Mathematical Modeling and Validation of Wall Shear Stress in Gas Stirred Vessels

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1. Introduction

Steel processing units designed to work at elevated temperatures are invariably lined with different grades of expensive refractory material. During refining and processing of liquid steel, lining material progressively erodes due to chemical attack by slag, mechanical wear due to fluid flow or softening and spalling of the lining due to high temperature as well as thermal shock. Naturally therefore, beyond certain number of heats, relining of steelmaking vessels becomes essential. This is a routine and important operation in steel melt shop and profoundly influences the economics of steelmaking since relining of vessels (e.g., furnaces, ladles, torpedoes, tundishes etc.) is both time and cost intensive. Refractory performance is therefore an issue of concern to the steelmakers.

Apart from chemical and thermal phenomena, hydrodynamics play important role and influence refractory wear. For example, high velocity regions prevalent in the vicinity of rising argon plumes lead to preferential localized wear of refractory lining in refining ladles. This is so as intense flow coupled with high degree of turbulence enhances mass transfer of various reactants and products to/from the refractory surface and thereby aid chemical attack. Similarly, strong turbulent flows can also cause higher penetration of the chemically active iron oxide, causing deterioration of refractory lining. Any reasonable velocity gradient produces requisite wall shear stresses and helps dislodge weakened refractory grains causing localized erosion of the lining material. In such context, it is important to investigate the role of fluid dynamics and the resultant distribution of wall shear stresses in steel processing units.

As high operating temperatures, relatively large size of steelmaking reactors and visual opacity of molten steel pose serious limitations to direct experimental observations, a three dimensional, two-phase, turbulent flow model has been developed to predict wall shear stress distribution in gas stirred vessels. Furthermore, to demonstrate the predictive capability of the model and study quantitatively the impact of gas injection rates on wall shear stress distributions, results thus obtained have been assessed against previously reported experimental observation of Ballal and Ghosh.11 In the subsequent sections, mathematical modeling, computational results together with their comparisons with previously reported experimental data are presented.

2. Mathematical Modeling

Mathematical modeling of fluid flow phenomena and the associated wall shear stress distributions have been carried out for an aqueous model of a bottom blown, gas stirred reactor that is essentially identical to the one employed by Ballal and Ghosh.11 This allows us to evaluate computational results against measurements and hence demonstrate the general adequacy of the modeling procedure with reference to the prediction of hydrodynamics in general and wall shear stress in particular. Physical dimensions of the model and the material properties of the medium used in the present study are summarized in Table 1. Despite a centric gas injection,1) a three dimensional turbulent flow model was applied. This is to realistically model bubble motion and predict fluid flow phenomena in their system as accurately as possible.

2.1. The Mathematical Model

Turbulent flow phenomena in the gas stirred system1) were predicted adapting the discrete phase model embodied in the commercial CFD software FLUENT6.2) In this the liquid-phase equations are solved in a fixed or Eulerian frame of reference, similar to a single phase calculation while the gas phase equations (i.e., equation of bubble motion) are solved in a Lagrangian frame of reference. Gas velocity and void fraction distributions are obtained by tracking a statistically a large number of bubbles and averaging the results subsequently. In the discrete phase model, drag coefficient and bubble diameter constitute two important input parameters which are specified a priori for computation of momentum exchange terms. These were accomplished on the basis of available information in the literature.

To represent the experimental flow system1) adequately, the following assumptions have been applied: viz.,
- fluid flow phenomena were considered to be steady, three dimensional, turbulent and isothermal.
- The experimental system was represented as a two-phase, gas–liquid system and therefore, an upper buoyant phase was not considered.
- The free surface was assumed to be flat and mobile through which the gas phase was allowed to escape from the system.
- Discrete mono size bubbles were assumed to form at the nozzle/orifice. Their size was assumed to be known from the following empirical relationship.13

\[
\frac{d_d}{d_{max}} = 0.35 \left( \frac{Q^2}{g} \right)^{0.2}
\]

- Since ferro-static head in aqueous systems is often not appreciable, the size of a gas bubble was considered to remain constant during its rise through the liquid.
- Bubble–bubble interactions were ignored. Standard drag laws for spherical geometry, proposed by Morsi and Alexander14 were applied.
- Turbulence generated within the two-phase region as well as the lateral lift forces were ignored since the objective was to investigate a near wall phenomenon rather than those within the two-phase, gas–liquid region. Finally,
- It was assumed that bubbles have no direct impact on the generation or dissipation of turbulence in the continuous phase.

Table 1. Dimensions and operating conditions1) together with thermo physical properties used in the present numerical simulation.

| Parameters                  | Numerical values                  |
|-----------------------------|-----------------------------------|
| Diameter of water bath, m   | 0.48m                             |
| Height of water bath, m      | 0.40m                             |
| Nozzle location              | z=0 and y=0                       |
| Nozzle diameter, m           | 6.5 x 10^-3                       |
| Gas flow rate, m/s           | 0.86 x 10^-7 to 3.33 x 10^-7      |
| Density of water, kg/m³      | 1000                              |
| Viscosity of water, kg/m²/s  | 0.001                             |
| Density of air, kg/m³        | 1.17                              |
The following boundary conditions were considered:
(a) Liquid phase equations
• At the side and bottom walls, normal velocity components vanish and no-slip boundary conditions were employed.
• At the free surface, tangential stress was zero while normal stress equaled applied pressure.
(b) Gas phase equations:
• At the gas injection nozzle/orifice, a known vertical velocity was applied; at the free surface, an escape condition and at the walls, reflection/rebound conditions were considered.
(c) Liquid phase turbulence
• At the solid walls, turbulence kinetic energy, $k$ and its dissipation rate, $\varepsilon$ were set to zero. Similarly, at the free surface their gradients were made zero.

Furthermore, in the immediate vicinity of the solid walls, flow and turbulence parameters were modeled invoking standard wall function procedure available in FLUENT®. Numerical details are summarized in Table 2 while a block diagram of the discrete phase computational procedure is shown in Fig. 1.

3. Results and Discussion

Wall shear stress is a function of the near wall velocity gradient and therefore, sensitive to the distribution of grid nodes in the immediate vicinity of the solid walls. Although finer grid size near the walls increases the accuracy of the prediction, discrete phase model requires that the grid size in the bulk of liquid is of the order of the mean bubble size in the system. In order to overcome this conflicting requirement, adaptive meshing technique was used where the grids near the wall were made fine while the rest of the domain consisted of relatively coarser grid.

Figure 2 shows the grid distribution in the flow domain in which grids near the walls have been made of finer resolution to capture velocity gradients as accurately as possible. It is to be noted here that three dimensional turbulent flow computations with extremely fine grid are time intensive. Therefore, adaptive meshing was deliberately done in the immediate vicinity of solid walls along which experimental wall shear stresses were reported. All the subsequent results presented in this work are drawn on the basis of a relatively fine grids in the bulk together with extremely fine grid network in the near wall regions. These, as illustrated in Fig. 3, were found to lead to predictions that were essentially independent of nodal configurations.

Experimental flow patterns deduced on the basis of visual observations and photographs of streak lines are reproduced from Ref. 1) and shown in Fig. 4 for both for high and low gas flow rates. There as seen, the stream traces are torus shaped with the liquid going up in the central region and coming down near the walls. Furthermore, velocities near the free surface and top part of the side walls were noted to be quite high. Some secondary recirculation at the corner of the ladle where the side wall meets the bottom of the ladle was also noted. Secondary recirculation was found to be prominent especially at higher flow rates.

Equivalent results derived from the discrete phase models are shown in Fig. 5. There, similar to the results presented in Fig. 4, stream traces are seen to be torus shaped.
with the liquid rising up in the central region and coming down along the walls. However, the model failed to capture the secondary recirculation near the junction of the vertical and horizontal walls, which are seen to be present in Fig. 5. A faint secondary recirculation nevertheless was observed computationally at relatively low gas flow rates. As Ballal and Ghosh did not provide quantitative flow fields, extensive comparison between model predictions and their experimental observations could not be attempted. None the less, Figs. 4 and 5 confirm that the general nature of flow pattern in the system as predicted are very similar to those observed experimentally.

To explore this further and to demonstrate the adequacy of the present approach, a detailed numerical simulation of an axi-symmetrical ladle gas injection configuration has been carried out. In Fig. 6, a comparison between predicted and experimental axial velocity profile at the mid bath depth level in the ladle is shown. There, it is at once evident that actual variation of axial flow is captured remarkably well by the present model. It is instructive to note here that despite ignoring lateral drift and turbulence production by bubbles in the present study, a solution extremely close to the experimentally observed flow have resulted essentially due to the deployment of a fine grid network (~20 mm) in the flow domain. Figure 6 in conjunction with Figs. 4 and 5 indicate that discrete phase modeling is reasonable to predict flow phenomena in gas agitated systems across a sufficiently larger range of specific flow rates (i.e., $6 \times 10^{-7} \text{m}^3/\text{s}$/kg$^3$ to $5 \times 10^{-5} \text{m}^3/\text{s}$/kg$^3$).

Following such, flow fields in the experimental system of Ballal and Ghosh were predicted as a function of gas flow rates and there form, shear stress at few specific locations along the base of the vessel was computed via the report panel available in FLUENT®. The shear stress values thus predicted are compared in Fig. 7 with the reported experimental values for two different flow rates. Very reasonable agreement between the two is readily evident. These figures indicate that wall shear stress distribution along the vessel’s base is fairly uniform at such gas flows and the present model is able to capture experimental trends reasonably accurately.

As a final point, shear stress measurements reported by Ballal and Ghosh were estimated on the basis of electro resistivity measurements assuming an intensity of turbulence equal to 0.4. Reasonable correspondence between measurements and predictions illustrated in Fig. 7 lends confirmation to this. It is generally acknowledged that bulk average intensity of turbulence in gas stirred systems, albeit at low specific flows, ranges between 0.3–0.5. In most of the two phase computational studies concerned with steel processing, discrete phase modeling has been applied to relatively low specific gas flow regimes, typical of ladle metallurgy operations. The flow rates considered in this study however are much larger and typical of bottom blown steelmaking reactors. The present study provides indication that discrete phase modeling concepts can be extended to such flow rate regimes. At substantially higher flow rates than those considered in Fig. 7, agreement between prediction and measurements expectedly deteriorates, as jetting ensues affecting flow fields in the vicinity of the gas injection nozzle remarkably. This is evident in Fig. 8. Further PIV based experimental work coupled with numerical simulation is currently being undertaken to shed more light on such issues.

4. Conclusion

The present study has indicated that provided an appropriate grid network is employed to delineate flows in the immediate vicinity of a solid wall, discrete phase modeling is adequate to predict wall shear stress distribution in gas agitated vessels across a relatively wide range of gas flow rates. It is demonstrated that predicted flow parameters and wall shear stress distribution correspond reasonably well with those measured experimentally.

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