Transient Flows in Gas Stirred Vessels during Initial and Post Gas Injection Periods

D. MAZUMDAR, C. SEYBERT,1) D. STEINGART1) and J. W. EVANS1)

Department of Materials and Metallurgical Engineering, Indian Institute of Technology, Kanpur, 208016.
1) Department of Materials Science & Engineering, University of California, Berkeley, 94720.

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1. Introduction

Considerable efforts have been made in the past to investigate fluid flow phenomena in ladles.3) In these, attention was primarily focussed to the steady state flow conditions. Recently, however, some studies2,3) were reported wherein transient flows during the initial period of gas bubbling were investigated experimentally in aqueous models of gas stirred ladle systems. In an earlier work, Iguchi et al.2) measured the flow establishment times (i.e., the duration over which flow is transient in the system) in an axisymmetric water model ladle (L = 300 mm and D = 200 mm) for various gas flow rates by monitoring velocity at two different locations in the bath through Laser Doppler Velocimetry. Their experimental results indicated that flow establishment times are typically small, of the order of 60 s and varies as (gas flow rate)0.5. In a subsequent work, Mazumdar and workers3) investigated mixing times in ladles under transient as well as steady flow regimes and developed a procedure for the inference of flow establishment time from such measurements. Their work too has appeared to indicate that the duration for which transient flow, following the starting of gas injection, exists in ladles, is small.

Transient flow phenomena are likely to exert considerable influence on the efficiency of refining process and as such, are important particularly for the emerging high speed refining processes. It is therefore naturally important to study the associated phenomena both theoretically and experimentally. Similarly, so far, practically no attention has been given to the decaying fluid motion in ladles during the post gas injection period. This is important as residual fluid motions are likely to be the source for subsequent thermal and particulate stratification in the melt. Consequently, the purpose of the present study has been to carry out a physical and mathematical model investigation on transient flows in ladles encompassing both the initial as well as the post gas injection periods. To this end, flow fields in a water model ladle were mapped as a function of time with a Particle Image Velocimetry (PIV) system and modelled concurrently with the commercial CFD software FLUENT as well as a two-phase, turbulent flow procedure developed in house.4) These are described in the subsequent sections of the present communication.

2. Present Work

2.1. Experimental

Transient flow fields during gas injection as well as durationing the post injection period were measured in a 1/10th scale water model (height=0.30 m and diameter=0.30 m) of a 185 tonne ladle, which was filled with water up to a depth of 0.21 m. In the beginning of each flow measurement experiment, the vessel was filled with water up to the required mark and sufficient time was allowed until the residual motion from the filling operation decayed completely. Following this, air was introduced into the vessel through a centrally fitted nozzle located at the base of the vessel. Simultaneously, the recording of flow was carried out via the PIV system. At a predetermined time, the gas was turned off while continuing the flow measurements until the fluid in the vessel came to a near halt. In this way, the evolution of the flow in the system from the point gas was injected, as well as the subsequent decaying motion after the gas injection was discontinued, was mapped.

The measurement technique used in the present investigation (cross-correlation PIV) determines the velocities in one illuminated plane (in the present case the central vertical plane of the vessel) of the flow by analyzing the frame to frame movement of tracer particles in video recordings. Three 1.5 kW halogen lamps contained in an air cooled aluminum box which had a narrow slit at its bottom, were used to produce an illuminated sheet spanning the central vertical plane of the cylindrical vessel. The sheet was approximately 7 mm thick. The tracer particles used have nearly neutral density, so that their rising/settling velocity in the fluid is negligible and they are carried along by the flow. In the present study, latex particles (Pliolite VTAC-L) in the size range 150–200 μm were used.

Recording of the flow was carried out through a digital camera (Pulnix TM 9700) having the usual 33.3 ms framing speed. The recording was continued from the initial stages of the injection through the steady state period up to a point when the bath had practically become stagnant (velocity had fallen to about 5 mm/s). The photographic images were transferred to the computer via an image acquisition board and were subsequently analyzed using specialized software (VidPiv 4.01, Optical Flow Systems, Edinburgh, United Kingdom). More details of the PIV system applied in the present study have already been described elsewhere and consequently are not re-iterated here.5) From the PIV measurements, instantaneous volume averaged speed of bath recirculation was calculated from the measured PIV data and this formed the basis for subsequent determination of time to attain practical steady state as well as the time taken for near complete decay of motion during the post gas injection period. This instantaneous average speed of bath recirculation defined as,

\[ U_i = \int_0^L \int_0^R \sqrt{u_i^2 + v_i^2} \frac{2\pi r dr dz}{} \int_0^L \int_0^R 2\pi r dr dz \]

was estimated through volumetric averaging of the resultant velocity (based on the instantaneous axial (ui) and radial (vi) components of motion). The velocity measurements were carried out for a set of three different flow rates and, for each flow rate, measurements were repeated thrice so as to arrive at a representative average value.

The gradual translation of the bath from an initial state of rest with the progress of time during gas injection operation is shown in Fig. 1 in which, the measured instantaneous average speed of bath recirculation is plotted as a function of time for the three gas flow rates investigated. On the basis of the measured velocity data presented in Fig. 1, the fol-
following observations can be made:

- The average speed in the aqueous phase increases rapidly with time. The higher the gas flow, higher is the rate (e.g., see the slope of the $U_i$ vs. $t$ curves in Fig. 1) at which steady state is approached. Since mean speed of bath recirculation at steady state is relatively more for higher gas flow (this varies as $(\text{flow rate})^{0.33}$), therefore a higher rate does not necessarily imply a shorter flow establishment time. In fact, it appears from Fig. 1 (see also later) that the flow establishment time is somewhat shorter for the smallest flow rate.

- As steady state is approached, the average speed fluctuates with time and the intensity of fluctuation is significantly more pronounced for the higher gas flow rates. Both small and large amplitude fluctuations, of short and relatively long periods respectively persist during the entire measurement periods. Similar observations were also reported earlier by Iguchi and coworkers. It is however important to note here that the intensity of velocity fluctuations relative to the magnitude of the average speed are not as appreciable as was experimentally observed for a point velocity measurement.

- Accurate estimation of flow establishment times from the instant at which steady state is approached can be made from the instant at which $U_i$ vs. $t$ curve first tend to merge with this long range average value. This is shown in Fig. 1. Flow establishment times thus deduced are found to lie in the range of about 12.5 to 17.5 s.

Small amplitude velocity fluctuations are known to be caused by small scale turbulent eddies. On the other hand, large amplitude fluctuations of relatively long periods were attributed to the wandering of the bubble plume (i.e., the zig-zag motion of the rising plume). The origin of such large amplitude fluctuations (viz, Fig. 1) can be traced by focussing attention to the flow within the vessel during the post gas injection period. Thus, the history of flow decay in the vessel during the post gas injection period is shown in Fig. 2 in which, instantaneous average speed of liquid recirculation is plotted as a function of time. This shows that as injection of gas into the vessel is stopped, the flow initially decays rapidly up to about 15 s. However, subsequent complete decay of the flow was sluggish and as a consequence, even after 35 s from the moment gas injection was stopped, some residual motion in the bath existed. It is interesting to note from Fig. 2 that the large amplitude velocity fluctuations are entirely absent during the post gas injection periods suggesting essentially that the former must be related to phenomena associated with the injection of gas into the bath. Since the frequency of bubble release into the bath at similar flow rates are known to be much higher (10 to 50 Hz), one can consequently anticipate that such fluctuations are the result of a combined manifestation of many phenomena such as:

- small and large scale wandering of the bubble plume in the system owing to the radial fluctuations of the rising bubble trajectories.

- pulsation of the interface separating the upper buoyant phase from the bulk liquid owing to the discontinuous escape of the bubble through the spout region and

- periodic re-entrainment and escape of air phase into and from the bulk of the aqueous phase.

Apart from these, Fig. 2 also indicates that small scale velocity fluctuations exist for some time following termination of gas flow and gradually die down, once the flow in the bulk of aqueous phase turned laminar. The final stage of flow decay as one would normally expect, is primarily controlled by the viscous forces and therefore, the three set of data ultimately merge together, as has been reflected in Fig. 2.

### 2.2. Numerical Prediction

In the present study, two different mathematical models were applied and these included (i) a marginally modified version of the previously reported axisymmetric, two phase, turbulent flow calculation procedure and (ii) the commercial, CFD software FLUENT. Transient flow fields were computed from the moment gas was injected into the bath encompassing the initial, the intervening steady state and the final post gas injections periods. As the two-phase, turbulent flow model has been described earlier consequently, salient features of multiphase flow simulation via FLUENT only is presented.

The Volume of Fluid technique together the geo-reconstruct scheme (for re-construction of the gas–liquid interface) embodied in FLUENT were applied to model the gas injection induced motion in the bath. In this, a single velocity, which is shared by each individual phase, is computed. Consequently, only one set of continuity and momentum conservation equations were solved. The mixture flow model equations and the volume fraction conservation are implicitly, mutually coupled. The volume fraction of the secondary phase (in this case the gas) is computed from the governing equation describing conservation of the volume fraction and is it is applied to deduce the average density and viscosity of the mixture in a given control volume as-
summing a flow continuum. The volume fraction of the primary phase is deduced by subtracting the secondary phase volume fractions from unity. The flow system was assumed to be isothermal and initially non-turbulent. To model turbulence within the system, a simplified, bulk effective viscosity model was applied. Furthermore, the turbulence model was incorporated into the calculation scheme once the instantaneous vessel Reynolds number \((DU/\rho \mu)\) reached a predetermined value \((\sim 3000)\).

Incorporating these into the CFD package FLUENT, numerical calculations was carried out for the 1/10\(^{th}\) scale water model. The numerical mesh applied contained about 34,000 quadrilateral volume elements. Such a fine mesh was required for realistic reconstruction of the moving, gas–liquid interfaces. In Fig. 3, predicted average speed of bath recirculation (deduced on the basis of the time averaged flow components) is directly compared with the corresponding experimental measurements at a gas flow rate of \(0.17 \times 10^{-4} \text{m}^3/\text{s}\) (1 l/min). There, prediction via the two phase turbulent flow model shows that the mean speed of bath recirculation steadily increases from zero and approaches its steady state value. In contrast, equivalent computational results derived from FLUENT shows some fluctuations of moderate intensity superimposed on the predicted average speed of bath recirculation. As such, perturbations on the mean speed of average recirculation are not expected as the latter is deduced from the time averaged flow components. Possible reasons for such velocity fluctuations are:

- inherent numerical oscillations associated with the solution of the volume advection equation and
- the approximations associated with the mathematical reconstruction of the gas–liquid interface.

Referring back to Fig. 3, it is seen that the steady state, average speed of bath recirculation as predicted via the two models tends to be higher than those observed. Corresponding predicted flow establishment times are of the order of 15 and 25 s respectively, of which the former value is in reasonable agreement with the experimentally measured value of \(\sim 12.5 \text{ s}\). It is to be emphasized here that significantly superior agreement between theory and experiment can be obtained by tuning model parameters such as bubble diameter, drag coefficient values for two phase flows etc. in the two phase model and by incorporating more realistic turbulence model in the FLUENT based calculation scheme.

Corresponding predicted and experimental results for the post gas injection period are shown in Fig. 4. It is interesting to note that predictions via FLUENT now shows significantly less velocity fluctuations confirming the earlier supposition that the latter phenomenon is essentially related to the procedure \((i.e., \text{VOF together with the geo-reconstruct scheme})\) applied to model the gas injection induced multi-phase flow phenomena. It is to be mentioned here that by refining the grids further, it is possible to eliminate such velocity fluctuations to a considerable extent.

As a final point, as reflected from Fig. 4, the decaying motion could not be simulated very well by either of the two modelling procedures applied. This is due to the fact that the decaying fluid motion in the vessel was found to be largely asymmetrical (despite the flow configuration being axi-symmetrical). This was due to the influence of the last stream of bubbles rising in an asymmetric path. Such observation were in direct opposition to the predicted results which indicated gradually fading, twin vortices in the main bulk of liquid. Clearly, a transient, 3-D mathematical model will be required to realistically simulate flow phenomena during the post gas injection period.

3. Conclusions

The phenomena of fluid motion in gas stirred ladle system during the initial as well as the post gas injection periods were investigated both theoretically and experimentally. From the history of the measured average speed of bath recirculation, flow establishment times were deduced and these were found to be small varying between 12.5 to about 17.5 s. Mathematical models, however predicted somewhat higher average speed and the associated flow establishment times. The decaying motion in the vessel during the post gas injection period was found to be relatively sluggish with the rate of flow decay progressively diminishing with time. The axi-symmetrical flow models applied could not realistically simulate the history of the decaying motion. This was attributed to the asymmetrical nature of the decaying fluid motion in the post gas injection period, which is far beyond the scope of any axisymmetric flow model.

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