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Research Paper

Experimental study of rotating dry slag granulation unit: Operating regimes, particle size analysis and scale up

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HIGHLIGHTS

- Operating conditions for fiber and particle formation are determined.
- Effect of liquid flowrate, rpm and disc diameter on particle diameter is studied.
- The particle size followed a lognormal distribution.
- Dimensionless correlation for particle size is obtained in terms of *Re*, *Oh* and *We*.
- Methodology of scale up from lab experiments to commercial plant is detailed.

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ABSTRACT

Blast furnace slag is a high-value by-product of the iron and steel industry. It leaves the plant at a very high temperature and possesses a large quantity of high-grade energy. One of the promising methods to extract this energy is dry slag granulation. In this study, the effectiveness of dry slag granulation was studied using a mixture of rosin and paraffin wax as an analogue for blast furnace slag. The effects of various parameters such as rotational speed of the disc, diameter of the disc and flow rate of the molten liquid have been studied. Different ranges of operating conditions in terms of non-dimensional numbers for fiber formation and particle formation were determined. This helps us determine the operating conditions under which particle formation is ensured. The study shows that with an increase in the rotational speed or disc diameter the average particle diameter decreases whereas with an increase in the flow rate the average particle diameter increases. The design of a granulation unit for a commercial plant utilizing the data from lab scale experiments is discussed.

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1. Introduction

The production of crude steel has increased significantly over the past decade. For example, the total crude steel production in Asia has gone up from 599 million tons in 2005 to 1139 million tons in 2014 [1]. Blast furnace (BF) slag is one of the main by-products of iron and steel industry. Approximately 0.3 tons of BF slag is produced for each ton of steel manufactured. The BF slag comes out at temperatures ranging from 1400 to 1500 °C and each ton carries 1.77 GJ of energy at 1500 °C [2]. Consequently, in Asia alone 340 million tons of BF slag is produced with energy content of 6×10^8 GJ. Heat recovery from BF slag is hence of great significance since it can result in making the process energy efficient.

BF slag is mainly composed of CaO, SiO_2, Al_2O_3 and MgO. These are the primary constituents of Portland cement. It can be used as an effective substitute for cement if the glassy content of the slag particles is high. The morphology of the slag particles directly depends on the cooling rate of the slag. Because of the limitation of natural resources for making concrete, a major focus of the civil engineering community is the utilization of waste products as a substitute for concrete without compromising on the properties of concrete. Buddhdev and Varia [3] found that BF slag particles with a significant glassy phase content can be used to replace sand in concrete. Currently, water quenching is used widely across the industries for immediate cooling of BF slag to get a glassy product. A primary drawback of this method is the consumption of large

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Nomenclature

d	number average particle diameter, m	Oh	Ohnesorge number
R	radius of the disc, m	$H(p)$	uncertainty
Q	volumetric flowrate of liquid, $m^3\ s^{-1}$	$H^*(p)$	normalised uncertainty
ω	angular velocity of the rotating disc, rad s^{-1}	N_{bins}	number of bins
μ	viscosity of liquid, Pa s	N	number of particles
ρ	density of liquid, kg m^{-3}	p_k	probability of kth bin
σ	surface tension of liquid, N m^{-1}	d_i	diameter of ith particle
Re	Reynolds number		
We	Weber number		

amounts of water and the fact that the energy from the slag is not recovered. Water quenching also causes air pollution by the emission of toxic gases such as sulphides in the atmosphere.

To overcome the above drawbacks various heat recovery technologies based on dry slag granulation have been proposed. These include use of a rotating cylinder [4,5], air blast [6] and centrifugal granulation system for BF slag [7]. Out of these, the centrifugal granulation system offers great promise because of its low cost, compact design, minimal power consumption and ease of operation [2].

In this method, the molten slag is added at a controlled flowrate on a rotating disc, over which it spreads uniformly as a thin film and moves radially outwards. The thin sheet of fluid breaks into ligaments or droplets when it reaches the perimeter of the disc. Droplets solidify to become particles and the heat of the particles is extracted by either physical or chemical methods. Sun et al. [8] reviewed the various chemical methods for heat recovery and suggested that a combination of both physical and chemical methods is the best for heat recovery from slags.

An important aspect of this technique is the design of a rotary disc granulation system to meet the twin objectives of (i) obtaining granules of a particular size which will favour heat recovery and (ii) simultaneously ensure that the product can be used as a substitute for Portland cement. This has led to many studies on the flow behaviour of various liquids on rotating discs. Liu et al. [9] experimentally studied the liquid disintegration by a rotary cup and found that, at a particular liquid flow rate and cup diameter the system shifts from direct droplet formation to ligament formation with an increase in rotational speed. They found that a further increase may lead to the merging of the ligaments to form a sheet. Frost [10] experimentally developed the criteria for different modes of droplet formation. They found that the droplet size in ligament formation mode depends on the angular speed of disc, disc diameter, liquid flow rate, surface tension, viscosity and density. Xie et al. [11] studied the effects of processing conditions in centrifugal atomization of tin and found that premature solidification of the melt on the disc and poor wetting of the disc by the melt caused unsuccessful atomization. Zhou et al. [12] carried out an experimental analysis of the dry slag granulation process using blast furnace slag and reported the effect of slag discharge temperature and the rotating speed of the disc on the particle size distribution and sphericity. Ahmed and Youssef [13] studied the effect of different configurations of spinning disc and cup atomizers on the Sauter mean diameter and compared it with that obtained from a regular flat disc. They reported that the regular flat disc is energy efficient and has higher stability at high rotating speeds. Teunou and Poncelet [14] produced paraffin microbeads using hot liquid paraffin on a rotating disc and derived a theoretical model to predict the trajectory of a droplet travelling in static air. Sungkhaphaitoon et al. [15] developed a mathematical model to predict the trajectory of flying zinc droplets from the edge of the disc. Wang et al. [16,17] developed a mathematical model for free surface film flow on a rotating disc and found that it is mainly governed by the balance between centrifugal and Coriolis forces and viscous drag. They proposed a mathematical model to characterise ligament formation at the edge of the disc and found that the number of ligaments increases with an increase in rotational speed, slag density and slag tapping rate but decreases with increasing viscosity and surface tension. Some researchers have also used CFD simulations to simulate the flow on the disc, ligament formation on the periphery and to study the effects of operating parameters on spreading of liquids [18,19].

While the above studies focussed on the granulation techniques there is another body of literature which focuses on the heat recovery from blast furnace slag particles. Several scientists have proposed different methods for heat recovery. Liu et al. [20] studied the thermal energy recovery from slag particles using a gravity bed heat boiler and reported that a decrease in slag particle diameter and increase in descending velocity increases the heat transfer coefficient. Sun et al. [21] proposed a multistage method for heat recovery from high-temperature slag, which will help extract waste heat and at the same time obtain a glassy phase in slag particles. Zhang et al. [22] reviewed the different heat recovery technologies and listed various technical challenges such as high viscosity and low thermal conductivity of slag, requirement of rapid cooling for glassy product, which have to be considered before choosing a method. Another challenge is that the output of the waste heat recovery should be preferably continuous while the slag discharge from the furnace is discontinuous. Purwanto et al. [23] developed a mathematical model for optimizing the dry granulation process and predicting the cooling rate and temperature distribution within the particle.

Several studies have focussed on the flow of liquid on a rotating disc and particle formation. However, data from the experimental studies of dry slag granulation using either BF slag or its analogue is scarce. Lab scale experiments with simulants have been used to obtain data and develop empirical correlations in terms of dimensionless numbers. The range of validity of the available correlations in the literature is however not available. The range of operating conditions under which particle formation is ensured is also not known. Besides most of these studies do not focus on how the data can be used for scale-up to commercial operations.

The focus of the work in this paper is to address the above gaps in the literature. This paper focuses on an experimental study of dry slag granulation process using an analogue for BF slag (a mixture of rosin and paraffin wax). This analogue can be used to experimentally study dry slag granulation at a relatively low temperature of 130 °C compared to BF slag at 1500 °C. Different ranges of operating conditions in terms of dimensionless numbers for fiber formation and particle formation have been developed. The effect of various parameters such as rotational speed of the disc, liquid flowrate and disc diameter on the average particle

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