Research Article

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Physical modeling of bubble behaviors in molten steel under high pressure

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Abstract: A water model was adopted to conduct an experimental study on the physical modeling of bubble behaviors and the effects of vessel pressure intensity, nozzle aperture diameter, bottom blowing location and bottom blowing flow rate on bubble properties were analyzed. Experimental results show that with the increase in vessel pressure intensity, the bubble breaking distance is shortened, the size is decreased, the number is increased, the degree of deformation in the rising process becomes smaller, and the fluctuation range of liquid level becomes small; in addition, the diameter of bubbles breaking away from the nozzle decreases. With the increase of bottom blowing aperture diameter, the average diameter of bubbles on the liquid level gets bigger and the number of bubbles decreases; moreover, the size of bubbles breaking away from the nozzle increases, their shape tends to be oval, and the time from bubble formation to bubble breaking is longer. With the increase of bottom blowing flow rate, the bubble breaking distance gets long, the size and number of bubbles increase, the bubble shape tends to be oval, and the impact force on the liquid level becomes larger. The greater the pressure intensity of the vessel, the closer the bottom blowing position is to the center, and the smaller the average diameter of bubbles.

Keywords: physical modeling, bubble, vessel pressure intensity, bottom blowing aperture diameter, bottom blowing flow rate

1 Introduction

Bottom blowing gas stirring can improve the kinetic conditions of the metallurgical molten pool, promote heat and mass transfer in the molten pool, and accelerate the chemical reaction of the molten pool. In addition, the reaction conditions in the reaction vessel can be changed to control the progress of each reaction to achieve the purpose of selective oxidation. It is widely used in the metallurgical process. The combination of bottom blowing gas stirring and various metallurgical equipment can achieve different metallurgical effects. In primary furnaces such as converters and electric arc furnaces, bottom blowing gas stirring can accelerate the chemical reaction speed in the molten pool, promote the reaction process, reduce the carbon and oxygen content in the molten steel, and reduce the oxide inclusions in the molten steel [1,2]. Moreover, during the AOD refining process [3], a certain proportion of oxygen–argon gas is sprayed into the furnace from the lower side of the furnace body. The sprayed mixed gas strongly stirs the molten steel. In addition, a violent decarburization reaction occurs on the surface of the bubbles. Moreover, the selective oxidation of carbon and chromium is changed to achieve the metallurgical purpose of carbon removal and chromium preservation [4]. Japan has transformed and developed traditional VOD equipment, forming SS-VOD (Strong Stirring VOD) technology [5]. When the carbon content in the molten steel is less than 0.01%, increase the vacuum and stir with argon to further improve the kinetic reaction of decarburization and denitrification, and promote deep decarburization and deep denitrification [6]. During the RH smelting process, the bottom blowing gas optimizes the flow and mixing of molten steel in the ladle, increases the collision and aggregation growth rate of inclusions and the average size of inclusions, improves the dehydrogenation effect, and increases the dehydrogenation rate [7,8].

AOD, VOD, VD and RH use low-pressure metallurgy. More importantly, it is used to reduce the partial pressure of carbon monoxide, promote the carbon-oxygen

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reaction, and remove free oxygen in the molten steel without adding oxides. Simultaneously, the CO product and the introduced gas improve the mass transfer conditions of the smelting process, accelerate the metallurgical reaction rate, and promote the movement of the phase equilibrium direction of the metallurgical reaction.

In the molten steel refining process, the bubble behaviors in molten steel play an important role in material transfer and energy transmission. The gases are blown from the steel ladle bottom to the molten steel, and various material transfer activities and physical and chemical reactions take place on the gas–liquid interface in the bubble rising process. During this process, the size, shape, and number of bubbles in molten steel constantly change, and there is bubble formation, growth, coalescence, and breaking processes. The rising bubbles cause molten steel to be stirred and circularly flowed, studying bubble behaviors in liquid steel has significant research value [9–11]. The probe into the rule of bottom blowing gas behavior in molten steel under high pressure has a certain significance, especially in the analysis of the form and movement behavior of bubbles in molten steel, and the high-pressure metallurgy attracts the attention of some metallurgists and experts [12].

When the bottom gas blowing is done at the molten steel bottom via one or more sharp-edged orifices, the bubble formation and movement processes are very complex. Many scientific researchers have conducted studies on the behaviors of orifice bubbles in molten steel [13–16], but there is not yet a unified cognition about the bubble formation mechanism. The behavioral research of single-orifice bottom blowing bubbles in the liquid indicates that [17,18] in the case of single-orifice bottom blowing at the viscous liquid bottom, the formation and change modes of bubbles in the liquid are different due to different bottom blowing flow rates. When the flow rate is small, bubbles individually break away from the bottom blowing nozzle one by one; when the flow rate is large, the bottom blowing gas forms a continuous jet flow in the liquid and the jet flow is quickly broken into bubbles with different sizes. Related research on bubble departure condition shows that when the narrow-necked length of the bubble is greater than or equal to the aperture diameter, the bubbles depart [19]. The study on the formation of a single bubble in solid suspension liquid indicates that [20], the pressure intensity has a great effect on the bubble size under the pressure intensity of 0.1–21 MPa. In addition to the liquid viscosity, density, surface tension, and pressure intensity, the gas flow and bottom blowing aperture diameter have a great effect on bubble movement behaviors. The correlation study on the behaviors of bubbles in the liquid under high pressure and temperature increase

conditions shows that [21] the physical property parameters of liquid change with the change of pressure intensity. When the temperature is below the normal boiling point, the pressure intensity increases from 0.1 to 21 MPa, and the density of liquid increases by about 5%. In the whole pressure intensity range, however, when the temperature rises from 293 to 393 K, the density of liquid decreases by roughly 6%; when the temperature is 293 K and the pressure intensity increases from 0.1 to 21 MPa, the liquid viscosity increases by 65%; when the temperature is at 300 or 351 K, the pressure intensity increases from 0.1 to 21 MPa and the surface tensions reduce by 25 and 35%, respectively.

In chemical reactions, the three most important thermodynamic factors are chemical composition, temperature, and pressure. Chemical composition and temperature have been widely used in traditional metallurgical processes. Due to the limitations of smelting equipment, the application of pressure in metallurgy in steel metallurgy production has been relatively slow. However, stress is the only one of these three factors that can change by orders of magnitude, and stress also plays a vital role. Low pressure metallurgy has been widely used in steel metallurgy production. For example, the development of vacuum metallurgy such as VD, VOD and RH has played a role in improving steel quality and expanding steel varieties. High pressure metallurgy is currently involved in molten steel metallurgy. This paper adopts a water modeling method to analyze the movement states and change rules of both bubbles on the liquid level and freely rising bubbles in the liquid under high pressure and normal pressure conditions, and study the effects of pressure intensity, bottom blowing flow rate, nozzle aperture diameter and bottom blowing location on the behaviors of gases in the liquid.

2 Experimental method of high pressure water model

In the simulation process of bottom blowing gas in molten steel under high pressure, the approximation model method is used to consider main dynamic similarity and geometric similarity.

2.1 Geometric similarity

Based on a 150 t ladle in a steel plant, Table 1 lists the main parameters of the prototype and model whose

Table 1: Main parameters in prototype and model

Parameter	Top diameter (mm)	Basal diameter (mm)	Ladle height (mm)	Density ($\text{kg}\cdot\text{m}^{-3}$)	
				Liquid	Gas
Prototype	3,000	2,651	3,915	7,100 (Liquid steel)	1.78 (Ar)
Model	115	100	150	1,000 (Water)	1.25 (N_2)

geometric similarity ratio is 1:26. The mathematical expression of geometric similarity ratio is:

$$\lambda = \frac{L_m}{L_p}, \quad (1)$$

where p is the prototype and m is the model.

2.2 Dynamic similarity

During the process in the ladle with bottom stirring, the main driving force for the liquid steel cycle contains bubble buoyancy and inertia force of jet velocity. Therefore, to remain dynamic similarity between prototype and model, simulation method is applied to keep Fr in model equal to that in a prototype. According to similarity theory, gas flow with bottom stirring is assured in the physical model. The modified formula of Fr is as follows:

$$Fr' = \frac{\rho_g u^2}{\rho_l g H}, \quad (2)$$

where H is the depth of molten pool, ρ_l is the liquid density, ρ_g is the gas density, and u is the characteristic velocity.

$$u = \frac{4Q}{(\pi d^2)}, \quad (3)$$

where Q is the gas volume capacity and d is the nozzle aperture diameter.

The formula (3) is applied in formula (2), resulting in

$$Fr' = \frac{1.621 \rho_g Q^2}{\rho_l d^4 g H}. \quad (4)$$

Given that $(Fr')_m = (Fr')_p$, it can be calculated as follows:

$$Q_m = \left[\frac{\rho_{g,p}}{\rho_{g,m}} \cdot \frac{\rho_{l,m}}{\rho_{l,p}} \left(\frac{d_m}{d_p} \right)^4 \left(\frac{H_m}{H_p} \right) \right]^{\frac{1}{2}} Q_p. \quad (5)$$

Therefore, formula (5) is used to assure nitrogen flow with bottom stirring in the physical model to keep dynamic similarity between model and prototype.

The major experimental equipment include high-pressure furnace, bottom blowing gas control device, image acquisition device, and lighting device, as shown in Figure 1. In the water model, the rated pressure intensity of the high-pressure furnace body is 2.5 MPa, and the measuring range of the gas flowmeter is $4\text{--}40 \text{ L}\cdot\text{h}^{-1}$.

The organic glass crucible is installed in the high-pressure furnace; the scale is fixed on the outside of the

(a)

(b)

Figure 1: High-pressure bubble water modeling device: (a) physical image of high-pressure bubble water modeling device and (b) schematic diagram for high-pressure bubble water modeling device.

crucible; water is added to the crucible; the furnace lid is closed; the furnace lid and furnace body are fixed with bolts. Before the experiment, the pressure gage at the reducing valve outlet is adjusted to 2.5 MPa to make the gas rotameter under the working pressure, and then the copper pipe valve is adjusted to blow gas in the high-pressure furnace. The high-speed camera is used to collect image data. After the experiment, the Image-Pro and Origin software are used to process experimental images and data.

3 Results and discussions

3.1 Effect of pressure intensity on single bubble behavior

Figure 2 is a composite diagram for a single bubble from departure from bottom blowing nozzle to rising to the liquid level with bottom blowing flow rate of $4 \text{ L} \cdot \text{h}^{-1}$, bottom blowing aperture diameter of 1 mm, as well as bottom blowing at the center. As shown in Figure 2(a), the bubble is formed under the pressure of 0.1 MPa; at the moment of the bubble departing from the nozzle, since the necking of the bubble at its tail causes the bubble shape center to rapidly move upward, there is accelerated movement of bubble; in the acceleration process, the

bubble changes from rigid spherical shape to long ball cap shape under the action of viscous resistance, the horizontal cross-sectional area of the bubble becomes large to make the bubble slow down, and then the bubble becomes a flat shape and then a concave pit shape; after that, the bubble floats upward in a bag shape in the rising process. In Figure 2(b), the bubble is formed under the pressure of 0.5 MPa; the shape changes at the earlier stage of bubble rising are similar to those at the earlier stage of bubble rising as shown in Figure 2(a); in the process from the later stage of bubble rising to the stage on which the bubble closes to the liquid level, there is no rising phenomenon of pocket-like rolling bubble which is arose under the pressure of 0.1 MPa. With the rise of pressure intensity, the degree of deformation of bubble shape becomes smaller in the rising process, especially the pressure range is between 1.0 and 2.0 MPa; when the bubble departs from the nozzle, it has a rigid spherical shape and then becomes a flat oval shape, in which the bubble always keeps in the rising process, with minimized degree of deformation.

The red line part in Figure 2 shows a diagram for the bubble just departing from the nozzle under different pressures. Under the condition where a single bubble is formed by an extremely small flow rate, the size of the bubble just departing from the nozzle gradually decreases with the increase of vessel pressure, and the bubble shape tends to a rigid ball with the decrease in bubble size. When the pressure intensity increases from 0.1 to 1.5 MPa, the

Figure 2: Shape changes in the case of bubble formation and rising under different pressures: (a) 0.1 MPa, (b) 0.5 MPa, (c) 1.0 MPa, (d) 1.5 MPa, and (e) 2.0 MPa.

Figure 3: Relationship between pressure intensity and initial diameters of bubbles departing from the nozzle.

bubble size obviously reduces; when the pressure intensity increases from 1.5 to 2.0 MPa, the size and shape of bubbles hardly change and tend to be stable.

The variation trend of initial diameters of the bubbles just departing from the nozzle under different pressures is shown in Figure 3. As seen in Figure 3, the bubble size gradually decreases with the increase of vessel internal pressure intensity, and when the vessel pressure intensity is equal to 1.5 MPa, the bubble diameter is 3.3 mm, and when the vessel pressure intensity is greater than 1.5 MPa, the bubble size hardly changes. The quadratic fit is used to obtain the relationship between the initial diameter of the bubble and pressure intensity as follows: $y = 7.42 - 5.03x + 1.97x^2 - 0.26x^3$, wherein “y” represents the initial diameter of bubble (mm) and “x” represents the vessel pressure intensity (MPa), and *R*-square is 0.982.

3.2 Effect of pressure intensity on multiple bubble behavior

Figure 4 shows the rising process of bubbles under different bottom blowing flow rates and pressures. In Figure 4(a)–(c), the bottom blowing flow rates are 4, 10, and 16 L·h^{−1}, respectively, and the pressure intensities from left to right are 0.1, 0.5, 1.0, 1.5, and 2.0 MPa, respectively. By contrasting Figure 4(a₁), (b₁), and (c₁), it can be found that under normal pressure and with the increase of bottom blowing flow rate, the air mass formed in the liquid at the moment of the gas departing from the bottom blowing nozzle becomes bigger

and the impact force on the liquid level becomes bigger as well. It can be seen from Figure 4(a₁–c₅) that when the bottom blowing flow rate is constant, with the increase of vessel pressure intensity, there is not a large air mass but a small bubble formed when the gas departs from the nozzle, and with the increase of pressure intensity, the bubble shape formed becomes more uniform.

Under different pressures, the liquid depths at which the gas departs from the nozzle and is broken into bubbles are different. It is observed that within the range of measured pressure, the gas has been broken into bubbles when it rises to the liquid depth of 40 mm. Figure 5 shows a relationship between pressure intensity and bubble rising time (i.e., the time of the bubble rising from the liquid depth of 40 mm to the liquid level). The bubble rising time is counted with high-speed camera. The shooting speed of high-speed camera is 200 frames/second in the case of image acquisition. The liquid depth in the crucible is 90 mm, and the gas is blown at the bottom blowing flow rate of 4 L·h^{−1} under normal pressure. Under normal pressure, with 90 mm of the liquid depth in the crucible and the gas blown at the bottom blowing flow rate of 4 L·h^{−1}, the gas is not broken into bubbles but forms a large air mass whose rising speed is not comparable with that of the bubble rising when departing from the nozzle. In this case, for the bottom blowing flow rates of 4, 10, and 16 L·h^{−1} as shown in Figure 5, the measurement and statistics of bubble rising time are made in the increase process of vessel pressure intensity from 0.5 to 2.0 MPa. In order to reduce statistical errors, the statistics of 5 bubbles is made under the same flow rate and pressure intensity and their rising time is averaged.

As shown in Figure 5, when the bottom blowing flow rate is 4 L·h^{−1}, the bubble rise time decreases with the increase of pressure intensity; when the bottom blowing flow rate is 10 L·h^{−1}, the bubble rise time slowly increases with the increase of pressure intensity; when the bottom blowing flow rate is 16 L·h^{−1}, the bubble rise time increases with the increase of pressure intensity.

Figure 6 shows a relationship between vessel internal pressure intensity and number of bubbles in the liquid under the same bottom blowing flow rate. Since under normal pressure, the gas is not broken into bubbles but forms a large air mass, the number of bubbles in the liquid is not measured under the normal pressure. As seen in Figure 6, when the bottom blowing flow rate is 10 or 16 L·h^{−1}, the number of bubbles produced increases with the increase of pressure intensity. When the bottom blowing flow rate is 4 L·h^{−1}, the number of bubbles decreases in the pressure intensity increase process from

Figure 4: Effects of bottom blowing flow rate and pressure intensity on bubble behavior: a_1 ($4 \text{ L}\cdot\text{h}^{-1}$, 0.1 MPa), a_2 ($4 \text{ L}\cdot\text{h}^{-1}$, 0.5 MPa), a_3 ($4 \text{ L}\cdot\text{h}^{-1}$, 1.0 MPa), a_4 ($4 \text{ L}\cdot\text{h}^{-1}$, 1.5 MPa), a_5 ($4 \text{ L}\cdot\text{h}^{-1}$, 2.0 MPa); b_1 ($10 \text{ L}\cdot\text{h}^{-1}$, 0.1 MPa), b_2 ($10 \text{ L}\cdot\text{h}^{-1}$, 0.5 MPa), b_3 ($10 \text{ L}\cdot\text{h}^{-1}$, 1.0 MPa), a_4 ($10 \text{ L}\cdot\text{h}^{-1}$, 1.5 MPa), b_5 ($10 \text{ L}\cdot\text{h}^{-1}$, 2.0 MPa); and c_1 ($16 \text{ L}\cdot\text{h}^{-1}$, 0.1 MPa), c_2 ($16 \text{ L}\cdot\text{h}^{-1}$, 0.5 MPa), c_3 ($16 \text{ L}\cdot\text{h}^{-1}$, 1.0 MPa), c_4 ($16 \text{ L}\cdot\text{h}^{-1}$, 1.5 MPa), and c_5 ($16 \text{ L}\cdot\text{h}^{-1}$, 2.0 MPa).

1.0 to 2.0 MPa . When the pressure intensities are greater than 1.0 MPa , the number of bubbles produced increases with the increase of the bottom blowing flow rate. Under the pressure intensity of 0.5 MPa and the bottom blowing flow rate of $16 \text{ L}\cdot\text{h}^{-1}$, the number of bubbles is smaller than that under the bottom blowing flow rate of 4 or $10 \text{ L}\cdot\text{h}^{-1}$. The bubble produced under the bottom blowing flow rate of $16 \text{ L}\cdot\text{h}^{-1}$ is similar to the air mass formed when the gas departs from the nozzle under normal pressure, and at this point, the air mass size is much larger than the bubble size, so the number of bubbles is smaller than that under the bottom blowing flow rate of 4 or $10 \text{ L}\cdot\text{h}^{-1}$.

3.3 Effect of pressure intensity on intensified bubble stirring

As shown in Figure 7, in the bottom blowing process, when the bottom blowing flow rate exceeds a critical value, the gas departing from the nozzle forms not a bubble but an air column, as shown in Figure 7(a). With the bottom blowing flow rate of $4 \text{ L}\cdot\text{h}^{-1}$, the air column becomes smaller and shorter with the increase of vessel pressure intensity. For the gas–liquid interphase mass transfer, if the gas departing from the nozzle is broken into bubbles as early as possible, it is beneficial

Figure 5: Relationship between pressure intensity and bubble rise time.

Figure 6: Relationship between pressure intensity and number of bubbles.

to intensify the stirring, balance the composition and temperature and promote the gas–liquid interphase mass transfer. In the experiment, the bubble breaking distance is defined as the perpendicular distance from the location at which the gas departs from the nozzle and is broken into bubbles to the nozzle.

Figure 8 shows a relationship between pressure intensity and bubble breaking distance. As seen in Figure 8, under the same pressure intensity, the bubble breaking distance increases with the increase of the bottom blowing flow rate. When the bottom blowing flow rate is constant, the bubble breaking distance gradually decreases with the increase of pressure intensity, and when the pressure intensity is less than 0.5 MPa, the reduction rate of bubble breaking distance is high. The air column formed by the gas leaving the nozzle is in a high-energy unstable state, and the main force of the bubble in the liquid to maintain its shape is the surface tension and pressure. As the pressure increases, the unbalanced force of the air column increases, so it tends to break and form spherical bubbles. The driving force of the air column increases, resulting in a decrease in the crushing distance of the air column at the same flow rate. However, the initial kinetic energy of the air column is large when the flow increases, and the distance when the crushing occurs is relatively long.

When the pressure intensity is 0.1 MPa, the gas departing from the nozzle forms a large air mass, and at this moment, the gas–liquid interphase contact area is smaller than the gas–liquid interfacial area when the gas is completely broken into small bubbles. The gas–liquid interfacial area is directly related to the gas–liquid interphase mass transfer. From a dynamic perspective, the impact force of a large air mass on the liquid level is much larger than that of an air bubble on the liquid level when the bubble is completely broken into minute bubbles. For the ladle bottom blowing refining process, too much impact force on the liquid level is easy to cause slag entrapment.

Figure 7: Effect of pressure intensity on the distance of bubble breaking with the bottom blowing rate of $4 \text{ L} \cdot \text{h}^{-1}$: (a) 0.1 MPa, (b) 0.5 MPa, (c) 1.0 MPa, (d) 1.5 MPa, and (e) 2.0 MPa.

Figure 8: Relationship between pressure intensity on bubble breaking distance.

In addition, nonmetallic inclusions in liquid steel are absorbed by small bubbles whose absorbing effect is stronger than that of air mass in the rising process.

The liquid level fluctuation range is defined as a distance between the highest point of level fluctuation and the lowest point. As shown in Figure 9, experimental results show that under the normal pressure, the level fluctuation range gradually increases with the increase of bottom blowing flow rate. When the bottom blowing flow rate is $10 \text{ L}\cdot\text{h}^{-1}$, a phenomenon like boiling appears on the liquid level and the fluctuation range reaches 35 mm; when the bottom blowing flow rate is increased to $40 \text{ L}\cdot\text{h}^{-1}$, the boiling phenomenon on the liquid level becomes more violent and the fluctuation range reaches 50 mm. With the increase of vessel pressure intensity, the

Figure 9: Relationship between pressure intensity and level fluctuation range.

liquid level fluctuation range gradually decreases. In the increasing process of pressure intensity from 0.1 to 0.3 MPa, the level fluctuation range significantly reduces. When the bottom blowing flow rates are 10, 20, 30, and $40 \text{ L}\cdot\text{h}^{-1}$, the fluctuation ranges decrease by 25, 29, 35, and 32 mm, respectively. In the increasing process of pressure intensity from 0.3 to 1.0 MPa, the liquid level fluctuation ranges slightly decrease under various bottom blowing flow rates, and when the bottom blowing flow rate is $30 \text{ L}\cdot\text{h}^{-1}$, the liquid level fluctuation range dramatically reduces by 13 mm.

Figure 9 also shows a relationship between bottom blowing flow rate and level fluctuation range under different pressures. If a pressurization mode is used to suppress the liquid level fluctuation so as to solve the problem of slag entrapment, then the argon bottom blown ladle needs to be under certain pressure intensity. The bigger the equipment bears the pressure intensity, the higher the manufacturing, operating, and maintenance costs of the equipment are. So, it is necessary to find out the maximum critical value of bottom blowing flow rate under the small pressure intensity. Given that the liquid level fluctuation range is less than 10 mm, the slag entrapment behavior is negligible. In this case, the maximum bottom blowing flow rate is optimal under the smallest pressure intensity, and the bottom blowing flow rate of $20 \text{ L}\cdot\text{h}^{-1}$ is optimal under the pressure intensity of 0.3 MPa. If the bottom blowing flow rate does not meet the refining requirements under these pressure intensities, the bottom blowing flow rate could be increased under the increased pressure intensity.

3.4 Effect of bottom blowing aperture diameter on air bubble

Figures 10 and 11 show the bubble shape changes under the pressure intensities of 0.1 and 2.0 MPa, at the bottom blowing flow rate of $8 \text{ L}\cdot\text{h}^{-1}$ and with the aperture diameters of 0.6, 1.5, 2.0, and 3.0 mm respectively. As shown in Figure 10, under the pressure intensity of 0.1 MPa, the bubble on the liquid level has an oval shape, and the impact force of bubbles on the liquid level increases with the increase of bottom blowing aperture diameter. As seen in Figure 11, under the pressure intensity of 2.0 MPa and at the same bottom blowing flow rate, the bubble on the liquid level tends to be positively circular, so the agitation of high pressure on the liquid level has a strong inhibition effect and the bottom blowing aperture sizes under high pressure can be selected in a large range.

Figure 10: Effect of bottom blowing aperture size on bubble under the pressure intensity of 0.1 MPa: (a) 0.6 mm, (b) 1.5 mm, (c) 2.0 mm, and (d) 3.0 mm.

Figure 11: Experimental image for the effect of bottom blowing aperture size on bubble under the pressure intensity of 2.0 MPa: (a) 0.6 mm (b) 1.5 mm. (c) 2.0 mm, and (d) 3.0 mm.

Figure 12: Effects of pressure intensity and bottom blowing aperture on the number and morphology of bubbles.

Figure 13: Effect of aperture diameter on bubble formation: a_1 (1 mm, 0.1 MPa), a_2 (1 mm, 0.5 MPa), a_3 (1 mm, 1.0 MPa), a_4 (1 mm, 1.5 MPa), a_5 (1 mm, 2.0 MPa); b_1 (2 mm, 0.1 MPa), b_2 (2 mm, 0.5 MPa), b_3 (2 mm, 1.0 MPa), b_4 (2 mm, 1.5 MPa), b_5 (2 mm, 2.0 MPa); and c_1 (3 mm, 0.1 MPa), c_2 (3 mm, 0.5 MPa), c_3 (3 mm, 1.0 MPa), c_4 (3 mm, 1.5 MPa), c_5 (3 mm, 2.0 MPa).

Figure 12 shows the relationship between the number, shape, and size of bubbles on the liquid level and the bottom blowing aperture diameter and vessel pressure intensity. Usually, the bubble shape is represented by a length–width ratio, and the bubble size is represented by an average diameter.

Figure 14: Effect of bottom blowing aperture diameter and pressure intensity on the air bubble.

As shown in Figure 12(a), at the bottom blowing flow rate of $8 \text{ L} \cdot \text{h}^{-1}$, the number of bubbles on the liquid level increases with the increase of vessel internal pressure intensity. When the pressure intensity increases from 0.1 to 2.0 MPa and the bottom blowing aperture diameters are 0.6, 1.5, 2.0, and 3.0 mm, the number of bubbles on the liquid level increases from 41, 31, 27, and 24 to 101, 83, 71, and 65, respectively, and when the pressure intensity is constant, the number of bubbles on the liquid level decreases with the increase of bottom blowing aperture diameter. As shown in Figure 12(b), when the bottom blowing aperture diameters are 0.6, 1.5, and 2.0 mm, the length–width ratio of bubbles decreases with the increase of vessel pressure intensity and the bubbles on the liquid level tend to be positively circular with the increase of vessel pressure intensity, and when the pressure intensity is increased to 2.0 MPa, the length–width ratio of bubbles is around 1.13, and the bubble shapes are almost the same; when the bottom blowing aperture diameter is 3.0 mm, the length–width ratio of bubbles increases with the increase of vessel pressure intensity.

Figure 4 shows that the greater the pressure intensity, the more spherical the shape of the bubble formed. When the bottom outlet aperture was below 3 mm, the bubble aspect ratio also followed this rule. However, it

Figure 15: Effect of Bottom Blowing Location on Bubble under the Pressure Intensity of 0.1 MPa. (a) Centre, (b) 2/5R, and (c) 4/5R.

can be seen from Figure 14 that the larger the bottom blowing aperture, the larger the diameter of the bubble leaving the nozzle. The shape of the bubble is mainly controlled by the surface tension and pressure of the bubble. Here there was a limit value for the bubble. When the pore size reached 3 mm (the bubble diameter is 5.8 mm), the surface tension dominates and the bubble was nearly spherical; when the bubble volume was greater than the limit value, the pressure dominated and the bubble aspect ratio. This indicates that the increase of vessel pressure intensity has an obvious effect on the length–width ratio of bubbles at small bottom blowing aperture diameter. As shown in Figure 12(c), when the bottom blowing flow rate is constant, the average diameter of bubbles increases with the increase of bottom blowing aperture diameter and decreases with the increase of vessel pressure intensity.

Figure 13 shows the image of the bubble just departing from the nozzle under different pressures and bottom blowing aperture diameters. In Figure 13(a)–(c), the bottom blowing aperture diameters are 1, 2, and 3 mm, respectively, and the pressure intensities from left to right are 0.1, 0.5, 1.0, 1.5, and 2.0 MPa, respectively. It is found by contrast in Figure 13(a)–(c) that the bottom blowing aperture diameter

has a significant effect on the bubble shape. When the bottom blowing aperture diameter is 1 mm, the bubble shape approximates a rigid ball shape; when the bottom blowing aperture diameter is 2 mm, the time of bubbles departing from the nozzle becomes longer, and under the action of buoyancy, the bubble becomes an oval shape; when the bottom blowing aperture diameter is 3 mm, the bubble departs from the bottom blowing nozzle with the increase of bottom blowing aperture diameter, but the bubble connects with the next bubble that about to emerge. The above analysis shows that with the increase of bottom blowing aperture diameter, the diameter of bubbles departing from the nozzle increases and the bubble shape tends to be oval, and the time from bubble formation to bubble departure increases.

Figure 14 shows a relationship diagram between the vessel pressure intensity and bottom blowing aperture diameter and the diameter of bubbles departing from the nozzle. In Figure 14, when the bottom blowing aperture diameter is constant, the diameter of bubbles breaking away from the nozzle decreases with the increase of pressure intensity; when the pressure intensity is greater than 1 MPa, the bubble diameter slowly decreases, and when the bottom blowing aperture diameters are 1, 2, and 3 mm, the

Figure 16: Effect of bottom blowing location on bubble under the pressure intensity of 2.0 MPa. (a) Center, (b) 2/5R, and (c) 4/5R.

bubble diameters are stabilized at 3.3, 4.4, and 5.8 mm respectively. When the vessel internal pressure intensity is greater than 1 MPa, the diameter of bubbles just departing from the nozzle increases with the increase of bottom blowing aperture diameter, and when the pressure intensity is less than 0.5 MPa, the diameters of bubbles formed at different aperture diameters differ slightly and the maximum diameter difference is 0.7 mm.

3.5 Effect of bottom blowing location on air bubble

Figures 15 and 16 show the bubble shape changes on the liquid level under the pressure intensities of 0.1 and 2.0 MPa, at the bottom blowing flow rate of $8 \text{ L}\cdot\text{h}^{-1}$ and with the bottom blowing aperture diameter of 1 mm and at the bottom blowing locations at the center, 2/5R and 4/5R, respectively.

As seen in Figures 15 and 16, when the bottom blowing flow rate and aperture diameter are constant, the bottom blowing location change has no obvious effect on the bubble agitation on the liquid level, and the high pressure has a strong inhibition effect on the bubble agitation.

Figure 17 shows the relationship between the number, shape, and size of bubbles on the liquid level and the bottom blowing location and vessel pressure intensity.

As seen in Figure 17(a), under normal pressure, the numbers of bubbles are almost equal in the case of bottom blowing at the location of 2/5R and the center; the number of bubbles in the case of bottom blowing at the 4/5R location is 13 more than that in the case of bottom blowing at the 2/5R location and the center; since the bottom blowing aperture at the 4/5R location is near the side wall, the bubble is easy to be broken ahead of time in its rising process. When the bottom blowing flow rate and bottom blowing location are constant, the number of bubbles increases with the increase of vessel pressure intensity. When the vessel pressure intensity is constant, the bottom blowing location has no obvious effect on the number of bubbles. As seen in Figure 17(b), When the pressure intensity is between 1.0 and 1.5 MPa, there is a minimum length–width ratio with respect to the bubbles and the bubble shape formed on the liquid level is closest to a positively circular shape. As seen in Figure 17(c), when the bottom blowing flow rate and bottom blowing aperture diameter are constant, with the increase of vessel pressure intensity, the bottom blowing location is closer to the center and the average diameter of bubbles is smaller.

Figure 17: Effects of pressure intensity and bottom blowing position on bubble number and morphology.

4 Conclusion

- (1) With the increase of vessel internal pressure intensity, the bubble size gradually decreases and the

number of bubbles gradually increases; with the increase of vessel pressure intensity, the size of a single bubble formed at the bottom blowing nozzle gradually decreases; when the vessel pressure intensity is equal to 1.5 MPa, the bubble diameter is 3.3 mm, and when the vessel pressure intensity is greater than 1.5 MPa, the bubble size hardly changes and tends to be stable.

- (2) With the increase of bottom blowing aperture diameter, the average diameter of bubbles on the liquid level increases, the number of bubbles decreases, and the impact force of bubbles on the liquid level increases; when the bottom blowing aperture diameter is constant, the diameter of bubbles breaking away from the nozzle decreases with the increase of pressure intensity; when the pressure intensity is greater than 1 MPa, the bubble diameter slowly decreases, and when the bottom blowing aperture diameters are 1, 2, and 3 mm, the bubble diameters are stabilized at 3.3, 4.4, and 5.8 mm, respectively.
- (3) The bottom blowing location change has no obvious effect on the number of bubbles on the liquid level, the bubble shape, and the liquid level fluctuation range; when the bottom blowing flow rate and bottom blowing aperture diameter are constant, with the increase of vessel pressure intensity, the bottom blowing location is closer to the center and the average diameter of bubbles is smaller.
- (4) With the increase of bottom blowing flow rate, the bubble breaking distance gets longer, the bubble size and the number of bubbles increase, and the impact force on the liquid level becomes larger.
- (5) With the increase of vessel pressure intensity, the bubble breaking distance in the liquid gradually decreases, the degree of deformation of bubbles floating upward is increasingly smaller, and the liquid level fluctuation range gradually decreases; and when the pressure intensity increases from 0.1 to 0.3 MPa, the liquid level fluctuation range significantly reduces.

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