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Research paper

Analogue experimental study on centrifugal-air blast granulation for molten slag

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ABSTRACT

Blast furnace slag is a by-product in iron and steel production process which has a high yield with extremely high discharge temperature. Aiming at energy and water saving as well as emission reduction, dry granulation technique appears to be a good application for the treatment of blast furnace slag. In this study, a granulation technique combining a high-speed rotating cup with air blast is proposed. The performance of this design was investigated by adopting a mixture of rosin and paraffin wax as the analogue of blast furnace slag. The effects of rotating speed of the atomizer, liquid flow rate and blast air flow rate on particle size, particle mass distribution and fiber mass fraction were studied. The effect of the function of air blast on the granulation performance was particularly discussed. The results showed that at a higher rotating speed and a smaller liquid flow rate, smaller particles can be easily obtained, yet the fiber mass fraction also increases. However, the increasing blast air leads to the increase of particle size and fiber mass fraction. For the operating conditions tested in this study, over 60% of total mass of particles fall within the size range of 0.5–1 mm, which means that the present system has a good performance in centrifugal granulation.

1. Introduction

Blast furnace (BF) slag, which is discharged at temperature about 1500 °C, is the main by-product in iron-making process. In the past few decades, iron and steel technology has seen tremendous development and production of iron has increased as a result, for example, the iron production in China reached about 750 million tonnes in 2013 [1]. For a slag generation rate of about 0.3 tonne per tonne liquid pig iron, 220 million tonnes of BF slag were produced. Furthermore, considering approximate 1770 MJ per tonne, the total energy carried by BF slag amounted to 13 million tonnes standard coal, which is about 13% of the energy consumption in a typical blast furnace process. This amount of heat is regarded as the last portion that has not been recovered in the steel and iron making industry. Therefore, heat recovery from BF slag is an important and rewarding task.

BF slag is rich in CaO, SiO_2, Al_2O_3, MgO, which is similar to the components of Portland cement. BF slag shows different inherent solid structures depending on the cooling processes. If a high temperature liquid slag is cooled very fast, it would not be crystallized and finally becomes glassy phase with high cementation activity, which can be a high value product, especially for substitution of Portland cement. By contrast, the value of crystallization slag formed by slow cooling is rather limited. Water quenching is widely employed to obtain glassy phase slag. This method refers to rapid cooling of molten slag in water, which prevents the crystallization of slag and breaks the slag into small particles by thermal stress. The water quenching method can recycle slag material but it fails to recover the waste heat of slag. Moreover, this method has several drawbacks such as consuming large amount of water, polluting the soil, water and air, thus it is not environmentally friendly.

For the purposes of water conservation, pollution mitigation and energy saving, a variety of heat recovery technologies through dry granulation have been proposed in recent years. Among these technologies, the centrifugal granulation technique, which was proposed by Pickering and his colleagues in 1985 [2,3], has a good application prospect because of its advantages of compact

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structure, less energy-consuming, water saving and easy operation. In their experiment, slag was granulated to particles with an average diameter of 2 mm and then the particles were cooled by air to reach a glassy content of 95%.

For the centrifugal granulation method, its technical process can be described as follows. High-temperature liquid slag is directly poured into a high-speed container (cup/disk/cylinder) and then the slag is radially projected outwards and subsequently broken into droplets. At the same time air is blown to cool the droplets. This process produces fine solid particles and hot air, realizing effective heat recovery and reuse of material. It is quite clear that good slag granulation is the most important requirement for this technique. This has attracted attention of researchers to further study on the centrifugal granulation, e.g., the work presented by Mizuochi et al. [4]. They examined the influence of cup speed, cup shape and slag viscosity on the granulation and their results showed that higher cup speed led to smaller slag particles. The size of the slag particles decreased obviously when the speed was in a range of 600–1800 rpm. However, the influence of speed appeared to be slight when it was over 1800 rpm. This finding also indicated that lower slag viscosity led to smaller particles and the cup shape had little influence on granulation. Akiyama et al. [5,6] explored the mechanism of granulation using a rotating disk. It was found that the liquid slag was firstly extended into a film on the disk, and then was ejected radially as plenty ligaments, and eventually, these ligaments were broken up into particles. A mathematical simulation of this experiment was developed by Purwanto et al. [7,8]. Through their mathematical model, the film thickness, the ligaments number and the particles diameter were predicted. The temperature distribution of a single particle was also analyzed. Xie et al. [9–11] developed a novel disc design to produce fine granules without the formation of slag wool. Their results indicated that more than 90% of the products were less than 1.5 mm in diameter. These slag samples are being further assessed for their suitability for cement applications.

Recently, Liu et al. [12,13] carried out experiments on slag granulation by rotating cup atomizer (RCA) and they found that larger cup edge resulted into smaller average particle diameter when rotational speed was below 1000 rpm. The effect of cup size declined when rotational speed exceeded 1000 rpm. Meanwhile, Liu et al. [13], Yu et al. [14] and Min et al. [15] carried out a series of experiments with different simulant materials to explore the mechanism of slag granulation. The mixture of rosin and paraffin was proved to be an ideal simulacrum. Yang et al. [16] found that fibers, which were not conducive to subsequent use, were also produced accompanying with particles, and the mass fraction of such fibers enhanced along with the increasing rotating speed, indicating the existence of an optimum rotating speed. Furthermore, Kashiwaya et al. [17,18] did the slag granulation experiment using a rotary cylinder with several rows of nozzles, where the slag was granulated by being squeezed out from the nozzles. They investigated the impact of nozzle size on the particle diameter and the results showed that smaller nozzle size led to smaller particles, but particle diameter was not well correlated with nozzle size. The mechanisms of granulation need to be investigated further.

To date, the mechanism of slag granulation has not been clearly explored, resulting in most studies on slag centrifugal granulation failing to out of laboratory yet. In the present study, the performance of a simplex centrifugal granulation and a centrifugal-air blast granulation was experimentally investigated using an analogue medium. The effects of rotating speed of the rotor, liquid flow rate and gas flow rate on particle size, particle mass distribution and fiber mass fraction were discussed.

2. Experiments and working medium

2.1. Experimental apparatus and procedure

The schematic of experimental apparatus for centrifugal granulation of BF slag and other working media is shown in Fig. 1a. A furnace equipped with a crucible, a controlling stick and a liquid outlet at the bottom was employed to melt the working medium and to release the molten liquid medium at a preset flow rate through a connected tube. A rotating cup was designed with 126 mm in diameter, 40 mm in height to granulate the released molten medium. The rotating cup was driven by a motor with stepless speed adjusting. A chamber with a collecting disk was designed to collect the granulated particles. To investigate the influence of introduction of air blast on the granulation performance, a wind ring was specially designed with small holes around the circumference and was assembled with the rotating cup, as shown in Fig. 1b. Air was blasted upwards from the wind holes to meet the working medium out from the rotating cup. Furthermore, a window was set for visualization of the granulation process and a camera was employed to capture the phenomena.

For the experiment on simplex centrifugal granulation, the working medium was firstly heated to a preset temperature and then, the molten medium was poured into the rotating cup that was preheated to the same preset temperature in advance to granulate the liquid medium. For the experiment on granulation with air blast, the blast air was sent through the holes on the wind ring prior to the release of liquid medium from the furnace. After the experiments, the collected particles were screened by a standard sieve and the mass in each individual size range was measured by an electronic balance. The average diameter of the particles was then calculated by Ref. [19].

$$d_a = \sum_i^n d_i \theta_i \tag{1}$$

where d_i is the average diameter of particles in each individual size range based on the adjacent standard screen size; θ_i is the mass percentage of each individual size range which represents the selection probability of the particles in each size range. The uncertainty in the average particles diameter is about 7%.

2.2. Working medium

A mixture of rosin and paraffin with a mass ratio of 4 to 1 was chosen as the analogue to simulate the BF slag. The physical property parameters of the analogue and the experimental conditions were determined by the similarity theory. For the centrifugal granulation process, the diameter of produced particles can be determined by the experimental correlation [20]:

$$\frac{d}{R} = 1.6(Re)^{0.26}(Oh)^{0.38}(We)^{-0.42}, \tag{2}$$

where three dimensionless numbers, Reynold's number Re, Ohnesorge number Oh and Weber number We, can be calculated as

$$Re = \frac{4\rho Q}{\pi \mu R} \tag{3}$$

$$Oh = \frac{\mu}{\sqrt{\rho \sigma R}} \tag{4}$$

$$We = \frac{\rho \omega^2 R^3}{\sigma}. \tag{5}$$