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Research Paper

Experimental study of gas–solid overall heat transfer coefficient in vertical tank for sinter waste heat recovery

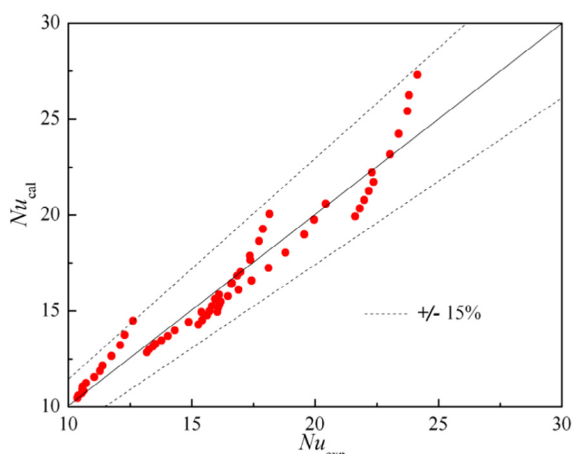
Junsheng Feng, Hui Dong *, Jianye Gao, Jingyu Liu, Kai Liang

SEP Key Laboratory of Eco-Industry, School of Materials and Metallurgy, Northeastern University, Shenyang, Liaoning 110819, China

HIGHLIGHTS

- Heat transfer between the non-uniform sinter particles and cooling air is studied.
- The influences of gas superficial velocity and particle diameter on heat transfer are analyzed.
- A suitable correlation for gas–solid overall heat transfer coefficient is obtained.
- The applicability of experimental correlation is investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

This work experimentally investigates the gas–solid heat transfer behavior in vertical tank for sinter waste heat recovery. With the purpose of predicting the heat transfer Nusselt number, a homemade experimental setup is built to obtain the temperatures of cooling air and sinter particles over time. Sinter particles of average diameter d = 18, 27 and 36 mm with a range of sphericity of $0.68 \le \Phi \le 0.89$ are used in the experiments. The experiments are performed in the range of gas superficial velocity of 1.04~1.75 m/s and the sinter temperature in bed layer from 100 to 750 °C. The influences of gas superficial velocity and sinter particle diameter on the gas–solid overall heat transfer coefficient are analyzed in detail for the covered test cases. The heat transfer Nusselt number is obtained according to the regression analysis of experimental data, and the reliability of the heat transfer Nusselt number is also verified. It is found that the gas–solid overall heat transfer coefficient increases with the increase of gas superficial velocity, and decreases with increasing sinter particle diameter. A small increase in gas–solid overall heat transfer coefficient with the temperature of sinter particles is also observed in the experiments. Compared with the previous literature correlations, the experimental correlation for gas–solid heat transfer in the form of Nusselt number best fits the experimental data. The mean deviation between the experimental data of Nusselt number obtained from this work and the values calculated by the experimental heat transfer correlation is 4.37%, showing good prediction.

* Corresponding author. Tel.: +86 24 83678808, fax: +86 24 83678808.
E-mail address: dongh@smm.neu.edu.cn (H. Dong).

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1. Introduction

The efficient recycling of sintering waste heat resources is one of the main ways to reduce energy consumption of sintering process and iron-making process [1]. In consideration of the inevitable drawbacks of existing sinter waste heat recovery unit [2], the vertical tank for sinter waste heat recovery has been presented by imitating the structure and process of coke dry quenching furnace [3,4], two key scientific problems of which to be solved are the gas–solid heat transfer and gas flow characteristics through sinter bed layer. Among them, the gas–solid overall heat transfer coefficient in sinter bed layer is one of the key factors that affect the feasibility of vertical tank. Essentially speaking, the sinter vertical tank is a random packed bed of larger particles, and the packing structure of sinter bed layer is approximately porous media. Therefore, the research methods of heat transfer characteristics in the packed beds can be used to analyze gas–solid heat transfer process in sinter vertical tank.

Packed beds with particles are widely used in lots of industries, such as chemical reactors, distillation process and heat storage systems, and the heat transfer processes and chemical reactions in the packed beds are also very common [5]. Understanding and predicting the detail heat transfer information in the packed beds are very important for achieving the optimal design of the packed bed as it directly influences chemical reaction rates, distillation effectiveness and convection heat transfer in these applications.

In recent years, the heat transfer mechanisms in packed beds with particles have been widely investigated by many researchers. Schröder et al. [6] measured heat transfer between particles and nitrogen gas flow in packed bed. They reported that increasing gas flow led to higher heat transport coefficient. Ratanadecho et al. [7] experimentally and numerically investigated the microwave drying in the packed bed of unsaturated particles with different porosities. They found that packed bed with a small particle size had capillary forces and drying rate higher than that with a big particle size. Hwang et al. [8,9] experimentally and numerically studied convection heat transfer of air in sintered porous channels. Their results showed that the heat transfer increased with the solid particle thermal conductivity, and the particle Reynolds number significantly affected the solid-to-fluid heat transfer coefficients. Lu et al. [10] performed analytical studies of forced convection heat transfer characteristics of pipes filled with high-porosity, open-cell metal foam. The results showed that both the pore size and the porosity of metal foams played important roles in overall heat transfer performance. Zhou et al. [11] studied heat transfer behavior between the fluid and particles in porous channels using the mathematical model. They found that convective heat transfer increased with gas superficial velocity, and the thermal conductivity of the bed particles affected the conductive heat transfer coefficient considerably, especially in the fixed bed. Some other relevant studies were also reported in literatures [12–15].

On the other hand, many studies have been conducted to derive the heat transfer correlation in the packed beds with particles [16–27]. Among them, several mentioned studies were focused on the correlations for heat transfer from a single immersed sphere in the packed beds of particles [20–22] and from the flowing gas to the single sphere in the packed bed [5,23]. The experimental techniques were developed for following the temperature change of single sphere in the bed. Collier et al. [20] developed the correlation for heat transfer of the hot sphere immersed in the cold bed of particles, which included the ratio of the diameters of the immersed sphere and the particles constituting the packed bed. The Nusselt and Reynolds numbers in their correlation were defined on the basis of the immersed test sphere diameter. Ranz and Marshall [23] proposed the correlation for heat transfer from the flowing gas to the single sphere in the form of Nusselt number. Their results showed significant effect of Reynolds number on the heat transfer coefficient, and the correlation of Nusselt number was seen as a function of Reynolds number, Prandtl number.

In addition, to estimate the overall heat transfer coefficient between the particles and flowing fluid, a variety of experimental and theoretical investigations have been published that address the heat transfer in the packed beds with spheres [24–27]. The above mentioned studies are focused on the overall heat transfer properties in the packed beds. The correlations for heat transfer in the packed beds are reported and listed in Table 1. These correlations are in the form of $Nu = Nu\,(\mathrm{Re_p}, \mathrm{Pr}, \varepsilon)$ with different validity ranges of $\mathrm{Re_p}$.

All these studies demonstrate that there are many achievements in the research of heat transfer behavior in the packed beds with spheres. But the heat transfer behavior in the packed beds with non-spherical particles is still unclear. In addition, determinations of the overall heat transfer coefficient in the packed beds with non-spherical particles are still in research due to the inhomogeneity and irregularity of packing particles. These would be far from sufficient for scientific and practical applications. Therefore, an experimental study is conducted to investigate the heat transfer behavior in the packed bed with non-uniform sinter particles. The aim of this study is to obtain a suitable heat transfer correlation for calculating the gas–solid heat transfer process in sinter vertical tank. Based on this, the experimental data for gas–solid heat transfer in the packed bed with sinter particles of different particle diameters under different gas superficial velocity are measured on a homemade gas–solid heat transfer experimental setup. The effect of sinter particle diameter as well as gas superficial velocity on gas–solid heat transfer process is also determined. The heat transfer correlation in the form of Nusselt number is presented on the basis of the experimental measurement data. Compared with the correlations listed in Table 1, the applicability of obtained experimental heat transfer correlation is investigated.

2. Experimental setup and procedure

The experiments were performed on a homemade gas–solid heat transfer experimental setup schematically shown in Fig. 1. The thermally insulated vertical tank of inner diameter $D = 450$ mm and height $H = 1000$ mm was used. The outside walls of experimental vertical tank were covered with insulation to reduce heat loss to the ambient. The bottom of vertical tank was equipped with a multihole plate (e) to insure the uniform flow of cooling air through sinter bed layer.

The cooling air flow was induced using an air blower (a). The cooling air first flew through the throttle valve (b), and then through the orifice plate flowmeter (c). The cooling air was discharged from the top of experimental vertical tank after exchanging heat with the hot sinter particles in vertical tank. The throttle valve was adjusted to control cooling air flow rate, and the specific value of cooling air flow rate was obtained through the orifice plate flowmeter. The obtained percent uncertainty in measurements for the orifice plate flowmeter was ±5.64%. The outlet temperature of cooling

Table 1
Correlations for heat transfer in packed beds.

Authors/reference	Correlation	Range of validity
Gupta and Thodos [24]	$Nu = \frac{\mathrm{Pr}^{1/3}}{\varepsilon}(2.876 + 0.3023 \cdot \mathrm{Re_p}^{0.65})$	$10 \le \mathrm{Re_p}$
Gupta et al. [25]	$Nu = \frac{\mathrm{Pr}^{1/3}}{\varepsilon} \cdot \mathrm{Re_p} \cdot \left(0.0108 + \frac{0.929}{\mathrm{Re_p}^{0.58} - 0.483}\right)$	$20 \le \mathrm{Re_p}$
Wakao et al. [26]	$Nu = 2.0 + 1.1[6(1-\varepsilon)]^{0.6}\,\mathrm{Re_p}^{0.6}\,\mathrm{Pr}^{1/3}$	$4 \le \mathrm{Re_p} \le 2100$
Bird et al. [27]	$Nu = 0.534[6(1-\varepsilon)]\mathrm{Re_p}^{0.59}\,\mathrm{Pr}^{1/3}$	$45 \le \mathrm{Re_p}$