D. XU, B. ZHENG, L. X. GUO, H. X. PANG

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A MATHEMATICAL MODEL OF CRITICAL JET HEIGHTS CAUSING DROPLETS SPLASHING IN BOF STEELMAKING

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It is important to understand the physical interaction between top-blown oxygen jet and liquid bath in basic oxygen steelmaking furnaces (BOF). In this study, cold model experiments were carried out to investigate the cavity depth, diameter and the instability at the gas-liquid interface. Images of the cavities were captured by a high-speed video camera to study cavity performances. A modified judging equation of the gas-liquid interface instability was developed by the critical jet flow and the critical jet height at a determined jet diameter. The critical parameters were in good agreement with experimental measurements.

Keywords: steelmaking, BOF, mathematical model, gas-liquid interface, critical lance height

INTRODUCTION

In liquid surface impinged behaviors, droplet splashing is a fascinating phenomenon attracting wide studies [1-4]. The ejection of the liquid phase by splashing is an important issue in the oxygen steelmaking process. The droplets splatter accompanying the unstable penetrating cavity generates the metal/slag/gas emulsion and causes splashing of metal/slag from the vessel in the BOF [3]. Therefore, the determination of the critical penetration parameters is of great significance for improving the BOF performance. In fact, it should be noted that only a few attempted to establish a model for predicting the critical states. He and Standish [2,5] proposed the “nominal Weber number”, N_{NWe}, as similarity criterion for droplet generation rate through top gas blowing. Deo et al. [6] further developed the Weber number into a correlation for predicting metal droplet generation in oxygen steelmaking. Moreover, Deo et al. reported that the onset of droplet generation in BOF steelmaking occurs at a value of N_{NWe} equals ten. However, the effect of the Froude number (Fr) on the splashing process is ignored during the determination of the dimensionless criterion number. This may lead to some deviation in the actual blowing process.

The aim of present work is to evaluate the relationship between cavity shape and operating parameters. Critical jet heights causing droplets splashing were studied for different penetrating conditions, which were further expressed by a modified formula.

EXPERIMENTAL METHODS

The water model experiment is carried out using the experimental device shown in Figure 1. In order to eliminate the refraction effect and accurately observe the cavity shape, a cylindrical vessel with an inner diameter (D) of 400 mm and a height of 500 mm was set inside the square vessel which has a side length of 500 mm. The depth of the water bath (h) was maintained at 50 mm, 70 mm and 100 mm respectively. Five different single-hole nozzles were employed. The internal diameter (d_e) and the corresponding number were listed in Figure 2.

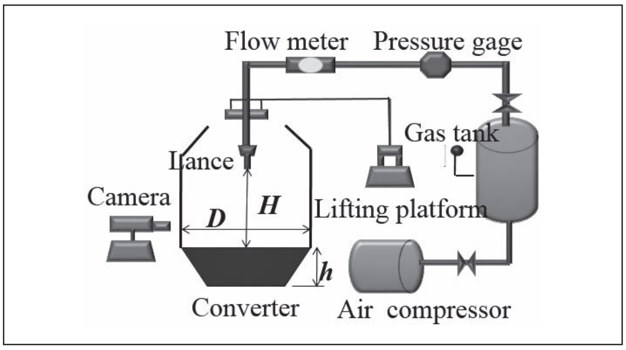

Figure 1 Schematic of experimental setup

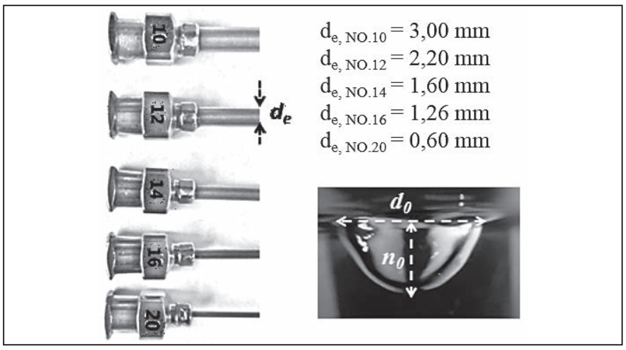

Figure 2 Nozzles and cavity shape

D. Xu, B. Zheng Email: 695260997@qq.com Technology Innovation Center for High Quality Cold Heading Steel of Hebei Province, Hebei University of Engineering, Handan, China

L. X. Guo, H. X. Pang Email: wangxi950715@sina.com Technology Innovation Center for Wear Resistant Steel Plate of High plasticity and High Toughness of Hebei Province, Hebei Puyang Iron and Steel Corp. Ltd, Handan, China

Experiments were carried out at the temperature of 20 C° and the environment pressure of 101,3 kPa. A rotameter with a range of 2,5 m^3/h for air was used to regulate the flow. To record the pressure of the gas, a pressure gauge was connected just before the jet. Compressed air was used for water model experiments and a surge tank with an effective volume of 0,3 m^3 was used to establish a stable pressure of the system.

The nozzles were positioned at different heights above the surface of the liquid ranging between 30 - 130 mm. The jet height (*H*) vertically from the nozzle to the liquid level of the container was adjusted by a lifting platform with an accuracy of 1 mm. The gas jet momentum would create droplets and the violent swing of the cavity at higher gas flow rates. Thus, the characteristic behaviors were observed in the stable and unstable states of gas-liquid interface by a high-speed video camera (EOS 1D X Mark II) In order to record the cavity size, a graduated wire was fixed horizontally at the gas–liquid interface. The cavity size obtained by reproducing six times the same experiment. An example of the observed cavity shape was illustrated in Figure 2.

RESULTS AND DISCUSSION

Cavity size affected by penetrating parameters

Obviously, the cavity size was determined by the penetrating parameters. Various sets of penetrating parameters can be found to generate in equable cavity size. a correlation Thus, giving between the cavity size and all penetrating parameters is significant to guide jet controls in industrial applications. Figure 3 presents the penetration depth versus the jet height at different gas flow rate with different nozzles. It was found that the cavity depth nearly linearly increases by raising the jet flow rate with a same jet height. The above phenomenon can be explained from the perspective of energy balance, i.e., greater flow rate provides more jet energy, thus pushing more heavy liquid away to create a deeper cavity. Comparisons of Figure 3(a) - (d) seem to suggest that smaller nozzle diameter creates deeper cavity under the same operating parameters. It can also be seen that an increasing jet height decreases the penetration depth at a given gas flow rate.

Besides, the cavity diameter versus the jet height at different gas flow rate with different nozzle diameter was shown in Figure 4. Similar as the cavity depth, the diameter of cavity also exhibits linear growth by raising the jet flow rate with a same jet height. However, the influence of jet height on the cavity diameter is little under the same nozzle diameter and jet flow rate. Identical conclusions were obtained in studies of Cheslak [7].

Modified instability criterion model

Critical cavities size were obtained under different jet height H and different jet diameters. It was clarified that the critical jet depth of the cavity is about 15 mm under various penetrating parameters. The behavior is in agreement with previous findings of Chatterjee and Bradshaw[8]. They determined the critical cavity depth to create droplets are 1,54 cm.

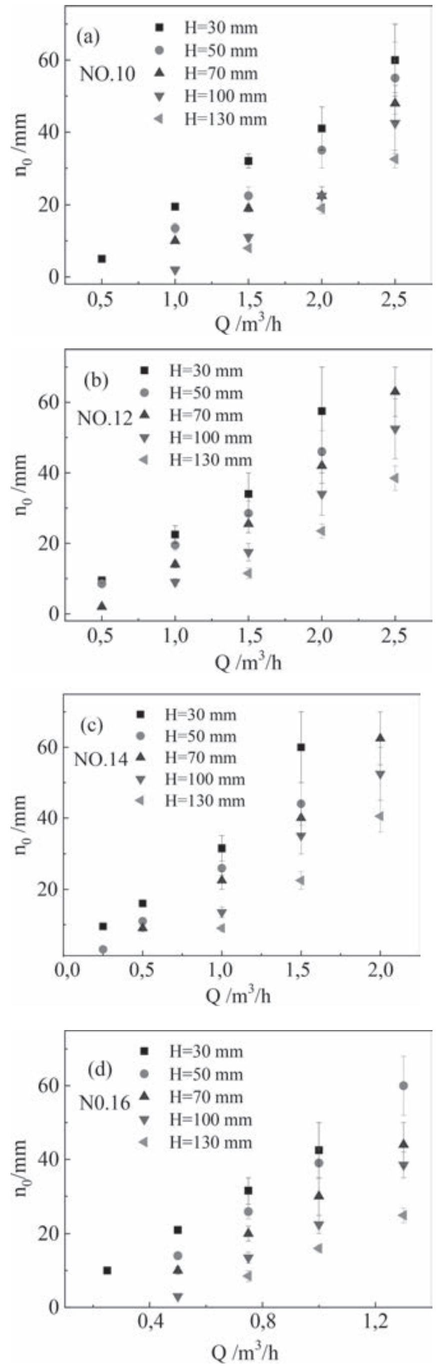

Figure 3 Experimental results of the penetration depths as a function of the flow rate at different jet heights

Banks and Cheslak served as the pioneers have launched comprehensive researches on the cavity size. The model suggested by Banks is accurate for the prediction of the cavity depth under critical conditions. Combined equation (2) and n_0 = 15 mm in critical state, equation (1) can now be expressed as equation (3).

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

$$Q = \frac{\pi d_e{}^2 u_e}{4} \tag{2}$$

$$\sqrt{\frac{2K^2 \times 4}{0,015\pi^2} \cdot \frac{\rho_g}{\rho_l g}} \cdot \frac{Q}{d_e} = H + 0,015 \tag{3}$$

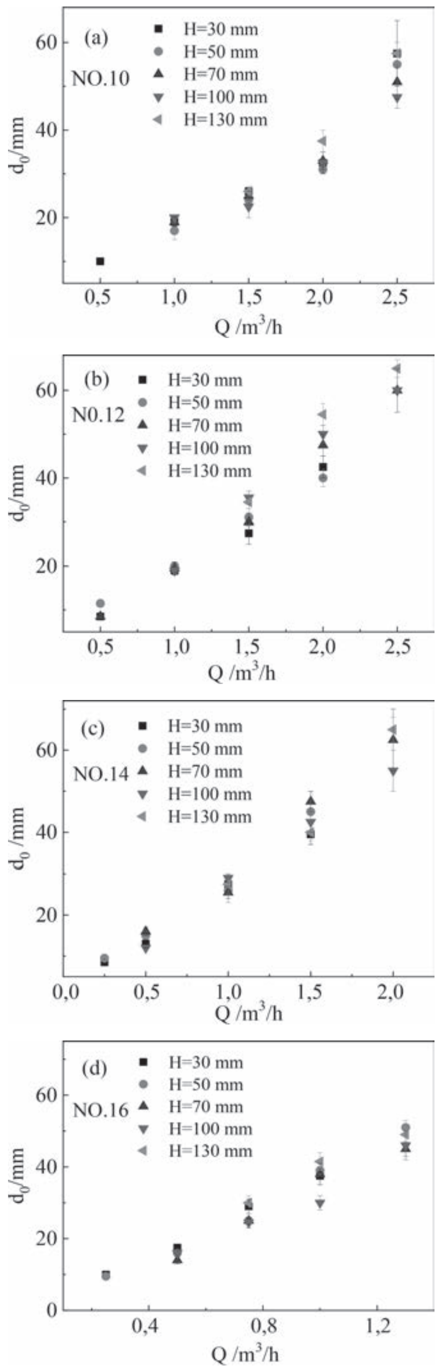

Figure 4 Experimental results of the cavity diameter as a function of the flow rate at different jet height

For value of constant K = 7,9, an equation for determining the critical jet heights of different nozzles was given.

$$Q=\frac{(H+0,015)d_e}{0,645} \tag{4}$$

All of the penetration depths under different jet diameters were plotted against the corresponding jet flow rates. The generalized correlation of equation (4) was also plotted in the same Figure 5. The modified equation (4) compares with the present experimental results. Calculation result of equation (4) shows well consistent with the present experimental results. Therefore, the equation presents a valuable relationship between Q and H, which not only provides jet control for industrial applications, but also reveals the mapping relationship between the jet height and instability in science.

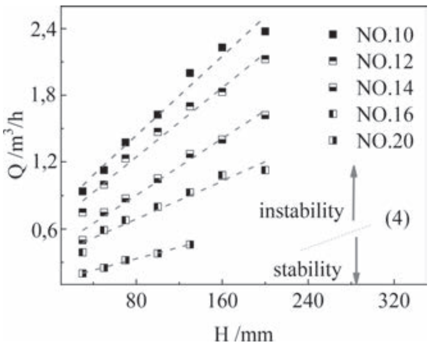

Figure 5 Comparison of equation 2(K = 7,9) with experimental results

It is noteworthy that the results are all about the interaction of single gas jet with the liquid bath. In industry, the oxygen lance is with a multi-nozzle structure. Therefore, it is necessary to further verify the cavity depth prediction model of porous oxygen lance.

CONCLUSIONS

The size created by the impinging jet was characterized under different penetrating conditions, including different nozzle diameters, bath depths, gas flow rates and jet heights. Critical jet heights causing cavity stability transition judged by the phenomenon of droplet splatter were studied for various penetrating conditions. An optimized equation for determining the critical jet heights of different nozzles was proposed. The experimental results showed good agreement with the equation. The investigation of the characteristic size of the cavity and the instability behavior in this paper can provide useful criteria for the jet controls in actual industry applications.

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Note: Hong Xuan Pang is the responsible translator and the corresponding author, Handan, Hebei, China.