Research of bottom blowing and slag layer thickness on bath stirring in a 120t ladle

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Abstract. The relationship between mixing time, ladle kinetic energy and bottom blowing radial position, bottom blowing flow rate, slag layer thickness and a series of operating variables are studied. The mixing time has been measured in a 1:6 scale model, and the method of adding tracers has been improved to obtain more accurate results. In addition, the kinetic energy in the bath is calculated through the VOF+DPM coupling model. The experimental results show that the mixing time in the bath decreases with the increase of the bottom blowing rate or the decrease of the thickness of the oil layer. Compared with the bottom blowing radial position of 0.55R and 0.65R, 0.45R is more conducive to mixing in the bath. As the radial position of the bottom blowing approached the wall, the gas-liquid phase zone began to tilt toward the ladle wall. The kinetic energy in the bath is not necessarily related to the mixing time, but when the bottom blowing flow rate and position are the same, the kinetic energy decreases with the increase of the oil layer thickness. When the thickness of the oil layer is 1 cm, 2 cm and 3 cm, the kinetic energy compared with the thickness of the oil-free layer decreases by 24.07%, 30.56% and 36.30%, respectively.

1. Introduction

Gas stirring can provide higher stirring efficiency for ladle, THE chemical efficiency of the ladle refining operation has been customarily quantified in terms of mixing times. There are usually one or two nozzles in the ladle, depending on the size of the ladle. Research scholars study the fluid flow in the ladle with physical and mathematical models.

In late 20th century, Zhu Miao-yong et al[1]. had found the eccentric position of a single nozzle is better than the center position. And an empirical correlation for mixing time in the ladle considering the number of tuyeres was proposed.

In a later work, MANDAL et al[2]. carried out similar research on a ladle model. They had found for relatively higher flow rates, the dependence was found to be less pronounced, mixing times decreasing nearly in proportion to a third power of gas flow rates.

In the past two decades, there has been continuous research on ladle mixing time. AMARO-VILLEDA et al[3]. had been found a negative effect of both slag thickness and slag viscosity on mixing time, on the other hand, the same properties are useful to decrease the exposed surface or ladle eye. TERRAZAS et al[4]. has been found that for a large decrease in mixing time when the nozzle radial position is changed from the center of the ladle to half radius and with further positions closer to the walls, the mixing time remains almost constant. HOANG et al[5]. had found that the oil thickness is
found to positively affect the mass transfer rate, while the oil viscosity does not influence the mass transfer process. Based on these observations, a mathematical correlation involving air (gas) flow rate, oil (slag) thickness was established. Haojian Duan et al[6], studied that the melting and mixing behavior of the alloy in argon stirred steel ladles is simulated based on the turbulent fluid flow. Haiyan Tang[7] found the slag layer will prolong the mixing time due to its consumption on the stirring energy compared with the situation without slag. Jardón-Pérez et al[8], though that although the numerical model can predict well the hydrodynamic behavior of the ladle, there is a deviation from the experimental mixing time when using both equal and differentiated gas injection at a high gas flow rate and a high slag thickness. This is probably due to the insufficient capture of the velocity field near the water oil (steel slag) interface and slag emulsification by the numerical model.

The tracer is generally added to the bath with a certain concentration of NaCl or KCl solution to measure the mixing time. However, the method of adding the tracer in the water model does not take into account the momentum of the tracer entering the bath. In addition, a relationship is established between factors such as the bottom blowing rate, the height of the bath, the position of the bottom blowing, the number of nozzles and the mixing time. Due to the existence of experimental errors, the relationship is not reliable. Therefore, we need other ideas to improve the errors and stability factors in the experiment.

2. Experimental Work

2.1. Physical Model Testing Methods

An industrial size ladle of 140 tonnes of nominal capacity was used as prototype to design a physical model with a geometric scale factor 1:6. The dimensions of both prototype and physical model are indicated in Table 1.

The experiment determines the influence of a nozzle at different radial positions, different flow rates and oil layer thickness on the fluid flow characteristics in the ladle. At present, the top slag layer has not included in most studies on water simulation. Because it is an unsolved problem to satisfy the top layer with the equivalent viscosity and density ratio of the actual steel-slag system. The flow rate of bottom gas in the physical model was computed employing the similarity criteria based on the modified Froude number. In the experiment, a conductivity instrument was used to measure the mixing time and record the instantaneous change of conductivity. The location of the conductivity probe is shown in Figure 1. At the bottom of the model, the distance between the middle and the bottom is 10mm, 20mm, and 300mm respectively. The tracer is a small ice cube made from 0.2g/mL sodium chloride aqueous solution. Compared with the solution, the small ice cubes reduce the momentum generated by the solution in the process of pouring, which will affect the measurement of the mixing time. The tracer is always placed in the upper center of the model. The concentration signal is recorded in the computer as a function of time. The standard for determining the mixing time is the conventional value of 97% homogenization. Each experiment was repeated three to five times.

![Figure 1. Water model setup.](image-url)
Table 1. Dimensions of prototype and physical model.

| Margin                | Prototype    | Water model |
|-----------------------|--------------|-------------|
| Top diameter          | 2923 mm      | 487.17 mm   |
| Bottom diameter       | 2618 mm      | 436.33 mm   |
| Bath height           | 3738 mm      | 623 mm      |
| Liquid height         | 2902 mm      | 483.67 mm   |
| Slag thickness        | 150 mm       | 10mm, 20mm, 30mm |
| Number of nozzles     | 1            | 1           |
| Nozzle radial position(r/R) | 0.55R      | 0.45R, 0.55R, 0.65R |
| Flow rate of bottom gas | 10-50 Nm³/h | 5.187-25.933×10⁻⁵ Kg/s |

Table 2. Physical properties of liquids phase.

| Margin               | Density, kg/m³ | Viscosity, Pa · s |
|----------------------|----------------|-------------------|
| Steel, 1600°C        | 7000           | 0.0062            |
| Water at 20°C        | 1000           | 0.001             |
| Slag                 | 3000           | 0.18-0.36         |
| White oil            | 850            | 0.003             |
| Argon                | 1.78           | 0.0000226         |

2.2. Mathematical Model
A three-dimensional, isothermal, incompressible, turbulent three-phase flow model was established to calculate the air-oil-water system. In order to describe the characteristics of the gas-stirred ladle and the interface between the phases, VOF simulations were performed. The bubbles are described using the discrete phase model. Through the physical model experiment process, the bubble size and the degree of random walk of the bubble under different schemes are determined. In order to better describe the movement of argon bubbles, the argon bubbles disappear when they reach the gas phase interface through a user-defined method. When simulating argon bubbles in high-temperature molten steel, additional consideration should be given to factors such as bubble expansion and floating growth. The physical parameters are shown in Table 2.

In the coupled DPM-VOF formula, the governing equations for fluid flow and discrete phase motion can be found in previous research work[9].

3. Result and discussion
The variables included in this study mainly include nozzle radial position, bottom blowing flow rate and oil layer thickness. The physical model is used to explore the influence of variables on the mixing time, and the mathematical model is used to point out the relationship between the kinetic energy of the ladle and the mixing time, and the conversion efficiency of the kinetic energy of the ladle stirring.

3.1. Effects of experimental Variables on Mixing Time

3.1.1. Stirring energy and radial positions
Figure 2 clearly shows the effect of the nozzle radial position and the bottom blowing flow rate on the bath mixing time. Keeping the bottom blowing position unchanged, the mixing time of the bath decreases with the increase of bottom blowing flow, which is consistent with the results of other researchers.
For example, when the nozzle diameter is 0.65R and the bottom blowing flow rate is 1.75 NL/min, the mixing time of the bath is 30.23 s. When the bottom blowing volume increases by 100%, 200%, 300% and 400%, the mixing time of the bath compared with the bottom blowing volume of 1.75 NL/min is reduced by 22.72%, 27.04%, 32.83% and 34.3%, respectively. When the radial position of the nozzle is 0.45R, the mixing time is always lower than that of 0.55R and 0.65R. This means that when the nozzle radial position is 0.45R, the alloying efficiency in the ladle is higher. At the same time, with the same bottom blowing rate, as the radial position of the bottom blowing becomes larger and larger, the mixing time presents a trend that first increases and then decreases. When the bottom blowing rate keeps increasing, the degree of influence of the bottom blowing position gradually decreases.

### 3.1.2. Oil thickness

*Figure 3* shows the effect of oil layer thickness on mixing time. The mixing time decreases as the thickness of the oil layer increases. The mixing time in the case of oil showed a downward trend, consistent with no oil.

![Figure 3](image)

**Figure 2.** Effect of nozzle radial position and bottom blowing flow rate on mixing time.

**Figure 3.** Effect of oil layer thickness on mixing time (0.65 R).

### 3.2. Effects of parameter variables on ladle flow

The mathematical model is used to calculate the water model. The calculation process and results are shown in *Figure 4*. When the bubbles reaches the air, it breaks, ignoring the momentum generated when the bubbles bursts. The bubbles rise into the bath. Due to the buoyancy, the bubbles drive the water upward. The bubbles continue upward and disappears in the air. When the water reaches the interface, it moves around. The gas-liquid phase zone and circulating flow are formed. When the radial position of the bottom blowing is 0.45R, two circulating flows are formed on the left and right sides of the bath (*Figure 4b*). When the radial position of the bottom blowing is 0.65R, the circulating flow on the side close to the bottom blowing position in the bath disappears (*Figure 4c*). It is worth noting that when the bottom blowing flow is the same, the greater the radial position of the bottom blowing changed, the more likely the bubble column will tilt, which will cause the gas-liquid phase zone to tilt.
3.3. Effects of stirring energy on the kinetic energy of the bath

In the current research, based on the steady flow, the characteristics of fluid flow are analysed in the bath with different nozzle position and oil layer thicknesses. Due to the limitations of the water model experiment, the development dynamics in the bath cannot be clearly obtained, especially the different cases. Therefore, it is necessary to monitor the kinetic energy in the bath. It is defined as follows:

\[ k = \sum_{i=1}^{n} \frac{1}{2} \rho \alpha v^2 \]

where \( k \) represents the kinetic energy of the whole bath by considering the water phase, \( n \) is the number of the cells in the calculation domain, \( \rho \) is the density of water, \( \alpha \) is the volume fraction of water for each cell, \( V \) is the Volume of each cell, and \( v \) is the flow velocity for each cell. At the same time, it is expected that the kinetic energy in the bath of the ladle will establish a relationship with the mixing time to clarify the mixing characteristics in the bath.

Figure 5 shows the kinetic energy of the bath under different cases. As the radial position of the bottom blowing gets closer to the bath wall, the kinetic energy in the molten pool becomes larger and larger. When the radial position of the bottom blowing is 0.55R and 0.65R, relative to the radial position of the bottom blowing of 0.45R, the kinetic energy of the bath increases by 4.17% and 12.50%, respectively. This trend results with the experimental model of water before the performance is inconsistent. It shows that the greater the kinetic energy in the bath, the overall mixing degree cannot be determined. As the thickness of the oil layer increases, the kinetic energy in the bath decreases. When the thickness of the oil layer is 1 cm, 2 cm and 3 cm, the kinetic energy compared with the thickness of the oil-free layer decreases by 24.07%, 30.56% and 36.30%, respectively. At the same bottom blowing rate, different nozzle positions cause different kinetic energy in the bath, but it has nothing to do with the mixing time. The key factor that depends on the size of the mixing time may be the range of the dead zone in the bath, which will be verified in the next work. At the same bottom blowing position, the increase in the thickness of the oil layer reduces the kinetic energy and thus reduces the mixing time in the bath.
4. Conclusion

From the present water model and numerical model research, the following conclusions can be drawn:

(1) the mixing time in the bath decreases with the increase of the bottom blowing rate or the decrease of the thickness of the oil layer. Compared with the bottom blowing radial position of 0.55R and 0.65R, 0.45R is more conducive to mixing in the bath.

(2) When the flow rate of the bottom blowing is the same, the radial position of the bottom blowing is close to the wall, and the kinetic energy in the bath is also increasing. The increase in kinetic energy is not necessarily related to the mixing time.

(3) When the bottom blowing flow rate and the position are fixed, the kinetic energy decreases as the thickness of the slag layer increases. The greater the kinetic energy is in the bath, the shorter the mixing time will be. When the oil layer thickness is 1 cm, 2 cm and 3 cm, the kinetic energy compared with no thickness of oil layer decreases by 24.07%, 30.56% and 36.30%, respectively.

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