International Journal of Multiphase Flow 62 (2014) 134–151

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

# Numerical study of single bubble motion in liquid metal exposed to a longitudinal magnetic field

S. Schwarz *, J. Fröhlich

*Institute of Fluid Mechanics, TU Dresden, 01062 Dresden, Germany*

A R T I C L E  I N F O

*Article history:*
Received 11 June 2013
Received in revised form 5 February 2014
Accepted 7 February 2014
Available online 13 March 2014

*Keywords:*
Immersed boundary method
Bubble
Magnetohydrodynamics
Liquid metal

A B S T R A C T

The paper presents numerical simulations modeling the ascent of an argon bubble in liquid metal with and without an external magnetic field. The governing equations for the fluid and the electric potential are discretized on a uniform Cartesian grid and the bubble is represented with a highly efficient immersed boundary method. The simulations performed were conducted matching experiments under the same conditions so that sound validation is possible. The three-dimensional trajectory of the bubble is analyzed quantitatively and related to the flow structures in the wake. Indeed, the substantial impact of the magnetic field in the bubble trajectory results from its influence on the wake. Quantitative data describing the selective damping of vortex structures are provided and discussed. As a result of applying a longitudinal field, the time-averaged bubble rise velocity increases for large bubbles, it reaches a maximum and then decreases when further increasing the magnetic interaction parameter. For small bubbles, the time-averaged bubble rise velocity decreases when increasing the magnetic field. The bubble Strouhal number as a dimensionless frequency is reduced with the application of a magnetic field for all bubbles considered and the zig–zag trajectory of the bubble becomes more rectilinear.



## 1. Introduction

The ascent of a single bubble in a quiescent liquid is a fascinating phenomenon, for the layman as well as for the scientist. The trajectory of the bubble which can exhibit forms ranging from straight vertical ascent to chaotic irregular motion, and regimes of shape ranging from strictly spherical to irregularly wobbling still challenge physicists and engineers. An interesting review assembling the early knowledge on rising bubbles is given in Prosperetti (2004). In this reference, the term Leonardo's paradoxon is suggested for the tendency of sufficiently large bubbles to rise along a zig–zag or spiraling path rather than along a rectilinear one. The reason for the latter is attributed to the structure of the bubble wake. Two-threaded vortices of opposite circulation induce a lift force on the bubble deflecting it from a strictly vertical trajectory. A review on the hydrodynamic forces acting on isolated, spheroidal high-Reynolds-number bubbles and the associated motion is provided in Magnaudet and Eames (2000). The vortical structures in the wake of air bubbles in water have been analyzed by modern optical experimental techniques like Schlieren optics (de Vries et al., 2002), digital particle image velocimetry (Brücker, 1999) or dye visualization (Sanada et al., 2007). Alternately shed vortex filaments are observed for a bubble rising in zig–zag, while a spiral trajectory is characterized by a continuous pair of parallel vortices wrapped around the axis of the helix. In experiments, it has been observed frequently that the path first follows a zig–zag and later on changes to a helical shape (Saffman, 1956; Tomiyama et al., 2002), whereas a transition in the opposite direction has not been reported so far. Not surprisingly, the structures in the wake behind bubbles rising in zig–zag are similar to those observed behind rising solid spheres following a zig–zag trajectory (Horowitz and Williamson, 2010). It has been shown experimentally (Ellingsen and Risso, 2001) as well as numerically (Mougin and Magnaudet, 2002; Mougin and Magnaudet, 2006; Magnaudet and Mougin, 2007) that path oscillations can appear in the absence of shape oscillations which proves that indeed the vortex structures in the wake are responsible for the former. This is extensively discussed in the review of Ern et al. (2012) which assembles current knowledge about the wake of fixed bodies and its relation to the onset and development of path instabilities of both bubbles and rigid objects.

Most experimental and numerical work on bubbles so far has been conducted for the air–water system, often using hyper-clean water which is almost free of contaminants and therefore justifies

* Corresponding author. Tel.: +49 35146334719.
*E-mail addresses:* Stephan.Schwarz@tu-dresden.de (S. Schwarz), Jochen.Froehlich@tu-dresden.de (J. Fröhlich).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.02.012
0301-9322/

the application of a shear-free boundary condition at the gas–liquid interface (Magnaudet and Eames, 2000; Magnaudet and Mougin, 2007). Nevertheless, there is a variety of industrial applications where gas bubbles play an important role and where these conditions are not met. The continuous casting process in metallurgy is one example (Timmel et al., 2010, 2011). Here, gas bubbles are injected into the melt to clean the liquid metal from contaminants and to stir and homogenize the liquid phase (Zhang et al., 2007). Magnetic fields are used in liquid metal processes to stir (Stiller and Koal, 2009) and to stabilize the flow regimes (Wang and Zhang, 2011). Liquid metals are prone to oxidation, so that an oxide layer forms at the gas–liquid interface. Furthermore, contaminants and inclusions agglomerate at the bubble surface. The appropriate condition for the velocity at the bubble surface hence is the no-slip condition. This is backed by the observation that the drag of a fully contaminated spherical bubble corresponds to that of a solid sphere (Magnaudet and Eames, 2000; Fdhila and Duineveld, 1996).

To illustrate the parameter range considered in the present work, Table 1 lists material properties of the eutectic alloy GaInSn and compares them to those of water. The definition of the non-dimensional numbers is given in Section 2.1 below. The alloy GaInSn has been selected here because the simulations reported below have been conducted for a configuration with argon bubbles in GaInSn which is liquid at room temperature, an attractive property for its use in experiments. Its density and surface tension are markedly higher than those of water, while the kinematic viscosity is smaller. As a consequence, the Galilei number which relates buoyancy forces to viscous forces is higher for an argon bubble in GaInSn than for an air bubble of equal size in water, hence resulting in a higher bubble Reynolds number. The high density ratio and high surface tension are difficult to deal with in many multiphase methods, e.g. the volume of fluid method where spurious currents may occur as numerical artifacts and small time step sizes become necessary. The most significant contrast with water is the difference in electrical conductivity by about eight orders of magnitude. An approximate value for tab water is listed for comparison. The Eötvös number relating buoyancy force to surface tension forces is almost the same, so that in GaInSn similar bubble shapes as in water can be expected for a given diameter. According to the review of Loth (2008), or extrapolating the regime map of Clift et al. (1978), the shape of an argon bubble with diameter around 5 mm in GaInSn is expected to be 'ellipsoidally wobbling', in the sense that it is close to ellipsoidal with the axes of the ellipsoid varying in time.

Liquid metals are opaque and therefore experimental data are difficult to obtain and rare. The optical measurement techniques specified above hence cannot be used to get detailed insight into liquid metal multiphase flows. Ultrasound Doppler velocimetry is an alternative approach in this case and has been used to study the motion of a single bubble (Zhang et al., 2005) and a bubble-driven liquid metal jet (Zhang et al., 2007) under the influence of magnetic fields. Local conductivity probes have also been used to measure the rise velocity of bubbles in mercury (Mori et al., 1977) as well as the behavior of gas bubbles in turbulent liquid metal magnetohydrodynamic flows (Eckert et al., 2000,).

Direct numerical simulation of bubbles in liquid metals is challenging due to the large differences of density and viscosity between the phases and the high bubble Reynolds number typically encountered. As a result, there are only very few phase-resolving simulations of bubbles in liquid metal under the influence of a magnetic field. A rising bubble in a small enclosure under a vertical magnetic field was computed in Shibasaki et al. (2010) by means of a volume of fluid approach with reduced density and viscosity ratio and very moderate Galilei number. Gaudlitz and Adams (2010) simulated the influence of a vertical magnetic field on the rise of a single bubble in electrically conductive liquids with a hybrid particle level set method neglecting the effect of interface contamination. The numerical parameters of this case correspond to a small bubble in mercury, i.e. the Galilei number is smaller by a factor of five compared to the present study.

It is known that homogeneous magnetic fields substantially modify vortical structures in turbulent flows (Knaepen and Moreau, 2008; Boeck et al., 2007) as well as the pressure field around fixed objects (Maxworthy, 1968). Therefore, a considerable impact of such a field on the bubble dynamics is to be expected (Fröhlich et al., 2013), which indeed was observed in experiments (Zhang et al., 2005, 2007). Despite these studies the actual influence of a magnetic field on bubbles in liquid metal is still not fully understood. In particular, the impact of a magnetic field on the interaction between bubble wake and bubble dynamics in metallurgical systems is unclear and also the modification of the bubble shape in that case is not fully understood to this date. This is mostly due to the lack of visual data impeded by the opaque liquid metal.

The aim of the present paper is to fill this gap and to provide insight into the influence of a longitudinal magnetic field on bubble wake and bubble dynamics. Phase-resolving numerical simulations of an argon bubble in the liquid metal GaInSn have been conducted for different values of magnetic interaction. The three-dimensional data of high spatial and temporal resolution obtained from the simulations are evaluated, visualized and compared against experimental data.

The paper is structured as follows: Section 2 gives a short description of the equations to be solved and the numerical approach employed, as well as a refinement study quantifying the numerical error. Section 3 contains the numerical results for the ascent of a single bubble with and without a magnetic field. Visualizations are presented to highlight conspicuous flow features in the bubble wake. Furthermore, the numerical results are compared against available experimental findings and other simulation data. The last section summarizes the results of the present study and outlines future research directions.

**Table 1**
Material properties of GaInSn and water at a temperature of 20 °C and ambient pressure of 1 bar (Zhang et al., 2005). The non-dimensional numbers are calculated for an argon bubble in GaInSn and an air bubble in water, both with an equivalent diameter of $d_{eq} = 4.6$ mm.

| | GaInSn | Water |
|---|---|---|
| Density $\rho_f$ (kg m$^{-3}$) | 6361 | 998 |
| Surface tension $\sigma$ (N m$^{-1}$) | 0.533 | 0.073 |
| Kinematic viscosity $\nu$ (m$^2$ s$^{-1}$) | $3.46 \cdot 10^{-7}$ | $9.82 \cdot 10^{-7}$ |
| Electrical conductivity $\sigma_e$ (S m$^{-1}$) | $3.27 \cdot 10^{6}$ | $\approx 5.0 \cdot 10^{-2}$ |
| Galilei number $G$ | 2825 | 995 |
| Eötvös number $Eo$ | 2.5 | 2.8 |

## 2. Method

### 2.1. Parameters of single bubble ascent

The problem of a single particle rising or falling in a pool of quiescent fluid due to the effect of buoyancy is governed by three parameters (Ern et al., 2012): The particle-to-fluid density ratio $\pi_\rho = \rho_p/\rho_f$, the Galileo number $G = \sqrt{|\pi_\rho - 1|g d_{eq}^3}/\nu$, and a geometrical parameter relating to the shape of the particle, such as the ratio of diameter to height for a cylindrical particle or the aspect ratio for an ellipsoid of rotation, for example. Here, $g$ is gravity, $d_{eq}$ is the diameter of a volume-equivalent sphere and $\nu$ is the kinematic viscosity of the liquid. In the following we will use the terms