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Pressure drop in packed beds of angular parallelepipeds, including the effects of particle interference

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HIGHLIGHTS

- Pressure loss in packed beds of parallelepipedal particles is measured.
- The reduction of effective surface by particle overlap in the bed is measured.
- A theory for calculating the effective surface from pressure loss is presented.

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ABSTRACT

Pressure loss measurements are reported in packed beds of seven different shapes of angular parallelepiped, ranging from nearly cubical particles to thin flat chips, and compared with a number of available correlations, most of which underpredicted the pressure loss. All particle types when packed in the bed were found to overlap each other to some degree, and the extent of this was estimated from photographs, from which the average particle surface area effectiveness η was found to range from 0.69 to 0.85. The pressure loss correlation of Nemec and Levec (2005) was modified to include the effects of particle overlap, and values of η deduced by fitting to the measurements. The resulting values agreed well with those estimated from photographs, indicating that a pressure loss test can be used to assess particle overlap in a bed of known particle geometry. The range of Reynolds numbers covered was about 150–900. This is expected to be useful in assessing effective surface areas for heat and mass transfer and chemical reaction in packed beds.

1. Introduction

There have been many works published on the pressure drop in packed beds of particles in the last seventy years. Most of these have dealt with spherical or roughly spherical particles or cylinders (Ergun and Orning, 1949; Ergun, 1952a; Reichelt, 1972; Macdonald et al., 1979; Crawford and Plumb, 1986; Fand and Thinakaran, 1990; Jordi et al., 1990; Eisfeld and Schnitzlein, 2001; Niven, 2002; Nemec and Levec, 2005; Luckos and Bunt, 2011; Allen et al., 2013; Harrison et al., 2013; Erdim et al., 2015), or with commercial packings. These types of particles have surfaces which are largely convex, so that the contact areas between particles are small and the contacts do not materially reduce the surface area exposed to the flow. However, for particles with flat surfaces there is the additional possibility that particles may overlap (Lee and Bennington, 2005; Mayerhofer et al., 2011), reducing the available surface and affecting pressure loss as well as heat and mass transfer. Such particles include wood chips as encountered in pulp and paper processes, wood and biomass fuels in packed bed combustion and gasification processes, and angular pieces of crushed rock as encountered in thermal storage. Only one pressure loss model in the literature - that of Comiti and Renaud (1989) - specifically includes this effect, and there is little else available on such packings. This paper therefore presents pressure loss measurements on packed beds of parallelepipeds of several different geometries, and compares them with available theories.

2. Models of packed bed pressure drop

Most theories of packed bed pressure loss take the following form:

$$f = \left(\frac{\Delta P}{\rho u^2}\right)\left(\frac{\Phi d_P}{L}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = \frac{A}{Re} + B \qquad (1)$$

where the Reynolds number is defined as

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Nomenclature

a_{VD}	particle specific surface area exposed to flow (m^2/m^3 particle volume)
a_{VS}	particle specific surface area from geometry (m^2/m^3 particle volume)
A, B	parameters in pressure loss Eq. (1)
A^*, B^*	parameters in Comiti and Renaud correlation, Eq. (12)
d_H	hydraulic diameter of bed channel (Eq. (3) - m)
d_P	particle diameter (volume-equivalent spherical diameter) (m)
D	bed diameter (m)
f	friction factor (Eqs. (1) and (9))
L	depth of bed (m)
M	wall effect correction (Eqs. (5) and (11))
ΔP	pressure drop (Pa)
Re	Reynolds number (Eqs. (2) and (10))
u	superficial velocity (m/s)
Greek letters	
ε	void fraction
η	particle surface effectiveness (Eq. (6))
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
τ	tortuosity of bed channel
Φ	particle sphericity (surface of volume-equivalent sphere/actual surface)
χ	proportion of particle surface covered by overlap with other particles

$$Re = \left(\frac{\rho u \Phi d_p}{\mu}\right)\left(\frac{1}{1-\varepsilon}\right) \tag{2}$$

The sphericity Φ, defined as the surface area of the volume-equivalent sphere of diameter d_P divided by the actual particle surface area, does not appear explicitly in all versions of this equation in the literature, but in most cases a definition of equivalent particle diameter is used which amounts to (Φd_P) (Ergun, 1952b; Macdonald et al., 1979; Comiti and Renaud, 1989; Eisfeld and Schnitzlein, 2001; Niven, 2002; Nemec and Levec, 2005; Allen et al., 2013). The inclusion of Φ arises from the derivation of Eq. (1) (Bird et al., 1960), which is based on the hydraulic diameter of a channel in the bed; this is defined as

$$d_H = \frac{4\varepsilon}{a_{VS}(1-\varepsilon)} = \frac{4\Phi d_P \varepsilon}{6(1-\varepsilon)} \tag{3}$$

where $a_{VS} = 6/(\Phi d_P)$ is the specific surface area per unit volume of particulate. The derivation also leads naturally to the inclusion of (Φd_P) and $(1 - \varepsilon)$ in the definition of Re, as given above.

The most common form of Eq. (1) is the original version given by Ergun (1952a), with parameter values $A = 150$, $B = 1.75$, but other values have been given as well (*e.g.* Macdonald et al., 1979; Allen et al., 2013). Nemec and Levec (2005) have given a particularly useful form of this in which A and B are given an explicit dependence on sphericity, the only correlation to do this so far.

The experiments presented here were performed with fairly large particles, such that in some cases the ratio of vessel diameter D to d_P was as low as 8, necessitating a correction for wall effects. Several of these are available in the literature, but the most widely used is that of Mehta and Hawley (1969), which defines a correction factor M multiplying a_{VS} such that the friction factor correlation becomes

$$f = \frac{A}{Re}M^2 + BM \tag{4}$$

The derivation of M is based on the combined bed and wall surface area, and therefore the sphericity Φ appears again:

$$M = 1 + \frac{2\Phi d_P}{3D(1-\varepsilon)} \tag{5}$$

This correction can be applied to any of the correlations in the literature which are given in the form of Eq. (1), including that of Nemec and Levec (2005). A number of published correlations include wall corrections which are similar in form (Reichelt, 1972; Fand and Thinakaran, 1990; Eisfeld and Schnitzlein, 2001; Harrison et al., 2013).

It is well known that the void fraction in a packed bed is anomalous in the near wall region. For spheres it oscillates in a regular fashion with radius near the wall (Hamel and Krumm, 2008), but for cylinders the effects are smaller and confined to a region within $d_P/2$ of the wall (Hamel and Krumm, 2012), a finding which Dixon (1988) attributes to the variety of orientations possible for cylinders and consequent greater randomness of the wall region. Flat rectangular chips like the ones used in the present experiments show even smaller wall region anomalies (Hamel and Krumm, 2008). Published wall corrections for pressure loss do not explicitly account for wall anomalies: they simply assume an overall average value of ε for the whole bed, and this is the sense in which ε is understood in this paper. Similar considerations apply to the void fraction anomaly near the distributor plate at the bottom of the bed (Zou and Yu, 1995).

3. Experimental methods

Experimental measurements of pressure loss were made in packed beds of wood particles cut to various proportions from standard 1 × 2 in. (nominal) spruce lumber. Fig. 1 gives the particle geometry and Table 1 the dimensions. The angular shape originated with fuel particles for packed bed combustion experiments (Girgis and Hallett, 2010), where it was found to encourage random packing to a greater extent than square cut particles. The regular shapes allow equivalent diameter d_P (defined as that of the volume-equivalent sphere) and sphericity to be known *a priori*. The original lumber had corners rounded with a radius of about 3 mm, leaving the particles with one or more rounded edges; the surface areas, d_P and Φ include corrections for this.

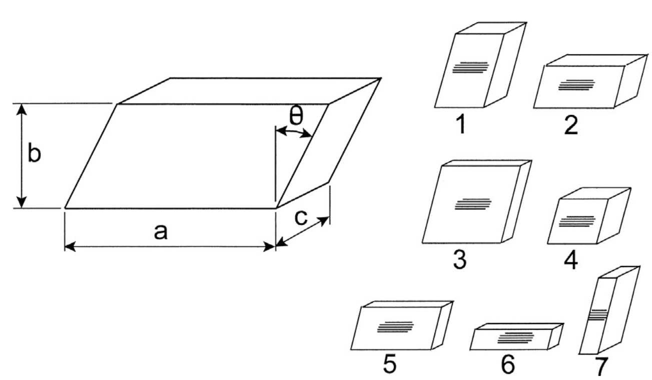

Fig. 1. Particle geometry. Definition of dimensions (left); roughly scale depictions of particle types, with direction of wood grain shown by light parallel lines (right).