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MHD velocity distribution and pressure drop in manifolds of a WCLL TBM

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Abstract In the frame of the EUROfusion breeding blanket research activities, two reference blanket concepts are developed, the helium cooled pebble bed and the water cooled lead lithium (WCLL) blankets, which represent the most attractive designs for a DEMO reactor [1]. Test Blanket Modules (TBMs) derived from these concepts will be tested in ITER.
The design of breeding blankets represents a major challenge for fusion reactor engineering due to the performance requirements and the severe operating conditions in terms of heat load and neutron flux. Liquid metal alloys such as lead-lithium, PbLi, are considered as breeder material due to their lithium content and as coolants because of their large thermal conductivity and the possibility to be operated at high temperature. On the other hand, the motion of the electrically conducting breeder in the plasma-confining magnetic field induces electric currents and generates strong electromagnetic forces that modify significantly the velocity distribution in the blanket compared to hydrodynamic conditions and increase pressure losses [2]. Magnetohydrodynamic (MHD) pressure drops have to be carefully quantified, since excessive values can jeopardize the feasibility of the considered blanket concept. The present work investigates numerically liquid metal MHD flows in manifolds of a WCLL TBM. Velocity and pressure distributions are analyzed.

Problem description A view of the WCLL TBM manifold design is shown in Figure 1a. It consists of two long poloidal ducts, which are electrically connected across a common wall. The liquid metal has to flow along a series of expansions and contractions due to the presence of horizontal stiffening plates that separate the breeder chambers arranged in a column. This type of MHD flow is known to cause additional pressure drop compared to flow in straight ducts [3]. Liquid metal flows are investigated in the model geometry depicted in Figure 1b whose dimensions are taken from the most recent WCLL TBM design. A uniform magnetic field is imposed in toroidal direction.

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Numerical simulations are performed for periodic fractions of the manifolds by assuming a stepwise decrease/increase of the flow in the feeding/draining manifolds. Velocity and pressure distributions in the entire manifolds that feed/drain 8 breeder zones are then reconstructed. The pressure drop depends linearly on the mean velocity and quadratically on the magnetic field strength. Therefore, results can be extrapolated and scaled, e.g. to other flow rates, depending on design specifications.
Calculations have been performed by using a finite volume code. Equations describing the MHD flow are implemented in the open source software OpenFoam [4]. Accurate simulations of MHD flows are pretty demanding since they require a proper resolution of thin boundary layers that form along all walls. Their thickness reduces by increasing the intensity of the magnetic field [5]. Moreover, electrically conducting walls provide closing paths for electric currents and their resolution is also crucial to determine the total current density in the fluid. About $4 \cdot 10^6$ nodes are needed in the fluid and in the wall to resolve an eighth fraction of the manifold.

Objectives of the study According to the ITER schedule the conceptual design for the WCLL TBM should be completed by 2020. Therefore, there is urgent need to reduce technical uncertainties of the present design. With this purpose, a task has been initiated by EUROfusion to investigate numerically liquid metal MHD flows in manifolds that distribute and collect PbLi in the WCLL TBM. Previous experimental and theoretical analyses for comparable manifolds of a helium cooled PbLi blanket showed the decisive role of the manifolds in determining pressure drop and flow distribution in the blanket module [6]. Results presented here serve four main purposes:

- to provide an estimate of pressure drop in the WCLL TBM manifold, which has to be compatible with the pumping capability in the PbLi loop
- to be compared with data from experiments that are currently prepared at the Karlsruhe Institute of Technology to study MHD flows in a scaled mock-up of a WCLL TBM. This permits a further validation of the implemented physical models and the employed predictive tool

- to complement the experimental data in order to obtain an overview of the investigated MHD phenomena and to derive scaling laws to extrapolate results to realistic ITER operating conditions
- to support correct interpretation of surface electric potential measurements in terms of velocity distribution inside the test-section. Especially when walls are thick and induced currents have to be taken into account a comparison with numerical simulations is compulsory.

Brief overview of numerical results Figure 2a shows as an example a 3D view of the velocity distribution in the considered geometry for the position at the bottom of the TBM where the fluid is supplied to duct 2, while the weak flow in duct 1 is only driven by electromagnetic coupling caused by leakage currents. In Figure 2b the vertical component of the velocity is plotted along the radial dashed lines in the two channels. Due to electromagnetic coupling across the common dividing wall the flow in duct 2 pulls that in the core of duct 1 in the same direction. This leads to a buildup of pressure along the flow direction that drives the backward oriented jets in duct 1 (red curve in Figure 2b).

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A principle sketch of the pressure distribution in the manifolds along the poloidal direction is depicted in Figure 3. Since the cross-section of the two channels remains constant, while the flow rate changes along the poloidal path of the liquid metal flow, the pressure exhibits a non-linear profile. This results in different pressure drops in the breeder units and a corresponding non-homogeneous partitioning of the fluid among them. The latter is further increased by the fact that the draining manifold has a cross-section larger than the one of the feeding duct and hence a smaller pressure gradient. From the calculated pressure distribution flow rates in the breeding zones can be estimated in order to get a picture of the way in which the liquid breeder distributes.

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