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3D MHD lead–lithium liquid metal flow analysis and experiments in a Test-Section of multiple rectangular bends at moderate to high Hartmann numbers

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HIGHLIGHTS

- Three dimensional simulation of lead–lithium (Pb–Li) liquid metal MHD flow has been carried out using FLUENT CFD code.
- Experiments were carried with magnetic fields of up to 4 T in an electrically conducting channel of multiple rectangular bends.
- The numerical predictions matched well with the measured values at all the locations for high magnetic fields and low flow rates.
- The analysis indicates that the flow becomes rapidly symmetric at the bend where both the legs are perpendicular to the magnetic field.
- The flow remains asymmetric for a longer distance when it turns from parallel to perpendicular direction of the magnetic field.

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ABSTRACT

Experiments with liquid lead–lithium (Pb–Li) were carried out in a stainless steel (SS) Test Section (TS) consisting of multiple 90° bends for various flow rates and applied magnetic fields of up to 4 T. Characteristic MHD flow parameter Hartmann number, Ha ($= B_0 a\sqrt{\sigma/\mu}$, Ha^2 is the ratio of electromagnetic force to viscous force) and interaction parameter, $N (= \sigma a B_0^2/\rho U$, N is the ratio of electromagnetic force to inertial force) of these experiments were varied from Ha = 515 to 2060 and N = 25 to 270 by changing the applied magnetic field and flow rates respectively. Three dimensional numerical simulations have been carried out using MHD module of FLUENT code. The measured Hartmann and side wall electric potential distribution at various locations of the Test Section have been compared with the numerical simulation results for different Hartmann numbers and interaction parameters (Ha = 1030, N = 25, 40, 67 for B = 2 T and Ha = 2060, N = 129, 161, 270 for B = 4 T). The numerical predictions based on laminar flow model are matching well with the measured values at all locations including bend regions for high magnetic field and low flow rates. However, at higher flow rates and lower magnetic fields (smaller Ha/Re values), the agreement was not good near the bend regions. This may be attributed to the significant presence of turbulence that was not accounted in the present simulation. The core velocity, estimated from the measured Hartmann wall potential at the locations far away from the bends, matched well with the numerical results. The analysis indicates that the flow distribution becomes rapidly symmetric when it turns at the bend where both the legs are perpendicular to the applied magnetic field. In contrast, flow distribution remains asymmetric for a longer distance when it turns from parallel to perpendicular direction of the applied field. The code is predicting reasonably well for MHD parameters relevant to Blanket Modules for single channel flows with bends.

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1. Introduction

Many magnetically confined fusion systems including, International Thermonuclear Experimental Reactor (ITER), are based on deuterium–tritium (D–T) reaction. Blanket Module (BM) is one of the key fusion components where the kinetic energy of 14.1 MeV neutrons, generated in the DT fusion, is converted to thermal energy for power production and to breed tritium. In many of the national schemes lead–lithium eutectic – Pb–Li – (enriched with ^{6}Li) liquid metal has been chosen for heat extraction from neutrons as well as for breeding tritium in Test Blanket Module TBM of the ITER [1,2]. Typically, in these TBMs, the flow under goes multiple 90° bend under high magnetic fields (present for the confinement of plasma). The flow of electrically conducting Pb–Li under transverse magnetic field drives an electric current in the liquid metal and the current interacts with the applied field producing MHD body force opposing the motion. The intense MHD effects, especially in the absence of electrical insulation between the liquid metal and structural components, modify the flow structure, leading to additional pressure drops and significant modification in the heat transfer characteristics etc. Some of these thermo-fluid MHD issues including instabilities, turbulence, buoyancy effects has been studied by Smolentsev et al. [3,4]. Analysis of MHD flow in a conducting rectangular U bends, where the flow turns from perpendicular to parallel direction of the applied magnetic field has been carried out by Molokov and Buhler [5] for high Hartmann number (Ha ≫ 1) and in the inertia less limit ($N > \mathrm{Ha}^{1/2}$). Various phenomena in liquid metal flows under blanket condition are complex and experimentally validated MHD codes are needed to design the TBMs as well as future DEMO Blankets. In this regard Ni et al. [6] and Smolentsev et al. [7] have developed advanced computational techniques for MHD flow simulation at high Hartmann number relevant to fusion systems.

In this paper, the results of the experiments carried out in a Test Section for various flow rates of lead–lithium eutectic and magnetic fields have been compared with the predicted values based on the numerical simulation. Three dimensional numerical simulation has been carried out using MHD module of FLUENT code [8] based on electric potential formulation (induction less approximation) [9]. The code has been benchmarked with Hunt's solution [10] for 4 T magnetic field (Ha = 1038). Pressure gradient, velocity and electric potential distribution have been compared with the analytical solution to determine the suitability of the code. The Test-Section under consideration consisted of multiple 90° bends. The orientation of the applied magnetic field with respect to the flow direction was different in different legs of the bend (parallel to perpendicular, and perpendicular to perpendicular direction with respect to the applied magnetic field). The magnetic field was steady and spatially uniform during each run. The maximum Hartmann number Ha ($= B_0 a\sqrt{\sigma/\mu}$) was 2060 corresponding to 4 T field. The interaction parameter N ($= \sigma a B_0^2/\rho U$) was varied from 25 to 270. Here B_0, a, σ, μ are the applied magnetic field, characteristic length scale, electrical conductivity of the liquid metal and dynamic viscosity respectively. Characteristic length scale 'a' has been considered as half the length along side walls (for present Test Section, a = 0.025 m).

The present paper has been organized as follows. The details of the experimental set up, Test Section and measured parameters have been presented in Section 2. Numerical model followed by benchmarking with analytical solution has been presented in Section 3 and Section 4. Numerical simulation in Test Section, comparison of measured Hartmann wall and side wall potential distribution with simulation result at various locations of the Test Section have been presented in Sections 5 and 6. Symmetry in flow distribution at different bend regions has been discussed in Section 7. Finally, a brief summary and concluding remark has been given in Section 8.

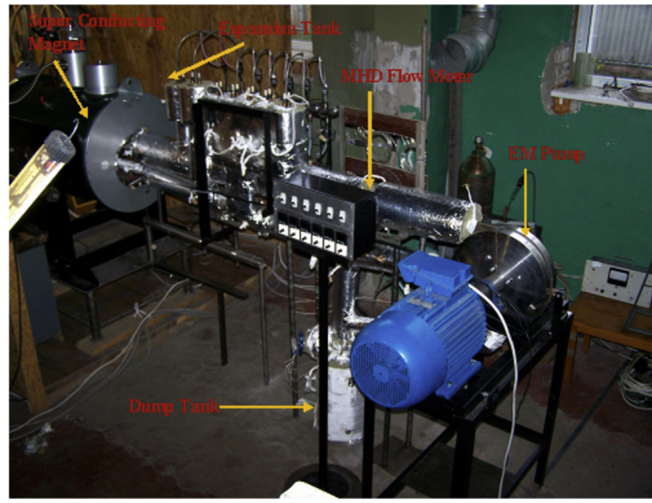

Fig. 1. Photograph of experimental loop with various components.

2. Experiments

2.1. Experimental set up and Test Section

Experiments were carried out with a stainless steel (SS) Test Section (TS) in the lead–lithium loop of Institute of Physics University of Latvia (IPUL). The solenoid superconducting magnet can provide uniform axial magnetic field up to 4 T in a circular region of diameter of 280 mm. The wall potential distribution at various locations was measured using SS pins. Lead–lithium loop (see Fig. 1) consists of Pb–Li system, super conducting magnet, electromagnetic pump, MHD flow meter, Test Section, Instrumentation and Data acquisition system, and heating system. The external magnetic field was provided by a cryogen-free liquid helium cooled superconducting solenoid magnet of inner diameter 300 mm and axial length of 1000 mm. The distribution of magnetic field was nearly uniform and can give maximum field strength of 4 T in a cylindrical region of diameter 280 mm. The Test Section with attached diagnostics integrated in this loop and was placed at the central zone of superconducting magnet. Liquid metal was circulated at temperature of 350 °C by an electromagnetic pump which can give variable flow rates limiting to a maximum pressure head of 5.0 bar. An electromagnetic flow meter was used to measure the flow rate [11].

Experimental Test Section consists of multiple 90° rectangular bends and the orientation of the applied magnetic field with respect to the flow direction was different in different legs of the bend (parallel to perpendicular, and perpendicular to perpendicular direction of the applied magnetic field). Two 90° channel bends were in the parallel plane where the flow turns from parallel to a transverse direction of the applied magnetic field and vice versa with sudden expansion/contraction (flow cross-section changing from 0.025 m × 0.025 m to 0.0247 m × 0.0496 m) and another two 90° bends in the plane perpendicular to the magnetic field (see Fig. 2). All the confining walls of the Test Section were made from 3 mm thick SS plates of 316L. The liquid metal at 350 °C enters the Test-Section through square inlet duct of cross section 0.025 m × 0.025 m which is parallel to the axial magnetic field. The flow then becomes perpendicular to the magnetic field after taking a 90° turn from the square inlet duct. The flow cross section where it is transverse to the applied magnetic field is of 0.0247 m (between side walls) × 0.0496 m (between Hartmann walls). The flow further