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Heat Recovery from Centrifugal Granulated Slag Particles in a Hybrid Cooling Granulation Cabin

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ABSTRACT

The blast furnace (BF) slag produced in the iron and steel smelting process contains abundant waste heat resources. The centrifugal granulation waste heat recovery technology is considered to be the most promising BF slag treatment process. In this paper, a granulation cabin structure is proposed to inhibit particles bonding, and the effects of initial slag temperature, cooling air flow rate and rotating speed on waste heat recovery are discussed. The results show that the waste heat recovery rate can be improved by increasing initial slag temperature and cooling air flow rate. At the same time, 1800 rpm is the suitable rotating speed for waste heat recovery.

Keywords: blast furnace slag, molten slag, centrifugal granulation, waste heat recovery

NONMENCLATURE

Abbreviations	
BF	Blast furnace
Symbols	
T_{ain}	Inlet temperature of cooling air
T_{aout}	Outlet temperature of cooling air
C_a	Heat capacity of cooling air
m_a	Mass flow of cooling air
T_{win}	Inlet temperature of cooling water
T_{wout}	Outlet temperature of cooling water
C_w	Heat capacity of cooling water
m_w	Mass flow of cooling water
m_p	Mass flow of slag particles
q_a	Cooling air flow rate
q_w	Water flow rate
C_{ps}	Heat capacity of solid slag
C_{pl}	Heat capacity of liquid slag
ρ_s	Density of solid slag
L_c	Latent heat of crystal phase
L_v	Latent heat of vitreous phase
L_p	Average latent heat of particles
T_{pin}	Initial temperature of slag particles
T_{pout}	Outlet temperature of slag particles
T_l	Liquidus temperature
η	Waste heat recovery rate

1. INTRODUCTION

The blast furnace (BF) slag released from the iron making process in molten state at temperature of 1450-1650 °C contains abundant waste heat [1], which is also one of the few waste heat resources that cannot be recovered in the steel industry. The current treatment method for molten BF slag is water quenching [2]. Although the water quenching process succeed in higher vitreous content formation in the slag particles during the cooling process, so as to be used as cement admixture, but it fails to recover the waste heat of slag. In order to pursue greater economic and environmental values, considering both material quality and waste heat recovery has become the development goal of BF slag treatment technology in industrial application.

In order to achieve this goal, many waste heat recovery technologies based on BF slag dry granulation have been proposed. In the dry granulation method, the liquid slag is physically granulated into small particles to increase the specific surface area of the slag. The granulated high-temperature slag particles then directly exchange heat with the cooling air or surface type heat

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exchanger to obtain available high-temperature air or high-temperature steam. In this way, the waste heat can be recovered efficiently. Based on different granulation mechanisms, three general methods have been promoted: wind quenching method [3], mechanical crushing method [4], and centrifugal granulation method [5, 6]. The centrifugal granulation technology has become the most promising BF slag treatment process due to its advantages of lower energy consumption and higher equipment stability.

Pickering et al. [5] initially proposed an equipment which combined a centrifugal granulation cabin with a two-stage fluidized bed to recover heat from centrifugal granulated slag droplets and particles. Shimizu et al. [7] verified the feasibility of the scheme recovering waste heat from slag particles in a fluidized bed through theoretical calculation and cold state experiments. Cao et al. [8] established a bubbling fluidized bed model and studied the flow and heat transfer characteristics of the BF slag particles at the bottom of the granulation cabin. So far, most of the researched slag centrifugal granulation cabin equipped with fluidized bed for heat recovery adopted horizontal air distributor structure, where the granulated slag particles were in dense phase fluidization at the bottom. Indeed, in practical operation, this scheme is very easy for the granulated particles to bond to each other due to their insufficient cooling and solidification before entering the fluidized bed, thus deteriorating the fluidization quality and blocking the slag discharge pipe, which seriously affects the recovery rate of waste heat and the operation safety of the equipment.

To solve the above problem, a specially designed centrifugal granulation cabin surrounded by a water-cooled wall and compounded with a fluidized bed having a straight pass inclined air distributor is proposed. The slag particles movement and heat recovery process are analyzed, and the effects of operation parameters on the waste heat recovery rate are investigated.

2. EXPERIMENTAL SYSTEM AND METHODS

2.1 Experimental apparatus

The schematic of the experimental system is shown in Fig 1. The input high temperature molten slag was granulated into small droplets by a high-speed rotating granulator. The droplets flew inside the granulation cabin with high velocity to imping on the water-cooled cabin wall. Thereafter, droplets fell onto an inclined air distributor (inclined angle of 30°) and slide along the air distributor under the action of cooling air to the particle collector. The air entered the granulation cabin from the air distributor to cool the high temperature particles.

A thermocouple and an anemometer were placed in the top outlet to measure the air temperature and velocity. A thermocouple was set in the middle of the granulation cabin to measure the air temperature heated by the sliding particles on the plate. Two thermocouples were fixed at the outlet of water-cooled wall and particles collector to measure the water temperature and slag particles temperature, respectively. All the thermocouples are connected to the data logger. A camera at the top of granulation cabin was used to capture the movement of granulated slag particles.

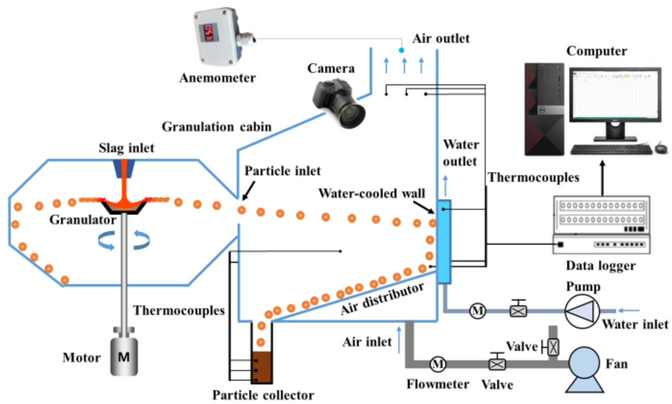

Fig 1 Schematic of the experimental system of centrifugal granulation and heat transfer of molten slag particles

2.2 Working medium and data processing

The water quenched BF slag taken from a steel and iron making company in Chongqing, China was used as the working medium. It was remelted and input into the experimental system. The physical properties of the BF slag are shown in Table 1.

Table 1 The physical properties of BF slag.

Parameter	value	parameter	value
C_{ps}(J·g^{-1}·°C^{-1})	1.15 [9]	C_{pl}(J·g^{-1}·°C^{-1})	1.30 [9]
ρ_s(g·cm^{-3})	2.84 [10]	T_l(°C)	1350 [10]
L_c(J·g^{-1})	456 [10]	L_v(J·g^{-1})	284 [10]

The particles movement process can be obtained based on the image analysis. The waste heat recovery rate of the slag can be calculated by

$$\eta = \frac{c_a m_a (T_{ain} - T_{aout}) + c_w m_w (T_{win} - T_{wout})}{c_{pl} m_p (T_{pin} - T_l) + c_{ps} m_p (T_l - T_{pout}) + m_p L_p} \quad (1)$$

3. RESULTS AND DISCUSSION

3.1 Analysis of the particles movement process in the granulation cabin

The whole movement process of the granulated particles inside the granulation cabin is shown in Fig 2. It can be found that the movement of slag particles actually experienced three stages in the granulation cabin:

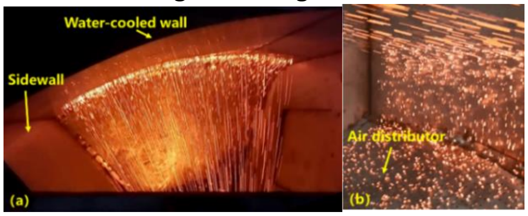

Fig 2 Movement process of slag particles in granulation cabin

① **Flying stage:** The liquid slag was granulated to liquid filaments and then small droplets by the high-speed rotary granulator and flew outwards inside the granulation, as shown in Fig 3(a). Due to wide size distribution, droplets dispersed in the space during the flying stage, as illustrated in Fig 3(b). During the flying stage, the slag droplets not only conducted convective heat transfer with the air, but also conducted radiation heat transfer with the wall. This resulted in a continuous drop of slag droplets temperature and then the droplets gradually solidified into soft particles.

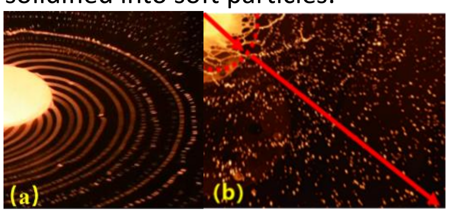

Fig 3 Images of slag droplets during the flying stage

② **Impacting stage:** Due to the limited size of the granulation cabin, the particles in the flying stage inevitably impacted the wall. Fig 4 (a) shows the process of slag particles impacting the water-cooled wall. The shape of particles changed from sphere to flat when they hit the wall, and then returned to sphere when they bounced back. During this process, the slag particles conducted heat to the water-cooled wall. Almost no slag particles remained on the wall after impacting, as in Fig 4(b), which shows that the water-cooled walls can effectively inhibit particles bonding.

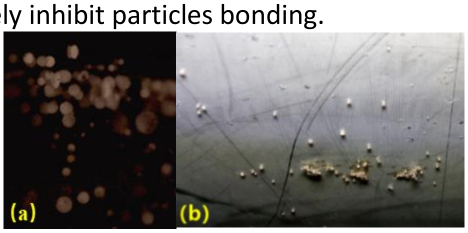

Fig 4 Process of particles impacting the wall

③ **Sliding stage:** As shown in Fig 5(a), the slag particles fell onto the inclined air distributor after hitting the wall. Fig 5(b) to 5(e) show the movement process of particles on the air distributor. One can see that the slag particles slided by jump on the inclined air distributor in the form of "no accumulation". The slag particles collided with the air distributor frequently and exchanged heat with the air distributor and the cooling air, rising the cooling air temperature. There is no adhesion of collision between the slag particles.

Based on the above visualization results, it can be seen the hybrid cooling granulation cabin proposed in this paper can effectively inhibit particle adhesion either on the wall or on the air distributor. Then, the effects of initial slag temperature, cooling air flow rate and rotating speed on the waste heat recovery rate in the proposed centrifugal granulation cabin are discussed.

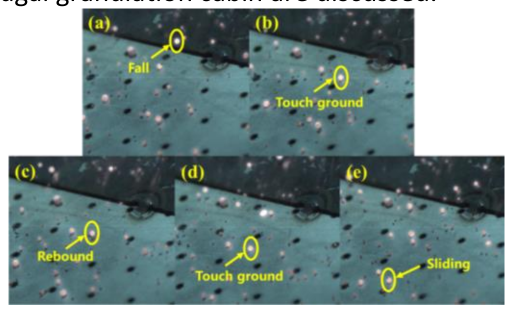

Fig 5 The process of slag particles sliding on the air distributor

3.2 *Effect of initial slag temperature*

Fig 6 shows the effect of initial slag temperature on the waste heat recovery rate. The waste heat recovery rate increased with the increase of the initial slag temperature due to higher heat transfer temperature difference. Moreover, higher temperature led to lower viscosity and hence good granulation performance, giving rise to smaller particles and higher heat transfer coefficient. When the initial slag temperature was 1500°C, the waste heat recovery rate from the granulation cabin reached 60%. This result suggests the importance of heat preservation for molten slag before entering granulation cabin.

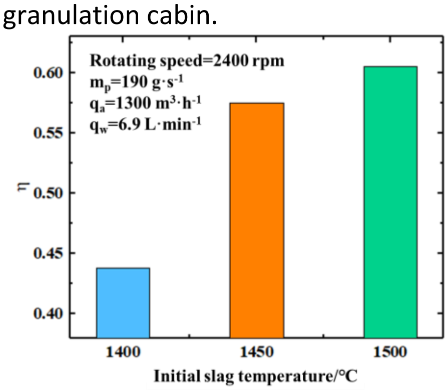

Fig 6 Effect of initial slag temperature on heat recovery rate

3.3 *Effect of cooling air flow rate*

Fig 7 shows the effect of cooling air flow rate on the waste heat recovery rate. The waste heat recovery rate increased with the increasing cooling air flow rate. This is because higher cooling air flow rate can significantly promote the convective heat exchange between the air and the slag particles. However, higher cooling air flow rate will result in lower hot air temperature, hence reducing the quality of hot air. So it is necessary to select the appropriate cooling air flow rate.

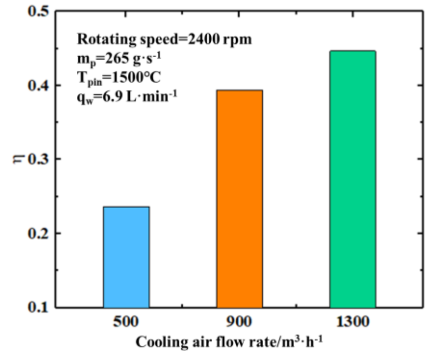

Fig 7 Effect of cooling air flow rate on heat recovery rate

3.4 *Effect of rotating speed of granulator*

Fig 8 exhibits the effect of rotating speed of the granulator on the waste heat recovery rate. One can see that the maximum waste heat recovery rate was achieved at the rotating speed of 1800 rpm. As the rotating speed was increased to 2400 rpm and 3000 rpm, the waste heat recovery rate decreased greatly. This is because the smaller particles result from the higher rotating speed solidify more easily when flying, thereby increasing the heat transfer resistance at impacting and sliding stages. In addition, higher rotating speed also consumed more energy. Thus, 1800 rpm can be regarded as the optimal rotating speed for waste heat recovery from slag particles.

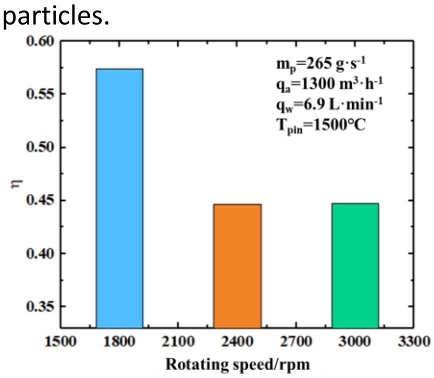

Fig 8 Effect of rotating speed on heat recovery rate

4. CONCLUSIONS

In this paper, the movement and waste heat recovery of centrifugally granulated slag particles in the proposed granulation cabin were studied. The main conclusions are as follows:

(1) The proposed granulation cabin effectively inhibited slag particles adhesion. The movement and heat transfer process of slag particles in the granulation cabin can be divided into three stages: flying stage, impacting stage and sliding stage.

(2) Higher initial temperature of slag and cooling air flow rate promoted the waste heat recovery rate. The optimal rotating speed of granulator was 1800 rpm in the present operating conditions.

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REFERENCE

[1] Feng Y-H, Zhang Z, Qiu L, Zhang X-X. Heat recovery process modelling of semi-molten blast furnace slag in a moving bed using XDEM. Energy (Oxford). 2019;186:115876.

[2] Zhang H, Wang H, Zhu X, Qiu Y-J, Li K, Chen R, et al. A review of waste heat recovery technologies towards molten slag in steel industry. Applied energy. 2013;112:956-66.

[3] Barati M, Esfahani S, Utigard TA. Energy recovery from high temperature slags. Energy. 2011;36:5440-9.

[4] Dai X-T, Qi Y-H, Zhang C-X, Xu H-C, Yan D-L, Hong Y-C. Analysis of blast furnace slag quenching dry granulation process. Journal of Iron and Steel Research. 2007;19:14-9.

[5] Pickering SJ, Hay N, Roylance TF, Thomas GH. New Process for Dry Granulation and Heat-Recovery from Molten Blast-Furnace Slag. Ironmak Steelmak. 1985;12:14-21.

[6] Tan Y, Zhu X, He X-Y, Ding B, Wang H, Liao Q, et al. Granulation characteristics of molten blast furnace slag by hybrid centrifugal-air blast technique. Powder technology. 2018;323:176-85.

[7] Shimizu T. Device for recovering heat of molten slag. Google Patents; 2014.

[8] Cao L, Wang H, Zhu X, He X-Y, Liao Q, Fu Q. Numerical investigation of the hydrodynamics in a bubbling fluidized bed with granulated molten slag particles during heat recovery process. p. 1092-3.

[9] Pan Y, Witt PJ, Xie D. CFD simulation of free surface flow and heat transfer of liquid slag on a spinning disc for a novel dry slag granulation process. Progress in Computational Fluid Dynamics. 2010;10:292-9.

[10] Ding B, Wang H, Zhu X, He X-Y, Liao Q, Tan Y. Crystallization Behaviors of Blast Furnace (BF) Slag in a Phase-Change Cooling Process. Energy & Fuels. 2016;30:3331-9.