Chemical Engineering Research and Design 139 (2018) 335–345

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Wall stresses in dual bottom purged steel making ladles

Vishnu Teja Mantripragada, Sabita Sarkar*

Department of Metallurgical and Materials Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 3 July 2018
Received in revised form 20 September 2018
Accepted 25 September 2018
Available online 3 October 2018

Keywords:
Wall stress
Gas purging
Secondary steel making
Computational fluid dynamics
Correlation

ABSTRACT

Dual gas purging is often done in a ladle to accelerate the refining operations in steel industries. The purged gas, mainly argon imparts momentum to the molten metal and establishes a turbulent recirculating flow in the melt, which generates shear stresses on the ladle walls. These stresses in-turn leads to the erosion of the refractory lining, which is undesirable. A three dimensional, transient, multi-phase turbulent model has been developed to predict the shear stress distribution along the wall in dual plug, bottom purged ladles. A parametric study has been performed to understand the dependence of wall stresses on various operating parameters like argon flow rate, metal bath depth, slag thickness as well as on the configuration of the gas injectors. A dimensionless correlation is proposed using regression analysis that predicts the maximum wall stress in the form of skin friction coefficient in terms of the above parameters.

1. Introduction

In steel industries, inert gas purging is a frequent practice during ladle refining processes. During these operations, argon gas is injected through porous plugs or through submerged lances into a ladle, containing molten steel obtained from basic oxygen furnace and electric arc furnace, and a layer of molten slag at the top. The purged argon gas imparts momentum to the molten metal and establishes a turbulent recirculating flow in the melt when it escapes through the melt. This flow in the melt improves the heat and mass transfer in the melt and helps to homogenize the molten steel composition and temperature. On that process, it also removes non-metallic inclusions to the slag layer, mixes alloying elements in the melt and facilitates slag–metal interactions.

However, due to turbulent momentum exchange, stresses are developed on the ladle walls which contributes to the mechanical erosion of the refractory lining. Further, the eroded refractory material enters the hot metal and deteriorates the quality of the steel produced. Erosion of refractory lining in steel making ladles is not only due to mechanical stresses but also because of thermal stresses and chemical reactions. The focus here is on the mechanical stresses which are caused due to interaction between the melt flow and the ladle walls.

Several experiments were performed to understand the two-phase flows in steel making ladles using water based models. It was concluded that ladle flows are Froude number dominated (Mazumdar et al., 2000). The gas–liquid flow behavior was studied in water based scaled-down models to understand and characterize the mixing and mass transfer phenomena (Sahai and Guthrie, 1981; Themelis and Goyal, 1983; Fruehan, 1985). The gas injected from the bottom disintegrates into small bubbles within a small distance from the point of entry, called penetration distance. These bubbles entrain the liquid and create a two-phase region or plume, which rises to the surface in the form of a cone (Sahai and Guthrie, 1981). There is also an exchange of momentum beyond the plume, which creates a re-circulatory flow in the melt. This re-circulatory flow enhances the mass transfer, thereby promoting gas–metal and slag–metal interactions

* Corresponding author.
E-mail addresses: mvishnutejaa@gmail.com (V.T. Mantripragada), sabita.sarkar@iitm.ac.in (S. Sarkar).
https://doi.org/10.1016/j.cherd.2018.09.036

(Themelis and Goyal, 1983). During bottom injection through a nozzle, it was visually observed that any larger bubbles formed at the orifice gradually break up into smaller sized bubbles (Fruehan, 1985). This observation was also confirmed by mass transfer rate experiments, which also indicated the presence of smaller bubbles.

Air–water plumes were characterized using still photographic techniques, and an expression for measuring the extent of gas dispersion was proposed in terms of plume cone angle (Murthy et al., 1988). Analysis was done on water based physical models to study the ladle flow behavior as well as to obtain the average plume characteristics like void fraction, shape and rise velocities (Krishnapisharody and Irons, 2010a,b,c). Based on the analysis, beyond the penetration distance, the plume shape is closely bounded to a parabolic profile than to a conical profile. All the major plume properties at a position can be predicted based on just two variables, viz., gas purging rate and metal bath depth. Beyond the penetration distance, the type of injector has a negligible effect on the bulk flow characteristics. The average recirculation velocity of the bulk liquid depends on the gas purging rate as well as on the aspect ratio of the ladle. It was ascertained that the ladle flows are gravity dominated flows, and thus Froude number similarity criteria is appropriate for physical modeling studies.

Experiments were performed in water based physical models to study the turbulence and velocity fluctuations in gas–liquid plume zone, using laser Doppler anemometry and electrical probe techniques (Sheng and Irons, 1993). It was observed that the turbulence in the bath is nearly isotropic, and hence conventional turbulence models can be used to estimate the turbulence numerically. Mathematical models describing turbulence in single, centric, bottom purged steel making ladles were critically analyzed (Mazumdar et al., 1993; Mazumdar and Guthrie, 1994). It was suggested that standard k–ϵ model with slip between the constituent phases provides a better description of actual gas injection phenomena, despite considerable differences between the predicted and measured values. The flow and mixing behavior in bottom purged industrial scale steel making ladles was studied using mathematical modeling approach (Jauhiainen et al., 2001; Ramirez-Argaez, 2007). The eccentric gas injection has uneven flow field and more mass and momentum transfer than those in centric gas injection ladles. A detailed review of modeling related to secondary steel making and gas stirred ladle systems is available in the literature (Mazumdar and Guthrie, 1995; Sichen, 2012; Mazumdar and Evans, 2010).

Physical modeling studies were done to study the effect of upper phase liquid on the flow behavior (Jonsson and Jonsson, 1996; Mazumdar et al., 1988). It was concluded that the presence of slag layer is essential for accurately modeling the flow velocities. Flow velocity, average turbulent kinetic energy of the fluid motion etc., were measured in water based physical models using Laser Doppler anemometry (Mazumdar et al., 1988). Oil is used as an upper phase liquid, to mimic the slag layer. It was observed that the intensity of liquid motion and liquid mixing in the vessel are relatively sluggish when an upper second phase liquid is present. The deformation of the upper buoyant phase as well as its entrainment in the bulk phase liquid was found to be responsible for this effect.

Several mathematical modeling studies were performed to study the flow dynamics in slag covered bottom purged steel making ladles (Liu et al., 2011; Llanos et al., 2010; Lou and Zhu, 2013). Volume of fluid (VOF) method was used to model the slag–steel, slag–argon and steel–argon interfaces (Liu et al., 2011; Llanos et al., 2010). A comparative study was performed to test the capability of VOF model and the results obtained using VOF model were compared with the experiments in a scaled down physical model. A reasonable agreement was observed between the predicted velocity and the phase distributions and the experimentally measured velocity profile and the phase distribution respectively (Llanos et al., 2010).

Several studies are available in the literature, that emphasize on the hydrodynamic interactions in ladles, however, a very few studies focus on the effect of flow on wall stresses in gas stirred ladles. The stresses at the bottom of a water filled tank were measured using electro-chemical resistivity measurement technique in a single, bottom purged air–water model, without a floating upper phase liquid (Ballal and Ghosh, 1981). The same was numerically predicted using discrete phase modeling approach (Singh et al., 2008). A study on flow behavior in single bottom purged as well as in two different configurations of dual bottom gas purged ladles was performed (Llanos et al., 2010). A comparison between maximum wall stresses, in the form of skin friction coefficient was done. It was shown that the dual plug gas purging reduces the skin friction coefficient significantly than single plug gas purging.

It is evident from the above discussion that the hydrodynamic interactions in steel making ladles play a major role in development of shear stresses on the walls and a very few literature focuses on understanding and predicting the stresses on the ladle walls. A comprehensive study on the ladle wall shear stresses and their dependence on the operating parameters as well as on the configuration of the gas inlets is not available in the literature and is indispensable for minimizing the stresses on the ladle walls, and identifying the area on the ladle walls, that is most prone to mechanical erosion. So, the current work focuses on prediction of wall stresses from hydrodynamic interactions between the liquid melt and the wall. Quantifying wall stresses experimentally, over a wide range of operating conditions is not feasible because of the high operating temperatures and costs involved. Hence, mathematical modeling approach has been adopted to study the multiphase hydrodynamic interactions in the ladle and to quantify the amount of shear stresses being generated on the ladle walls. A three dimensional, transient, coupled level-set volume of fluid (CLSVOF) model has been chosen for this purpose. The effects of different parameters, such as argon flow rate, metal bath depth, slag thickness, radial and angular positions of gas injectors on the wall stresses are studied in dual plug, bottom purged ladles. Further, non-linear regression analysis was performed and a correlation has been proposed that predicts the maximum wall stresses in terms of the above parameters in non-dimensional form.

2. Mathematical modeling

As mentioned earlier, mathematical modeling approach has been adopted to study the multiphase hydrodynamic interactions in the ladle, and to predict the shear stress on the ladle walls based on the following assumptions.

2.1. *Assumptions*

- Slag layer is a homogeneous, Newtonian liquid.
- Molten steel and slag have constant density and viscosity.