Study on Water Model Experimental of Waste Circuit Board Treatment by Top-Blowing Bath Smelting Method

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Abstract. Through the water model experiment of oxygen-enriched top-blowing bath smelting, the effects of factors such as gas flow, lance position and liquid height on the bubble size distribution and liquid splash height during top blowing process of waste circuit boards were studied. The results showed that, the mixing effect worked best when the lance blew in the center of the molten pool. With a suitable increase of the gas flow, the impact of bubble refinement in the molten pool can be optimized. At the same time, the liquid splash, slag entrapment and liquid level fluctuation were aggravated. Appropriately increasing the liquid height can inhibit liquid splash to a certain extent. Considering the effect of bubble refinement and liquid splash height, the optimal experimental conditions of this experimental system were as follows. A straight barrel lance with a diameter of 15mm was installed in the center of the furnace body, the liquid height was 80mm, the lance submersion depth was 40mm, and the gas flow was 7.48Nm³/h.

1. Introduction
Waste circuit boards (WCBs) are an essential part of electronic wastes. At present, more than 500 thousand tons of WCBs need to be disposed of each year in China. WCBs contain a variety of heavy metals, toxic and hazardous substances. Without proper treatment, it will cause serious pollution of water and soil resources, thus endanger human health [1-2]. WCBs are called "urban mines" [3-4], which have high economic value. The metal content of WCBs is as high as 40% [5], among which the copper content is the highest, about 10-20%, and the gold and silver contents are about 300g/t and 5 ~ 10kg/t [6]. The utilization of WCBs can not only recover valuable metals [7], realize the green recycling of WCBs, but also contribute to the sustainable development of China's economy.

The traditional treatment methods of WCBs mainly include mechanical treatment method, hydrometallurgy method and pyrometallurgy method. The mechanical treatment method is based on the difference of physical properties to separate metallic materials and non-metallic materials [8]. The mechanical treatment method is economical and environmental friendly with a high recovery rate. However, the dissolved metals are the mixture of copper, aluminum, lead, zinc and other metals, which need further separation treatment [9]. The hydrometallurgy method is based on the different chemical properties of various substances. Metal enrichment is achieved by acid leaching or alkaline leaching, then further separated and purified. The hydrometallurgical process is simple with high economic benefits, but a large amount of waste is generated during the recycling process. If it is not processed in time, the toxic heavy metals and organic pollutants will cause secondary pollution [10]. The pyrometallurgy method is the traditional process for recycling non-ferrous and precious metals in...
WCBs, including incineration, plasma arc furnace or blast furnace smelting, slag skimming, calcining, melting and high-temperature gas-phase reaction processes [11]. The pyrometallurgical process has high recovery rate and simple operation, which is suitable for industrialized production.

The pyrometallurgy method separates the metal alloy and the slag by means of overflowing as gas-phase or entering into the molten slag after the combustion of non-metallic organic matter, so as to achieve the metal enrichment. It is an improved pyrometallurgical process to dispose WCBs in top-blowing furnace to recover valuable metals [12]. In the process of oxygen-enriched top-blowing bath smelting, the WCBs are broken and added to the molten slag together with the solvent. The lance is inserted from the top and immersed in the slag layer. The lance injects the oxygen-rich air by the lance at high speed, which drives the material to stir violently, and the molten copper alloy and non-metallic dross are generated by burning, slagging and metal melting in sequence. The organic combustible waste gas is converted into CO$_2$ and water vapor by the secondary combustion, which controls the production of toxic gas dioxins from the source [13], and provides a certain amount of heat for the system. The gas forms a large number of bubbles in the slag layer. The mutual movement of bubbles and molten slag drives intense agitation in the molten pool so that the materials are evenly mixed [14]. The heat transfer, which can keep the temperature of the molten pool in equilibrium, keeps the alloy phase in a molten state.

During the melting process, the number of large bubbles in the system grows, due to the hit of top blowing airflow to the molten pool and the continuous outflow of CO$_2$ gas which generated by the intense reaction of carbon and oxygen, the slag and liquid metal splash around [15]. The splashed slag and metal may stick to the furnace mouth, flue, oxygen lance and slag path, which not only leads to the loss of metal and slag and reduces the recovery rate, but also is not conducive to the conveying and continuous production of slag [16-18]. In addition, the splashing of high-temperature melt will bring some risks. The scalding accidents caused by it account for more than 80% of all scalding accidents [19].

Bubble refinement analysis can intuitively reflect the flow state of gas phase and liquid phase through the bubble distribution in the system. Small bubbles are dispersed uniformly in the system, which can enlarge the contact area of the gas phase and liquid phase, inhibit the formation of splashes, and improve the reaction efficiency. Therefore, the study of the flow state of gas phase and liquid phase through bubble refinement analysis and the inhibition of the formation of splashing play an extremely important role in molten pool smelting, providing an absolute guarantee for industrial production safety and continuous operation.

In this paper, the cold state simulation of the oxygen-enriched top blowing water model was adopted to study the bubble distribution and splashing situation under the conditions of gas flow, lance position, liquid height, and explore the influence and change rule of various factors on the gas-liquid two-phase in the molten pool, which will provide an essential basis for subsequent industrial development.

2. Experimental design

2.1. Experimental principle
Geometric similitude means that the physical model and the prototype are similar in shape. The main size of the model is enlarged or reduced in a certain proportion of the prototype. Kinetic similarity refers to the equal ratio of forces at corresponding points. Taking into account inertial force, surface tension, pressure, elastic force, viscous force, electromagnetic force and gravity, it is necessary to ensure that the physical model and prototype have the same modified Frode number ($Fr'$) [20].

The modified Frode number is defined as follow:

$$Fr' = \frac{\rho_g \cdot u^2}{\rho_l \cdot g \cdot H}$$

(1)
Where $u$ is the characteristic speed, m$/h$; $H$ is the height of the molten pool, m; $\rho_g$ is the gas density, kg/m$^3$; $\rho_l$ is the liquid density, kg/m$^3$. The gas flow of the physical model can be obtained by the following formula:

$$Q_m = \left( \frac{\rho_{gp}}{\rho_{gm}} \cdot \frac{\rho_{lp}}{\rho_{lm}} \cdot \frac{d_m}{d_p} \cdot \frac{H_m}{H_p} \right)^{1/2} \cdot Q_p$$  \hspace{1cm} (2)

Where $Q$ is the gas flow, m$/h$; $d$ is the nozzle diameter, mm; the model and prototype are marked with the subscripts m and p respectively.

2.2. Physical model
This research used the top blowing furnace of a Beijing company as the prototype, a full-length hydraulic simulation system with a geometric similarity ratio of 1:10 was designed and made of plexiglass. Water was used to replace molten slag, compressed air was used to replace oxygen-enriched air. A physical model was established according to the similarity theory, with the inner diameter of 160mm and the height of 254.7mm. The specific dimensions are shown in Table 1.

| Specification       | Molten pool radius (mm) | Molten pool height (mm) | Liquid height (mm) | Liquid density (kg.m$^{-3}$) | Gas density (kg.m$^{-3}$) |
|---------------------|-------------------------|-------------------------|--------------------|------------------------------|---------------------------|
| Industrial size     | 800                     | 2547                    | 800                | 4600                         | 1.37                      |
| physical simulation | 80                      | 254.7                   | 80                 | 1000                         | 1.25                      |

2.3. Experimental method
A certain height of water was added to the top blown water model. The lance was installed to be immersed in the water, and the compressed air was blown into the molten pool through the lance. The LIGHT NING RDT high-speed camera made by the American DRS company was used to take pictures and record the experimental phenomena. Image processing software Image Pro-Plus was used to analyze and process bubbles. The experimental setup is shown in Figure 1. The effects of factors such as gas flow, lance position and liquid height on the bubble size distribution and liquid splash height were studied in the experiment.

3. Results and discussion
3.1. Effects of gas flow on bubbles
A straight barrel lance with an aperture of 15mm was installed in the center of the model, with a liquid height of 80mm and a lance immersion depth of 40mm. The effects of gas flow on bubble distribution and liquid splash height were investigated. The experimental renderings of spraying at different gas flow are shown in Figure 2.

It can be seen from Figure 2 that the increase of gas flow led to unusual intense splashing in the molten pool. A large number of bubbles were formed at the bottom of the molten pool, which meant
that the gas phase was distributed uniformly in the liquid phase. In industrial production, the melt spraying not only accelerated the abrasion of refractory materials, but also further led to the loss of metal and slag, which made it more difficult to recycle the slag.

**Figure 2.** Experimental renderings of spraying at different gas flow

(a.3.48Nm$^3$/h; b.5.48Nm$^3$/h; c.7.48Nm$^3$/h; d.9.48Nm$^3$/h; e.11.48Nm$^3$/h)

Figure 3 shows the histogram of bubble distribution at different gas flow. As the gas flow continued to increase, the number of large bubbles decreased significantly, and the number of small bubbles increased. The distribution range of the bubbles was reduced, and the effect of bubble refinement worked well. When the gas flow rate was 7.48Nm$^3$/h, the small bubbles were distributed uniformly, the particle size distribution was concentrated in the range of 0 – 2mm, and there was no large bubble generated. The number of bubbles below 1mm grew significantly, which accounted for more than 75% of the total bubbles. At this time, the bubble distribution in the molten pool was uniform, and the gas-liquid contact area enlarged, which was more conducive to the progress of the reaction. With the further increase of gas flow, the distribution range of bubbles gradually expanded, and large bubbles were formed.

**Figure 3.** Histogram of bubble average distribution at different gas flow

**Figure 4.** Relation curves of gas flow vs. average bubble diameter and splash height, respectively

It can be seen from Figure 4 that as the gas flow increased, the average bubble diameter first decreased and then increased. When the gas flow increased, the frequency of bubble generation increased, and the jet broke to form a large number of tiny bubbles. However, when the gas flow was too large, the gas had no time to diffuse in the liquid phase and directly overflowed in the form of large bubbles, resulting in a sudden decrease in the number of bubbles. In addition, the increased gas flow led to more severe splash phenomenon. This was because under the same lance diameter, a larger gas velocity could provide more gas at the same time, which provided more kinetic energy for the molten pool, which made the fluid flow in the molten pool more intense.
3.2. Effects of lance position on bubbles

A straight barrel lance with an aperture of 15mm was installed at the lance position of 1#, 2# and 3# in the model respectively, with a liquid height of 80mm, an immersion depth of 40mm, a gas flow of 7.48 Nm³/h (as shown in Figure 5). The experimental renderings of spraying at different lance positions are shown in Figure 6.

![Figure 5. Lance position arrangement](image)

As shown in Figure 6, the lance position had a great influence on the flow of the fluid in the molten pool. As the distance from the lance to the wall increased, the number of bubbles at the bottom gradually increased, but the bubbles were distributed unevenly on both sides of the lance. This was because after the rising gas-liquid flow hit the wall, it moved downwards and entrained the bubbles to flow to the bottom. The circulation process on the side away from the wall was longer; the bubbles had enough time to break and were evenly distributed in the molten pool. It could be seen from the photos taken continuously that the closer the distance between the lance and the wall, the weaker the liquid splash, which was conducive to reducing the slag rolling and avoiding the blockage of the feed inlet. This was consistent with the curve of the splash height in Figure 8.

![Figure 6. Experimental renderings of spraying at different lance positions](image)

As seen from Figure 7, the number of small bubbles grew significantly as the distance between the lance and the wall increased. When the lance was located in the center, the bubble distribution was mainly concentrated in the interval of 0 ~ 2mm, and 76% of the bubble diameter was in the narrow region of 0 ~ 1mm. Occasionally large bubbles appeared, but the effect on the average diameter of bubbles in the container was not significant.
Figure 7. Histogram of bubble distribution average at different lance positions

It could also be seen from the curve in Figure 8 that the average diameter of bubbles fluctuated wildly with the lance position. When the lance was installed at 2#, the bubble distribution widened and the bubble diameter enlarged relatively. When the lance was installed in the center, the average diameter of the bubble decreased as the number of small bubbles increased.

Taking into account the contact of the gas and liquid phases in the smelting process, it could be considered that the effect of bubble refinement worked best when the lance was located in the center of the molten pool, which was more conducive to the progress of the reaction. However, without the obstructive effect of the vessel wall, the spray height increased.

3.3. Effects of liquid height on bubbles
A straight barrel lance was installed in the center of the model, with an immersion depth of 40mm and a gas flow of 7.48Nm³/h. The effect of the liquid height on the bubble distribution and splash height was investigated. The different liquid heights were 80mm, 120mm and 160mm respectively.

Figure 9 is the experimental renderings of spraying at different liquid heights. It could be seen that the increase in liquid height made the liquid level more stable and appropriately suppressed the generation of fluctuations. When the liquid height was 40mm, the immersion depth of the lance was so short that the gas couldn't drive the liquid at the bottom of the molten pool to move. The fluctuation at the liquid level was relatively stable. Part of the liquid was sprayed directly on the wall of the vessel to form droplets, which resulted in the waste of raw materials and it was unable to drive the flow of liquid in the molten pool. When the liquid height increased to 80mm, a large number of small bubbles were formed in the molten pool, but the splash phenomenon was relatively obvious. This was because that the gas splashed into the shallow molten pool, the action time of gas was short, which ultimately resulted in a low utilization rate of the gas phase in the furnace. With reference to Figure 11, when the liquid height further improved to 120mm and 160mm, the fluid flow speed decreased and the splash height reduced. It showed that a proper increase in the liquid height could effectively inhibit the splashing phenomenon and improve the stability of the molten pool.
Figure 9. Experimental renderings of spraying at different liquid heights
(a.40mm; b.80mm; c.120mm; d.160mm)

Figure 10 showed the effect of liquid height on bubble distribution. As the liquid height increased, the number of large bubbles grew. It could be seen from Figure 11 that the average bubble diameter also grew with the increase of the liquid height. When the liquid height was 80mm, the bubble diameter was controlled below 3mm, the number of bubbles in the range of 0 ~ 1mm accounted for more than 76%, and the particle size distribution was uniform. Under the condition of the liquid height of 120mm and 160mm, the bubble size distribution range enlarged, and the large bubbles increased obviously, which was not conducive to the contact between the gas phase and liquid phase, however the splash phenomenon reduced obviously. Because as the liquid height increased, the distance between the gas jet and the liquid got larger, and the gas-liquid action time got longer. In general, keeping a deep molten pool depth was beneficial to reduce the droplet splashing and the fluctuation of the liquid height, and further improve the mixing effect of the molten pool and the utilization rate of jet energy. Based on the results of water model experiments, it could be predicted that maintaining a higher liquid height in the top-blown furnace in industrial practice was helpful to suppress the droplets splashing and improve the mixing efficiency in the molten pool.

Figure 10. Histogram of bubble distribution average at different liquid heights
Figure 11. Relation curves of liquid height vs. bubble diameter and splash height, respectively

4. Conclusion
In this paper, the water model experiment of oxygen-enriched top-blowing bath smelting was build to explore the effects of factors such as gas flow, lance position and liquid height on the bubble size distribution and liquid splash height during top blowing process of waste circuit boards. The conclusions were as follows.

(1) The proper increase of the gas flow made the gas and liquid phase collide more intense, the mixing was more uniform and the gas content was higher in the molten pool, which was helpful to the
mass transfer and heat transfer in the molten pool, but the surface splash phenomenon was relatively evident.

(2) With the increase of the liquid height, the number of large bubbles got more and the size distribution range enlarged. However, an appropriate increase of the liquid height made the liquid level more stable and suppressed the splash phenomenon to a certain extent.

(3) When the lance was installed in the center of the molten pool, the stirring effect on the liquid was stronger, so that the gas distributed evenly, which was beneficial to the mass and heat transfer in the molten pool, but the liquid splashing increased accordingly.

(4) Considering the effect of bubble refinement and liquid splash height, the optimal experimental conditions of the experimental system were as follows. A straight barrel lance with a diameter of 15mm was installed at the center of the furnace body, the liquid height was 80mm, the lance submersion depth was 40mm, and the gas flow was 7.48Nm³/h.

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