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ScienceDirect
Chemical Engineering and Processing 46 (2007) 329–333
Chemical Engineering and Processing
www.elsevier.com/locate/cep

About a correlating equation for predicting pressure drops through packed beds of spheres in a large range of Reynolds numbers

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Received 24 October 2005; received in revised form 4 July 2006; accepted 5 July 2006
Available online 8 July 2006

Abstract

This work aims at validating and extending the applicability of an existing correlating equation for predicting pressure drop through packed beds of spheres. A new set of data points out its use for bed geometric aspect ratio D/d_{part} in the range 3.8–14.5, in the case of dense packings. The case of loose packings is also discussed using literature data. As a conclusion, a correlation is proposed for predicting pressure drops through fixed beds of spheres (dense and loose packings) for large ranges of Reynolds numbers ($\sim 10 < Re_{\text{part}} < \sim 2500$) and of geometric aspect ratio ($\sim 3.5 < D/d_{\text{part}} < 40$–$50$).

Keywords: Packed beds; Spherical particles; Laminar flow; Turbulent flow; Voidage; Geometric aspect ratio

1. Introduction

Flow through packed beds of spheres has been extensively studied. In particular, the aspects of pressure drop variation, porosity profiles and effects of the bed geometric ratio have often been discussed in the literature. Although in the opinion of many engineers and researchers, this subject is considered as almost "exhaustively" studied, yet many tasks remain to be considered. In fact, the available knowledge is rather fragmented. For example, the link between the bed structure and the observed flow behaviour is not completely understood. In the sense of practical Chemical Engineering, there is no reliable universal equation for predicting the pressure drop.

In a recent paper [1], the nature of the pressure drop variation in the case of a Newtonian fluid flow through beds of spheres was emphasised, covering laminar and turbulent flow regimes. Indeed it is well established that, for a very large interval of Reynolds number and especially for large values of the Reynolds number, the pressure drop variation cannot be correctly represented with an equation of the Forchheimer type, namely

$$\frac{|\Delta P|}{H} = AU_0 + BU_0^2 \quad (1)$$

We then suggested the use of a form of equation proposed by Rose [2] and Rose and Rizk [3], and modified it by adding a correlating factor based on the bed porosity and on the bed geometric aspect ratio. Indeed, Rose and Rizk pointed out the respective effects of these two parameters on the relative resistance variation but did not propose a correlating equation taking them into account. As reported in Table 1, the most common correlating equations from the literature do not include these two parameters or include only a porosity factor. In our opinion, the bed porosity is a parameter which cannot represent all the effects of the bed geometric ratio on the flow. Thus, taking into account the bed geometric ratio seems to be necessary.

In Ref. [1], a first form of a correlating equation is presented, but it is based on only a limited number of data. The necessity of getting new data sets in order to validate its usefulness was emphasized. Despite the great amount of experimental data present in the literature, most of them are not reproducible or inadequate to provide a satisfying correlating equation. In our opinion, the experiments must satisfy several criteria as using a "cloud of data" cannot provide an equation which takes into account the sensitivity of the pressure drop on the geometric ratio. Thus, in order to cover a range of Reynolds number as large as possible in a given bed, different fluids and pumps have to be used and each set of data needs to belong to the same part of this bed. This requirement alone eliminates most of the literature data. Moreover, special care is needed to avoid air bubbles

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doi:10.1016/j.cep.2006.07.002

Table 1
Main literature equations proposed for pressure drop predictions in large ranges of Reynolds number

Author/reference	Equation		Range of validity in terms of Re_{part}
Rose [2]	$f_{part} = 1000\,Re_{part}^{-1} + 60\,Re_{part}^{-0.5} + 12$	(2)	Rather large but not precisely given by the authors
Rose and Rizk [3]	$f_{part} = 1000\,Re_{part}^{-1} + 125\,Re_{part}^{-0.5} + 14$	(3)	Rather large but not precisely given by the authors
Kuerten, reported by Watanabe [4]	$f_{part} = \left[\frac{25}{4\varepsilon^3}(1-\varepsilon)^2\right][21 Re_{part}^{-1} + 6 Re_{part}^{-0.5} + 0.28]$	(4)	0.1–4 × 10[3]
Hicks [5]	$f_{part} = 6.8 \times \frac{(1-\varepsilon)^{1.2}}{\varepsilon^3} Re_{part}^{-0.2}$	(5)	500–6 × 10[4]
Tallmadge [6]	$f_{part} = \left[\frac{150}{Re_{part}}\frac{(1-\varepsilon)^2}{\varepsilon^3}\right] + \left[\frac{4.2(1-\varepsilon)^{1.166}}{\varepsilon^3} Re_{part}^{-1/6}\right]$	(6)	0.1 to 10[5]
Lee and Ogawa [7]	$f_{part} = \frac{1}{2}\left[\frac{12.5}{\varepsilon^3}(1-\varepsilon)^2\right][29.32\,Re_{part}^{-1} + 1.56\,Re_{part}^{-n} + 0.1]$ with $n = 0.352 + 0.1\varepsilon + 0.275\varepsilon^2$	(7)	1 to 10[5]

Presently, these equations are presented in terms of a modified particle friction factor f_{part} vs. the Re_{part}.

in the beds in order to ensure sufficient accuracy in the determination of the bed porosity. The uncertainties brought about by the use of flow-meters and manometers must be minimised since a great accuracy is needed for the data in view of the subtle scatter observed between some sets of experimental pressure drop variations and a quadratic Forchheimer type equation.

The objective of this work is to present a new set of experimental data in order to discuss and confirm the usefulness of the previously proposed correlating equation. In conclusion, the relevance of the proposed equations is discussed, based on a comparison with correlating equations from the literature.

2. Experimental details

The new data presented in Section 3.1 of this paper correspond to a variation of the bed geometric aspect ratio in the range 3.8–14.5 for which the wall effect is clearly not negligible. These new data sets supplement those formerly used in [1] which were characterized by a bed geometric aspect ratio in the range 12.3–41.3.

The equipment used to obtain the new data is the same as that described previously in [1], except for one set of data which was obtained with another apparatus. This one complies to the same requirements, the only difference being that the nominal diameters of the pipes and of the cell (99.8 mm) are larger. This second apparatus allows to extend the range of variation of geometric aspect ratio of tested beds.

It is important to highlight the keypoints of the experimental methods used in this work. The beds are packed according to a well established procedure [8] in order to get the beds as homogeneous as possible. To minimise the end effects, the pressure drop was measured in a central part of each bed. The tested part of the bed is high enough to consider that its porosity is close to that of the whole bed [9]. For each set of data, a large range of Re_{part} is tested using different fluids such as water or aqueous solutions of glycerol, but the measurements are still made in the same part of the bed. Different manometers, flow-meters and pumps are used in order to ensure a high level of accuracy, whatever the experimental conditions [1]. The dynamic viscosity of the aqueous solutions of glycerol is measured from a sample of liquid taken from the experimental apparatus and with a Couette viscosimeter (Reference: Rheoanalyzer, Contraves, module: MS 145). Commercial particles have been used such as glass particles or particles made of a rigid synthetic material. All the used particles are smooth and rigid. Tables 2 and 3 recapitulate the main characteristics of the tested beds, particles and experiments.

3. Experimental results and procedure for correlating the data

3.1. Case of dense packings

The data presented in this section have been obtained with dense packings characterized by porosities in the range 0.36–0.39 (uniform spheres) or even less (mixtures); with the exception of the bed characterised by $D/d_{part} = 3.8$, for which the porosity is 0.419. In the next section, the case of loose beds will be discussed.

Each set of experimental data, i.e. group of data, obtained with a given bed, is modelled with an equation of the form:

$$f_{part} = \alpha[1000\,Re_{part}^{-1} + 60\,Re_{part}^{-0.5} + 12]$$

$$\text{with } \alpha\left(\frac{1-\varepsilon}{\varepsilon^3}, \frac{D}{d_{part}}\right) = a\left(\frac{1-\varepsilon}{\varepsilon^3}\right)\left[\frac{D}{d_{part}}\right]^b \quad (8)$$

where α is considered to have a constant value for a given bed. As previously pointed out in Ref. [1] and as can be seen, for example in Fig. 1, this form of equation conveniently represents a set of data. On the opposite, for low values of (D/d_{part}) studied in this work, the well known equation of Ergun [10] yields a great scatter with experimental data in the range of particle Reynolds numbers larger than 100–200 (Fig. 1).

The recomputed values of the constants a and b, including all available data (new data, the characteristics of which are presented in Tables 2 and 3, as well as data previously used in Ref. [1], are

$$a = 0.061 \quad \text{and} \quad b = 0.20 \quad (9)$$