Deformation Induced by Magnetic Field on GaInSn Flow Surface*)

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Liquid metal divertors are expected to have higher thermal load tolerance compared with solid divertors. Precise prediction of liquid metal behavior using magnetohydrodynamic (MHD) simulation enables the practical designing of a liquid metal divertor. The aim of this study is to confirm the accuracy of an MHD simulation that is developed for liquid metal flow prediction. As a benchmark test of the MHD simulation, a comparison of the Galinstan flowing through a vertical magnetic field and the simulated results was performed, and qualitative reproduction using the MHD simulation was confirmed. In addition, the source of wave creation and the causes of failure of the quantitative reproduction were investigated, which is may caused by the variations of the Galinstan surface tension.

Keywords: fusion reactor material, simulation and visualization

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1. Introduction

The divertors in tokamaks are one of the key components for receiving and exhausting heat and particles from plasma. Due to their application, they receive enormous heat loads in reactors. The heat tolerance limit of a tungsten divertor used in an ITER is approximately 10 MW/m^2 in steady-state heat loads [1]. The heat load beyond the tolerance limit results in the meltdown of tungsten, and local melting accelerates further melting due to deformation and reduction of thermal capacitance [2]. Considering the low tolerance value, it is not feasible to apply the same type of divertor to DEMO class devices where the heat load is expected to be from 10 to ≤ 70 MW/m^2 and ∼1 GJ disruption [3]. Japan-DEMO published a special issue on the design activity to describe the process to develop a tungsten-based divertor [4].

Liquid metals do not demonstrate exceptionally high thermal conductivities but have high thermal exhaust capabilities based on their flow properties. Their flowability makes them a promising candidate in the improvement of the heat handling capability of divertors. Liquid metal divertors are operated by continuously replenishing the liquid on their surface; this process dissipates the incoming heat through forced convection and can diminish the meltdown risk of plasma-facing components. When a high heat load accompanied by a significant event of core plasma, such as a large edge localized mode and disruption, gets to the divertor along the magnetic field line, the heat resistance of the divertor can be effectively improved by incorporating the mechanism of evaporation. This process dissipates the heat from the surface of the divertor and causes a vapor shielding effect, in which the heat from the plasma is reduced by the vapor that forms on the surface of the liquid metal after collisions with charged particles from the scrape-off layer [5].

Low-melting-point metals such as tin and lithium are currently under investigation as candidates of working fluids [6–8]. Due to the high electric conductivity, however, these are subjected to strong magnetohydrodynamic (MHD) forces by electromagnetic induction. These forces are robust when the magnetic field is perpendicular to the flow direction (i.e., MHD drag). The force works as a deterrent to the liquid metal flow and causes the accumulation of the liquid metal, which leads to a reduction in the heat tolerance of the liquid metal surface and causes rapid evaporation and flooding of the liquid metal. In contrast, applying a magnetic field in parallel to the flow direction does not create any MHD force [9]. The asymmetry of the MHD force may challenge the applications of the liquid metals to divertors. A qualitative study of the effect of MHD forces on liquid metal flows is indispensable in this sense, and incorporation between basic experimental research and MHD simulations [10] is adequate to proceed. This study aims to create the MHD simulation for the prediction of the liquid metal flowing system and verify the accuracy of calculations by making quantitative comparisons. This paper describes a comparison between the experimental results and simulation.

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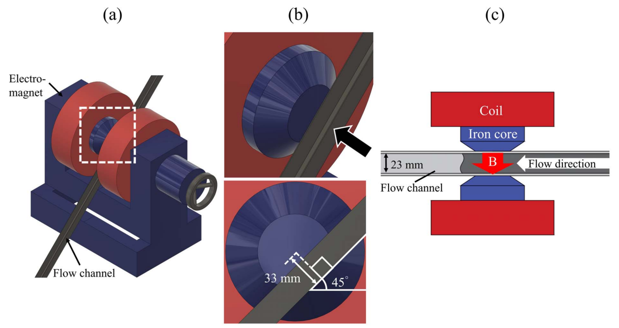

Fig. 1 (a) shows the overall view of the experimental setting. GaInSn starts flowing from the higher position in the flow channel. (b) indicates the position and angle of the channel relative to the iron core. The upper image is the enlarged view inside the white box of (a), arrow indicates a point of sight of a bottom image. At the right side, Helmholtz coil and iron core are buried for visualization of the channel. (c) is the schematic view of flowing GaInSn. The right side shows the upper stream of flow (higher position).

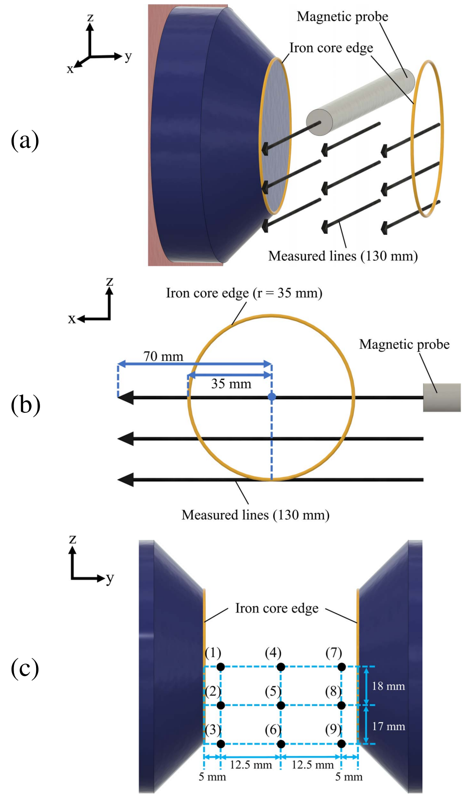

Fig. 2 Schematic diagram of the magnetic field measurement. (a) shows the overview of the placement of the electromagnet with the magnetic probe. The diameter of the probe is approximately 8 mm, and the active area (spatial resolution) of the internal hall sensor is approximately 1.5 mm. (b) indicates the measured area. The movement of the magnetic probe is shown using the nine arrows and the magnetic field magnitude data is obtained. (c) shows the placement of the measured line. These distances of the measured lines numbered (1) - (9) indicate the placement of the center of the probe.

2. Experiment

2.1 Liquid metal flow experimental setup

Figure 1 shows the experimental setup used in this study. For the experiment, an open channel was placed between the poles of an electromagnet (iron cores) at a 45° angle (Fig. 1 (b)). The walls and floor of the flow channel were 1 mm thick. The channel had 25 mm high, and 25 mm wide, which was placed to remove any gap with the iron core. The surface of the iron cores in contact with the channel was circular with a radius of 35 mm, and the channel bed was oriented tangentially at approximately 34 mm from the center of the circle. From the upstream of the apparatus (high up in the channel), Galinstan (GaInSn, Ga: 67.5%, In: 24.5%, Sn: 12.5%), a low-melting alloy that is liquid at room temperature and non-toxic to the human body, was manually poured to create the flow. The insertion point of GaInSn was at least 1 m upstream to the flow path from the iron core of the electromagnet since the experimental conditions required at least 0.72 m for sufficient flow to develop [11]. The flowing GaInSn passed through the vertical magnetic field generated between the iron cores of the electromagnets, as shown in Fig. 1 (c). The applied magnetic field strength was 0.3 to 1.0 T based on the numbers measured at the center of the circle, i.e., the reference point. The flow around the iron core and before and after the passage of the electromagnet was observed using a video camera (HAS-U2, DITECT, Tokyo, Japan). The experiment was conducted in atmospheric conditions. The flow velocity was assumed to be about 1 m/s, as visually estimated from the videos taken. Under these conditions, the Hartmann number was 1.4×10^2 to 4.8×10^2 [9], which was in the same order as that of tin and lithium, and thus appropriate for emulating the flow of tin or lithium. It was also turbulent as the Reynolds number was 4.0×10^4 [9], which was considerably greater than the critical Reynolds number of 2300.

2.2 Magnetic field measurement

To investigate the distribution of the applied magnetic field essential in reproducing MHD, measurements were obtained using a magnetic probe built into the tip of a Hall sensor perpendicular to the three axes of the Cartesian coordinate system (8030 Gauss / Tesla meter, F. W. Bell, Portrand, Oregon). Assuming that the magnetic field distribution was axisymmetric as the iron core was cylindrical, the magnetic field distribution was measured in a straight line in the horizontal direction, parallel to the flow path. Since the Hall sensor responded only to the vertical magnetic field component, the magnetic probe was oriented so that the internal Hall sensor maximized the measured value at the y-axis as shown in Fig. 2 (a), and the xz direction was set horizontally using a laser displacement meter. During the measurement, the probe was moved 5 mm along nine straight lines as shown in Figs. 2 (a) and 2 (c). Data were obtained at nine positions along a straight line of approximately 130 mm with the center of the iron core as the midpoint (the probe was moved only 5 mm at (1), (4), and (7)).

2.3 MHD simulation

The MHD simulation code was built on OpenFOAM, a C++ toolbox for numerical fluid dynamics calculations [10].

3. Results

Figure 3 shows the flow behavior when magnetic fields of 0.3 to 1.0 T were applied. These photographs were captured perpendicular to the channel, and GaInSn flowed from the left to the right side. When the magnetic field was larger than 0.4 T, waves appeared at the downstream side of the flow path after passing through the iron core. These waves appeared to occur more clearly as the magnetic field became stronger. They emerged from the channel wall around the iron core edge, where the face of the iron core switched at an angle and moved to the center as they migrated downstream, creating a characteristic X-shaped surface profile. Previous studies of open-channel GaInSn flow passing through vertical magnetic fields have reported variations, such as hydraulic jumps in water level [12] and narrowing and breaking of the flow width [13]. The flow was also altered by applying a perpendicular magnetic field and visualized as an X-point in the experiment. Waves of this shape have never been reported in previous studies. As the only variable parameter in the experiment was the magnetic field, the suspected cause of the appearing X-point was the magnitude and the distribution of the field.

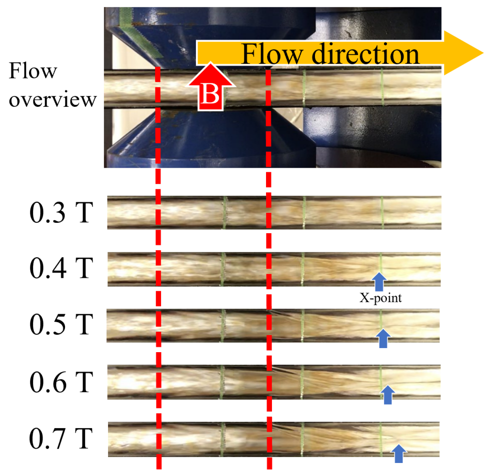

Fig. 3 Flow overview and surface patterns through a magnetic field of 0.3 - 0.7 T.

Figure 4 indicates the magnetic field distribution of the measured lines (1) - (9). Each value was normalized using the measured value of around 65 mm. The measured lines (1), (2), (7), and (8) showed two positive peaks. These were in proximity to the electromagnet plane and passed through the iron core edge two times, as shown in Fig. 2 (b). In addition, peak-to-peak distances in (1) and (7) were 70 mm, while those in (2) and (8) were 55 mm. This decrease in length was influenced by the distance between the intersection of the iron core edge and the measured line in the xz plane, as shown in Fig. 2 (b). The magnetic field distribution in the experiment had a region of high magnetic flux density near the circular iron core edge.

A 3D model of a permanent magnet with the same geometry as the iron core was simulated using COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden). The MHD simulation code was used to calculate the three-dimensional magnetic field distribution with peaks (Fig. 5 (a)). A magnetic field distribution without peaks was calculated (Fig. 5 (b)) for comparison with (a). It was removed peaking part from the data (Fig. 5 (a)) and computed using spline interpolation by Python. The magnetic field strength was 1.0 T at position of 0 mm, atmospheric pressure conditions, flow velocity of 2.0 m/s, and GaInSn properties. The simulation using the magnetic field distribution with flow velocity peak (a) qualitatively reproduced the X-shaped waves downstream of the iron core edge as indicated by the dashed line, while the simulation using (b) did not reproduce the X-shaped waves. (b) did not reproduce the X-shaped waves, confirming the high reproducibility of liquid metal flow in the MHD simulation code

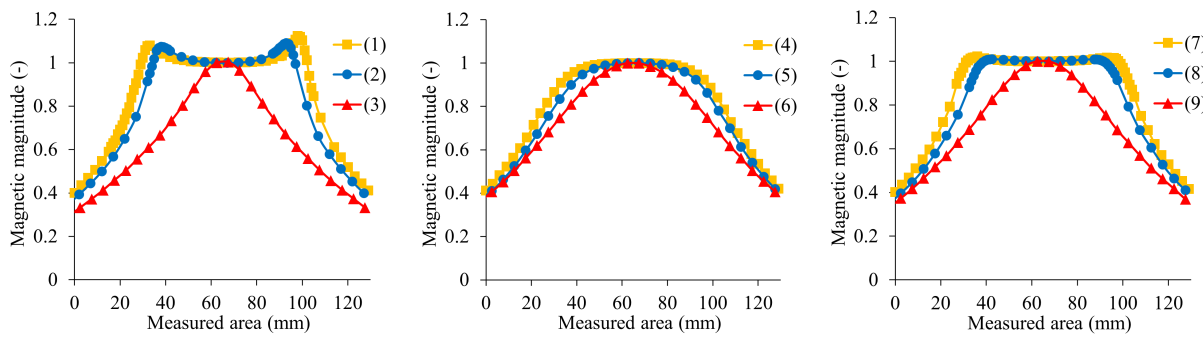

Fig. 4 Measured values normalized by the magnetic field strength of approximately 65 mm. The measurement positions of (1) - (3) are approximately 1.5 mm closer to the wall than those of (7) - (9) due to the position of the internal probe.

and suggesting wave formation due to the peaked magnetic field distribution in the experiment.

4. Discussion

Figure 6 shows the change in position of the X-shaped intersection point (X-point) with an increase in the magnetic field. In the experiment, the distance of the X-point from the center of the iron core increased with the increase of the magnetic field strength as shown in Fig. 6 (a). In contrast, the decrease in the distance in the simulation with increasing magnetic field strength is shown in Fig. 6 (b). Since the only variable was the magnetic field strength, we suspected that the characteristics of the working fluid, GaInSn, were a factor of this contrast. The material GaInSn reacts with oxygen, forming a film of gallium oxide at the interface between the GaInSn liquid and oxygen, and that GaInSn with an oxide film has a reduced surface tension [14]. Since the formation of GaInSn oxide was left in the flow path after the experiment, it was assumed that the oxides formed in the flow and accumulated every time we used. When the surface tension of GaInSn was decreased using MHD simulation in Fig. 6 (c) at the conditions of the flow velocity 1.0 m/s or 2.0 m/s and the magnetic field 1 T, the X-points gradually moved downstream. This trend is consistent with Fig. 6 (b), suggesting that the oxidation of GaInSn progressed every time we used in the experiment and the surface tension drop affected to the position of X-point. It is challenging to incorporate the time variations of surface tension into simulations while considering the replacement of liquid on the surface of the flow due to turbulence. Therefore, stable surface tension during flow is necessary to obtain relevant experimental results for comparison in benchmark tests. In the future, we will conduct similar experiments under an inert gas (argon) atmosphere for quantitative comparisons.

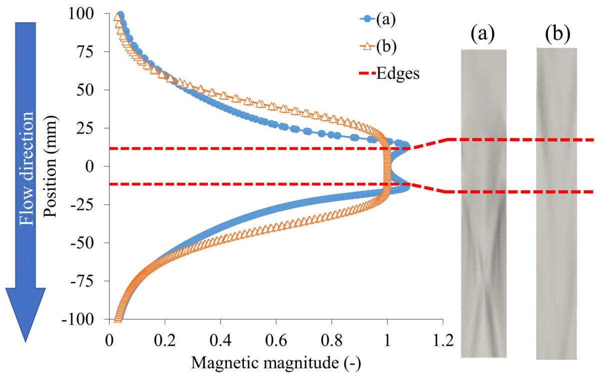

Fig. 5 The peaked (a) and no-peaked (b) magnetic field distributions used in the simulation and the visualized simulation results.

5. Conclusions

A basic study for benchmark testing was conducted for the development of MHD simulations for flow prediction in liquid metal divertors. In this study showing the flow of a low-melting-point alloy, GaInSn, through a perpendicular magnetic field, X-shaped waves were generated after passing through the magnetic field. The flow passed through a magnetic field distribution with two peaks as confirmed by measurements. The MHD simulation using the magnetic field distribution qualitatively succeeded in reproducing the X-shape, confirming the ability of the MHD simulation to reproduce the flow. Furthermore, the simulation demonstrated the relationship between the shape of the distribution and wave generation by comparing it with a peak-free distribution. However, the X-shape movement downstream with an increase in the magnetic field could not be reproduced quantitatively. This was predicted to be due to the decrease in the surface tension caused by the oxidative properties of GaInSn. We will conduct further experiments under an inert argon atmosphere

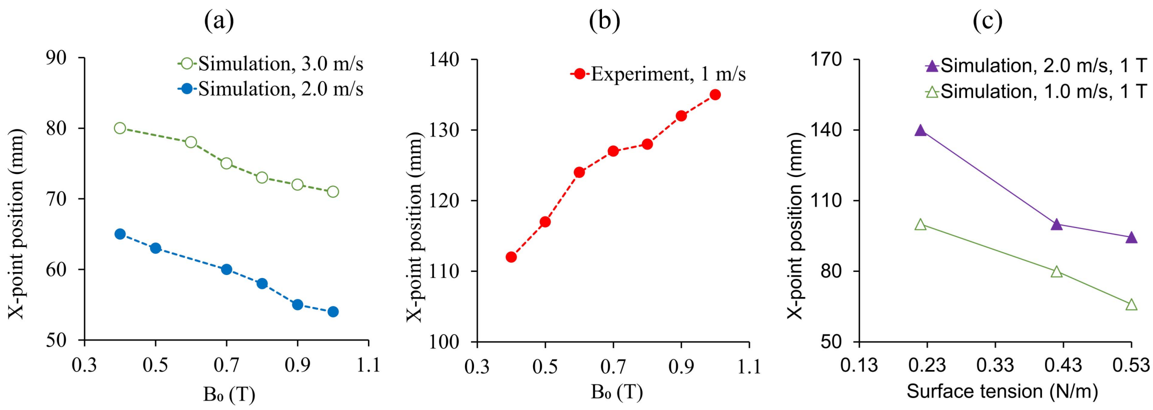

Fig. 6 Position of the X-point formation in the simulation (a) and the experiment (b) as a function of the magnetic field. The dependence on surface tension is denoted in (c). A surface tension of 0.53 N/m was used for (a). The X-point positions at 2 m/s, 1 T, and 0.53 N/m did not agree in figures (a) and (c). This mismatch may occur because the magnetic distribution used in the figure (a) is narrower than that used in the figure (c), and the distance of the peaks is shorter than 6 mm.

to avoid oxidation and obtain data for quantitative comparisons.

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