Dynamic Neutron Imaging of Argon Bubble Flow in Liquid Gallium in Horizontal or Vertical Magnetic Field

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Abstract **— This paper details the results of the latest dynamic neutron imaging experiments with magnetohydrodynamic argon bubble chain flow in liquid gallium. We perform parameter space mapping for our model system by imaging bubble flow without and with applied static horizontal or vertical magnetic field over a range of gas flow rates and reproduce the experiments numerically.**

Keywords — neutron imaging, liquid metal, bubble flow, magnetic field, computational fluid dynamics (CFD)

I. Introduction

Bubble flow in liquid metal occurs in industrial processes such as metal stirring, purification, continuous casting, etc. These processes can potentially be controlled and stabilized via applied magnetic field (MF) [1-4]. However, bubble flow exhibits complex collective dynamics, which make it difficult to predict, especially with applied MF. Some aspects of magnetohydrodynamic (MHD) bubble flow are still not fully understood, preventing accurate modelling with effective Euler-Euler and Lagrangian models. Experimental and numerical data from explicit simulations, such as volume of fluid, are required to understand how MF orientation/intensity and gas flow rate affect system dynamics. To this end, downscaled systems with model liquid metals and gases, such as gallium and argon, are used, wherein bubbles are introduced via submerged tubes such that bubble chain flow forms [1-4]. It is known that bubble trajectories are mostly controlled by wake flow dynamics and are influenced by bubble shape oscillations, which also determines bubble chain flow characteristics [1-4]. Bubble chain flow is a simplified representation of industrially relevant processes, but despite the simplicity exhibits complex quasi periodic patterns and entails a wide range of time scales. This is especially true for higher flow rates when frequent collisions between bubbles ensue. Liquid metal opaqueness to the visible light makes it very challenging to obtain experimental data regarding bubble shapes and trajectories with sufficient precision. Recently, however, there have been significant advances in both neutron [2-4] and X-ray [1] radiography for bubble flow in liquid metal. Despite this, there are currently no systematic studies available where model systems are imaged for different MF orientations for a broad range of MF magnitudes and gas flow rates, particularly in the case of thicker liquid metal layers. The aim of this publication is to address this issue and present the results of the latest dynamic neutron imaging experiments conducted at the Paul Scherrer Institute (PSI). In addition, we perform numerical simulations mirroring the experimental conditions to verify the results of imaging. We use the data obtained both *in situ* and *in silico* for an in-depth analysis of bubble flow characteristics over the parameter space of our model system.

II. Experiments & Simulations

A modified version of the model gallium/argon system described in [3,4] was designed for the new experiments. As before, we imaged a rectangular 150 mm x 90 mm x 30 mm glass vessel (boron-pure, Figure 1) filled with liquid gallium up to the 130-mm mark.

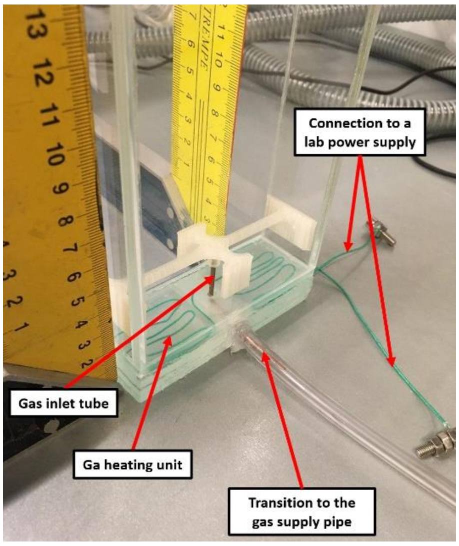

Figure 1. The glass vessel used in the experiments.

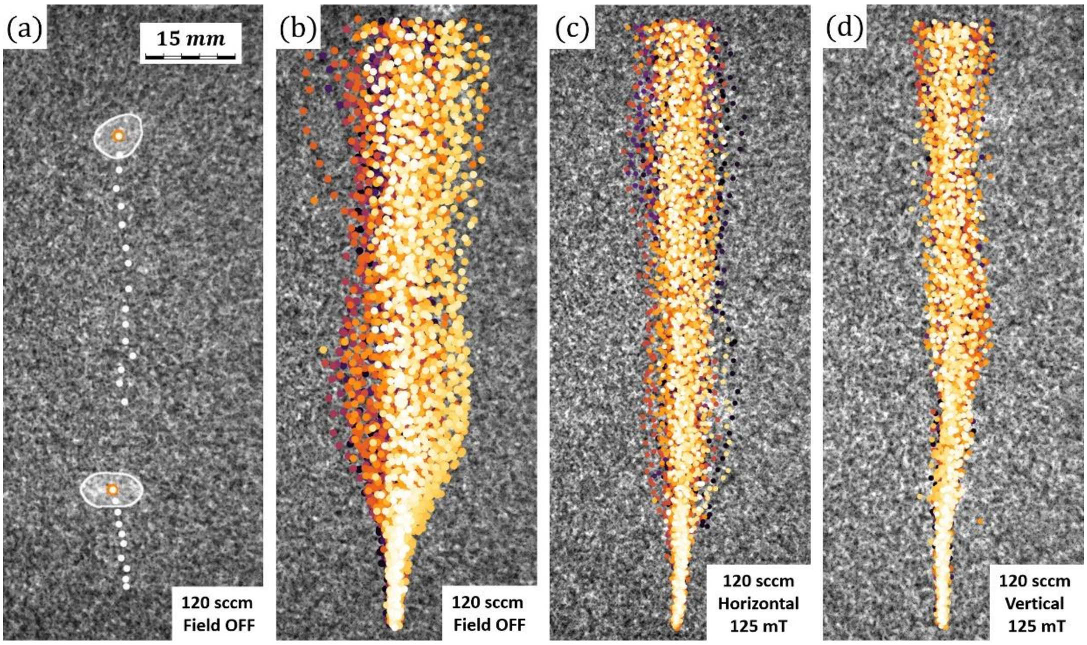

Figure 2. (a) An example of detected bubbles: white contours are shapes, orange dots are current positions and white dots are preceding detections; (b-d) detected bubble positions over 3000 frames (30 seconds), color coded black to white in order or appearance, with (b) no applied MF, (c) $\sim 125\ mT$ horizontal MF and (d) $\sim 125\ mT$ vertical MF for $120\ sccm$ gas flow rate.

A resistive heating unit at the vessel bottom kept the gallium above its melting point throughout experiments (constant $4.13\ W$). A vertical copper gas inlet tube (1 mm diameter) was inserted 20 mm into the vessel through the bottom glass plate. The gas flow rate was adjusted via a digital mass flow controller. Neutron imaging was performed at the thermal neutron beamline NEUTRA (SINQ, PSI, 20 mm aperture, $10^7 n\ cm^{-2} s^{-1} mA^{-1}$ flux) for gas flow rates in the 0-1200 $sccm$ (standard cubic centimetres per minute) range without MF, as well as for $\{75, 125, 200, 265\}\ mT$ horizontal MF and $\{75, 125\}\ mT$ vertical MF in the bubble flow region. Neutron flux was parallel to the 30-mm dimension of the vessel. A square field of view (FOV, 123.125 mm) above the inlet was imaged at 100 frames per second (FPS). Static MF was generated by tailored permanent magnet/iron yoke systems assembled at the Institute of Physics in Salaspils. Individual bubble trajectories, envelopes of all trajectories, and velocity, aspect ratio, tilt angle and other parameter correlations were obtained. An example of detected bubble positions within the FOV is shown in Figure 2. Image processing was performed using an improved version of the pipeline described in [3,4] which now includes multi-stage global filtering for bubble detection and features multiscale recursive interrogation filtering (among other methods) for improved bubble shape estimates and segmentation for images with many bubbles within the FOV and/or unusually low signal-to-noise ratio (SNR). In addition, reference experiments were performed at the cold neutron beamline ICON (SINQ, PSI, 20 mm aperture, $\sim 1.3\times$NEUTRA flux) to validate the developed image processing methodology. A brass reference body (stationary and moving) with a spherical cavity (5-mm radius) was imaged to reproduce imaging conditions like those for argon bubbles in liquid gallium. It was demonstrated that the image processing code performs well and is therefore adequate for the analysis of images with a priori unknown bubble shapes. Reference neutron imaging with 40- and 80 mm apertures (4× and ~11×20-mm flux, respectively) was performed to obtain reference images and see how the image processing code performs for different SNR. Finally, greater flux was leveraged for FPS up to 600, which should aid the in-depth analysis of bubble shape variations via image-based strain rate measurements. Numerical simulations were performed with MF configurations and flow rates matching the cases in our imaging experiments. The numerical model used in [3,4] was modified: the previously utilized volume of fluid phase interface compression method was replaced by the *isoAdvector* algorithm, which is more precise and numerically stable, while only slightly more computationally expensive.

III. Outlook

The ultimate goal of this study is to present a “roadmap” describing what flow characteristics to expect for a given combination of MF orientation, magnitude, and flow rate. One can then analyze how different metrics and correlations vary over the parameter space and understand how magnetic control can be applied in industrial systems with bubble flow in liquid metal.

Acknowledgments

This work is funded by the ERDF project "Development of numerical modelling approaches to study complex multiphysical interactions in electromagnetic liquid metal technologies" (No. 1.1.1.1/18/A/108) and supported by the Paul Scherrer Institut (PSI).

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