Removal Behavior of Inclusions in Molten Steel by Bubble Wake Flow Based on Water Model Experiment

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In order to make clear the mechanism how the non-metallic inclusions were removed by bubble wake flow in the molten steel, water model experiments were conducted by high speed video and image processing software. The bubble wake flow zone was partitioned and the characteristics of removing inclusions through bubble wake flow were analyzed, and the effects of various factors including bubble size, inclusion size and concentration on the removal behavior of inclusions were also investigated. The results show that the bubble wake flow is useful for the floatation of inclusions. The bubble wake flow involves the boundary zone and the rising zone, and the process of inclusion removal by the bubble wake flow can be decomposed into three sub-processes: firstly approaching and passing into the boundary zone, secondly passing into the rising zone and finally going on floating up or escaping from the rising zone. The increasing of the bubble diameter $D_b$ and the particle concentration $C_p$ is in favor of inclusion removal by bubble wake flow. If the particle diameter $D_p$ is smaller, the inclusions are easier to be removed by wake flow.

KEY WORDS: bubble wake; inclusion removal; mechanism; molten steel; water model.

1. Introduction

The inclusion quantity, size and distribution are important factors for steel cleanliness, therefore, it is a principal objective to remove them as many as possible from liquid steel. It is known that removing inclusions by bubble flotation is an important way to improve steel cleanliness.1) The mechanism of removing inclusions by floating bubbles can be classified into two kinds:2) one is bubble adhesion, and the other is bubble wake flow. The study about bubble adhesion is relative more,4–8) which is widely used in inclusion mathematical simulation in the refining process.9–13) However, researches about the bubble wake flow are rare, especially the influence of the bubble wake flow on removing inclusions is not clear. The present work studied the process of inclusion removal from molten steel by bubble wake flow with the hydraulic model experiments and high-speed video camera, partitioned the bubble wake flow, and analyzed the characteristics of removing inclusions by bubble wake flow, finally investigated the effects of different factors including bubble size, inclusion size and concentration on the removal behavior of inclusions by bubble wake flow. The work not only provides theoretical basis for removal inclusions by bubble wake flow, completes the theories on removing inclusions by bubbles, but also put forward guides on removal inclusions for the ladle bottom blowing.

2. Experimental Methods

2.1. Experimental Device

The experimental apparatus is shown in Fig. 1. The container is made of plexiglass, with a length of 20 cm, width of 5 cm, and height of 40 cm. The air is blown into the bath through the hole in the bottom of the container. The flow rate of the air is adjusted with a highly precise gas rotor flow meter. The slit light source is attempted to compensate light intensity from one side of the container, and a high-speed camera and video camera are used to record the experimental process in front of the container.

2.2. Experimental Contents

In the experiment, the PS (Polystyrene) particles were used, and the water and the compressed air were respective-
ly applied to simulate the liquid steel and the argon. The air flow varied within the range of 0.05–0.21 L/min, the PS particle size changed in the range of 15–589 μm, and its density and contact angle are 1.02 g/cm³ and 91°, respectively.

The experiment includes three procedures: Firstly, the particles were added in the water bath with a syringe and uniformly dispersed in the water. Secondly, the air was blown into the water bath through the entrance of the container bottom. Thirdly, the behaviors of inclusions and bubble wake were recorded and photographed by high-speed camera, the depth of water was about 19 cm, which is the height of the shaded zone in Fig. 1. Finally, image analysis method was used to make a statistics on the capture rate. The number of inclusion particles which were driven by a bubble to float in an unit time and the entire water bath was defined as the capture rate $V$ (np/s). Through making a statistics on the images recorded by the high-speed camera in one second, the capture rate can be calculated. When the bubble is ellipsoidal, the bubble diameter $D_b$ takes the diameter value of the long axis of the bubble. The inclusion particle diameter $D_p$ is the diameter value of the long axis of the inclusion.

3. Results and Discussion
3.1. Ways of Removing Inclusions by Bubble
The experiment phenomena showed that there were two ways for removing inclusions by bubble, which were bubble adhesion and bubble wake flow. It is seen from Fig. 2 that the first way can be regarded as adhesion removal that the inclusions above the bubble collide and adhere to the bubble, and the second way can be considered as bubble wake removal that the inclusions rise up following the bubble wake flow. In the figure, the difference of the two ways is above or below the bubble axis horizontal line (dashed line in Fig. 2). The article mainly aims at the bubble wake flow to study.

3.2. Process Monitoring of Removing Inclusions by Bubble Wake Flow
In this experiment, the gas was blown at the bottom of the container by a nozzle with the diameter 7 mm, the PS particle sizes were within the range of 350–495 μm. In the case of forming a string of bubbles, the high-speed camera and video camera were used to record the processes of removing inclusions by bubble wake flow.

The inclusion particles are captured by the wake flow formed by an approximate 10 mm spherical cap bubble. During the bubble floating process, the liquid below the bubble fills the volume of voids due to the bubble rising and departure, thereby the bubble wake flow is formed. When the inclusions turn to the wake zone fast floating up, they are easily wrapped into the bubble wake flow due to the relatively lower pressure and the relatively stronger turbulence intensity in the wake zone. It is seen from the figure that the particles first slowly approach and pass into the bubble wake zone (Figs. 3(a) and 3(b)). Then the particles begin to float up following the bubble wake flow (Figs. 3(c) and 3(d)). When the particles rise for some distance, their velocities change because of the effect of the flow field. Some particles continue rising until to the surface of the liquid, and others start to move toward the side direction until departing from the bubble wake zone while they float up, then they suspend in the liquid again and have not be brought to the surface of the liquid (Figs. 3(e) and 3(f)).

![Fig. 2. Ways of removing inclusions by bubble. (Online version in color.)](image)

![Fig. 3. Processes of removing inclusion particles by bubble wake flow. (Online version in color.)](image)
is suggested that the bubble wake flow is useful to promote the inclusions to float up. Some inclusions in the liquid steel are brought to the surface of the liquid steel and absorbed by the slag layer by the bubble wake flow, and others are not removed because they depart from the bubble wake zone in the rising process.

3.3. Characteristics of Removing Inclusions by Bubble Wake Flow

The mechanism diagram Fig. 4 can be obtained after simplifying the process in Fig. 3 according to the wake bubble flow field observed from the experiment. It showed that the bubble wake flow included two important zones: the boundary zone and the rising zone. The red rectangle with the height $H_b$ and width $D_b$ is the boundary zone of the bubble wake flow, which is shown in Fig. 4(1). The height is defined as the boundary zone height $H_b$, from the surface below the bubble to the wake flow boundary at the Y-axis direction. The distance of the wake flow boundary at the X-axis direction is defined as the rising zone diameter $D_r$. The red rectangle with the height $H_r$ and width $D_r$ is the rising zone of the bubble wake flow (Fig. 4(2)). The height of the bubble wake flow which can make the inclusions rise is defined as the rising zone height $H_r$. The diameter of the wake flow which can make the inclusions rise is defined as the rising zone diameter $D_r$.

According to the zones of the bubble wake flow, the process of removing inclusions can be decomposed into the following three sub-processes:

1. **Approaching and passing into the boundary zone**

   When the inclusions pass into the wake boundary zone, the wake flow will make the inclusions produce large turbulence and the speed of one particle is gradually changed, no matter which direction (the X-direction or Y-direction) component of the velocity is increasing or decreasing. The first process can be referred as ‘Approaching and passing into the boundary zone’. Through the analysis of a large number of images and the experimental phenomena, the height $H_b$ and width $D_b$ can be obtained by measuring the region where the inclusion speed has changed. It is found that the basic scope of the boundary zone of bubble wake flow is $H_b=7D_b$ and $D_b=2D_b$.

2. **Passing into the rising zone**

   The inclusions will rise following the wake flow when they pass into the rising zone of the bubble wake flow. The second process can be referred as ‘Passing into the rising zone’. Through the analysis of a large number of images and the experimental phenomena, the height $H_r$ and width $D_r$ can be obtained by measuring the region where the Y direction velocity component of the inclusion is greater than zero. It is found that the basic scope of the rising zone of bubble wake flow is $H_r=5.5D_b$ and $D_r=1.5D_b$.

3. **Going on floating up or escaping from the rising zone**

   When the inclusions pass into the rising zone, their velocities change because of the effect of the flow field. When the X-axis velocity component of the inclusion is not equal to zero or the resultant force component at the Y direction is less than 0, the inclusion particles begin to escape from the rising zone, then they pass into the boundary zone again or escape from the boundary zone and freely float due to the density difference of inclusions and liquid steel, otherwise they will keep floating up in the rising zone (Fig. 4(3)). The third process is referred as ‘Go on floating up or escaping from the rising zone’.

   There are two ways of inclusions to approach and pass into the wake flow in the process (1) and process (2): one is beside the wake flow zone, the other is below the wake flow zone, as seen in Fig. 4.

   It can be seen that the processes of passing into the rising zone and escaping from the rising zone may occur independently, or simultaneously. However, it is found from the experimental observation that both of them occur at the same time in most cases.

3.4. Effect of Different Factors on Removing Inclusions by Bubble Wake Flow

Many factors affect the inclusion removal by bubble wake flow including bubble diameter $D_b$, inclusion diameter $D_p$ and concentration $C_p$. The capture rate $V$ was obtained by statistics through the image analysis.

3.4.1. Effect of Bubble Diameter $D_b$

Different bottom blowing elements were used. The bubble diameters generated by bottom blowing elements were approximately 2.5 mm, 5 mm, 7 mm, 9 mm, 10.5 mm and 12 mm. During the experiment, the number of bubbles, namely the bubble rate of $N_b$ (n/s) was a constant value within the entire volume and unit time. The effect of the bubble size on the capture rate is shown in Fig. 5, the vertical axis represents the capture rate $V$ (n/p/s), the horizontal axis is the bubble diameter $D_b$ (mm). It can be seen from the figure that the capture rate $V$ gradually increases with increasing the bubble diameter, which is mainly because the...
3.4.2. Effect of Inclusion Diameter $D_b$

Five PS particle groups with different size extents were applied which were 15–83 μm, 83–198 μm, 198–350 μm, 350–495 μm and 495–589 μm. The effect of the inclusion size on the capture rate is shown in Table 1.

It can be seen from the table that as the particle concentration $C_p$ is, and the easier the inclusions are to be removed by wake flow, while the particle diameter $D_b$ is smaller, the inclusion removal by wake flow is higher.

### Table 1. Effect of inclusion diameter $D_b$ on capture rate $V$.

<table>
<thead>
<tr>
<th>Inclusion diameter $D_b/\mu$m</th>
<th>15–83</th>
<th>83–198</th>
<th>198–350</th>
<th>350–495</th>
<th>495–589</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture rate $V (n_p/\text{s})$</td>
<td>12.2</td>
<td>9.5</td>
<td>7.4</td>
<td>5.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

bubble shapes have changed when the bubble size increase. It is found in the experiment that bubbles with diameter below 3 mm are spherical, 3–10 mm bubbles are spheroidal, and bubbles with diameter greater than 10 mm are spheri-cal cap shape. When the bubble shape varies from sphere to spheroid and then spherical cap with increasing the bubble size, the wake flow produced by the bubble is more obvious, so the capture rate is gradually getting bigger, which can be seen in Fig. 6.

3.4.3. Effect of Inclusion Concentration $C_p$

Five concentration values $C_p$ were chosen which were approximate 5, 10, 15, 25 and 30 $n_p$ cm$^{-3}$. During the experiment, the bubble rate $N_b$ ($n_b$ s$^{-1}$) was 1. It can be found from the Fig. 7 that as the particle concentration $C_p$ increases, the capture rate $V$ gradually increases. Therefore, it is inferred that the inclusion removal probability also increases.

### 4. Conclusions

This paper studied the process and the characteristics of inclusion removal from molten steel by bubble wake flow. The conclusions are as follows:

(1) The bubble wake flow is useful to promote the inclusions floatation.

(2) The bubble wake flow has two zones: boundary zone and rising zone.

(3) The processes of inclusion removal by bubble wake flow can be decomposed into three sub-processes: Firstly the particles approach and pass into the boundary zone of bubble wake flow. Secondly the particles pass into the rising zone. Finally the particles escape from the rising zone.

(4) It is beneficial to remove inclusions by bubble wake flow to increase the bubble diameter $D_b$. The bigger the particle concentration $C_p$ is, and the easier the inclusions are to be removed by wake flow, while the particle diameter $D_b$ is smaller, the inclusion removal by wake flow is higher.

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### REFERENCES