Journal of Iron and Steel Research, International 24 (2017) 490—494

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn

Hydraulic experiment on mushroom head in bottom-blown smelting furnace

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ARTICLE INFO

Key words:
Bottom-blown smelting furnace
Mushroom head
Hydraulic experiment
Thermal equilibrium
Similarity criterion

ABSTRACT

There are many bottom-blown smelting furnaces in metallurgical industry. When oxygen or air sprays from the jet nozzle into the bottom of the furnace, the melting phase will be frozen and a hemispherical porous zone with a mushroom head shape will be formed around the nozzle. The mushroom head can protect the jet nozzle and mitigate the liquid spray on the surface of melt. In order to analyze the formation process of a mushroom head in the bottom-blown smelting furnaces, a hydraulic experiment system was designed and the formation of the mushroom head was investigated by hydraulic experiment. The hydraulic experiment results show that the formation process is mainly divided into generating crushing generating process and stable mushroom head generation process. The formation of stable mushroom head requires certain thermodynamic condition and water splash is more intense without a mushroom head than with a mushroom head. The size, porosity and diameter of the mushroom head are affected by the flow rate, temperature and heat capacity of the bottom-blowing gas and the temperature of the superheat and the physical parameters of the melt.

1. Introduction

Various bottom-blown smelting furnaces, such as converters and bottom-blown copper smelting furnaces, are used in metallurgical industry[1-3]. When a furnace is utilized, gas is jetted strongly from the bottom of the furnace, and its temperature is lower than that of the melt. A cold area will be generated around the outlet of the jet nozzle. High-temperature melt will curdle in the cold area and transform to a porous medium similar to a mushroom. This porous medium is called mushroom head[4-8]. A mushroom head can protect the jet nozzle of furnaces. However, it also increases the resistance for jetting gas. Thus, the formation process of mushroom heads must be analyzed[9-13].

Yuan et al.[14] conducted a hot simulation to investigate the formation of a mushroom above the outlet of a bottom-blowing nozzle in a combined blowing converter; the correlation among the temperatures of the bottom-blowing nozzle, its peripheral refractory lining, the temperature of hot metal, and the flow rate of bottom blowing gas, was examined. The result showed that hot metal would form a mushroom above the nozzle outlet and protect the nozzle only when the outlet temperature is lower than the solidification temperature of hot metal by approximately 333 K. Thus, a blowing pattern was proposed to control the formation, growth, melting, and dissolution of mushroom heads. Zhang et al.[15] examined the growth pattern of a mushroom at the end of the tuyere of the top and bottom combined blown converter, and investigated the thermodynamics and kinetics of nucleation and the influence of technical parameters on the dimension of the mushroom and the variations of gas flow rate and pressure. The effect of the distance between neighboring pipes of multiple-pipe tuyere and the influence of different kinds of tuyeres on the formation of a stable mushroom were also investigated. However, the experiment was relatively simple, and most conclusions were obtained using thermal equilibrium mathematical models. Yu[16] discussed the thermodynamic conditions for the stability of a mushroom head at a bottom-blown converter by using a heat balance model. The relationship between the size of a mushroom head and the flow rate of the bottom-blowing gas was established. The formation process of a mushroom head and the effect of a mushroom head on furnace flow were not analyzed.

The previous studies focused on the mushroom head in the bottom-blown converter and employed

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Received 9 August 2016; Received in revised form 20 October 2016; Accepted 20 October 2016
Available online 15 May 2017

simulations of the thermal process. The jet nozzles of a bottom-blown smelting furnace and a bottom-blown converter are different. The jet nozzle of a bottom-blown smelting furnace must be located deeply in the furnace. Thus, the form and formation process of a mushroom head differ from those in the bottom-blown converter. The current study focused on the bottom-blown smelting furnace. In the actual production process, the temperature of the melt is always higher than 1573 K; thus, conducting experiments by using actual melt is difficult. Therefore, the formation process of a mushroom head in the bottom-blown smelting furnace was investigated by using hydraulic model experiments based on previous studies on the mushroom head in the bottom-blown converter to analyze the effects of temperature and gas flow on the formation process of a mushroom head.

2. Hydraulic Model Experiment

2.1. *Similarity criterion*

The experimental setup in the current paper is similar to a bottom-blown copper smelting furnace. Similarity criterion must be established to ensure that the model flow and prototype flow are similar. The similarity criterion in the current study is as follows.

(1) Geometric similarity

Geometric similarity was the first condition that must be followed in a similarity criterion. This feature indicates that a model and prototype must have the same geometric shape; their corresponding size must have the same ratio, and their corresponding angles must be similar. The value of geometric similarity is computed using Eq. (1).

$$\lambda=\frac{L_{\mathrm{m}}}{L_{\mathrm{p}}} \tag{1}$$

where, λ is the number of geometric similarity; L_{m} is the length of the model, m; and L_{p} is the length of the prototype, m.

(2) Dynamic similarity

A modified Froude number Fr' was selected in dynamic similarity, as shown in Eq. (2).

$$Fr'=\frac{v_{\mathrm{g}}^{2}}{gd_{0}}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}} \tag{2}$$

where, v_{g} is the velocity of gas, m/s; g is the acceleration of gravity, $\mathrm{m/s^2}$; d_0 is the diameter of a jet nozzle, m; ρ_{g} is the density of gas, $\mathrm{kg/m^3}$; and ρ_{l} is the density of liquid, $\mathrm{kg/m^3}$.

The modified Froude numbers of the model and prototype must be the same, as described in Eq. (3).

$$\left(\frac{v_{\mathrm{g}}^{2}}{gd_{0}}\right)_{\mathrm{m}}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)_{\mathrm{m}}=\left(\frac{v_{\mathrm{g}}^{2}}{gd_{0}}\right)_{\mathrm{p}}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)_{\mathrm{p}} \tag{3}$$

2.2. *Experimental parameters*

Based on various conditions, such as laboratory size and economic cost, 1 : 10 was set as the geometric similarity number. The structural parameters of the model and prototype are shown in Table 1.

Table 1

Structural parameters of model and prototype

Parameter	Prototype	Model
Geometric similarity number	1 : 1	1 : 10
Diameter of furnace/mm	3880	388
Length of furnace/mm	2850	285
Height of liquid level/mm	1545	154.5
Angle of jet nozzle/(°)	0	0
Length of jet nozzle/mm	180	18
Outlet area of jet nozzle/mm^2	798.42	About 8

The current study focused on the formation process of a mushroom head when cold gas was jetted to a furnace. Water was used instead of copper matte, and cold air was utilized instead of jetting gas. All the parameters of the prototype were provided by a copper production company. The parameters of the prototype and the model are presented in Table 2.

Table 2

Parameters of prototype and model

Prototype	
Density of copper matte/(kg · m^{-3})	4500
Density of N_2/(kg · m^{-3})	1.25
Density of O_2/(kg · m^{-3})	1.429
Gas flow/(m^3 · h^{-1})	2000
Initial water temperature/K	278
Model	
Density of water/(kg · m^{-3})	998
Density of air/(kg · m^{-3})	1.293
Air flow/(m^3 · h^{-1})	1.0, 1.5, 2.0, 2.5

2.3. *Experimental facility and scheme*

The experimental facilities in the experiment included a furnace model, a cold air-supply system (dry ice was used to reduce temperature), air drying system, and control system. The schematic diagram and actual facilities are shown in Figs. 1 and 2.

The working principle of this experiment is as follows:

(1) Air was provided by an air compressor, and its pressure was stabilized by a regulator valve.

(2) Air passed through an air-drying system, and dry air can be provided.

(3) Dry air passed through a cold air-supply system, and its temperature will be reduced to an appropriate temperature.

(4) Dry cold air was jetted into a furnace model.

A high-speed camera was used to record the formation process of the mushroom head, and thermo-