ISIJ International, Vol. 46 (2006), No. 11, pp. 1731–1733

Note

Consideration of Bubble Slippage Phenomena in Numerical Modelling of Mixing in Gas Stirred Steel Ladles

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(*Received on June 27, 2006; accepted on August 28, 2006*)

1. Introduction

Fluid mixing assumes an important role in various processing industries, in which the chemical efficiencies of typical processing operations carried out are intrinsically related to their hydrodynamic performance. In order to achieve high product qualities in steelmaking, submerged gas injection in ladles has now become a widely accepted industrial practice in almost every steelmaking shop. The gas injected from the bottom of the ladles rises through the liquid steel and induces a spontaneous mixing, promotes chemical reactions, thereby helping the system to achieve a compositional and thermal homogeneity. In addition, the gas injection also aids inclusion agglomeration and float-out.

Primarily because of such significant technological implications, serious attention has been paid over the last few decades to study the fluid flow[1–4] and mixing phenomena[5–8] in gas stirred ladle systems.

Szekely *et al.*[1] were the first to model the flows in gas-stirred ladles by solution of the turbulent Navier–Stokes equations in conjunction with the k–ω turbulent model. Hsiao *et al.*[2] investigated fluid flow phenomena in the water model and industrial argon-stirred ladles. Their work indicated the importance of buoyancy force of upward rising gas bubbles to generate a recirculatory flow field in the gas-stirred ladle. Zhu *et al.*[3] carried out water-model experiments and mathematical modeling studies of fluid flow and mixing phenomena in argon-stirred ladles with multi-tuyere arrangements. The experimental work of Nakanishi *et al.*,[5] for the first time, proposed a functional relationship ($\tau_m \geqq \varepsilon^{-0.4}$) between the mixing time (τ_m) and specific energy input rates (ε), for a wide range of metal processing operations. Since then, many empirical relationships similar to this type have been reported.[6] In all these, influence of different operating variables (*e.g.*, gas flow rates, vessel geometries, nozzle configurations) on mixing were studied and expressed by a suitable correlation.

Two most common hydrodynamic models used to characterise the gas-liquid two-phase regions, as commonly employed in these studies, have been the quasi-single phase approach[9] and a combined Lagrangian–Eulerian calculation procedure.[9] Of these, in terms of computational complexities, the quasi-single phase procedure is the simplest and has been widely used for numerical modeling purpose. In this method, the gas-liquid mixture in the upwelling plume is considered to rise like a homogeneous fluid and the gas volume fraction in the two-phase plume region is calculated by applying the principle of volume continuity. It may be mentioned here that although this method has been quite effective in capturing the relevant flow physics in a gas-stirred system, the important consideration of bubble slippage phenomena in developing the numerical models have largely been ignored. However, earlier studies[10] indicated that in gas-stirred ladle systems, slippage between rising bubbles and the surrounding fluid can dissipate a significant part of the input energy. Therefore, the calculated value of gas volume fraction corresponding to zero or no bubble slippage tend to be overestimated, thereby producing an erroneous velocity field. On the other hand, incorporation of the bubble slippage phenomena in a mathematical model can provide a more realistic description of the gas-stirred system and adequately simulate the bulk phase hydrodynamics. Such an improved numerical model can then be utilized to predict the mixing phenomena in a more accurate manner, which in turn, can have important applications and far-ranging consequences in the industry. Although some preliminary studies with similar objective[11] have been reported recently, a systematic study addressing this extremely significant issue is yet to be found in the literature.

The present work is an attempt to study the mixing process and investigate the effects of bubble slip phenomena in predicting the mixing time through a mathematical modeling procedure. This is accomplished by three-dimensional numerical simulation of fluid flow in the ladle *via* a modified version of the previously reported computational fluid dynamics (CFD) model pertinent to this process.[12] The hydrodynamic description of the gas-liquid two phase region is suitably modified to take into account the slippage between rising gas bubbles and the surrounding liquid. Particular attention is paid to model the transient mixing phenomena and critically analyze the capability of the present model to predict the mixing time in an accurate manner. This is accomplished by comparing the numerical simulation predictions with results from an ongoing experimental study at Tata Steel, India. Parametric studies are also undertaken to examine the effects of gas flow rate and bottom nozzle positioning on the mixing time. The combined model, therefore, throws a significant insight on the effect of bubble slippage considerations on the numerical prediction of mixing time in a gas stirred ladle and is expected to provide an effective quantification of flow characteristics and mixing behaviour, thereby facilitating the subsequent optimization of the overall process.

2. Mathematical Modelling

2.1. The Physical Problem

The physical system considered for the present investigation is a scale down water model of a typical 140-tonne industrial ladle. The bath is of cylindrical shape and is agitated by bottom gas injection through different nozzle arrangements. A three dimensional computational fluid dynamics (CFD) model is developed to obtain the flow field in the bath, and the composition distribution of the tracer particle in the flow domain is obtained by numerically solving the species-conservation equation.[8] The mixing time is defined as the time when the monitoring point concentration satisfies the following constraints:

$$\left|\frac{C-C_f}{C_f}\right| \le 0.05 \quad \text{..............................(1)}$$

where, C is the tracer concentration and C_f is the final uniform concentration.

It can be noted here that the details of the governing equations and the associated numerical solution procedure are available in literature[8,12] and are not mentioned here for the purpose of brevity.

2.2. Consideration of Bubble Slippage in the Hydrodynamic Model

The physical processes associated with a gas stirred system essentially consists of a gas-liquid two phase region rising upward through the liquid. This is known as plume. The interaction of the plume with its surrounding liquid metal forms an important part of all the modelling techniques of the gas injection phenomena. In the numerical procedure adopted for the present study, gas injection is treated as a pseudo single-phase flow phenomenon (quasi single phase approach), in which the gas-liquid metal plume is characterized by a region of lower density steel. The shape of the plume region is taken to be conical[9,12] with an average plume radius, r_{av}, given by[9]

$$r_{\mathrm{av}}=(1/\sqrt{3})\ \text{radius of the conical plume at surface} \quad \text{....(2)}$$

The gas voidage, α, within a rising gas-liquid plume is accounted for by introducing a buoyancy term $(=\rho_{\mathrm{L}} g\alpha)$, in the axial direction momentum balance equation[9] where, α, can be calculated by applying the principle of volume continuity as follows:

$$\alpha=\frac{Q}{\pi r_{\mathrm{av}}^{2} U_{\mathrm{p}}} \quad \text{................................(3)}$$

Sahai and Guthrie[13,14] provided a simple algebraic equation for estimation of plume rising velocity, U_{p}, according to

$$U_{\mathrm{p}}=K\frac{Q^{1/3}H^{1/4}}{R^{1/3}} \quad \text{...........................(4)}$$

where, Q is the flow rate, H is the liquid depth and R is the radius of the vessel, constant K is estimated[9] to be 4.17 in SI system of units.

The continuum density of the plume can then be obtained by

$$\rho=\alpha\rho_{\mathrm{G}}+(1-\alpha)\rho_{\mathrm{L}} \quad \text{...........................(5)}$$

where, ρ_{G} and ρ_{L} are density of gas phase and liquid phase respectively.

It can be noted here that the above expression (Eq. (4)) for estimating the average rise velocity of the bubble plume has been derived on the basis of energy balance calculations between the rate of energy supplied by rising bubbles in a gas-stirred system and the turbulence energy dissipation losses within the system. There are, however, evidences present in the literature[15,16] that bubble slippage phenomena, in addition to turbulence, can dissipate a considerable part of the input energy which has been entirely ignored on derivation of the plume rise velocity. The gas voidage value calculated on the basis of the above formulation, therefore, tends to get overestimated and results in a higher value of velocity in the two phase region and in the bulk flow domain. It is, therefore, necessary to modify the gas voidage values in the existing mathematical framework for more realistic description of the ladle hydrodynamics and associated transport phenomena during gas injection.

Based on the preceding discussion, the volume fraction estimates of the gas within gas-liquid two phase region, as given by Eq. (3), are suitably modified on the basis of the drift flux model,[17] which incorporates the effect of slip between the rising bubbles and the surrounding fluid into the existing model, according to the following expression:

$$\alpha_{\mathrm{s}}=\frac{Q-\pi r_{\mathrm{av}}^{2}\alpha_{\mathrm{s}}(1-\alpha_{\mathrm{s}})U_{\mathrm{s}}}{2\pi\displaystyle\int_{0}^{r_{\mathrm{av}}} rU_{\mathrm{p}}dr} \quad \text{...................(6)}$$

Here, α_{s} is the gas voidage value considering slippage phenomena, U_{p} is the constant plume rise velocity (as given by Eq. (4)), U_{s} is the slip velocity and is typically considered to be equivalent to the terminal rise velocity of a characteristic single bubble and can be calculated from the knowledge of average bubble size in the system[14,18] *viz.*,

$$U_{\mathrm{s}}=1.08\left(\frac{gd_{\mathrm{B}}}{2}\right)^{1/2} \quad \text{...........................(7)}$$

Here, d_{B} represent diameter of the gas bubbles forming at the nozzle tip and is given by the following correlation reported in the literature,[19]

$$d_{\mathrm{B}}=0.35\left(\frac{Q^{2}}{g}\right)^{0.2} \quad \text{...........................(8)}$$

In the present study, the definition of the plume region is based on the experimental studies of vertically injected gas bubbles into water, as performed by several researchers in the past,[20] and has been established as an effective way of treating pseudo-single phase problems of identical nature.[14]

3. Experimental

The experimental work is carried out in a 0.2 scale, cylindrical shaped, water model of a typical 140-tonne steel ladle in operation in Tata Steel. The experimental setup consists of a plexiglass vessel containing tap water at room temperature, with provisions of air injection into the bath through bottom nozzles located at different radial positions at the base (at center, R/2 and 3R/4 position). The model has a bottom diameter of 0.536 m, a top diameter of 0.619 m, and a liquid height of 0.620 m. Thus, for single nozzle blowing, local conductivity of water is measured after the addition of tracer (1 N KCl solution) over the plume surface. The electrical conductivity probe is placed at 200 mm above the bottom and at $r/4$ location from the side wall in the ladle. The output signal of electrical conductivity meter is recorded by a personal computer. Mixing time is defined as the time beyond which the changes of conductivity are less than 5% of the steady state. For each case, five to six measurements are performed, and the mean value is taken as mixing time.

4. Results and Discussions

Before proceeding to the analysis of mixing time in the gas stirred vessel, the validity of the present flow model is first tested for three dimensional situations by comparing the model predictions with experimental results corresponding to off-centric gas injection system described in Mietz and Oeters.[21] The cylindrical vessel considered for the study[21] was 0.63 m in diameter and 0.58 m in height, with bottom gas injected at a position of 2/3 R from the center of the vessel at a flow rate of $5.0\times10^{-4}\,\mathrm{N\cdot m^{3}/s}$. **Figure 1** shows a comparison between the predicted radial (r) variation of the axial (z) velocity component and the corresponding experimental measurements,[21] at mid axial plane (at $z/H=0.5$). Predictions are made with the present model considering 'bubble slippage' (subsequently referred to as 'bubble slip' model) and also without slip (subsequently referred to as 'no slip' model) phenomena. It can be seen that the velocity profiles predicted by the 'no slip' model overestimates the experimental observations, while results from 'bubble slip' model matches well with the experimental data, thereby establishing the authenticity of the present formulation.

Figures 2 through **4** show the variation of mixing times with gas flow rates for various combinations of bottom nozzle configuration. The mixing time is calculated by using both 'bubble slip' model and 'no slip' model and compared with the experimental results. The following observations can be made:

- In general, mixing time decreases with increasing gas flow rate. This is due to the fact that the input energy provided by the injected gas increases with an increase in gas flow rate. This would increase the turbulence in the flow as well as bulk velocity, which in turn, reduces the mixing time.
- The 'no slip' flow model predicts a faster mixing, *i.e.*, the predicted values of mixing time from 'no slip' model is less than that obtained from a 'bubble slip' model. This is because of the fact that the calculated flow field corresponding to 'no slip' condition is associated with an increased rate of solutal transport, due to higher velocities prevailing in the vessel. In general, the numerical predictions from 'bubble slip' model matches well with the experimental observations.
- Mixing time decreases for the off-centric gas injection case, as compared to the axisymmetric gas injection system (compare Figs. 2–4), with a minimum value predicted for mid-radius gas injection (Fig. 3). This is because, in the case of off-centric blowing, the angular momentum of fluid motion increases to a great extent, as compared to the center blowing. This ultimately results in an enhanced solute transport, yielding faster mixing in the vessel. The numerical predictions are in close agreement with the corresponding experiments.
- The close agreement between experimental observations and the numerically predicted results from the 'bubble slip' model shows that the present mathematical model embodying the physical phenomena of bubble slippage is capable of describing the flow characteristics and mixing phenomena in a single-nozzle, gas stirred industrial ladle system.

5. Conclusions

A combined physical and numerical modelling exercise has been carried out to investigate mixing phenomena in a single nozzle stirred steel ladle. This is accomplished by three-dimensional numerical simulation of fluid flow in the ladle along with the determination of the mixing time. Particular attention has been paid to incorporate the effect of slippage between rising gas bubbles and surrounding fluid in the numerical model, to capture the relevant flow physics in a more effective manner. The flow model has been tested with experimental data reported in literature. Capability of the present model to predict the mixing time accurately has been critically analysed by comparing the numerical simulation predictions with the results from an ongoing experimental study at Tata Steel. The influence of various parameters on the mixing time in a gas stirred ladle system has been critically assessed. The study suggests that the relatively simple 'quasi-single phase' model based on the consideration of bubble slippage phenomena can be effectively applied to predict the flow characteristics and mixing time in an industrial ladle refining process.

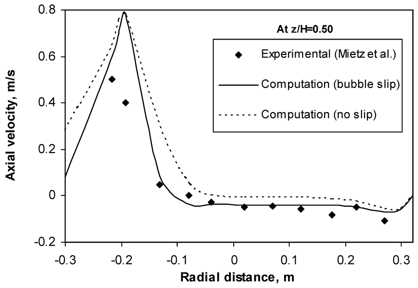

Fig. 1. Comparison of numerically predicted radial variation of the axial velocity component at $z/H=0.5$ for an off-centric gas injection system, with the corresponding experimental observations reported in literature.$^{21)}$

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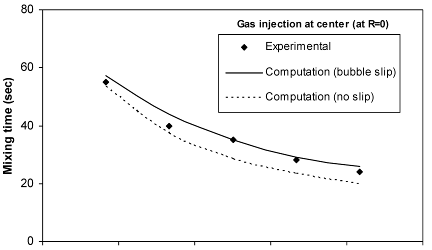

Fig. 2. Variation of mixing time with gas flow rate for bottom nozzle placed at center (*i.e.*, at $r=0$) of the ladle. Comparison of numerical predictions with corresponding experimental results.

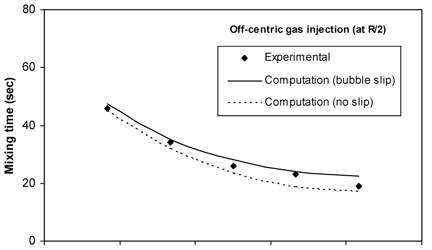

Fig. 3. Variation of mixing time with gas flow rate for bottom nozzle placed at half radius (*i.e.*, at $r=R/2$) of the ladle base. Comparison of numerical predictions with corresponding experimental results.

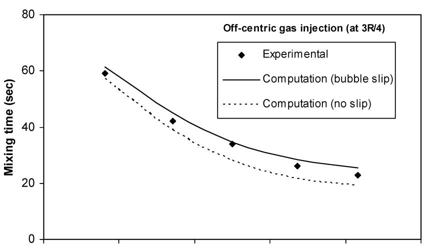

Fig. 4. Variation of mixing time with gas flow rate for bottom nozzle placed at three-fourth radius (*i.e.*, at $r=3R/4$) of the ladle base. Comparison of numerical predictions with corresponding experimental results.