Engineering Analysis with Boundary Elements 96 (2018) 179–186

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

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

Numerical modeling of single bubble rising in metal liquid based on electrical field change and boundary element method

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ARTICLE INFO

Keywords:
Electrical field
Molten metal liquid
Single bubble characteristic
Boundary element method

ABSTRACT

It is a challenge to measure the bubble behaviors in molten metal liquid, which is normally nontransparent and hyperthermal. This paper developed a novel contactless and simple method for modeling the single bubble characteristics in bubble-melt flow. Based on the applied external electric field, the receiving signal was calculated using boundary element method to indicate the relationships between several bubble parameters and electrical field change. The effects of bubble position, shape and size were investigated and in comparison to the theoretical results, the numerical approach was validated. The simulation results show that a single bubble has a significant impact on the electric field distribution and experimental platform will be setup in future to work cooperatively.

1. Introduction

Bubbly flows have found wide applications in metallurgical and other industrial processes. Bubbles are often generated by gas injection through tuyere or porous plugs in metallurgical processes [1–5]. In many cases, in order to mix and homogenize the metal, gas bubbles are injected at the bottom of a bulk liquid metal to stir the metal liquid. For steel making, argon bubbles are commonly injected in the process of continuous casting of steel [6,7].

For another example, the aluminum foams could be manufactured by directly injecting gas into the liquid and this method is low cost, easy to implement and control to realize a continuous process production. This approach is wider used among several preparation methods, e.g. casting process, powder metallurgic method. To obtain the bubble diameter homogeneity, high temperature is needed and the bubbles will be cut into shape with appreciate size [8].

If the gas injection rate is relatively low, bubbles will be generated separately in a foaming tank. Since the melt flow is always opaque and with high temperature, pollutions always occur when detecting the comprehensive bubble characteristics and mutual effect between molten metal and bubbles by invasive methods and experiments. For non-invasive detect technology, high-speed camera [9], PIV (Particle Image Velocimetry) [10], UDV (Ultrasound Doppler Velocimetry method) [11], VOF (Volume of Fluid) [12] and EMT (Electromagnetic Tomography) [13] are applied in the laboratory and the actual production process. The disadvantages are huge equipment, high cost and lack of convenience [14].

According to previous research, bubble behaviors in liquid are complicated, no matter in molten metal or other not so conductive liquid such as water. In the past several decades, numerous theoretical, experimental, and computational studies have been carried out on the dynamics of a rising bubble in metal liquids [2,3,6,7,15,16]. Experience is usually utilized to explain the experimental results that are valid in special preconditions and lacks universality. For a better control of the experiment procedure, theoretical explanations of the bubble characteristics are needed.

Numerical methods provide a feasible approach to computer the bubble behaviors and parameters in melt flow by building mathematic model based on massive calculations. However, the numerical study of a bubbly flow is also sophisticated and only a limited number of studies have published since the late 20th century. Some of the theoretical papers are devoted to the rising single bubble behaviors, especially for the air-steel system [7,15].

Sometimes, it is difficult to obtain a good agreement between numerical results and experimental results. Zhang and Ni [12] found that the terminal velocity increases when the magnetic field is moderate and decreases when the magnetic field is much stronger. The conclusion is quite different from experimental results. Considering the complicated conditions in which the experiments were carried out, numerical simulations could provide a reference for optimizing experiment process.

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https://doi.org/10.1016/j.enganabound.2018.09.001
Received 30 May 2018; Received in revised form 28 August 2018; Accepted 3 September 2018

Boundary element method, only requires elements at the boundary, and therefore could reduce the dimension of the problem by one and greatly conserves computational effort compared to FEM for example. BEM has been commonly applied in bubble dynamics simulations in mechanics context. The inherent property greatly conserves computational effort and becomes a critical issue in the simulation of three-dimensional bubble-melt liquid in the presence of more complex geometrical boundaries [17,18]. In the work of Blake and Gibson, they employed BEM for studying a vapor cavitation near a free surface and the evolution of a cavity bubble near a solid wall. The numerical results match well with the experiment, suggesting that BEM could be a feasible approach to describe the bubble dynamics in two-phase or multi-phase liquid [19,20].

In essence, BEM has been extensively used for the study of the bubble dynamics problems including so-called direct boundary element method (DBEM) [21,22] and Indirect boundary element method (IBEM) [17]. Thus far, it is fair to say that most simulations of three-dimensional bubble dynamics are primarily from the point of hydromechanics in which several hydromechanics parameters, instead of electric or magnetic parameters, are considered to build and solve the integral equations. Furthermore, no previous reports have been found that are aimed at applying BEM in studying bubble dynamics in molten metal flow based on electrical field analysis.

The goal of this work is to develop and verify a novel numerical model based on boundary element method (BEM) and applied external EM fields to describe the bubble dynamics in molten metal flow. Simulations of the rise of a single bubble in a square duct subject to a vertical electrical field were carried out. The fundamental aspects of rising single bubble inside the liquid phase were studied in terms of the bubble's position, shape and velocity over a range of bubble diameters. The results are compared with the theoretical results to verify the effectiveness of the numerical model. The experiment platform will be developed in future to work cooperatively with the numerical analysis.

2. Measurement principle

The system employs vertically aligned DC electrical field to measure the bubble dynamics in a contactless way. Assuming there are no bubbles, the electric field line will go through the conducive metal fluid just like through the metal and the flow mobility could be described in a similarly way as the sensor moves along a piece of static metal solid. In the presence of bubbles, an electrically insulating gas bubble does not experience a direct impact of the electromagnetic force, however, the electrical field distribution in the surrounding conducting fluid are strongly affected by the applied electrical field and bubble. The electric field lines bend in the presence of the gas bubble and the whole electric field distribution changes totally in the measurement region. The theoretical analysis and simulations can be categorized from the point of the conductivity differences between bubbles and molten fluids.

There are always several important dimensionless numbers that govern the dynamics of the bubble rise in field of fluid mechanics such as Reynolds number, characteristic velocity, Bond number and Morton number, etc. [17] in the hydromechanics. Instead, a crucial non-dimension function $\boldsymbol{E}_{\mathrm{b}}$ is proposed here to describe the influence of a single bubble on a steady electrical field $\boldsymbol{E}$ inside an electrically conducting fluid. More precisely, $\boldsymbol{E}_{\mathrm{b}}$ is the function of bubble behaviors such as positions, shape, size, etc. For the convenience of calculation, the equivalent current and equivalent resistance is defined, which has direct mathematic and physical relations with $\boldsymbol{E}_{\mathrm{b}}$. Simulations by Ansoft Maxwell were also conducted as shown in Fig. 1, from which we can see that theoretic analysis matches well with the simulation results.

A full-scale simulation could be carried out based on the following assumptions when developing the mathematical model:

- Gas and liquid are incompressible Newtonian fluids.
- The physical properties are constant/time-invariant.

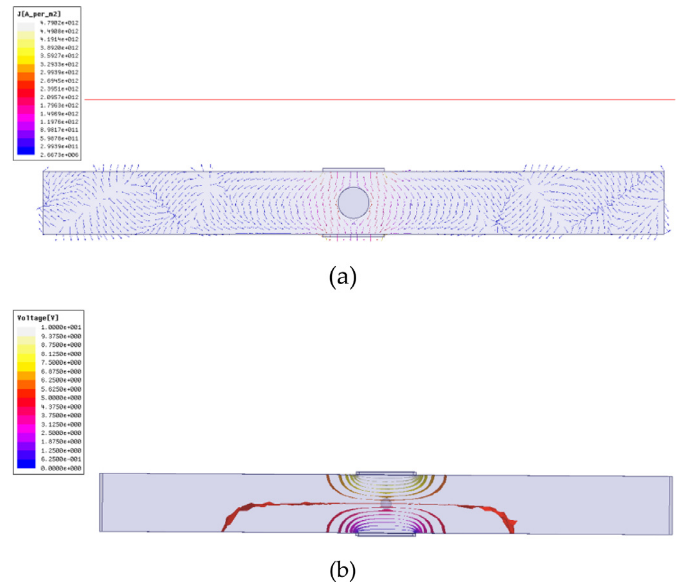

Fig. 1. Electric field distribution simulated by Ansoft Maxwell when a bubble exists: (a) electrical field line and (b) equipotential line.

- No chemical reactions take place.
- The temperature is constant in the pipe.

One major difficulty of BEM lies in building appropriate integral equations according to basic electromagnetic theory and calculating the scalar potential function, which can give rise to some singular integrals leading to uncertainty.

3. Theoretical analyses and numerical modeling

Several numerical methods such as Marker-chain method, coupled LS-VOF, Euler–Euler method have been used to study the bubble characteristics in an air-water system or in similar flow systems [3], which represent a promising complement to experimental measurements. However, there are few simulation results in a molten metal system focusing on the individual bubble behaviors [23].

The motivations are to investigate non-trivial phenomena under the influence of a single gas bubble with a transverse DC electrical field applied to the plates installed on the outside surface of the square pipe. For isotropic molten metal fluid and DC power supple, according to the Maxwell equations, the electrical parameters can be written as follows:

$$\nabla \cdot \boldsymbol{J} = 0 \tag{1}$$

$$\nabla \times \boldsymbol{E} = 0 \tag{2}$$

$$\boldsymbol{J} = \gamma \boldsymbol{E} = -(\gamma \nabla \varphi) \tag{3}$$

where $\boldsymbol{E}$ is the electrical field, φ is the scalar electrical potential in bubble surface and γ denotes the conductivity. Combined with (1)–(3) produces a Laplace equation related to φ:

$$\nabla^2 \varphi = 0 \tag{4}$$

To obtain the relationship between bubble characteristics and electrical field change, the theoretical analysis is limited to the approximate far-field flow for an ideal spherical or elliptic bubble, ignoring its contact with the pipe wall. Because the measurement region is small compared to the long pipe, bubbles are supposed to pass with a steady speed.

Together with divergence theorem, the electrical scalar potential satisfies Laplace equation that is equivalent of a boundary integral equation