Numerical Simulation of Two-Phase Liquid Metal Interacting with Strongly Inhomogeneous Magnetic Fields

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Abstract

Lorentz Force Velocimetry (LFV) is a non-contact flow measurement technique for liquid metal flow developed by Thess et al [1]. LFV relies on the basic principle of measuring the Lorentz force acting on a magnet system due to the eddy currents induced in the liquid flow. This force depends on the velocity of the liquid metal and has the same magnitude as the braking Lorentz force in the flow. The main aim of the project is to broaden the LFV technique to include two-phase local flow measurement and to numerically study the effects of two-phase fluid flow on the Lorentz force. Such bubble flow plays an important role in metallurgical processes such as ladle treatment and continuous casting and is responsible for removing inclusions as well as for deoxidizing and homogenizing the melt.

Introduction

Electromagnetic fields produced either by electric currents or by simple permanent magnets have a strong influence on the flow of liquid metals [2, 3]. Electromagnetic fields are considered a convenient method of influencing bubble dynamics, providing a variety of useful industrial applications. The drops and bubbles have homogenizing effects on the alloy [4] and provide a contactless control of electromagnetic flow [5]. Further research regarding bubble dynamics within liquid metals is necessary. Moving bubbles in liquid metals are not as easily calculated using the classical methods applied to bubbles in water. Bubbles in liquid metals have high Reynolds numbers, large density ratios, and high surface tension [4, 6]. Furthermore, liquid metals are opaque [7]. It is difficult to evaluate the flow field through experimental studies, which is why Lorentz Force Velocimetry (LFV) is a promising measurement technique. LFV measures the force acting on a magnet system proportional to the velocity of the moving fluid [1]. For standard LFV a large magnet system is typically applied to the magnetically conducting flow in order to measure the volume flux [8]. However, standard LFV is not sufficient to obtain information about the local flow disturbances, which crucially impact product quality in many metallurgical processes. Therefore, the Lorentz force flow meter is modified with a small permanent magnet but strongly localized magnetic field [9]. The pattern with which the bubbles rise to the top of the melt in this case will be compared with another experiment to achieve scientific validation. This work contains the Lorentz force calculations when the bubble rises in different positions using the two-phase Magnetohydrodynamics (MHD) model. In the first part of this paper, the fundamental aspects of two-phase flow and the numerical MHD model are presented. In the second part, a Volume of Fluid (VoF) MHD model is established to investigate the Lorentz force signals in relation to bubble size, velocity, and position. This provides a first step towards a more complete two-phase LFV model, where a single bubble influences the Lorentz force signal.
1. Numerical Method and Model Description

In this work we consider a single Argon bubble rising in an initially quiescent column of GaInSn with an external magnetic field. An Electric Potential Method can then be used to compute the electric current and Lorentz force distribution. The magnetic field is generated by a permanent magnet cube and then analytically calculated using the analytical permanent magnet model established by Furlani, E. P. [10]. In general, the electrical current density \( J \) can be obtained using Ohm’s law, where the electrical field \( E \) originates from the gradient of the electric potential \( \nabla \phi \) and the current-conservation law is divergence-free:

\[
J = \sigma (E + u \times B).
\]  

(1)

The Lorentz force density is computed by taking the cross product of current density \( J \) and the external magnetic field \( B \):

\[
F_L = J \times B.
\]  

(2)

The magnetic field induced by the flow is neglected due to the low magnetic Reynolds number \( \text{Re}_m \). Thus, a quasi-static approximation can be used. According to the divergence theorem, the continuity equation can be written in a differential form in (3), where \( \sigma \), \( u \), and \( B \) are continuously differentiable:

\[
\nabla \cdot (\sigma \nabla \phi) = \nabla [\sigma (u \times B)].
\]  

(3)

We should consider the high ratio of electrical conductivity between Argon and GaInSn, which means that \( \sigma \) discontinues abruptly in those regions. The commercial software ANSYS FLUENT is not able to calculate \( \nabla \phi \) correctly during the phase (liquid-air) transition. Therefore, an in-house “least square” approach is used in order to deliver the correct gradient of electric potential. A diffusion equation is used to calculate the electrical potential \( \phi \) by implementing the User-Defined-Scalar (UDS) in FLUENT:

\[
\frac{\partial \rho \phi_k}{\partial t} + \frac{\partial}{\partial x_i} \left( F_i \phi_k - \Gamma_k \frac{\partial \phi_k}{\partial x_i} \right) = S_{\phi k}, \quad k = 0, ..., N_{\text{scalars}} - 1.
\]  

(4)

When \( \sigma \) discontinues at the interface, we divide the phase transition into 2 subdomains \( \Omega_A \) and \( \Omega_B \) (Fig. 1) with their respective electrical conductivities \( \sigma_A \) and \( \sigma_B \). At the phase transition we have potential and current density continuity (5) and (6):

\[
\phi_A(x_T) = \phi_B(x_T),
\]  

(5)

\[
J_A(x_T) \cdot \vec{n}_A + J_B(x_T) \cdot \vec{n}_B = 0.
\]  

(6)

The current density fulfills the charge conservation when:

\[
\left[ J_{\text{ext}} + \sigma_A (u \times B) \right] \cdot \vec{n}_A + \left[ J_{\text{ext}} + \sigma_B (u \times B) \right] \cdot \vec{n}_B = 0.
\]  

(7)

This makes following following current density correction \( J_{\text{corr}} = J_{\text{ext}} - J_{\text{ext}} \) necessary at the domain transition:
\[(J_{\text{ext}} - J_{\text{off}}) \cdot \vec{n}_A \mid r = (\sigma_B - \sigma_A)(u \times B) \cdot \vec{n}_A \mid r. \]  

(8)

In ANSYS FLUENT solver, the domain is discretized into a finite set of control volumes [11]. However, FLUENT is not designed to impose \( J_{\text{corr}} \) through the interface of the two cells and therefore, an equivalent current

\[ I_{\text{corr}} = J_{\text{corr}} \cdot A_r. \]  

(9)

is injected into the adjacent cell while considering the various electrical conductivities. The factor \( k \) depends on the electrical conductivity in cell A and B. Comparing the analytical solution with the numerical FLUENT algorithm, we obtain:

\[ k = \frac{\sigma_A}{(\sigma_A + \sigma_B)}. \]  

(10)

The normal component of \( J \) is zero at the outer boundary region of the electrically conducting fluid:

\[ J \cdot \vec{n} = \sigma \left[ -\nabla \varphi + (u \times B) \right] \cdot \vec{n} = 0. \]  

(11)

From (11), one can obtain a boundary condition (Neumann, Flux [11]) for the electrical potential \( \varphi \):

\[ \sigma \nabla \varphi \cdot \vec{n} \mid r = \sigma \cdot (u \times B) \cdot \vec{n} \mid r. \]  

(12)

Detail verification and validation regarding the algorithms is published in [12] and it implies that the numerical analyses provide considerable results.

2. Result for single argon bubble in GaInSn without magnetic field

The FLUENT solver with the correct electric potential implementation has previously validated through comparing predicted bubble rise velocity and bubble behavior. Several simulations of argon bubble with different sizes rising in a tube of quiescent GaInSn were performed and compared with previous experimental and computational works. In the simulation, a hexaeder \( (x, y, z) = (27.6 mm, 27.6 mm, 138 mm) \) with a bubble diameter of \( d = 4.6 mm \) is used. At the initial simulation stage, an Argon bubble is imposed at the position \( (x_b, y_b, z_b) = (13.8 mm, 13.8 mm, 2.48 mm) \) [13]. We use the reference time scale \( t = t / t_{\text{ref}} \) with \( t_{\text{ref}} = \sqrt{d / g} \).
In our two-phase model, the governing equations were solved using the commercial CFD package Ansys FLUENT 17.0, which is based on the finite-volume method. No-slip boundary conditions are used at the walls. The pressure-based solver is chosen and the VOF model computes a time-dependent solution. The phase continuity is solved through the explicit time discretization and the geometric reconstruction scheme is applied to track the interface between the Argon bubble and GaInSn. The VOF method is used because it is well suited for tracking 3D interfaces with good volume conservation. The time step is set to $1e^{-4}$ or lower. The primary material phase is argon gas and the secondary material phase is GaInSn. Each phase is set with its initial volume fraction, which is patched in a part of the domain. In this work, the liquid phase is patched with the volume fraction 1. Based on the volume fraction $\alpha_s$ of each phase, the appropriate properties and variables are assigned to each control volume within the domain. $\alpha_s$ has a value from 0 to 1. The important dimensionless numbers of argon-GaInSn for $d_{mmd} = 6.4$ are $E_0 = 49.2$, $M_o = 13 \times 10^{-13}$, $R_e = 2649$. Simulation results were first examined and compared with the data of Schwarz’s simulation, Zhang’s experiment, and Zhang and Ni’s Simulation in order to bench mark our computational methods[13, 14, 15]. Fig. 3 shows that the Reynolds number results are in good agreement with other data. It can be seen that the present model reasonably captures the flow behavior of the argon phase. The bubble terminal velocity obtained by the VOF model is shown in Fig. 4. The results indicate that the predicted terminal rising velocity is in good agreement with the theoretical Mendelson’s equation [16] and other simulation and experimental data.

3. Result for single argon bubble in GaInSn with permanent magnet

In this section, a cubic permanent magnet $(l_x, l_y, l_z) = (12\,mm, 12\,mm, 12\,mm)$ is applied and the bubble $d = 7\,mm$ is set at the near, middle, and far positions. The domain size was increased to 220mm in z-direction. The center of the permanent magnet is chosen at the position $(C_x, C_y, C_z) = (-10\,mm, 13.8\,mm, 90\,mm)$. The non-dimensional parameters in MHD are the bubble Reynolds number $R_e = u d o p / u = 3360$, the Hartmann number $Ha = B_o D_i \sqrt{\sigma / u} = 35.6$, the magnetic Reynolds number $Re_m = \mu_o u_d / D_i = 0.018$, and the interaction parameter $N = \sigma B^2 / \rho u_d = Ha^2 / R_e = 0.4$. As shown in Fig. 6 the Lorentz force has the highest negative value when the bubble is at the near position. For $t < 0.4s$, the bubble accelerates due to the
buoyancy and the velocity vectors point upwards. The negative Lorentz forces break the upwards velocity streamline and suppress the upward velocity in the z direction. \( t = 0.4s \) corresponds to the center of the permanent magnet. It shows that the Lorentz force changes abruptly because of the lack of effective volume in the fluid flow. Eddy current is not produced inside the bubble (Fig. 7) and therefore the force is almost stagnant at this time. It is obvious that for \( t < 0.4s \) the current density flows counterclockwise in the upper part of the bubble, while a clockwise flow is observed in the lower part. For \( t = 0.4s \), the current density flows counterclockwise in the left side of the bubble, while a clockwise flow is observed in the right hand part. For \( t > 0.4s \), a path instability occurs and vortex structures are observed below the bubble. The bubble deformation and the pressure difference at the top and bottom of the surface lead to vortices on the side of the bubble. The eddy current flows mostly below the bubble and interacts strongly with the magnetic field. It produces a high negative Lorentz force. While rising to the top, there are changes in the local flow velocity. Now, the induced Lorentz force density acting towards the bubble center and the Lorentz force density acting outward from the bubble compensate each other and cause Lorentz force distribution. At far and middle positions, the Lorentz force decreases slowly due to the weak interaction between magnetic field and eddy current.

Fig. 5. Computational domain. PM center is set close (10mm) to the fluid wall. Bubbles are injected in different positions.

Fig. 6. Lorentz force distribution of a bubble in different positions. The permanent magnet center is set close (10mm) to the fluid wall and far (20mm) to the fluid wall. It shows that the Lorentz force increases when the permanent magnet is near to the fluid domain.

Fig. 7. The current density vectors for bubble at near position are plotted.
3. Conclusions

To satisfy the physical conservation law when the electrical conductivities change abruptly in the fluid an algorithm for multiphase MHD flows in FLUENT was designed to calculate the Lorentz force. A Volume of Fluid method is applied to accurately capture the interface between two phases. The Lorentz force calculation in two-phase liquid metal is performed and the influence of the inhomogeneous magnetic field is analyzed. This simulation shows that the bubble positions influence the Lorentz force in the conducting fluid flow. A validation of the 3-D model with a rising Argon bubble in GaInSn is in progress.

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