Powder Technology 280 (2015) 89–93

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Modification of Ergun's correlation in vertical tank for sinter waste heat recovery

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ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form 15 April 2015
Accepted 16 April 2015
Available online 24 April 2015

Keywords:
Sinter
Vertical tank
Pressure drop
Voidage
Sphericity

ABSTRACT

An experimental study was conducted on the pressure drop characteristics in a vertical tank with non-uniform sinter particles. The aim of this study was to present a modified Ergun's correlation to calculate the pressure drop in packed beds with non-spherical particles. The sinter particles of different diameter, d_p, with a range of sphericity, $0.68 \le \Phi \le 0.89$ were used in random packing with a range of bed layer voidage, $0.44 \le \varepsilon \le 0.53$, and the bed geometrical factor (inner diameter of vertical tank to sinter particle equivalent diameter ratio) was from 13.8 to 45.2. The pressure drop of unit bed layer height $\Delta P_{Bed} / H$ of the packed beds was measured in a range of air superficial velocity, 0.383 m/s $\le u \le$ 3.33 m/s. The effects of air superficial velocity and sinter particle diameter on the pressure drop of unit bed layer height were determined in the covered test cases. The results show that compared with the well-known Ergun's equation and other proposed experimental correlations, the modified Ergun's correlation is able to fit the whole set of measurements of $\Delta P_{Bed} / H$ best, and the mean error between the experimental values of $\Delta P_{Bed} / H$ from this work and the values calculated from the modified Ergun's correlation is 4.6%.

1. Introduction

Aiming at the drawbacks of existing sinter waste heat recovery unit [1], a vertical tank for sinter waste heat recovery is presented by imitating the structure and process of coke dry quenching furnace [2,3]. Among the key factors affecting the feasibility of the vertical tank are the pressure drop characteristics in sinter bed layer. Essentially speaking, the vertical tank is a kind of gas–solid countercurrent moving bed, which belongs to the category of large granular packed beds. Therefore, the related researches of pressure drop characteristics in packed beds are used to analyze the gas flow process in a vertical tank.

The studies on pressure drop characteristics in packed beds go back to Carman [4] and Burke et al. [5]. Carman [4] found that the change in pressure drop at viscous flow was proportional to $(1-\varepsilon)^2 / \varepsilon^3$, and Burke et al. [5] found that the change in pressure drop at turbulent flow was proportional to $(1-\varepsilon) / \varepsilon^3$. Most of the studies concerning the pressure drop characteristics of packed beds were either based on an overall analysis of the bed as a continuum [6] or as a porous medium [7] affected by the porosity distribution which was a function of the shape and size of the packing materials. The pressure drop through bed layer in packed beds is the joint result of viscosity losses and inertia losses characterized by the linear dependence of superficial velocity and quadratic dependence of superficial velocity respectively. The well-known Ergun's equation [8] used for calculating the pressure drop in packed beds with spherical particles is as follows.

$$\frac{\Delta P_{Ergun}}{H} = 150\frac{\mu(1-\varepsilon)^2}{\varepsilon^3 {d_p}^2}u + 1.75\frac{\rho(1-\varepsilon)}{\varepsilon^3 d_p}u^2. \quad (1)$$

In the previous literature, many further studies to check the values of empirical constants 150 ($=k_1$) and 1.75 ($=k_2$) in Eq. (1) have been performed. The values of empirical constants in Ergun's correlation have been, respectively, proposed as 200 and 1.75 [9], as 180 and 1.8–4.0 [10], as 229 and 1.96 [11], and as 160 and 1.61 [12]. The reason for variation in the constants is determined as the variations in particle shape for non-spherical particles. But according to a recent study [13], the previous Ergun's correlation is only able to accurately predict the pressure drop for flow over spherical particles, whereas it systematically predicts the pressure drop for flow over non-spherical particles with a large deviation. Besides Ergun's correlation which can be regarded as a direct method of calculation for $\Delta P_{Bed} / H$, there are also some other approaches using particle friction factor, f_p, as an indirect method of calculation for $\Delta P_{Bed} / H$ through the following definition:

$$f_p = \frac{\Delta P_{Bed} d_p}{\rho H u^2}. \quad (2)$$

These alternative correlations [14–17] are reported and listed in Table 1. The correlations are in the form of $f_p = f_p$ (Re, ε) with a rather different validity range of Re.

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http://dx.doi.org/10.1016/j.powtec.2015.04.033
0032-5910/

Table 1
Alternative correlations for pressure drop calculation through packed beds.

Authors/reference	Correlation	Range of validity
Hicks [14]	$f_p = 6.8\frac{(1-\varepsilon)^{1.2}}{\varepsilon^3}\text{Re}^{-0.2}$	$500 \le \text{Re} \le 60000$
Tallmadge [15]	$f_p = 150\frac{(1-\varepsilon)^2}{\varepsilon^3 \text{Re}} + 4.2\frac{(1-\varepsilon)^{1.1666}}{\varepsilon^3}\text{Re}^{-1/6}$	$0.1 \le \text{Re} \le 100000$
Sug Lee and Ogawa [16]	$f_p = \frac{1}{2}\left[\frac{12.5(1-\varepsilon)^2}{\varepsilon^3}\right]\left[29.32\text{Re}^{-1} + 1.56\text{Re}^{-n} + 0.1\right]$ with $n = 0.352 + 0.1\varepsilon + 0.275\varepsilon^2$	$1 \le \text{Re} \le 100000$
Kürten et al. [17]	$f_p = \left[\frac{25(1-\varepsilon)^2}{4\varepsilon^3}\right]\left[21\text{Re}^{-1} + 6\text{Re}^{-0.5} + 0.28\right]$	$0.1 \le \text{Re} \le 4000$

Table 2
Bed layer parameters and range of test cases.

d_p (mm)	H (mm)	Φ	ε	$D / (\Phi d_p)$	u (m/s)
14	300	0.68	0.44	45.2	0.383, 0.765, 1.148, 1.531, 1.914, 2.30, 2.679
	500				
	800				
24	300	0.72	0.49	24.9	0.383, 0.765, 1.148, 1.531, 1.914, 2.30, 2.679, 3.062
	500				
	800				
35	300	0.89	0.53	13.8	0.383, 0.765, 1.148, 1.531, 1.914, 2.30, 2.679, 3.062, 3.33
	500				
	800				

However, determinations of pressure drop in a vertical tank are still in research due to the inhomogeneity and irregularity of sinter particles. Therefore, an experimental study was conducted to investigate the influence of air superficial velocity and particle diameter on pressure drop in sinter bed layer, and then present a new modified Ergun's correlation for calculating pressure drop in a vertical tank with non-uniform sinter particles. In addition, the applicability of modified Ergun's correlation compared with the alternative correlations cited in the literature [14–17] for the pressure drop determination of packed beds with non-spherical particles was also investigated.

2. Experimental set-up and procedure

The blower type air flow experimental test set up consisting of a vertical tank of inner diameter D of 430 mm and height L of 1400 mm shown in Fig. 1 was designed and constructed. The air flow was induced using an air blower. The cooling air first flowed through the throttle valve, and then through the orifice plate flowmeter, and finally traveled through the bed layer towards the upper surface of sinter situated inside the test section. The throttle valve was adjusted to control cooling air flow rate, and the specific value of cooling air flow rate was obtained by the orifice plate flowmeter. Sinter particles were used as packing materials, and three kinds of particle diameters (10–18 mm, 18–30 mm, 30–40 mm) were sieved out by standard test sieves of different size. The particle diameter, d_p, of the conducted test cases was the average diameter of sieved sinter particles, which provided a range of $13.8 \le D / (\Phi d_p) \le 45.2$. The sphericity of sinter particles was measured by means of gas flow technique presented in [18]. The bed layer voidage was measured according to the method cited in [19]. The pressure tappings set at three different heights (400 mm, 700 mm, 1200 mm) of the vertical tank were used to measure the air flow pressure drop by the differential pressure gauge. The sinter particle diameter, measured bed layer voidage and the air superficial velocity range of the conducted test cases are given in Table 2.

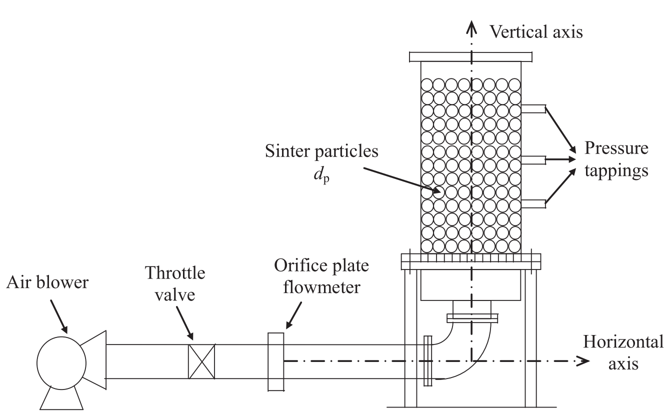

Fig. 1. Schematic of air flow experimental test set-up.

The systematic experimental study resulted in a data set for 24 separate test cases using a vertical tank with different particle diameters, and the reference flow Reynolds number through sinter bed layer, $\text{Re}_p = u\Phi d_p / \upsilon$, varied in the range of $242 \le \text{Re}_p \le 6888$ at the atmospheric condition of $T_0 = 293.15$ K and $P_0 = 0.1$ MPa. The cross-sectional pressure drop distribution at three different heights, $\Delta P / H = \Delta P / H(\text{r})$, used to calculate the mean pressure drop of air flow, $\Delta P_{\text{Bed}} / H$, was measured by using pressure tapping and a tube inserted into the sinter bed layer. The inner diameter of pressure tapping was 16 mm, and the external diameter of the tube with rubber plug was 10 mm. The rubber plug was used to prevent the secondary flow effect resulting from elbow on test results. The measured values of pressure drop were obtained by the differential pressure gauge.

The procedure was such that the experimental data in terms of $\Delta P_{\text{Bed}} / H$ were first expressed as a modified Ergun's correlation for calculating pressure drop in a vertical tank. The applicability of modified Ergun's correlation was later investigated to compare with the correlations shown in Table 1.

3. Results and discussion

3.1. Influence of related parameters

Due to the existence of wall effect in a vertical tank, the cross-sectional pressure drop distribution of bed layer is not the same. The pressure drop near the wall of a vertical tank is larger than that in the center of the sinter bed layer. Therefore, it is necessary to measure the values of pressure drop at different locations of the bed layer cross-section. The variation of particle friction factor, f_p, with r/R can be seen from the sample plot in Fig. 2 for air superficial velocity of $u = 1.914$ m/s and particle diameter of $d_p = 24$ mm. R is the radius of the vertical tank, and r is the distance from the measured point to the center of the bed layer. As can be seen from Fig. 2, the values of pressure drop at

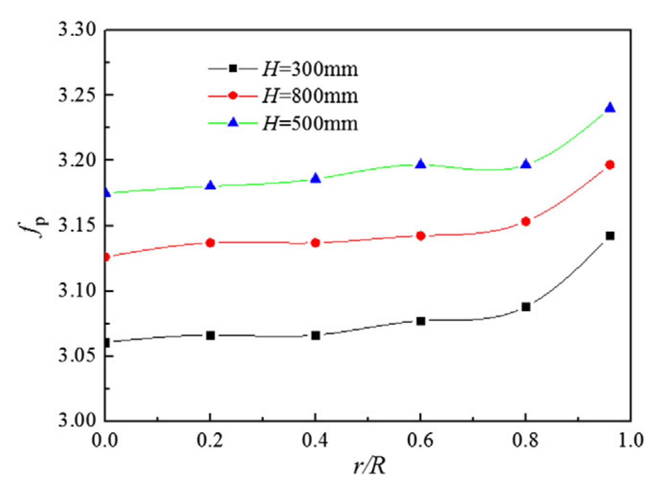

Fig. 2. Variation of f_p with r/R for different bed layer heights.