Mushroom Formation by Water Model for Double-Tuyere in a Bottom-Blowing Process

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A bottom blown oxygen steelmaking process known as the OBM or Q-BOP, has been adopted to efficiently agitate the bath in vessels to enhance the reaction rate. The method has eliminated the problem of rapid bottom lining deterioration encountered in earlier attempts to bottom blow oxygen. The tuyeres were design in such a way that the oxygen stream passing through a tuyere into the bath is surrounded by a sheath of hydrocarbon gas. By using a hydrocarbon gas, the washing effect on the refractory near the tuyere is significantly reduced. Additionally, the formation of relatively large solid built up at the tuyere tip, the so-called 'mushroom' prohibits the lining wear around the tuyere due to a more favorable flow characteristic of the melt that shifts the hot spot away from the tuyere tip and refractory. The protection of the tuyere by hydrocarbon, bottom blowing, results in shorter tap to tap times, better process control and longer refractory life in tuyere and slag zones, allowing for a longer lining life. In this study, a water model with a low temperature gas blow-in system was established to simulate the phenomena inside oxygen bottom-blowing vessels for investigating the effects of blowing conditions on the shape and size of solid accretion on the refractory lining near the tuyeres. The size of the ice mushrooms was found to be generally proportional to the outer gas flow rate and inversely proportional to the water temperature.

Keywords: Oxygen bottom blown, Steelmaking, Mushroom, Double-tuyeres, Water model

1. INTRODUCTION

The oxygen bottom-blowing technique has been applied to agitate the bath to enhance process efficiency via the high mixing intensity of the bath in pyrometallurgical processes. In general, the erosion of refractory lining near the gas bottom-blowing tuyeres is more severe than other areas due to the attack of back blown gas bubbles. One countermeasure to alleviate the erosion is to generate an iron accretion, usually referred to as a 'mushroom', which sits on the refractory lining via appropriate bottom-blowing conditions. The mushroom protects the refractory lining from being attacked by gas bubbles. Therefore, how to generate a mushroom with proper size and shape is one of the more important issues for extending the lining life.

Since it is impossible to observe the mushroom in a steelmaking furnace at high temperature, the water model was adopted to investigate the effects of gas bottom blowing conditions on the shape and dimensions of a mushroom formation. In this study, The Buckingham Pi theorem, a dimensional analysis technique, was adopted to derive the dimensionless parameters for correlating conditions of mushroom formation in similar systems. By combining dimensionless parameters with heat transfer equations for the heat transfer across the mushroom, quantitative relations based on the similarity conversions between different conditions of similar systems was established.

2. EXPERIMENTAL METHOD

2.1 Experimental apparatus and procedures

A water model with its cold gas supply system as shown in Fig.1 was established to investigate the conditions of the mushroom formation in the double tuyeres gas bottom-blown vessel. The vessel is made of transparent acrylic plates for observing the mushroom formation. A gas blowing double tuyere, structured of two gas channels, inner tuyere and outer loop tuyere, was installed at the center of the vessel bottom. The cross section and dimensions of the double tuyere are shown in Fig.1. Cold compressed nitrogen was used to blow through the outer loop tuyere channel as coolant, which was controlled at -170±1°C by flowing air through a pipe immersed in a liquid nitrogen bath. The nitrogen at room temperature was used to blow through the inner channel. The cold nitrogen and the room temperature nitrogen were used to simulate the cooling natural gas and oxygen respectively in the pyrometallurgical vessel.

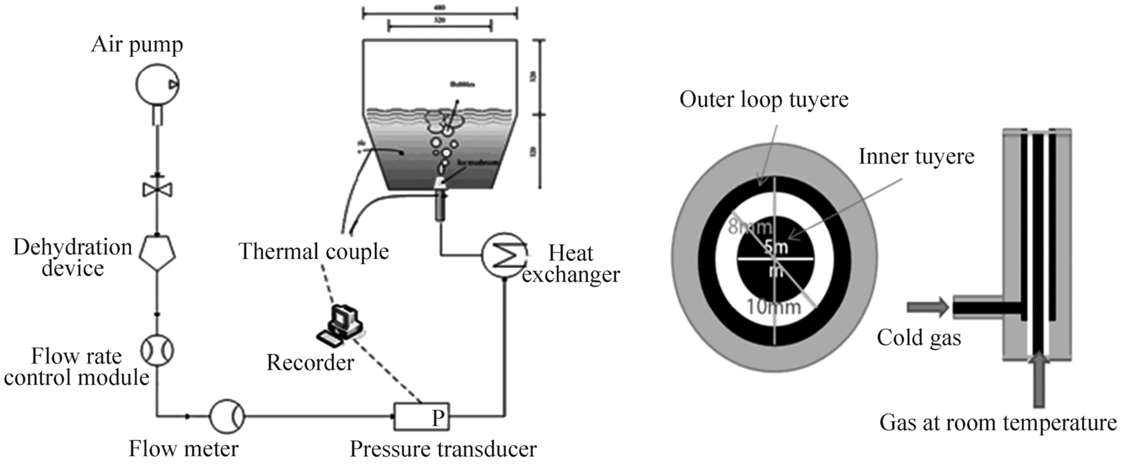

Fig.1. Schematic illustration of the water model with its gas supply system.

The variables studied in the experiments were flow rate of bottom-blown gas and water temperature. The range of variables is listed in Table 1. The mushroom formation was recorded by a video camera. Dimensions of the accretion were measured when the system reached a stable state.

2.2 System description

When low temperature gas is injected into the liquid bath through the bottom tuyeres of a steelmaking furnace, the gas comes into contact with and agitates the high temperature liquid during its ascent in the liquid bath. The basic mechanism of the mushroom formation inside the steelmaking furnace includes the phase change from liquid metal to solid iron resulting from a sufficiently fast heat transfer from liquid metal to the gas near the tip of the tuyeres. In fact, there are many variables that affect not only whether the mushroom can exist in the system or not, but also the shape and size of the formed mushroom. The mushroom usually looks like a hollow cone. The dimensions of the hollow cone are determined by the complicated heat transfer conditions of the system. Basically, the heat transfer of the system includes three different mechanisms, as follows:

(1) Heat transfer from the liquid bath to the solid mushroom at the liquid-solid interface (outer surface of the cone), by a forced convection in a liquid.
(2) Heat transfer across the solid mushroom, from outer surface to the inner surface, by conduction in a solid.
(3) Heat transfer from the solid mushroom to the gas flowing through the hollow channel at the solid-gas interface, by a forced convection in a gas.

Ideally, when the system reaches a state of heat equilibrium, the dimensions of the mushroom will be kept at a constant, this is called steady state of the system.

2.2.1 Dimensionless groups and heat transfer equations

On the thermal and dynamic similitude of the mushroom formation, The Buckingham Pi theorem was applied to derive a set of dimensionless groups that can be used to correlate the conditions between two similar systems. Five dimensionless groups including, Stefan number, Nusselt number, Peclet number, Reynolds number and Prandtl number were selected as important dimensionless numbers of the system for the similarity conversion.

In addition, the heat transfer Eqs(1)-(4), of a cone-shaped mushroom were applied to correlate the variables in the system illustrated in Fig.2. In the similarity conversion, these equations are required for the estimation of the height and diameter of the mushroom in a steelmaking furnace from results of the water model.

Table 1 Experimental conditions

Variables	Gas temperature in outer loop tuyere (°C)	Inner tuyere gas flow rate (Nl/min)	Outer loop tuyere gas flow rate (Nl/min)	Water temperature (°C)
Range	-170±1	50	100, 200, 300	10, 20, 30, 40

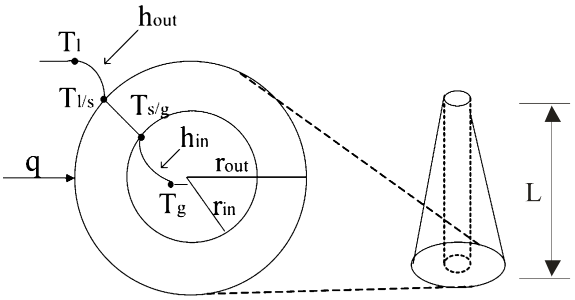

Fig.2. Simple mushroom formation.

$$q_{out} = A_{out} h_{out} (T_l - T_{l/s}) \quad (1)$$

$$q_{mid} = \frac{T_{l/s} - T_{s/g}}{\frac{\ell n\left(\frac{r_{out}}{r_{in}}\right)}{2\pi k_m L}} \quad (2)$$

$$q_{in} = A_{in}\, h_{in} (T_{s/g} - T_g) \quad (3)$$

$$h_{out} = \left(\frac{T_{l/s} - T_g}{T_l - T_{l/s}}\right) \times \frac{2k_{MU}\, h_{in}\, r_{in}}{\left(k_{MU}(r_b + r_{in}) + 2r_{in}h_{in}(r_b - r_{in})\right)} \quad (4)$$

Where T_l, $T_{l/s}$, $T_{s/g}$ and T_g are temperature of the liquid bath, temperature at the interface of the liquid and solid, temperature at the interface of the solid and gas and temperature of gas, respectively. K_m is the conductivity of the mushroom. h_{in} and h_{out} are inner and outer convection heat transfer coefficient. r_{in} and r_{out} are inner and outer radius of the mushroom, and r_b is the outer radius of the mushroom base. A_{in}, A_{out} and K_{MU} are inner, outer interface area and the thermal conductivity of the mushroom, respectively.

2.2.2 Similarity Conversion

In developing the similarity conversion, some assumptions were made to simplify the real system as follows:

(1) The mushroom is in a cone shape with a hollow and cylindrical channel for gas flow.
(2) The heat transfer rate at the interface of the mushroom and the bottom wall of the furnace is zero.
(3) The conductive heat transfer is uni-directional across the mushroom.
(4) The liquid flow is in parallel with the outer surface of the mushroom.
(5) The temperature of gas, liquid and solid at the upper tip of the mushroom are equal.
(6) The temperature gradient of the flowing gas along the channel axis inside the mushroom is linear.

The major procedures in similarity conversion for correlating the conditions of a cold model and a hot model (steelmaking furnace), as shown in Fig.3.

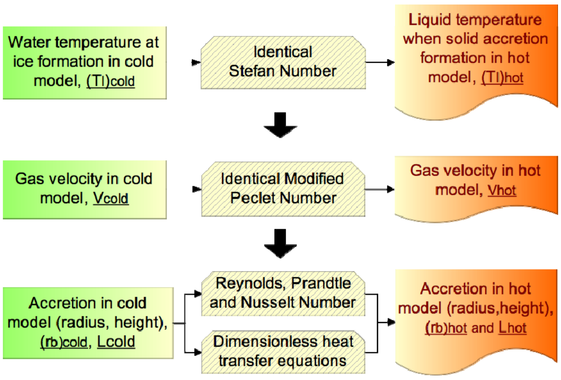

Fig.3. Major procedures in similarity conversion.

3. RESULTS AND DISCUSSION

3.1 Results of water model

In the water model, ice mushrooms were observed in a shape of a cone with a hollow channel for gas to flow through. The left side of Fig.4 is the ice mushroom formed in the outer loop channel with a gas flow rate of 100 NL/min at a water temperature of 10°C. And the right side is the schematic shape of the mushroom. Almost all the ice mushrooms formed were cone shaped with a hollow cylindrical channel for the gas to flow through.

Fig.4. The shape of the ice accretion.

Figure 5 shows the relationship between the mushroom dimensions and the water temperature under different outer gas flow rates. Increasing the outer gas flow rate or decreasing the water temperature increases the size of the ice mushroom. Generally, the dimension of ice mushrooms is proportional to the outer gas flow rate and inversely proportional to the water temperature.

In the water model, it was found that the radius of the gas channel inside the mushroom is approximately equal to the inner radius of the bottom blowing tuyere. Based on the relationship between the ice radius and the water temperature, the highest water temperature for ice mushroom formation under different gas flow rates can be estimated, as shown in Fig.6. An ice mushroom would be generated and be stable if the conditions fall in the region below the line.

3.2 Similarity conversion results in a steelmaking furnace

The mushroom formation in a steelmaking furnace was estimated from experimental data of the water model by similarity conversion and were appropriate for the steelmaking furnace. The dimensions of the mushroom formation in the steelmaking furnace, which are shown in Table 2, were calculated by similarity conversion results. It shows the relationship between the dimensions and the molten steel temperature under different gas flow rates. Just as the trend in water model results shows, the dimensions of the steel mushrooms are proportional to the gas flow rate and inversely proportional to the steel temperature.

4. CONCLUSIONS

(1) A low temperature water model with a gas bottom-blown double tuyere was constructed for this study. The effects of operating conditions, mainly inner and outer gas flow rate and liquid temperature, on the mushroom formation were investigated.

(2) Generally, the dimensions of the ice mushrooms were proportional to the outer gas flow rate and inversely proportional to the water temperature. As the gas flow rate was increased, the ice mushroom formation in the highest most stable water temperatures also increased in the water model.

(3) The similarity conversion of cone-shaped mushrooms had been developed, to estimate the dimensions of the mushroom generated via the bottom gas blowing into the steelmaking furnace. The dimen-

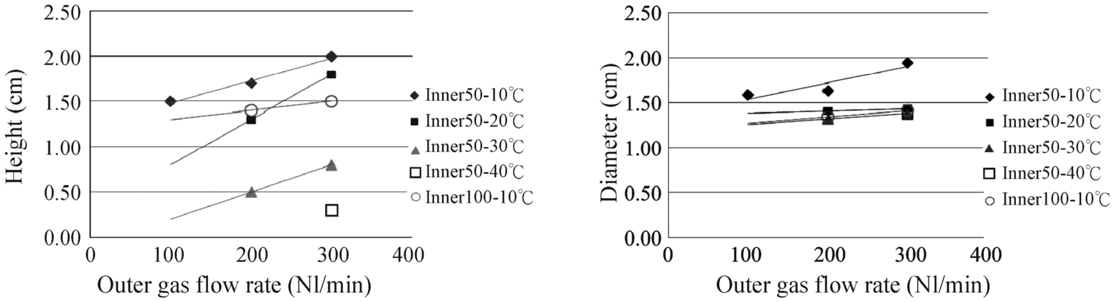

Fig.5. The relationship between gas flow rate and mushroom sizes.

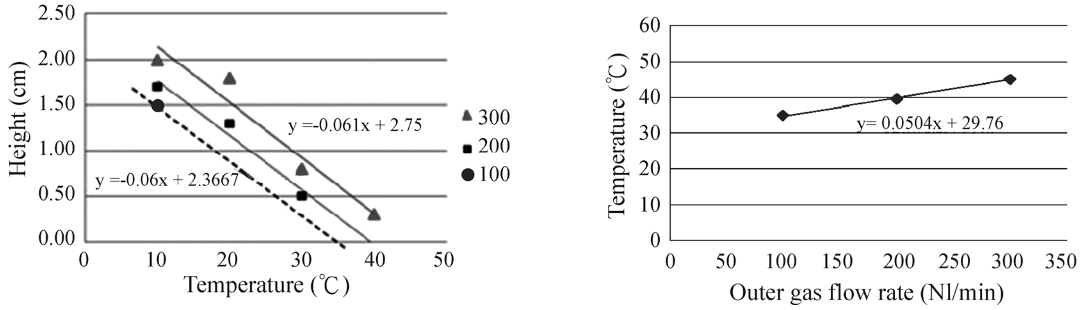

Fig.6. The relationship between water temperature and mushroom sizes.

Table 2 Relationship between mushroom radii at bottom and the steel temperature under different gas flow rates

Gas flow rate (Nm3/hr)	27.4(outer) 37.6(inner)		27.4(outer) 75.1inner)		27.4(outer) 105.3(inner)	
Superheat(℃)	Radius(m)	Height(m)	Radius(m)	Height(m)	Radius(m)	Height(m)
22.0	0.42	0.38	0.27	0.23	0.39	0.09
44.0	0.38	0.37	0.38	0.23	0.29	0.09
66.0	0.30	0.37	0.24	0.22	0.33	0.07
88.0	0.23	0.36	0.20	0.21	0.13	0.06

sions of the mushroom in the steelmaking furnace were calculated by similarity conversion results. The results show the dimensions of steel mushroom sizes are proportional to the gas flow rate and inversely proportional to the molten steel temperature.

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