Analysis of Plunging Pool Formation and Gas Absorption Phenomenon during Tapping

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Gas absorption phenomenon during tapping from converter to ladle was studied by water model experiments in water-air system. Changes of dissolved oxygen, DO in the vessels were observed by DO meter and volumetric coefficient for gas absorption rate, $Ak$ was estimated. In addition, the amount of gas engulfment at plunging pool with the same water model was also observed and calculated with CFD method. Observed and Experimental results were in good agreement with each other when the criterion for liquid ratio was set as 0.5. Surface area of bubbles at plunging pool calculated by CFD was used to estimate mass transfer coefficient, $k_B$, $k_B$ in tapping and bottom bubbling experiments were discussed and linear relation between $k_B$ and stirring power density was found. The Plunging pool was divided into 9 parts and velocity at bubble surface and area of bubbles in each part were calculated. It was found that the center and middle part of plunging pool was the main gas absorption region through this discussion. Bubble generation phenomenon at plunging pool in steel-air system was also calculated with the same mesh as water-air system and calculated results were compared with each other.

KEY WORDS: tapping; dissolved oxygen; gas absorption; plunging pool; bubble volume; CFD; mass transfer.

1. Introduction

Nitrogen and oxygen absorption at plunging pool during metal tapping from converter to ladle or ladle to tundish are inevitable phenomenon in a steelmaking process. It is necessary to prevent gas absorption for the lower nitrogen steel or clean steel so that many basic studies have been reported by many researchers. Related to the gas absorption phenomenon into molten steel during Ar gas bottom bubbling, changes of nitrogen in molten steel have been experimentally observed by many researches.1–4) In addition, the effects of the surfactants (sulfur and oxygen), and pressure of gases on nitrogen absorption rate to molten steel have been reported.5,6) Related to gas absorption phenomenon during tapping, visualization experiments focused on plunging pool have been studied. Direct measurements of plunging pool7) and gas absorption rates with water model8,9) have been reported in the chemical engineering field. Some estimation formulas about the height of plunging pool and the amount of air engulfment from water and mercury experiments10) have been reported. In addition, according to the gas absorption phenomenon during tapping, the estimation formulas about gas absorption regarding the surface area of tapped steel11,12) have been reported. However, it is difficult to take metal samples during tapping so that deep discussions of the kinetics of the gas absorption phenomenon have been little made. The authors have developed the water model experiment related to the gas absorption during tapping. Previous studies have shown that gas absorption phenomenon during tapping could be estimated by the kinetics formula considering dilution13) and the effect of atmospheric gas on gas absorption phenomenon was quantitatively discussed.14) However, it is difficult to estimate the surface area of bubbles precisely so that volumetric coefficient $Ak$ has been used to estimate the gas absorption rate in previous studies. To discuss gas absorption phenomenon in detail, it is essential to estimate $k_B$ and $A_B$ separately. On the other hand, recent developments on CFD (Computational Fluid Dynamics) have been remarkable so that the researches about the gas bottom bubbling in water-air system15) and the circulation of RH in steel-Ar system with the unsteady multiphase solver using VOF (Volume of Fluid) method16) have been reported. By applying this method to the tapping phenomenon, detailed discussions could be made because surface area of bubble and velocity on the bubble during tapping can be calculated and volumetric coefficient could be converted into mass transfer coefficient.

In this study, the gas absorption phenomenon during tapping imitating the tapping from BOF to the ladle was experimentally estimated with the water model. In addition, the amount of gas engulfment at plunging pool with the
same water model was also experimentally estimated and calculated with CFD method. $k_B$ during tapping was estimated with experimentally observed $A_k$ and calculated $A_B$. Furthermore, tapping phenomenon in steel-air was estimated by changing the physical properties from water to steel with the same mesh.

2. Experimental

Water model experiments were performed and dissolved oxygen (DO) in the water was used as index of gas absorption to reproduce the behavior in steel-air system in which the same Weber numbers were adopted. In water-oxygen system, physical properties such as density, temperature and pressure were different from those in steel-nitrogen system. However, it is thought that formation of plunging pool and gas absorption reaction based on mass transfer do not depend on the system and model size. In addition, the amount of engulfed gas at plunging pool with the same water model as above was estimated by measuring the change of pressure around the plunging pool before and after tapping. The amount of engulfed gas, the surface area of bubbles and the velocity on bubbles were also estimated with CFD method described below.

2.1. Gas Absorption Rate

Figure 1 shows the experimental apparatus in which BOF and ladle are substituted for the upper and lower vessels, respectively. Experimental conditions are shown in Table 1. Water in the upper vessel was plunged to the lower vessel through the nozzle and valve (upper) located on the bottom of the upper vessel. Changes of DO were measured using DO meters set in both upper and lower vessels during tapping in every second. At the initial state, total amount of water was 0.055 m$^3$ (0.050 m$^3$ in the upper vessel and 0.005 m$^3$ in the lower vessel) and height from nozzle tip to water surface in the lower vessel was 0.80 m. Water was remained at temperature of 293 ± 1 K during the experiments because saturated DO is sensitive to the water temperature. DO in both upper and lower vessels were reduced to less than 0.80 ppm by Ar bottom bubbling before tapping. The measurement was started after opening the valve (upper) and DO was measured until the water in the upper vessel run out. The video image of plunging pool was taken with the high-speed camera in 5000 fps and compared with the CFD images.

2.2. Amount of Engulfed Gas at Plunging Pool

The middle vessel was installed to measure the amount of engulfed gas at plunging pool to the same water model. Experimental apparatus is shown in Fig. 2 and experimental conditions are shown in Table 2. The valve (middle) and the manometer were set on the top of the middle vessel. The amount of engulfed gas was converted from the change of the pressure in the middle vessel. The side hole was set on the upper vessel and the L shape pipe was set on the side wall of the lower vessel. The heights of water in upper and lower vessels were controlled by changing the vertical position of the hole and the L shape pipe. After the valve (middle) was set to released position, plunged water was overflowed through the side hole and the L shape pipe so that the heights of the water in upper and lower vessels were kept constant and the plunging pool was made in the middle vessel. When the valve (middle) was set to stop position afterward, the plunging pool remained and the pressure in the middle vessel remained at atmospheric pressure, $P_0$. Next, when the valve (upper) was set to the stop position, the pressure in the middle vessel changed due to the disappearance of plunging pool whereas the height of water in the lower vessel was kept constant. The mass of gas in middle vessel could be expressed by Eqs. (1) and (2) because it should not change before and after stopping plunging. Based on Eq. (2), the bubble volume at plunging pool, $V_B$ could be calculated by measuring the pressure in the middle vessel, $P_{obs}$ after stopping the plunging.

\[ P_0 \cdot (V_M - V_W + V_B) = P_{obs} \cdot V_M \quad \text{......... (1)} \]

\[ V_B = \left( \frac{P_{obs}}{P_0} \right) \cdot V_M - V_M + V_W \quad \text{......... (2)} \]

Where, $P_0$: atmospheric pressure (Pa), $V_M$: volume of gas

| Item                  | Setting                          |
|-----------------------|----------------------------------|
| System                | Water-oxygen                     |
| Amount of water       | 0.050 + 0.005 m$^3$              |
| Initial height        | 0.80 m                           |
| Diameter of vessel    | φ400 mm                          |
| Diameter of nozzle    | φ14.0 mm                         |
| Temperature of water  | 293 ± 1 K                        |
| Atmosphere            | Air, 1 atm (O$_2$=20.9 vol%)     |

![Fig. 1. Experimental apparatus.](image-url)
2.3. CFD

The mesh for the water model was made and the calculation to reproduce the plunging pool was executed with CFD software, OpenFOAM 2.3.1. Unsteady VOF solver “compressibleInterFoam” was adopted in the CFD. Governing equations are shown in Eqs. (3) to (9).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)
\]

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla P + \Theta + f_s + \rho g \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

\[
\frac{\partial \rho T}{\partial t} + \nabla \cdot (\rho uT) - \nabla \cdot \alpha \nabla T + \left( \nabla \cdot (\mu P) + \frac{\partial \rho K}{\partial t} + \nabla \cdot (\rho u K) \right) \left( \frac{F}{C_{1-\ell}} + \frac{1-F}{C_{1-g}} \right) = 0 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)
\]

Where, \( \rho \): density (kg/m\(^3\)), \( u \): velocity (m/s), \( P \): pressure (Pa), \( \Theta \): viscosity stress (kg/(m\(^2\)·s\(^2\))), \( f_s \): surface tension term (kg/(m\(^2\)·s\(^2\))), \( \rho_g \): density (kg/m\(^3\)), \( T \): temperature (K), \( \alpha \): thermal diffusivity (kg/(m·s)), \( K \): kinetic energy (=1/2 |u|\(^2\)), \( F \): void ratio of liquid (–), \( C_{1-\ell} \): specific heat at constant volume (J/(kg·K)), \( R \): gas constant (J/(kg·K)).

The mesh configuration is shown in Fig. 3 and the mesh size is shown in Table 4. As shown in Fig. 3, the boundary conditions for top of calculation domain, bottom and side walls in the lower vessel were set as “Wall” where the velocity gradient is zero. The boundary conditions for side area above the lower vessel were set as “InletOutlet” where gas can inward and outward through the boundary. The gas engulfment at plunging pool was explained as the turbulence of plunged stream.\(^{17}\) In the present calculation, the turbulence around plunged stream was reproduced by setting the mesh size to 1 mm around surface of the water. In addition, the mesh size in the region of bubble generation was also set to 1 mm. The total mesh number was over 6 million in this mesh condition so that the calculation with rougher mesh was done until the amount of water in the lower vessel became 0.030, 0.040, 0.050 m\(^3\) and afterward the finer mesh as above. The open-source and visualization application software ParaView 4.3.1 was used for the post processing.

![Fig. 2. Experimental apparatus.](image)

![Fig. 3. Boundary conditions.](image)

| Table 2. Experimental conditions. |
|-----------------------------------|
| Item                          | Setting                         | |
| Amount of water                | 0.055 m\(^3\)                  | |
| Diameter of vessel             | \( \phi 400 \) mm              | |
| Diameter of nozzle             | \( \phi 0.5, 14.0, 16.5 \) mm   | |
| Diameter of middle vessel      | \( \phi 300 \) mm              | |
| Height of water (\( h^{u} \))  | 279, 199, 199, 40 mm           | |
| Height of water (\( h^{l} \))  | 159, 239, 319, 398 mm          | |
3. Result

3.1. Gas Absorption Rate

Changes of DO in upper and lower vessels during tapping are shown in Fig. 5. DO in the lower vessel began to increase after 5 second from starting tapping. Large increase of DO was found in early period of tapping and DO showed constant value thereafter. On the other hand, DO in the upper vessel did not change during tapping. Change of DO in the lower vessel can be expressed as follows.

\[ \frac{dC_{DO}}{dt} = A_{KO} \left( C_{DO} - C_{DO}^* \right) + \frac{C_{DO}^* \cdot Q}{\rho \cdot V'} \]  \hspace{1cm} (10)

Where, \( C_{DO} \): DO in the lower vessel (ppm), \( A_{KO} \): volumetric coefficient \( m^3/s \), \( V' \): volume in the lower vessel \( m^3 \), \( C_{DO}^* \): DO in the upper vessel (ppm), \( Q \): flow rate of stream \( kg/s \), \( \rho \): density of water \( kg/m^3 \). The superscript * means the equilibrium and the subscript \( t \) means the time.

The change of \( A_{KO} \) calculated with Eq. (10) using the values in Fig. 5 is shown in Fig. 6. \( A_{KO} \) began to increase after starting tapping and maximum value was found at 50 second. The gas absorption phenomenon was strongly related to the formation of the plunging pool so that \( A_{KO} \) would increase as the area of bubble become larger.

3.2. Amount of Engulfed Gas at Plunging Pool

Volume of bubble at plunging pool calculated with Eq. (2) using the change of pressure in the middle vessel is shown in Fig. 7. Large volume of bubble was found under the conditions of long stream or large nozzle diameter. The engulfed bubbles were brought to the bottom of the lower vessel with the flow of water so that volume of bubble would increase as the stream length, \( L_s \) or the amount of
plunged water became larger.

3.3. CFD

The example of comparison between high speed camera image and CFD image at the condition that $V$ is 0.040 m$^3$, $L_S$ is 520 mm and depth of water in the lower vessel, $H$ is 320 mm is shown in Fig. 8. Unless otherwise noted, nozzle diameter is $\phi14.0$ mm hereafter. Liquid ratio in CFD was set to 0.5 to determine the boundary of water and gas. The behavior that the bubbles were engulfed with the plunged water was visually found in high speed camera observation. The depth of bubble penetration was around 270 mm, width of plunging pool was around 120 mm and the bubble size distribution were 2 to 5 mm in the experiment. Considering this situation, the behavior of the engulfed bubbles was reproduced by CFD. The depth of bubble penetration was around 300 mm, width of plunging pool was around 120 mm and the bubble size distribution were 2 to 5 mm in CFD so that the reproduction of generation of plunging pool by CFD was generally confirmed.

3.4. Comparison of the Amount of Engulfed Gas in Experiment and CFD

In this work, the bubble volume was calculated from the total sum of the product of gas ratio, $\Phi_g$, ($=1-\Phi_l$; $\Phi_l$ as liquid ratio) and the cell volume. However, the cells with gas ratio, $\Phi_g$, below the criterion were excluded from the summation because gas could not create bubble shape. As a result, the total bubble volume could be calculated larger in case of lower criterion for $\Phi_g$, that is, higher criterion for $\Phi_l$.

Relation between $L_S$ and $V_B$ is shown in Fig. 9. Triangle, square and diamond marks are observed values and correspond the conditions that the amount of water in the lower vessel are 0.030, 0.040 and 0.050 m$^3$ (in the upper vessel are 0.025, 0.015 and 0.005 m$^3$) respectively. Cross and X marks are calculated values in the criterion for liquid ratio of 0.5 and 0.6 respectively in the same conditions with the water model experiments.

Large volume of bubble was found in the long stream length conditions. The experimental and CFD results were in good agreement in the criterion for liquid ratio, $\Phi_l$, of 0.5. In this work, the size of cell around surface of water and region of bubble generation were set to 1 mm and, as a result, the resolution size of bubble might be limited. The cell size is considered as one big reason of the difference between experimental and CFD results. However, following discussions were done with these results which were calculated in the criterion for liquid ratio of 0.5.

4. Discussion

4.1. Area of Bubbles at Plunging Pool

Area of bubbles at plunging pool, $A_B$ was calculated by CFD with setting criterion for liquid ratio as 0.5. The changes of $A_{k0}$ and $A_B$ during tapping are shown in Fig. 10. The time when the bottom of plunging pool left from the bottom of the lower vessel was around 70 second after starting tapping. At that time, height of plunging pool showed its maximum. On the other hand, the maximum $A_{k0}$ was found earlier than the time when the plunging pool left from the bottom of the lower vessel and gradually decreased with time. $A_B$ was ranging from 0.09 to 0.17 m$^2$ in this condition and decreased with time too. The area of water surface was around 0.13 m$^2$ calculated from the diameter of the lower vessel (0.4 m) so that the same area of bubble was newly generated by tapping.

$A_{k0}$ calculated in this work included the effect of the area
of plunging pool and water surface. However, the effect of the area of water surface was little in the other experiment in which the plunging pool was not generated. For this reason, the discussion was done assuming that the plunging pool was not generated. For this reason, the area of water surface was little in the other experiment in which the plunging pool was not generated.

4.2. Arrangement with Stirring Power Density

The mass transfer phenomenon dealt in mechanical mixing was often arranged with the stirring power density, \( \varepsilon \) in the field of chemical engineering.\(^{18}\) Thus, experimental results in this work were compared with the reported results of overall volumetric coefficient, \( K = \frac{k_B V}{1/\varepsilon} \) (1/s). Sakaguchi et al.\(^{19}\) and Y. Higuchi et al.\(^{20}\) which were bottom bubbling system and arrangement with stirring power density was executed. The experimental conditions in the different authors are shown in Table 5. The stirring power density of bottom bubbling and plunging could be estimate with Eqs. (11)\(^{21}\) and (12)\(^{22}\):

\[
\varepsilon = 37.1 \cdot \left( \frac{Q_g}{V_w} \right) \cdot T \cdot \ln(1 + \rho_L \cdot g \cdot h / P) \quad \text{(11)\(^{21}\)}
\]

\[
\varepsilon = \frac{1}{2} \cdot \frac{Q_j \cdot \rho_L \cdot u_i^2}{V_w} \quad \text{(12)\(^{22}\)}
\]

Where \( \varepsilon \): stirring power density (W/m\(^3\)), \( Q_g \): flow rate of bottom bubbling (Nm\(^3\)/s), \( V_w \): volume of water (m\(^3\)), \( \rho_L \): density of liquid (kg/m\(^3\)), \( g \): acceleration of gravity (m/s\(^2\)), \( h \): depth of bubbling (m), \( P \): atmospheric pressure (Pa), \( Q_j \): flow rate of stream (m\(^3\)/s), \( u_i \): velocity of stream (m/s).

\( A_B \) in bottom bubbling system could be estimated with Eqs. (13) to (16).\(^{21,23,24}\) \( k_B \) was estimated from \( K \) with \( A_B \) and \( V_w \) and compared with that of plunging system.

\[
A_B = 6 \cdot H \cdot \frac{Q_j}{(d_B \cdot u_B)} \quad \text{(13)\(^{23}\)}
\]

\[
d_B = \left[ 6 \cdot \frac{Q_j}{n} \right]^{1/3} \pi \cdot f_B \quad \text{(14)\(^{23}\)}
\]

\[
f_B = 1.06 \cdot \left( \frac{\rho_L \cdot g^2}{\sigma} \right)^{1/4} \cdot (\rho_g / \rho_L)^{1/5} \cdot \left( \frac{Q_j}{g} \right)^{1/5} / d_i \quad \text{(15)\(^{23}\)}
\]

\[
u_B = 1.76 \cdot (Q_j \cdot g^2)^{1/5} \quad \text{(16)\(^{24}\)}
\]

Where \( d_B \): diameter of bubble (m), \( u_B \): bubble rising velocity (m/s), \( n \): number of tuyere (–), \( f_B \): frequency of bubble generation (Hz), \( \sigma \): surface tension (N/m), \( \rho_g \): density of gas (kg/m\(^3\)), \( d_i \): diameter of tuyere (m).

Relation between \( A_B \) and \( K \) is shown in Fig. 12. Although there is difference in mixing system, the range of \( A_B \) and \( K \) in this work was larger than those of previous studies.

Relation between \( \varepsilon \) and \( k_B \) is shown in Fig. 13. Although the mechanism of bubble generation was different between plunging and bottom bubbling system, \( \varepsilon \) and \( k_B \) in this work was located on the extended line of the previous values so that \( k_B \) can be expressed as the function of \( \varepsilon \). It is suggested that gas absorption phenomenon was deeply related to the flow in the vessel. However, considering that the horizontal axis in Fig. 13 was expressed by logarithm, considerably

### Table 5. Experimental conditions in different authors.

| Author          | Type         | Diameter of vessel (m) | Height of water (m) | Volume of water (m\(^3\)) | Diameter of nozzle (m) | Gas flow rate (Nm\(^3\)/s) | Gas, Density (kg/m\(^3\)) | \( K \) (1/s) |
|-----------------|--------------|------------------------|---------------------|---------------------------|------------------------|----------------------------|--------------------------|--------------|
| Sakaguchi et al.\(^{19}\) | Bottom bubbling | 0.19                   | 0.21                | 0.006                     | 0.002                  | 8.4 \times 10^{-6} \cdot 1.7 \times 10^{-4} | CO\(_2\), 1.977          | 5.2 \times 10^{-6} \cdot 1.1 \times 10^{-3} |
| Higuchi et al.\(^{20}\)    | Bottom bubbling | 0.40                   | 0.28                | 0.035                     | 0.002                  | 8.3 \times 10^{-7} \cdot 3.3 \times 10^{-4} | Ar, 1.784               | 4.0 \times 10^{-5} \cdot 8.7 \times 10^{-5} |
| This work             | Plunging     | 0.40                   | 0.24–0.40           | 0.030–0.050               | –                      | –                          | –                        | 6.7 \times 10^{-7} \cdot 9.0 \times 10^{-5} |
low \( \varepsilon \) was necessary to reduce \( k_B \). Thus, the decrease of the area of bubble was effective to inhibit the gas absorption.

### 4.3. Gas Absorption Site at Plunging Pool

The plunging pool at the water volume of 0.050 m\(^3\) in the lower vessel was virtually divided in 9 regions as shown in Fig. 14 to discuss the gas absorption phenomenon in detail. The estimated region was set 10 mm below water surface to avoid the turbulence of water surface. In this paper, we refer to the distance from center to 34 mm as center part, 34 to 48 mm as interval part and 48 to 59 mm as outside part. Similarly, we refer to the height between 10 to 90 mm from water surface as upper part, 90 to 170 mm as middle part and 170 to 280 mm as lower part. Velocity at bubble surface, \( u_B \) and area of bubble surface, \( A_B \) in the same volume at plunging pool were respectively compared.

Distributions of \( u_B \) and \( A_B \) at plunging pool are shown in Fig. 15. The maximum \( u_B \) was found at the center and upper part. It is considered that the velocity of plunged stream was so fast that the large \( u_B \) was found at the center part. In addition, the velocity of plunged stream reduced at the lower part of plunging pool so that small \( u_B \) was found at lower part. On the other hand, large \( A_B \) was found at the center and middle part, not upper part. It is considered that small bubbles were generated by the shearing of the engulfed bubbles due to the plunging stream in the center part. The numbers of bubbles at the lower part were small and bubble coalescence was occurred during rising so that the \( A_B \) in upper part was small.

It is assumed that \( k_B \) was proportional with square root of \( u_B \), \( u_B^{1/2} \), based on the penetration theory. Distribution of the product of \( u_B^{1/2} \) and \( A_B \) at plunging pool is shown in Fig. 16. It is found that the gas was most frequently absorbed at the center and middle part at plunging pool and 40% of gas absorption occurred at this region.

### 4.4. Expansion to the Steel-air System

Bubble generation phenomenon at plunging pool in steel-air system was calculated with CFD by changing the physical properties from those of water to steel as shown in
Fig. 16. Distribution of $u_{1/2} A_B$ at plunging pool.

Fig. 17. Comparison of bubble distributions.

Fig. 18. Comparison of $V_B$ between water-air and steel-air system.

Fig. 19. Comparison of $A_B$ between water-air and steel-air system.

Table 6. Simulation settings.

| Item     | Setting                     |
|----------|----------------------------|
| System   | Steel-air                   |
| Temperature | 1 873 K                   |
| Fluid density | liquid: 7 000 kg/m$^3$, gas: 1.78 kg/m$^3$ |
| Fluid viscosity | liquid: 4.54 mPa·s, gas: 0.0184 mPa·s |
| Surface tension | 1.72 N/m                   |

Table 6. Comparison of bubble distributions at the condition when the volume of liquid in the lower vessel was 0.030 m$^3$ (in the upper vessel was 0.025 m$^3$) is shown in Fig. 17. The bubbles which reached at the lower part of plunging pool were engulfed again by the plunging stream in water-air system. On the other hand, the large size bubbles were generated intermittently at the middle part of plunging pool in steel-air system. It was suggested that the bubble generation phenomenon at plunging pool in steel-air system was far different from that of water-air system. Additionally, temperature in steel-air system was set as 1 873 K so that the expansions of engulfed bubbles in the steel were not considered in this calculation.

The plunging pool was virtually divided into 5 parts in vertical direction and the volume and the area at bubble surface in each part were quantitatively calculated. Comparison of $V_B$ between water-air and steel-air system is shown in Fig. 18 and comparison of $A_B$ is shown in Fig. 19. Large bubbles were found in water-air system. The density of steel is higher than that of water and the static pressure is considerably large so that air was hard to be engulfed into steel. Large bubbles were found at lower part of plunging pool in both water-air system and steel-air system. It is thought that engulfed bubble remained at the bottom of plunging pool. On the other hand, large area at bubble surface was found in steel-air system at the upper part of plunging pool but large area at bubble surface was found in water-air system at the lower part of plunging pool. There is a size distribution of bubble in the real plunging pool but assuming that the plunging pool was constructed by the single sphere bubble, the volume of bubble could be expressed as Eq. (17) and the area of bubble surface could be expressed as Eq. (18) so that the average size of bubble could be calculated with Eq. (19).

\[ V_B = n \cdot \pi \cdot d_{ave}^3 / 6 \]  \hspace{1cm} (17)

\[ A_B = n \cdot \pi \cdot d_{ave}^2 \]  \hspace{1cm} (18)

\[ d_{ave} = 6 \cdot V_B / A_B \]  \hspace{1cm} (19)

Where $V_B$: volume of bubble (m$^3$), $n$: number of bubble per volume (–), $A_B$: area of bubble surface (m$^2$), $d_{ave}$: average diameter of bubble (m).

Comparison of $d_{ave}$ of bubble between water-air and steel-air system is shown in Fig. 20. Small average size of
bubble was found in steel-air system. It is thought that a lot of small size bubbles were generated but bubble coalescence occurred at the center of plunging pool in water-air system. On the other hand, the large size bubble was easy to found but it is suggested that many small size bubbles were generated too in steel-air system. In this work, temperature in steel-air system was set as 1873 K. However, bubble expansion would occur practically so that it is expected that bubble generation phenomenon in steel-air system was more complex. The problem related to gas expansion will be future work and linking between experimental and CFD result is essential.

5. Conclusions

The gas absorption phenomenon during tapping imitating the tapping from BOF to the ladle was experimentally estimated with the water model in this study. In addition, the amount of gas engulfment at plunging pool with the same water model was also experimentally estimated and calculated with CFD method. Gas absorption phenomenon was discussed with the calculated distribution of the area of bubble surface and volume. The results were as follows.

(1) The water model which could evaluate the gas absorption phenomenon during tapping was established and gas absorption rate was quantitatively estimated as volumetric coefficient, $A_k$.

(2) The volume of engulfed gas by plunging stream was quantitatively estimated with water model and CFD method. Experimental results were in good agreement with those of CFD when the criterion for liquid ratio was set as 0.5.

(3) The relation of mass transfer coefficient, $k_B$ between tapping and bottom bubbling experiment could be expressed with stirring power density, $\dot{\varepsilon}$.

(4) The product of $t_B^{1/2}$ and $A_B$ calculated by CFD method showed maximum value at the center and middle part of plunging pool and 40% of gas absorption occurred at this region.

(5) Along with the large size bubble, it is suggested that a lot of 1–2 mm size bubbles were generated at plunging pool in steel-air system.

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