Transient Fluid Flow Phenomena in a Gas Stirred Liquid Bath with Top Oil Layer—Approach by Numerical Simulation and Water Model Experiments

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The flow characteristics in a gas stirred ladle with oil layer were investigated with the help of water model experiments and numerical simulation. The oil layer has a great influence on the fluid flow and mixing behavior in the ladle. While the mixing time decreased with the increase of the gas flow rates, the oil layer over the top of the bath extended the mixing time in the whole range of gas flow rates, and at constant gas flow rate, the mixing time was extended with the increase of oil thickness. From the results of water model experiments and numerical simulations, transient formation of plume eye from the start of gas bubbling was matched well each other. Based on water model experiment the plume eye size was found to increase with the increase of gas flow rates and to decrease with the increase of the oil thickness. These were precisely confirmed with numerical simulated results. From the results of numerical simulation fluid flow pattern without oil layer showed that bubbles rising eventually made a recirculation loop at the central area of the bath forming uniformly distributed velocity vectors in the bath. This flow pattern regarded as a good flow pattern for the better mixing behavior. However, flow pattern with oil layer showed distorted and localized recirculating loop near side wall below oil layer. This eventually gave extended mixing time in the bath with oil layer.

KEY WORDS: water model experiment; ladle; gas injection; vacuum oxygen decarburization (VOD) process; plume eye; slag layer; fluid flow; volume of fluid (VOF); numerical analysis.

1. Introduction

High alloy steels like stainless steel is usually produced in Vacuum Oxygen Decarburization (VOD) ladle which enables the decarburization reaction under reduced vessel pressure without loss of high oxidisable chromium element. Carbon in stainless steel deteriorates oxidation resistance and welding characteristics and therefore carbon content in stainless steel needs to be decreased to a certain limited low level.

For these while oxygen is blown from the top lance to reduce a carbon content, as combined blow inert gas is introduced from the bottom of the ladle to activate a recirculation of bath to bring carbon-bearing melt to the top. When the top oxygen jet hits the bath surface, then a crater is produced at the bath surface. If the slag layer over the melt is not properly removed, the decarburization reaction from the melt can not be made effectively.

For this purpose a naked melt is forcefully made by forming on top of the melt by inert gas blowing from the bottom of the ladle. During gas bubbling bubbles injected form a plume zone and eye of the plume is then appeared on the top of the melt by bulging naked melt where the bubbles are ejected through the slag layer. Then, the location of the formation of plume eye needs to be aligned with oxygen jet from the top lance for the enhancement of decarburization reaction.

Since the plume eye formed by the gas bubbling can be also used for alloying control and etc. a quantitative analysis about the size of the plume eye of the melt system with top slag layer plays an important roles in the process operation.

So far, there are literatures reported about the process optimization of VOD operation through model approaches.\textsuperscript{1–3)} However, importance about the existence of the slag layer in decarburization reaction of VOD process has not emphasized yet. As general approaches there are some literatures reported about the qualitative analysis about the effect of slag layer on the behavior of melt flow characteristics during gas bubbling from the bottom of the ladle.\textsuperscript{4–8)} Those
have reported about the effect of top slag layer on the melt flow fields by mentioning mixing behavior of the melt deduced from the hot and cold model experiments. Haida et al. investigated the role of an upper slag layer on bulk liquid mixing with the aid of water model experiments. These authors found that mixing times measured with a simulated slag tended to be considerably different to those for equivalent situation without slag and upper slag phase dissipates a part of the input energy rate and therefore, mixing times in ladles, in the presence of the overlying second phase liquid will be somewhat longer than those to be expected under an equivalent no slag situation. Recently, several works based on the numerical solutions based on mathematical modeling about both the slag layer and the melt flow fields have been reported. However, little is known about the transient effect of slag layer on flow characteristics of gas stirred system and the exact explanation about the formation mechanism of plume eye is not made.

Our final goal is to quantify the mixing time and the size of plume eye in the VOD process of combined blow under reduced pressure condition.

However, in this study as a preliminary work transient fluid flow characteristics in a gas stirred liquid bath with top oil layer is discussed. For the purpose of these a quantitative analysis about the effect of slag layer on the formation of plume eye, and mixing behavior of melt based on the water model is carried out and results obtained from water model experiments are compared and discussed with the results of the numerical simulation.

2. Experiment

Figure 1 shows a schematic diagram of water model setup. A small 1:9 scale of prototype VOD ladle is chosen for the water model experiments. The water model vessel is made of transparent acrylic cylinder of 0.4 m height and 0.3846 m inner diameter and water is filled to a height of 0.16 m. Air is introduced through the central bottom of the vessel to simulate argon in the ladle using a porous plug. Air is supplied from a air compressor and flowmeter is used to measure flow rates. Air flow rate is changed from 0.3 l/min to 1 l/min based on the similarity criteria of modified Froude number as shown in Eq. (1).

\[ A_m = \frac{Q_m^2}{L_m D_m^4} = A_p \frac{Q_p^2}{L_p D_p^4} \]

where, subscript \( m \) and \( p \) represent prototype and model experiment, respectively.

\( \rho_g \): Density of gas (kg/m³)

\( \rho_l \): Density of liquid (kg/m³)

\( g \): Gravity constant (9.8 m/s²)

\( L \): Height of liquid (m)

\( Q \): Gas flowrate (Nm³/s)

\( D \): Nozzle diameter (m)

In order to simulate the behavior of top slag layer, a silicon oil is used and physical properties of the silicon oil are listed in Table 1. The thickness of top oil layer is changed from 0.002 to 0.01 m. For the clear observation of the inter-

![Fig. 1. Experimental setup used in the water model experiments.](image)

<table>
<thead>
<tr>
<th>Table 1. Physical properties associated present studies.</th>
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<tbody>
<tr>
<td>Properties</td>
</tr>
<tr>
<td>Melt</td>
</tr>
<tr>
<td>dynamic viscosity (kg/m/s)</td>
</tr>
<tr>
<td>density (kg/m³)</td>
</tr>
<tr>
<td>kinematic viscosity (m²/s)</td>
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</tbody>
</table>
face between oil and water, oil was colored before the experiments.

To get the size of the plume eye with respect to gas flow rates and slag thickness, a digital video camera is installed on top of the vessel and photo frames grabbed from the start of gas injection are analyzed. The mean size of plume eye is measured from the photo frames taken at each time by drawing a line from the center of the plume eye.

In order to measure the mixing time electrical conductivity measurement is adopted in this study. A platinum electrode as a conductivity sensor connected to Wheatstone bridge\(^1\) was installed at 0.08 m high from the bottom edge in the vessel as shown in Fig. 1.

The thickness of oil and air flow rates are chosen as variables for measuring mixing time and 5 mole of KOH solution is used as a tracer.

3. Numerical Simulation

3.1. Governing Equations

In order to investigate the dynamic behavior of liquids and gases, a commercial computational fluid dynamic package FLOW-3D is used, which is originally developed by Hirt \textit{et al.}\(^1\) In FLOW-3D VOF (Volume of Fluid) function\(^2\) is used to track the interface between metal and slag phase which is usually found in the steelmaking ladle.

Therefore, the following governing transport equations including VOF function and turbulence equations need to be solved.

- Conservation of total mass
- Conservation of momentum
- Conservation of Volume of Fluid Function
- Regarding turbulence equation built-in \(K-\varepsilon\) turbulence model is used.\(^3\)

Mass continuity and momentum equations are shown in Eqs. (2) and (3), respectively.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \hspace{1cm} \text{(2)}
\]

\[
\rho \frac{\partial \mathbf{V}}{\partial t} = \nabla p + \nabla \cdot \mathbf{t}_g \hspace{1cm} \text{(3)}
\]

where, \(\rho\): Density of fluid
\(\mathbf{V}\): Vector-gradient operator
\(\mathbf{V}\): Velocity-vector field
\(g\): Gravity force
\(p\): Pressure
\(\mathbf{t}\): Shear stress tensor

In order to treat liquid interface like slag/melt system in steelmaking ladle, a volume of fluid (VOF) function is used. This function represents the volume of fluid per unit volume and satisfies the Eq. (4)

\[
\frac{dF}{dt} = \frac{\partial F}{\partial t} + (\mathbf{V} \cdot \nabla)F = 0 \hspace{1cm} \text{(4)}
\]

The interpretation of \(F\) depends on the type of problem being solved. In slag/melt two fluid system, \(F\) represents the volume fraction occupied by the two fluids. Thus, fluid 1 exists where \(F=1\) and fluid 2 correspond to locations where \(F=0\). Details are well explained in the Ref. 15)

3.2. Assumptions

A gas stirring ladle in VOD process is described as complex flows with three phases(gas, melt and slag). Even though simultaneous expressions of three phases is possible, there exist limits in the use of VOF algorithm in FLOW-3D. Accordingly only two fluids (melt and slag) are considered in the calculation of the fluid flow.

All assumptions used in this study are summarized below;

1. Gas bubbles are considered as particles with gas density.
2. In VOD ladle aspect ratio \(H/D\) (\(H\): Height of melt, \(D\): Inner diameter of vessel) is low enough to ignore the bubbles expansion in the water and based on the preliminary experiment it is found that size of bubbles are measured to be 0.002 m in this system and shape is almost sphere-like. Thus, for the calculation the size of bubbles are fixed as 0.002 m in diameter.
3. The flow rates is converted from the number of gas bubbles generated per unit time which total volume is equivalent to the gas flow rate.
4. Slag free surface was assumed to be flat.

3.3. Method of Solution

Two dimensional axisymmetric condition in cylindrical coordinate system is used as is shown in Fig. 2. The number of gas bubbles generated per unit time is controlled to determine gas flow rates. Table 2 shows the conversion of the number of bubbles generated at each gas flow rates.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{gas flow rate(\text{ml/min})} & \textbf{number of bubbles generated(numbers/sec)} \\
\hline
0.3 & 99 \\
0.5 & 165 \\
0.7 & 231 \\
1.0 & 330 \\
\hline
\end{tabular}
\caption{Number of bubbles generated at various gas flow rates—converted based on the calculation of gas flow rate divided by the volume of bubble.}
\end{table}

Fig. 2. Computational domain and mesh generation for numerical simulation.
Bubbles are assumed to escape at the rate at which it reaches the free surface.

The calculations are performed in a transient-solution mode. All the computations were performed on a PC with P-II 450 MHz. With a two-dimensional grid containing 2250 cells ($r \times z = 50 \times 40$) a typical simulation takes about 5 hours of CPU time.

4. Results and Discussion

4.1. Effect of Oil Layer on the Mixing Time

In this study measured mixing time against gas flow rates are shown in Fig. 3. Despite of different experimental conditions (without or with 5 mm of oil layer), mixing time is measured to decrease with the increase of gas flow rates. Since the early studies about mixing time, a large number of experimental studies on mixing phenomena, of relevance to gas stirred ladle systems, have been reported in the literatures.17–19 In these, widely varying gas flow rates and vessel geometries and nozzle configurations were applied and their influences on mixing behavior investigated. The results were that mixing time decreased with the increase of the mixing power density. From Fig. 3 it is also found that the oil layer over the top of the bath extends mixing time in the whole range of gas flow rates from 0.3 to 1 l/min, especially higher the gas flow rates, mixing time is extended.

Attempts have been also made to investigate the effects of oil layer thickness on the mixing time in Fig. 4. At constant gas flow rate of 0.5 l/min the mixing time was found to be extended with the increase of oil thickness. As reported by Haida et al.8 one can imagine a liquid flow field may be influenced by the existence of an oil layer.

Thus, in order to quantify the liquid flow field under the existence of the oil layer a numerical simulation is carried out.

4.2. Transient Flow Characteristics without Oil Layer

For the sake of comparison flow patterns in bath without an oil layer when gas flow rate is 0.5 l/min were obtained as shown in Fig. 5. From the start of gas injection transient motions of flow patterns are displayed by marching time. one second after the gas injection, as shown in Fig. 5(a), bubbles, which is not shown here, exert a rising motion forming a plume zone by exchanging momentum between bubbles and liquid and recirculating loop has started to form near top of the plume zone. In 1.4 s (Fig. 5(b)) center of recirculating loop near free surface started to move towards the side wall and fluid velocities at top surface strongly develop. Thereafter, the center of the recirculating loop keeps going towards the edge of the top surface and side wall (Fig. 5(c)), followed by turning down towards the bottom of the bath (Figs. 5(d) and 5(e)) and then, finally in 30 seconds after the gas injection the center of the recirculating loop locates around central area of the half bath. After that the center of recirculation loop did not move further. Fig. 5(f) is regarded a typical calculated flow fields which can be obtained by a steady state assumption. From these figures it is understood that when the loop center is located around the central area the recirculating flow is shown to be well developed. This may give faster mixing time in the bath.

![Fig. 3. Influence of gas flow rates on mixing time with and without oil layer.](image)

![Fig. 4. Influence of oil thickness on mixing time at gas flow rate of 0.5 l/min.](image)

4.3. Effect of Gas Flow Rates and Oil Thickness on the Formation of Plume Eye

4.3.1. Transient Observation of the Initial Formation of Plume Eye

Figure 6 shows the comparison of water model experiments and the results of numerical simulation for a transient observation of an initial formation of a plume eye. After 0.529 s, plume eye started to form, and to grow to a certain size in a few seconds, and then, in 30 s after the gas injection the plume eye reached a nearly constant plume eye size.

In the numerical simulation the predicted flow patterns with top oil layer were compared with the water model experiments. In 0.6 s top oil layer starts to deform on top of plume zone and the recirculating loop has started to form near top of the plume zone as was well explained in Fig. 5. But the difference in the flow fields can be easily seen in 1.4 s. The oil started quickly to move away from the center of the bath to form a plume eye and the center of recirculating loop was still resided near plume zone below the oil layer. Even in 10 s the center of the recirculating loop was located far behind the side wall. On the contrary, the center of the recirculating loop in flow pattern without oil layer in 5.6 s as shown in Fig. 5(c) reached the side wall. And in 30 s it is seen that the loop center stays constant near wall-side compared to the Fig. 5(f). The loop center did not move further either. The size of plume eye being increased from the start, however, nearly remained constant after 10 s.
Moreover it is interesting to note that velocity vectors in flow fields with top oil layer are not uniformly distributed in the bath and the recirculating loop with oil layer is biased comparing to that without oil layer and the secondary recirculating loop is developed near edge of the side wall which is below the oil layer. This may give the clue why the oil layer over the bath extends the mixing time, that is, a localized secondary recirculating flow dissipating a part of the input energy may give adverse effect on the mixing behavior in the bath and therefore, mixing times in ladles, in the presence of the oil layer is somewhat longer than those to be expected under an equivalent no oil situation.

Figure 7 shows the comparisons of plume eye size obtained from water model experiments and numerical simulations. It can be said that the results of numerical simulation show good agreements with the water model experiments.

4.3.2. Effect of Gas Flow Rates and Oil Thickness on the Size Change of Plume Eye

In order to figure out how the size changes of plume eye is related to the bottom gas blowing and oil thickness, In water model experiment gas flow rates are changed from 0.3 to 1 l/min and the thickness of oil are changed from

Fig. 6. Comparisons of photos of plume eyes grabbed by marching time in water model experiments, (a), and calculated flow fields of half bath at each corresponding time, (b). The oil thickness is 0.005 m for both in the water model and numerical calculations.
0.002 to 0.01 m in the system. Figure 8(a) shows the variation of plume eye size with respect to gas flow rates. The oil thickness was set to be 5 mm. It is seen that the plume eye size increases with the increase of gas flow rates. Figure 8(b) also shows the variation of plume eye size with respect to the oil thickness. Plume eye size tends to decrease with the increase of the oil thickness. These are easily shown in the Fig. 9. The reason of the change of plume eye size can be interpreted by the analysis of the change of the flow field caused by the oil layer, which will be explained by the results of numerical simulation.

(i) Effect of Gas Flow Rates

Figure 10 shows the comparisons of the size of plume eye measured in the water model experiments and that calculated from numerical simulations. Those two results matched well each other. Likewise already pointed out, higher the gas flow rate the size of plume eye increased as well. These phenomena can be easily understood from the results of numerical simulation. As shown in Fig. 11, higher the gas flow rates, velocity vectors at top surface of the bath develops further and most of input energy can be used for the formation of the plume eye and moreover high velocities developed below oil layer make the secondary recirculating flow at the edge of the side wall below the oil layer.

![Fig. 7. Relationship between the diameter of plume eye and time as obtained from numerical calculations (circles) and the water model experiments (squares).](image)

![Fig. 8. Photos of plume eye at water model experiments at various gas flow rates (oil thickness of 0.005 m), (a) and oil thickness (gas flow rate of 0.5 l/min), (b).](image)

![Fig. 9. Relationship between diameters of plume eye and gas flow rates at various oil thickness.](image)

![Fig. 10. Comparison of measured and calculated diameter of plume eye at various gas flow rates, as obtained from water model experiments (squares) and numerical simulations (circles), the oil thickness is 0.005 m.](image)
These also consume a lot of input energy.

However, from the viewpoint of the location of the recirculating loop center, it is found that higher the gas flow rates as seen in Fig. 11(d), the location of the recirculating loop center moves toward the central region of the bath having rather uniformly distributed flow patterns with high average velocity vectors. That is, the total average velocity seemed to be larger and a dead zone, where fluid moves slowly at the bottom of the bath, disappeared, giving fast mixing time as shown in Fig. 3. On the contrary when the center of recirculating loop is located upper region of the bath at lower gas flow rate as shown in Fig. 11(a), velocity vectors at the bottom of the bath show relatively low values. This may extend the mixing time in the bath.

(ii) Effect of Oil Thickness

For the sake of comparison, the size changes of plume eye was obtained from different oil thickness as shown in Fig. 12. This figure shows the comparisons of the size of plume eye measured in the water model experiments and that predicted from numerical simulation. The thicker the oil layer, the size of plume eye decreased. Those two results agreed well each other.

Likewise in the interpretation as in Fig. 11, from the viewpoint of loop center location, it is found in Fig. 13 that thicker the oil layer, the location of the loop center moves toward the upper region of the bath having rather distorted flow pattern, giving low value of mixing time as shown in Fig. 3. Especially at a constant flow rate of 0.5 l/min when the oil thickness was 10 mm as shown in Fig. 13(d) the loop center moved toward the upper region of the bath and strongly developed secondary recirculating flow was found at the edge of oil layer and side wall.

4.4. Discussions on the Effect of Oil Layer on the Flow Fields

The intrinsic efficiencies of reaction vessel like steelmaking ladles are intricately related to mixing phenomena. It is desirable to ascertain the extent of mixing to evaluate the process performance of argon stirred ladle. It has been already known that since mass transfer of carbon and oxygen becomes the rate determining step of the decarburization reaction at low carbon steel, mixing plays an important role for the efficiency of the process. Therefore, mixing characteristics need to be quantified for the better efficiency of the process.

Clearly speaking, hydrodynamic state of the vessel be-
comes different in the presence of the overlying second phase liquid, as was reported by Haida et al.\textsuperscript{8}) The upper slag phase dissipates a part of the input energy rate and therefore, mixing time in ladles, in the presence of the overlying second phase liquid will be somewhat longer than those to be expected under an equivalent no slag situation.

However, a complete and consistent description for the mixing phenomena in a gas stirred bath with top oil layer has not been reported yet. The present study may be the first numerical approach which relates flow patterns to the mixing behavior from the viewpoint of the location of the recirculating loop center in a gas stirred bath with oil layer in different gas flow rates and oil thickness.

The existence of oil layer greatly influence on the fluid flow and mixing behavior by forming plume eye in the bath. While mixing time is decreased with the increase of the gas flow rates, the oil layer over the top of the bath extended mixing time over the entire gas flow rates and at constant gas flow rate, the mixing time was extended with the increase of oil thickness. These phenomena can be understood as follows; all the input energy from the gas bubbling in the bath without oil layer can be used for the mixing itself. But the existence of the oil layer hinders the use of input energy for mixing by forming plume eye and by developing the secondary recirculating loop near edge of the oil layer and side wall. And as a result, the center of the recirculating loop was located near upper region of the bath with oil layer.

As concluding remarks, in order to ensure fast mixing in the bath with oil layer, it can be said that from the viewpoint of the recirculating loop center location, the recirculating loop center has to move toward the center of the vessel to ensure uniformly distributed flow pattern in order to give fast mixing in the bath. However, further quantitative analysis has yet to be made for the process optimization in the bath with slag layer.

5. Conclusions

The flow characteristics in a gas stirred ladle with oil layer were studied with the help of water model experiments and numerical simulation. Considering the effects of oil layer on mixing behavior, the formation mechanism of plume eye coupled with mixing behaviour based on the water model experiments were discussed with the results of the numerical simulation. On the basis of above results and discussions, the following conclusion can be drawn.

(1) The oil layer has a great influence on the fluid flow and mixing behavior in the ladle.
(2) While mixing time was decreased with the increase of the gas flow rates, the oil layer over the top of the bath extended mixing time over the entire gas flow rates and at constant gas flow rate, the mixing time was extended with the increase of oil thickness.
(3) From the results of water model experiments and numerical simulation, transient formation of plume eye from the moment of the start of gas bubbling was matched well each other.
(4) Based on water model experiment the plume eye size was found to increase with the increase of gas flow rates and decreased with the increase of the oil thickness. These were precisely confirmed with numerical simulated results.
(5) From the results of numerical simulation flow pattern without oil layer showed that bubbles rising eventually made a recirculation loop at the central area of the bath.
forming uniformly distributed velocity vectors in the bath. This flow pattern regarded as a good flow pattern for the better mixing behavior.

(6) However, flow pattern with oil layer showed distorted and localized recirculating loop near side wall below oil layer. This eventually gave extended mixing time in the ladle with oil layer.

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