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Experimental study of single bubble motion in a liquid metal column exposed to a DC magnetic field

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Abstract

The motion of single Argon bubbles rising in the eutectic alloy GaInSn under the influence of a DC longitudinal magnetic field (parallel to the direction of bubble motion) was examined. The magnetic field strength was varied up to 0.3 T corresponding to a magnetic interaction parameter N (which measures the ratio of electromagnetic forces to inertial forces) slightly greater than 1. The liquid metal was at rest in a cylindrical container. Bubble and liquid velocities were measured using ultrasound Doppler velocimetry (UDV). The measured bubble terminal velocity showed oscillations indicating a zigzag movement of ellipsoidal bubbles. For small bubbles ($d_e \leqslant 4.6$ mm) an increase of the drag coefficient with increasing magnetic interaction parameter N was observed, whereas for larger bubbles ($d_e \geqslant 5.4$ mm) the application of the magnetic field reduces the drag coefficient. The measurements revealed a distinct electromagnetic damping of the bubble induced liquid velocity leading to more rectilinear bubble trajectories when the magnetic field is applied. Moreover, significant modifications of the bubble wake structure were observed. Raising of the magnetic field strength caused an enlargement of the eddies in the wake. The Strouhal number decreases with increasing magnetic interaction parameter N.

Keywords: Single bubble; Liquid metal; Magnetic field; Terminal velocity; Drag coefficient; Bubble wake; Ultrasound Doppler velocimetry

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1. Introduction

Bubble driven flows have found wide applications in industrial technologies. In metallurgical processes gas bubbles are injected into a bulk liquid metal to drive the liquid into motion, to homogenise the physical and chemical properties of the melt or to refine the melt. For such gas–liquid metal two-phase flows, external magnetic fields provide a possibility to control the bubble motion in a contactless way.

Numerous experimental and theoretical studies have been carried out on the movement of bubbles in transparent liquids, especially in water. An air bubble keeps its spherical shape and rises rectilinearly in water, as long as the bubble diameter is less than 0.7 mm (Saffman, 1956). The behaviour of larger, ellipsoidal bubbles is unstable and shows a transition to non-rectilinear motion with zigzag or spiral trajectories. This phenomenon has mainly been attributed to the influence of the bubble wake. For a detailed review about the onset of bubble path instabilities we refer to Fan and Tsushiya (1990) or Magnaudet and Eames (2000). Ellingsen and Risso (2001) investigated 2.5 mm diameter air bubbles rising in water by high-speed video and LDA. They found path oscillations developed in the absence of shape oscillations. Two unstable modes were identified having the same frequency but showing a phase shift of $\pi/2$. The first appearing primary mode leads to a plane zigzag trajectory, whereas the secondary mode is shown to be responsible for the helical motion. The vertical velocity component was found to oscillate with twice the frequency of the horizontal ones, but with a weaker amplitude. Using dye visualisation Lunde and Perkins (1997) observed a continuous pair of parallel helical vortex filaments in the wake of a bubble rising on a spiral trajectory, while intermittent and alternately shed hairpin vortices were found behind a bubble moving on a zigzag path. Similar vortex structures have also been found by DPIV measurements behind bubbles with diameters from 4 to 8 mm (Brücker, 1999). Recently, de Vries et al. (2002) visualised bubble wakes by a Schlieren optics technique showing a double-threaded wake of zigzagging bubbles. The authors estimated the lift force induced by this wake structure on the bubble concluding that the zigzag motion may occur without periodic vortex shedding.

Our interest is devoted to the motion of gas bubbles in liquid metals under the influence of a DC magnetic field. Previous experimental work showed the effect of transverse and longitudinal magnetic fields, respectively, on the slip ratio and the bubble dispersion in a turbulent bubbly channel flow (Eckert et al., 2000a,b). In this paper, we consider the case of a single, isolated bubble rising in a cylindrical column of stagnant liquid metal exposed to a longitudinal magnetic field. Because the gas bubble is electrically non-conducting, it does not experience the effect of the electromagnetic force directly. However, the bubble behaviour can expected to be influenced by the magnetically induced modifications in the liquid flow structure around the bubble. The possibility to influence the bubble wake by an additional body force may also contribute to a better general understanding of the interaction between bubble path and wake.

The number of publications dealing with gas bubbles rising in liquid metals is comparatively small. Andreini et al. (1977) detected the noise generated by the bubbles releasing from the orifice by means of an acoustic microphone attached to a brass seal. In this way the authors were able to determine the bubble formation frequency in tin and lead and consequently the equivalent bubble diameter. Schwerdtfeger (1968) used an ultrasonic pulse-echo instrument to study the rise of argon bubbles in mercury. The terminal velocities he determined in mercury were slightly smaller