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# Numerical investigation on phase change cooling and crystallization of a molten blast furnace slag droplet

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ABSTRACT

To realize the dual goals of high efficient heat recovery and high value-added utilization of blast furnace (BF) slag by the dry heat recovery technology, an enthalpy-based model is established to analyze the phase change cooling and crystallization of a molten BF slag droplet. In the present model, besides the consideration in both the variable physical properties of BF slag and the phase change temperature range of crystal and glassy phase, the effect of crystal phase content on the enthalpy-temperature curve is firstly taken into account due to the coupling relationships between phase change heat transfer and crystallization inside the BF slag droplet. As the results, the evolutions of temperature and crystal phase content in the BF slag droplet are obtained for an air cooling process. The effects of cooling air velocity and temperature as well as droplet diameter and initial temperature are discussed on the phase change heat transfer and crystallization process. The numerical results indicate that a slow cooling rate leads to the precipitation of crystal phase and thus more latent heat release, which gives rise to an obvious decrease in the cooling rate. Moreover, to achieve the dual goals for the droplet with a diameter of 5 mm, 773–973 K is an appropriate temperature of cooling air, correspondingly, 0.87–1.96 $m\cdot s^{-1}$ is the optimal air velocity. The optimal air velocity reduces about 72% when the droplet diameter decreases to 4 mm.



## 1. Introduction

Blast furnace slag (BF slag) is one of the main by-products in iron-making process and contains plentiful high-grade thermal energy. In 2015, the output of pig iron in the world was more than 1153 million tons accompanying with nearly 384 million tons of BF slag production [1]. That means the total heat is equivalent to 22.3 million tons of standard coal [2], which is the last portion that fails to be recovered in the iron-making industry. Besides, BF slag having the main components of CaO, $SiO_2$, MgO and $Al_2O_3$ is similar to the cements and is one of the main cement auxiliary materials [3]. The BF slag will be of different solid structures (glassy and/or crystal phase) once it experiences various cooling conditions. The glassy slag is formed in a fast cooling condition, which is increasingly utilized as cementitious materials due to the high content of calcium silicates as well as the better hydraulic activity [4]. By contrast, the crystal phase is precipitated once the slag is cooled slowly and then seriously reduces the commercial value. To obtain the high value-added glassy slag, water quench with a high cooling rate is the most popular treatment. Unfortunately, this treatment faces essential shortcomings, such as residual heat waste, water consumption as well as environmental pollution [5,6].

Aiming at heat recovery, water saving and environment protection, dry heat recovery technology characterized by slag granulation and air cooling has been developed. The bottleneck of this technology lies in the quite lower heat transfer capability of air. Thus, granulating the slag flow is spontaneously adopted as the first step to enlarge the heat transfer surface. Researchers promoted various techniques for slag granulation, such as mechanical crushing method [7,8], air blast method [3,9] and centrifugal granulated method [10,11]. Among them the centrifugal granulation method is the most feasible method, through which the molten slag is granulated into small droplets by a high-speed rotating cup/disk [12,13] and concurrently is cooled by air. Besides a good granulation performance of granulated BF slag droplets still requires high-speed air flow to realize fast cooling rate, otherwise, the appearance of undesirable crystal phase is inescapable. Especially, the latent heat released in the solidification process will further reduce the cooling rate and subsequently increase the crystal phase content. However, the resulted large air flow rate seriously debases the air temperature rise and limits the

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**Nomenclature**

| | |
|---|---|
| $c_p$ | heat capacity ($J\cdot kg^{-1}\cdot K^{-1}$) |
| $d$ | diameter of BF slag droplet |
| $H$ | equivalent enthalpy of BF slag ($J\cdot kg^{-1}$) |
| $H_i$ | equivalent enthalpy of BF slag at $\tau = \tau_i$ ($J\cdot kg^{-1}$) |
| $H_{i\ glassy}$ | equivalent enthalpy of glassy slag at $\tau = \tau_i$ ($J\cdot kg^{-1}$) |
| $H_{i\ crystal}$ | equivalent enthalpy of crystal slag at $\tau = \tau_i$ ($J\cdot kg^{-1}$) |
| $h$ | average heat transfer coefficient ($W\cdot m^{-2}\cdot K^{-1}$) |
| $L_{glassy}$ | latent heat of glassy slag ($J\cdot kg^{-1}$) |
| $L_{crystal}$ | latent heat of crystal slag ($J\cdot kg^{-1}$) |
| $Nu$ | Nusselt number |
| $n$ | number of space nodes |
| $Pr$ | Prandtl number |
| $R$ | radius of droplet (mm) |
| $Re$ | Reynolds 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) |
| $T_f$ | temperature of cooling air (K) |
| $u$ | cooling air velocity ($m\cdot s^{-1}$) |
| $v$ | cooling rate ($K\cdot s^{-1}$) |
| $v_{average}$ | average cooling rate in the crystallization zone ($K\cdot s^{-1}$) |
| $v_\alpha$ | growth rate of crystal phase ($\%\cdot s^{-1}$) |
| $Y$ | total length of alloy/BF slag bar (mm) |
| $y$ | relative position along the alloy/BF slag bar (mm) |

*Greek*

| | |
|---|---|
| $\alpha$ | crystal phase content (%) |
| $\alpha_i$ | crystal phase content at $\tau = \tau_i$ (%) |
| $\lambda$ | thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$) |
| $\rho$ | density of BF slag ($kg\cdot m^{-3}$) |
| $\tau$ | time (s) |
| $\tau_l$ | time at $T = T_l$ (s) |
| $\tau_o$ | time at $T = T_o$ (s) |
| $\tau_e$ | time at $T = T_e$ (s) |
| $\sigma$ | space step (mm) |

follow-up application. In consequence, a good understanding of phase change cooling and crystallization performance of molten BF slag droplets under various conditions 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.

Currently, in experiment, differential scanning calorimetry (DSC), X-ray diffraction (XRD) and single hot thermocouple technique (SHTT) are the common ways to investigate the crystallization behaviors of slag under a constant temperature or cooling rate. However, most of the researches focused on the coal ash or coal slag [14–18], few worked on the BF slag [19–21]. Moreover, tiny amount of sample in these experiments limits the detailed exploration of phase change heat transfer process as well as the interplays between phase change heat transfer and crystal phase growth. Directional solidification technique is another way to explore the phase change heat transfer process in materials. Ding et al. [22] adopted this method in combination with the XRD to explore the phase change cooling and the crystallization behaviors of a BF slag column with diameter of 32 mm and length of 52 mm. Nevertheless, the above experimental methods fail to deal with the temperature distribution and crystallization evolution inside a granulated BF slag droplet with a diameter range of 1–5 mm.

Complementally, a series of modelling researches have been carried out to explore the temperature evolution inside a BF slag droplet. For instance, CFD software ANSYS Fluent was adopted by Liu et al. [23], Sun et al. [24] and Qiu et al. [25] to simulate the phase change heat transfer process between a BF slag droplet and air. In these simulations, the latent heat was assumed to release in a fixed temperature and the physical property parameters such as thermal conductivity and heat capacity were regarded as constants. These assumptions deviate far from real scenario of the multicomponent BF slag with variable physical parameters. More recently, Liu et al. [26] promoted a heat transfer model based on the enthalpy method to analyze the solidification process of BF slag droplet and have confirmed that the phase change temperature range and variable thermal conductivity have significant effects on the cooling process of BF slag droplet. The results suggested that smaller droplet diameter and faster air velocity is benefit to shorten the solidification time. Unfortunately, up to now, a step further to the interplays between phase change cooling and crystallization behaviors has not been reported.

Base on this, an enthalpy-based model is established to analyze the phase change cooling and crystallization behaviors inside a molten BF slag droplet. Moreover, the phase change temperature ranges of the crystal and glassy phase slag as well as the variable physical property parameters in the solidification process are taken into consideration in the present model. Furthermore, the effect of crystal phase content on the enthalpy-temperature curve is taken into account. The effects of velocity and temperature of cooling air as well as droplet diameter and initial temperature are investigated on the crystal phase content and crystallization ending time. The calculated results are expected to provide theoretical guidance to determination of operating conditions for the dry graduation and waste heat recovery technology.

## 2. Formulation of physical model

In the phase change cooling process, the latent heat of BF slag droplet is released in a temperature range, resulting in appearance of the liquid zone, the mushy zone (coexistence of solid and liquid phase) and the solid zone. The previous research [27] indicated that the mushy zone is bounded by two isothermal boundaries, one at the glass transition temperature ($T_g$) and the other at the liquidus temperature ($T_l$). Moreover, solid structure (glassy phase or crystal phase) of the slag is governed by the cooling rate. As schematically shown in Fig. 1, when the droplet is cooled rapidly, the glassy phase dominantly forms in the mushy zone. On the contrary, the crystal phase precipitates in a slow cooling rate. Furthermore, the crystallization process appears in a narrower temperature range between crystallization onset temperature ($T_o$) and crystallization ending temperature ($T_e$), meanwhile, more latent heat is released in this process. To focus on the crystallization behaviors in the phase change cooling process of a molten BF slag droplet, prior to the model establishment, some assumptions are made based on the practical conditions:

(1) The temperature changes along the radial direction only.
(2) Effect of natural convection in the liquid zone is ignored.
(3) Values of $T_o$ and $T_e$ are constant.