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Water Modeling of Mushroom Formations in a Gas Bottom-Blowing BOF Steelmaking Process

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A water model with a low temperature (-170℃) gas blow-in system was established to simulate the phenolmena inside a steelmaking furnace, to investigate the effects of gas bottom blowing conditions on the shape and dimensions of the mushroom formation, sitting on the gas tuyeres. It was observed that ice mushroom formations in the shape of cones with hollow channels for gas flow through were formed. As the gas flow rate was increased, the ice mushroom formations in the highest, most stable water temperatures of the water model also increased. In addition, The Buckingham Pi theorem was adopted to derive the important dimensionless parameters for correlating conditions of mushroom formation in similar systems. Then, by combining dimensionless parameters with heat transfer equations that describe the heat transfer across the mushroom, quantitative relations based on the similarity conversion of similar systems was established. The dimensions of the mushroom formation in the steelmaking furnace were calculated by ssimilarity conversion results. The results show the dimensions of steel mushroom formation sizes are proportional to the gas flow rate and inversely proportional to the molten steel temperature.

Keywords: Mmushroom, Water model, Dimensionless parameters, Similarity conversion, Steelmaking furnace, Gas bottom-blowing

1. INTRODUCTION

In the steelmaking process, the gas bottom-blowing technique has been widely applied to agitate the liquid bath to enhance metallurgical efficiency via the high mixing intensity of the liquid bath inside the furnace. In general, the erosion of refractory lining near the gas bottom-blowing tuyeres is more severer than that of other areas inside the furnace due to back attack of blown gas bubbles. One of the countermeasures to alleviate refractory erosion is to generate a mushroom formation sitting on the refractory lining via appropriate bottom-blowing conditions. The covering created by the mushroom can protect the refractory lining from being eroded by the back attack of gas bubbles. Therefore, how to generate a mushroom formation is one of the most important issues in high performance bottom blowing furnace technology.

Due to the extremely high temperature, it is impossible to visualize what is happening inside the steelmaking furnace. Therefore, the water model was adopted to investigate the effects of gas bottom blowing conditions on the shape and dimensions of mushroom formation. In the study, The Buckingham Pi theorem, a dimensional analysis technique, was adopted to derive the important dimensionless parameters for correlating conditions of mushroom formation in similar systems. Then, by combining dimensionless parameters with heat transfer equations that describe the heat transfer across the mushroom, quantitative relations based on the similarity conversions between different conditions of the similar systems was established.

2. EXPERIMENTAL METHOD

2.1 Experimental apparatus and work

A water model with its cold gas supply system, illustrated in Fig.1, was established to investigate the conditions of the mushroom formation in the furnace. In this study a single tube type with a 6.25 mm inner diameter was installed at the center of the furnace bottom. Cold compressed air was used as the bottom blown gas. The air temperature was controlled at -170±1 ^{o}C by flowing air through a pipe immersed in a bath of liquid nitrogen.

The variables studied in the experiments are flow rate of bottom-blown air, and water temperature. The range of variables is listed in Table 1. The phenomena of the mushroom formation were recorded by a video camera. And, the dimensions of the mushroom were measured when the experimental conditions reached a stable state.

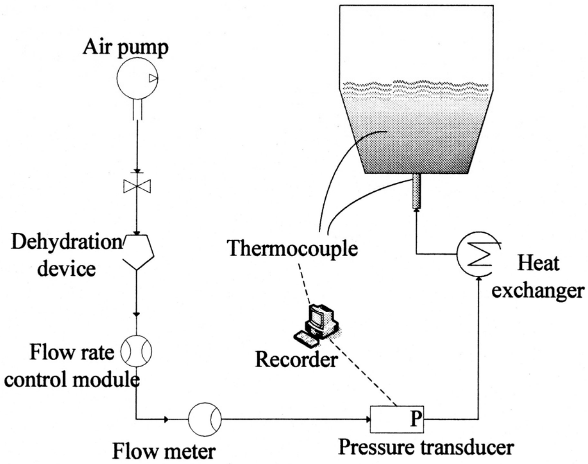

Fig.1. Schematic illustration of the water model with its gas supply system.

Table 1 Experimental conditions

Variables	Gas temperature (℃)	Gas flow rate (Nl/min)	Water temperature (℃)
Range in experiment	-170 ± 1	60, 90, 120, 150	12, 18, 24

2.2 System description

When low temperature gas is injected into the liquid bath through the bottom tuyeres of a steelmaking furnace, the low temperature gas comes into contact with and agitates the high temperature liquid during it's ascent of 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 high heat transfer from liquid metal to the blown-in gas near the tip of the tuyeres. In fact, there are many variables to determine whether the mushroom cans exitst in the system or not. Furthermore, the variables also affect the shape and size of the mushroom formation. In general, the geometric shape of the solid mushroom looks as 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 explained below:

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

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

2.3 Dimensionless groups and heat ttransfer 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 any 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 ttransfer Equations (1) to (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, based on experimental results of the water model.

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

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

$$q_{in} = A_{in}h_{in}\left(T_{s/g} - T_g\right) \cdots\cdots (3)$$

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

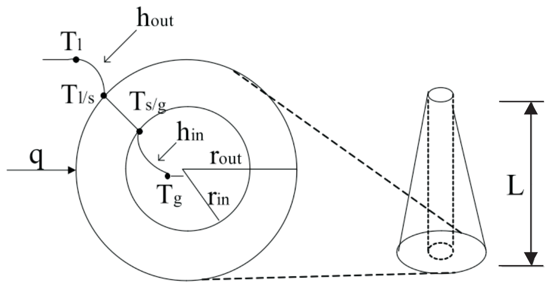

Fig.2. Simply mushroom formation.

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

2.4 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 unit-directional across the mushroom.
(4) The liquid flows in parallel with the outer surface of the mushroom.
(5) The temperature of gas, liquid and solid at the upper tip of the mushroom is 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), are shown in Fig.3.

3. RESULTS AND DISCUSSION

3.1 Results of water model

In the water model experiments, it was observed that ice mushrooms were in the shape of cones with a hollow channel for gas flow through. The left part of Fig.4 is the ice mushroom formed in a gas flow rate of 120 Nl/min at a water temperature of 24^{o}C. And the right part is the schematic shape of the mushroom. Almost all the ice mushrooms formed are cone shaped with a hollow cylinder channel for the gas flow through.

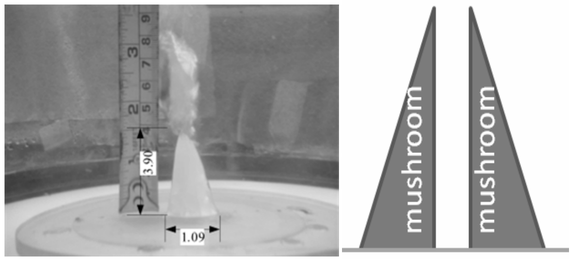

Fig.4. The shape of the ice accretion.

The dimensions of ice mushrooms formed in the experiments are shown in Table 2. It was found that increasing the gas flow rate or decreasing the water temperature increases the size of the ice mushroom. Figure 5 shows the relationship between the dimensions and the water temperature under different gas flow rates. Generally, the dimension of ice mushrooms is proportional to the gas flow rate and inversely proportional to the water temperature.

In the water model experiments, it was found that the radius of the gas channel inside the solid 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 obtained, as shown in Fig.6. In the figure, an ice mushroom would be generated and be stable if the conditions fall in the region below the curve.

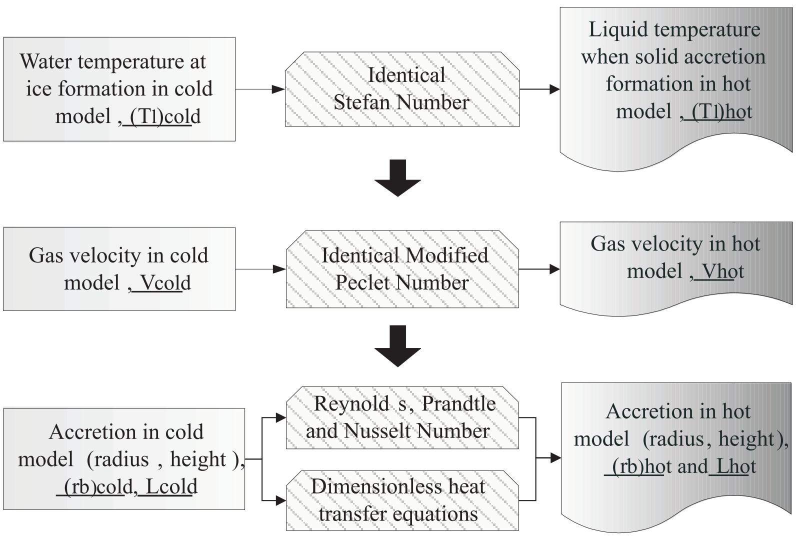

Fig.3. Major procedures in similarity conversion.

Table 2 Mushroom dimensions of water model

Gas flow rate (Nl/min)	60		90		120		150	
Water temperature (℃)	R	H	R	H	R	H	R	H
12	0.93	4.10	1.11	5.30	1.25	7.50	1.40	11.50
18	0.72	2.20	0.90	3.00	1.20	5.20	1.25	6.10
24	0.50	1.50	0.70	2.30	1.09	3.90	1.20	4.50

(Unit: cm, R: the radius of mushroom base, H: the height of mushroom)

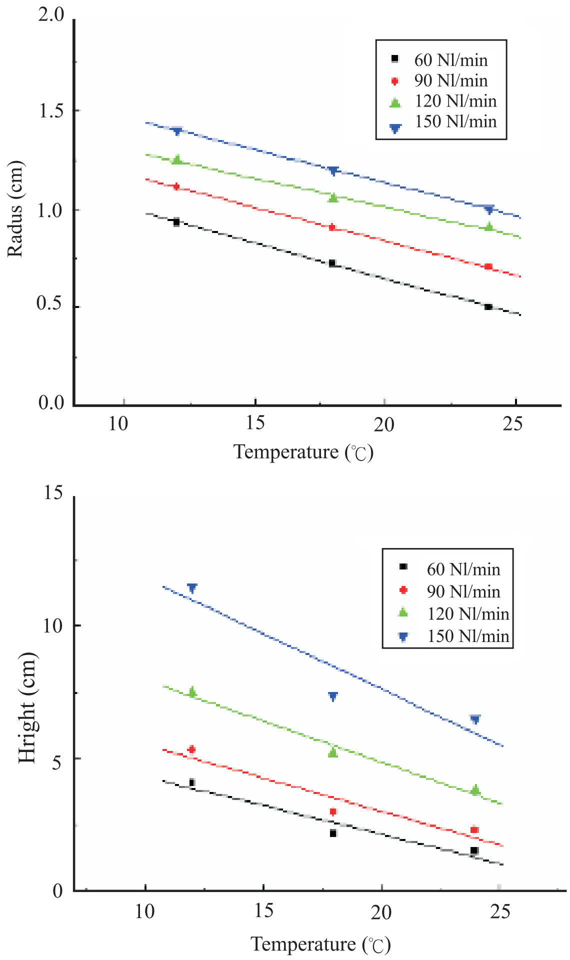

Fig.5. Relationship between ice dimensions and the water temperature under different gas flow rates.

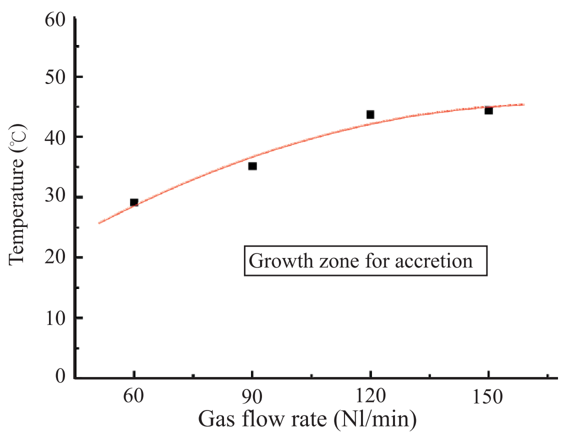

Fig. 6. The growth zone of ice mushroom formation.

3.2 Similarity conversion results in a steelmaking furnace

The experimental conditions of the steelmaking furnace were estimated from experimental data of the water model by ssimilarity conversion and were appropriate for the steelmaking furnace. The dimensions of mushroom formation in the steelmaking furnace, which are showed in Table 3, were calculated by ssimilarity conversion results. Figure 7 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 molten steel temperature.

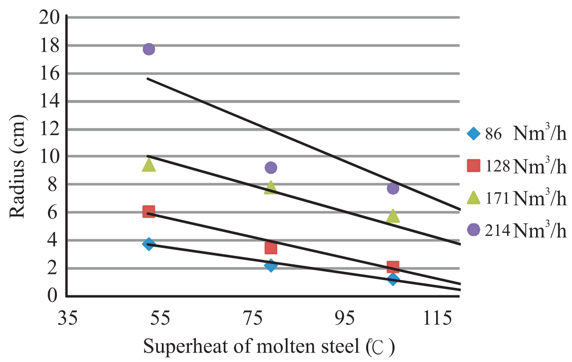

Fig.7. Relationship between mushroom radii and the molten steel temperature under different gas flow rates.

4. CONCLUSION

A low temperature water model with a low temperature gas piping system was constructed in this study. The effects of operating conditions; mainly gas flow rate and liquid temperature, on the conditions of the solid mushroom were investigated. Generally, the dimension of the ice mushrooms was proportional to the 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. The similarity conversion of cone-shaped mushrooms had been developed, to estimate the dimensions of the mushroom generated via the bottom gas blown into the steelmaking furnace. The dimensions of the mushroom in the steelmaking furnace were calculated by similarity

Table 3 Mushroom dimensions in the steelmaking furnace

Gas flow rate (Nm^3/h)	85.6		128.3		171.1		213.9	
Molten steel temperature (℃)	R	H	R	H	R	H	R	H
52.8	3.77	4.52	6.10	7.32	9.48	11.37	17.79	21.35
79.2	2.23	2.68	3.48	4.18	7.85	9.41	9.27	11.12
105.6	1.25	1.50	2.13	2.55	5.80	6.96	7.78	9.34

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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