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Research Paper

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

HIGHLIGHTS

- The calculation model of gas solid heat transfer process in sinter bed layer is established.
- The reliability of calculation model is verified through the comparison analysis.
- The influences of structural and operating parameters on gas solid heat transfer are analyzed.
- A suitable parameter combination condition is determined through orthogonal experiment.

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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 3,900,000 tons for 360 m^2 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.

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

* Corresponding author.
E-mail address: dongh@smm.neu.edu.cn (H. Dong).

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Nomenclature

$1/a$	viscous resistance coefficient (–)
a_v	specific surface area of sinter particles ($m^2 \cdot m^{-3}$)
c	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
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 ($W \cdot m^{-2} \cdot K^{-1}$)
h_v	volume heat transfer coefficient ($W \cdot m^{-3} \cdot K^{-1}$)
H	height of cooling section (m)
M	air flow rate ($kg \cdot s^{-1}$)
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 ($m \cdot s^{-1}$)

Greek symbols

ε	bed layer voidage (–)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
μ	dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)

Subscripts

g	cooling air
in	inlet
out	outlet
s	sinter

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