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Research Paper

Constructal optimization of a sinter cooling process based on exergy output maximization

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HIGHLIGHTS

- A constructal optimization model for a sinter cooling process is established.
- Exergy output of recovery waste heat is taken as optimization objective.
- Optimal cross-sectional shape of sinter layer is obtained.
- Exergy performance is evidently improved after constructal optimization.

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ABSTRACT

Based on constructal theory, sinter cooling process optimization is performed in this paper. Exergy output of recovery waste heat is maximized, and the optimal cross-sectional shape of the sinter layer is obtained. The result shows that the exergy output of the recovery waste heat with optimal height of the sinter layer is increased by 22.80% compared with that with the height equal to a common value of 1.40 m. The exergy performance of the recovery waste heat is evidently improved after constructal optimization, and it can be further improved by adopting a lower porosity and a higher initial temperature of the sinter layer, a smaller equivalent diameter of the sinter particle as well as a larger velocity of the inlet air. Moreover, an upright trapezoidal cross-sectional area of the sinter layer leads to an improvement of the exergy performance, but the conclusion is reversed for an inverted trapezoidal one. The results obtained herein can provide some new guidelines for the optimal designs of the sinter cooling processes.

1. Introduction

Higher energy saving and lower emissions [1–3] are two popular subjects in the iron and steel industry. The energy consumption of sintering process takes up about 10–15% [4] in the production process of the steel [5–13], and it is important to carry out energy saving studies on this process [14–17]. The high temperature sinters need to be cooled in high efficiency and quality on the one hand, and the waste heat should be recycled on the other hand. The energy saving potentiality of the sinter cooling process is considerable, and many scholars have implemented various studies focusing on the two aspects.

In the thermal performance investigations of sinter cooling processes, Caputo et al. [18] simulated the temperature distribution of the process, and analyzed the effects of the initial temperatures of the sinter layer and cooling air on the temperature fields of the sinter layer and cooling air. Caputo and Pelagagge [19] further minimized the total cost of a sinter cooling bed, and obtained the optimal cooing bed moving speed, air flow rate and width, length and thickness of the cooling bed. Jang and Chiu [20] solved the 3-D governing equations of a sinter cooling process by using finite difference method, and obtained a correlation equation of Nusselt number for conjugated heat transfer. They concluded that the Nusselt number decreased with the increases in the equivalent diameter of the sinter particle and the porosity of the sinter layer. Liu [21] obtained the temperature distribution of a sinter bed temperature in the annular cooler, and verified the validity of the theoretical result based on the results of previous work and actual production process. Wen et al. [22] built a 1-D sinter cooling model, and analyzed the effects of some thermal parameters on the sinter outlet temperature. They concluded that the sinter outlet temperature increased with the increases in the equivalent diameter of the sinter particle, cooling bed moving speed and the porosity of the sinter layer, and the decrease in the velocity of the inlet air. Liu et al. [23] combined the energy balance equations of the sinter and cooling air into one equation, and obtained the pressure, velocity and temperature fields of

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the sinter cooling process. They concluded that the cooling time increased and the temperature of waste hot air decreased when the porosity of the sinter layer was increased. Liu et al. [24] further investigated the sinter cooling process based on multi-optimization, and improved the energy gains and reduced the operational costs simultaneously.

In the heat recovery investigations of sinter cooling processes, Dong et al. [25] implemented the waste heat recovery of the process by using a steam turbine system, and analyzed the exergy performance of the waste heat. They concluded that the heat recovery should be laid at the first and second zones according to the exergy performance, and the heat recovery system had the benefits both from the economic and environmental viewpoints. Zhang et al. [26] considered a heat recovery method of a sinter cooling process by using high temperature inlet air, and maximized the waste heat utilization (WHU) by varying 10 parameters. They concluded that the WHU after optimization was increased by 26.26% compared to the previous condition. Liu et al. [27] built a cost model of a sinter cooling process, and analyzed the effects of some thermal parameters on the equivalent annual operating cost of the process. Liu et al. [28] further considered the energy and exergy performances of a sinter cooling process, and found that the quality and quantity of the WHU could be increased by increasing the sinter layer height, sinter heat flux and moving speed of the cooling bed. Tian et al. [4] carried out a sinter cooler simulation to obtain a higher amount of WHU, and optimized the size distribution of the sinter particles. They concluded that compared with the standard conditions, the average temperature of the outlet air and amount of WHU were increased by 33.8 *K* and 10.3%, respectively.

Constructal theory [29–34] has being widely used in the performance optimizations of various transport processes. This theory has also been introduced into the energy saving optimizations of the steel production processes. Kang et al. [35,36] implemented the constructal design of the heaters in a reheating furnace, and obtained the minimum heat consumption by adopting the nonuniform heaters and the heat transfer contact area. Kang et al. [37] further optimized the distributions of the multi-layer insulations, and obtained the minimum heat loss rate of the reheating furnace. Feng et al. [38] carried out constructal optimization of a continuous casting solidification process, and obtained the optimal distributions of the cooling water in the secondary cooling zone. Based on those work, constructal theory will be introduced into the performance optimization of sinter cooling process by combining with the exergy analysis method [39–48] in this paper. For the specified cross-sectional area of the sinter layer, the cross-sectional shape of the sinter layer will be optimized, and maximum exergy output of the recovery waste heat will be obtained. The effects of the sinter layer porosity, inlet air velocity, initial temperatures of the sinter layer and inlet air on the maximum exergy output will be analyzed. Moreover, the performance comparison between the rectangular and trapezoidal sinter layer cross-sections will be performed.

2. Model of sinter cooling process

A sinter cooling process is shown in Fig. 1. The high temperature sinter particles (temperature $T_{s,in}$) are fed to the sinter cooling bed. The cooling bed is moved at certain speed, and the cooling air (temperature $T_{g,in}$ and velocity $v_{g,in}$) is injected into the cooling bed from its bottom to cool the high temperature sinters. The total cooling time of the high temperature sinters is t_c. The hot air after cooling is recycled by the waste heat recovery system during the time interval 0 to t_r ($t_r < t_c$). The shape of the sinter layer in the cooling bed is assumed as a cube (height H, width W and length L) [22]. The rectangular cross-sectional area perpendicular to the length direction of the sinter layer is A_c(= $H \times W$). When the cooling amount of the high temperature sinters is fixed, A_c and L are also fixed. For the fixed A_c, the height H or the width W of the sinter layer can be free to vary.

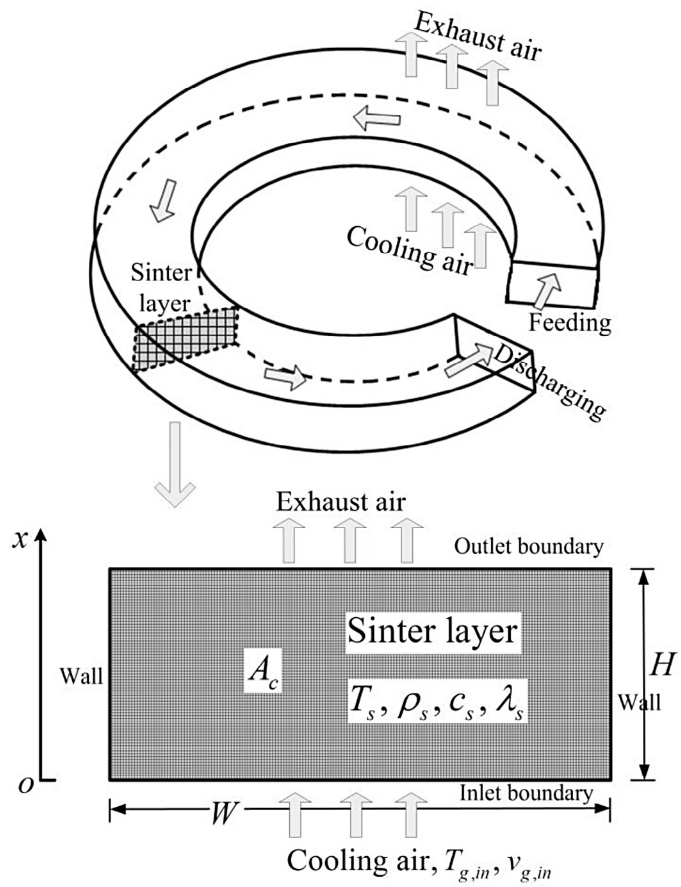

Fig. 1. Model of sinter cooling process with rectangular sinter layer cross-section.

Ignore the heat transfers along the length L and width W of the sinter layer, the one-dimensional heat transfer equations of the cooling air and sinter can be, respectively, given by [4]

$$\frac{\partial(\varepsilon\rho_g c_g T_g)}{\partial t}+\frac{\partial(\rho_g c_g \bar{v}_g T_g)}{\partial x}=\frac{\partial(\lambda_g \varepsilon\cdot\partial T_g/\partial x)}{\partial x}+h_{sg}A_s(T_s-T_g)(0<x<H,0<t\le t_c) \quad (1)$$

$$\frac{\partial[(1-\varepsilon)\rho_s c_s T_s]}{\partial t}=\frac{\partial[\lambda_s(1-\varepsilon)\cdot\partial T_s/\partial x]}{\partial x}+h_{sg}A_s(T_g-T_s)(0<x<H,0<t\le t_c) \quad (2)$$

where ρ_i, c_i, λ_i and T_i ($i = s, g$) are the density, specific heat capacity, thermal conductivity and temperature of the sinter and air, respectively; H is the height of the sinter layer, t is the cooling time, ε is the porosity of the sinter layer, $\bar{v}_g$ is the apparent velocity of the air along the height direction, h_{sg} is the heat transfer coefficient between the sinter and air, and A_s is the specific surface area of the sinter particle.

The corresponding boundary conditions can be given by

$$T_s(x,0)=T_{s,in}(0\le x\le H) \quad (3)$$

$$T_g(0,t)=T_{g,in}(t\ge 0) \quad (4)$$

$$\frac{\partial T_s}{\partial x}=0(x=0,H,t>0),\quad \frac{\partial T_g}{\partial x}=0,(x=H,t>0) \quad (5)$$