International Journal of Multiphase Flow 48 (2013) 32–45

Contents lists available at SciVerse ScienceDirect

International Journal of Multiphase Flow

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

Numerical modeling of bubble-driven liquid metal flows with external static magnetic field

X. Miao [a], D. Lucas [a], Z. Ren [b], S. Eckert [a,*], G. Gerbeth [a]

[a] Helmholtz-Zentrum Dresden-Rossendorf, P.O. Box 510119, 01314 Dresden, Germany
[b] Shanghai University, P.O. Box 275, Yanchang Road, 200072 Shanghai, PR China

ARTICLE INFO

Article history:
Received 26 April 2012
Received in revised form 27 July 2012
Accepted 28 July 2012
Available online 15 August 2012

Keywords:
Liquid metal
Bubble-driven flow
DC magnetic field
Multiphase model

ABSTRACT

Three-dimensional numerical simulations are presented considering the impact of a steady magnetic field on a bubble-driven liquid metal flow inside a cylinder. The injection of moderate gas flow rates through a single orifice at the bottom of the fluid vessel results in the formation of a bubble plume. The magnetic field is applied in either vertical or horizontal direction. The calculations were performed by means of the commercial software package CFX using the Euler–Euler multiphase model and the RANS–SST turbulence model. The non-isotropic nature of MHD turbulence was taken into account by specific modifications of the turbulence model. The numerical models are validated with recent experimental results. (Zhang, C., Eckert, S., Gerbeth, G., 2007. The flow structure of a bubble-driven liquid–metal jet in a horizontal magnetic field, J. Fluid Mech. 575, 57–82.) The comparison between the numerical simulations and the experimental findings shows a good agreement. The calculations are able to reproduce a striking feature of a horizontal magnetic field found in the range of moderate Hartmann numbers revealing that such a steady transverse magnetic field may destabilize the flow and cause distinct oscillations of the liquid velocity.

1. Introduction

Bubbly flows have found wide applications in metallurgical processes (Mazumdar and Guthrie, 1994; Wang et al., 1999; Iguchi et al., 1995, 1997; Bai and Thomas, 2001). In many cases the presence of bubbles modifies the flow structure considerably. The detailed knowledge of liquid metal two-phase flows is important with respect to a potential process control for a superior product quality and a high efficiency of the production. An interesting example is the continuous casting of steel where Argon gas is injected through the submerged entry nozzle to prevent it from clogging. This two-phase flow pours into the mold and forms there a highly-turbulent submerged jet. So-called electromagnetic brakes (EMBR's), which employ horizontally aligned DC magnetic fields, are proposed to control such kind of flows in a contact-less way. For example, a recent work done by Haverkort and Peeters (2010) concerns the magnetohydrodynamic effects on the movement of gas bubbles or insulating inclusions inside a metallic melt and draws respective conclusions for the situation in a continuous steel caster. However, the interplay between the turbulent liquid metal two-phase flow and the magnetic field turns out to be rather complex. On one hand, the magnetic field should have a considerable influence on the bubble velocity, the bubble shape or the distribution of the gas in the cross section of the mold. On the other hand, the void fraction also determines the closure of the induced electric current in the melt and, therefore, the distribution of the Lorentz force. An electrically insulating gas bubble does not experience a direct impact of the electromagnetic force, however, the pressure and the velocity field in the surrounding conducting fluid are strongly affected by the applied magnetic field. Modifications of the bubble shape, the drag coefficient or the trajectory are expected to exert a significant influence on the dynamics of a dispersed bubbly flow. The crucial non-dimensional parameters describing the influence of a steady magnetic field B on a single bubble inside an electrically conducting fluid are the Hartmann number Ha_B, the magnetic interaction parameter N_B and the bubble Reynolds number, which can be written as:

$$Ha_B = Bd_B\sqrt{\frac{\sigma_{el,L}}{\mu_L}} \tag{1}$$

$$N_B = \frac{Ha_B^2}{Re_B} = \frac{\sigma_{el,L} d_B B^2}{\rho_L U_L} \tag{2}$$

$$Re_B = \frac{\rho_L |U_L - U_G| d_B}{\mu_L} \tag{3}$$

where ρ_L, μ_L, $\sigma_{el,L}$ and U_L represent the material properties of the liquid (density, dynamic viscosity, electrical conductivity) and the characteristic velocity of the liquid. The variables U_G and d_B denote

* Corresponding author. Tel.: +49 3512602132; fax: +49 3512602007.
E-mail address: s.eckert@hzdr.de (S. Eckert).

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2012.07.014

the velocity of the rising bubble and the equivalent bubble diameter, respectively. To delineate the parameter range within this study we also use the non-dimensional numbers Ha, N and Re, which refer to the dimensions of the fluid container and result from a substitution of the equivalent bubble diameter d_B by the radius of the fluid cylinder R in the Eqs. (1)–(3).

Some few theoretical papers are devoted to the magnetic field impact on the shape of a single bubble rising in a liquid metal (Takatani, 2007; Shin and Kang, 2002; Shibasaki et al., 2010). Unfortunately, respective experimental results are not available because of the still missing capacity of measuring techniques to provide a reliable reconstruction of a gas bubble inside an opaque liquid metal. Shin and Kang (2002) considered an incompressible gas bubble in an axisymmetric straining flow under the influence of a uniform magnetic field. They predicted an elongation of the bubble along the direction of the magnetic field. This bubble elongation increases monotonously as the magnetic interaction parameter N_B increases. The phenomenon of bubble elongation in field direction was also reported by Shibasaki et al. (2010) for a bubble rising inside a steady magnetic field parallel to the gravity force. Takatani (2007) studied two configurations of a bubble ascending in either a vertical or a horizontal magnetic field. In case of a longitudinal field the bubble contour is transformed to a bullet-like shape, which reduces the flow resistance, but leaves the terminal velocity almost unaffected compared to the situation without magnetic field. In contrast, the shape of the bubble becomes flat if a transverse field is applied. The resulting bubble velocity is supposed to be lower than that without magnetic field.

Experimental investigations on rigid spheres revealed an increase of the drag coefficient proportional to the square root of the interaction parameter N_B (Gelfgat et al., 1976). Eckert et al. (2000b) investigated the influence of a transverse magnetic field on the slip ratio in a channel flow. The linear dependence of the drag coefficient on the magnetic field strength would imply a continuous decrease of the slip ratio with rising magnetic flux. However, the slip ratio was found to be reduced only at moderate values of the magnetic field strength, but increases again at higher values of the field intensity. This tendency is caused by the braking effect on the liquid metal flow, which is proportional to B^2 and becomes dominant at high field intensities therefore. As the bubble shape has not been measured, the experiments did not provide any information concerning the possibility of magnetically-induced modifications of the bubble shape.

Experiments with single bubbles in stagnant liquid metal pools have demonstrated that an imposed DC magnetic field modifies the drag coefficient. A vertical magnetic field damps the horizontal components of the bubble velocity. This effect forces the bubble into a straighter path and reduces the apparent drag force (Zhang et al., 2005). Similar observations were made by Mori et al. (1976) in a transverse magnetic field. A suppression of the zigzag motion of the bubble leads to a higher terminal velocity. By contrast, the terminal velocity of bubbles moving along a rectilinear way decreases with increasing field strength.

Another study was focused on turbulent dispersion of gas bubbles in an MHD duct flow (Eckert et al., 2000a) which were initially injected from a point source. The application of a transverse magnetic field results in an anisotropic distribution of the void fraction over the duct cross-section with a significantly lower dispersion coefficient found for the direction parallel to the field lines. This finding indicates that the damping of turbulent fluctuations is much more pronounced in the direction parallel to the magnetic field than in the perpendicular direction. That means that the bubble dispersion is determined by the existence of quasi-two-dimensional fluctuations with a vorticity along the magnetic field direction being well-known for MHD turbulence (Sommeria and Moreau, 1982).

The rise of gas bubbles drives a flow inside the liquid metal and acts as a source of turbulence. Gherson and Lykoudis (1984) investigated a mercury pipe flow with dispersed nitrogen bubbles. At large magnetic fields they found regions with liquid turbulent fluctuations higher than in the case without magnetic field. The authors explain this observation by a magnetically-induced redistribution of the void fraction with the formation of large but unstable bubbles. The higher frequency of bubble break-up processes cause an additional turbulence production.

Recently, Zhang et al. (2007a,b) presented an experimental study with respect to the impact of a DC magnetic field on a bubble plume in a cylindrical liquid metal column. Measurements of the liquid velocity revealed that a transverse magnetic field might provoke a destabilization of the global flow resulting in transient, oscillating flow structures with predominant frequencies. That outcome seems to be contrary to usual expectations, because the Lorentz force is often supposed to cause a deceleration of the mean flow and a damping of turbulent fluctuations.

The numerical study of a turbulent bubbly flow is sophisticated. In recent years, two approaches are primarily implemented in modeling two-phase flows. One approach is the Euler–Lagrange (Sommerfeld, 1996; Garg et al., 2009) and another is the Euler–Euler approach (Simonin and Viollet, 1988; Chahed et al., 2003). With the recent developments in computational capability, bubbly flow simulations set out to develop from uniform mono-size to multi-size (Politano et al., 2003; Frank et al., 2008). In this model, the momentum exchange between gas phase and liquid phase sensitively depends on the bubble sizes, wherein the effects of bubble coalescence and breakup can be taken into account as well.

The scope of the present paper is concerned with the same configuration as investigated by Zhang et al. (2007b) where magnetically triggered oscillating flow structures were observed. Numerical simulations of the bubble driven flow in a stagnant liquid metal in a cylindrical vessel have been carried out using an Euler–Euler approach. All parameters and the geometry of the problem have been chosen according to the reported experimental conditions. The motivations are to develop suitable numerical models in investigating non-trivial phenomena under the influence of a longitudinal and a transverse DC magnetic field and to reproduce the experimentally observed magnetic field effects.

2. Numerical modeling

2.1. Basic equations

In our simulations we apply the Euler–Euler approach considering both the liquid and the gaseous phase with certain volume fractions α_L and α_G, respectively. On the supposition that any mass exchange between the phases can be neglected, the system of equations of continuity and momentum is given as follows (Drew, 1997):

$$\frac{\partial(\alpha_k\rho_k)}{\partial t} + \nabla\cdot(\alpha_k\rho_k\mathbf{u}_k) = 0 \tag{4}$$

$$\frac{\partial(\alpha_k\rho_k\mathbf{u}_k)}{\partial t} + \nabla\cdot(\alpha_k\rho_k\mathbf{u}_k\mathbf{u}_k) = -\nabla p - \nabla\cdot(\alpha_k\tau_k) + \alpha_k\rho_k\mathbf{g} + \mathbf{F}_{I,k} + \mathbf{F}_{EM} \tag{5}$$

where the subscript $k = L$ denotes the liquid metal phase and $k = G$ the gas phase, respectively. The terms on the right-hand side of Eq. (5) represent the pressure gradient, the turbulent viscous stress, the gravity force, the interfacial forces $\mathbf{F}_{I,k}$, and the electromagnetic force $\mathbf{F}_{EM}$. The variable α_k stands for the volume fractions of both phases, whereas the sum of the void fraction α_G and the liquid fraction α_L is unity.

In multiphase fluid flow, the summation of the net interfacial forces is equal to zero. The interfacial forces $\mathbf{F}_{I,L}$ in Eq. (5) can be expressed as