 50 positions in order to get an overview of the temperature distribution and to estimate the amount of transferred heat. The thermocouples used for the experiment should be able to give precise results also in high magnetic fields. Standard thermocouples such as type K are known to be problematic in magnetic environments. Manufacturer's experience with thermocouples in high magnetic fields suggests that thermocouples of type T (Cu-CuNi) are most suitable for accurate results while offering similar sensitivity than those of type K. For that reason, all thermocouples are of type T. Numerical calculations show that small temperature differences have to be resolved during the experiment, which requires a very precise data acquisition system. This is achieved by measuring all temperatures with respect to a multichannel high-precision type T reference ice point, for all incoming signals.

In MHD flows, electric potential is a property that can be measured with high precision for comparison with 2D and 3D numerical results. Electric potential will be measured on the fluid-solid interface by a large number of copper electrodes that penetrate specific walls of the test section. Highest flow-induced values of potential are expected at the vertical end walls. Therefore, one of those walls is instrumented with a dense population of electrodes (see Figure 7). The cables will be connected to a multichannel multiplexer and a multichannel nano-voltmeter.

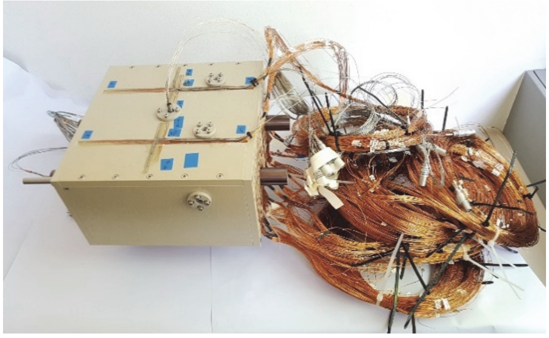

Figure 7 Instrumented WCLL mockup with copper cables and thermocouples.

Preliminary numerical simulations show that the highest velocities occur in thin layers tangent to the heating/cooling pipes. It is planned to record velocity data from those layers by using Ultrasound Doppler Velocimetry (UDV) [6]. A principle sketch showing the position of the sensors and the propagation zones of the ultrasonic pulses is displayed in Figure 8. Two sensors will give information (velocity component in direction of pulse propagation) about the flow in the tangent layers and one in the cores.

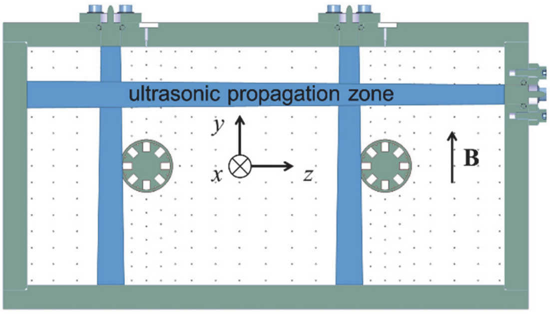

Figure 8 Sketch showing positions of UDV sensors on the walls and propagation zones of ultrasonic pulses, in which the beam-aligned component of velocity can be detected.

For measuring velocity along other directions, a movable probe with two UDV sensors is foreseen. The probe is mounted on a rotatable rod and can be turned on in *yz* plane (see Figure 9). It is centered in the middle of the box. The rotatable shaft is guided through the front plate and it can be rotated during the experiment from outside for scanning a large portion of the *yz* plane.

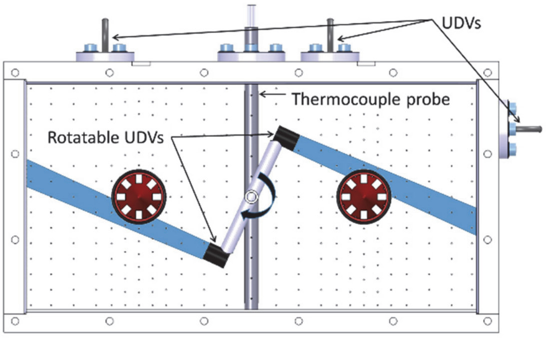

Figure 9 Instrumentation of the test section: Thermocouples at probe and inside the copper pipes; electric potential sensors on the end wall; UDV sensors fixed at walls or on rotatable probe.

4 Preliminary experiments with water

Before the test section is filled with liquid metal, first experiments will be performed using water as a test fluid. These preliminary tests are foreseen to show full functionality of the instrumentation, and they will give already results for the hydrodynamic limit, when no magnetic field is present. Moreover, unlike liquid metals, water is transparent, which allows optical access and application of Particle Image Velocimetry (PIV), for flow visualization. For this purpose, end walls and one sidewall that are already instrumented for liquid metal experiments (see Figure 7) are replaced by transparent material. The test section for these preliminary experiments is shown in Figure 10.

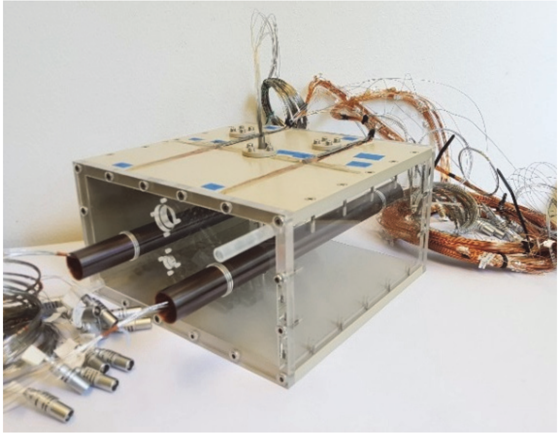

Figure 10 WCLL mockup for preliminary experiments with water: front, side and back walls made of Plexiglas.

A sketch of the optical setup is shown in Figure 11. A laser light sheet illuminates a *yz* plane while the movement of seeding particles with the flow in this plane is observed by a camera along the *x* direction.

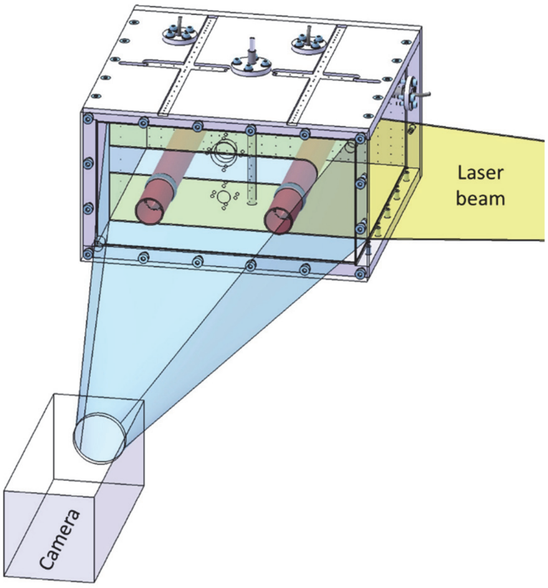

Figure 11 Arrangement of test section, laser beam and camera for preliminary hydrodynamic experiments with water.

5 Conclusions

In order to investigate experimentally magneto-convective liquid metal flows for WCLL blankets, a test section with a simplified model geometry has been designed and manufactured, supported by preliminary numerical simulations. The test section is instrumented for measuring simultaneously temperature, potential and velocity distribution. It is foreseen to perform experiments for various values of the applied magnetic field and driving temperature differences, i.e. for various Hartmann and Grashof numbers, respectively. The WCLL model geometry consists of a box made of Peek plates, where two parallel copper pipes simulate the cooling tubes and volumetric heating in the blanket module. They generate the non-uniform temperature and density distribution that drives the buoyant flow under the influence of gravity.

First experiments will be performed with water instead of liquid metal. This will allow to test instrumentation for temperature measurements and to obtain, with laser optical methods, velocity results in the hydrodynamic limit. In a second step, the test section will be filled with liquid metal GaInSn and exposed to magnetic fields for final magneto-convection experiments.

6 Acknowledgments

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7 References

[1] F. Romanelli, P. Barabaschi, D. Borba, G. Federici, L. Horton, R. Neu, D. Stork and H. Zohm, "Fusion electricity: A roadmap to the realisation of fusion energy," EFDA, 2012.

[2] A. Tassone, A. D. Nevo, P. Arena, G. Bongiovì, G. Caruso, P. A. di Maio, G. di Gironimo, M. Eboli, N. Forgione, R. Forte, F. Giannetti, G. Mariano, E. Martelli, F. Moro, R. Mozzillo, A. Tarallo and R. Villari, "Recent Progress in the WCLL Breeding Blanket Design for the DEMO Fusion Reactor," *IEEE Transactions on Plasma Science,* vol. PP, no. 99, pp. 1-12, 2018.

[3] L. Barleon, K.-J. Mack and R. Stieglitz, "The MEKKA-facility a flexible tool to investigate MHD-flow phenomena," 1996.

[4] C. Mistrangelo and L. Bühler, "Magneto-convective flows in rectangular ducts with internal cylindrical obstacles," in *17th MHD-Days 2016, Göttingen, November 30 - December 2*, 2016.

[5] L. Bühler and C. Mistrangelo, "MHD flow and heat transfer in model geometries for WCLL blankets," *Fusion Engineering and Design,* vol. 122, pp. 919-923, 2017.

[6] D. Brito, H.-C. Nataf, P. Cardin, J.Aubert and J.-P. Masson, "Ultrasonic Doppler Velocimetry in Liquid Gallium," *Experiments in Fluids,* vol. 31, pp. 653-663, 2001.