MOTION OF SINGLE GAS BUBBLES RISING IN A LIQUID METAL EXPOSED TO A DC MAGNETIC FIELD

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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.

Our interest is devoted to the motion of gas bubbles in stagnant liquid metals under the influence of a DC magnetic field. Previous experimental works showed the effect of transverse and longitudinal magnetic fields, respectively, on the slip ratio and the bubble dispersion in a turbulent bubbly channel flow [1]. Because the gas bubble is electrically non-conducting, it does not experience the effect of the electromagnetic force directly. However, the bubble behaviour is, of course, 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 the bubble path and the wake. The number of publications dealing with single gas bubbles rising in liquid metals is comparatively small. Schwerdtfeger [2] 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 compared to corresponding measurements in water. His data fit well with the theoretical expression derived by Mendelson [3]. Mori et al. [4] studied the influence of a transverse magnetic field on the rise velocity of nitrogen bubbles in mercury. It was found that the magnetic field effect depends on the bubble size. Small bubbles with diameters of about 2 mm show a distinct helical motion without magnetic field. Here, the application of magnetic field intensities up to 1 T once increases the bubble velocity, before it decreases with a further increase of the field strength. For larger bubbles the terminal velocity decreases monotonically with the increasing strength of the transverse field.

1. Experimental set-up. The experiments were performed within an open cylindrical container made of Perspex with a diameter of $D = 100$ mm. The cylinder was filled until a height of $H = 220$ mm with a ternary alloy GaInSn as a working fluid. The melting point of the eutectic composition is about 10°C allowing measurements at room temperature. The GaInSn column is positioned concentrically inside a Helmholtz configuration of two water-cooled copper coils. The magnetic field direction was chosen to be parallel or perpendicular to the mean bubble path, respectively. The coils were supplied with the DC electric current up to 1600 A corresponding to a maximum field strength of 0.3 T.

Several nozzles made of stainless steel with an inner diameters between 0.3 and 5 mm were used to inject argon bubbles into the bulk of the liquid. The nozzle outlet was positioned at the midpoint of the cylindrical cross-section 10 mm above the cylinder bottom. The gas flow rate was controlled using a mass flow controller

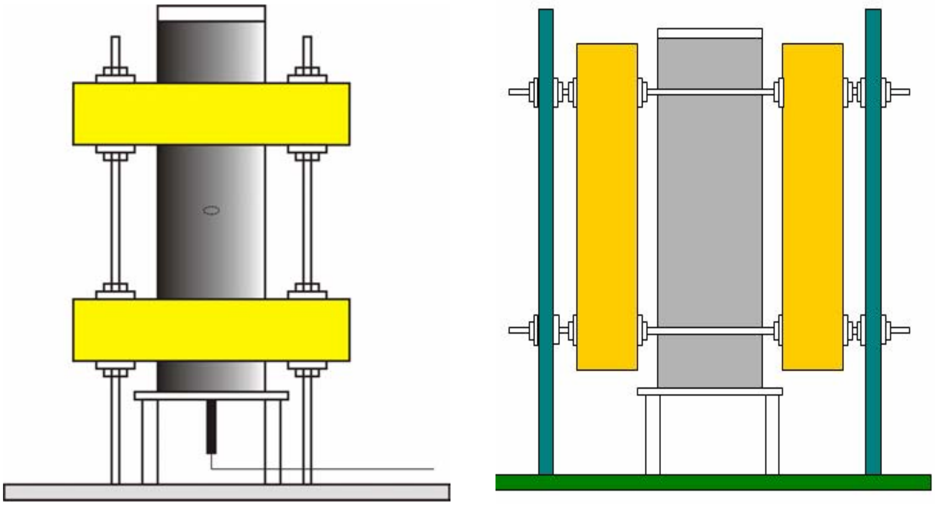

Fig. 1. Schematic view of the experimental set-up with a longitudinal magnetic field (left) and a transverse field (right), respectively.

(MKS 1359C, MKS Instruments). The DOP2000 velocimeter (model 2125, Signal Processing SA) with a standard 4 MHz transducer (TR0405LS) was used to carry out the velocity measurements.

2. Single bubbles in the DC magnetic field. In the parameter range covered by our experiments the bubbles do not rise along a rectilinear trajectory. Oscillations of the vertical bubble velocity indicate the occurrence of horizontal velocity components. The application of the longitudinal magnetic field suppresses the liquid motion in the direction perpendicular to the magnetic field lines, thus diminishing also the lateral components of the bubble velocity. As displayed in Fig. 2, the amplitude of the vertical bubble velocity oscillations decreases with the increasing magnetic interaction parameter N for both field configurations, whereas the damping is found to be much more pronounced in the transverse case. The measured drag coefficient calculated from the vertical bubble terminal velocity is displayed in Fig. 3. A tendency for reduction of the drag coefficient can be observed for the transverse case and for the larger bubbles in the longitudinal case. This effect may result from a modification of the bubble path caused by the magnetic field.

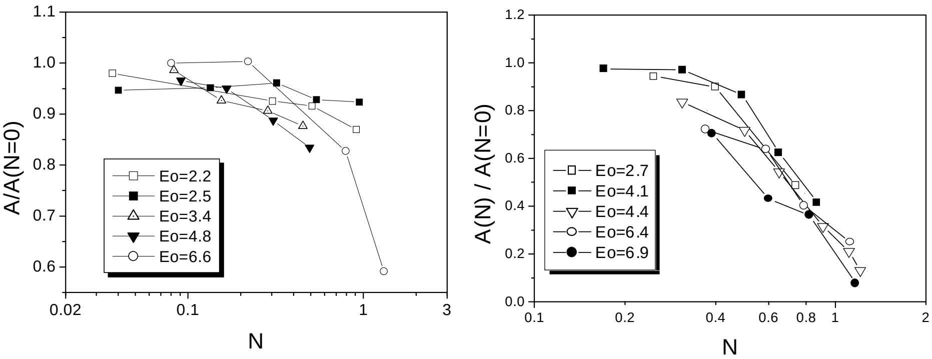

Fig. 2. Bubble velocity oscillation amplitude vs. rge magnetic interaction parameter: longitudinal field (left), transverse field (right).

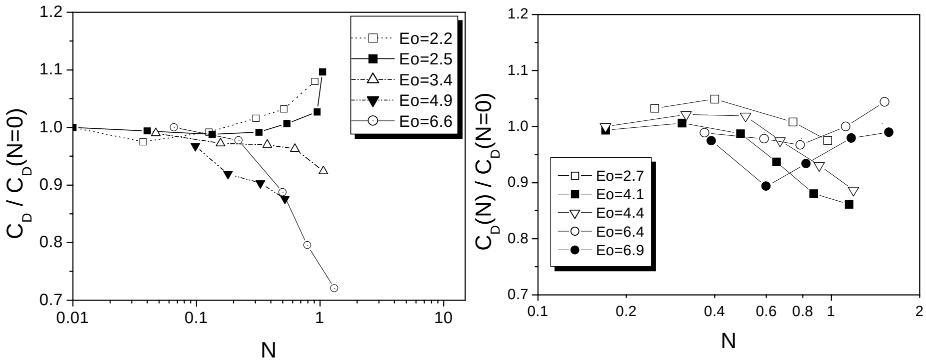

Fig. 3. Drag coefficient vs. the magnetic interaction parameter: longitudinal field (left), transverse field (right).

Fig. 4 contains the dependence of the Strouhal number St calculated from the bubble velocity oscillations on the magnetic interaction parameter N. The magnetic field considerably influences the structures in the bubble wake: the application of a longitudinal field results in an increase of the wave length of the velocity oscillations with the increasing N corresponding to a reduction of St, on the other hand, a transverse magnetic field causes an increase of St indicating a vortex shedding at higher frequencies.

Vertical velocity measurements along the cylinder axis performed in the presence of a longitudinal magnetic field reveals the effect on the bubble wake. Snapshots from these measurements shown in Fig. 5 were acquired at that moment when the bubble was detected at a vertical position of 170 mm. In the case without magnetic field, the vortex structure of the wake can clearly be recognized in the signal. The vertical liquid velocity behind the bubble generally becomes more uniform if the magnetic field is turned on, in other words, the velocity gradient along the field lines is significantly reduced. Besides the damping of the velocity in the wake region, an elongation of the wake structure in the vertical direction due to the anisotropy of the magnetic field influence can be observed.

It is known that the flow structure is distinctly affected by a DC magnetic field if the magnetic interaction parameter N exceeds the value of 1. The electromagnetic dissipation term reveals a strong anisotropy. As shown by Sommeria and Moreau [5], vortices are weakly damped if their axes are parallel with respect to the magnetic field lines. Knowledge about the wake behind the bubbles ris-

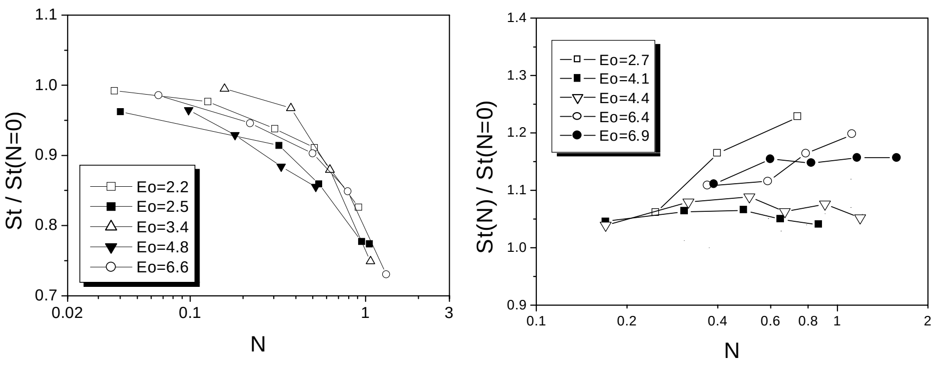

Fig. 4. Strouhal number vs. the magnetic interaction parameter: longitudinal field (left), transverse field (right).

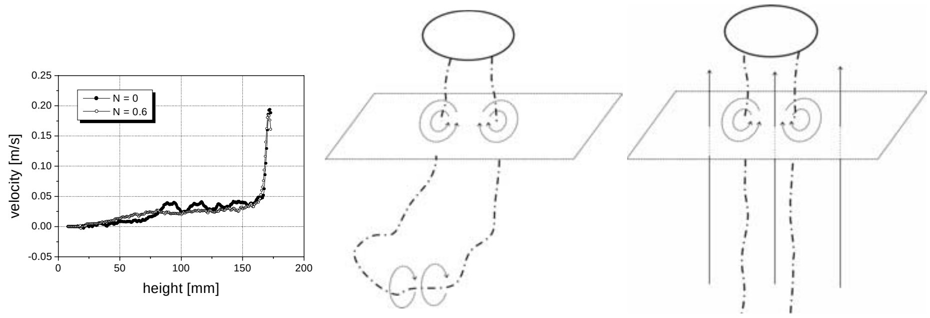

Fig. 5. Snapshot of the vertical velocity in the bubble wake (left), sketch of the bubble wake structure without magnetic field (middle) and within a longitudinal DC magnetic field (right).

ing in transparent liquids was obtained from visualization techniques by several authors and reviewed by Ellingsen and Risso [6]. Lunde and Perkins [7] found the wake of bubbles, rising along a helical trajectory, consisting of two attached vortex filaments, whereas hairpin-like vortex structures were associated with bubbles showing a zigzag or rocking motion. Such observations were confirmed by Brücker [8] relating the zigzag bubble path to the alternate shedding of oppositely oriented hairpin-like vortices. How should such a vortex structure be affected by a longitudinal magnetic field? The axes of the legs of a hairpin vortex are almost aligned with the direction of the vertically applied magnetic field. According to the knowledge about MHD turbulence, we expect only a weak damping for such kind of vortices, but a straightening and stricter alignment with the field lines should occur as sketched in Fig. 5. On the other hand, the head of the hairpin vortex should fully be governed by the Joule dissipation resulting in an efficient damping. According to these considerations, it can be observed that the oscillations of the liquid vertical velocity obviously disappear if the longitudinal magnetic field is applied.

Acknowledgements. The research is supported by the Deutsche Forschungsgemeinschaft (DFG) in form of the SFB 609 Electromagnetic Flow Control in Metallurgy, Crystal Growth and Electrochemistry. This support is gratefully acknowledged.

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