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Euler-Euler simulation and X-ray measurement of bubble chain in a shallow container filled with liquid metals

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HIGHLIGHTS

- Bubble chain in liquid metals was studied by X-ray radiography.
- Oscillating frequencies of bubble chains were identified by FFT method.
- Significance of the BIT model and turbulent viscosity approach for simulating bubble chains was demonstrated.
- Resolved and unresolved liquid velocity fluctuations were studied.

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ABSTRACT

An Euler-Euler two-fluid approach was used to simulate the behavior of gas bubbles rising in a stagnant liquid metal. A single point injection with four gas flow rates resulted in the formation of bubble chains undergoing either slight or distinct oscillations of the bubble trajectories. A set of interfacial closures with a shear stress transport (SST) k-ω turbulence models was applied for simulating the transient behavior of the bubble chain. X-ray radiography measurements were conducted to establish an experimental data base for validating the numerical results. The experiments provide a visualization of the bubble chain in a flat container and allow determining the bubble size and integral void fraction. Two bubble induced turbulence (BIT) models (Rzehak and Krepper, 2013a, Sato et al., 1981) and a modified turbulent viscosity approach (Johansen et al., 2004) were applied within this study. For all gas flow rates, the Rzehak and Sato BIT model alone predicted a steady bubble chain in contrast to the oscillating bubble plume observed in the experiments. Without a BIT model the oscillating bubble chain can be predicted but the oscillation frequency is underestimated especially for high gas flow rates. In addition, calculations without a BIT model predicted over-dispersion of the averaged gas fraction through the whole fluid container for the high gas flow rates. The best results in terms of a satisfying agreement with the experimental data were achieved by adopting a modified turbulent viscosity approach proposed by Johansen together with the Rzehak and Krepper BIT model. These findings demonstrate the significance of the turbulence model.

1. Introduction

Liquid metal two-phase flows are widely encountered in many industrial processes, such as metallurgical and power engineering (Mazumdar and Guthrie, 1995; Glasstone and Sesonske, 2012; Zhan et al., 2017, 2018; Sarkar et al., 2018). One typical example is the continuous casting process in which argon bubbles are injected to prevent clogging of the submerged entry nozzle and to separate undesired inclusion from the melt. Effective control and optimization of this process requires a comprehensive understanding of the behavior of liquid metal two-phase flows.

Unlike the transparent air-water two-phase flow, the opaqueness of the liquid metal makes the application of traditional measurement techniques such as high-speed video observation (Liu et al., 2015, 2016), Particle Image Velocimetry (PIV) (Delnoij et al., 1999; Deen et al., 2002, 2008; Sathe et al., 2010; Hessenkemper and Ziegenhein, 2018) and Laser Doppler Velocimetry (LDV) (Mudde et al., 1997a) impossible so that direct

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measurements in gas-liquid metal two-phase flow are difficult. Thus, over the past decades, air-water model experiments (Iguchi et al., 1994, 1998; Li and Tsukihashi, 2005; Ma et al., 2016, 2018), which were designed by the similarity principle, were conducted to study the bubble behavior in water. However, due to the significant differences in material properties of liquid metals compared to water, in particular the high density and surface tension, the bubble dynamics and the two-phase turbulence in gas-liquid metal system can be different. Therefore, experimental studies in liquid metal are of particular importance and indispensable. Previous measurements in liquid metal bubbly flows were performed by means of conductivity probes (Oryall et al., 1976; Xie et al., 1992; Iguchi et al., 1997; Eckert et al., 2000a, 2000b; Xie and Oeters, 1994), by ultrasound Doppler velocimetry (UDV) (Zhang et al., 2005; Timmel et al. 2010; Wang et al., 2017), by Local Lorentz force velocimetry (LLFV) (Lyu and Karcher, 2017), by Gamma-ray attenuation method (Thiyagarajan et al., 1995) or by neutron radiography (Mishima et al., 1999; Saito et al., 2005). The capability of X-ray radiography to be an efficient and accurate tool for the visualization of liquid metal two-phase flows has been demonstrated by recent studies (Iguchi et al., 1995; Wang et al., 1999; Shevchenko et al., 2013; Timmel et al., 2015; Vogt et al., 2015; Keplinger et al., 2017; Liu et al., 2018).

During the last decades, computational fluid dynamics (CFD) became more and more efficient and powerful for the simulation of multiphase flows. An analysis of bubble properties and the liquid flow structure in a liquid metal bubble chain was provided recently by Krull et al. (2017) using a new hybrid method for phase-resolving direct numerical simulation (DNS) combining advantages of front tracking and the immersed boundary method (IBM). Among various modeling approaches dealing with large-scale industrial multiphase flows, the Euler-Euler two-fluid model shows advantages over the Euler-Lagrange model and interface resolved methods such as volume of fluid, front tracking, and immersed boundary method, since it causes significantly lower computational costs. Thus, the Euler-Euler two-fluid model has been widely used in chemical and metallurgical process engineering. Taking the example of bubble chain/plume investigation in gas-liquid two-phase system, two-dimensional (2D) and three-dimensional (3D) Euler-Euler simulations were extensively conducted and the results were compared to experimental data (Becker et al., 1994; Mudde and Simonin, 1999; Pfleger et al., 1999; Deen et al., 2001; Pfleger and Becker, 2001; Buwa and Ranade, 2002, 2004; Oey et al., 2003; Bech, 2005; Díaz et al., 2008, 2009; Gupta and Roy, 2013; Miao et al., 2013; Liu and Li, 2018). Despite these extensive and detailed studies, an appropriate modeling of the liquid turbulence and the bubble induced turbulence need further investigations and development for bubble chains or plumes due to the sensitivity to the turbulence models used. Several investigations (Mudde and Simonin, 1999; Pfleger et al., 1999; Sokolichin and Eigenberger, 1999; Bech, 2005) demonstrated that the oscillating frequency and amplitude of bubble plumes depend strongly on the turbulence viscosity. The bubble plume dynamics can be damped by an increased turbulent viscosity caused by the BIT model used (Ma et al., 2015). Therefore, a consistent selection of suitable turbulence models that describe the turbulent viscosity is very important and should be further investigated for the bubble chain case.

In the present work, bubble chains rising in a liquid metal (eutectic GaInSn alloy) were investigated experimentally by X-ray radiography and numerically by the Euler-Euler two-fluid model. The SST k-ω turbulence model with the default and modified turbulent viscosity approach was used including or excluding a bubble induced turbulence (BIT) to simulate the two-phase turbulence. The present work aims to (i) experimentally determine the bubble diameter and chain oscillating behavior in liquid metals; (ii) study the influence of the turbulence and BIT model on the dynamics of the liquid metal two-phase flow. The paper is organized as follows. The numerical modeling is explained in detail in Section 2. Section 3 presents a description of the experimental setup and the data processing. Section 4 is devoted to the comparison between simulation results and experimental data followed by discussion and conclusions in Section 5.

2. Numerical modeling

2.1. Basic equations

In the present work, the Euler-Euler two-fluid model is used, which has been discussed in many publications (e.g. Ishii and Hibiki, 2010). For adiabatic flows, the continuity and momentum equations are given as follows:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{u}_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_i \rho_i \boldsymbol{u}_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{u}_i \otimes \boldsymbol{u}_i) = -\alpha_i \nabla p + \nabla\left[\alpha_i \mu_i^{eff}\left(\nabla \boldsymbol{u}_i + (\nabla \boldsymbol{u}_i)^T\right)\right] + \alpha_i \rho_i \boldsymbol{g} + \boldsymbol{F}_i \tag{2}$$

where α is the gas void fraction, ρ the density, $\boldsymbol{u}$ the velocity vector. The subscript $i = G$ denotes the gas phase and $i = L$ the liquid phase. The terms on the right-hand side of Eq. (2) represents the pressure gradient, the effective viscous stress, the gravity force, and the interfacial force. In the turbulent viscous stress term, μ_i^{eff} is the effective viscosity of phase i, which is the summation of the molecular viscosity μ_i^{mol} and turbulent viscosity μ_i^{turb}.

2.2. Interfacial forces

To close Eq. (2) a model for the interfacial force F_i is required. F_i is formulated as a sum of specific forces for which empirical correlations from experiments or theory were proposed. Modeling and validation of interfacial forces acting on a bubble in a two-phase flow have been intensified over the past ten years, for example by Zhang et al. (2006), Lucas et al. (2007), Díaz et al. (2008) or Tabib et al. (2008). Recently, Rzehak and Krepper (2013b) proposed a baseline model which combines a set of models. It was validated by comparing the CFD simulations with experimental results for air-water two-phase flows (Rzehak et al., 2015; Rzehak and Krepper, 2013a, 2015; Rzehak and Kriebitzsh, 2015; Lucas et al., 2016; Ziegenhein et al., 2015, 2017). The corresponding interfacial transfer models employed here are listed in Table 1. A complete description of all interfacial transfer models can be found in the investigations of Rzehak and Krepper (2013b) or Liu et al. (2018).

Table 1
Empirical correlations for interfacial forces employed in the present work.

Interfacial force	Reference	Formula
Drag force (F_D)	Ishii and Zuber (1979)	$\mathbf{F}_D = -\frac{3}{4d_B} C_D \rho_L \alpha_G \lvert \mathbf{u}_G - \mathbf{u}_L \rvert (\mathbf{u}_G - \mathbf{u}_L)$
Lift force (F_L)	Tomiyama et al. (2002)	$\mathbf{F}_L = -C_L \rho_L \alpha_G (\mathbf{u}_G - \mathbf{u}_L) \times rot(\mathbf{u}_L)$
Wall force (F_W)	Hosokawa et al. (2002)	$\mathbf{F}_W = \frac{2}{d_B} C_W \rho_L \alpha_G \lvert \mathbf{u}_G - \mathbf{u}_L \rvert^2 \hat{\mathbf{y}}$
Turbulence dispersion force (F_{TD})	Burns (2004)	$\mathbf{F}_{TD} = -\frac{3}{4} C_D \frac{\alpha_G}{d_B} \lvert \mathbf{u}_G - \mathbf{u}_L \rvert \frac{\mu_L^{turb}}{\sigma_{TD}} \left(\frac{1}{\alpha_G} + \frac{1}{\alpha_L}\right) \nabla \alpha_G$
Virtual mass force (F_{VM})	Mougin and Magnaudet (2002)	$\mathbf{F}_{VM} = -C_{VM} \rho_L \alpha_G \left(\frac{D\mathbf{u}_G}{Dt} - \frac{D\mathbf{u}_L}{Dt}\right)$