Experimental Study on Spreading Characteristics of Liquid Metal Film Flow under Magnetic Field (Postprint)

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Abstract

This study employs a self-constructed liquid gallium-indium-tin loop and, through rational design of the liquid film generation device, conducts experimental investigations on the spreading characteristics of metal liquid films, considering the influences of liquid film outlet flow velocity and horizontal magnetic field strength. High-speed photography is adopted in the experiments, and a high-precision laser displacement sensor for measuring minute displacements is introduced to obtain extensive characteristic data on metal liquid film thickness. The experimental results indicate that the wave characteristics of the metal liquid film gradually intensify with increasing Reynolds number, with waves transitioning from two-dimensional to three-dimensional, and high-frequency fluctuations gradually becoming dominant, while the enhancement of the magnetic field has a stabilizing effect on liquid film surface waves.

Full Text

Preamble

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

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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 was employed to obtain extensive characteristic data on metal film thickness. Experimental results demonstrate that film fluctuation characteristics increase progressively with Reynolds number, with waves transitioning from two-dimensional to three-dimensional structures and high-frequency fluctuations becoming dominant. Enhanced magnetic field strength exhibits a stabilizing effect on film surface waves.

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

Introduction

Thin liquid film flows represent 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 analytically studied liquid film flow on smooth walls, obtaining analytical solutions for film velocity and thickness based on assumptions of smooth laminar flow and negligible gas-phase forces[i]. The Kapitza father-son team[ii] 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 investigations. Over the subsequent century, researchers conducted numerous experimental and theoretical studies focusing primarily on analyzing relationships between flow patterns and parameters, as well as connections between heat transfer performance and flow morphology. These efforts established a solid foundation for film flow applications across various disciplines, including film cooling in engineering thermophysics, thin film preparation and coating in materials science, and distillation in chemistry.

However, most existing film flow research has employed conventional fluids such as water and ethylene glycol—non-conductive liquids—and considered only factors like temperature, gravity, and solid surface structure. Studies on liquid metal film flows relevant to magnetically confined fusion reactors remain scarce. In such reactors, uniformly and extensively spread liquid lithium film flows are considered optimal materials for plasma-facing first walls. However, high-temperature liquid metals in the complex, strong magnetic field environment of fusion reactors experience Lorentz forces that prevent stable flow formation. The fundamental physical explanation for magnetic field effects is 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 flow renders the resulting Lorentz forces similarly complex, increasing the difficulty of studying metal film flows under magnetic fields. Consequently, the resulting phenomena and instability characteristics differ completely from conventional film flows, necessitating extensive research from theoretical, numerical simulation, and experimental perspectives.

In theoretical analysis, stability studies of liquid metal film flows under magnetic fields still employ conventional linear and nonlinear stability analysis methods. Hsieh[iii] and Ladikov[iv] used linear stability methods to analyze film flow stability in transverse magnetic fields while neglecting surface tension effects, demonstrating that magnetically coupled film flows are more stable than those without magnetic fields studied by Yih et al[v]. Gordeev et al[vi] and Korsunsky[vii] found that coupled electric and magnetic fields can control flow stability and instability, though this remains theoretical without experimental verification. Mukhopadhyay et al[viii] employed linear and weakly nonlinear stability analysis under low magnetic Reynolds number assumptions to quantitatively investigate electromagnetic field effects on metal film flows at moderate Reynolds numbers. Linear stability analysis indicated that magnetic fields stabilize film flow, while electric field effects depend on direction; however, nonlinear stability analysis showed that only magnetic fields significantly influence stability, with electric field effects being minimal.

In numerical simulations, forces acting on conducting fluids in magnetic fields are obtained by solving either the electric potential equation or magnetic induction equation. The electric potential approach offers high accuracy but, by neglecting induced magnetic fields, is limited 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 accuracy. Gao et al[ix] and Huang et al[x] studied liquid metal film flows under magnetic fields using the magnetic induction equation in two and three dimensions, respectively, capturing interfaces with the VOF method. This approach can obtain film flow characteristics at low Hartmann numbers (around 20) that somewhat match experimental results, 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 at Hartmann numbers up to 10^4—a format now widely applied worldwide. Recently, Xu et al[xiv] numerically investigated effects of inlet velocity, inlet film thickness, bottom wall width, and wall roughness on lithium film flows in transverse strong magnetic fields, providing preliminary physical mechanisms for MHD stability. However, adding electromagnetic force terms to momentum equations significantly increases solution difficulty and computational cost, slowing progress in MHD-related theoretical analysis and numerical simulation.

Experimentally, Professor Abdou’ s team at UCLA[xi,xv,xvi] conducted a series of liquid metal film flow experiments in magnetic fields using conventional photography and ultrasonic techniques. Results showed that magnetic fields significantly affect film flow stability, causing phenomena such as gradual thickening along the flow direction, increased flow resistance, and flow separation from side walls with incomplete bottom surface coverage. At higher magnetic field strengths (>2 T), unstable surface fluctuations appear. 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 $Na_{22}K_{78}$ alloy and GaInSn jet/film experiments using a liquid metal loop, obtaining flow patterns under MHD effects. Results showed that non-uniform magnetic fields (~2 T) shortened jet range, increased cross-sectional area, and extended continuous jet length. However, unlike UCLA' s observations of jet breakup when crossing transverse magnetic fields[xvi], SWIP experiments only used high-speed photography to obtain basic jet/film morphologies, preventing quantitative investigation of detailed flow characteristics. Recently, Osaka University researchers conducted free-surface lithium film experiments using a 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 and obtaining flow characteristics without magnetic fields, though these methods' accuracy in magnetic environments requires further verification. Our research group conducted preliminary film experiments using a GaInSn loop, obtaining basic poorly-spreading film morphologies and magnetic field effects through visualization methods[xxiii].

Despite these experimental, theoretical, and numerical studies providing general understanding of magnetic field effects on liquid metal film flows (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) for regular film flows cannot be applied to liquid metal films, and no accurate measurement method currently exists for liquid metal film flows under magnetic fields, resulting in a severe lack of precise experimental data.

Building on previous research, this paper further optimizes the film generation structure and employs high-speed camera visualization and laser displacement sensors for quantitative measurements of film flows 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.

1 Experimental System

While liquid lithium is used in actual magnetic confinement fusion reactors, its operational hazards make it unsuitable for preliminary measurement method validation and fundamental research. GaInSn alloy, with similar conductivity, low toxicity, and liquid state at room temperature, is considered optimal for fundamental liquid metal research. 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. The system primarily includes a liquid metal storage tank, circulation tank, calibration tank, electromagnetic pump, electromagnetic flowmeter, heat exchanger, film generation structure, film spreading section, strong magnetic field from electromagnets, stainless steel pipes, bellows, and valves. Since GaInSn easily oxidizes to form impurities, 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, magnetic interference with electronic components), two suitable techniques were identified for measuring film flow characteristics: one for overall surface profiles and another for precise thickness at specific points over time.

Figure 2 [Figure 2: see original paper] shows the liquid film test section and measurement methods. The test section has internal dimensions of 180 mm height, 800 mm length, and 60 mm width (perpendicular to the plane). The outlet film thickness is adjustable from 0-20 mm, and the inclination angle between the flow direction and horizontal plane is also adjustable. The test section bottom plate is made of acrylic. 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 from 0-2 T. Since the test section only has transparent windows at the top, all measurements are performed from above. The schematic illustrates two methods: high-speed camera visualization (Phantom V341 with light source) and laser displacement sensor (Keyence LJ-V7200) for surface profile measurement.

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

Figure 3 [Figure 3: see original paper] shows error bars for measured average film thickness. Before formal experiments, we validated the laser sensor’ s accuracy through a simple method: setting different liquid metal film thickness values, measuring them with the sensor, and comparing measured versus actual values. Results show that for static films, measurement error is small (within 10%), with higher precision for thinner films.

2 Experimental Results and Discussion

Using the GaInSn loop and installed test section, numerous film flow experiments were conducted under various conditions. The methods described in the previous section provided detailed measurements of film characteristics, analyzing effects of outlet velocity and magnetic field strength on flow behavior.

2.1 Metal Liquid Film Surface Morphology

Surface morphology was obtained primarily through high-speed camera imaging, with results shown in Figure 4 [Figure 4: see original paper]. The upper four subfigures show basic surface patterns at 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 is relatively smooth with only small ripples. As Re increases, distinct streaks appear, exhibiting 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, with amplitude increases evident from light intensity distribution. 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, the flow changes. The lower four subfigures in Figure 4 show surface characteristics at fixed Re under different magnetic field strengths (increasing left to right). To quantitatively describe the relative magnitude of electromagnetic and viscous forces, the Hartmann number Ha is used, where $\mathrm{Ha} = \mathrm{B} \cdot \mathrm{h} \cdot \sqrt{(\sigma/\ )}$, with B being magnetic field strength, h characteristic length (film thickness), σ electrical conductivity, and dynamic viscosity. The lower subfigures reveal that for GaInSn flowing on acrylic at fixed Re=3458.4, increasing Ha significantly alters surface fluctuations: at Ha=31, wave width narrows and amplitude increases; with further Ha increase, wave width decreases further, concentrating toward the center. Scale measurements show corresponding wavelength increases.

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

However, image distortion from camera angle may introduce visual errors. To further substantiate these results, the following sections present quantitative analysis from displacement sensor measurements.

Figure 5 [Figure 5: see original paper] shows film thickness fluctuations over time at a fixed point near the edge for three different conditions. For the same Ha at different Re, higher Re produces more pronounced fluctuations. At constant Re, increasing Ha (magnetic field strength) reduces thickness fluctuation intensity while significantly increasing film thickness by nearly 1 mm.

Conclusions

Motivated by uniform, stable liquid lithium film formation in tokamak fusion devices, this study investigated magnetic field effects on liquid metal spreading characteristics. Using GaInSn as the working fluid, extensive experiments were conducted with high-speed camera and laser displacement sensor measurements, followed by detailed analysis of numerous results. 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 displacement sensor measurements further validate these visualization results, while thickness data also demonstrate significant film thickening under magnetic fields due to MHD drag effects.

(3) Preliminary results indicate that combining these two measurement methods can capture basic flow characteristics of liquid metal films under magnetic fields. Future work should conduct extensive experiments using these methods to obtain richer original experimental data.

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Note: Figure translations are in progress. See original paper for figures.