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Modeling of bubble behaviors and size distribution in a slab continuous casting mold

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ABSTRACT

Population balance equations combined with Eulerian–Eulerian two-phase model are employed to predict the polydispersed bubbly flow inside the slab continuous-casting mold. The class method, realized by the MUltiple-SIze- Group (MUSIG) model, alongside with suitable bubble breakage and coalescence kernels is adopted. A two-way momentum transfer mechanism model combines the bubble induced turbulence model and various interfacial forces including drag, lift, virtual mass, wall lubrication, and turbulent dispersion are incorporated in the model. A 1/4th scaled water model of the slab continuous-casting mold was built to measure and investigate the bubble behavior and size distribution. A high speed video system was used to visualize the bubble behavior, and a digital image processing technique was used to measure the mean bubble diameter along the width of the mold. Predictions by previous mono-size model and MUSIG model are compared and validated against experimental data obtained from the water model. Effects of the water flow rate and gas flow rate on the mean bubble size were also investigated. Close agreements by MUSIG model were achieved for the gas volume fraction, liquid flow pattern, bubble breakage and coalescence, and local bubble Sauter mean diameter against observations and measurements of water model experiments.

Introduction

Continuous casting (CC) has been widely accepted as the most important production process in the steel industry. In the casting process, molten steel from the ladle flows through the tundish into a mold. Within the mold, the molten steel freezes against the water-cooled copper mold walls forming a solid shell. Details of the main complex phenomena in the continuous casting process of steel can be found in some previous works (Szekely and Yadoya, 1972; Thomas et al., 1990; Li and Tsukihashi, 2005). As demonstrated in previous studies, fluid dynamic of the molten steel plays an important role in the continuous casting process. In the molten steel at a temperature above 1500 °C, flow structures and its characteristics such as turbulence, mixing, vortexing, fluid flow separation, and generation of recirculation zones, are of decisive importance for the quality of the final steel product. The physical–chemical reactions, phase changes, mixtures, and floatation processes of non-metallic inclusions suspended in the molten steel are affected by the fluid flow. Consequently, the flow field of molten steel in a mold is one of the important factors for the control of slab qualities.

In most of the modern system, argon gas is usually employed in the continuous casting process to prevent nozzle clogging, encourage mixing and promote the floatation of non-metallic inclusion particles from the molten steel by changing the flow field (Thomas et al., 1994; Iguchi and Kashi 2000; Liu et al. 2013; Krishnapisharody and Irons, 2013). The argon gas is injected into the molten steel which enters into the continuous casting mold through the submerged entry nozzle (SEN). After the SEN, due to intense shear forces exerted by molten steel, the argon gas disintegrates into swarm of bubbles with different diameters, as shown in Fig. 1. However, previous studies in Iguchi and Kashi (2000) had found that the trajectories of bubbles are sensitive to its size. Large bubbles have the tendency to escape from the liquid steel surface through the mold flux power layer, while smaller bubbles follow the main stream of molten steel flowing deep into the mold cavity. However, these small bubbles and non-metallic inclusions adhering to the surface of these bubbles may be entrapped by solidified shell, forming defects in the final product, such as slivers, "pencil pipe" blisters, and other costly defects. In order to improve the quality of the final steel products, it is crucial to gain an in-depth understanding of the structure characteristics of molten steel–argon gas two-phase flows as well as the characteristics of bubble size distribution and its related defects in the current continuous casting process.

Extensive experimental studies on the bubble formation in the SEN (Wang et al., 1999; Bai and Thomas 2001; Lee et al., 2010) and

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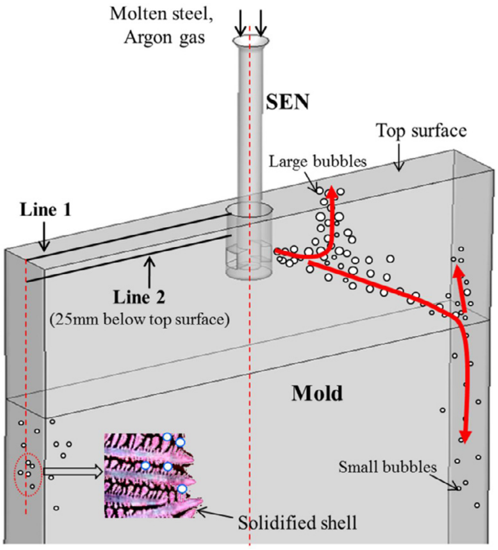

Fig. 1. Schematic of argon bubbles transport in the continuous-casting mold.

bubble size and distribution in the mold (Sánchez-Perez et al., 2003; Ramos-banderas et al., 2005;) have been performed using cold water models. Wang et al. (1999) studied the air-bubble formation phenomenon by injecting air into the flowing water through a porous refractory at the upstream of the acrylic nozzle. They found that considerably uniform-sized bubbles were formed from the porous refractory and mixed with the main water stream. Instead of porous refractory, Bai and Thomas (2001) used a horizontal hole for injecting air into a shearing downward turbulent liquid flow. Detailed experimental analyses were carried to investigate the contact angles, bubble-elongation length, mode of bubble formation, bubble size, and size distribution of bubble formation. Ramos-Banderas et al. (2005) performed a series of water model experiments to analyze the coalescence-breakage phenomena of bubbles. Based on their experimental measurements, they concluded that the population and bubble sizes of bubbles within the model were proportional to the gas loads and the casting speeds. During the past decades, due to the extremely high costs on experimental facilities and its complexity of measurement, only very few hot experimental studies have been performed to measure the bubbly flow inside the mold. Li et al. (2000) measured the velocity fields of argon gas injection in a reduced scale continuous molten tin casting system using a two-dimensional sensor. Recently, Eckert et al. (2014) analyzed the size and the motion of gas bubbles in the SEN using a small-scale mockup X-LIMMCAST where eutectic alloy GaInSn at room temperature was used as model fluid.

In terms of modeling, two main approaches (i.e. the Euler–Lagrange and Euler–Euler approach) are widely adopted to simulate the two-phase flow in the continuous casting process. Detailed descriptions of the Euler–Lagrange and Euler–Euler approaches can be found in previous studies of Deen et al. (2001). The Euler–Lagrange approach involves tracking individual bubbles trajectory in the liquid phase and it was followed by many researchers (Miki and Takeuchi, 2003; Wang and Zhang, 2011). This approach gives a direct physical interpretation of the fluid–bubble interaction but it is computationally intensive. It is therefore impractical for simulating the system with high dispersed phase volume fraction including bubbly flows studied in the present study. On the other hand, the Euler–Euler approach assumes both of liquid and gas phases to be interpenetrating continua. It is more economical and hence more popular. The Euler–Euler two-phase model with a constant bubble size has been widely used to study the two-phase flow inside various vessels such as ladle (Lou and Zhu, 2013) and mold (Thomas et al., 1994; Liu et al., 2014) in the continuous casting process, bubble column (Dhotre et al., 2008; Tabib et al., 2008) in the chemical process. Nevertheless, the size of bubbles varies significantly in these vessels due to bubble coalescence and breakage mechanism. The bubble sizes are also sensitive to the operating conditions (e.g. water and gas flow rate and pressure) as well as physical properties of both phases (e.g. density, viscosity and surface tension). Furthermore, local flow pattern and turbulence characteristics of the two-phase flow are also the crucial factors affecting the argon bubble diameter.

Owing to the importance of bubble size in two-phase flows, the predictions of argon bubble size distribution become very important to understand the underlying physics and hydrodynamic in the continuous casting mold. Recently, the application of the population balance approach towards better describing complex bubbly flow inside the mold has received an increasing attention. The MUltiple-SIze- Group (MUSIG) model provides a framework in which the population balance equation can be incorporated into the generic computational fluid dynamics solution procedures. Rather than prescribing a dispersed phase size as in the standard Eulerian treatment, the MUSIG model allows us to predict a mean bubble size based on fundamental considerations of coalescence and breakup mechanism. The evolution of the bubble size distribution is determined by the relative magnitudes of bubble coalescence and breakage rates. Since the bubble size distribution is discretized into multiple bubble class, the MUSIG model is capable to simulate polydispersed multiphase flows in which the dispersed phase features a large variation in its characteristic sizes. Several studies (Yeoh and Tu, 2006; Cheung et al., 2007; Moilanen et al., 2008; Duan et al., 2011) based on the MUSIG model have been performed to study the bubble size distribution in bubble column reactors and stirred reactors, which are extensively used in a various chemical, petroleum, mining and pharmaceutical industries. Nonetheless, only a few numerical works have been carried out to investigate the bubble size distribution in the continuous casting model. Yuan et al. (2001) attempted to simulate the bubble dynamics using MUSIG model. However, coalescence of bubbles was neglected in their model.

The objectives of this work are twofold: (i) to present a Mono-Size (MS) Euler–Euler two-phase model to further describe the effect of bubble size on the two-phase flow inside the mold; and (ii) to develop a MUSIG model to study the polydispersed bubbly flow and bubble size distribution inside the mold. A 1/4th scale water model was established to observe the breakage and coalescence of bubbles and quantify the bubble size distribution in the width of the mold.

Mathematical model formation

In order to investigate the two-phase flow behaviors inside a continuous casting mold, two Euler–Euler two-phase models are employed in the present study, named MS model and MUSIG model, respectively. In the MS model, bubbles inside the mold are considered to be identical such that breakage and coalescence between bubbles are not accounted. The effects of argon gas bubble sizes on flow-related phenomena were investigated using this model. However, the argon gas disintegrates into small bubbles of varying sizes as it issues out of the SEN. Based on the two-phase Euler–Euler approach and population balance principle, the MUSIG model for poly-dispersed bubbly flow is developed and constructed. Bubbles are divided into 10 groups and these groups are used to analyze the bubble size distribution inside the mold through coupling with appropriate coalescence and breakage models. Fig. 2 shows the discrete bubble groups employed to characterize the multi-size bubbly flow. In comparison to conventional two-phase Euler–Euler approach (MS model), it gives additional engineering parameters such as bubble size, interfacial area concentration by describing coupled mechanisms of interphase turbulence, momentum transfer and bubble coalescence and