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Packed bed pressure drop dependence on particle shape, size distribution, packing arrangement and roughness

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ABSTRACT

Packed beds have been used or proposed for many different applications, including thermal storage in buildings and in solar thermal power plants. In order to size the blowers and predict the operating and capital cost, the packed bed pressure drop must be known. The Ergun equation, commonly used for predicting packed bed pressure drop, over-predicts the pressure drop through randomly packed or structured beds of smooth spheres at Ergun Reynolds numbers in excess of ≈700, and previous work has found it to under-predict the pressure drop through beds of rock by a factor as high as 5. Present measurements of the pressure drop for air flow through beds of rough spheres, smooth cylinders, cubes and crushed rock are significantly higher than those for smooth spheres, and all differ from the Ergun equation. Particle shape, arrangement (including packing method) and surface roughness are shown to influence the pressure drop. Recent correlations for non-spherical particles are shown to differ significantly from present measurements. Different pressure drop measurements obtained for irregularly shaped rock packed into the test section in two different directions relative to the flow direction show that random packing is not necessarily isotropic. In order to predict the pressure drop over a packed bed of irregular particles such as crushed rock with any degree of accuracy, an empirical equation must be obtained from a sample of the particles for a given packing arrangement.

1. Introduction

Packed beds of particles have been used in a number of different applications such as building heating and cooling (for example Hughes et al. [1]), absorption or ion-exchange resin beds [2]. Packed beds of rock have been proposed for use as thermal storage in solar thermal power generation, an application for which there is "great potential", although further work is needed on understanding pressure drop [3]. The pressure drop through a packed bed must be known in order to estimate the capital and operating costs and to size the blowers or pumps required to force fluid through it. The present work looks at pressure drop through packed beds of regular, irregular, rough and smooth particles in order to show which are the most important parameters that influence the pressure drop, and to better understand the complexity of pressure drop through packed beds, particularly rock beds.

1.1. Correlations for packed bed pressure drop prediction in the literature

The Ergun friction factor f_{Erg} of a packed bed is [4]

$$f_{Erg} = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{150}{Re_{Erg}} + 1.75. \tag{1}$$

The Ergun Reynolds number Re_{Erg} is defined as

$$Re_{Erg} = \frac{\rho v_s D}{\mu(1-\varepsilon)} = \frac{Re_p}{1-\varepsilon}. \tag{2}$$

The superficial speed v_s is defined as

$$v_s = \frac{\dot{m}}{\rho A_{cs}}. \tag{3}$$

D is the particle size, defined by Ergun in terms of particle volume and surface area:

$$D = \frac{6\Sigma V_p}{\Sigma A_p}. \tag{4}$$

Ergun proposed estimating this ratio indirectly by means of pressure drop measurements over a packed bed of the material at low flow rates in the viscous regime. For a sphere, Eq. (4) reduces to the sphere diameter. Ergun does not explicitly state the range of validity of Eq. (1). The measurements on which his correlation is based, or with which he compared it, are in the range $1 < Re_{Erg} < 2400$. He does not specifically state what particles he used; tables and graph legends in Ergun [4] or Ergun and Orning [5] suggest spheres, pulverized coke/coal, sand, cylinders and tablets were used. The correlation

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is not based solely on pressure drop measurements through spheres or smooth particles.

Montillet [6] states that equations of the form $\Delta p/L = av_s + bv_s^2$ – such as the Ergun equation – should not be used for $Re_p > 500$–600, because, in the turbulent regime, the pressure drop in a finite packed bed is not proportional to the square of the flow speed. He attributes this to the combined effect of transition to a new flow regime and the finite nature of the packed bed. Niven [7] argues that the v_s^2 pressure loss term is strongly dependent on local losses — expansion, contraction and change in flow direction, which occur even in laminar flow. He states that in fully turbulent flow, the local losses should be dominant, rather than turbulent losses, which results in "a second transition, from laminar to turbulent flow," which occurs at Reynolds numbers higher than the transition within the Ergun equation.

The Ergun equation, for $Re_{Erg} > 700$, over-predicts the pressure drop for randomly packed beds of smooth spheres. The over-prediction can be seen in Ergun [4] from some of the graphical data he shows. On the other hand, the measurements of Zavattoni et al. [8] for rock beds were 10–30% higher than the Ergun equation, and Shitzer and Levy [9] measured rock bed pressure drops a factor of 1.5–5 times higher than the Ergun equation. Tobiś [10] has shown, by inserting obstacles into the flow passages between spheres in a simple cubic packing arrangement, that the constant 1.75 in the Ergun equation can vary by a factor up to almost five, depending on the alignment and shape of the obstacle. Mayerhofer et al. [11] have shown, for irregularly shaped wood chips, that the packing alignment of the wood chips relative to the air flow direction influences the pressure drop.

Hicks [12] warns that the constants in the Ergun equation may be dependent on the Reynolds number. He notes that, although the Ergun equation is "advanced by several textbooks without restriction to flow range," it may not be applicable for spheres when $Re_{Erg} > 500$.

A range of correlations for spherical and non-spherical particles is given below. The selection includes recent correlations, two of which include parameters to estimate the influence of wall effects.

Carman [13] gives the following correlation for spheres in a test section with negligible wall effects, for $0.1 < Re_{Erg} < 60\,000$:

$$f_C = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{180}{Re_{Erg}} + \frac{2.87}{Re_{Erg}^{0.1}}. \tag{5}$$

Hicks [12] proposes a relation for the range $300 < Re_{Erg} < 60\,000$ for spheres:

$$f_H = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{6.8}{Re_{Erg}^{0.2}}. \tag{6}$$

Brauer [14] gives an equation for packed beds of spheres, plotted against measured data for the range $0.01 < Re_{Erg} < 40\,000$, which may be written as

$$f_B = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{160}{Re_{Erg}} + \frac{3.1}{Re_{Erg}^{0.1}}. \tag{7}$$

This equation is almost identical to the equation used by the KTA 3102.3 standard for pebble bed nuclear reactors [15]; the only difference is that the constant 3.1 is changed to 3.

Jones and Krier [16] give a correlation for spherical glass beads in the range $1000 < Re_p < 100\,000$, $8 < D_c/D < 52$, which can be written as

$$f_{JK} = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{150}{Re_{Erg}} + \frac{3.89}{Re_{Erg}^{0.13}}. \tag{8}$$

Another correlation for pressure drop in a bed of spheres of uniform diameter is found in Idelchik [17], which presents a correlation by Bernshtein for void fractions between 0.3 and 0.8:

$$f_I = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{\varepsilon^3}{(1-\varepsilon)} \frac{0.765}{\varepsilon^{4.2}} \left(\frac{30}{Re_I} + \frac{3}{Re_I^{0.7}} + 0.3 \right) \tag{9}$$

where $Re_I = (0.45/\varepsilon^{0.5})\, Re_{Erg}$. The range of applicability of the equation is not specifically stated; Idelchik uses it in graphs over the range $0.001 < Re_I < 1\,000$.

For beds of spheres, Montillet et al. [18] propose

$$f_M = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = a \left(\frac{D_c}{D} \right)^{0.20} \left(\frac{1000}{Re_p} + \frac{60}{Re_p^{0.5}} + 12 \right) \tag{10}$$

where a is 0.061 for dense packings ($\varepsilon < 0.4$) and 0.050 for loose packings ($\varepsilon > 0.4$). The equation is valid for $3.8 < D_c/D < 50$ and $10 < Re_p < 2500$. For $D_c/D > 50$, $(D_c/D)^{0.2}$ is set to 2.2. This equation was obtained from measurements with water or aqueous solutions of glycerol in a cylindrical column. Montillet et al. do not state how the value D_c should be calculated for test sections of a non-circular cross-section.

Singh et al. [19] present a correlation for pressure drop through beds of differently shaped particles, with the particle shape taken into account by means of a sphericity factor ψ:

$$\psi = \frac{A_s}{A_p} = \left[\frac{36\pi V_p^2}{A_p^3} \right]^{1/3}. \tag{11}$$

Here A_s is the surface area of a sphere that has the same volume as the particle. The correlation is based on data for pressure drop through spherical and other non-spherical objects from measurements in the range $1000 < Re_p < 2700$ (approx. $1500 < Re_{Erg} < 5000$), and the particle diameter D_{ve} is defined as the diameter of a sphere that has the same volume as the particle volume V_p:

$$f_S = \frac{\Delta p}{L\rho v_s^2} D_{ve} \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{\varepsilon^3}{(1-\varepsilon)} 4.466 Re_p^{-0.2} \psi^{0.696} \varepsilon^{-2.945} e^{11.85(\log\psi)^2} \tag{12}$$

where

$$D_{ve} = \left(\frac{6}{\pi} V_p \right)^{1/3}. \tag{13}$$

An equation for spherical or non-spherical particles with wall correction terms is found in Eisfeld and Schnitzlein [20]:

$$f_{ES} = \frac{\Delta p}{L\rho v_s^2} D \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{K_1 A_w^2}{Re_{Erg}} + \frac{A_w}{B_w}. \tag{14}$$

A_w and B_w are the wall correction terms, defined as

$$A_w = 1 + \frac{2}{3(D_c/D)(1-\varepsilon)} \tag{15}$$

$$B_w = \left[k_1 (D/D_c)^2 + k_2 \right]^2. \tag{16}$$

The values of K_1, k_1 and k_2 presented by Eisfeld and Schnitzlein are shown in Table 1. They are based on experimental data largely with spheres and cylinders for $0.33 < \varepsilon < 0.88$, $0.01 < Re_p < 17\,700$ and $2 < D_c/D < 250$. Eisfeld and Schnitzlein do not specify how D_c should be calculated for non-circular bed cross-sections.

For non-spherical particles, Nemec and Levec [21] propose altering the constants in the Ergun equation by means of the particle