1. Introduction

Gas bubbling can be a practical approach for removing inclusions from liquid steel in tundish operations.1–4) During bubble flotation, non-wetting inclusions can be attached to bubble surface,5) or captured by rising bubbles’ wakes.6) Micro-bubbles can effectively promote the removal of inclusions, especially for those smaller than 50 microns in diameter, which are currently very difficult to be removed in steelmaking operations. Zhang and Taniguchi7) have made a comprehensive review of possible mechanisms for inclusion removal in liquid steel involving their flotation with bubbles, based on theories derived from the flotation of particles in mineral processing operations. According to their report, the smaller the bubble size is, the higher is the inclusion removal efficiency. To reduce bubbles size in water systems, some researchers8–10) have investigated injecting gas through orifices on the inner wall of ladle shroud. There, bubbles were formed under the shearing action of the inertial flow of gas. Several researchers8,9) have also investigated the micrometer-sized bubbles’ growth in a liquid by the injection of argon gas to the liquid from orifices submerged in high velocity cross flow coupled with strong turbulence. This was accomplished by using hydrophobic coating, sprayed onto the inner surface of the vertical acrylic ladle shroud, forming a contact angle of 150° at the three-phase line of contact, versus an angle of −45° on the bare plexiglas surface. As such, the poor wettability of the treated acrylic surface of the ladle shroud led to slight increases in the diameters of micro-bubbles of 8.0%–22.4%, vs wetting systems, depending on gas flow rate and gas injection position. The present results indicate that the cross flows of liquid and their associated kinetic energy of turbulence within a ladle shroud flow can effectively refine bubbles into the micron size range, and prevent bubble growth caused by the poor wettability of liquid steel. Thus, argon gas injection through a ladle shroud could be an effective approach of producing small bubbles in liquid steel, even under the non-wetting conditions associated with such flows, which cannot be achieved by conventional gas curtain technique.

KEY WORDS: continuous casting tundish; inclusion removal; micro-bubbles; water modeling; non-wetting conditions; contact angle.
face of a nozzle, and then tend to grow based on the outer circumference of the nozzle (Fig. 1(b)). Therefore, the water modeling of gas bubbling in tundish cannot reliably reflect the size of bubbles formed in liquid metal systems. Irons and Guthrie\(^{16}\) used an acoustic device to detect the vibrations caused by the submerged argon bubbles released into liquid pig iron at 1 523 K through a graphite nozzle. The bubble sizes were calculated by the sound frequency and the gas flow rate. Considering the large volume of a typical tundish and the non-wetting condition on the solid-liquid interface, the sizes of bubbles generated in liquid pig iron is at least 5 mm in diameter, which is much larger than those obtained from aqueous systems. Sano \textit{et al.}\(^{17}\) investigated the formation of bubbles in mercury contained in a glass tank with a diameter of 10 cm. Nitrogen was injected through two non-wetting nozzles with different dimensions. A fine molybdenum probe was placed above the nozzle to record the resistance variation caused by the bubbles passing through the probe, which reflected the frequency of bubble formation. According to their results, the bubbles formed by nozzle No.1 (with a larger outer diameter of 7 mm and smaller inner diameter of 2 mm) were always greater than those generated from nozzle No.2 (with a smaller outer diameter of 4 mm and a larger inner diameter of 2.4 mm), under gas flow rates from 10 to 20 000 mL/s. This illustrated that the size of bubbles formed in non-wetting conditions was controlled by the outer diameter of the nozzle, while independent from the nozzle inner diameter.

Ideally, liquid metals should be used to study the bubble formation behavior under non-wetting conditions. Nevertheless, there are some inconveniences when conducting experiments with liquid metals, such as the high melting temperature of liquid steel, potential toxicity for mercury spills, and the high cost of alloys with low-melting range of temperature. Furthermore, almost all kinds of liquid metals are non-transparent, which will cause even more difficulties for bubble measurements. Therefore, water modeling is still a practical approach to simulate the gas bubbling phenomena in the steelmaking process.

This article, as a continuation of previous work,\(^{18,19}\) is aimed at studying the formation of micro-bubbles under non-wetting conditions in the ladle shroud of a full-scale water model tundish. A hydrophobic coating was sprayed on the surface of the gas ports in the aqueous system, in order to simulate the non-wetting interface between the refractory gas port and liquid steel. A novel ladle shroud, with small orifices in its upper section, was developed to produce micro-bubbles with various gas injection schemes. Micro-bubbles were formed, using the combined effects of shearing water flow and the kinetic energy of turbulence within the flow system. The influence of wettability on bubble formation in complex flow is discussed, by comparing the sizes of bubbles generated from the orifices either with or without a hydrophobic coating, under correspondingly same gas injection parameters.

2. Experimental Works

The experimental works were carried out in a full-scale, four-strand water model tundish, located at the McGill Metals Processing Centre, which was designed based on an industrial prototype tundish with a capacity of 12 t, producing 165 mm square billets at a casting speed of 1.5 m/s. The tundish configuration and its key dimensions are shown in Fig. 2.

A water flow rate of 170 L/min was maintained by a water height of 1.25 m in the ladle above, and a slide gate with an opening ratio of 39%. The total flow rate through the four outlets was equal to that of inlet flow through the ladle shroud, so as to keep the depth within the tundish, steady at 550 mm. Figure 3 shows the construction of the ladle shroud. There are 12 gas injecting ports located at the upper section of the ladle shroud, uniformly distributed into three layers, 42 mm, 62 mm and 82 mm below the bottom of the slide gate, respectively. Each gas port was formed by laser drilling with a diameter of 0.3 mm, which can be connected to a gas injection system, or sealed by nylon screw, through the screw hole outside. Given that the main purpose of this work was to investigate the impact of interfacial wettability on bubble formation, complicated gas injection combinations included in the design.

![Fig. 1. Bubble formation in a virtually stagnant volume of a liquid, through a submerged nozzle under: (a), wetting conditions, and (b), non-wetting conditions.](image1)

![Fig. 2. Top view of the water model tundish with key dimensions (mm).](image2)

![Fig. 3. The structure of the novel ladle shroud.](image3)
schemes were avoided. Gas was injected through a single gas port located at different positions. The flow rate of gas was precisely controlled by a needle valve and measured with a thermal volume flow meter, having a range from 0.1 to 0.8 L/min.

**Figure 4** shows the experimental set-up for bubble measurements. It is well known that the distance between the bubble and the lens affects the bubble sizes shown on the image, during the photo shooting process. To solve this problem, an inclined plexiglas plate was placed beneath the ladle shroud. After coming out from the ladle shroud, bubbles, moving downward with the entry flow, would hit the plate, and then, be washed away by the water stream immediately. A high-speed camera was used to record bubbles, with its primary lens focused on the inclined, transparent, plexiglas plate. Sufficient background lighting was provided by Two LED light fixtures. The shutter speed was 2,500 frames per second, and the photo interval was set as 5 s. As such, only the bubbles hitting the plate could be filtered out during image post-processing. The impact zone on the inclined plate remained blurred, and those away from the shooting area, could be clearly displayed on the image, during the photo shooting process. To solve this issue, an inclined plexiglas plate was placed beneath the orifice, in order to protect the gas channel from being sealed, but simultaneously leaving the front face of orifice be covered.

At the beginning of each experiment, a steady level of water in the tundish was obtained by controlling the inlet and the four outlet water flow-rates. Before the start of bubble measurements, gas was pre-injected for ten minutes, at the specified flow rate, so as to obtain a steady bubble swarm.

3. Numerical Simulations

A numerical model was developed to calculate the turbulence dissipation within the upper section of the ladle shroud, using the standard k-epsilon turbulent model, coupled with the discrete phase model. The continuous phase was assumed as an incompressible Newtonian fluid. In terms of discrete phase, all bubbles were spherical and their volume changes during movement were neglected. For the calculation of continuous phase, the following governing equations were solved in a three-dimensional Cartesian coordinate system.

The continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \hspace{1cm} \text{(1)}$$

The momentum conservation equation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho \alpha_i F$$

Two-way coupling was achieved by calculating the momentum change caused by the discrete phase movement

$$F = -\sum F_{Dp} (u - u_k) m_b \Delta t \hspace{1cm} \text{(3)}$$

The kinetic energy of turbulence

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu_{eff} + \mu_t \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \hspace{1cm} \text{(4)}$$

The turbulent dissipation rate

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu_{eff} + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \frac{\varepsilon}{k} G_k - C_2 \frac{\varepsilon^2}{k} \rho \hspace{1cm} \text{(5)}$$

The generation rate of turbulence kinetic energy, $G_k$, and the effective viscosity, $\mu_{eff}$, can be expressed by the following equations.

$$G_k = \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \hspace{1cm} \text{(6)}$$

$$\mu_{eff} = \mu + \mu_t = \mu + C_\mu \rho \frac{k^2}{\varepsilon} \hspace{1cm} \text{(7)}$$

The empirical constants appearing in the model were set as $C_1=1.44$, $C_2=1.92$, $C_\mu=0.09$, $\sigma_\varepsilon=1.0$, $\sigma_i=1.3$, in accordance with the recommendation of Launder and Spalding. The trajectories of bubbles can be calculated using an
Euler-Lagrangian approach, namely as Discrete Phase Model (DPM),\textsuperscript{23}) since the maximum gas flow rate was still far less than 1\% of the flow rate of water. The force balance acting on each bubble can be given by

\[
d\frac{u_b}{dt} = F_D (u - u_b) + F_r + F_g \quad \ldots (8)
\]

Due to a significant difference between the densities of bubbles and water, the effect of virtual mass force and pressure gradient force need to be considered in the source term, \( F_r \).

\[
F_m = \frac{1}{2} \frac{d}{dt} (u - u_b) \quad \ldots (9)
\]

\[
F_r = \left[ \frac{\rho_b}{\rho_g} \right] u_b \nabla u \quad \ldots (10)
\]

\( F_D (u - u_b) \) represents the drag force per unit bubble mass, where \( F_D \) is given by

\[
F_D = \frac{18 \mu}{\rho_b d_b^2} C_D Re \quad \ldots (11)
\]

Here, the size of bubbles (\( d_b \)) is 0.894 mm, corresponding to a typical experimental result under non-wetting conditions. The drag coefficient (\( C_D \)) can be expressed based on the model proposed by Morsi and Alexander.\textsuperscript{23} The values of the constants, \( a_1, a_2, a_3 \), depend on the bubble’s Reynolds number.

\[
C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \quad \ldots (12)
\]

The effect of turbulence on bubble dispersion was incorporated using discrete random work (DRW) model. The instantaneous velocity of continuous phase can be expressed as the sum of mean flow velocity and the random velocity fluctuation caused by turbulence.

The system of equations was solved based on ANSYS Fluent 14.5 package. As shown in Fig. 5, the computation domain was meshed into 74,000 hexahedral grids, using ICEM 14.5. Water was injected from a velocity inlet, with a vertical velocity of 1.8 m/s, and flowed out through a pressure outlet, with a zero gauge pressure. The initial turbulence parameter of the inlet flow can be specified by following equations.

\[
k = \frac{3}{2} (u_w l)^2 \quad \ldots (13)
\]

\[
\epsilon = C_\mu \frac{k^{3/2}}{l} \quad \ldots (14)
\]

Since the liquid flow in ladle shroud is similar to a pipe flow, the turbulence intensity, \( I \), and the turbulence length scale, \( l \), can be expressed by the following equations.

\[
l = 0.16 Re^{-1/8} \quad \ldots (15)
\]

\[
l = 0.07 L \quad \ldots (16)
\]

By assigning the diameter of the ladle shroud, \( L \), the initial value of the turbulence intensity and the turbulence length scale can be obtained as 0.039 and 0.0031 m, respectively.

All the solid walls were assumed to be no-slip. The SIMPLEC algorithm was applied to the velocity–pressure coupling. The second upwind order scheme was employed for the discretization of momentum, \( k \), and \( \epsilon \) equations. Calculation was regarded as being converged when the normalized residuals of all variables were smaller than \( 10^{-4} \). A fixed time step of 0.0001 s was used in the time dependent solution.

4. Results and Discussion

4.1. Contact Angle Measurement

Contact angle is a measurement of how a liquid interacts with a solid surface, which is defined as the angle between the liquid-gas interface and the solid surface. For a water droplet on an ideal surface, the contact angle can be expressed as a function of three interfacial energies, appearing in Young’s equation. A contact angle below 90° corresponds to a wetting condition, where the liquid will spread over a large area of the surface. By contrast, a contact angle larger than 90° indicates a non-wetting condition, where the liquid will minimize contact with the surface, forming a compact liquid droplet.\textsuperscript{24} Hence, the wettability of the liquid-solid interface can be presented through contact angle measurement for a sessile drop of liquid. Figure 6 shows the comparison between the water droplet on the plexiglas surface with and without the hydrophobic coating. It is apparent that the water was well spread on the bare plexiglas surface, forming a contact angle around 45°, indicating a wetting condition at the three-phase interface. However, it was observed that water droplet is shaped into a nearly perfect sphere when it rests on the surface of plexiglas with a hydrophobic coating. The angle at the three phase contact line is around 150°. The water droplet even rolls down when slightly inclining the substrate. This is very close to the motion behavior of liquid steel on smooth refractory surfaces.
4.2. Bubble Formation Under Different Gas Flow Rates

Figure 7 shows the bubbles produced using a wetting orifice (bare plexiglas) and a non-wetting orifice (plexiglas with hydrophobic coating), respectively, under various gas flow rates. The vertical black line on each photo is the gap between two pieces of LED lights, which can be filtered out in image post-processing. The scale at the right bottom corner of each photo was determined by photographing the ruler at the same position, and was used for unit length calibration in bubble measurements. It is clear from the figures that a higher gas flow rate leads to the formation of larger bubbles. Under the same gas flow rate, it can also be observed that the bubbles formed from a wetting orifice were slightly smaller than those formed from a non-wetting orifice.

According to the post-processing results, the bubbles size follows a quasi-normal distribution, and about 90% of the bubbles were concentrated around the mean bubble size within a narrow range of ±0.05 mm. It is worth noticing that, for each case, the image on Fig. 7 is one of the photos taken in the experiment, while the corresponding bubbles size listed in Table 1 is a statistical result, obtained from a total of 25 photos. The average diameter of bubbles was 0.675 mm under a wetting condition with a gas flow rate of 0.1 L/min. With a non-wetting orifice instead, the average bubble size increased by 22.4%, up to 0.826 mm. As the gas flow rate was doubled to 0.2 L/min, the bubbles under non-wetting condition grew to 0.894 mm in diameter, displaying an 11.0% rise, compared with those generated with the wetting orifice under the same gas flow rate. In further tests, bubbles size exhibited a rising trend with further increases in gas flow rate. The relative differences between wetting and non-wetting conditions were +19.4% and +18.5%, under gas flow rates of 0.4 L/min and 0.8 L/min, respectively.

Table 1. Comparison of the size of bubbles generated with different gas flow rates, under wetting and non-wetting conditions.

<table>
<thead>
<tr>
<th>Gas flow rate (L/min)</th>
<th>Wetting (mm)</th>
<th>Non-wetting (mm)</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.675</td>
<td>0.826</td>
<td>22.4%</td>
</tr>
<tr>
<td>0.2</td>
<td>0.812</td>
<td>0.894</td>
<td>11.0%</td>
</tr>
<tr>
<td>0.4</td>
<td>0.966</td>
<td>1.153</td>
<td>19.4%</td>
</tr>
<tr>
<td>0.8</td>
<td>1.117</td>
<td>1.324</td>
<td>18.5%</td>
</tr>
</tbody>
</table>

4.3. Regimes of Bubble Formation

Gnyloskurenko et al. performed water modeling to investigate the surface phenomena effect on bubbles generated from a submerged nozzle with an inner diameter of 1 mm. The gas flow rate was fixed as 0.002 L/min. Three types of orifice surfaces, including bare acrylic plastic, surface coated by silicon vacuum grease and paraffin, were used to obtain a wide range of contact angle at the boundary of the three phase interfaces. Very poor wettability was achieved by coating paraffin on the surface of nozzle, with a contact angle of 110°. When gas was injected through this nozzle, the bubbles size was 62.86 mL in volume, i.e. 4.933 mm in diameter. This is much bigger than the bubbles produced in the present study. It was also reported that the size of bubbles substantially depended on the effect of con-
tact angle hysteresis, making an increase by more than 30% with the contact angle rising from 68° to 110°.

Gerlach et al.\textsuperscript{26)} discussed the influence of the contact angle on bubbles generated from a submerged nozzle, based on the force balance analysis. In the experimental work, a shadow imaging technique was used to measure the shape of bubbles during its expansion. Figure 8 shows the contours of the bubbles formed, using a submerged Teflon gas nozzle with a theoretical contact angle of 108° at the three phase contact line, which can be defined as a non-wetting condition. The result shows that bubbles tend to spread along the horizontal surface rather than grow based on the rim of the nozzle under non-wetting conditions. According to their model, the size of bubble would increase by more than three times when the contact angle rises from 70° to 150°.

Chesters\textsuperscript{27)} had proposed a model to predict the growth of bubble from a submerged nozzle under the slow-formation regime, assuming that the contact line would spread along the horizontal surface, once the instantaneous contact angle at the bubble boundary during its growth reached the Young’s equilibrium contact angle, as determined by the surface energies of the three phases. According to his theory, the greater the Young’s equilibrium contact angle is, the larger is the size of bubbles formed. In addition, many other studies\textsuperscript{28–30)} have proved that both a lower gas flow rate and a smaller orifice size are beneficial for reducing bubbles size. Therefore, the bubbles produced by Gerlach et al.\textsuperscript{26)} should be much smaller than those in the present work, due to a combination effect of the smaller nozzle size of 0.26 mm in diameter, the extremely low gas flow rates in their experiment, 0.02 L/min in maximum, along with the smaller contact angle of 110° in their study. However, it can be estimated from Fig. 8 that the size of the bubbles they produced was around 1.5 mm in diameter, much bigger than the bubbles formed in the present study. This totally went against the theoretical prediction. Table 2 summarized the size of bubbles and relevant bubbling parameters in the present experimental study, and compared with the results of the reference works mentioned above. The differences between bubble sizes can be expressed by the following equation.

\[
\text{% Difference} = \frac{\text{Present result} - \text{Result from other research}}{\text{Present result}} \times 100\% \quad \text{(17)}
\]

It is noteworthy that the experiments of Gerlach et al.\textsuperscript{26)} and Gnyloskurenko et al.\textsuperscript{25)} were both operated under quasi-static conditions, in which the liquid flow velocity was approximately equal to zero. As such, liquid flow had no effect on bubble formation. By contrast, the present experiments generated bubbles in the entry flows where a relatively high liquid velocity coupled with strong turbulence prevailed. This leads to a refining effect during the birth of bubbles within the liquid, and explains why bubbles size produced in their studies were much larger than those obtained in the present experiments, by some 500% higher.

In industrial operations, the liquid steel flows very smoothly outside the entry region of the tundish, at velocities of less than about 10 cm/s.\textsuperscript{31,32)} As such, when gas is injected through a porous plug at the bottom of the tundish, the bubbles can be regarded as being formed under quasi-static conditions. More importantly, bubble expansion under non-wetting conditions will cause coalescence of bubbles on the surface of a porous plug nozzle. This will dramatically increase the final size of bubbles in liquid steel versus those obtained from water modeling.

In contrast, for gas injection into a vertical ladle shroud, two phenomena were responsible for producing micro bubbles in non-wetting system. At the start of gas injection, the primary bubble initially grew up to form a hemisphere at the gas orifice. This is referred to as the “gas base”; the gas will then spread downstream, along the ladle shroud surface, under the effects of interfacial tension and the shearing forces of the liquid flow. During this stage, the gas base remains attached to the orifice, and will also be deformed under the effect of the shearing force generated by a mean water flow velocity of 1.8 m/s. The deformation of the gas film became increasingly severe with continued gas injection, until it separated from the gas base, finally resulting in a bubble release.

Marshall et al.\textsuperscript{33)} performed water modeling experiment to study bubble forming at an orifice exposed to liquid cross-flow. According to the statistical analysis of experimental data, an empirical formula was proposed to express the correlation between the forming bubble diameter and other variables.

\[
d_b = 0.96 R_o 0.826 \left( \frac{u_g}{u_l} \right)^{0.36}
\]

where, \(R_o\) is the orifice radius, \(m\); \(u_l\) represents the liquid flow velocity and \(u_g\) stands for the velocity of gas flow passing through the orifice, m/s. By assigning the gas injection parameters of the water experiment to Eq. (18), the initial size of bubbles formed by shear action can be predicted to be 1.68, 2.02, 2.77, and 3.56 mm under gas flow rates of

\[
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Bubble size mm} & \textbf{Gas flow rate L/min} & \textbf{Nozzle size mm} & \textbf{Contact angle \textdegree} & \textbf{Difference of bubble sizes} \\
\hline
\textbf{Present work} & 0.826 & 0.1 & 0.30 & 150 & -- \\
\hline
\textbf{Gerlach et al.\textsuperscript{24)}} & 1.500 & 0.02 & 0.26 & 110 & -81.6\% \\
\hline
\textbf{Gnyloskurenko et al.\textsuperscript{25)}} & 4.933 & 0.002 & 1.00 & 108 & -497.2\% \\
\hline
\end{tabular}
\]
0.1, 0.2, 0.4 and 0.8 L/min, respectively. These are much greater values compared with the corresponding experimental measurement in the present water modeling experiments.

After releasing from the orifice, the initially formed bubbles were entrained into the liquid flow field within the ladle shroud. There, the bubbles would oscillate violently and could be further refined under the impact of the liquid’s kinetic energy of turbulence. This was caused by the high speed entry flow, combined with the non-fully opened slide gate.

In order to investigate the effect of turbulence on the break-up of bubbles, additional experiments were performed using gas injection from different positions, corresponding to different turbulence dissipation rates. The gas flow rate was fixed at 0.2 L/min, leaving the injection position as the only variable. Results of bubble record were shown in Fig. 9. Under wetting condition, the average bubble size increased to 0.895 mm and 0.915 mm when the gas was injected from the port located at the second and third injection layer, respectively. More detailed post-process results are listed in Table 3. In non-wetting systems, bubbles size followed the same tendency with the moving down of gas injection port, and showed a growth of 8.0–10.8%, compared with the size of bubbles generated under wetting conditions. The impact of interfacial wettability on bubble sizes is not significant.

Evans et al.34) have proposed a model to predict the maximum size for bubbles to remain stable within turbulent flows, based on the assumption that a bubble would be broken once the Weber number of the bubble had reached a critical value. Extensive experiments were performed with various operational parameters, in order to calibrate the critical Weber number. The results showed that a critical Weber number of 1.2 indicated a good consistency between experimental measurements and model predictions. Therefore, the maximum bubble size, \( d_b \), can be simplified to be a function of the dissipation rate of the kinetic energy of turbulence, as follows:

\[
d_b = \left( \frac{1.2 \sigma}{\rho_w C \varepsilon^{2/3}} \right)^{3/5}
\]

where, \( \sigma \) is the interfacial surface tension, N/m; \( \rho_w \) represents the density of water, kg/m\(^3\); \( \varepsilon \) stands for the dissipation rate of the turbulence kinetic energy, m\(^2\)/s\(^3\); and the empirical constant \( C \) is equal to 2.

A three dimensional numerical simulation was conducted to predict the distribution of the turbulence dissipation rate. The comparison between numerical results with and without gas bubbles indicates that gas injection can hardly impact the flow field within the ladle shroud. This is mainly due to the strong turbulence and the small flow rate of gas, only accounting for 0.12% of the entry flow rate. As shown in Fig. 10, owing to high-speed entry flows coupled with a non-fully opened slide gate, high turbulence dissipation rates were concentrated in top region of the ladle shroud, which can be referred to as the “turbulence dissipation region”. By assigning distribution of turbulence dissipation rates to Eq. (19), bubbles should have reached predicted sizes of 0.403, 0.557, and 0.625 mm, when being generated from the gas port located at the first, second and third injection layer. Obviously, the predicted bubble sizes are much

![Fig. 9. Bubbles generated in wetting systems using a gas port located at: (a) the first layer, (c) the second layer, (e) the third layer, compared with those obtained in non-wetting systems using a gas port located at: (b) the first layer, (d) the second layer, (f) the third layer.](image)

![Table 3. The size of bubbles generated from different gas injection positions, under wetting and non-wetting conditions.](table)

<table>
<thead>
<tr>
<th>Gas injection layer</th>
<th>Wetting (mm)</th>
<th>Non-wetting (mm)</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>0.812</td>
<td>0.887</td>
<td>9.2%</td>
</tr>
<tr>
<td>2nd</td>
<td>0.895</td>
<td>0.967</td>
<td>8.0%</td>
</tr>
<tr>
<td>3rd</td>
<td>0.915</td>
<td>1.014</td>
<td>10.8%</td>
</tr>
</tbody>
</table>

![Fig. 10. Distribution of the turbulence dissipation rate at the top part of the ladle shroud. (Online version in color.)](image)
smaller than actual bubble measurements. It is noteworthy that Eq. (19) was proposed based on the assumption that bubbles were entrained within this turbulent flow regime for sufficiently long time. However, under the effect of drag force, the bubbles formed in the present study moved downward with the entry flow at an equivalent velocity. Hence, it can be deduced that the initial formed bubbles could only be partially broken down by the turbulent flow, due to their limited residence time within the turbulence dissipation region, as well as the attenuation of turbulence dissipation rate during bubble movement. In conclusion, the final bubble size was determined by the effects of turbulent flow on breaking down the initial bubbles, combined with the birthing bubbles being sheared away from the orifice under the shearing actions of the vertical flow of liquid.

5. Summary

Experimental work was carried out in a full scale, four-strand water model tundish, in order to investigate the formation of bubbles, shearing by cross flow under different interfacial wettabilities and further refining in turbulent flow. A novel ladle shroud, with 12 small orifices close to its top, was employed to produce micro-bubbles. A surface modification technique was used to create poor wettability of the orifice surface, for simulating bubble formations in a liquid metal in contact with a refractory material. The sizes of bubbles formed at different gas flow rates and gas injection positions were measured using a novel optical methodology. For comparison, bubbles were also produced from a bare plexiglas orifice in a ladle shroud, using the same operating parameters. The main conclusions drawn from this work are as follows:

(1) Water modeling using a surface modification technique is an appropriate approach to study gas bubbling operations in real metallurgical processes. The hydrophobic coating decreases the wettability of the nozzle surface in an aqueous system, producing an angle of 150° at the contact line of three phases. This makes the regime of bubble formation in aqueous system similar to that in liquid metals.

(2) The bubble refining by ladle shroud gas injection can be divided into two stages. In the first stage, bubbles were split from the orifices under the shearing action caused by the high-speed vertical cross flow of liquid. In the second stage, the initially formed bubbles were partially broken by the dissipation of turbulence kinetic energy, due to their limited residence time in turbulence dissipation area. The final bubble size of micro bubbles was still dependent on the size of birthing bubble.

(3) The size of bubbles increases with the increasing gas flow rate and moving down gas injection port. Since the bubble formation was dominated by the liquid flow within the ladle shroud, size of bubble from non-wetting gas ports was slightly increased over wetting ports, by +8.0% to +22.4%, depending on gas injection schemes.

(4) By comparison with bubble formation using gas curtain technique, it can be concluded that gas injection through a ladle shroud can effectively prevent bubble growth caused by the poor wettability, so as to achieve the production of micro bubbles in liquid steel.

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