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Surface waves of liquid metal film flow under the influence of spanwise magnetic field

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ABSTRACT

The present paper focuses on the investigation of the surface wave of liquid GaInSn film which flows along a non-electric conductivity surface in the presence of a spanwise magnetic field. Using the high-speed camera with frame rate 1000 1/s, we experimentally observed the time-varying surface waves at different Reynolds number and Hartmann number. Furthermore, we also extracted the gray value from two fixed lines in photos to show the wave information quantitatively along the streamwise direction and spanwise direction. Experimental results show that the present spanwise direction magnetic field plays an important role in the regularization of film surface waves, namely when gradually increasing the strength of magnetic field, the random surface waves can be firstly damped along the direction of magnetic field and then strongly inhibited due to the induced Lorentz force. The decreasing of wave velocity also indicates that the spanwise magnetic field has a stabilizing effect on the film flow.

1. Introduction

Due to the extreme environment of high heat flux, intense radiation, complex magnetic field, and chemical interactions in the fusion reactor, the development of a suitable plasma facing component (PFC) is of great importance in the safe running of a future fusion power plant [1]. Although many kinds of solid materials have been tested for PFC materials in theoretical and experimental, it seems that there is no perfect solution. Considering the advantages of liquid film flow exist in engineering applications, scientists have proposed a new concept of liquid metal film flow as PFC materials for a fusion reactor to solve the related problems [2]. The lithium has been selected as a superior working liquid because of its advantages of high thermal efficiency, tritium breeders, and improving plasma performance [3]. However, it is still a challenging goal to form a continuously flowing liquid lithium film with both stable surfaces and uniform thickness due to the magnetohydrodynamic (MHD) effect, namely when the liquid metal film flow crosses a magnetic field B, the generated Lorentz force will change the force balance, resulting a completely different flow compared with situations without magnetic field. It may have a bad influence on the safely running of a fusion reactor.

In order to verify the feasibility of liquid lithium PFC, Hu et al. [4,5] designed a continuously flowing liquid lithium film limiter and carried out some preliminary experiments in the EAST superconducting Tokamak. Their results prove that the lithium limiter can enhance the performance of plasma. However, since the lacking of online flow measurement method in the fusion device, a serious damage on part of the liquid lithium limiter surface not covered by the lithium film is not observed until stop of fusion reactor. Consequently, for the design purpose of liquid metal PFC, we are facing two great challenges: the development of an online measuring method for liquid metal film in a fusion reactor and the development of a suitable technique to realize a stable and uniform film on the solid surface. Plenty of efforts have been put on these two aspects through experiments and numerical simulations. A recent review of the liquid metal flow related to nuclear fusion technologies is given by Abdou et al. [6].

As pioneering works conducted on the liquid metal film flow with a magnetic field using a linear stability analysis method, Hsieh [7] and Ladikov [8] have reported that the magnetic field can stabilize the flow under the hypothesis that the surface-tension is negligible in a horizontal film. Using mercury as a working liquid, Alpher et al. [9] measured the surface height and velocity of an inclined film flow to explore the fluctuation of waves on a free surface. Their quantitative results show that the wave can be damped by an imposed vertical magnetic fields up to 0.42 T (T). They also checked the appearing of hydrodynamic jump under the influence of magnetic field. In the group led by Abdou [10–14], several experiments and numerical simulations have been carried out for the liquid metal film flow. It has been proved

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by their experimental results that a hydraulic jump happens at a higher flow velocity and moves downwards along the flow with the increase of magnetic field. Moreover, a strong tendency of the fluid move away from the side walls was observed under the influence of a vertical magnetic field. By adopting a laser reflection diagnostic which is used to measure the wave number and the damping rate of driven waves, Ji et al. [15] clarified the dispersion relation for gravity-capillary waves on a stationary pool of gallium with a streamwise magnetic field. Besides, Li et al. [16] used the ultrasonic transmission technique to measure the thickness of a vertically falling liquid NaK film. They observed the phenomenon of film thickening and surface wave suppression in the presence of a transverse magnetic field. Xu et al. [17] conducted an experimental research of – MHD effect on a liquid metal film flow using GaInSn as the fluid, and obtained three different flow states: flat, rivulet and retardance flows. Abderrahmane et al. [18] used the Karman–Polhausen integral method to carry out an instability analysis of a thin film flow under the influence of electromagnetic fields, their research results showed that the electric and magnetic field can stabilize or destabilize the film flow. In the engineering of fusion reactor, using the liquid lithium as working liquid, several experiments have been conducted in fusion devices, such as NSTX, FTU, T–11 M, TJ-II [19–22]. However, it is still an open topic in understanding the MHD effect of a liquid metal film flow in the circumstance of a real fusion reactor.

In this paper, we present the experimental results on surface waves of a liquid GaInSn film flow under the influence of a spanwise magnetic field. In the next section, an introduction to the experimental system and the data process method, which is used to obtain the surface waves, is given. In Section 3, the surface contour, the surface waves and the surface wave speed are reported and analyzed in detail. Finally, a preliminary conclusion and future prospect are presented.

2. Experimental methods

Fig. 1 shows the photograph of liquid metal experimental system, which contains the EMP pump, flow meter, tanks, electromagnet, vacuum pump, pipes, and valves. In this system, the electromagnet can generate a magnetic field between two magnet poles with a distance of 80 mm, varying from 0 to 2 T in the horizontal direction. A specially designed test section, which is used to generate liquid metal film flow along a titled solid surface (inclined by an angle 9° to the horizontal direction, 60 mm in width) with two side walls, is inserted into space between two magnetic poles. The initial film thickness from the film generator section is about 1.5 mm. It states that the liquid film can only

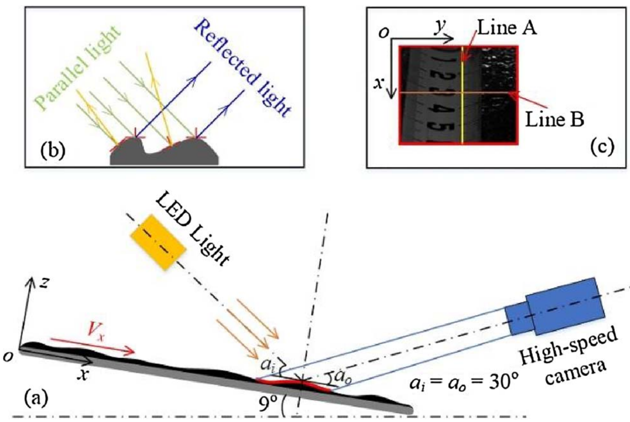

Fig. 2. Sketch of the measurement system. (a) the arrangement of equipment, (b) the reflection model of lights on a curved surface, (c) the calibration photograph.

flow on a plate with a finite width, thus the influence of two side walls on film flow cannot be omitted in the present study. Moreover, in the present experimental condition, both the initial kinetic energy of film generator and gravity should be considered in the film flow. Based on the theory of MHD [23], the electrical conductivity of solid material also has a great influence on the flow in a magnetic field. The vacuum system, which can minimize the oxygen concentration in system is used to connect the liquid metal system to reduce the production of oxides. As a preliminary study on the MHD effect of liquid metal film flow, we only consider the non-electrical conductive case and adopt the electricity insulating Plexiglas material to manufacture the solid plate. Other information about the GaInSn flow loop and physical properties of liquid metal can be seen from reference [24].

Referring to the measurement method, here we choose the high-speed visualization method to obtain the surface contour of liquid metal film. The schematic of present measurement method has been illustrated in Fig. 2(a). In this measurement system, the high-speed camera (*Vision Research Inc.*, Phantom V341, with resolution 1024 × 1024 at 1000 fps in present captures) equipped with macro lens (*TOKINA*, M100, PRO, D, 100 mm, F2.8) is used to capture figures, and a LED light (LPS-1000R, 100W) is used to afford a continuous illumination. By adopting the image processing method, it is easy to extract the gray value of photos from a high-speed camera. However, it should be noted that the alignment of the illuminating light and high-speed camera hold the same angle, ≈30°, with respect to the substrate of liquid film flow for each case to get a reliable result. The brightness of photos taken by

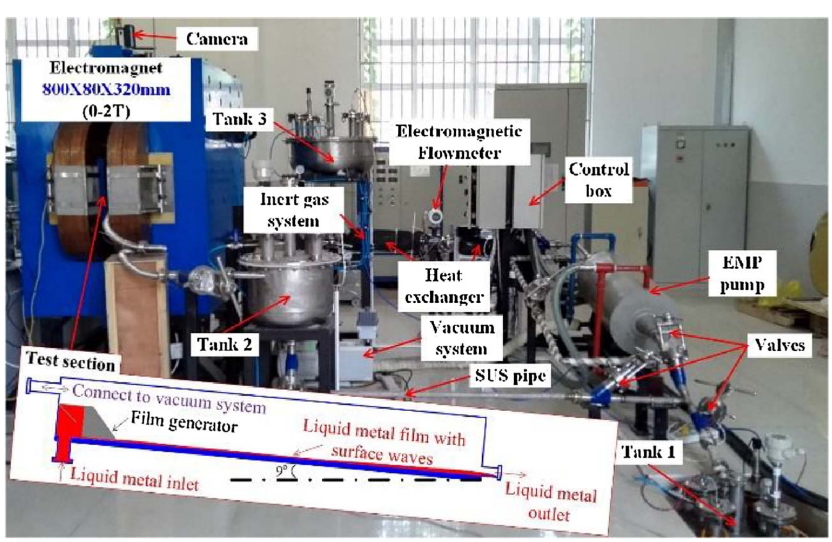

Fig. 1. Experimental system and schematic of test section.