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Exergy transfer characteristics of gas-solid heat transfer through sinter bed layer in vertical tank

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ABSTRACT

The examination of exergy transfer characteristics caused by gas-solid heat transfer through sinter bed layer in vertical tank has been presented. Correlations involving relevant variables to predict the mean exergy transfer coefficient, the mean exergy transfer Nusselt number and the non-dimensional exergy flux have been derived by applying the second law of thermodynamics and non-equilibrium thermodynamics theory. The relationships of mean exergy transfer Nusselt number with the heat transfer Nusselt number, Reynolds number, the non-dimensional heat flux and the non-dimensional pressure drop are determined. The experimental results of exergy transfer characteristics in sinter bed layer with different gas superficial velocity, sinter particle diameter and bed layer height are obtained from homemade gas-solid heat transfer setup, and the effects of air outlet temperature, non-dimensional temperature and Reynolds number on the exergy transfer characteristics are analyzed. The research results show that for a given experimental condition, the mean exergy transfer Nusselt number gradually decreases with the increase of Reynolds number and sinter bed layer height. The mean exergy transfer Nusselt number would be less than zero for a lower air outlet temperature, which is pointless for gas-solid heat transfer process in sinter bed layer.

1. Introduction

Aiming at the drawbacks of traditional annular cooler and straight-line cooler for sinter waste heat recovery, the vertical tank for sinter waste heat recovery is presented by imitating the structure and process of coke dry quenching furnace [1–3]. The key problems that affect the feasibility of vertical tank are the gas flow resistance problem and gas-solid heat transfer problem in sinter bed layer of vertical tank. Previous studies on the gas flow and heat transfer in sinter bed layer of vertical tank mainly determined the pressure drop characteristics and gas-solid heat transfer characteristics [4–6], while the exergy transfer process in sinter bed layer of vertical tank was not fully described. Because of that the essence of energy transfer process is the exergy transfer process, and the exergy transfer process in sinter bed layer of vertical tank directly affects the temperature and energy level of outlet cooling air. Therefore, fully analyzing the exergy transfer process and studying the exergy transfer characteristics in sinter bed layer have great significance to optimize energy transfer process and raise energy utilization level.

Exergy is a thermodynamic quantity that represents the available energy. An exergy-based performance analysis is the performance analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis. In recent years, the exergy analysis of convective heat transfer process has been discussed and demonstrated. Prommas et al. [7,8] studied the energy and exergy analyses in convective drying process of multi-layered porous media and in the drying process of non-hygroscopic porous packed bed, and presented the investigations on the effects of porous structural parameters and thermodynamics conditions on energy and exergy profiles. Bindra et al. [9] investigated the thermal analysis and exergy evaluation of thermal energy storage in a packed bed during cyclic storage and recovery. They found out that the sensible heat storage systems in packed beds can provide much higher exergy recovery as compared to phase change material storage systems under similar high temperature ($T = 873$ K) storage conditions. Liu et al. [10] conducted a numerical study on the energy and exergy analysis of waste heat in sinter cooling bed. The effects of different operating parameters on the cooling air temperature and waste heat

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utilization quantity were examined. They found out that both the recovery quantity of sinter waste heat and the exergy value of outlet cooling air would be improved by increasing sinter cooling bed height, trolly's moving speed and sinter heat flux. Laljia et al. [11] experimentally studied the exergy performance of packed bed solar air heater for high porosity range (0.9614–0.9964) and for different shapes of matrices. They found out that the packed bed solar air heater having lower porosity performed better than higher porosity due to greater turbulence ($Re > 1000$), and the exergy loss was less in case of lower porosity system due to higher heat transfer coefficient that leads to lesser losses to the atmosphere. Some other relevant studies were also reported in literature [12–15].

On the other hand, the gas–solid heat transfer process in sinter bed layer usually contains the momentum transfer process and the energy transfer process, and the essence of which is the energy transfer and conversion process. In fact, the energy transfer and conversion are inevitably accompanied with the exergy transfer and conversion. In order to understand the energy transfer and conversion process clearly, it is very important to study the change rules of exergy transfer and conversion process in sinter bed layer.

Since Soma [16] and Dunbar et al. [17] put forward the concept of exergy transfer and its equation, the research on exergy transfer has been conducted by some researchers. Wang et al. [18] derived a phenomenological equation of exergy transfer by applying the non-equilibrium thermodynamics theory, and proposed a simplified expression of exergy transfer coefficient by neglecting some minor engineering couplings in the exergy transfer process. Wu et al. [19,20] investigated the exergy transfer characteristics of forced convective heat transfer through a duct with constant wall temperature and constant wall heat flux. The effects of the Reynolds number and non-dimensional cross-sectional position on the exergy transfer characteristics were carefully analyzed. Kurtbaş et al. [21] experimentally investigated the exergy transfer characteristics of forced convection heat transfer process through a horizontal rectangular channel with metal foams. They found out that the mean exergy transfer Nusselt number decreased with the increase of Reynolds number and the wall heat flux.

As mentioned above, the researches on the exergy transfer characteristics of convective heat transfer mainly focus on the convection heat exchanger and porous channel. So far, the research on the energy transfer and conversion process in the packed bed with particles mainly contains the gas flow resistance characteristics and heat transfer characteristics in bed layer [22–24], and the research on the exergy transfer characteristics in the packed bed with particles has not been reported in the previous literature. Therefore, the objective of this work is to examine the exergy transfer characteristics of gas–solid heat transfer process in sinter bed layer of vertical tank. By applying the second law of thermodynamics and non-equilibrium thermodynamics theory, the expressions calculating the mean exergy transfer coefficient, the mean exergy transfer Nusselt number and the non-dimensional exergy flux in sinter bed layer have been proposed. The experimental results obtained from our homemade heat transfer experiment setup were used to analyze the main influencing factors on the mean exergy transfer coefficient, Nusselt number and the non-dimensional exergy flux.

2. Experimental setup

The experiments were performed in air-sinter heat transfer experimental setup schematically shown in Fig. 1. The inner diameter and height of thermally insulated vertical tank are respectively 450 mm and 1000 mm. The outside walls of experimental vertical tank are covered with insulation to reduce heat loss to the ambient. In order to insure the uniform flow of cooling air through sinter bed layer, the bottom of vertical tank is equipped with a multihole distributor plate (e), which contains 435 holes. The size of each hole is 15 mm, and the fraction of open area is 48.3%.

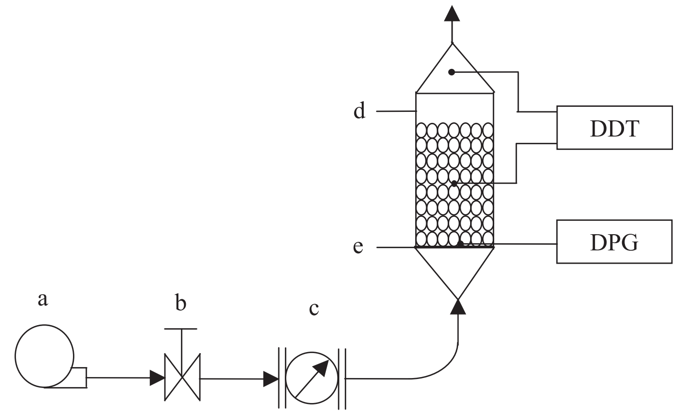

Fig. 1. Schematic of air-sinter heat transfer experimental setup. (a) air blower. (b) throttle valve. (c) orifice plate flowmeter. (d) experimental vertical tank. (e) multihole distributor plate.

The cooling air flow is induced using an air blower (a). The cooling air first flows through the throttle valve (b), and then through the orifice plate flowmeter (c). The cooling air is discharged from the top of experimental vertical tank after exchanging heat with the hot sinter particles in vertical tank. The throttle valve is adjusted to control cooling air flow rate, and the specific value of cooling air flow rate is obtained using the orifice plate flowmeter. The inlet pressure of cooling air is measured by using pressure tapping and a tube with rubber plug inserted into the sinter bed layer. The rubber plug is used to prevent the secondary flow effect resulting from elbow on test results. The measured values of inlet air pressure can be obtained by the differential pressure gauge (DPG). The outlet temperature of cooling air is measured by the suction-type thermocouple, and the thermocouple is connected to the temperature digital display table (DDT).

Three kinds of sinter particles used as packing materials are sieved out by the standard test sieves of different size. The particle diameter, d, of the conducted test cases is the average diameter of sieved sinter particles. The sphericity of sinter particle is measured by means of gas flow technique presented in Ref. [25]. The bed layer voidage is measured according to the method cited in Ref. [26]. The particle equivalent diameter, d_p, is the product of the average particle diameter and particle sphericity. The average particle diameter, bed layer voidage, particle sphericity, particle equivalent diameter, particle packing density and particle porosity are given in Table 1.

The sinter particles of the average diameters 18, 27, 36 mm heated to 1073 K by the resistance furnace were loaded into experimental vertical tank by means of the transportation equipment. Two types of thermocouples were used in the experiments. The K-type thermocouple was used to measure the initial temperature of hot sinter particles, and the suction-type thermocouple was used to measure the outlet temperature of cooling air. Both of them were connected to the temperature digital display table. The

Table 1
Information of sinter particles used in the experiments.

d (mm)	E	Φ	d_p (mm)	ρ_p (kg m^{-3})	ε_p
18	0.487	0.68	12.24	1744	0.36
27	0.518	0.72	19.44	1639	0.38
36	0.537	0.89	32.04	1574	0.40