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RESEARCH OVERVIEW ON RECOVERY OF WASTE HEAT FROM HIGH TEMPERATURE SLAG PARTICLES

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ABSTRACT

The high temperature slag discharged from metallurgical industry has the characteristics of high temperature and large discharge. In 2017, the total amount of liquid slag produced by the world iron and steel industry is about 913 million tons and the amount of waste heat resources contained in liquid slag is equivalent to about 38 million tons of oil equivalent. It has great value of waste heat recovery and resource utilization. Among all kinds of slag treatment methods, dry centrifugal granulation has the advantages of small particle size and high vitrification, which is a developmental slag treatment process. The slag particles produced by centrifugal granulation are typical semi-melt and wide-screening particles. This paper reviews the current status of basic scientific research of gas-solid heat transfer, solid-solid heat transfer and phase evolution of semi-melt particles by scholars all over the world. On this basis, in order to achieve efficient waste heat recovery and resource utilization of centrifugal granulated blast furnace slag particles, this paper puts forward specific research contents and technical development ideas about the heat transfer mechanism of semi-melt and wide-screening particles and the high-temperature waste heat recovery technology of high-temperature slag particles.

Keywords: Waste Heat Recovery, Particle phase transformation, High temperature slag

1. INTRODUCTION

As a pillar industry of national economy, iron and steel industry is an important symbol of national economic strength and comprehensive national strength. According to the latest data released by the World Iron and Steel Association, global crude steel production increased by 5.3% in 2017, reaching 1.691 billion tons. Globally, the steel industry accounts for 5-6% of global industrial energy consumption, producing about 6% of global carbon dioxide emissions [1].

In the process of iron and steel smelting, severe oxidation-reduction reaction takes place in the iron-making blast furnace, and its energy consumption accounts for more than 60% of the total process (as shown in Fig 1). At the same time, the waste heat resources contained in blast furnace slag and other wastes from blast furnace ironmaking account for more than 35% of the total waste heat resources in the metallurgical process (as shown in Fig 2)[2].

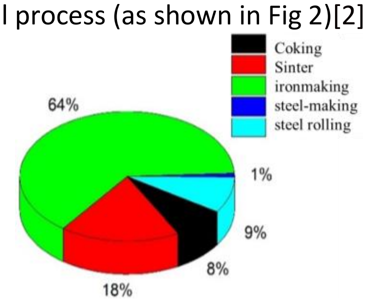

Fig 1 Distribution of Energy Consumption in Metallurgical Processes

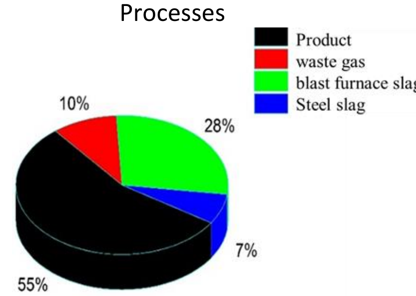

Fig 2 Distribution of waste heat resources in iron and steel industry

Blast furnace slag is the main by-product in the metallurgical process. The impurities such as silicate and aluminate in the raw material of blast furnace iron smelting form liquid slag at 1400-1600°C. Since the 1980s, blast furnace slag has been used as a secondary resource in many countries.

2. EXISTING HIGH TEMPERATURE LIQUID SLAG TREATMENT METHODS

At present, more than 80% of the slag is treated by water quenching method. Although different water quenching methods differ in the specific process, they all have common disadvantages[3-4]: 1) waste of the heat resources in blast furnace slag; 2) waste of large amount of water; 3) producing a large amount of harmful gases such as SO_2 and H_2S; 4) Additional energy consumption.

Compared with traditional water quenching method, the dry treatment method does not consume water resources, and it can recover the heat contained in blast furnace slag. Dry treatment methods mainly include air quenching, drum granulation, Merotec process, mechanical stirring granulation, continuous casting and rolling process, dry centrifugal granulation, etc. The comparison of these methods is shown in Table 1. Syntheses show that the dry centrifugal granulation process has the advantages of small particle diameter, good sphericity, high vitrification, compact equipment and low energy consumption.

Researchers from all over the world mainly study the centrifugal granulation process of slag from the aspects of the flow characteristics of slag on the rotor surface and the formation mechanism of centrifugal granulation droplets of high temperature blast furnace slag. However, the slag particles produced by centrifugal granulation are still above 1100°C. How to recycle the heat contained in the slag particles efficiently has not yet been a mature scheme. The granulated slag particles are about 2-4 mm, and there is a wide particle size range. The surface temperature of the particles is above 1100°C, while the center is still in the melting state. The granulated slag particles are typical semi-melt and wide-screening particles. In order to recover the heat efficiently, it is necessary to study the gas-solid, solid-solid heat transfer mechanism and phase evolution law of the slag particles.

Table 1 Comparison of Technical Indicators of Water Quenching Method

Processing method	Power consumption (k·Wh/t)	Water consumption (Slag/Water)	Slag moisture content%	Area covered	Investment	Application Situation of Domestic Steel Mills
Bottom filtration method	8	1:10	24-40	Maximum	Relatively large	Maximum
INBA method	5	1:(6-8)	15	Medium	Maximum	Many
TYNA method	2.5	1:8	8-10	Medium	Large	Relatively large
RASA method	15~16	1:(10-15)	15-20	Relatively large	Relatively large	Relatively few

Table 2 Comparison of Technical Indicators of Slag Dry Treatment

Processing method	Processing capacity (t/h)	Shape and particle size (mm)	Cooling rate	Heat transfer medium	Vitrification rate and its application	Heat recovery rate (%)
Drum granulation method	/	Slices, 2-3 mm thick	Quench	Organic liquid	95，cement	40
Continuous casting and rolling method	/	/	Slow cooling	Water and air	/	66.5
Mechanical agitation method	30	About 20	Slow cooling	Water	Concrete aggregate	43
Merotec method	40	90-95%<5	Slow cooling	Water and air	Concrete	64
Air quenching method	100	95%<5	Quench	Air	>95，cement	63
Dry centrifugal granulation method	6	Average 2	Quench	Water and air	>95，cement	75

3. REVIEW OF HIGH TEMPERATURE PARTICLE HEAT TRANSFER TECHNOLOGY

3.1 Research Status of Gas-Solid Heat Transfer of High Temperature Particles

The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) divided the waste heat recovery process of liquid slag into dry centrifugal granulation process and waste heat recovery process. After dry centrifugal granulation, the temperature of blast furnace slag particles was about 900°C. Then the particles entered the packed bed for heat transfer, resulting in hot air of 500-600°C[5].

Shun Li from Sinosteel Anshan Research Institute of Thermal Energy used blast furnace slag particles produced by centrifugal granulation experiment as experimental working materials, and reheated the particles to 850°C. They used air as heat transfer medium, and designed moving bed to carry out waste heat recovery experiments of high temperature slag particles[6]. The effect of slag mass flow rate, airflow rate and initial temperature on hot air temperature and waste heat recovery efficiency was studied.

Wang Meng from Northeastern University used sinter as heat source and air as medium to simulate the heat transfer of moving bed with self-built packed bed experimental device[7]. They tested the data of heat transfer process of tank material layer under different working conditions. They studied the influence of cold airflow rate, particle size, height of material layer and edge effect on heat transfer coefficient of material layer, and finally deduced the empirical correlation formula of heat transfer coefficient of material layer by dimensional analysis method:

$$Nu = 1.205\,\mathrm{Re}^{0.508}\,\mathrm{Pr}^{0.4}\left(\frac{H}{d}\right)^{-0.137}\left(\frac{T_f}{T_w}\right)^{0.5}$$

Yuanqiu Luo from Northeastern University obtained the influence of cooling air volume and material layer thickness on hot air temperature through semi-industrial experiments of sinter gas-solid heat transfer[8]. Based on porous medium model, the cooling process of sinter was calculated by Fluent software, and the influence of airflow rate, material layer thickness and cross-section shape on hot air temperature was analyzed. Finally, according to the experimental and simulation results, the effects of air flow rate and bed height on the quantity and quality of heat recovery were analyzed, and the appropriate operating parameters were given.

Wei Shao from Shandong University studied the heat transfer of particle accumulation in cement grate cooler theoretically and experimentally based on the differential equation of kinetic fluid energy, gas-solid energy equation, entropy analysis method and genetic algorithm[9]. According to the experimental results and simulation results, the cooling air distribution system in grate cooler was optimized. The convective heat transfer process of cement particles with different sizes and Reynolds numbers was measured experimentally, and the convective heat transfer criterion equation considering wall effect in particle-filled channel was fitted. The results showed that:

$$Nu = 0.19 Re_d^{0.775}$$

Jintao Wu from Zhejiang University studied the momentum and heat transfer processes in a moving bed by using particle random motion model, discrete element model and particle contact heat transfer model[10]. Taking the moving bed as the research object, they studied the momentum and heat transfer processes in it from different scales and angles. A particle contact heat transfer model was proposed based on the consideration of multiple processes of particle contact heat transfer. The model included four heat transfer processes: 1) heat conduction through solids; 2) heat conduction through particle-to-particle interface; 3) heat conduction of gas film near particle-to-particle interface; 4) convective heat transfer between particle-to-fluid-to-particle, which was combined with DEM model to simulate the heat transfer process between particles and heat transfer surface in a moving bed. The relationship between heat resistance of each heat transfer process was: $R_{convection} > R_{film} > R_{contact} > R_{interior}$. Under the same heat transfer temperature difference, the heat transfer through the contact surface had the greatest impact on the overall effective heat transfer.

Runhua Huang set up a gas-solid fluidized bed to study the flow and heat transfer characteristics of granulated slag particles in the fluidized bed[11]. The experimental results showed that the particle concentration decreased with the increase of wind speed in the area near the buried tube of fluidized bed. When the fluidized air velocity ranged from 1.06 to 1.33 $m \cdot s^{-1}$, the bed pressure drop was maintained at about 10 kPa. When the difference of heat transfer temperature was constant, the heat transfer coefficient between the bed and the buried tube was basically constant, and was little affected by wind speed. The lower the wind speed, the better to maintain the bed temperature.

3.2 Research Status of Solid-Solid Heat Transfer of High Temperature Particles

Junxiang Liu from Northeastern University studied the effects of particle diameter, particle velocity, arrangement of heat exchanger tubes, Reynolds number of water and flow mode of water on the comprehensive heat transfer coefficient, heat transfer coefficient on slag side, heat recovery rate and temperature drop rate of slag particles at the first row of heat exchanger tubes[12]. Finally, the experimental correlation of slag particle-tube heat transfer was obtained by fitting the experimental data, which had certain industrial application value.

Qingbo Yu from Northeastern University established a three-dimensional mathematical model by CFD method[13]. The heat transfer process of blast furnace slag particles flowing around a circular tube was simulated numerically. The effects of particle inlet velocity, cooling water inlet velocity and cooling water inlet temperature on heat transfer were studied. The simulation results showed that the heat transfer coefficient increased with the increase of slag particle inlet velocity and cooling water velocity.

Jiayan Peng from Northeastern University summarized the heat transfer process between particles and between particles and walls on the basis of the current research on the heat transfer of particles in the process of particle flow[14]. The heat transfer process between particles was mainly contact heat conduction and collision heat transfer. The heat transfer between particles and wall mainly included collision heat transfer, heat conduction and radiation heat transfer.

Xuejun Zhu from Sichuan University studied the heat transfer between a vibrating fluidized bed and immersed horizontal tube using glass beads with an average diameter of 0.71 mm, 1.83 mm and millet with a diameter of 1.66 mm[15]. The effects of gas velocity, vibration frequency, bed height and horizontal tube diameter on the average heat transfer coefficient were investigated. The results showed that the average heat transfer coefficient increased with the decrease of particle size, and the thermophysical properties of particles and the diameter of tubes also had a great influence on the average heat transfer coefficient.

Cidong Fan from Sichuan University took sludge particles in fluidized bed as research objects[16]. The effects of fluidized air velocity and pipe vibration on local heat transfer coefficient were studied. The experimental results showed that the local heat transfer coefficient increased first and then decreases with the increase of air, vibration frequency and amplitude. The results provided a basis for the design of sludge dryer.

Zixuan Guo used CFD method to study the single-phase flow and heat transfer characteristics of a regular packed pebble bed in turbulent flow[17]. The effects of particle diameter and type of fluids on the single-phase flow and gas-solid heat transfer characteristics were investigated.

Anyuan Liu et al. established a particle collision heat transfer model considering the internal thermal resistance and the contact thermal resistance between particles, and analyzed the heat transfer mechanism of particle collision and particle-wall heat transfer[18]. On this basis, the researchers used discrete element method (DEM) to simulate the collision heat transfer coefficient between particles in the bed.

Hiromi Takeuehi studied the particle motion and local heat transfer in a moving bed with buried tubes[19]. They took X-ray photographs to observe the movement of particles passing through buried tubes during the experiment, and studied the effects of particle velocity, tube spacing and arrangement on particle flow. The influence of pipeline layout on particle flow pattern and local heat transfer coefficient was studied as well.

3.3 Research Status of Phase Evolution of Semi-Melt and Wide-Screening Slag Particles

Xiaoying Liu from Chongqing University established a numerical model for heat transfer of molten blast furnace slag particles with constant phase change by temperature method[20]. The effects of particle diameter, cooling air velocity, cooling air temperature and particle incident temperature on heat transfer of phase change characteristics of single blast furnace slag were studied. The results showed that in the solidification stage of slag particles, radiation heat transfer contributes a lot to the total heat transfer, accounting for 50%-60% of the total heat transfer. At the same time, the proportion of radiation heat transfer decreased with the decrease of particle temperature.

Yongjun Qiu from Chongqing University, based on VOF coupled solidification and melting model, established the phase transformation model of multi-slag particles in air cooling[21]. The distribution of air velocity field and temperature field between particles and the movement law of solid-liquid interface inside particles were obtained. The effects of particle diameter, particle spacing, air velocity and initial slag temperature on the heat transfer and phase transformation law of slag particles were studied.

Yuelin Qin from Chongqing University studied the crystallization behavior of blast furnace slag by single hot wire method[22]. The continuous cooling transformation (CCT) curve and isothermal transformation (TTT) curve of blast furnace slag cooling were obtained. The critical cooling rate of slag to avoid crystal formation during cooling process was $10°C·s^{-1}$.

Bin Lin studied the phase transformation cooling and phase evolution of blast furnace slag under different cooling conditions, and obtained the critical cooling rate of glass blast furnace slag with high content[23]. The results showed that the critical cooling rate of the selected blast furnace slag at constant temperature was $9±0.13°C·s^{-1}$ and the critical cooling rate at constant speed was $5.5+0.08°C·s^{-1}$. Meanwhile, it was found that the increase of SiO_2/Al_2O_3 was beneficial to the amorphous formation of blast furnace slag during cooling process. With the increase of CaO/MgO ratio, it was easier for blast furnace slag to precipitate crystals, which led to the increase of critical cooling rate.

KASHIWAYA et al. studied the phase evolution of blast furnace slag under constant temperature and constant speed cooling conditions by hot wire method[24]. The results showed that the crystals formed by blast furnace slag under constant cooling rate were Calcium Aluminum Feldspar ($2CaO·Al_2O_3·SiO_2$) and Magnesia-Silica ($3CaO·MgO·2SiO_2$). At the same time, the crystallization rate of Magnesia-Silica was higher than Calcium Aluminum Feldspar.

Qin et al. used single hot wire method (SHTT) to observe the crystallinity of blast furnace slag on-line[25], and determined that the critical cooling rate of blast furnace slag sample used in the experiment was $10°C·s^{-1}$. The crystalline phases were feldspar and wollastonite, and their crystallization activation energies were $238.07±28.81$ and $523.52±58.56$ $kJ·mol^{-1}$, respectively.

Hadi Purwanto established the mathematical model of centrifugal granulation and solved it[26]. The model was used to predict droplet size, particle cooling rate and temperature distribution. At the same time, the model estimated the cooling rate of amorphous transformation of blast furnace slag particles.

4. RESEARCH PROSPECTS

4.1 Limitations of Existing Research

Blast furnace slag particles produced by centrifugal granulation are typical semi-melt and wide-screening particles. The heat transfer process is unsteady in the bed height distribution. At the same time, the unsteady heat conduction within the particles is involved in a single particle. The different heat transfer intensity outside the particles will also affect the internal melting, solidification and latent heat release of semi-melt slag. However, in the current research on heat transfer of blast furnace slag particles, cooling slag particles reheating is mostly used as heat source for gas-solid heat transfer, which can only highlight the wide screening characteristics to a certain extent, but cannot reflect the actual characteristics of semi-melt blast furnace slag particles. At the same time, the only research on granulated blast furnace slag mainly focuses on the influence of air volume, initial slag temperature on air outlet temperature and waste heat recovery efficiency, and little research on gas-solid heat transfer mechanism and quantitative dimensionless analysis is found.

The goal of comprehensive utilization of blast furnace slag is not only to recover the waste heat of blast furnace slag efficiently, but to ensure the cooled blast furnace slag as a resource to the maximum extent. Blast furnaces with vitreous content higher than 85% can be used as cement mixtures with high added value. The amorphous transformation of blast furnace slag is completed at about 800°C. It is necessary to cool the slag particles above 800°C rapidly to ensure the high glass transformation. However, existing research on heat transfer of blast furnace slag has not yet aimed at optimizing the glass conversion rate of particles.

4.2 Prospects for Future Research Contents

In order to achieve high efficient waste heat recovery and resource utilization of centrifugal granulated blast furnace slag particles, the heat transfer mechanism of semi-melt and wide-screening particles should be studied first.

On the research level of heat transfer mechanism, we should clarify the quality control mechanism of high temperature slag particles based on the characteristics of the particles. Then, the processes of gas-solid two-phase flow, slag particle flow around heating surface and unsteady composite heat transfer should be studied, so as to understand the unsteady heat conduction, surface convection and radiation coupled heat transfer process of the particles in moving bed, and to know the gas-phase flow field, slag particle flow field and gas-solid temperature field distribution characteristics.

Based on it, we can obtain the effects of air velocity, initial temperature and particle size, flow velocity of slag particles on gas-solid heat transfer, cooling rate of slag particles and temperature distribution in the bed. We can capture the gas-solid heat transfer correlation based on experimental data. Meanwhile, the effects of key parameters such as particle size and distribution, movement speed, initial temperature, structure parameters and layout of heating surface on heat transfer coefficient between slag particles and heating surface, cooling rate of slag particles and temperature distribution of slag particles can be obtained.

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