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Research paper

Centrifugal granulation performance of liquid with various viscosities for heat recovery of blast furnace slag

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HIGHLIGHTS

- Centrifugal granulation is crucial for heat recovery of blast furnace slag.
- The disintegration mode transition was experimentally investigated.
- The mechanism of disintegration mode transition was analyzed.
- The variation ligaments and droplets with viscosities were discussed.
- The analogy analysis was applied to the molten blast furnace slag.

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ABSTRACT

Centrifugal granulation is a crucial step in the most promising heat recovery technique for molten blast furnace slag. Facing the fact that slag viscosity changes during the granulation process, in the present work, visualization experiments were conducted for centrifugal granulation of mixture liquids by a spinning disc. Then, the effect of liquid viscosity on granulation performance was discussed. It was found that the increase in liquid viscosity resulted in granulation mode translation under the same disc rotating speed and liquid flow rate, that is, from direct droplet formation mode to ligament formation mode. The Sauter Mean Diameter of the granulated droplets was increased and the droplets size distribution was narrowed with increasing liquid viscosity. Meanwhile, the ligament number increased in direct drop formation mode while decreased in ligament formation mode as the liquid viscosity was increased. Furthermore, for a specific mixture liquid, the increase in flow rate also resulted in the translation from direct droplet formation mode to the ligament formation mode and from ligament formation mode to the film formation mode in the end. The critical flow rate for this translation was found for various liquid mixtures. Finally, dimensionless correlations were developed to predict the average diameter and critical flow rate, and the analogy analysis was applied to the molten blast furnace slag.

1. Introduction

Blast furnace slag (BF slag) is one of the main solid by-products in steel making with the yield of 300 kg per ton of crude steel. Moreover, the slag is exhausted in high temperature of about 1500 °C with huge heat content amounting to 1770 MJ per ton BF slag [1]. In 2013, China's crude steel production reached up to about 822 million tons [2], namely, the total waste heat contained in hot slag was almost equivalent to 14.8 million tons standard coal. Currently, water quench technique has been widely adopted to directly cool the molten slag in most of the steel plants, giving rise to huge loss in both the water and heat. Therefore, great efforts have been made by researchers to explore an effective heat recovery technique.

A heat recovery technology coupling dry granulation of the molten slag with air cooling has aroused general concern since 1984 [3]. During the following development process of this technology, several granulation techniques have been proposed and investigated by various researchers including rotary drum [3], air blast [4], centrifugal granulation [5–7]and so on. Among all the techniques, the centrifugal granulation coupling with heat recovery by air is considered as one of the most promising techniques for BF

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slag due to its simple construction, easy operation, sufficient capacity, less energy consumption and suitable granule size distribution. Therefore, intensive studies have been performed since Pickering et al. [5] firstly designed a centrifugal granulation system. During the centrifugal granulating process of molten BF slag, liquid slag firstly flows from the top injection port onto the center of a rotating atomizer and spreads radially along the atomizer surface to form a thin liquid film. The liquid film is then broken into droplets at the rim of or out of the atomizer, and these droplets are finally solidified by air cooling. The centrifugal granulation, in deed, is a complex and comprehensive process affected by multifarious parameters. These influential parameters can be sorted to three aspects: (1) Atomizer material and structure [8,9]; (2) Physical properties of liquid slag such as density, viscosity and surface tension; (3) Operational conditions including atomizer rotary speed [10–14] and liquid slag feeding rate [15–17].

However, superhigh temperature as well as blinding light of the released molten BF slag brings grave difficulties in experimental study (especially the visualization experiments) on the mechanism of BF slag granulation. Consequently, most of the researches, up to now, adopted low-temperature working media to investigate the granulation phenomena under various conditions. Mizuochi and Akiyama [18] experimentally investigated water granulation by vaned-disc and vaned-wheels, and found that vaned-atomizers were helpful to decrease the large-size droplets. Ahmed and Youssef [9] also employed water as the working medium to investigate the droplets size and velocity characteristics produced by various cup atomizers. They found that, compared with the droplets generated by flat disc, the Sauter Mean Diameter of droplets produced by atomizer with different configurations varied between −8% and 12%. Frost [19] studied the granulation using water and glycerol mixture and tackled the mechanism of ligament formation in detail. A criteria for ligament disintegration occurrence and the expression to predict the resultant droplets size were developed. Recently, Liu et al. [20,21] also carried out cold experiments using water and glycerol mixture with three kinds of cups to investigate the transition of different disintegration modes. Yi et al. [22] compounded rosin and wax with a mass ratio of 4:1 to simulate the liquid molten slag and then investigated the influence of operational conditions on granulation process of this mixture liquid. Zhu et al. [23] proposed a granulation system combining a rotating cup with air blast and investigated the granulation performance by adopting a mixture of rosin and paraffin wax. The effects of rotating speed, liquid flow rate and blast air flow rate were discussed, and the results indicated that higher rotating speed and lower liquid feeding rate gave rise to smaller particle as well as higher fibers fraction.

In addition to the low-temperature working media, very few experimental works and numerical simulations were conducted for the real BF slag. Mizuochi et al. [6] investigated the feasibility of the rotary cup atomizer for slag granulation, and found that the BF slag droplets were strongly dependent on the rotating speed of atomizer. Higher rotating speed resulted in more uniform and spherical particles. Liu et al. [24] experimentally investigated the ligament formation in BF slag granulation, and found the slag wools took place inevitably during the granulation. Qin et al. [25] adopted a rotating multi-nozzle cup atomizer to granulate the molten slag and discussed the characterization of slag particles. Moreover, some numerical simulations were carried out on the centrifugal granulation. Pan et al. [26,27] adopted a CFD model to simulate free surface flow of liquid slag on a spinning disc and discussed the effects of operating parameters on the liquid spreading. Wang et al. [28] developed a theoretical analysis for free-surface flow on the disc, and it was found that the film thickness distribution of molten slag was mainly determined by liquid volume flow rate, rotary speed of atomizer and viscosity. Only two documents [29,30] reported the simulation on slag droplets or ligaments formation by the spinning disc.

The previous works mainly focused on the effects of atomizer structure and operating conditions (rotating speed and liquid feeding rate) on the granulation performance for a certain working medium with constant physical properties. It was noticed that diverse outcomes even contradictory statements were exhibited among the references for different working media. However, a systematic study on the granulation of liquid with different physical properties has not been reported, and the centrifugal granulation mechanism also has not been well understood. Moreover, almost all of the references ignore a reality that is unavoidable in practical dry heat recovery system of BF slag, that is, the physical properties of slag, especially the viscosity, change during the granulation process due to air cooling. This requires a well understanding of the effect of liquid viscosity on granulation performance. For this purpose, in the present study, the effect of liquid physical properties on the disintegration mode translation and granulation performance was investigated by visualization experiments using various glycerol/water mixtures. The mechanism of granulation under different disintegration modes were analyzed in detail and the experimental results were compared to the granulation of blast furnace slag.

2. Experimental system and method

2.1. Experimental setup

The visualization experimental setup for centrifugal granulation, as shown in Fig. 1, consisted of a granulation system, a liquid supply system and a data acquisition system. In the granulation system, a disc atomizer with 55 mm in radius was connected to a motor by a live shaft. A frequency converter was utilized to control the rotary speed of disc atomizer in a range of 0–3000 rpm. According to Qin [25], the aforementioned attempts for slag granulation revealed that the rotary speed in a range of 600–1800 rpm is suitable for particle production. Thus in this study, the rotary speed of disc was fixed at 1200 rpm for all cases. The liquid supply system consisted of a pump, a stabilivolt tank, a valve, a flowmeter, a nozzle and a collecting tray. The nozzle of 8 mm in inner diameter located centrically above the disc with a distance 20 mm from the disc surface. The size ratio of the nozzle to the disc was 15%. The working medium from the tank flowed through the nozzle to hit the disc surface and then, it was collected in the collecting tray and was pumped into the tank. The liquid volume flow rate was adjusted by the valve. The data acquisition system consisted of a high speed camera (i-Speed TR, Olympus), a light source and a computer. The high speed camera was set at the rim of the disc and the plane LED light was installed underneath the disc rim, as shown in Fig. 1b. The dynamic behavior of the granulation process was then recorded by the high speed camera with a shooting speed of 2000 fps. All the experiments were carried out under the room temperature.

2.2. Data processing

For numerous gray-scale images obtained during the granulation process, a self-compiled MATLAB program was utilized to extract the diameter of produced droplets. The extraction process is shown in Fig. 2. Firstly, choose an image which was shot during the stable granulation stage, cf. Fig. 2a. Secondly, set a processing area on the image that contains droplets or ligaments, cf. Fig. 2b. Thirdly, convert the chosen area into binary images according to a threshold value, that is,