Cold Model Study of Submerged Peripheral Gas Bubbling from a Cylindrical Dispenser

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Modeling of the emerging gas flow through the cylindrical dispenser was important and critical where magnesium vapors were generated through chemical reaction between \( \text{MgO} \) and \( \text{Al} \) at \( 1 \, 673 \, \text{K} \) inside the dispenser and forced out through its perforations along with a carrier gas (\( \text{Ar} \)) into the liquid iron bath for desulphurization of hot metal. At lower part of the dispenser and 5 mm above from bottom, six equidistant perforations each of 1 mm diameter were drilled along the axis of the dispenser. Cold model study was carried out to assess the flow rate of carrier gas, dispenser clearance and bath height on the rate of ascent of gas bubble through the bath influence and mixing time, when gas emerges from the periphery of a cylindrical dispenser immersed into a liquid bath. Water was used for representing the liquid bath. The diameter of the gas bubbles which were released through the perforations of immerged dispenser increased with increase in gas flow rate and was not significantly influenced by dispenser clearance. The minimum gas flow rate required to escape the gas bubble from dispenser decreased with clearance. The mixing time in the bath due to the agitation caused by the bubbles was found to be a function of the gas flow rate, clearance and the bath height. The rate of ascent and the mixing time could be modeled successfully with mathematical formulations. The data were used for predicting the behavior of gas bubbles in 5 ton liquid iron bath.

KEY WORDS: submerged gas bubbling; cylindrical dispenser; clearance; mixing time; cold model; desulfurization; rise velocity; carrier gas flow rate; liquid iron.

1. Introduction

The gas flows through the top lance and the bottom blowing through liquid baths have been studied extensively via physical and mathematical modeling for steelmaking process. These two types of gas blowing are not feasible when a reactive gas is generated in situ when the dispenser is immersed into the liquid bath and the reactive gas emerges from the dispenser to the bath. An example of such a metallurgical process is the in situ generation of magnesium vapor (reduction of \( \text{MgO} \) by \( \text{Al} \) at \( 1 \, 673 \, \text{K} \)) in a dispenser which is immersed in a liquid iron bath and allows the magnesium vapor to pass into the bath for desulfurization of hot metal. In this case, blowing an inert gas through the bottom of the reactor is not ideal since the gas is likely to carry away the particles of the oxide and aluminium metal placed inside the reactor to generate the magnesium vapor. Therefore, the reactor is so designed that the magnesium vapor produced in situ is swept away by an inert gas through perforations on the cylindrical surface of the reactor. An additional advantage of this design is that the passage of gas through the bath will be symmetrical and not significantly influenced by any tilt in the position of the vertically-held dispenser. Several experiments at high temperature were carried out in the laboratory to desulfurize hot metal on a 30 kg scale, through in situ generation of magnesium in a vertical reactor submerged in liquid pig iron. The process consisted of reduction of \( \text{MgO} \) inside a graphite reactor, immersed in the bath, using aluminium as the reductant. Magnesium vapor produced in the reactor was released into the bath through peripheral six equidistant perforations of the graphite reactor. Argon was used for carrying the magnesium vapor into the bath. It is necessary to understand the process better to enhance the degree of utilization of magnesium and also to lower the sulfur substantially. The efficiency of the process critically depends on the interaction between magnesium inside the gas bubble and sulfur dissolved in the bath, at the gas bubble/liquid interface. The following parameters determine the degree and rate of interaction at the interface:

(a) Specific surface area of the bubble
(b) Concentration of magnesium vapor in the bubble
(c) Density of bubble plume
(d) Bubble rise time and
(e) Time required for complete mixing of bath due to bubbling.

To understand the influence of these parameters on the nature of the bubbles formed, extensive experiments were conducted using a cold model in which water was used for
representing the metal bath and the graphite reactor which was used in the desulphurization of hot metal. The present study was carried out for assessing the influence of carrier gas flow rate, the immersion depth of dispenser and the bath height on the rate of ascent of gas bubble through the bath and on mixing time in the bath. The rate of ascent and the mixing time could be modeled successfully with mathematical formulations. The data were used for predicting the behavior of gas bubbles in 5 ton liquid iron bath.

2. Modeling of Submerged Gas Injection

In the physical modeling Morsi et al.\textsuperscript{1,3) reported the influence of flow rate and immersion depth on the properties of the gas-liquid system. It was observed that a recirculating vortex was formed at the top and displaced towards the wall of the tank. In case of swirl injection of gas, there was a significant movement of the recirculating region towards the wall, creating high velocity regions away from the wall. The bubbles created by swirl injection were smaller than those created by non-swirl injection. The axial velocity of the liquid was very little influenced by the flow rate of gas. On the other hand, the radial velocity was significantly influenced. When the lance was submerged to 2/3 of the bath height there was a high velocity vector beneath exit of the lance and became smaller when the submergence depth reduced to 1/3. The influence of gas flow rate on the mean velocity was not significant. It was found that turbulence was not isotropic in the region adjacent to the plume. Similarly, Liow developed a mathematical model\textsuperscript{2) and derived the size of gas bubble formed during submerged gas injection through a lance. He investigated that the maximum bubble diameter depended on the diameter of the lance; it took about 5 sec for the formation of bubble in the case of a 2.42 mm diameter of lance; the detachment of the bubble from the lance took about 0.06 sec. The growth of the bubble was initially controlled by the lance diameter. Irons and Guthrie\textsuperscript{4) conducted experiments on the influence of various parameters on the size of gas bubble formed at the submerged nozzle tip in liquid pig iron. The bubble volume was directly proportional to the gas flow rate and the frequency of bubble formation was independent of the gas flow rate. The volume of the gas train influenced the size of the gas bubble. The chamber volume was defined as the volume between the last large pressure drop in the train and the orifice. Pressure in the ante chamber increased to a maximum before the release of the bubble. This is known as the capacitance effect and is caused by the compressibility of the gas.

Mazumdar and Guthrie\textsuperscript{5) noted that the formation of recirculating flows, in submerged injection of gas into a liquid bath, by the rising plume helped to increase the homogeneity of the metal. The authors studied a cold model simulating the generation of flows by submerged gas injection in steelmaking ladle. The average plume velocity, \(U_p\) (ms\(^{-1}\)) was related to the flow rate of gas, \(Q\) (m\(^3\)s\(^{-1}\)), liquid depth, \(L\) (m), and the radius of the ladle, \(R\) (m).

\[
U_p = k \cdot \frac{Q^{1/3} \cdot L^{1/2}}{R^{1/3}} \quad \text{(1)}
\]

where, \(k\) is a constant. The residence time, \(T_r\) (s) of each bubble in the plume was given by

\[
T_r = \frac{L}{U_p} \quad \text{(2)}
\]

The number of discrete bubbles in an idealized, ascending plume was given by

\[
N_B = \left( \frac{Q}{V_b} \right) \left( \frac{L}{U_p} \right) \quad \text{(3)}
\]

where, \(V_b\) is the volume of the bubble (m\(^3\)). The experiments showed that the flows generated when the lance was submerged in the bath to 50% were identical to those generated when the gas entered at the base of the model ladle. The intensity of turbulence was higher in regions adjacent to the bubble plume and surface. Sheng and Irons\textsuperscript{6) used a cold model to study the behavior of gas injected into liquid baths. The studies showed that the flow inside the two-phase plume was much faster than the flow in the single phase region. The velocity decreased rapidly along the radial direction. Along the walls, the downward flow was strong. In the region close to the bottom wall, the flow was slow and a stagnant layer could exist. In the centre of the plume, bubble rose with much higher velocity compared to those away from the plume. The decrease in the upward liquid flow resulted in a rapid decrease in the velocity of the gas bubble along the radial direction. The turbulence in the plume region was not isotropic and slightly skewed to the vertical direction. This was because the shear in the vertical direction was greater than that in any other direction. The anisotropy decreased with increase in the energy input into the system.

3. Experimental Setup and Procedure

Figure 1 shows a schematic of the complete experimental set-up for the present cold model study. It consists of a water bath, graphite reactor, nitrogen gas system, tracer injection, digital watch and video camera. A glass beaker of 0.01 m\(^3\) capacity, measuring 210 mm inner diameter and 340 mm height was used as the container and installed it properly at the platform of steel furniture. Beside this, a measuring scale was vertically fixed at the platform outside and near to the cylindrical wall of glass container. A hollow graphite reactor measured 540 mm in height, and 56 mm diameter at the bottom, was used. The inner diameter of the reactor was 28 mm. It had a wall thickness of 14 mm and the flange at the top had a diameter of 120 mm as illustrated in Fig. 2. Six perforations having 1 mm diameter at an angle of 60° to each other were made on the cylindrical surface of the lower part of the reactor at a height of 5 mm form bottom. The top graphite flange of the reactor and the steel flange were exactly fitted with gas-ker from which the MS gas pipe was centrally aligned with the cylindrical reactor as clearly shown in Fig. 1. Further MS gas pipe was connected with a rotameter for measuring the flow rate of gas, along with a nitrogen gas cylinder and a digital pressure gauge. Also, a tracer injection device was vertically installed in the glass container and a timer (digital watch capability of capturing the time in the order of millisecond) installed at the platform of the steel furniture. All sensitive devices were claimed with steel stands.
Initially, water was carefully filled up to the desired height in the glass container. A controlled nitrogen gas was passed through the graphite reactor emerged into the water bath through its perforations. After achieving the steady state operation, a tracer (methylene blue) was introduced instantaneously into the water bath at the bottom through the injection device. The emergence and rise of bubbles in the bath were recorded using a high-speed video camera (model-SONY DSC-HX7V; fps-30 frames/sec) and parallelly time was recorded with a digital watch to estimate the total mixing time of the bath. The time for total mixing was taken as the time required for the entire bath to acquire the color of the tracer uniformly. Qualitatively this method was chosen due to simultaneously visualize the flow field in the water-gas system; however, the possible associated error in this process could be laid in the range of 10–20%. It was observed in experiments, especially with flow rates less than 3 lpm (liter per minute), that the flow of bubbles was irregular and intermittent. Also, the gas was released only from one or two orifices due to inadequate pressure difference between the interior of dispenser and water bath.

4. Result and Discussions

Several experiments were conducted at different flow rates, different water bath heights and various clearances of dispenser, i.e. distance between the bottom of the glass container and the lower tip of the graphite reactor. Most of the experiments were repeated 2–3 times to check the reproducibility.

4.1. Effect of Gas Flow Rate on Bubble Size

The influence of flow rate on bubble size in a 270 mm liquid bath at different clearances of dispenser was illustrated in Fig. 3. These are the high-speed photographs taken during experiments. It can be observed from the figure that the bubble sizes released from the dispenser is relatively higher at high flow rate for both the bath clearance of 26 mm and 100 mm. The bubble sizes were found in the range of 5–8 mm for the Ar flow rate range of 3–6 lpm. It may also be noted that the bubbles are elongated in shape and some of them coalesced to form large bubbles. This may be a reason for large bubble size in the case of larger bath
height with lesser bath clearance, since the time available for coalescence is greater. It was also observed during experiments that the bubble plume tended to hug the dispenser rather than spreading into the bulk liquid. The bubble size was modeled after Deo and Boom\textsuperscript{8}) and Odenthal \textit{et al.}\textsuperscript{9}) The investigators have modeled the bubble size over a wide range of gas flow rates and bubble sizes in the range of 0.7 to 40 mm diameter, and derived the following empirical equation. The model considered the bubble size as a function of surface tension, orifice diameter, density of liquid, and the volumetric flow rate.

\begin{equation}
\label{eq:4}
d_b = \left( \frac{6\sigma d_o}{\rho g} \right)^{1/2} + 0.0242 \left( \frac{V_g d_o}{V_g} \right)^{0.867} \quad \text{......... (4)}
\end{equation}

Here, $d_b$ is the bubble diameter (m), $d_o$ is the nozzle diameter (m), $\sigma$ is the surface tension (kgs$^{-2}$) and $V_g$ is the gas flow rate (m$^3$s$^{-1}$), $g$ is acceleration due to gravity (ms$^{-2}$), $\rho_l$ is the density of liquid bath (kgm$^{-3}$).

From video films of each experiment the mean bubble diameter for each orifice was measured. The released bubble just after detaching and before getting coalescence was taken into consideration to measure its diameter along horizontal direction. Total numbers of 10 such bubbles were collected from arbitrarily snapped photographs for the measurement and then averaging the data to get the mean value.

The predicted bubble diameters at different flow rates for each orifice obtained from expression (4) are compared with those of experimental results in Fig. 4. There is good agreement between the model and the present experimental observations. The model does not take into consideration the effect of bath height. Hence there is deviation from the model prediction when the bath height was changed.

Thus the measured mean bubble diameter of the water-gas system at 298 K in the present work was elaborated for industrial applications and computed from those results for
liquid iron-gas system at 1 673 K (at which Mg vapor was generated) by using gas-laws (PV/T = constant) coupled with expression (4) to account for the effect of temperature, density, surface tension, etc., to understand the in-situ desulphurization of hot metal. Further the computed results were overall compared with Iguchi et al.\textsuperscript{10} who used an electro resistivity probe in liquid iron baths at 1 873 K. The calculated values of bubble diameter were existed with those of the measured values in wide range of Iguchi’s measurements as shown in Table 1; however, the methodology of bubble generation was different. Iguchi’s measurements deviate from the predicted values of Mori et al.\textsuperscript{11} This is probably due to the range of flow rates used by Mori et al.\textsuperscript{11} i.e. 0.1 to 36 cm$^3$/s at 1 873 K, are much smaller than those used Iguchi and the present authors.

### 4.2. Effect of Flow Rate on Bubble Rise Velocity

Unlike the other systems discussed in literature, where a stream of gas is released at a single point inside a water bath, gas is released, in the present case, through perforations at the bottom of a dispenser which is held vertically inside the water bath. Most of the bubbles released in the bath tend to rise very close to the reactor wall. This increases the drag force on the bubbles considerably. Figure 5 shows the experimental average bubble rise time at different gas flow rates, bath heights and various clearances of dispenser. It is noted that for smaller bath height the rise time is less as compared to the larger one. Also, when the clearance is larger, the rise time is less. Increasing flow rate results in lower bubble rise time. It is apparent from the figure that at about 4 lpm of gas flow rate, the average rise time reaches a peak and then decreases. This could be due to a complex fluid flow behavior where large downward flow of liquid retards the rise velocity of bubbles and hence increases the bubble rise time. The rise velocity of a bubble in liquid, $V_b$ (ms\textsuperscript{-1}) is expressed by Krishna et al.\textsuperscript{12} as follows:

$$V_b = 0.71\sqrt{gd_b}$$ .................................. (5)

where, $d_b$ is the bubble diameter (m) and $g$, the acceleration due to gravity (ms$^{-2}$). The model is simplistic as it does not consider other effects such as the acceleration caused by the wake of bubbles in plume and the drag on the bubble due to the geometry of the system. The investigators\textsuperscript{12} derived an expression for the modified rise velocity taking these two factors into consideration. If $V_b$ is the estimated bubble rise velocity, in the absence of these two factors, then the modified rise velocity, $V'_b$ (ms$^{-1}$), taking into consideration the scale factor (SF) and the acceleration factor (AF) is given by

$$V'_b = V_b * SF * AF$$ .................................. (6)

Also these authors derived an empirical formula for the acceleration factor, AF, for gases passing through water. Assuming that this correlation (though derived for systems different from that discussed in this communication), is applicable to the experimental conditions employed here, the modified rise velocity was calculated. The model calculation is compared with experimental data in Fig. 6 which shows the effect of bubble size on average bubble rise velocity for a different bath height at a dispenser clearance of 26 mm. It is found that the predicted rise velocities are higher than the experimental values. This is because of the drag effects on the bubbles due to the geometry of the system, i.e. the wall drag near the plunger. There is no information available in published literature on the methods of

<table>
<thead>
<tr>
<th>Gas flow rate used in present water model (lpm)</th>
<th>Measured bubble diameter at each orifice from water model* (mm)</th>
<th>Predicted bubble size for molten iron at each orifice (using gas laws) (mm)</th>
<th>Experimental bubble size from Iguchi et al.\textsuperscript{10} mm (Bottom blowing)</th>
<th>Predicted bubble size for molten iron (mm) according to ref.\textsuperscript{11}</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8.15</td>
<td>24.15</td>
<td>22 to 39</td>
<td>13.73</td>
</tr>
<tr>
<td>5</td>
<td>6.60</td>
<td>22.92</td>
<td>–</td>
<td>13.02</td>
</tr>
<tr>
<td>4.2</td>
<td>6.10</td>
<td>21.81</td>
<td>–</td>
<td>12.39</td>
</tr>
<tr>
<td>3.1</td>
<td>5.88</td>
<td>19.78</td>
<td>16 to 26</td>
<td>11.35</td>
</tr>
</tbody>
</table>

* - bath height = 270 mm, clearance = 26 mm
estimating this drag force for this kind of a system. More investigations are required to estimate this drag force and arrive at a more realistic prediction of bubble rise velocity in systems of the kind studied here. Table 2 shows the comparison of measured bubble rise velocity in water-gas system of present work, predicted results reported by Krishna et al.\(^{12}\) and rise velocity data of Iguchi’s measurement in liquid iron-gas system. It is evident from the above Table that the measured rise velocities for water model, prediction based on expression (6) and measurements in molten iron bath\(^{10}\) are in close agreement. It could be happened due to the kinematic viscosities (\( \nu = \frac{\mu}{\rho} \)) for water at 298 K and liquid iron at 1 873 K are nearly identical\(^{5}\) and therefore the flow fields for both the systems were supposed to be practically the same.

<table>
<thead>
<tr>
<th>Gas flow rate used in present water model (lpm)</th>
<th>Measured bubble rise velocity from water model (m/s)</th>
<th>Predicted bubble rise velocity for molten pig iron (m/s) (^{12})</th>
<th>Experimental bubble rise velocity reported by Iguchi et al.(^{10}) (m/s) (Bottom blowing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.42</td>
<td>0.54</td>
<td>0.42 to 0.72</td>
</tr>
<tr>
<td>5</td>
<td>0.367</td>
<td>0.55</td>
<td>–</td>
</tr>
<tr>
<td>4.2</td>
<td>0.341</td>
<td>0.48</td>
<td>–</td>
</tr>
<tr>
<td>3.1</td>
<td>0.38</td>
<td>0.476</td>
<td>0.24 to 0.48</td>
</tr>
</tbody>
</table>

4.3. Effect of Flow Rate on Plume Diameter

Around the axis of dispenser, there is two phase region consisting of gas bubble and liquid, idealized as a truncated cone. This region is called plume. Plume diameter was taken as the diameter of the base of the plume cone, at the surface of the liquid. Plume diameter was measured in water modeling experiments from photographic images. Figure 7 depicts the effect of flow rate on plume diameter for various bath heights and clearance of dispenser. It is evident from Fig. 7(a) that smaller clearance of dispenser results in larger plume diameter because the liquid height available above the perforation (orifice) is greater. Also, the average plume diameter increases with flow rate since the bubble density is greater for large flow rates. It is also clear from Fig. 7(b) that, the plume diameter is larger for a greater bath height. It may be noted that there is a divergence for two different bath heights. This is because of increase in cone angle at larger flow rates.

4.4. Effect of Flow Rate on Mixing Time

Mixing time could be predicted as a function of gas flow rate (\( Q, \; \text{m}^3\text{s}^{-1} \)), density of liquid (\( \rho, \; \text{kgm}^{-3} \)), height of surface of liquid above orifice (\( H, \; \text{m} \)), volume of liquid (\( V_l, \; \text{m}^3 \)), absolute bath temperature (\( T_l, \; \text{K} \)) and logarithmic mean pressure (\( P_M, \; \text{Nm}^{-2} \)). The formulation for mixing time (\( \tau_{\text{mix}}, \; \text{s} \)) was obtained\(^{13}\) in terms of buoyancy energy per unit liquid volume (\( \dot{\varepsilon}_b, \; \text{kgm}^{-1}\text{s}^{-1} \)) as:

\[
\tau_{\text{mix}} = \frac{2\dot{\varepsilon}_b^n}{B} \tag{7}
\]

Further, the term \( \dot{\varepsilon}_b \) was correlated\(^{14}\) with gas flow rate at logarithmic mean pressure (\( Q_M, \; \text{m}^3\text{s}^{-1} \)), \( P_M, \; \text{Nm}^{-2} \) liquid bath head (\( P_{bl}, \; \text{Nm}^{-2} \)) and atmospheric head (\( P_{atm}, \; \text{Nm}^{-2} \)) through the expression (8) to (11) as follows:
Based on present investigations, the pre-exponential term ‘$B$’ and exponential term ‘$n$’ in expression (7) were estimated to be 93.0 and 0.69 respectively. The estimated values of mixing time at different flow rates were calculated through expression (7) to (11) and were listed in Table 3. The table also shows the effect of flow rate, clearance of dispenser and bath height on mixing time, for experimental results. Each experimental data was represented as an average of the 2–3 experimental data sets to obtain the mixing time. The mixing time decreases with increasing flow rate. The mixing time increases with increase in clearance of the dispenser. This is due to larger dead volume available when the dispenser clearance is increased. It has been observed that the dispenser clearance and the gas flow rate determined the complete mixing time and the optimum residence time. The mixing time decreased with increase in gas flow rate but vice versa at higher flow rates due to bath recirculation caused by plume dynamics since the average plume velocity decreased leading to an increase in mixing time. When the gas flow rate was increased, the penetration of the gas

\[ \dot{e}_b = \frac{\dot{Q}_M \rho g \Delta H}{V_I} \]  \hspace{1cm} (8)

\[ \dot{Q}_M = \dot{Q} \frac{P_{atm}}{P_M} \left( \frac{T_i}{298} \right) \]  \hspace{1cm} (9)

\[ P_M = \frac{P_H - P_{atm}}{\ln \left( \frac{P_H}{P_{atm}} \right)} \]  \hspace{1cm} (10)

\[ P_H = P_{atm} + \rho g H \]  \hspace{1cm} (11)

### Table 3. Effect of bath height, flow rate and clearance on mixing time and comparison between experimental and estimated values.

<table>
<thead>
<tr>
<th>Bath height (mm)</th>
<th>Flow rate (lpm)</th>
<th>Clearance (mm)</th>
<th>Experimental Mixing time (s)</th>
<th>Estimated Mixing time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>270</td>
<td>4.2</td>
<td>26</td>
<td>14.67</td>
<td>12.95</td>
</tr>
<tr>
<td>270</td>
<td>6</td>
<td>26</td>
<td>9.58</td>
<td>10.12</td>
</tr>
<tr>
<td>270</td>
<td>3.5</td>
<td>100</td>
<td>15.16</td>
<td>17.94</td>
</tr>
<tr>
<td>270</td>
<td>6</td>
<td>100</td>
<td>13.5</td>
<td>12.37</td>
</tr>
<tr>
<td>160</td>
<td>3.2</td>
<td>26</td>
<td>10.66</td>
<td>10.85</td>
</tr>
</tbody>
</table>

Fig. 8. A typical flow pattern to measure mixing time in a 270 mm liquid bath with 26 mm clearance at flow rate of 6 lpm.
stream also increased. This increased the residence time of gas in the bath. On the other hand, the liquid velocity increased at higher flow rate which decreased the residence time of the gas in the bath. When the clearance of dispenser decreased, the plume radius at the surface extended towards the wall. This led to a decrease in the energy transmitted from the plume “eye” to the bulk liquid at the surface. This reduced the velocity of the liquid at the surface. On the other hand, an increase in the plume radius due to decrease in dispenser clearance enhanced the circulation within the bath. Therefore, there was an optimum clearance of dispenser at which the mixing time was minimum for a constant bath height. At lower gas flow rate, the residence time increased with decrease in dispenser clearance. A typical flow pattern of a 270 mm liquid bath with 26 mm dispenser clearance at flow rate of 6 lpm is illustrated in Fig. 8 to measure mixing time.

### 4.5. Predicted Parameters for 5 Ton Molten Pig Iron Ladle

The efficiency of utilization of magnesium vapor (Mg) will depend upon the time required for the diffusion of Mg from the centre of the gas bubble to the bubble-liquid bath interface. It is assumed that reaction between Mg and sulfur at the bubble-liquid interface is instantaneous. The time required for Mg to diffuse to the bubble-liquid interface was estimated. Analogy of heat conduction was employed to determine the time taken for Mg to reach the bubble-liquid interface. Heisler charts for heat conduction in sphere used to determine the corresponding Fourier number at $1/Bi = 0$, where “$Bi$” is the Biot number. The dimensionless concentration, $(C_{eq} - C_0)/(C_S - C_0)$ and Fourier number, $F_n = \alpha \eta R^2$ were used in the computations. For an example, if efficiency of Mg reacting with S is only 60%, i.e. 40% Mg escapes with argon bubble to the atmosphere, the values of dimensionless concentrations become $C_{eq} = 0.4 \times C_S$ and $C_0 = 0$. It was found that the time taken for 90% of magnesium in the bubble to diffuse to the bubble-liquid interface was about 0.09 sec, for a bubble diameter of 20 mm, assuming the gas bubble to be spherical as summarized in Table 4. Hence, it can be concluded that the efficiency of desulfurization is controlled by the transfer of sulfur to the bubble-liquid interface. Therefore, mixing time in the bath is a critical parameter for achieving rapid desulfurization.

Based on the results obtained from the water model studies, the optimum operational parameters for a 5 ton ladle of iron bath were estimated. This capacity of bath size was chosen here for predicting the parameters in scaled up operation which is commonly used in foundries for ferrous castings. The height of metal bath in this ladle was assumed to be 1 200 mm, for a ladle diameter of 1 000 mm. Table 5 gives the predicted parameters. Tables 1 and 2 describe the methodology for predicting the bubble size and bubble rise velocity, respectively. Volkova et al. have studied the characteristics of plume in ladles where the bath is stirred with gas in industrial operations. They have estimated the ratio of the plume cross-sectional area (at maximum plume diameter) to ladle cross-sectional area to be 25% in these operations. The number of dispensers required and the cross-sectional area of the dispenser required were estimated based on the water model (present study) to arrive at this ratio on a 5 ton scale. The present study gives the cross-sectional area of the plume for the given dispenser dimensions. For structural stability under real operation conditions of a 5 ton bath of liquid pig iron, it is necessary to use larger diameters of dispensers. On the other hand, the size is restricted by mass and heat transfer requirements in the system. Adequate heat has to be transmitted to the interior of dispenser in order to initiate chemical reactions between Al and MgO, due to rise in temperature. A graphite reactor of 50 mm diameter was used successfully for desulphurization on a 30–50 kg bath size. Heat transfer calculations indicated that 330 mm dia. and height of 1 250 mm may set the limit for the size of the graphite reactor to be used for desulphurization on 5 ton bath size. However, this configuration would leave a considerable dead-volume in the ladle. This will restrict the desulphurization process. Hence, the number of perforations of each 1 mm dia. was increased from 6 to 12 to maintain area ratio to be 42.4%. Based on modified Froude number ($Fr$) similarity the gas flow rate was predicted in the range of 33.8–67.8 lpm for a 5 ton iron bath ladle. Modified Froude number is defined as:

$$Fr = \frac{V_g^2 \rho_g}{gH \left( \rho_L - \rho_g \right)} \quad \text{(12)}$$

### Table 4. Time required for transfer of magnesium to bubble-bath interface.

<table>
<thead>
<tr>
<th>% Mg transferred to bubble-bath interface</th>
<th>Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.088</td>
</tr>
<tr>
<td>60</td>
<td>0.059</td>
</tr>
<tr>
<td>40</td>
<td>0.047</td>
</tr>
</tbody>
</table>

### Table 5. Predictions for 5 ton molten iron bath ladle configuration based on cold model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Water model (present work)</th>
<th>Predicted for 5 ton molten iron ladle</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble size (mm)</td>
<td>5.88–8.15</td>
<td>21.7–26.3</td>
<td>Table 1</td>
</tr>
<tr>
<td>Bubble rise velocity (m/sec)</td>
<td>0.38–0.42</td>
<td>0.34–0.37</td>
<td>Table 2</td>
</tr>
<tr>
<td>Ratio of plume area to ladle cross section area (%)</td>
<td>25</td>
<td>42.4</td>
<td>Refer text</td>
</tr>
<tr>
<td>Flow rate of Argon gas (lpm)</td>
<td>3–6</td>
<td>33.8–67.6</td>
<td>Modified Fr. No = 0.05–0.2</td>
</tr>
<tr>
<td>Dimension of dispenser (diameter &amp; height)</td>
<td>50 mm × 540 mm</td>
<td>330 mm × 1 250 mm</td>
<td>Refer text</td>
</tr>
<tr>
<td>Number of perforations</td>
<td>6</td>
<td>12</td>
<td>assumed</td>
</tr>
<tr>
<td>Orifice diameter (mm)</td>
<td>1</td>
<td>1</td>
<td>assumed</td>
</tr>
</tbody>
</table>

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where, \( V_g \) is the velocity of carrier gas (ms\(^{-1}\)), \( \rho_g \) is the density of carrier gas (kgm\(^{-3}\)), \( g \) is the acceleration due to gravity (ms\(^{-2}\)), \( H \) is the liquid bath height (m), \( \rho_L \) is the density of liquid bath (kgm\(^{-3}\)). Lee et al.\(^{18}\) studied bubble rise velocities for a top lance water model for flow rates ranging from 5 to 12 lpm for a bath size of 380 mm diameter and 340 mm height. Additionally, they used CFD (Computational Fluid Dynamics) computations to predict mixing time and velocity vectors in a 300 ton molten steel ladle. The flow rates of argon were in the range 833 lpm to 3333 lpm (50–200 Nm\(^3\)/hr). When these results were compared with flow rates for 5 ton molten pig iron ladle predicted in the present work, they were found to be comparable.

5. Conclusions

Water model studies were conducted for measuring the gas bubble size, rise velocity and mixing time for nitrogen injected into the bath through orifices on the sides of a cylindrical graphite reactor immersed vertically into the bath. These properties were studied as a function of bath height, clearance and flow rate of gas. The properties were modeled using standard methods. Predictions of the model are consistent with experimental results published in literature. Based on the present studies, the optimum conditions for desulphurization through in-situ generation of magnesium in a 5 ton liquid iron bath were predicted. It is recommended that a graphite dispenser of 330 mm diameter and 1250 mm height and having 12 perforations of each 1 mm diameter may be used at this scale for in-situ desulphurization with a gas flow rate of 33–69 lpm.

REFERENCES