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Research Paper

Solidification behaviors of a molten blast furnace slag droplet cooled by air

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HIGHLIGHTS

- Enthalpy method is adopted to analyze the solidification of a slag droplet.
- A temperature range for solidification is considered.
- Movement of phase change interfaces are obtained in solidification.
- Effect of droplet diameter and air velocity are discussed on the solidification.

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ABSTRACT

Aiming at the heat recovery of BF slag by dry granulation technology, a heat transfer model based on the enthalpy method is promoted to analyze the solidification behaviors of a molten BF slag droplet cooled by air. In this model, a temperature range instead of a constant temperature for solidification and variable physical properties during the cooling process are taken into consideration. Furthermore, both convective and radiative heat transfer are employed as the boundary conditions. With the finite difference method, the temperature distribution, movement of phase change interfaces, cooling rate and solidification time are obtained for the air cooling of a molten BF slag droplet. The effects of phase change temperature range, variable thermal conductivity, droplet diameter, air velocity and initial air temperature are discussed on the solidification process. The results suggest that solidification occurred in a temperature range as well as the variable thermal conductivity have an opposite effect on the heat transfer and solidification process. The decrease of the slag droplet diameter and increase in the air velocity fasten the cooling rate and shorten the solidification time.

1. Introduction

Energy-saving and emission-reduction is a perpetual subject in the iron and steel industry. As one of the main by-products during the process of iron and steel making, blast furnace (BF) slag is discharged in a super-high temperature of 1450–1650 °C and carries heat content of about 1700 MJ per tonne that is equivalent to the calorific value of 0.058 tone standard coal [1]. Considering the yield of 1 tonne BF slag from 3 tonnes pig iron, the sensible heat and latent heat stored in the slag is of great value to recover.

However, the molten slag is characterized by high viscosity and low thermal conductivity (0.1–0.3 $W{\cdot}m^{-2}{\cdot}K^{-1}$), and this increases the difficulties of heat recovery. During the slag cooling process, two types of microstructure (crystal phase and glassy phase) are obtained with different mass percentages depending on cooling rate. Slag with high percentage of crystal phase is produced at a slow cooling rate and only can be used as road base materials after crush and screening. Slag with high percentage of glassy phase is achieved at a high cooling rate and can be used as cementitious materials for cement manufacture. Currently, quick cooling of the high temperature slag is realized by water quenching. However, distinct drawbacks are presented during the course of water quenching process, including a full waste of sensible and latent heat; discharge of harmful gases (such as hydrogen sulfide, sulfur dioxide and others) and huge waste of cooling water [2–4]. Aiming at 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 [5], owns the advantages of compact

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Nomenclature

c_p	heat capacity ($kJ \cdot kg^{-1} \cdot K^{-1}$)
d	diameter of BF slag droplet
f	liquid fraction
H	equivalent enthalpy of BF slag ($kJ \cdot kg^{-1}$)
h	average convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
L	latent heat of BF slag ($kJ \cdot kg^{-1}$)
Nu	Nusselt number
Pr	Prandlt number
Re	Rrynolds number
r	relative position inside the droplet (mm)
r_1	radius of droplet (mm)
s_1	interface position of the liquid-mushy (mm)
s_2	interface position of the mushy-solid (mm)
t	temperature (K)
t_d	middle temperature of the phase change temperature range (K)
t_m	melting temperature of the BF slag (K)
t_0	initial temperature of BF slag (K)
t_f	temperature of cooling air (K)
v	cooling air velocity ($m \cdot s^{-1}$)
Greek	
ε	emissivity
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density of BF slag ($kg \cdot m^{-3}$)
τ	time (s)
σ	Stefan-Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)
Subscript	
s	solid phase
l	liquid phase
w	outside wall of the droplet

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%. Thus the integrated dry centrifugal granulation and air cooling heat recovery technology [6] has a good application prospect.

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 due to the role of centrifugal force and subsequently broken into small droplets. At the same time air is blown to cool the droplets. Considering the dual-purpose of efficient heat recovery and reuse of the slag as cementitious materials, fast air cooling rate should be realized in the process. Consequently, the granulation of the slag flow and heat transfer of the granulated droplets are the key steps for the technology.

As for the liquid slag granulation, the structure and the operating conditions of granulation system have important effects on the droplets size and size distribution, and then further on the heat transfer performance. Therefore, a lot of attentions have been devoted to the liquid granulation process. Recently, Liu et al. [7] carried out experiments on slag granulation by rotating cup atomizer (RCA). Meanwhile, Liu et al. [7], Wu et al. [8,9] and Min et al. [10] 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. Zhang et al. [11] investigated experimentally the performance of a simplex centrifugal granulation and a centrifugal-air blast granulation using the mixture of rosin and paraffin. 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. Purwanto et al. [12] carried out the blast slag granulation experiments with the method of rotary cup atomizer (RCA), and they correlated the relationship of the size of granulated slag droplet with the cup diameter and the cup rotation speed. In addition, some numerical investigations also have been contributed to the slag granulation performance. Purwanto et al. [13] developed a mathematical model for the molten slag granulation using a spinning disk atomizer, which can be used for predicting the drop size and then optimizing the granulation process.

As for the heat transfer of the granulated slag droplets with liquid-solid phase change, bearing the significant difficulties in experiments raised by the super-high temperature of the slag, numerical studies other than experimental works take the main stream. Xing et al. [14] established the physical and mathematical models for heat transfer process of the slag granule. The temperature distribution within the slag granule were calculated and the effects of the granule diameter, wind speed and the cooling medium temperature were discussed. Furthermore, Liu et al. [15] simulated the heat transfer process of slag particles in a fluidized bed. It is noted that almost all the researches focused on the systematic heat transfer performance, and some simplification assumptions, such as constant physical properties, deviate far from the practical conditions. That is to say, a detailed understanding of heat transfer and solidification process of a liquid slag droplet has not been well concerned. As a basic element in the technology of centrifugal granulation coupling with air cooling heat recovery, this process is a complicate heat transfer process coupling with various heat transfer modes, variable physical properties, solidification and crystallization. Well understanding of this basic phase change heat transfer process will be helpful for the guide to the system design and operational conditions determination for high heat recovery rate and slag with high content of glassy phase.

Actually, phase change heat transfer problem is of great importance in lots of engineering and natural systems. Related problems include the metals melting and casting, thermal energy storage, crystal growth and etc. In these processes, matter is subject to a liquid-solid or solid-liquid phase change with a moving interface separating two different phases. Consequently, absorption or release of latent heat happens in the vicinity of this interface. Mathematical modelling of such problems is always a challenging task because of the complex boundary conditions as well as varied thermal physical properties. A detailed introduction of various mathematical models for such problems can be found in the review by Henry and Stavros [16]. Because of the complexity, analytical results cannot be obtained except for some extremely simple situations, and therefore, numerical methods have been developed [17,18]. There are mainly two models to deal with the liquid-solid or solid-liquid phase change heat transfer problems: temperature-based model [19] and enthalpy-based model [20–23]. Many researches have been carried out about heat storage or cold storage using phase change materials [24–26], continuous casting [27], preparation [28,29] and the performance strength [30] of phase change materials, and etc. Most of these researches were based on the ideal assumptions or conditions during the