Results in Physics 11 (2018) 385–393

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Analogue experimental investigation on ligament granulation of molten slag in various rotary disk configurations for waste energy recovery

Hao Peng[a,*], Xuekun Shan[a], Xiang Ling[a,*], Dongxiang Wang[a,b], Juan Li[c]

[a] Jiangsu Key Laboratory of Process Enhancement and New Energy Equipment Technology, School of Mechanical and Power Engineering, Nanjing Tech University, No. 30 Pu Zhu South Road, Nanjing 211816, PR China

[b] School of Mechanical Engineering, Jiangnan University, No. 1800 Li Hu Road, Wuxi 214122, PR China

[c] School of Mechanical and Electrical Engineering, Nanjing Forestry University, No. 159 Long Pan Road, Nanjing 210037, PR China

ARTICLE INFO

Keywords:
Rotary disk
Molten slag
Ligament
Disk configuration
Particle size
Fiber fraction

ABSTRACT

Rotary disk centrifugal granulation is one of the most promising methods for molten slag recovery with lower power consumption, compact and coupling with a variety of waste heat devices easily. In this paper, high temperature analogue experiments were performed by four types of disks with molten aluminum as the working fluid. The particles characteristics which include particles size distribution, particles mean size and fiber mass fraction were studied. The results show that the majority of the particles size is populated in the range of 2.0 mm ~ 4.0 mm for all the ω and Q. Both theoretic and experimental analyses indicate that the ω has more impact on particles size than Q. The particles produced by curved-block disk and arc-edge disk configurations are more concentrated than the other two types of disks. Besides, the mean size of particles generated by curved-block disk is smaller. A simple correlation of d_m for four types of disks is proposed, which agrees well with the experimental data (R^2 = 0.9172). Meanwhile, when the Q is relative low, a lower ω can contribute to the reduction of produced fiber. The main conclusions drawn from this work will be helpful for future development of the high-temperature molten slag dry granulation systems.

Introduction

Molten slag is the main by-product in iron-making process. In 2017, the production of pig-iron in China reached 710 million tons [1], and 212 million tons of molten slag were generated accordingly. The discharged molten slag has high temperature of 1450 °C ~ 1550 °C [2] and carries a substantial high quality waste heat energy adding up to about 3.81×10^8 GJ. If this waste heat energy can be utilized efficiently, about 12.9 million tons standard coal will be saved. At present, water quenching is the main processing method. However, it fails to recover the waste heat energy from molten slag, but also causes a lot of environmental and energy problems, including low thermal utilization, freshwater consumption and pollution emissions [3–7]. Therefore, dry granulation method is proposed for energy recovery and material recycle from molten slag. However, it is worth highlighting that the cooling rate is a crucial factor that will affect the microstructure in the molten slag [8,9].

Among the dry granulation methods, centrifugal granulation has become the most promising method for waste heat recovery of molten slag because of its many advantages. Normally, the discharged molten slag is poured onto the surface of a rotary atomizer, and then the liquid film is formed and gradually moves to the edge of the rotary atomizer. Finally, the liquid film breaks into slag droplets and these droplets are cooled down by air or other cooling medium. The high-temperature waste energy recovered from the molten slag can be utilized for power or steam generation, or be stored in thermal energy storage system such as thermochemical energy storage systems [10], water pit/compressed air/liquid air energy storage systems [11–15], PCMs energy storage systems [16], and etc.

In 1985, the molten slag centrifugal granulation experiments were first performed by Pickering et al. [17], and the slag particles with the average diameter of 2 mm were obtained, since then, many scholars paid more attention to this technology for molten slag heat recovery. However, rarely experimental works were developed because of the super-high melting temperature of slag, instead, a considerable number of analogue experiments (cold experiments, high-temperature analogue experiments) were carried out in recent years.

* Corresponding authors.
E-mail addresses: phsight1@hotmail.com (H. Peng), xling@njtech.edu.cn (X. Ling).

https://doi.org/10.1016/j.rinp.2018.09.037
Received 14 August 2018; Received in revised form 17 September 2018; Accepted 17 September 2018
Available online 21 September 2018

Nomenclature

d_m	particles mean diameters [m]
P	density [kg/m^3]
m	mass [kg]
σ	surface tension [N/m]
Q	volume flow rate [mL/s]
M	dynamic viscosity [Pa·s]
Q_R	dimensionless volume flow rate
Λ	capillary wavelength [m]
R	disk radius [m]
T	time [s]
Re	Reynolds number

Subscripts

R^2	correlation coefficient
Al	aluminum
St	Stanton number
Copper	copper slag
T	Temperature [°C]
L	ligament
We	Weber number
L	liquid

Greek symbols

M	mean
Z	mass fraction of each size range
S	molten slag
Ω	Rotary speed [rad/s]

Cold analogue experiments

Cold analogue experiment is an effective and simple way to investigate the mechanism of centrifugal granulation. Low-melting point medium, such as glycerol/water mixture, water, and Rosin/Paraffin mixture, are the commonly used working fluids. Liu et al. [18,19] carried out a series of cold experiments on rotary cup granulation by using glycerol/water mixture as the working fluid. Correlations describing the relationship between the liquid drop diameter and various factors were presented, which were applicable for calculating diameter in a wide range of operating conditions. Wang et al. [20] performed the cold experiments on rotary disk granulation to characterize the ligament break-up mode with the same working fluid. The regression models for ligament number, ligament tail end diameter and mean diameter of particles were proposed. They also found that the ligament pinch-off mode was the short-wave mode caused by the centrifugal forces. Wu et al. [21] conducted the visualization experiments for rotary disk centrifugal granulation by using glycerol/water mixtures with different mass ratios, and the effect of liquid viscosity on granulation behaviors was discussed. Some correlations were presented to predict the particles diameters and critical mass flow rates. In addition, the influence of disk configuration on granulation modes and droplet characteristics were investigated by using water as the working fluid [22]. It was found that the cup-like atomizer can produce fine particles with smaller size. Peng et al. [23] performed the experimental studies on the critical transition characteristics for rotary disk granulation. Glycerol/water mixture was adopted as the analogue of the molten slag, the results showed that the transitions from direct-drop to ligament, and ligament to sheet were promoted with the increases of the liquid flow rate, rotary speed, fluid density, and viscosity.

Compared to the experiments with glycerol/water mixture as the working fluid, the experiments with the working fluid of Rosin/Paraffin mixture are more similar to the molten slag experiments in physical reality due to the droplets solidification process during the granulation. Min et al. [24] and Dhirhi et al. [25] conducted the experimental investigations on rotary disk granulation with rosin/paraffin mixture as the working fluid. The effects of operational parameters (disk diameter, flow rate, rotary speed, etc.) on droplet size were discussed. The correlations with relative high precision for predicting the particles size were presented in both works. Zhu et al. [26] used Rosin/Paraffin mixture as the analogue of molten slag to investigate the rotary cups centrifugal-air blast granulation. The experimental results exhibited the influences of liquid flow rate, rotary speed, cup configuration and blast air flow rate on centrifugal granulation characteristics. For the tested operational conditions, more than 60% of total mass of particles within the size range of 0.5 ~ 1 mm was found. Most recently, Peng et al. [27–29] did plenty of experiments to investigate the rotary disk granulation by using Rosin/Paraffin mixture as the analogue of molten slag, the influence of rotary disk configurations on critical transition characteristics, ligament behaviors and particles characteristics were discussed. In their works, transition equations and maps were proposed to identify the critical transition regimes for different breakup modes in rotary disk at a given set of operational conditions. The characteristics of ligament number, ligament diameter, capillary wavelength, droplet mean diameter, droplet size distribution, fiber fraction, and among others, were analyzed, which were very useful for the design and development of dry granulation systems.

High temperature analogue experiments

Considering the possible shortcomings of the existing equipment and some unknown operational factors, high melting point working fluids were adopted to analyze the mechanism of centrifugal granulation based on the similarly theory. Xie et al. [30] reported the effects of the atomizer design and the operational parameters on the morphology and size distribution of molten tin in centrifugal granulation. It was found that the rotary cups with steep walls could reduce the particle sizes ~25% compared with a flat disk. Wang et al. [31] performed the high-temperature analogue experiments by rotary disk using molten aluminum as the working fluid according to the similarity theory. The solid particles mean diameter, mass fraction distribution, morphology of particles and the fiber characteristics were analyzed. It was indicated that the circularity shape factor of particles was mainly determined by the rotary speed and cooling air rate, and the cooling air rate represented little influence on the particle size distributions.

Molten slag experiments

Mizuochi et al. [32] studied the dry granulation of molten slag by rotary cup, and the effect of rotary speed on slag particles size was examined. In their experiments, the average diameter of slag particles less than 1 mm was obtained at the rotary speed of 3000 rpm. Purwanto et al. [33] carried out the high-temperature experiments where a rotary cup was used to produce dry glassy slag. A relationship between the particle size and two parameters (cup diameter and rotary speed) were expressed. They also pointed out that the smaller particles produced at a higher rotary speed have compression strength twice higher than the water granulated slag. Kashiwaya et al. [34,35] developed two kinds of rotary cylinders for molten slag granulation, and the slag atomizing behaviors were investigated. They found that the higher rotary speed and smaller nozzle diameter could produce smaller particles with high sphericity. Xie et al. [36] and Jahanshahi et al. [37] developed a