Effect of Vacuum on Mixing Behavior in a Ladle—a Watermodel Study

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Rising inert gas bubbles in a vacuum ladle experience phenomenal expansion in the top portion of the bath due to the steep variation of absolute pressure. This makes the top layers of the melt substantially more agitated than the bottom regions. The present study is an attempt to characterize the mixing process in such a vacuum ladle by a watermodel, simulating the effect of extra stirring in the top layers of the bath. The simulation is done through a two-level blowing, in which an additional gas stream is injected into the main bubble plume at 75% of the bath height. It was found that mixing under such a simulated condition is worse than that in a bottom purged ladle, for identical total energy inputs to the bath. The study reveals that the energy imparted in the top layers of the liquid in the vacuum ladle is less effective in promoting mixing. The pattern of stirring energy input distribution along the height of the bath is an important parameter in determining the mixing behavior in a ladle, apart from the total energy input.

KEY WORDS: mixing time; vacuum ladle; mixing phenomena.

1. Introduction

Ladle metallurgical operations occupy an important position in the present-day steelmaking scenario. Many of these off-furnace treatments of the metal employ vacuum as a means of improving the quality of metal. These processes, like Vacuum Degassing, Vacuum Oxygen Decarburization (VOD) *etc.*, reduce the pressure above the melt, in order to ensure effective refining. In all these processes, an inert gas is also introduced through the bottom of the ladle, to promote stirring of the bath thereby enhancing the homogeneity of the bath. This is essential, since the applied vacuum is effective only in the top layers of the bath, and the bottom layers should be continuously brought to the top and the refined metal from the top should be diluted with the rest of the bath. This highlights the importance of mixing inside a vacuum ladle in the production of high quality refined metal.

Over the years, mixing in metallurgical reactors has been a topic of active research. An accepted method of characterizing the mixing phenomena inside a reactor is by the use of a measurable quantity called mixing time, which represents the intensity of mixing inside the fluid in the reactor. Several researchers have performed extensive experimental and theoretical investigations in agitated metallurgical baths^{1–7)} as well as in aqueous models^{8–19)} to obtain an insight into the qualitative and quantitative aspects of mixing.

It is worth noting that most of these studies pertain to reactors kept at normal atmospheric pressures. In

vacuum ladles, the variation of absolute pressure inside the molten bath is quite steep, and hence different from that of a similar vessel kept at atmospheric pressure. As a result of the large variation in pressure especially in the top portion of the bath, the purge gas bubbles experience phenomenal expansion during their rise through these top layers. This makes the upper layers of the bath more agitated than the lower layers. Due to this non-uniform distribution of mixing energy, the mixing process can be significantly different from that in a similar ladle kept at atmospheric pressure. The present study is aimed at investigating mixing in such a vacuum ladle through a watermodel simulation, accounting for the effect created by the large expansion of rising gas bubbles in the top layers of the melt.

2. Watermodel Simulation of a Vacuum Ladle

2.1. Analysis of Stirring Energy Distribution in a Vacuum Ladle

As explained earlier, the variation of absolute pressure inside a vacuum ladle is larger in the top layers than in the bottom layers. This can be illustrated by a simple example. Consider a steel ladle containing molten steel upto a height of 1000 mm. If this ladle is kept in a vacuum chamber at 20 torr, the absolute pressure doubles at a depth of 40 mm and becomes 8 times larger at a depth of 270 mm. From the depth of 270 mm to the ladle bottom, the increase is only three fold. This pressure distribution is quite different from that in a steel

Fig. 1. Comparison of cumulative energy release along the bath height in a steel ladle (20 torr), a steel ladle (1 atm) and a bottom purged waterbath (1 atm). Liquid height in all the three cases is 1 m.

ladle maintained at atmospheric pressure.

Mixing in a bath of liquid is determined by the mixing energy input into the bath. It is generally accepted that in a bottom purged liquid bath, work done by the buoyancy force during the rise of gas bubbles is the effective source of energy for mixing.^{5,9)} This buoyant energy is related to the gas volume. The cumulative rate of buoyant energy released when gas bubbles rise from the bottom of a ladle to any height h is given by

$$E_b = \dot{n}RT \ln \left(\frac{p_b}{p_b - \rho gh} \right) \quad (1)$$

where $\dot{n}$ is the molar flow rate of gas, R is the gas constant, T is the absolute temperature, p_b is the absolute pressure at the bottom of the bath, ρ is the density of the liquid and g is the acceleration due to gravity.

In Fig. 1, the cumulative rate of energy released, as percentage of total energy released inside the bath, is plotted against the dimensionless height h/H (where H is the height of the bath). This is done for three cases: a vacuum ladle kept at a top pressure of 20 torr, a transfer ladle kept at 1 atm pressure and a watermodel also at 1 atm pressure. The depth of liquid in each case is 1 m. It is evident from the figure that the nature of energy distribution is similar for the waterbath and the steel ladle kept at atmospheric pressure. In the vacuum ladle, on the other hand, the distribution is significantly different, much of the energy being released in the top layers of the bath. This difference becomes more pronounced at lower tank pressures in the vacuum ladle. In such a case, simulation with a watermodel, with the gas introduced from the bottom as above is not satisfactory. One way to simulate the energy distribution is to introduce gas at several points along the height of the waterbath. This permits independent control of energy release at different levels of the bath, thereby approximating the energy distribution in the vacuum ladle.

2.2. Method of Simulation

In the present work, an attempt is made to approximately simulate a vacuum ladle by employing a

Fig. 2. Schematic representation of two-level blowing.

two-level blow. This consists of bottom purging through a nozzle at the bottom as well as injection of a second gas stream at $3/4^{\text{th}}$ of the bath height. This is illustrated in Fig. 2. Thus the bath can be considered to be divided into two regions: the bottom region agitated by the bottom purging gas alone (upto $3/4^{\text{th}}$ bath height) and the top region agitated by the combined action of both the gas streams. In such a case, the rate of buoyant energy dissipations inside the two regions are given by

$$E_b = \dot{n}_b RT \ln \left(\frac{p_b}{p_s} \right) \quad (2)$$

$$E_t = (\dot{n}_b + \dot{n}_t) RT \ln \left(\frac{p_s}{p_t} \right) \quad (3)$$

where E_b and E_t are the rates of energy dissipated in the bottom and top regions respectively, $\dot{n}_b$ and $\dot{n}_t$ are the bottom and top flow rates in mol/s respectively, p_s is the pressure at the injection point of second blow, and p_b and p_t are the pressures at the bottom and top of the bath respectively.

It should be noted that the two-level gas injection may differ from the vacuum ladle in several ways. The downward flow at the top lance exit can change the local gas hold up and bubble numbers in this region. Moreover, the continuous change in energy release in the vacuum ladle is replaced by a sudden change at the point of top gas injection. It has been shown earlier that the major contribution to mixing is from the buoyant energy of the rising plume.^{5,9)} The contribution from the kinetic energy of the jet at the tuyere exit or of expansion of the bubbles due to temperature change have generally been neglected, as their contribution have been shown to be quite small. If the top lance is selected to have a large enough diameter, the effect of downward momentum and the distance of downward travel of the top jet can be made quite small. Considering these facts, the effects of differences mentioned above may be neglected as a first approximation and the two level blowing proposed may be regarded as a reasonable approximation to the vacuum ladle.

For any configuration of the vacuum ladle, the top and bottom flowrates in the geometrically similar waterbath can be selected using Eqs. (2) and (3) so as to

Fig. 3. Comparison of cumulative stirring energy release along the bath height in a vacuum ladle (20 torr), a water-model operating at atmospheric pressure with bottom gas injection alone and a watermodel with a two-level gas injection.

give equal cumulative energy dissipation at 75% of the bath height in both cases. Figure 3 presents the pattern of cumulative energy release inside such a simulated waterbath of a vacuum ladle at 20 torr with a metal height of 1 m. It is seen from Fig. 3 that this approach gives a better approximation of the energy dissipation profile in the vacuum ladle. In this configuration, any top flow rate Q is equivalent to a bottom flow rate of $Q/4$, in terms of providing total energy input to the bath. Since the gas expansions in the top layers in the vacuum ladle are large, the top flow rates used in simulation are also much higher than bottom flow rates.

2.3. Experimental Set-up

The simulation tank used in the present study was a cylindrical perspex vessel of 500 mm inner diameter and 650 mm height. A nozzle of 3 mm was fitted at the center of the bottom plate for bottom purging. A straight tube of large inner diameter (10 mm) was used as the lance for the second blow to keep the momentum of this jet low. The height of waterbath was kept at 250 mm. Flow rates for bottom blowing were varied in the range of 5–25 l/min and for top blowing, in the range of 10–100 l/min. Mixing was characterized by the measurement of mixing times by conductivity technique using a solution of KCl as tracer. The tracer was added to the top of the bubble plume and the probe was placed at the mid-radius position of the vessel, inserted to a depth of 100 mm inside the bath. Mixing times were identified for 99% mixing. Each reported value represents the average of at least 6 experiments. The standard deviation at low values of mixing times (~ 75 s) is about 10% and at higher values (~ 125 s) is about 7%. The experimental set up and the procedure are described in detail elsewhere.¹⁹⁾

3. Results and Discussions

In Fig. 4, mixing times for the model experiments are plotted against the respective specific power input, $\dot{\epsilon}$ (W/ton). The crosses shown in the figure correspond to bottom gas injection through the centrally placed nozzle.

Fig. 4. Variation of mixing time with power input (W/ton) for model experiments. The solid points represent simulation experiments by two-level blow and the crosses represent bottom blow through the center; the bottom and top flow rates in l/min are given in brackets.

The results of the simulation experiments with two-level blowing are shown as solid squares. The figures in the brackets indicate the bottom and the top flow rates respectively in l/min.

In conformity with the observations of others,^{2,5,9,10)} mixing times decreased exponentially as power input was increased during blowing with the bottom nozzle alone. Redistribution of the total energy due to injection at two levels, however, led to significant increase in the mixing times. For a given total energy input, higher mixing times are obtained for experiments in which larger proportions of energy are introduced at the top level.

In a vacuum ladle, due to the reduced top pressure, small amounts of bottom gas flow rates result in same total mixing energy inputs as large gas volumes in an ordinary ladle at atmospheric pressure. It is generally expected that the mixing times are scaled from one reactor to another geometrically similar one on the basis of total mixing energy input. Such an approach does not differentiate between a vacuum ladle and a ladle at atmospheric pressure, both having the same total energy input. However, the results presented above make it clear that mixing in a vacuum ladle could be much worse than that in a similar ladle kept at atmospheric pressure, for identical power inputs applied to the bath.

In Fig. 5, variation of mixing time with bottom flow rate is plotted at different top flow rates. As expected, the mixing times are found to decrease with increase in bottom purging rates. At all flow rates through the bottom, however, introduction of additional gas into the system at the top level increases the mixing time. The effect of the top gas is more marked at lower bottom flow rates. At very high top flow rates, the trend does get reversed and the mixing time decreases. These effects become clearer when the mixing times are plotted against top flow rate at different bottom flow rates (Fig. 6). At all bottom flow rates, the mixing times increase with top flow rate, upto a particular value. This suggests that the introduction of the gas at the higher level modifies the flow patterns in such a way that the overall mixing becomes worse. When the bottom flow rates are very

Fig. 5. Effect of bottom blow on mixing times in simulation experiments. The top flow rates are shown in the legend.

Fig. 6. Effect of top blow on mixing times in simulation experiments. The bottom flow rates are shown in the legend.

small, large amount of gas introduced at the top level starts controlling the mixing phenomena. Mixing times decrease at such high top flow rates. The trend of increase in the mixing times with top flow rate can be explained on the basis of flow patterns in the vessel during such a dual blowing operation.

Flow visualization experiments were attempted to ascertain the nature of flow inside the model vessel under such a two-level blowing. At low levels of gas injection as in agitated ladles, however, the flow is unstable and the flow lines change their positions periodically. It is difficult to obtain time-averaged flow profiles by flow visualization in such a flow system. After observing the flow, therefore, typical flow patterns were photographed to get a qualitative understanding of the flow behavior in the two cases, namely, bottom blowing and simulated two level blowing (Fig. 7). The photographs were obtained by employing fine aluminium particles as tracers and slit lighting. Fig. 7(a) corresponds to bottom blowing through the center with a flow rate of 10 l/min and Fig. 7(b) is obtained for a two-level blowing in which the bottom and top flow rates employed are 10 l/min and 40 l/min respectively.

Figure 7 indicates that, for bottom blow experiments,

Fig. 7. Time-lapse photographs of flow lines observed for (a) bottom purging through the center at 10 l/min and (b) two-level simulation with bottom and top flow rates 10 l/min and 40 l/min respectively. The plume and the vessel are co-axial.

the overall recirculation is better as the liquid passing through the bottom layers of the vessel is more compared to those for two-level blowing. Significant entrainment of the liquid to the top portion of the plume and diminution in the size of the main recirculatory loop is observed in the case of simulation experiments. Since the second blow is coaxial to the bubble plume and its flow rates are much higher, the upward velocity of the plume is also higher at the top. This enhances the entrainment of liquid to the top part of the plume from the regions of the bath surrounding it. Due to this entrainment, some elements of the main recirculatory loop may take a short circulation path and the liquid passing through the bottom layers of the bath may become somewhat reduced. This can lead to an increase in the extent of dead zone near the bottom corner of the vessel as can be seen in Fig. 7. This results in a slower overall mixing, since the exchange between the dead zone and the remaining volume also affects the rate of mixing, as described by Mietz and Oeters.¹³⁾

These observations are similar to the ones for a combined blowing situation in which a gas jet is directed onto the top of the bubble plume, as explained in an earlier publication.¹⁹⁾ In that study, the presence of a gas jet penetrating the bubble plume was found to

weaken the mixing, even though the top jet imparts additional energy to the bath in its top layers.

From the results of Figs. 4 and 6, it can be understood that for a configuration of the vacuum ladle in which the purge gas bubbles expand 5–8 times in the top portion, mixing times could be somewhat higher compared to a similar ladle kept at normal atmospheric pressure, under identical specific energy inputs. The observed nature of the increase in the mixing times with top flow rate indicates that mixing in the vacuum ladle worsens slightly as the vacuum level increases, though the corresponding energy input values are increasing. This suggests that the distribution of stirring energy input along the height of the bath also dictates strongly the mixing behavior in a ladle. Mixing in a vacuum ladle therefore needs to be simulated with multilevel injection of gas in a watermodel.

3.1. Application of Results to a Vacuum Ladle

The results of the watermodel study, if scaled up using a proper method, can be used to provide approximate estimates of mixing times in a vacuum ladle under various operating conditions. A criterion for scaling down the specific power input in bottom purged steel ladles to geometrically similar model vessels, based on the correlation of Asai *et al.*⁹⁾ can be obtained for equal mixing times in the prototype and the model vessel¹⁹⁾:

$$\frac{\dot{\epsilon}_p}{\dot{\epsilon}_m} = \left[\left(\frac{D_p}{D_m} \right)^{1.36} \cdot \left(\frac{H_p}{H_m} \right)^{-1} \right]^3 \dots\dots\dots (4)$$

where $\dot{\epsilon}$ is specific power input, D is bath diameter, H is bath height and the subscripts p and m stand for the prototype and the model.

Consider a vacuum ladle of 2.5 m diameter containing molten steel to a height of about 1.25 m with a top pressure of 20 torr at 1900 K. An inert gas flow rate of 50 l/min in this ladle provides a specific power input of about 50 W/ton. This can be scaled down to the model vessel (1 : 5 scale) using Eq. (4). The scaled down specific power input in the model is 9 W/ton. Now, this can be distributed inside the model in various ways. If a bottom blow alone is used to impart this power, the corresponding bottom flow rate is 10 l/min. Experimentally obtained mixing time in the model for this condition is 106 seconds. If the same power input is distributed as 5 l/min through the bottom and 20 l/min through the top to approximately simulate the energy distribution [see Eqs. (2) and (3)], the corresponding mixing time obtained is about 135 sec. This mixing time of 135 sec could be a better approximation of the mixing time in the actual ladle for the operating conditions specified above. Simi-

lar mixing time approximations can be obtained from simulation experiments conducted for other vacuum conditions.

4. Conclusions

Effect of large expansion of the inert gas in the top regions of the bath in a vacuum ladle has been simulated in a watermodel by a two-level blow and mixing has been analyzed. Mixing phenomena in such a simulated watermodel of a vacuum ladle were found to be quite different from those in a bottom purged ladle kept at atmospheric pressure. The generation of extra agitation at the top regions in the vacuum ladle due to the large gas expansion is, in general, found to weaken the mixing. This indicates that the pattern of stirring energy distribution inside a ladle also has a decisive role in determining the mixing behavior. The results of such a two-level simulation, if scaled up, could provide better estimates of mixing times in a vacuum ladle than those obtained from simple bottom purging in a scaled down model of the vacuum ladle.

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