Experiment and numerical simulation of sinter cooling in annular cooler

Shujie Ma*, Jingfu Wang
School of Environment and Energy Engineering, Beijing University of Technology, Beijing 100020, China

*Corresponding author e-mail: 18811071094@163.com

Abstract. Based on the empirical constant value of the thermal physical parameters of sinter, this paper combines experimental measurement and finite element simulation to study the equivalent thermal conductivity of sinter and establish a heat transfer model suitable for the cooling process of sinter. The influence of the empirical value and the change value on the cooling process is analyzed by analyzing the thermal property parameters of the sinter. The effects of sinter size and inlet air temperature on the cooling process are investigated by using varying thermal physical parameters. The results show that the smaller the particle size is, the higher the inlet air temperature is, and the higher the waste heat utilization rate of the outlet heat exhaust gas is.

1. Introduction

China is a large steel country, and a large amount of waste heat resources will be generated in the steel production process. The residual heat generated by the sintering process is second only to the ironmaking process, accounting for 21.91% of the total waste heat [1]. The whole sintering process is divided into two processes: sintering machine sintering and cooling machine cooling. The residual heat taken away by the sintering part of the flue gas accounts for 13%~23% of the energy consumption of the sintering process, and the residual heat taken away by the cooling machine flue gas accounts for about 20%~25% of the energy consumption of the sintering process [2]. It can be seen that there is a large amount of waste heat resource in the cooling process of the cooling machine, and recycling it is important.

As an irregular porous medium, the thermal conductivity of sinter is difficult to be measured. In previous studies, empirical values were mostly used. Caputo et al. [3-5] proposed a one-dimensional steady-state mathematical model, which made assumptions on physical parameters and calculated the convective heat transfer coefficient using a general relational formula. Leong et al. [6] used a porous medium model to numerically simulate the flow and heat transfer models inside the annular cooler, but assumed that the physical parameters of the sintered were the same as that of iron, which would cause large deviations.

In the previous studies, the physical parameters were mostly taken as constant values. Based on the related research, this paper puts forward a method combining experimental measurement and finite element simulation to study the equivalent thermal conductivity of sinter and measure its experimental value changing with temperature, and establish relevant mathematical model. The factors of the cooling process are analyzed to improve the utilization rate of the waste heat of the hot exhaust gas at the outlet of the annular cooler.
2. Experimental scheme
The equivalent thermal conductivity of sinter is the key physical parameter affecting the cooling process. In this paper, the thermal conductivity of sinter is studied by using Hot Disk thermal constant analyzer and finite element numerical simulation.

2.1. Finite element simulation of equivalent thermal conductivity
APDL language is used to program finite element numerical simulation in ANSYS. Macroscopically, sinter belongs to uniform porous medium, and its pore structure is randomly distributed according to volume void. The relationship between equivalent thermal conductivity of porous material and porosity is analyzed [7]. According to the average particle size of the sinter, the size of the finite element model is set as 10mm×10mm×5mm, and the mesh side length of the element is divided into 0.5mm. The thermal conductivity of solid and air are respectively assigned. The solid thermal conductivity is 1-60W/(m·K). Air thermal conductivity in room temperature 20°C to 800°C average 0.04W/(m·K) for calculation of the heat transfer process. The upper boundary temperature is 20°C, and the lower boundary temperature is 20.01°C, x, y direction are adiabatic wall boundary conditions.

1) Finite element simulation of heat transfer process
This model does not consider the heat transfer process in the x and y directions, but only considers the heat conduction in the z direction. Its partial differential governing equation is:

$$\lambda_z \frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

The upper and lower surfaces of the model use the first type of boundary conditions, namely:

$$T = T(t) \tag{2}$$

The initial temperature of the sinter is about 800°C, the solid skeleton coefficient of thermal conductivity $\lambda_s$ and porosity $\Phi$ values are respectively: (1) $\lambda_s$ is 5W/(m·K), $\Phi$ is 5%; (2) $\lambda_s$ is 40W/(m·K), $\Phi$ is 16%; (3) $\lambda_s$ 20W/(m·K), $\Phi$ is 40%. The distribution of heat flux in finite element analysis is shown in figure 1.
\[ \lambda_e = \frac{\sum_{i=1}^{N} q_i L}{N \Delta t} \]  

According to the above formula, the section heat flux obtained by finite element simulation is calculated, and the relationship between the model's equivalent thermal conductivity and the porosity and thermal conductivity of the solid skeleton can be obtained.

2.2. Experimental measurement of equivalent thermal conductivity

First, the solid sinter is ground into a powder, and then the powder is weighed into a cylindrical sample, and the thermal conductivity of the sample is measured by a Hot Disk thermal constant analyzer. Figure 2 shows the overall structure of the thermal conductivity meter.
3. Model establishment

3.1. Physical model
The annular cooler is connected by a number of fixed beds, and the number of pores between the sintered block and the sintered block in the annular cooler is huge, so it needs to be averaged. The flow of gas through the sinter is a standard fluid through the solid filling layer in the annular cooler, which is a typical fluid-solid coupling flow in porous media. The following assumptions need to be made during modeling:

1) The cold air uniformly enters the bottom of the sinter through the air duct.
2) The sinter in each trolley passes through each air duct in turn, and the sinter cooling process in each trolley is the same;
3) The axial heat conduction in the energy equation is neglected.

The thickness of the material layer is 1.5m, the trolley height is 1.6m, width is 3.5m and the bottom air duct height is 1.5m. According to the parameters of the annular cooler and the above assumptions, a two-dimensional physical model of the annular cooler is established.

![Figure 2. Structure of Hot Disk Thermal constant analyser](image)

3.2. Mathematical model
The numerical simulation in this paper is based on the fluent platform and uses user-defined scalar (UDS) and user-defined functions (UDF) for secondary development. Because of the large temperature difference between the gas and solid in the trolley, the local non-thermodynamic equilibrium double energy equation is adopted to solve the problem.

The energy equation can be expressed as [8]:

Gas energy equation:

\[
\begin{align*}
\epsilon \frac{\partial (\rho_v C_g T_g)}{\partial t} + \frac{\partial (\rho_v v_g C_g T_g)}{\partial y} &= hA(T_s - T_g) \\
\end{align*}
\]

(4)

Solid energy equation:

\[
(1 - \epsilon) \frac{\partial (\rho_s C_s T_s)}{\partial t} = (1 - \epsilon)\nabla(\lambda_s \nabla T_s) + hA(T_g - T_s)
\]

(5)

Where, A is calculated by formula (6) [9]:

\[
A = \frac{6(1 - \epsilon)}{D_p}
\]

(6)
The gas-solid heat transfer coefficient $h$ of the annular cooler can be calculated by the following empirical formula [10]:

$$Nu = \frac{1}{\varepsilon} \left( 2 + 0.75 \Pr^{0.33} \Re^{0.5} \right)$$

(7)

$$h = \frac{\lambda\varepsilon}{\varepsilon D_p} \left( 2 + 0.75 \Pr^{0.33} \Re^{0.5} \right)$$

(8)

For momentum equations in porous media models, additional volume source terms are required.

$$S_i = \sum_{j=1}^{3} D_{ij} \mu v_j + \frac{1}{2} \sum_{j=1}^{3} C_{ij} \rho |v_j| v_j$$

(9)

Using the Ergun equation, the viscous resistance coefficient and internal loss coefficient can be defined as:

$$\frac{1}{\alpha} = \frac{150 (1 - \varepsilon)^2}{D_p^2 \varepsilon^3}$$

(10)

$$C_2 = \frac{3.5}{\varepsilon^3} \left( \frac{1 - \varepsilon}{D_p} \right)$$

(11)

4. Results and discussion

4.1. Equivalent thermal conductivity

The relation between equivalent thermal conductivity of sinter and porosity and thermal conductivity of solid skeleton is obtained by finite element simulation, in which the porosity is the measured value at normal temperature. The fitting relation is

$$\lambda_e = \lambda_s (-1.2292\Phi + 0.9993)$$

(12)

The equivalent thermal conductivity of the sinter measured in the experiment is

$$\lambda_e = 2.97103 - 0.01563T + 4.96957 \times 10^{-5} T^2 - 3.52134 \times 10^{-8} T^3$$

(13)

Equation (13) and the porosity value at normal temperature are substituted into equation (12) to obtain the relation between the change of solid thermal conductivity with temperature, and then the equation and the porosity value changing with temperature are substituted into equation (12) to obtain the relation between the change of equivalent thermal conductivity with temperature:

$$\lambda_e = 2.3991 - 0.0126T + 4.0128 \times 10^{-5} T^2 - 2.8434 \times 10^{-8} T^3$$

(14)
4.2. Model verification
The equivalent thermal conductivity of sinter was put into the model with constant value and the experimental relation with temperature change, and the curve of the temperature of hot exhaust gas at the monitored outlet changing with cooling time was shown in figure 3. It can be seen from the figure that, at the beginning, when the equivalent thermal conductivity coefficient is used as a variable, the outlet temperature of hot waste gas is higher than that when it is used as a constant value. As the process progresses, the distance between the two curves gradually decreases. The value of the variable is closer to the actual working condition.

![Figure 3. Hot exhaust gas temperature with variational and fixed thermal physical property of sinter](image)

4.3. Numerical simulation analysis

4.3.1. Influence of sinter particle size on cooling process. The average particle size of the sinter is 60mm, and the particle size of the sinter is set as 50mm, 60mm, 70mm and 80mm in numerical simulation. The change curves of outlet hot waste gas temperature and sinter surface temperature with time under different particle sizes are monitored, and the results are shown in figure 4 and 5.

It can be seen from the figure, as the average particle size of the sinter increases, the temperature of hot exhaust gas decreases, the surface temperature of sinter increases and the cooling time increases. This is because the sinter particle size increases, and the heat inside the sinter is not easy to transfer to the particle surface, leading to weakened convection and heat transfer between the sinter and cold air. Therefore, particle size of sinter can be appropriately reduced while cooling effect is ensured.
Figure 4. Effect of sinter size on hot exhaust gas temperature

Figure 5. Effect of sinter size on sinter surface temperature

4.3.2. Influence of inlet air temperature on cooling process. The average inlet air temperature of the sinter is 553K, and the inlet air temperature is set as 523K, 553K, 583K and 613K in the numerical simulation. The change curves of outlet hot exhaust gas temperature and sinter surface temperature with time under different inlet air temperature are monitored, and the results are shown in figure 6 and 7.

Figure 6. Effect of inlet air temperature on hot exhaust gas temperature

Figure 7. Effect of inlet air temperature on sinter surface temperature

As can be seen from the figure, as the inlet air temperature increases, the outlet hot exhaust gas temperature increases, the surface temperature of sinter increases, and the cooling time increases. This is because the inlet air temperature increases, the temperature difference between the gas and the solid decreases, and the convection heat transfer decreases. Therefore, while ensuring the cooling effect, the inlet air temperature can be appropriately increased.

5. Conclusion

1) Along with the change of temperature, the change of equivalent thermal conductivity follows a nonlinear function;
2) The empirical value and variation value of thermal property parameters were used to monitor the temperature of hot exhaust gas at the outlet, and it was found that the variation value of thermal property parameters was closer to the actual operating condition;

3) The smaller the particle size of sinter is, the higher the inlet air temperature is, and the higher the outlet hot waste gas temperature is, and the higher the waste heat utilization rate of hot waste gas is.

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