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Research Paper

Numerical study on solidification behaviors of a molten slag droplet in the centrifugal granulation and heat recovery system

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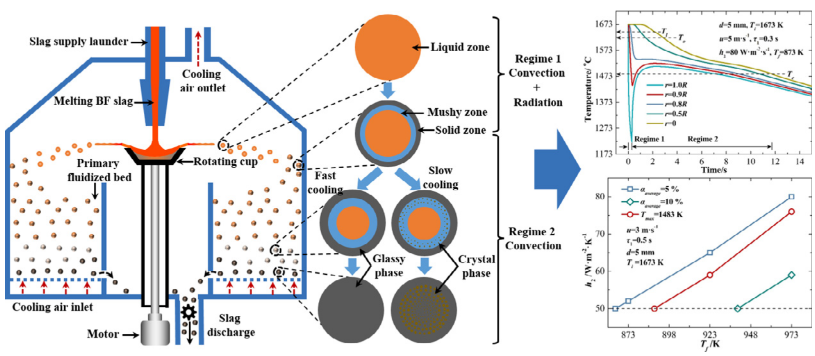
HIGHLIGHTS

- Enthalpy method is adopted to analyze the solidification of a slag droplet.
- Effect of the variable cooling conditions on the solidification is taken into account.
- Evolutions of temperature and crystal phase content inside the droplet are obtained.
- Economic operating parameters of the heat recovery system are obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

Centrifugal granulation technique is the most feasible method for heat recovery from molten blast furnace (BF) slag. The granulated slag droplets experience a complex cooling process to achieve a glassy phase for cement clinker. In the present study, an enthalpy-based model is established to investigate solidification behaviors of a molten BF slag droplet cooled in the centrifugal granulation and heat recovery system. Moreover, influences of droplet flying speed and time in the flying process, heat transfer coefficient and cooling air temperature in the primary fluidized bed as well as droplet initial temperature and diameter are discussed on the solidification behaviors of the BF slag droplet. The numerical results indicate that the temperature of droplet outer surface successively experiences a rapid drop in the flying process, rebound and then gradual decrease in the primary fluidized bed due to the variable cooling condition. Moreover, for a specific granulating device as well as the slag droplet with diameter of 5 mm and initial temperature of 1673 K, the condition with heat transfer coefficient of 50–76 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and cooling air temperature of 889–973 K are the optimized cooling conditions for the heat recovery stage to satisfy the multiple goals.

1. Introduction

Blast furnace (BF) slag is the main by-product generated in the iron-making process, which is discharged at a temperature about 1500 °C [1]. In 2015, nearly 384 million tons of blast furnace slag was produced worldwide containing a tremendous amount of high grade thermal energy [2]. At present, the molten slag is rapidly quenched by water or dumped into open pits and cooled slowly

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Nomenclature

c_p	heat capacity ($J\cdot kg^{-1}\cdot K^{-1}$)
D	diameter of granulation device (m)
d	diameter of BF slag droplet (mm)
H	equivalent enthalpy of BF slag ($J\cdot kg^{-1}$)
H_{glassy}	equivalent enthalpy of glassy slag ($J\cdot kg^{-1}$)
$H_{crystal}$	equivalent enthalpy of crystal slag ($J\cdot kg^{-1}$)
h_1	heat transfer coefficient in regime 1 ($W\cdot m^{-2}\cdot K^{-1}$)
h_2	heat transfer coefficient in regime 2 ($W\cdot m^{-2}\cdot K^{-1}$)
L_{glassy}	latent heat of glassy slag ($J\cdot kg^{-1}$)
$L_{crystal}$	latent heat of crystal slag ($J\cdot kg^{-1}$)
Nu	Nusselt number
Pr	Prandlt number
R	radius of droplet (mm)
Re	Rrynolds number
r	relative position inside the droplet (mm)
T	temperature (K)
T_i	initial temperature of BF slag (K)
T_l	liquidus temperature (K)
T_o	crystallization onset temperature (K)
T_e	crystallization end temperature (K)
T_g	glass transition temperature (K)
T_{max}	maximum temperature of droplet surface in regime 2 (K)
T_f	temperature of cooling air (K)
T_w	internal face temperature of the granulating device (K)
u	flying speed of droplet in regime 1 ($m\cdot s^{-1}$)
v	average cooling rate in the crystallization zone ($K\cdot s^{-1}$)
v_α	growth rate of crystal phase ($\%\cdot s^{-1}$)

Greek

α	crystal phase content (%)
$\alpha_{average}$	average crystal phase content of the whole droplet
λ	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)
ρ	density of BF slag ($kg\cdot m^{-3}$)
ρ_l	density of BF slag in liquid zone ($kg\cdot m^{-3}$)
ρ_s	density of BF slag in solid zone ($kg\cdot m^{-3}$)
τ	time (s)
τ_1	flying time of BF slag droplet in regime 1 (s)
τ_2	discharging time of BF slag droplet in regime 2 (s)
τ_2-τ_1	minimum residence time of droplet in regime 2 (s)
τ_l	time at $T = T_l$ (s)
τ_e	time at $T = T_e$ (s)
σ	Stefan-Boltzmann constant
ε	emissivity of BF slag

[3]. As a result, the slag presents various solid structures (glassy or/and crystal phase) when it undergoes various cooling conditions [4]. Generally speaking, high value-added glassy slag is obtained under a fast cooling rate, which is used as cement clinker directly. By contrast, crystal phase presents in the slag when it is cooled slowly. The crystal slag is usually used as aggregate for road construction and landfilling purposes, of which the commercial value is quite limited. Nevertheless, these treatments fail to recover the huge waste heat carried by the slag. Furthermore, in the process of water quenching plenty of water is consumed and toxic gases are released into the environment.

In order to achieve the multi purposes of heat recovery, water saving and environment protection, various dry granulation heat recovery technologies have been gradually developed, such as mechanical crushing [5,6], air blast [7,8] and centrifugal granulation [9–11]. Among them, the centrifugal granulation technology is the most feasible method, of which the technical process can be described as follows. The molten BF slag is consecutively poured onto a high-speed rotating container (cup/disk), subsequently, the slag is projected outwards owing to the centrifugal force and then broken into small droplets [12,13]. In the flying process, droplets are rapidly cooled by air and crust at the outer surface firstly. After that, the semi-melting droplets are fast cooled to a temperature below the devitrification temperature of the BF slag and finish solidification in a primary fluidized bed. Eventually, the slag particles are slowly cooled in a secondary fluidized bed/moving bed to further recover the residual heat [14,15]. However, this faces with two opposing constraints: one is the demand for large air flow to realize a fast cooling rate for glassy slag as well as to prevent droplet bonding, another is the requirement for low air volume to achieve high-grade waste heat recovery under a small cooling rate. Consequently, a good understanding of solidification behaviors of the molten BF slag droplet cooled in the heat recovery system is essential and crucial to achieve the simultaneous harvest of high temperature air and high-performance glassy slag during the dry heat recovery process and to guide the system design.

In the early 1980s, the solidification process of a BF slag droplet (5 mm in diameter) cooled by air was experimentally explored by Yoshinaga et al. [16]. The temperature evolution in the center of slag droplet was measured by a thermocouple and the effect of cooling air speed was discussed. However, with the limitation of the droplet size and super-high temperature, they failed to measure the temperature distribution inside the slag droplet. Since then, numerical studies other than experimental works has taken the main stream. CFD software ANSYS Fluent was adopted by Sun et al. [17] and Qiu et al. [18] to simulate the solidification process of a BF slag droplet cooled by air. The temperature distribution inside the slag droplet was calculated and the effects of the droplet diameter and cooling air speed were discussed. Furthermore, the heat transfer process between the slag droplets and cooling air in a fluidized bed was simulated by Liu et al. [19]. It is noted that some typical properties of the BF slag including the variable physical properties and the phase change temperature ranges were not taken into account in these researches. Recently, Liu et al. [20] promoted a heat transfer model based on the enthalpy method to analyze the solidification process of a BF slag droplet, and it confirmed that the phase change temperature range and variable thermal conductivity have significant effects on the cooling process of BF slag droplet. Their results indicated that the simplification assumptions deviate far from the actual solidification process of the slag droplet. Moreover, it should be noticed that in the practical centrifugal granulation and heat recovery equipment the cooling condition of the BF slag droplets changes with the process, which is quite different from that mentioned in the previous researches. Specifically, during the slag droplet flying the solidification process is governed by the convection and radiation heat transfer, whereas, in the primary fluidized bed it is mainly under the control of convection heat transfer. Furthermore, more latent heat is released in a narrower temperature interval once the crystal phase presents inside the BF slag, which leads to a significant effect on the solidification behaviors. Unfortunately, up to now, the solidification behaviors of BF slag droplets experiencing a variable cooling condition have not been reported.

Complementally, the crystallization behaviors of slag have been extensively investigated using the methods such as differential scanning calorimetry (DSC) [21–23], single hot thermocouple technique (SHTT) [4,24–26], the double hot thermocouple technique (DHTT) [27,28] and confocal laser-scanning microscopy (CLSM)