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Granulation characteristics of molten blast furnace slag by hybrid centrifugal-air blast technique

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ABSTRACT

Of the molten blast furnace (BF) dry granulation techniques that are currently employed, the centrifugal granulation technique is very promising owing to its simple and compact structure, ease of control, and low energy consumption. To better understand the mechanism responsible for the centrifugal granulation of molten BF slag, and to achieve high granulation performance, in the present work, we propose a hybrid technique that combines centrifugal granulation with blast air. We visualize the granulation evolutions under various operating conditions using a high-speed camera. We discuss the effects of the blast air volume flow rate on the granulation characteristics under different granulator rotating speeds and different molten slag mass flow rate conditions. During the granulation process, products including slag particles, slag wool, and coked slag were yielded. The results show that the centrifugal granulation process was accelerated by blast air, and the average particle diameter decreased with an increasing blast air volume flow rate in most operating conditions, achieving a minimum value of 1.06 mm. We obtain a less slag block product when we employ blast air, and the greatest reduction reaches 33%. The effect of blast air on the slag wool mass fraction was negligible in most cases. This study highlights a feasible and promising industrial application of the proposed hybrid centrifugal-air blast granulation technique for molten BF slag.

1. Introduction

Molten blast furnace (BF) slag is one of the main by-products in the iron-making process, and has a yield of 300 kg/t-pig iron [1]. The heat contained in molten BF slag (1500 °C) reaches up to 1600 MJ/t. Globally, the production of pig iron was nearly 1153 million t in 2015 [2], and about 345.6 million t of BF slag were produced. The total energy carried by molten BF slag amounted to the equivalent of 1.8 million t of standard coal. At present, the water-quenching technique is widely adopted to treat BF slag in most iron and steel plants worldwide, where the molten BF slag is rapidly cooled by cool water to form particles with diameters ranging from 0.1–2 mm owing to stress blasting. The harvested slag particles consist mainly of a vitreous phase, and are used as a substitute for portland cement [3]. However, this technique not only fails to recover the large thermal energy carried by the molten slag, but also contributes to the release of waste cooling water and waste gas, resulting in severe environmental problems. It is therefore well recognized that water-quenching treatment for BF slag is not in conformity with the requirements of sustainable development.

In recent years, in order to realize energy recovery and water savings as well as air pollution control, dry slag treatment technology, coupling of dry slag granulation and waste heat recovery has been proposed by researchers [4–7]. With this technology, dry slag granulation acts as a prerequisite and key role towards realizing the ultimate heat recovery rate and slag quality. To this end, several techniques including rotary drum, air blast, and centrifugal granulation have been developed [8]. Of these techniques, the centrifugal granulation technique is very attractive because of its simple and compact structure, ease of control, low energy, and water consumption [9]. The technique of centrifugal granulation integrated with heat recovery using a fluidized bed for molten BF slag was first proposed by Pickering et al. [6], who built a test bench and carried out an experimental study to verify the feasibility of this technique. Their results showed that a cost savings of about 2–3 million pounds could be achieved for a BF with a daily capacity of 7700 t of iron. Recently, a comprehensive assessment, called the life-cycle assessment, was conducted by Wang et al. [10] to assess the feasibility of the centrifugal granulation heat recovery (CGHR) system, and it demonstrated the large economic and environmental benefit that can be obtained from the CGHR system compared with the traditional water-quenching system. Therefore, the CGHR technique is a very promising solution for BF slag treatment.

A typical CGHR system usually consists of a high-speed rotating granulator and an air-cooling equipment or water-cooling jacket. The

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molten slag is consecutively poured into the rotating granulator and then radially spread outwards to reach the granulator rim, where the spread slag film is fragmented by the centrifugal force into molten droplets that fly away from the granulator. For the air-cooling system, the molten droplets are first cooled by blown air during flight to complete rapid solidification. The solidified slag particles, which still have a high temperature, then precipitate into a subsequent heat-recovery appliance for sufficient cooling. This process produces fine solid particles and hot air, realizing effective heat recovery and reuse of material. From the perspective of heat-transfer enhancement and slag reuse, the granulation performance not only determines the heat-recovery rate as well as the quality of vitreous particles. Therefore, a good understanding of the promotion mechanism of BF slag centrifugal granulation is important and beneficial to the entire system design.

Considering the challenge of harsh experimental conditions for the molten BF slag, with a temperature of 1500 °C, various low-temperature liquid media, such as water and glycerin, have been adopted by researchers to simulate the granulation of molten BF slag. Mizuochi et al. [11] and Ahmed et al. [12] experimentally studied the granulation mechanism of water and determined the performance of different granulators. Their results showed that the granulated droplet diameter was influenced by the granulator structure. Liu et al. [13,14] conducted visualization experiments using glycerol/water mixture as a substitute medium to investigate the disintegration mechanism in a rotary cup. They observed three types of fragmentation modes, namely direct drop formation, ligament formation, and film formation. The transform between different fragmentation modes was triggered by varying the granulator rotating speed and working medium flow rate. More recently, Wu et al. [15,16] adopted a flat disk as a granulator as well as mixtures of water and glycerol with various mixing ratios as working media to investigate the granulation phenomena and to discuss the effect of fluid viscosity. They visualized the fragmentation evolutions under various operational conditions, and attributed the mechanism of ligament break-up to the symmetric disturbing waves. In addition, they characterized the translations between different granulation modes and proposed dimensionless correlations to predict the average diameter of granulated droplets and critical flow rate for the granulation mode translation. Moreover, some low-temperature phase change materials have also been adopted to simulate the granulation process of molten BF slag. Min et al. [17] and Zhu et al. [18] adopted a mixture of rosin and paraffin as a working medium, which has a phase-change temperature of about 108 °C, to experimentally study the granulation characteristics in a rotating cup based on the similarity theory. It was reported that the particle size of granulated BF slag could be predicted when the mass ratio of rosin and paraffin was 4:1. However, in their experiment, a considerable amount of fibers, which were not conducive to subsequent use, were also produced, and were accompanied by particles.

Furthermore, authentic molten BF slag has also been implemented as a working medium to study the centrifugal granulation characteristics, e.g., the feasibility verifying tests proposed by Mizuochi et al. [19,20]. Their results revealed that the particle size was mainly controlled by the rotating speed of the granulator, and the produced particles were smaller than 1 mm when the rotating speed reached 3000 rpm. Purwanto et al. [21] also experimentally and numerically investigated the granulation process of molten BF slag. In their experiments, the average particle diameter decreased with an increased rotary speed, and the resulting particles had a good spherical shape as well as high glassy phase content. Meanwhile, a mathematical modeling approach was proposed for a rotary disk to predict the film thickness, the number of ligaments, and the particle diameter. The numerical simulation results showed good agreement with the experimental data when the rotary speed was greater than 16.6 s^{-1}. Liu et al. [22,23] conducted visualization experiments to observe the disintegration phenomena of molten BF slag granulation, and the vitreous phase content of the obtained particles was determined via XRD tests. It was found that the vitreous phase content of the obtained particles decreased with increasing particle speed. The vitreous phase content of particles with a diameter of 0.8 mm and a speed of 2.04 $m \cdot s^{-1}$ reached up to 94%, which meets the quality requirement of cement feedstock. Chang et al. [24] found that in the centrifugal granulation process of BF slag, the particle size decreased at a lower molten slag surface tension and a lower viscosity. In addition, slag wool was acquired during the granulation process, which was not conducive to the stable operation of the system.

From the previous study, we can learn that the solution to obtain fine slag particles using centrifugal granulation requires a larger granulator diameter or an increase in the granulator rotating speed. However, the increased granulator mass and rotating speed will cause increased motor energy consumption; meanwhile, the requirement for larger granulation chamber owing to the longer flight distance of granulated particles will also increase the manufacturing cost. A new technique is required to meet the problem based on the understanding of the granulation mechanism. Because the fragmentation of the ligament or film from the granulator is dominated by the development of symmetric disturbing waves, the granulation process can be enhanced by strengthening the disturbing waves using other methods that increase neither the granulator diameter nor the rotating speed. One of the methods, i.e., a hybrid atomization method, which was proposed by Czisch and Fritsching et al. [25,26] to atomize viscous-melt, was introduced into the granulation of low-temperature phase change material by Zhu et al. [18]. In this method, a rotary disc associated with gas blast was adopted to obtain fine granules. They experimentally investigated the granulation characteristics of a mixture of rosin and paraffin using the centrifugal-air blast method. They found that the air blast played a dual role, in that it had a disturbance effect as well as a cooling effect; however, the two effects acted against each other with respect to the diameter of the granulated particles and the fiber formation. Their results showed that the cooling effect of the blast air played a dominant role in the granulation process, resulting in enlarged particle size and fiber mass fraction. Nevertheless, it remains unclear whether the results from low-temperature phase-change material are appropriate for the high-temperature molten BF slag granulated by the centrifugal-air blast method.

In the present study, we applied a hybrid method, which involves combining centrifugal granulation with auxiliary low-pressure air blast, to realize the granulation of molten BF slag. We visualized the granulation evolutions under various operational conditions, and we analyzed the mechanism of the centrifugal-air blast method. Then, we discussed the influences of the blast air volume flow rate on the granulation characteristics under different granulator rotating speeds and different molten slag mass flow rates.

2. Experimental system and method

The molten slag granulation experimental system consisted mainly of a molten slag supply unit, a centrifugal-air blast granulation unit and an image capture unit, as shown in Fig. 1. For the molten slag supply unit, we employed a high-temperature furnace with a graphite crucible to melt the BF slag. We designed a stopper and a slag-supplying pipe to be placed at the bottom of the graphite crucible to control the discharge flow rate of molten BF slag. In the centrifugal-air blast granulation unit, we employed a rotary cup, a wind ring, a granulation chamber, and a collection plate to achieve granulation process. The rotary cup was manufactured using 304 stainless steel with a diameter of 126 mm, a depth of 40 mm, and a leaning angle of 125°. The cup was driven by a variable-frequency motor with an adjustable rotating speed range of 0–3000 rpm. The wind ring was set around the rotary cup with 42 holes having 5 mm diameter on the top, and the blast air was blown straight up with pressure of 0.001 MPa. The granulation chamber was 1.5 m in diameter, and the collection plate was set at its bottom. We set a high-speed camera (phantom V 5.1) in the upper left corner to record the granulation phenomena of molten BF slag with frames of 3100 fps.