Experimental Study on Spreading Characteristics of Liquid Metal Film Flow Under Magnetic Field: Postprint

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Abstract

This study employs an in-house constructed liquid gallium-indium-tin loop and, through rational design of a liquid film generation device, conducts experimental investigations on liquid metal film spreading characteristics under the influence of liquid film outlet velocity and horizontal magnetic field strength. High-speed imaging was utilized in the experiments, and a high-precision laser displacement sensor for measuring micro-displacements was incorporated to obtain extensive characteristic data on liquid metal film thickness. The experimental results demonstrate that the wave characteristics of the liquid metal film gradually intensify with increasing Reynolds number, with waves transitioning from two-dimensional to three-dimensional and high-frequency fluctuations gradually becoming dominant, while magnetic field enhancement exhibits a stabilizing effect on liquid film surface waves.

Full Text

Experimental Study on Spreading Characteristics of Liquid Metal Film under Magnetic Field

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Abstract: This paper presents an experimental investigation of liquid metal film spreading characteristics using a custom-built liquid GaInSn loop and a specially designed film generation device. The study examines the effects of film outlet velocity and horizontal magnetic field strength on metal film flow behavior. High-speed videography combined with a high-precision laser displacement sensor for measuring micro-displacements were employed to obtain extensive characteristic data on metal film thickness. Experimental results demonstrate that film surface fluctuations increase progressively with Reynolds number, transitioning from two-dimensional to three-dimensional waves, with high-frequency fluctuations becoming dominant. Conversely, increasing magnetic field strength exerts a stabilizing effect on film surface waves.

Keywords: liquid metal film; magnetohydrodynamics; surface wave; spreadability

Introduction

Liquid film flow represents a ubiquitous phenomenon in nature that has attracted widespread academic attention, such as rainwater flowing down windows. The stability of such flows directly influences film spreading on solid surfaces. Nusselt first derived an analytical solution for film velocity and thickness on smooth walls through theoretical analysis, based on assumptions of laminar flow and negligible gas-phase forces[i]. The Kapitza father-son team[ii] subsequently observed unstable surface wave flows and isolated waves on film surfaces through simple experiments, revealing the rich flow patterns inherent in film flows and inspiring extensive experimental and theoretical research. Over the past century, scholars have conducted substantial work on film flows, focusing primarily on relationships between flow patterns and parameters, as well as correlations between heat transfer performance and flow morphology. These studies have established a solid foundation for applications in engineering thermophysics (film cooling), materials science (thin film preparation and coating), and chemistry (distillation).

However, most existing film flow research has employed conventional nonconductive fluids such as water and ethylene glycol, considering only factors like temperature, gravity, and surface structure. In contrast, investigations of liquid metal film flows relevant to magnetic confinement fusion reactors remain scarce. In such reactors, uniformly spread, large-area liquid lithium films are considered optimal plasma-facing first-wall materials. Yet high-temperature liquid metals in the complex, strong magnetic field environment of fusion reactors experience Lorentz forces that prevent stable flow formation. The fundamental physics underlying magnetic field effects can be explained as follows: highly conductive liquid metals generate induced currents when moving through magnetic fields, which in turn induce Lorentz forces that react back on the flow and alter its fundamental characteristics. The inherent complexity of film flows produces correspondingly complex Lorentz forces, increasing the difficulty of studying liquid metal films in magnetic environments and resulting in phenomena and instability characteristics fundamentally different from conventional films. Comprehensive research through theoretical, numerical, and experimental approaches is urgently needed.

Theoretical analyses of liquid metal film flow stability under magnetic fields have employed conventional linear and nonlinear stability methods. Hsieh[iii] and Ladikov[iv] used linear stability analysis to examine film flow down an inclined plane in a transverse magnetic field, neglecting surface tension effects. Their results indicated that magnetically coupled film flows are more stable than those without magnetic fields studied by Yih et al.[v]. Conversely, Gordeev et al.[vi] and Korsunsky[vii] found that coupled electric and magnetic fields could control flow stability and instability, though this remained theoretically predicted without experimental verification. Mukhopadhyay et al.[viii] employed linear and weakly nonlinear stability analysis under the small magnetic Reynolds number assumption to quantitatively investigate electromagnetic field effects on liquid metal film flow at moderate Reynolds numbers. Linear stability analysis revealed that magnetic fields stabilize film flow, while electric field effects depend on orientation. Nonlinear stability analysis, however, showed that only magnetic fields significantly affect flow stability, with electric field effects being negligible.

In numerical simulations, electromagnetic forces on moving conductive fluids are obtained by solving either the electric potential equation or magnetic induction equation. The electric potential approach offers high accuracy but neglects induced magnetic fields, limiting its application to low magnetic Reynolds number cases. The magnetic induction equation can handle higher magnetic Reynolds numbers but suffers from difficult boundary condition treatment and lower precision. Gao et al.[ix] and Huang et al.[x] simulated liquid metal film flows under magnetic fields in two and three dimensions, respectively, using the magnetic induction equation and VOF interface capturing. Their studies achieved reasonable agreement with experimental results for small Hartmann numbers (Ha ~ 20), capturing phenomena such as film fluctuations and detachment from channel side walls[xi]. For high Hartmann number studies, Ni et al.[xii,xiii] developed a current density conservative scheme and software platform (HIMAG) based on the electric potential equation, successfully simulating MHD flows with Hartmann numbers up to 10 —a formulation now widely applied internationally. Recently, Xu et al.[xiv] numerically investigated effects of inlet velocity, inlet film thickness, bottom wall width, and wall roughness on lithium film flow in strong transverse magnetic fields, providing preliminary physical mechanisms for MHD stability. However, the electromagnetic force term in momentum equations significantly increases solution difficulty and computational cost, slowing progress in MHD-related theoretical and numerical research.

Experimentally, Professor Abdou’ s team at UCLA[xi,xv,xvi] conducted series of liquid metal film flow studies in magnetic fields using conventional photography and ultrasonic techniques. Their results demonstrated significant magnetic field effects on flow stability, including progressive thickening along the flow direction, increased flow resistance, and flow detachment from side walls, resulting in stream-like flows that fail to completely cover the channel bottom. At higher magnetic field strengths (>2 T), unstable surface fluctuations appeared. However, measurement limitations prevented detailed characterization of film fluctuation development under various conditions or methods for suppressing MHD instabilities. The Southwestern Institute of Physics (SWIP) team led by Xu[xvii,xviii,xix] conducted jet/film flow experiments with Na K alloy and GaInSn using their liquid metal loop, obtaining flow patterns under MHD effects. Results showed that non-uniform magnetic fields (~2 T) reduced jet range, increased cross-sectional area, and extended continuous jet length. However, unlike UCLA' s observations of jet breakdown when crossing transverse magnetic fields[xvi], SWIP' s experiments used only high-speed photography to obtain basic flow morphology, preventing quantitative investigation of detailed flow characteristics. Recently, Osaka University researchers conducted free-surface lithium film experiments using their liquid lithium loop, validating contact probe[xx], laser reflection[xxi], and high-speed velocimetry[xxii] methods for measuring thick, high-speed (5-15 m/s) lithium films, obtaining flow characteristics without magnetic fields. However, the accuracy of these methods in magnetic environments requires further verification. Our research group conducted preliminary film flow experiments using a GaInSn loop, visualizing poorly spread film patterns and magnetic field effects[xxiii].

Despite these experimental, theoretical, and numerical studies providing general understanding of magnetic field effects on liquid metal films (primarily thickening, flow resistance, and stability impacts), knowledge remains limited due to the complexity of the phenomena and scarcity of research. Particularly in experiments, conventional measurement techniques—especially optical methods—are unsuitable for liquid metal films, and no accurate measurement method currently exists for liquid metal films under magnetic fields, resulting in a severe lack of precise experimental data.

Building on previous research, this study further optimized the film generation structure and employed high-speed camera visualization combined with laser displacement sensors for quantitative measurement of film flow under magnetic fields, obtaining more detailed flow characteristics. The paper is organized as follows: Section 1 introduces the experimental loop, magnetic field environment, measurement methods, and their reliability.

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1. Experimental System

While liquid lithium serves as the first-wall material in actual magnetic confinement fusion reactors, its operational hazards make it unsuitable for fundamental research on measurement method validation. GaInSn alloy, with similar electrical conductivity, low toxicity, and liquid state at room temperature, is considered optimal for liquid metal 基础研究. Using GaInSn as the working fluid, our laboratory constructed a liquid metal loop system for fundamental flow research.

[Figure 1: see original paper] Photo of liquid metal loop

1.1 Experimental Loop Description

Figure 1 shows the GaInSn liquid metal loop, which primarily comprises a liquid metal storage tank, circulation tank, calibration tank, electromagnetic pump, electromagnetic flowmeter, heat exchanger, film generation structure, film spreading section, electromagnet-generated strong magnetic field, stainless steel pipes, bellows, and valves. Due to GaInSn' s susceptibility to oxidation and impurity formation, the entire loop must maintain low oxygen content and an inert gas environment during operation.

1.2 Measurement Methods and Error Analysis

Through investigation of conventional film flow measurement methods and consideration of liquid metal characteristics (opacity, oxidation susceptibility, and magnetic interference with electronic components), two suitable techniques were identified for measuring film flow characteristics: one for overall surface profile and another for precise thickness at specific temporal points.

Figure 2 illustrates the liquid film generation test section and corresponding measurement methods. The test section' s internal space measures 180 mm in height, 800 mm in length, and 60 mm in width (perpendicular to the plane). The outlet film thickness is adjustable (0–20 mm), and the inclination angle between the flow direction and horizontal plane is a variable parameter. The test section bottom plate is made of acrylic glass. The entire section is inserted into a uniform horizontal magnetic field with 80 mm pole spacing, where the field direction is perpendicular to both the plane and flow direction, with continuously adjustable strength (0–2 T). Since the test section only has transparent windows at the top, all measurements are performed from above. Two methods are depicted: high-speed camera visualization (Phantom V341 with LED light source) and laser displacement sensor (Keyence LJ-V7200) for surface profile measurement.

High-speed camera visualization primarily provides qualitative information on overall spreading width and surface features, while the laser displacement sensor quantitatively measures thickness variations. The sensor' s measurement error depends primarily on laser reflection from the measured surface; stronger reflection reduces diffuse reflection signal strength and increases error.

[Figure 3: see original paper] Error bars of the measured average film thickness

Before formal experiments, a simple method validated the linear laser sensor' s accuracy: measuring static film thickness at various set values and comparing measured versus actual values, as shown in Figure 3. For static films, measurement error remains small (within 10%), with higher precision for thinner films.

2. Experimental Results and Discussion

Based on the GaInSn loop and installed test section, numerous film flow experiments were conducted under various conditions using the methods described above. The effects of outlet velocity and magnetic field strength on flow characteristics were analyzed as follows:

2.1 Metal Liquid Film Surface Morphology

Surface morphology was obtained primarily through high-speed camera imaging, with results shown in Figure 4.

The upper four subfigures in Figure 4 show basic surface patterns under different flow velocities (Re). All results represent stable flow conditions. From (a) to (d), Re increases progressively. At low Re (Re = 1080.7), the film surface appears smooth with only small ripples. As Re increases, distinct streaks emerge, displaying parabolic shapes along the flow direction similar to two-dimensional roll waves where upstream liquid pushes downstream liquid. With further Re increase, surface patterns become more complex, transitioning from horizontal streaks to oblique, interlacing three-dimensional waves. Light intensity distribution indicates increased fluctuation amplitude. Notably, at Re > 5079.5, a small unspread region appears approximately 10 cm downstream, possibly related to side wall roughness.

When a magnetic field perpendicular to the flow direction is applied, flow characteristics change. The lower four subfigures in Figure 4 show surface features at fixed Re under varying magnetic field strengths (increasing left to right). To quantitatively describe the relative magnitude of electromagnetic and viscous forces, the Hartmann number is employed: $Ha = Bh\sqrt{\sigma/\mu}$, where B is magnetic field strength, h is characteristic length (film thickness), σ is electrical conductivity, and μ is dynamic viscosity.

The lower subfigures reveal that as Ha increases at fixed Re = 3458.4, significant changes occur: at Ha = 31, surface wave width narrows while amplitude increases. With further Ha increase, wave width decreases further, concentrating toward the center. Scale measurements show corresponding wavelength increases.

These magnetic field effects arise because moving liquid metal generates induced currents, with upward current at the film interface center producing Lorentz forces opposing the flow direction, thereby suppressing fluctuations. Additionally, for acrylic glass bottom walls, both the free surface and bottom wall are non-conductive boundaries, causing induced electric potential lines to close entirely within the film—fundamentally different from our previous stainless steel bottom wall studies[23].

[Figure 4: see original paper] The flow patterns of liquid metal film flow on the organic glass surface varied with Re number and Ha number

However, image distortion from camera angle may introduce visual errors. To further validate these results, quantitative analysis using displacement sensor thickness measurements follows.

[Figure 5: see original paper] The fluctuation of film thickness varied with time for different Ha number at fixed point

2.2 Liquid Film Surface Statistical Characteristics

While visualization data qualitatively captured Re and Ha effects on surface fluctuations, quantitative investigation requires analysis of extensive thickness data to better understand film characteristics.

Figure 5 shows temporal thickness variations at a fixed point near the edge under three conditions. For constant Ha, higher Re produces more pronounced fluctuations. At constant Re, increased Ha (stronger magnetic field) reduces fluctuation intensity while significantly increasing film thickness by nearly 1 mm.

Conclusions

Motivated by uniform, stable liquid lithium film formation in tokamak fusion reactors, this study investigated magnetic field effects on liquid metal spreading characteristics. Using liquid GaInSn, extensive experiments were conducted with high-speed camera and laser displacement sensor measurements, followed by detailed data analysis. The main conclusions are:

1. High-speed camera visualization shows that with increasing Re, surface fluctuations of high-surface-tension GaInSn intensify, transitioning from two-dimensional to three-dimensional waves. Magnetic field introduction significantly suppresses surface fluctuations, with stronger fields producing more pronounced stabilization effects.
2. Quantitative laser sensor measurements validate these visual observations, while thickness data further reveals that magnetic fields increase film thickness due to MHD drag effects.
3. Preliminary results demonstrate that combining these two measurement methods effectively captures basic flow characteristics of liquid metal films under magnetic fields. Future work should conduct extensive experiments using these methods to acquire richer raw experimental data.

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