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Numerical Investigation on Phase Transformation Thermal Characteristics of High Temperature Slag Particle

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ABSTRACT

After the molten slag was granulated by centrifugal granulation, it would fly in the granulation bin for a period of time. The slag particles exchanged heat with the cold air and water wall by convection and radiation was a typical multi-component unsteady phase-change thermal process. The study of heat characteristics of the air-cooled phase transition of slag particles has important guiding significance for the enhancement of the cooling rate and design of the granulation chamber. In the paper, the solidification-melting model coupled with the radiation heat transfer model method was used to investigate the effects of the temperature of air and water wall, the velocity of air, and diameter of slag particles on the cooling characteristics. The variable thermal conductivity, variable viscosity, variable density at different temperature range and the physical properties of the phase transition temperature zone were fully considered in the model. The results indicated that the solidification time of the particles decreased with the decrease of the temperature and of cooling air, the increase of the velocity of air, the reduction of the temperature of the water wall and the reduction of the diameter of slag particles. Moreover, the diameter of slag particles has the most significant influence, and the temperature of the water wall had the least impact. By adjusting the above influencing factors, the cooling rate of the slag particles can be accelerated to prevent them from sticking to the water wall.

Keywords: Molten Slag, Numerical investigation, Phase Transformation.

NONMENCLATURE

Symbols	
λ	Thermal Conductivity
T	Temperature
ρ	Density
R	radius

1. INTRODUCTION

The existing dry centrifugal granulation technology used a high-speed rotating granulator to granulate the molten slag under the action of centrifugal force and surface tension, and the granulated slags were further cooled in the granulation chamber. The cooling process of high-temperature particles was a complex heat exchange process involving multiple components and changing physical properties. Examination of the air-cooled phase transformation heat characteristics of slag particles had crucial guiding significance for the design of granulation bins and enhanced slag particle cooling rate. Bin Ding et al. [1]used the directional solidification technology to experimentally investigate the change of the internal temperature of the molten slag, and calculated the average heat transfer coefficient and cooling rate of the molten slag, and performed XRD analysis on the molten slag to study the effect of cooling rate on vitreous content. Purwanto et al. [2]established

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a thermal conductivity model for single-particle slag. They mainly studied the unsteady heat transfer characteristic of 0.7mm and 2.5mm slag particles. Simultaneously they found that the maximum temperature difference between the surface and the center of the diameter for 2.5mm slag was 122K, and the cooling rate from the center to the surface of the slag decreased. Sun et al. [3]used SHTT and CFD methods to study the cooling process of high-temperature slag. They designed a series of sample of slags with a CaO/SiO_2 ratio of 1:1 and different Al_2O_3 content. The results pointed out that the change of Al_2O_3 content greatly changed the slag performance and had a great influence on the heat recovery of slag. Bin Ding et al.[4][5] developed a self-made program in the FORTRAN environment based on the enthalpy solidification/solidification melting model to simulate the solidification behavior of molten slag under different cooling conditions. And the model took into account the effect of the slag crystal phase content on the enthalpy temperature curve, the density of the solid phase zone, the paste zone and the liquid phase zone were different, and the slag physical properties vary with temperature. Liu[6] and Qiu et al[7]. also used fluent software to simulate the cooling process of single slag particle. The effects of temperature and velocity of cooling air, the diameter of slag particle on cooling characteristics was investigated. However, throughout previous research, they either did not thoroughly consider the complex physical properties of the molten slag for complex variable density, variable thermal conductivity, and variable viscosity, or did not thoroughly analyzed the heat exchange mechanism and the mutual influence of heat transfer between particles. So the variable thermal conductivity, variable viscosity, variable density, and the physical characteristics of the phase transition temperature zone were considered in the paper. Furthermore, the effect of radiation heat transfer between the slag particles and the water wall was considered. The numerical simulation method was used to study the effect of temperature of air and water wall, velocity of air and diameter of slag particles on the cooling characteristics of particles.

2. ESTABLISHMENT

2.1 Physical model

The physical model of the thermal numerical simulation study of high-temperature slag particle-phase transformation is shown in Fig 1. The calculation domain is divided into two parts: C1 (fluid medium is air) and C2 (fluid medium is slag). The radius of slag particles is R, the length of AB and AC are 2R and 5R, respectively. The boundary conditions and types were shown in table 1.

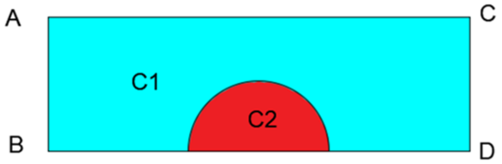

Fig 1 Physical model of high-temperature slag particle

Table 1 boundary conditions and types

Geometric boundary	Boundary type
AB	Velocity inlet
CD	Pressure outlet
AC	Axisymmetric
BD	Velocity
Slag grain boundary	Coupling wall

At the same time, the change of physical properties such as the change of the conductivity of slag, the change of phase change temperature, the evolution of density and the viscosity with temperature are considered. The physical properties of slag were shown in the table 2 below.

Table 2 physical properties of slag

Physical parameters	Symbol	Value
Density of liquid phase	ρ_l (kg·m^{-3})	2750
Density of solid phase	ρ_s (kg·m^{-3})	2840
Latent heat	L (kJ·kg^{-1})	209
Liquidus temperature	T_l (K)	1623.15
Solidus temperature	T_s (K)	1483.15
Thermal Conductivity	λ	Equation(1)
Viscosity	μ(pa·s)	Equation(2)
Emissivity	ε	0.8

$$\lambda=\begin{cases}0.71+7.347\times10^{-4}T+7.668\times10^{-7}T^2-6.572\times10^{-10}T^3 & (T<1373K)\\ -99.552+0.197T-1.257\times10^{-4}T^2+2.625\times10^{-8}T^3 & (T\geq1373K)\end{cases} \quad (1)$$

$$\mu=\begin{cases}232.824-0.14543T & (T<1592.15K)\\ 120.5501-0.13824T+3.97397\times10^{-5}T^2 & (T\geq1592.15K)\end{cases} \quad (2)$$

Density of solid-liquid coexisting zone was calculated by Equation (3).

$$\rho=\begin{cases}2840 & (T<1013)\\ 2984.859-0.143T & (1013<K<1623.15K)\\ 2750 & (T\geq1623.15K)\end{cases} \quad (3)$$

2.2 Model validation

In order to verify the grid independence of the model, grid sizes of 0.01mm, 0.02mm and 0.05mm were selected to verify the model. Took the coordinate (0, 0.8) as the temperature monitoring point, and observed the temperature change of this point under different grid sizes. Fig 2 shows that the temperature changes of the monitoring point with time under different grid sizes. It would be seen from the figure that under different grid sizes, the temperature of the monitoring point is relatively close in the high temperature section, and there was a difference in the low temperature section. The temperature of the monitoring point calculated by the 0.02mm grid and the 0.01mm grid tends to be the same, so select 0.02mm is used as the final grid size.

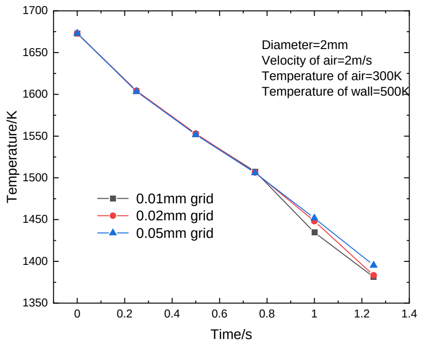

Fig 2 Grid independence verification

3. RESULTS AND DISCUSSION

3.1 Effects of cooling air temperature on solidification time

Engineering practice has proved that when the area's temperature from the outer surface of the slag particles to the 0.8R position is lower than the solid phase temperature, the slag particles can form a hard shell. Even if the slag particles hit the wall, the particles would not stick to the wall. Therefore, the article focused on the area's cooling condition from the outer surface to the 0.8R position. And it is believed that when the slag particles were solidified at the 0.8R position, the particles were considered to be completely solidified.

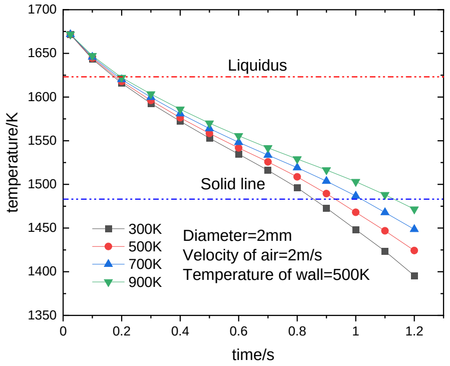

Fig 3 Effects of cooling air temperature

It can be seen from the Fig 4 that as the temperature of cooling air increased, the solidification time of the particles also increased. Under the temperature of cooling air was 300K, the particles' solidification time was 0.86s, and when the temperature increased to 500K, 700K and 900K, the solidification time of the particles were 0.93s 1.02s and 1.14s, respectively. The increase in cooling time were 8.1%, 18.6% and 32.6% respectively. Because when the temperature of air rise, the convective heat exchange between the particles and the cooling air weakened, resulting in that the heat inside the slag particles cannot be taken away in time, the cooling time was lengthened. Therefore, reducing the temperature of the incoming air could speed up the cooling of the particles to a certain extent, but the temperature of the incoming air depended on the temperature of the air discharged from the moving bed. Under the condition of a specific temperature of the incoming cooling air, it can be directly introduced into the granulation to accelerate the particles' cooling.

3.2 Effects of velocity of air temperature on solidification time

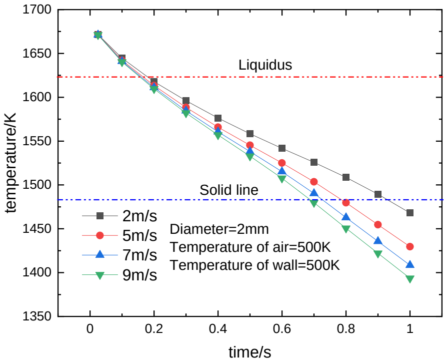

Fig 4 Effects of velocity of air temperature

It can be seen from Fig 4 that as the velocity of air increased, the convective heat exchange effect between the slag particles and the cooling air was enhanced. In addition, the starting solidification time and the complete solidification time of the particles were advanced. When the velocity was 2m/s, the particles began to solidify at 0.18s, and solidify completely at 0.93s. When it increased to 5m/s, the complete solidification time of the particles was 0.78s, which was 16% shorter. When the velocity increased to 7m/s and 9m/s, the entire solidification time of the particles were 0.72s and 0.68s, respectively. Compared with the working condition of 2m/s, the solidification time were shortened by 22.5% and 26.9% respectively. It indicated from the above analysis that increasing the velocity of cooling air would speed up the solidification of the particles, thereby avoiding the phenomenon of particle sticking to the water wall.

3.3 Effects of temperature of water wall on solidification time

Fig 5 depicted the temperature changes of the monitoring points at different temperatures of water wall. It could be recognized that as the wall temperature increased, the particles' solidification time became longer. When the temperature was 300K, the solidification time was 0.924s. However, the solidification time of 500K, 700K, 900K were 0.930, 0.947 and 0.986s respectively. The maximum time difference of solidification time was only 0.062s. In addition, the maximum temperature difference of the particles at the same time was only 13°C. It indicated that the temperature of water wall had little effect on solidification. Because at a 0.8R position, the particles' heat was mainly dissipated through heat conduction, so the wall temperature has little effect on the temperature change.

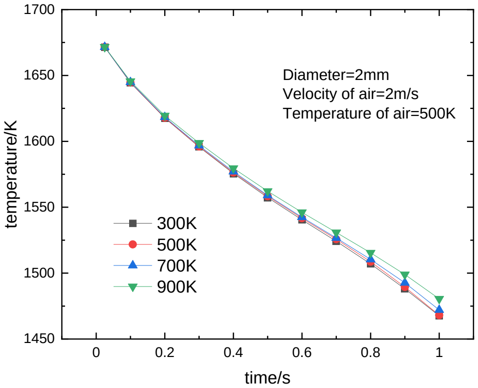

Fig 5 Effects of temperature of wall

3.4 *Effects of diameter of granulated slags on solidification time*

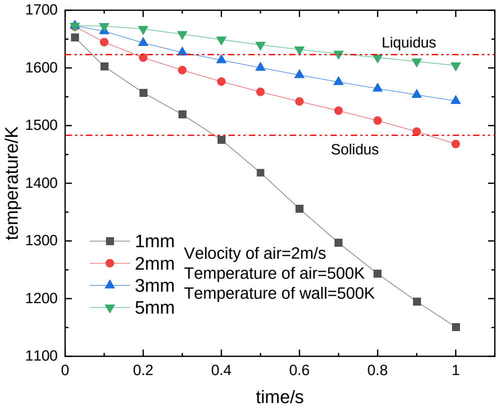

Fig 6 Effects of diameter of granulated slags

The results in Fig 6 shows that the diameter of granulated slags had a significant effect on the solidification time. When the diameter of granulated slags was 1mm, the solidification time was only 0.38s. When it increased to 2mm, the particle surface's solidification time was 0.92s, and it was almost 2.4 times that of 1mm particles. When the particle diameter increased to 5mm, the solidification time has reached 1.825s. At this time, if the particle hit the wall of the granulation chamber, there would be a danger of sticking the wall, which was not conducive to granulation, so the particle diameter should not be too large.

3.5 *Conclusion*

In the paper, a solidification melting model coupled with a radiation heat transfer model was used to establish a cooling model for high-temperature slag particles, and the influence of factors such as the temperature of cooling air and water wall, velocity of air, and diameter of slag particles on the cooling characteristics was investigated. The results revealed that the solidification time decreased with the decrease of the temperature of cooling air and water wall, the increase of the velocity of air and the decrease of the diameter of slag particle. Among them, the diameter of slag particle has the greatest influence and the temperature of water wall has the least impact.

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