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# UDV measurements of single bubble rising in a liquid metal Galinstan with a transverse magnetic field

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A B S T R A C T

Liquid metal is an important type of energy transport carrier in nuclear reactors, such as in accelerator-driven sub-critical systems, fusion reactors and spallation neutron source devices. It is necessary to conduct research for bubbles rising in a liquid metal under different magnetic field intensities. The Perspex container is positioned concentrically inside a transverse magnetic field, which provides a homogeneous DC longitudinal magnetic field that passes through the fluid district. The coils are supplied with maximum field strength of 1.97 T. The equivalent diameter of the bubble is 3.1–5.6 mm. The Ultrasonic Doppler Velocimetry (UDV) method is used to evaluate the internal flow velocity of opaque liquid metals. Research shows that the influence of the Lorenz force on the bubble ascension velocity is not simply positive or negative. The magnetic field inhibits the ascension velocity of small bubbles with diameters of 3.1 mm and 3.4 mm. The terminal velocity for large bubbles with diameters of 4.57 mm, 5.15 mm and 5.6 mm is higher under a weak magnetic field than without a magnetic field. The positive effect happens under strong magnetic intensity. The target is to obtain the hydro-dynamical relationships between the terminal velocity, drag coefficient, the Eötvös number, Reynolds number, and Stuart number in a strong magnetic field using a multiple regression method to reveal that the mechanism of the induced current's restraining influence determines the ascension velocity of the bubble in viscous electric liquids with a strong magnetic field.



## 1. Introduction

Bubble motion in liquid metals and magnetic fluids plays an important role in many industrial processes including steam generators, cooling systems, fusion reactor, etc. It has been investigated repeatedly over the past 70 years because of its importance in industrial applications. Despite these sustained efforts, important questions remain unclear and thus research into the bubble rising remains an important field in multiphase flow. The complexity is caused by the transitional interfaces separating the bubble from the liquid, and two fluids have notably different chemical and physical parameters, particularly when there is a bubble in a liquid metal. Liquid metal is an important type of energy transport carrier in nuclear reactors, such as in accelerator-driven sub-critical systems, fusion reactors and spallation neutron source devices. The most promising method in future fusion reactors is using liquid metal in the blanket of a fusion reactor to produce tritium. There is a 6–8 Tesla strong magnetic field in fusion reactors that strongly influences flow and heat transfer processes. There is an important value to obtain the flow velocity on the heat transfer analysis when there is a magnetic field, but it is difficult to determine the velocity information of opaque liquid metals accurately.

The three-dimensional motions of a bubble rising in still water is one of the most fascinating and important aspects of bubble hydrodynamics. The typical types of motion are: A zigzag path in which a bubble moves in an oscillatory fashion in one vertical plane and a helical path showing a circular or an ellipsoidal horizontal motion. This phenomenon is called "path instability" or "Leonardo's paradox," which can be widely seen in natural and industrial processes. Although bubble rising is a very common phenomenon, it is a complex problem since it involves interactions between bubble deformation, the liquid flow field induced by the bubble motion, and the Lorentz force induced by the liquid flow if there is a conductive liquid with a magnetic field.

Some experimental and theoretical studies have been carried out on bubbles rising in transparent liquids for gas–liquid metal two-phase flows (Shin and Choi, 2016; Scammell and Kim, 2015; Chakraborty et al., 2013; Bai and Thomas, 2001). Vortex analysis, measurement technique development, and heat transfer around a bubble have also been studied (Uchiyama and Ishiguro, 2016; Richter et al., 2015). Mendelson studied the velocities of bub-

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bles rising in various different liquids with different bubble sizes (Mendelson, 1967). According to the wave equation, the terminal velocity of bubbles in infinite media has been acquired and unified with the existing correlations between surface tension and buoyancy. The effects of different strengths of a uniform magnetic field on the interactions between two bubbles rising side by side in a viscous and initially stagnant liquid have been studied numerically (Hadidi and Jalali-vahid, 2016). The hydrodynamic behavior of a bubble rising in a fluid was analyzed with an external electric field (Qing-Zhen et al., 2014). These studies show that the magnetic field affects the motion of the conducting flow with strong directionality. With regard to the experimental study on bubble rising under a strong magnetic field, Mori et al. found a transverse magnetic field that forced the bubble into a straighter path and reduced the apparent drag force (Mori et al., 1977). The suppressing bubble zigzag rising for a small Stuart number resulted in a higher terminal velocity. This means that the bubble rising was determined by the existence of magneto-hydrodynamic (MHD) with a magnetic field. Local measurements were carried out in a mercury-nitrogen two-phase flow using the hot-film anemometric technique in a cylindrical pipe with electrically insulated walls developed by Gherson and Lykoudis (1984). The flow was turbulent ($Re = 63000$) and the maximum intensity of the magnetic field was 0.94 T. Large magnetic fields developed regions with liquid turbulent fluctuations higher than in such cases without a magnetic field. A bubble rising in a magnetic field could be controlled in a contactless way in which there is a liquid metal magneto-hydrodynamic (MHD) flow. Recent work done by Miao et al. (2013) studied bubble-driven liquid metal flow inside a cylinder by considering the impact of a steady magnetic field using three-dimensional numerical simulations. The calculations revealed that a horizontal transverse magnetic field may destabilize the flow and cause distinct oscillations of the liquid's velocity in the range of moderate Hartmann numbers. Some numerical simulations have been developed of the shape of a single bubble rising in a liquid metal with its magnetic field impact (Ni, 2012; Zhang et al., 2016; Zhang and Ni, 2014; Tian et al., 2016).

It is difficult to measure bubble velocity in an opaque liquid metal. The lack of suitable measuring techniques is the main reason for research into non-transparent gas-liquid metal flows. Due to the opacity and electrical conductivity of liquid metal, the application of conventional optical and contact electrical measurement methods are limited to measure the velocity. Therefore, it is expected to use acoustic technology to measure the internal velocity of liquid metal. Ultrasonic Doppler Velocimetry (UDV) is used to measure the velocity of opaque liquids using the acoustic reflection receiving technology, and has advantages over conventional techniques such as PIV or LDV. Zhang et al. (2005, 2007) studied a single bubble rising in a liquid metal column exposed to a magnetic field. The magnetic field strength was varied by up to 0.3 T corresponding to a magnetic interaction parameter slightly greater than 1. The bubble and liquid velocities were measured using UDV; an increase in the drag coefficient with increasing magnetic interaction parameter was observed for small bubbles, whereas the application of the magnetic field reduced the drag coefficient for larger bubbles. The previous research studies are demonstrated by the simulations of Schwarz and Froehlich (2014). A significant modification of the bubble wake structure was observed in the studies. Raising the magnetic field strength caused the eddy in the wake to enlarge. The previous research studies showed that the UDV technique offered the possibility of measuring bubble and liquid velocities simultaneously in opaque liquids. In addition, an experimental study that examined the impact of a DC magnetic field on a bubble plume was finished for a cylindrical liquid metal column (Zhang et al., 2007) in which a transverse magnetic field might provoke the destabilization of the global flow resulting in transient oscillating flow structures with predominant frequencies caused by the deceleration of the Lorentz force. Shibasaki et al. (2010) simulated the bubble ascension path with a magnetic field and found that while a weak field promoted bubble rising, a strong one inhibited it. The influence of the magnetic field shows that the flow field is completely different from the conventional two-phase flow, and the experimental study of the multi field coupling provides a good basis for solving these complex problems.

In the current research, the key problem is how a single bubble rises in a still liquid metal with a magnetic field. The motivations are to analyze the non-trivial bubble rising phenomena under the influence of a transverse DC magnetic field and to analyze the magnetic field's effects on the bubble ascension; the bubble size is 3.1–5.6 mm. In this paper, we focus on the experimental verification of the turning point of the bubble rising velocity and the variation law of the bubble rising velocity and drag coefficient under the strong magnetic field which is difficult to be accurately simulated by the numerical simulation. At each instant, the liquid velocity description for the interface of the bubble-driven flow in a stagnant liquid metal in a rectangle container was determined via Ultrasonic Doppler Velocimetry (UDV). UDV can measure the velocity of liquid metal and the velocity of gas-liquid interface, we regard the gas-liquid interface velocity as the bubble rising velocity (Zhang et al., 2005 ,2007). The measurements of the bubble's ascension velocity will be compared to the predictions of the Mendelson equation. The target is to obtain the hydro-dynamical relationships between the terminal velocity, drag coefficient, the Eötvös number, Reynolds number, and Stuart number in a strong magnetic field using a multiple regression method and to compare our experimental results with those of previous studies.

## 2. Experimental set-up

The experimental set-up is shown in Fig. 1. The test section is a 200 mm high rectangle container made from Perspex with a square 60 mm wide cross-section that allows full optical access from all four sides. There is a retaining valve at the top of the experiment section that protects the liquid metal from contamination from oxygen in the air. The container is positioned concentrically inside a transverse magnetic field, which provides a homogeneous DC longitudinal magnetic field that passes through the fluid district. The coils are supplied with maximum field strength of 1.97 T. The distance between two successive bubbles in the present experiment is always large enough to prevent interactions.

A stainless steel capillary tube (inner diameter 0.5–1 mm) is located in the mid-point of the tank base. The nozzle outlet is positioned at the mid-point of the container cross-section, 5 mm above the rectangle bottom. The container is filled to 190 mm with Galinstan (a GaInSn eutectic alloy) as a working fluid. The melting point of the eutectic composition is 10.8 °C, which allows room temperature measurements. Individual bubbles are formed by injecting argon through the capillary with a flow controller (at 0.0167–0.167 $cm^3/s$) to ensure that the bubble volume at detachment is controlled by a static balance between the surface tension and the buoyancy in order to guarantee a single bubble formation.

The UDV method has become an important flow velocity measurement technique based on pulse echo technology to determine velocity information. First, a UDV sensor emits an ultrasonic pulse along the direction of the probe placement, and then the reflection echo signal is received by small suspended particles in the fluid. Determining the delay time between the transmitter and receiver via an ultrasonic signal allows us to obtain information about the reflected particle's velocity and fluid flow velocity. Ultrasonic pulses of a few cycles are emitted from the transducer along the measuring line into the fluid. The knowledge of the sound velocity through the liquid allows an observer to calculate