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A MATHEMATICAL MODEL OF CAVITY DEPTH IN CONVERTER STEELMAKING

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In this study, cold model experiments were carried out to investigate the cavity depth. It was found that the existing model prediction deviated from the experimental results at higher gas flow rate. The normalized linear relationship was obtained between the dimensionless characteristic cavity depth (n_0/H) and a combined dimensionless parameter of the Froude number (*Fr*) and the ratio of nozzle diameter to jet height (d_e/H). Further, the linear law of the slope and the intercept of normalized fitting line with the nozzle diameter were obtained.

Keywords: steelmaking, converter, nozzle diameter, cavity depth, mathematical model

INTRODUCTION

Process of gas-jet impinging into liquid is applied in various industrial fields [1]. The resulting interaction between the jet and liquid surface is often of critical importance to the transfer of mass, kinetic, and thermal energy in the process units involved and thus determines their performance [2]. In basic oxygen furnace (BOF), the top jet blowing of oxygen is the main characteristic of the process. The cavity induced by top-blow gas jet impinging on the bath surface is one of the most important parameters, which has overwhelming influence on the metallurgical performance. Most of the studies relies on water modeling due to experimental difficulties associated with study of penetration depth in opaque liquids. Banks [3] and Cheslak [4] served as the pioneers have launched comprehensive researches on the cavity size (depth, width and peripheral lip height) by stagnation-pressure and weight displaced analyses and established the first basic relationship between the penetrating depth and the jet momentum:

$$\frac{M}{\rho_l g H^3} = \frac{\pi}{2K^2} \cdot \frac{n_0}{H} \cdot (1 + \frac{n_0}{H})^2 \qquad (1)$$

where M is the gas jet momentum, H is the jet height (m), ρ_l is the density of the liquid (kg/m^3), g is the gravitational constant (m/s^2), n_0 is the cavity depth and K is a constant. Based on the model suggested by Banks *et al*., extensive experimental studies were also carried out to investigate the dimensions of the cavity induced by the jet impinging onto the surface of liquid. It was found that, in the literatures, different values are reported for the constant K in the model established by Banks *et al*. For example, K is equal to 6,4 as suggested by Cheslak *et al*. [4], 7,81 by Hwang and Irons [5], 9,8 by Ek et al. [6] and 11,5 by Meidani et al [7]. The difference indicates that even under the same experimental conditions, the K value determined at a certain lance height may not be applied well to other cases of lance height. Different researchers likely show some deviations in different experimental conditions. The reason maybe that the impinging kinetic energy of jet at the impact point contributes not only to the formation of cavity but also to other phenomena related to deflecting of gas flow, spitting and splashing of liquid droplets, stirring of liquid bath, etc.

The aim of present work is to evaluate the accuracy of the existing models, predominantly based on a physical model consisting of an air jet and water bath. A theoretical model for predicting penetration depth was established based on normalization analysis.

EXPERIMENTAL METHODS

The experimental device shown in Figure 1 was used to conduct the water model experiment at a temperature of 20 C° and an ambient pressure of 101,3 kPa. In order to eliminate the refraction effect and accurately observe the cavity shape, a converter model with an inner diameter (D) of 400 mm and a height of 500 mm was set in a square container with a side length of 500 mm. Where, (h) represents the depth of the molten pool, and (H) represents the vertical injection height from the nozzle to the liquid level of the molten pool, which ranges from 30 – 130 mm. During the experiment, compressed air was used for water model test, and a pressure regulator tank with an effective volume of 0,3 m^3 was used to provide stable pressure for the system. Use an air rotameter with a range of 2,5 m^3/h to regulate the

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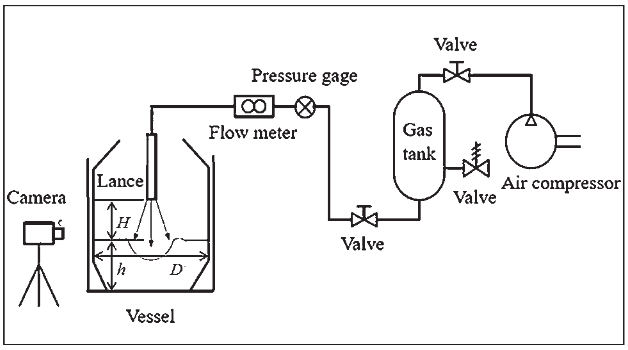

Figure 1 Schematic of experimental setup

flow. In order to intuitively observe the gas pressure, a pressure gauge with a range of 1,0 MPa is connected in front of the flowmeter. Four different single-hole nozzles are used. In order to record cavity depth, scale lines are fixed horizontally at the gas-liquid interface. The cavity depth was obtained by repeating the same experiment six times.

RESULTS AND DISCUSSION

Comparison of the existing mode

As mentioned in the introduction part, a number of models have been developed to predict the penetration depth in the case of jet impinging on the surface of liquid. Most of these studies have been carried out based on water model experiments. Many models share a common structure suggested by Banks [3]. In order to examine the applicability of the model, the predicted penetration depths of NO.1 and NO.3 jet were plotted under different flows for the jet heights of 30 – 130 mm, respectively. The results of the theoretical prediction model of Banks were plotted against the experimental results in Figure 2. It was found that the model developed by Banks predicts the penetration depths reasonably well under most conditions, while, it predicts much smaller penetration depths at higher gas flow rates. The reason for this deviation may be that the larger flow rate leads to the development of the cavity from splashing mode to penetrating mode. The energy exchange between the gas and the liquid increases obviously in the penetration mode. The disturbance on the surface of the cavity is obviously enhanced, and the increased roughness of the surface in turn promoted the exchange of momentum to the liquid and a deeper cavity will be formed.

Normalization analysis

According to the comparison of the experimental data with the existing model previously discussed, a modification is needed to correlate the penetration depth for higher jet flow parameters. The penetration behavior of the jet can be expressed as a function of the following influencing factors [3]:

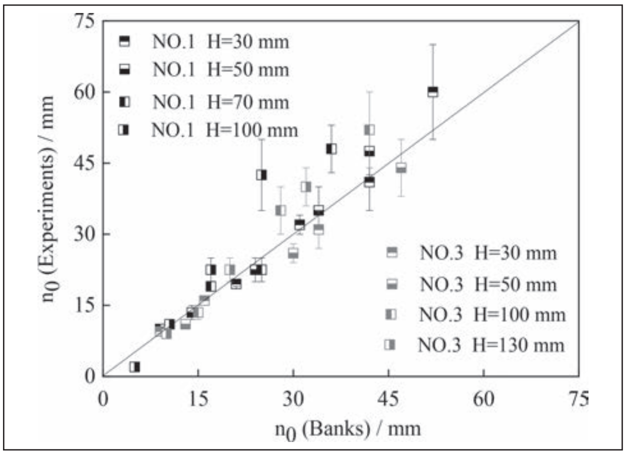

Figure 2 Comparison of equation 1(K = 7,9) with experimental results

$$n_0 = f(M, H, g, \rho_l, \mu_l, \sigma) \tag{2}$$

Three fundamental quantities H, g and ρ_l were chosen as three independent dimensions and the remaining physical quantities can be expressed as:

$$\begin{aligned}
[n_0]&=[H]^{a_1}\cdot[g]^{b_1}\cdot[\rho_l]^{c_1}=[L]^{a_1}\cdot[LT^{-2}]^{b_1}\cdot[ML^{-3}]^{c_1}=[L]\\
[M]&=[H]^{a_2}\cdot[g]^{b_2}\cdot[\rho_l]^{c_2}=[L]^{a_2}\cdot[LT^{-2}]^{b_2}\cdot[ML^{-3}]^{c_2}=[MLT^{-2}]\\
[\mu_1]&=[H]^{a_3}\cdot[g]^{b_3}\cdot[\rho_l]^{c_3}=[L]^{a_3}\cdot[LT^{-2}]^{b_3}\cdot[ML^{-3}]^{c_3}=[ML^{-1}T^{-1}]\\
[\sigma]&=[H]^{a_4}\cdot[g]^{b_4}\cdot[\rho_l]^{c_4}=[L]^{a_4}\cdot[LT^{-2}]^{b_4}\cdot[ML^{-3}]^{c_4}=[MT^{-2}]
\end{aligned} \tag{3}$$

The four dimensionless numbers π_1, π_2, π_3 and π_4 can be written as:

$$\pi_1 = \frac{n_0}{H} \tag{4}$$

$$\pi_2 = \frac{M}{\rho_1 H^3 g} = \frac{\pi}{4}\cdot\frac{\rho_g v_g^2 d_e^2}{\rho_l g H^3} = \frac{\pi}{4}\cdot\left(\frac{d_e}{H}\right)^2 Fr \tag{5}$$

$$\pi_3 = \frac{M}{\mu_l H^{\frac{3}{2}} g^{\frac{1}{2}}} = \frac{\pi}{4}\frac{\rho_g v_g d_e^2}{\mu_l H^{\frac{3}{2}} g^{\frac{1}{2}}} = \frac{\pi}{4}\frac{d_e}{H} Fr\,\mathrm{Re} \tag{6}$$

$$\pi_4 = \frac{M}{\sigma H} = \frac{\pi \rho_g v_g^2 d_e^2}{4\sigma H} = \frac{\pi}{4}\frac{d_e}{H} We \tag{7}$$

where Fr is the Froude number, representing the ratio of inertial force to gravity; Re is the Reynolds number, representing the ratio of inertial force to viscous force; We is the Weber number, representing the ratio of inertial force to surface tension. The final dimensionless relationship can be obtained:

$$\frac{n_0}{H} = \frac{d_e}{H}\cdot f(Fr, \mathrm{Re}, We) \tag{8}$$

In view of the research of droplets splashing in gas jet into molten bath, Fr and We were used as control parameters to normalize the onset conditions of droplet splashing. As a dimensionless parameter, Fr can normalize all the penetration parameters, especially the inertial force, which has a great influence on the development of the cavity in the process of gas jet penetration. Although the surface tension is considered, the We cannot do that for the neglecting of the inertial force. Therefore, Fr was used to normalize the critical penetration conditions of

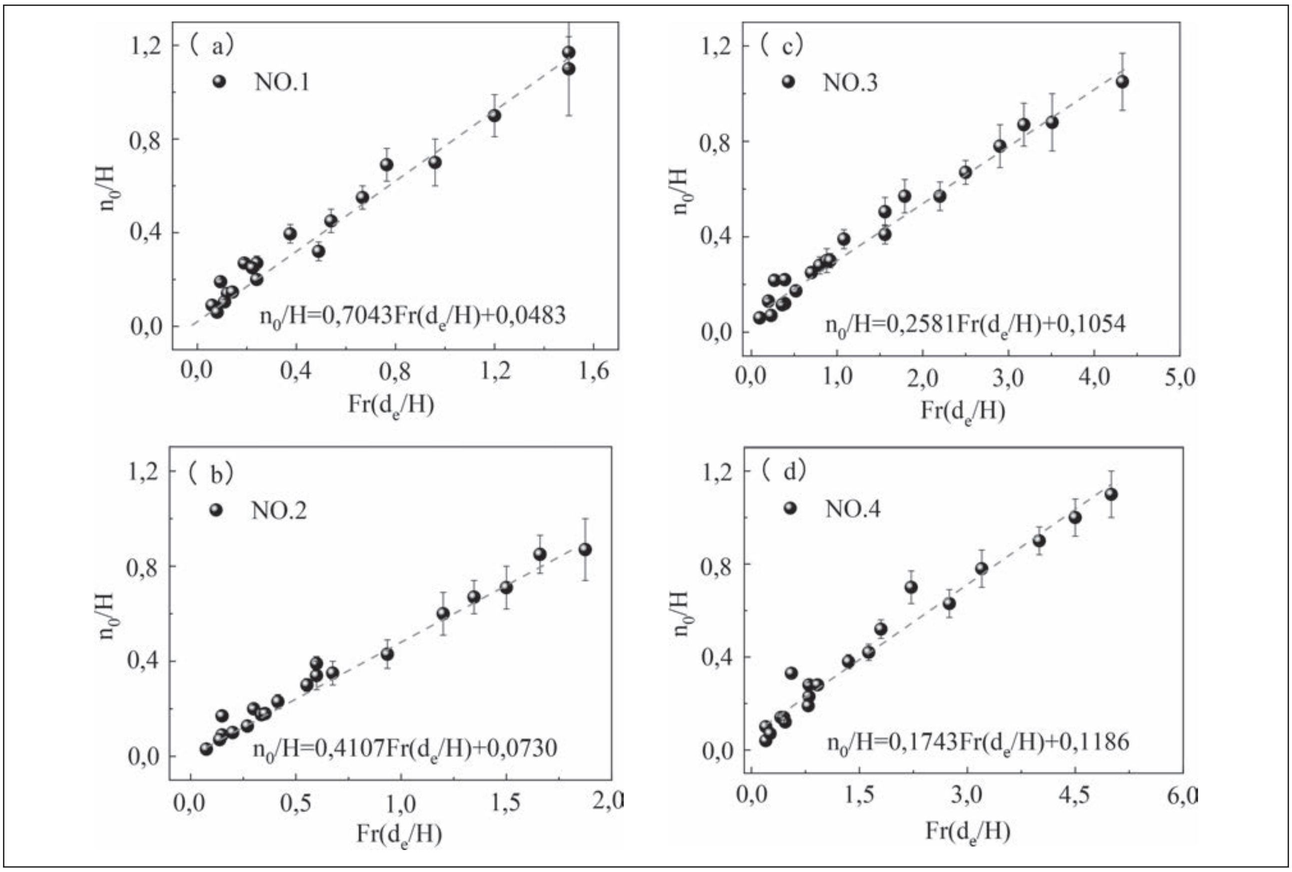

Figure 3 Dimensionless results of the cavity depths for different nozzle diameters. (fitted by the dash lines) (d_e = 3,00 mm in Figure 3a; d_e = 2,20 mm in Figure 3b; d_e = 1,60 mm in Figure 3c; d_e = 1,26 mm in Figure 3d)

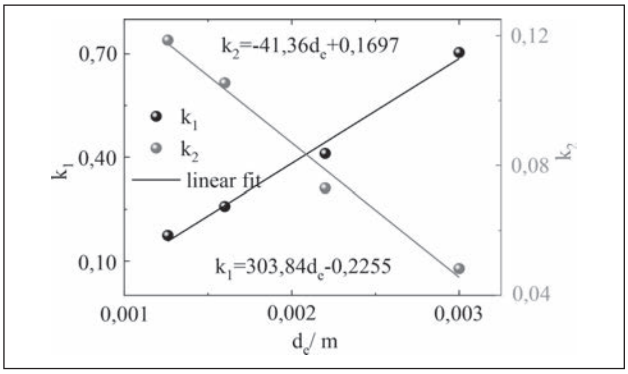

Figure 4 The slope and the intercept of fitting lines as a function of the nozzle diameter

droplet splashing occurrence. Therefore, dimensional analysis yields the following expression:

$$\frac{n_0}{H} = f(Fr \cdot \frac{d_e}{H}) \tag{9}$$

Abundant of experiments were performed to obtain the cavity depths under various penetrating parameters. Refer to the dimensionless form equation (9), the results about the ratio of the cavity depth to the jet height (n_0/H) with the combined dimensionless parameter of the Fr and the ratio of the nozzle diameter to the jet height d_e/H were arranged and plotted in Figure 3. Apparently, the experimental results show that the function of equation (9) can be fitted by a linear governing formula:

$$\frac{n_0}{H} = k_1\left(Fr \cdot \frac{d_e}{H}\right) + k_2 \tag{10}$$

Accordingly, four straight fitting dash lines corresponding to four different nozzle diameters were shown in Figure 3. The slope k_1 and the intercept k_2 of the fitting dash line can also be fitted to a straight line related to diameters, respectively. The two fitted lines were shown in Figure 4 and expressed by:

$$k_1 = 303{,}84 d_e - 0{,}2255 \tag{11}$$

$$k_2 = -41{,}36 d_e + 0{,}1697 \tag{12}$$

Oriented by the dimensionless analysis, a better experimental result of dimensionless cavity depth was obtained. All sizes of the depth were collapsed to a significant linear expression as long as the jet nozzle diameter was determined. In addition, the linear relationship of the slope and the intercept of the governing line to the nozzle diameter were given to broaden industrial applications.

CONCLUSIONS

The cavity depth created by the impinging jet was characterized under different penetrating conditions, including different nozzle diameters, bath depths, gas flow rates and jet heights. The experimental results were compared with the existing models, and it is found that there are differences between them at high gas flow rate. A generalized phenomenological model was established for predicting the penetration depth. As normalization, the ratio of cavity depth to jet height was expressed by a linear function of a combined dimensionless parameter of the *Fr* and the ratio of nozzle diameter to the jet height; meanwhile, the slope k_1 and the intercept k_2 of the linear function were determined by the fitting of the experimental results.

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