Numerical investigation of gas-solid heat transfer process in vertical tank for sinter waste heat recovery

Junsheng Feng, Hui Dong*, Jianye Gao, Hanzhu Li, Jingyu Liu

SEP Key Laboratory of Eco-Industry, School of Metallurgy, Northeastern University, Shenyang,

Liaoning 110819, PR China

*E-mail: dongh@smm.neu.edu.cn, Tel: +86 24 83678808, Fax: +86 24 83678808

Abstract: In the present paper, a three-dimensional mathematical model is established on the basis of the porous media theory and the local thermal non-equilibrium model, to investigate the gas solid heat transfer in sinter bed layer of vertical tank. The reliability of mathematical model is verified through the comparison of calculated results with the experimental results according to the homemade experimental setup. Numerical simulations are conducted to examine the influences of different structural and operating parameters on the air and sinter temperatures in sinter bed layer. Furthermore, an optimal combination of each parameter is determined through the orthogonal experiment for improving the outlet exergy of cooling air. The results show that the outlet air and sinter temperatures decrease with the air flow rate increasing. Decreasing the inner diameter and height of cooling section, or increasing the particle diameter, the outlet air temperature decreases and the outlet sinter temperature increases. Based on the sinter annual output of 3900000 tons for 360m² sintering machine, the suitable structural and operating parameters of vertical tank are 150 kg/s for the air flow rate, 0.015 m for the sinter particle diameter, 10 m for the inner diameter of cooling section and 8 m for the height of cooling section.

Keywords: sinter; porous media; gas solid heat transfer; local thermal non-equilibrium; numerical optimization

1. Introduction

The efficient recovery and utilization of sinter waste heat resource is one of the main ways to reduce energy consumption of sintering process in the iron and steel industry [1,2]. In consideration of the inevitable drawbacks of existing sinter cooling machine [3], the vertical tank for sinter waste heat recovery has been proposed as an efficient way for sinter waste heat recovery by imitating the structure and process of coke dry quenching furnace [4-6]. As one of the main factors to determine the feasibility of waste heat recovery technology of sinter vertical tank, the gas solid heat transfer process in vertical tank directly influences the outlet sinter temperature and the quality of outlet heat carrier, and then influences the recovery rate of sinter waste heat and the subsequent waste heat generation. Therefore, the study of gas solid heat transfer process in the vertical tank is of great importance for improving the quality of sinter waste heat recovery and optimizing the structural and operating parameters of vertical tank.

The study and analysis of gas solid heat transfer process in vertical tank are still in the theoretical and experimental research stage. The determination of structural and operating parameters of vertical tank are lacking of systemic study and analysis, without corresponding theoretical guidance. At present, the researches on gas solid heat transfer process in sinter bed layer mainly focused on the sinter annular cooler. Caputo et al. [7] developed a one-dimensional unsteady mathematical model to investigate the gas solid heat transfer in the moving beds, and presented the bed behaviors of different operating parameters and design choices. Wen et al. [8] established a 1-D steady-state mathematical model to investigate the effect of operation parameters on the cooling process of the annular cooler, and put forward the proposals for optimizing operations of the annular cooler. Jang and Chiu [9] developed a 3-D model to

determine the influence of porosity and particle diameter on the fluid flow and heat transfer in a sintered bed, and the sintered bed was simplified as an ideal 4-row packed bed of spheres during the cooling process. Leong et al. [10] and Liu et al. [11] numerically investigated the sinter cooling process and obtained the gas flow field and sinter temperature field for different distributions of sinter porosity. However, the temperatures of sinter and gas were set as the local thermal equilibrium status in the model, and the convection heat transfer between the sinter and the gas was ignored, which disagreed with the actual condition. Liu et al. [12] established the cost model to evaluate effects of operational parameters on the equivalent annual operational cost, and calculated the cost benefits ratio to assess the comprehensive performance of the sinter cooling bed.

The waste heat recovery in sinter cooling process has also been studied and some useful results have been obtained. Caputo and Pelagagge [13,14] developed a dynamic simulation approach and optimized solutions of segmental waste heat recovery at different inlet air velocity and temperature, as well as different initial sinter thermal flow. In a subsequent study, the fuzzy control system of the waste heat recovery was also designed and optimized. Zhang et al. [15] and Tian et al. [16] numerically investigated the influence of multi-layer feeding and designed parameters on sinter waste heat recovery by optimizing parameters with the mixed orthogonal experimental method. Ahamed et al. [17] focused on improving the energy, exergy and recovery efficiencies of a grate cooling system through the optimization of its operational parameters such as masses of cooling air and clinker, cooling air temperature, and grate speed. Liu et al. [18] established a two-dimensional unsteady mathematical model to describe three dimensional steady transport process and waste heat utilization in the sinter cooling bed, and numerically investigated

the effects of different operating parameters on the cooling air temperature and waste heat utilization quantity. Then, Liu et al. [19] further investigated the sinter cooling process, and performed bi-objective optimization of the sinter cooling bed to achieve the optimal operational conditions from both waste heat utilization and economic cost aspects. Feng et al. [20] developed a one-dimensional unsteady mathematical model to perform the sinter cooling process on the basis of the constructal theory, and obtained the optimal cross-sectional shape of the sinter layer according to the maximum exergy output of waste heat recovery.

The studies mentioned above mainly focused on the analysis of the gas solid heat transfer process and waste heat recovery in sinter annular cooler, and there are little studies on the gas solid heat transfer process in sinter bed layer of vertical tank. In essence, the gas solid heat transfer process in vertical tank is the steady-state heat transfer process of gas-solid countercurrent moving bed, which is different from the unsteady-state heat transfer process of gas solid cross flow fixed bed in the sinter annular cooler. Although Dong et al. [21] and Huang et al. [22] studied the gas solid heat transfer process in the vertical tank through numerical simulation and analytical calculation, but the influence of sinter particle diameter on the gas solid heat transfer process in sinter bed layer was not considered. Meanwhile, the structural parameters of vertical tank in some studies [21, 22] were obtained by reference to that of coke dry quenching furnace. In addition, the air flow viscosity resistance coefficient, inertia resistance coefficient and the gas solid heat transfer coefficient of the calculation model in the literatures mentioned above were calculated on the basis of the traditional empirical correlations, which were not suitable for solving the gas flow and gas solid heat transfer process in the vertical tank.

To sum up, few researches have been conducted on the numerical optimization of structural

and operating parameters of vertical tank. Therefore, according to the previous theoretical and experimental research results of gas flow and gas solid heat transfer in sinter bed layer [23-26], a three-dimensional steady state heat transfer model was established on the basis of the porous medium theory and the two-equation energy model of local non-equilibrium thermodynamics. The effects of structural and operating parameters of vertical tank on the gas solid heat transfer process in sinter bed layer were studied numerically. A suitable combination of structural and operating parameters was determined through the orthogonal experimental method for improving the outlet exergy of cooling air. These results are of great importance and helpful for the design and operations of vertical tank.

2. Determination of calculation model

2.1. Physical model

The vertical tank for sinter waste heat recovery examined in this work is schematically shown in Fig. 1(a). The sinter particles of high temperature are fed into the pre-store section from the top of vertical tank after sintering and crushing. The cooling air is introduced into the vertical tank by the air blower, and then flows through the sinter bed layer in the cooling section. Finally, the cooled sinter particles are discharged at the bottom of vertical tank, and the high temperature air is discharged at the outlet of ramps section. Because of that the gas solid heat transfer in the sinter bed layer mainly focuses on the cooling section, and the functions of ramps section and pre-store section are to ensure the heat recovery of high temperature air and the continuity of sinter production, respectively. Therefore, the cooling section is selected as the computational domain in this work, and the mesh generation of cooling section is shown in Fig. 1(b), as well as the boundary conditions of corresponding computational domain.

Due to the larger difference of geometric size between the cooling section and the central air inlet, considering the effects of the orthogonality and the smoothness of the boundary grids on the simulated calculation precision and convergence, the sub block grid generation technique is applied to improve the quality of grid generation. The refined grid is used for the strong heat transfer domain, and the sparse grid is used for the other computational domain.

The inhomogeneity and irregularity of sinter particles result in the complexity of the gas flow and gas solid heat transfer process in the vertical tank. It is difficult to develop the accurate mathematical description and numerical calculation for the whole heat transfer process. Because of that the sinter particle diameter in bed layer is much smaller than the structural size of cooling section, the sinter bed layer in the cooling section is assumed to be the porous zone based on the average and statistical processing [9,27]. To do this, the following assumptions are made to simplify the physical model [15,18].

(1) The vertical tank is running under the condition of stable operation, which means that the operating parameters are constant, and there is no fluctuation.

(2) The sinter particles in bed layer are the homogeneous porous medium. The porosity of sinter particle is not considered, and an average voidage of sinter bed layer is adopted.

(3) The cooling air in sinter bed layer is incompressible, and the property variations of cooling air in bed layer with the air temperature are taken into consideration.

(4) The radiation between/in the sinter particles and cooling air is ignored, as well as the wall heat loss of cooling section.

Based on the above assumptions, a three-dimensional steady computational model can be established. With the aid of computational fluid dynamics, the computational model can be used to

describe the gas solid steady-state heat transfer process in the vertical tank.

2.2. Mathematical model and computational methods

The Brinkman–Forchheimer extended Darcy model developed by Ergun [28] is employed to describe the gas flow in sinter bed layer. Meanwhile, the standard k – ε turbulence model is adopted for turbulent flow when the Reynolds number is greater than 300 [29]. In addition, considering the difference between the sinter temperature and the air temperature in sinter bed layer, the local thermal non-equilibrium model is used to describe the gas solid heat transfer in sinter bed layer [30]. The three dimensional equations for mass, momentum, turbulent kinetic energy k , dissipation rate ε and energy are as follows.

Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho_g u_j) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho_g u_i u_j) = -\frac{\partial}{\partial x_i}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + S_i \quad (2)$$

k equation:

$$\rho_g u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \mu_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \rho_g \varepsilon \quad (3)$$

ε equation:

$$\rho_g u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{c_1 \varepsilon}{k} \mu_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - c_2 \rho_g \frac{\varepsilon^2}{k} \quad (4)$$

where μ_t is the turbulent viscosity, $\mu_t = c_\mu \rho_g k^2 / \varepsilon$, c_μ , c_1 and c_2 are the turbulent constants, σ_k and σ_ε

are the Prandtl numbers in k and ε equations. Their specific values are listed in Table 1.

It is necessary to consider the effect of porous media on viscosity and inertial of fluid. The momentum conservation equation in the porous media model can be corrected by adding a source term. The source term S_i , which is consisted of two parts, i.e. the viscous loss term and the inertial loss term, can be described as follows for the homogeneous porous media [15].

$$S_i = -\left(\frac{\mu}{\alpha} u_i + \frac{1}{2} C_2 \rho_g |u| u_i\right) \quad (5)$$

The modified Ergun equation is used to calculate the viscous resistance coefficient ($1/\alpha$) and inertial resistance coefficient (C_2) [24].

$$\frac{1}{\alpha} = \frac{85.4(1-\varepsilon)^2}{\varepsilon^3 d_p^2} \quad (6)$$

$$C_2 = \frac{0.632(1-\varepsilon)}{\varepsilon^3 d_p} \quad (7)$$

Dual energy equations for describing the gas solid stable state heat transfer in sinter bed layer are as follows [30].

Sinter:

$$\frac{\partial}{\partial x_i}(\rho_s c_s u_s T_s) = (1-\varepsilon) \frac{\partial}{\partial x_i} \left(\lambda_s \frac{\partial T_s}{\partial x_i} \right) - h_v (T_s - T_g) \quad (8)$$

Cooling air:

$$\frac{\partial}{\partial x_i}(\rho_g c_g u_g T_g) = \varepsilon \frac{\partial}{\partial x_i} \left(\lambda_g \frac{\partial T_g}{\partial x_i} \right) + h_v (T_s - T_g) \quad (9)$$

The volume heat transfer coefficient (h_v) is calculated with the following correlation developed by Kye et al. [31].

$$h_v = \frac{6h(1-\varepsilon)}{d_p} \quad (10)$$

The h in Eq. (10) is the heat transfer coefficient of per unit area, and calculated with the

following correlation [25].

$$Nu = \frac{hd_p}{\lambda_g} = 0.2\varepsilon^{0.055} Re_p^{0.657} Pr^{1/3} \quad (11)$$

The Reynolds and Prandtl numbers in Eq. (11) are expressed as follows.

$$Re_p = \rho_g u d_p / \mu \quad (12)$$

$$Pr = \mu c_g / \lambda_g \quad (13)$$

In order to analyze the quality of sinter waste heat recovery from the cooling section, the following equations used to calculate the outlet exergy of cooling air are determined [32].

$$Q = M (c_{g,out} T_{g,out} - c_{g,in} T_{g,in}) \quad (14a)$$

$$Ex = Q \left(1 - \frac{T_0}{T_{g,out} - T_{g,in}} \ln \left(\frac{T_{g,out}}{T_{g,in}} \right) \right) \quad (14b)$$

The gas solid heat transfer process in sinter bed layer is solved numerically through CFD software Fluent. The solution equations mentioned above are discretized with the implicit scheme, and the coupling of pressure and velocity is solved through the SIMPLE algorithm. Because of that the physical parameters of sinter and air change with the temperature, with the aid of secondary development platform, the physical parameters of sinter and air are compiled into the solution equations through the user-defined functions, as well as the source terms in the momentum and energy equations.

The gas inlet is set to be the mass flow inlet boundary condition, and the mass flow rate and temperature of cooling air are given at the inlet of cooling air. In the turbulence specification methods, the turbulent intensity and hydraulic diameter are selected to describe the gas turbulent flow on the boundary region. Adiabatic boundary conditions are adopted for the walls of cooling section without consideration of heat dissipation. The gas outlet is set to be the pressure outlet

boundary condition, and the relative pressure is set to be 0 at the outlet of cooling air.

3. Grid independence analysis and model validation

3.1. Grid independence analysis

Before numerical calculation further, the grid generated in the computational domain should be checked. Therefore, a specific condition of numerical calculation is used to analyze the grid independence of computational domain. The main parameters of sinter bed layer and operating conditions used in the calculation are shown in Table 2. The geometry construction and structured grid are conducted in ICEM-CFD, and a three-dimensional structured grid with the quadrilateral elements is obtained. In the present study, the outlet temperature changes of sinter and cooling air are mainly concerned, and six grids with different number of elements are chosen to check the grid independence. The total numbers of grid elements in the computational domain vary from 259767 to 906379, and the calculation results are shown in Fig. 2. The result shows that the total grid number of 549557 is good enough for the calculation. Grids employed in the other conditions of simulation study are established similarly to the grid discussed above.

3.2. Model validation

At present, the vertical tank for sinter waste heat recovery is in the theoretical and experimental research stage, and the comprehensive and actual operation data of vertical tank are not obtained. Therefore, a homemade experimental setup shown in Fig. 3 is developed to validate the reliability and accuracy of calculation model. The inner diameter and height of cooling section in the experimental setup are 1m and 1.8m, respectively. The physical model of cooling section and the settings of boundary conditions for the corresponding computational domain are shown in Fig. 4.

The validation parameters are the outlet temperature of cooling air and sinter under different operating conditions. The settings of experimental operating parameters under different conditions are shown in Table 3. Through the experimental measurement and numerical simulation, the comparison between the measured values and the calculated values under different conditions is shown in Table 4.

As can be seen from Table 4, the deviations of inter outlet temperature between the measured value and the calculated value under different conditions are all greater than 10%. This may be explained that the sinter export of experimental setup has a distance with that of calculation model, the gas-solid heat transfer process between the sinter particles and cooling air at the bottom of experimental setup doesn't stop, so the sinter outlet temperatures of simulation under different conditions are higher than those of measurement. But the air outlet temperatures of simulation are good accordance with those of measurement, and the mean deviation between the measured values and the calculated values in Table 4 is 8.66%. Therefore, the computational model and methods established in the present work are verified to be correct and reliable.

4. Analysis of influencing parameters

The sinter annual output of 3900000 tons for 360m² sintering machine in an iron and steel company is taken as the research object. The inlet parameters of sinter vertical tank is listed in Table 5. The physical parameters of sinter particles are calculated with the methods proposed by Tian et al. [33]. As is known from the previous studies of sinter cooling process in the sinter annular cooler [15–16,18], the air flow rate and sinter particle diameter are the main operating parameters to affect the sinter cooling process. Because of that for a given air flow rate, the changes of the inner diameter and height of cooling section also have an influence on the gas solid

heat transfer process in sinter bed layer, as well as the recovery efficiency of sinter waste heat. Therefore, the effects of air flow rate, sinter particle diameter, inner diameter and height of cooling section on the gas solid heat transfer process in sinter bed layer are studied numerically by changing one parameter to different levels while keeping other four parameters fixed in this work. The values of structural and operating parameters at different levels are listed in Table 6.

As we know, for a given sinter output, the larger the air flow rate is, the larger recovery quantity of sinter waste heat is and the lower quality of outlet cooling air, and vice versa. Based on the considerations of quantity and quality of waste heat recovery, the variation range of outlet air temperature is mainly from 700 K to 800 K. According to the energy conservation equation and gas solid heat transfer equation, the range of air flow rate is set from 150 kg/s to 180 kg/s through the heat balance calculation of gas solid heat transfer.

The ranges of inner diameter and height of cooling section are also based on the considerations of quantity and quality of waste heat recovery. In addition, the structural parameters of coke dry quenching furnace are used for reference, and the gas flow resistance loss through sinter bed layer and the power consumption of air blower are considered to set the ranges of inner diameter and height of cooling section.

The range of sinter particle diameter is set by reference to Ref. [15] and Ref. [16], and used to discuss the effect of sinter particle diameter on the gas solid heat transfer in sinter bed layer. The numerical results and analysis are as follows.

4.1. Influence of air flow rate

Fig. 5 shows the influence of air flow rate on the outlet air temperature and outlet sinter temperature. As can be seen from Fig. 5, both the outlet air temperature and outlet sinter

temperature gradually decrease with the increase of air flow rate. This may be explained that for the given sinter production capacity and inlet sinter temperature, the outlet air temperature gradually decreases with the increase of air inlet flow rate according to the first law of thermodynamics. In addition, the increase of air flow rate results in the inlet air velocity, and then results in the increase of convective heat transfer coefficient between the sinter and cooling air in sinter bed layer, the sinter cooling rate in sinter bed layer also gradually increases, which results in that the outlet sinter temperature gradually decreases with the increase of air flow rate.

Based on the calculation data in Fig. 5, the variation of outlet exergy of cooling air with the air flow rate is shown in Fig. 6. As seen from Fig. 6, the outlet exergy of cooling air gradually decreases with the air flow rate increasing. This is because the energy level of outlet cooling air gradually decreases with the decrease of outlet air temperature, and the recovery quantity of sinter waste heat gradually increases with the decrease of outlet sinter temperature. Meanwhile, the downtrend of energy level of outlet cooling air is greater than the uptrend of recovery quantity of sinter waste heat. Because of that the outlet exergy of cooling air is the product of energy level of outlet cooling air and recovery quantity of sinter waste heat, so the outlet exergy of cooling air gradually decreases with the increase of air flow rate.

4.2. Influence of sinter particle diameter

Fig. 7 shows the influence of sinter particle diameter on the outlet air temperature and outlet sinter temperature. As can be seen from Fig. 7 that with the increase of sinter particle diameter, the outlet air temperature gradually decreases, and the outlet sinter temperature gradually increases. It is due to that the increase of sinter particle diameter results in the increase of particle thermal resistance, the conduction heat transfer coefficient between the sinter and cooling air gradually

decreases. Meanwhile, the increase of sinter particle diameter also results in the increase of bed layer voidage, the gas solid heat transfer area between the sinter and cooling air decreases. Therefore, the outlet air temperature gradually decreases with the increase of sinter particle diameter. In addition, because of that the sinter heat flux, air flow rate and inlet temperature of cooling air are constant, the decrease of outlet air temperature results in the increase of outlet sinter temperature based on the first law of thermodynamics.

According to the calculation data in Fig. 7, the variation of outlet exergy of cooling air with the sinter particle diameter is shown in Fig. 8. As seen from Fig. 8, the outlet exergy of cooling air gradually decreases with the sinter particle diameter increasing. This is because the energy level of outlet cooling air gradually decreases with the decrease of outlet air temperature, and the recovery quantity of sinter waste heat also gradually decreases with the increase of outlet sinter temperature. Therefore, the outlet exergy of cooling air gradually decreases with the increase of sinter particle diameter.

4.3. Influence of inner diameter of cooling section

Fig. 9 shows the influence of inner diameter of cooling section on the outlet air temperature and outlet sinter temperature. As can be seen from Fig. 9 that with the inner diameter of cooling section increasing, the outlet air temperature gradually increases, and the outlet sinter temperature gradually decreases. This may be explained that the increase of inner diameter results in the decrease of inlet gas velocity and the increase of the heat transfer area between the sinter particles and cooling air in sinter bed layer. As know from Eq. (11), the area heat transfer coefficient is proportional to the 0.657 power of gas velocity. To our knowledge, the gas velocity is inversely proportional to the square of inner diameter, and the heat transfer area is proportional to the square

of inner diameter. Therefore, the volume heat transfer coefficient in sinter bed layer, which is the product of the area heat transfer coefficient and the heat transfer area, gradually increases with the increase of inner diameter of cooling section. Because of that the sinter heat flux and air flow rate are constant, the outlet air temperature also gradually increases. Meanwhile, the outlet sinter temperature gradually decreases based on the first law of thermodynamics.

According to the calculation data in Fig. 9, the variation of outlet exergy of cooling air with the inner diameter of cooling section is shown in Fig. 10. As seen from Fig. 10, the outlet exergy of cooling air gradually increases with the inner diameter of cooling section increasing. This is because the energy level of outlet cooling air gradually increases with the increase of outlet air temperature, and the recovery quantity of sinter waste heat also gradually increases with the decrease of outlet sinter temperature. Therefore, the outlet exergy of cooling air gradually increases with the increase of inner diameter of cooling section.

4.4. Influence of height of cooling section

Fig. 11 shows the influence of height of cooling section on the outlet air temperature and outlet sinter temperature. As can be seen from Fig. 11 that with the height of cooling section increasing, the outlet air temperature gradually increases, and the outlet sinter temperature gradually decreases. This may be explained that the increase of height of cooling section results in the increase of the residence time of cooling air in sinter bed layer, the heat transfer quantity between the sinter and cooling air also gradually increases, which results in the increase of outlet air temperature. On the contrary, the outlet sinter temperature gradually decreases with the height of cooling section increasing.

According to the calculation data in Fig. 11, the variation of outlet exergy of cooling air with

the height of cooling section is shown in Fig. 12. As seen from Fig. 12, the outlet exergy of cooling air gradually increases with the height of cooling section increasing. This is because the increase of height of cooling section results in the increase of outlet air temperature and the decrease of outlet sinter temperature, and then results in the increase of both the energy level of outlet cooling air and the recovery quantity of sinter waste heat. Therefore, the outlet exergy of cooling air gradually increases with the increase of height of cooling section.

5. Orthogonal experiments of parameter optimization

In order to obtain the suitable structural and operating parameters of vertical tank, the combination conditions of the air flow rate, the sinter particle diameter, the inner diameter of cooling section and the height of cooling section are analyzed numerically through the orthogonal experiment of parameter optimization. The orthogonal experiment method is an efficient, fast and economic design method to study the calculation conditions with multiple factors and levels, which can reduce the workload greatly. According to the design standard of orthogonal experiment [34], and combined with the parameter values in different levels shown in Table 6, a mixed orthogonal experimental table of $L_{16}(4^4)$ is designed, shown in Table 7.

The optimization index is the out exergy of cooling air per unit time. The outlet air temperature and the out exergy of cooling air of the 16 experiments are also shown in Table 7. According to the orthogonal conditions and the calculation results mentioned above in Table 7, a group of optimal parameters is easily obtained on the basis of the maximum out exergy of cooling air. It can be concluded that the optimal values for each parameter are 150 kg/s for the air flow rate, 0.045 m for the sinter particle diameter, 10 m for the inner diameter of cooling section and 8 m for the height of cooling section.

However, according to the calculation results in Fig. 8, the out exergy of cooling air gradually decreases with the sinter particle diameter increasing. Therefore, another additional experimental condition is calculated numerically to determine the suitable thermal parameters of vertical tank. The values for each parameter of additional experimental condition are 150 kg/s for the air flow rate, 0.015 m for the sinter particle diameter, 10 m for the inner diameter of cooling section and 8 m for the height of cooling section. Through the numerical calculation, the out exergy value of cooling air of additional experimental condition is 35.093 MW, which is higher than that of experimental no.(4) in Table 7. Based on the analysis results mentioned above, the suitable structural and operation parameters of vertical tank are 150 kg/s for the air flow rate, 0.015 m for the sinter particle diameter, 10 m for the inner diameter of cooling section and 8 m for the height of cooling section, respectively.

6. Conclusions

In the present paper, a three-dimensional model is established to investigate the gas solid heat transfer process in sinter bed layer of vertical tank. The influences of four different structural and operating parameters, including the air flow rate, the sinter particle diameter, the inner diameter of cooling section and the height of cooling section are studied particularly. The major conclusions are as follows.

(1) The porous media model, the standard $k-\varepsilon$ turbulence model and the local thermal non-equilibrium model are used to describe the gas flow and gas solid heat transfer process in sinter bed layer. The outlet sinter and air temperatures of simulation are good accordance with those of measurement in the homemade experimental setup, and the mean deviation between the calculated values and the measured values under different conditions is 8.66%. Therefore, the

computational model and methods presented in this paper are reasonable and reliable.

(2) The influences of structural and operating parameters on the outlet air and sinter temperatures are quite significant. It is concluded that both the outlet air and sinter temperatures gradually decrease with the air flow rate increasing. Decreasing the inner diameter of cooling section and the height of cooling section, or increasing the sinter particle diameter, the outlet air temperature decrease, and the outlet sinter temperature increase. The outlet exergy of cooling air decreases with the increase of air flow rate and the sinter particle diameter, and increases with increasing the inner diameter and the height of cooling section.

(3) For improving the outlet exergy of cooling air, four different structural and operating parameters mentioned above are optimized through the orthogonal experiment, and the calculation results of different orthogonal conditions are analyzed. Based on the sinter annual output of 3900000 tons for 360m² sintering machine, a suitable parameter combination condition is determined, and the suitable structural and operation parameters of vertical tank are 150 kg/s for the air flow rate, 0.015 m for the sinter particle diameter, 10 m for the inner diameter of cooling section and 8 m for the height of cooling section, respectively.

These conclusions would be helpful for further understanding the gas flow and gas solid heat transfer in the vertical tank. And they would also be of great importance and useful for the design and operations of vertical tank.

Acknowledgements

The authors wish to thank the financial support for this work provided by the National Science Foundation of China (No. 51274065) and the Science and Technology Planning Project of Liaoning Province, China (2015020074-201).

Nomenclature

$1/a$	viscous resistance coefficient (-)
a_v	specific surface area of sinter particles ($\text{m}^2 \cdot \text{m}^{-3}$)
c	specific heat ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)
C_2	inertial resistance coefficient (-)
D	inner diameter of cooling section (m)
d_p	sinter particle diameter (m)
Ex	outlet exergy of cooling air (kW)
h	area heat transfer coefficient ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)
h_v	volume heat transfer coefficient ($\text{W} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$)
H	height of cooling section (m)
M	air flow rate ($\text{kg} \cdot \text{s}^{-1}$)
Nu	heat transfer Nusselt number (-)
Pr	Prandtl number (-)
Q	recovery quantity of sinter waste heat (kW)
Re_p	particle Reynolds number (-)
T	temperature (K)
u	superficial velocity ($\text{m} \cdot \text{s}^{-1}$)
Greek symbols	
ε	bed layer voidage (-)
λ	thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)
μ	dynamic viscosity ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$)

ρ density ($\text{kg}\cdot\text{m}^{-3}$)

Subscripts

g cooling air

in inlet

out outlet

s sinter

References

- [1] J.J. Cai, J.J. Wang, C.X. Chen, Z.W. Lu, Waste heat recovery and utilization in iron and steel industry, *Iron Steel* 42(6) (2007) 1–7 (in Chinese).
- [2] Y. Ammar, S. Joyce, R. Norman, Y.D. Wang, A.P. Roskilly, Low grade thermal energy sources and uses from the process industry in the UK, *Appl. Energ.* 89 (1) (2012) 3–20.
- [3] H. Dong, Y. Zhao, J.J. Cai, J.W. Zhou, G.Y. Ma, On the air leakage problem in sintering cooling system, *Iron Steel* 47(1) (2012) 95–99 (in Chinese).
- [4] M.R. Errera, L.F. Milanez, Thermodynamic analysis of a coke dry quenching unit, *Energ. Convers. Manage.* 41(2) (2000) 109–127.
- [5] J.J. Cai, H. Dong, Method and device of sinter waste heat recovery and utilization with vertical tank, Chinese Patent 200910187381.8, 2011–01–05 (in Chinese).
- [6] H. Dong, L. Li, W.J. Liu, B. Wang, Y.S. Suo, J.J. Cai, Process of waste heat recovery and utilization for sinter in vertical tank, *China Metallurgy* 22(1) (2012) 6–11 (in Chinese).
- [7] A.C. Caputo, G. Cardarelli, P.M. Pelagagge, Analysis of heat recovery in gas solid moving beds using a simulation approach, *Appl. Therm. Eng.* 16 (1) (1996) 89–99.
- [8] Z. Wen, H.Z. Shi, X. Zhang, G.F. Lou, X.L. Liu, R.F. Dou, F.Y. Su, Numerical simulation and parameters optimization on gas-solid heat transfer process of high temperature sinter, *Ironmak. Steelmak.* 38(7) (2011)

525–529.

[9] J.Y. Jang, Y.W. Chiu, 3-D Transient conjugated heat transfer and fluid flow analysis for the cooling process of sintered bed, *Appl. Therm. Eng.* 29 (14) (2009) 2895–2903.

[10] J.C. Leong, K.W. Jin, J.S. Shiau, T.M. Jeng, C.H. Tai, Effect of sinter layer porosity distribution on flow and temperature fields in a sinter cooler, *Int. J. Min. Met. Mater.* 16 (3) (2009) 265–272.

[11] Y. Liu, J. Wang, X. Yuan, J. Yang, Q.W. Wang, Numerical investigation of sinter cooling process in sinter cooler, 7th international symposium on multiphase flow, heat mass transfer and energy conversion, AIP Conference Proceedings 1547(1) (2013) 788–795.

[12] Y. Liu, J. Yang, Z.L. Cheng, J. Wang, Q.W. Wang, Cost benefits analysis for waste heat utilization in sinter cooling bed, *Chem. Eng. Trans.* 39 (2014) 841–846.

[13] A.C. Caputo, P.M. Pelagagge, Heat recovery from moving cooling beds: transient modeling by dynamic simulation, *Appl. Therm. Eng.* 19 (1) (1999) 21–35.

[14] A.C. Caputo, P.M. Pelagagge, Fuzzy control of heat recovery systems from solid bed cooling, *Appl. Therm. Eng.* 20 (1) (2000) 49–67.

[15] X.H. Zhang, Z. Chen, J.Y. Zhang, P.X. Ding, J.M. Zhou, Simulation and optimization of waste heat recovery in sinter cooling process, *Appl. Therm. Eng.* 54(1) (2013) 7–15.

[16] W.Y. Tian, J.Y. Zhang, C.D. Dai, X.Y. Long, Recovery of waste heat from sinter cooling process: simulation and optimization, *Ironmak. Steelmak.* 42(2) (2015) 97–104.

[17] J.U. Ahamed, N.A. Madloul, R. Saidur, M.I. Shahinuddin, A. Kamyar, H.H. Masjuki, Assessment of energy and exergy efficiencies of a grate clinker cooling system through the optimization of its operational parameters, *Energy*, 46(1) (2012) 664–674.

[18] Y. Liu, J. Yang, J. Wang, Z.L. Cheng, Q.W. Wang, Energy and exergy analysis for waste heat cascade

utilization in sinter cooling bed, *Energy*, 67(4) (2014) 370-380.

[19] Y. Liu, J. Yang, J.Y. Wang, X.G. Ding, Z.L. Cheng, Q.W. Wang, Prediction, parametric analysis and bi-objective optimization of waste heat utilization in sinter cooling bed using evolutionary algorithm, *Energy* 90(1) (2015) 24–35.

[20] H.J. Feng, L.G. Chen, X. Liu, Z.H. Xie, F.R. Sun, Constructal optimization of a sinter cooling process based on exergy output maximization, *Appl. Therm. Eng.* 96 (2016) 161-166.

[21] H. Dong, L. Li, J.J. Cai, J. Li, Numerical simulation of heat exchange in vertical tank of waste heat recovery, *Journal of Northeastern University (Natural Science)* 33(9) (2012) 1299–1302 (in Chinese).

[22] L.F. Huang, F.Y. Tian, Q. Li, L.W. Fan, Z.T. Yu, H.Y. Wu. Analysis of gas-solid heat transfer performance in vertically-arranged sinter coolers, *Journal of Zhenjiang University (Engineering Science)* 49(5) (2015) 916–923 (in Chinese).

[23] J.S. Feng, H. Dong, J.Y. Liu, K. Liang, J.Y. Gao, Experimental study of gas flow characteristics in vertical tank for sinter waste heat recovery, *Appl. Therm. Eng.* 91 (2015) 73–79.

[24] J.S. Feng, H. Dong, H.D. Dong, Modification of Ergun's correlation in vertical tank for sinter waste heat recovery, *Powder Technol.* 280 (2015) 89–93.

[25] J.S. Feng, H. Dong, J.Y. Liu, K. Liang, Gas-solid heat transfer characteristics in vertical tank for sinter waste heat recovery, *CIESC Journal* 66(11) (2015) 4418–4423 (in Chinese).

[26] J.S. Feng, Study on gas-solid heat transfer model in vertical tank for recycling sinter waste heat (Master Thesis), Northeastern University, Shenyang, China, 2014 (in Chinese).

[27] J. Hinkley, A.G. Waters, J.D. Litster, An investigation of pre-ignition air flow in ferrous sintering, *Int. J. Miner. Process.* 42(1/2) (1994) 37–52.

[28] S. Ergun, Fluid flow through packed columns. *Chem. Eng. Prog.* 48(2) (1952) 89–94.

- [29] F. Lesage, N. Midoux, M.A. Latifi, New local measurements of hydrodynamics in porous media. *Exp. Fluid* 37(2) (2004) 257–262.
- [30] Y. Mahmoudi, M. Maerefat, Analytical investigation of heat transfer enhancement in a channel partially filled with a porous material under local thermal non-equilibrium condition, *Int. J. Therm. Sci.* 50 (12) (2011) 2386–2401.
- [31] S.H. Kye, H.J. Jae, K.L. Won, Fixed-bed adsorption for bulk component system: non-equilibrium non-isothermal and non-adiabatic model, *Chem. Eng. Sci.* 50 (5) (1995) 813–825.
- [32] G. Bisio, First- and second-law analyses of energy recoveries in blast-furnace regenerators, *Energy*, 21(2) (1996) 147-155.
- [33] F.Y. Tian, L.F. Huang, L.W. Fan, Y. K. Weng, X.Y. Ying, Z.T. Yu, K.F. Cen, A comprehensive characterization on the structural and thermophysical properties of sintered ore particles toward waste heat recovery applications, *Appl. Therm. Eng.* 90 (2015) 1007–1014.
- [34] J.J. del Coz Díaz, P.J. García Nieto, A.L. Martínez-Luengas, J.L. Suárez Sierra, A study of the collapse of a WWII communications antenna using numerical simulations based on design of experiments by FEM, *Engineering Structures* 32 (7) (2010) 1792–1800.

Table 1 Coefficients of k - ε model

Coefficient	c_μ	c_1	c_2	σ_k	σ_ε
Value	0.09	1.44	1.92	1.0	1.3

Table 2 Main parameters of sinter bed layer and operating conditions

Parameter	value
Inner diameter of cooling section (m)	9
Height of cooling section (m)	7
Mass flow rate of sinter (kg/s)	152
Mass flow rate of cooling air (kg/s)	170
Inlet temperature of sinter (K)	973
Inter temperature of cooling air (K)	293
Sinter equivalent diameter (m)	0.025
Bed layer voidage	0.418
Sinter specific heat (J/(kg·K)) [33]	$337.03(T_s-273)^{0.152}$
Sinter thermal conductivity (J/(m·K))	2.87
Sinter density (kg/m ³)	3400

Table 3 Settings of different conditions for model validation

Parameters	Condition 1	Condition 2	Condition 3
Sinter equivalent diameter (m)	0.025	0.035	0.035
Sinter flow rate (kg/s)	1.4	1.4	1.2
Cooling air flow rate (kg/s)	1.25	1.5	1.25
Sinter inlet temperature of (°C)	620	650	630
Air inlet temperature (°C)	20	20	20

Table 4 Comparison between measured values and calculated values

Parameters	Sinter outlet temperature			Air outlet temperature		
	Measured value (°C)	Calculated value (°C)	Deviation (%)	Measured value (°C)	Calculated value (°C)	Deviation (%)
Condition 1	121	139	14.88	522	511	-2.11
Condition 2	106	125	17.92	475	462	-2.74
Condition 3	110	123	11.82	483	471	-2.48

Table 5 Inlet parameters of sinter vertical tank

Parameters	Sinter production capacity (t/h)	Inlet sinter temperature (K)	Inlet temperature of cooling air (K)
Value	547.2	923	293

Table 6 Parameters of different levels

Levels	Air flow rate (kg/s)	Sinter particle diameter (m)	Inner diameter (m)	Height (m)
1	150	0.015	7	5
2	160	0.025	8	6
3	170	0.035	9	7
4	180	0.045	10	8

Table 7 Orthogonal conditions and calculation results

Experimental	Parameters				Results	
no.	M (kg/s)	d_p (m)	D (m)	H (m)	$T_{g,out}$ (K)	Ex (MW)
1	150	0.015	7	5	761.9	31.007
2	150	0.025	8	6	779.7	32.931
3	150	0.035	9	7	788.3	33.874
4	150	0.045	10	8	796.6	34.792
5	160	0.015	8	7	759.1	32.738
6	160	0.025	7	8	762.8	33.177
7	160	0.035	10	5	748	31.47
8	160	0.045	9	6	755.3	32.302
9	170	0.015	9	8	742.5	32.776
10	170	0.025	10	7	739	32.358
11	170	0.035	7	6	719.7	30.087
12	170	0.045	8	5	716	29.658
13	180	0.015	10	6	714.2	31.218
14	180	0.025	9	5	700.6	29.536
15	180	0.035	8	8	718.6	32.721
16	180	0.045	7	7	708.7	30.513

Fig.1. Schematic of sinter vertical tank and computational domain

Fig.2. Variations of outlet temperature of cooling air and sinter with total grid numbers

Fig.3. Schematic of homemade heat transfer experimental setup: 1. Air blower, 2. Orifice plate flowmeter, 3. Throttle valve, 4. Rotating discharge valve, 5. Experimental vertical tank.

Fig.4. Physical model of cooling section in experimental setup

Fig.5. Influence of air flow rate on air temperature and sinter temperature

Fig.6. Variation of outlet exergy of cooling air with air flow rate

Fig.7. Influence of sinter particle diameter on air temperature and sinter temperature

Fig.8. Variation of outlet exergy of cooling air with sinter particle diameter

Fig.9. Influence of inner diameter of cooling section on air temperature and sinter temperature

Fig.10. Variation of outlet exergy of cooling air with inner diameter of cooling section

Fig.11. Influence of height of cooling section on air temperature and sinter temperature

Fig.12. Variation of outlet exergy of cooling air with height of cooling section