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Pressure drop in slender packed beds with novel packing arrangement

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ABSTRACT

With the low pressure drop requirement in industry applications, a kind of slender packed bed with novel packing arrangement is proposed in the present study. It is based on the well-known principle that, in packed bed at $2 < D/d < 3$, particles in contact with the wall tend to form a highly ordered ring structure. The pressure drop characteristic is investigated by experiment. The hydrodynamics in the novel packing is quite different from the random packing. Therefore, the Carman equation is modified to fit the experimental data with the mean deviation of 4%. The novel packing shows more favorable pressure drop characteristics than the random packing and the simple cubic structured packing. It would be useful for the optimum design in industry applications.

1. Introduction

Packed beds have a wide application in the chemical, agricultural and metallurgical industries as reactors, dryers, filters, heat exchangers, and adsorbers. The popularity of packed beds originates largely from the convenience in construction and operation as well as their low cost. It has driven an almost incredible number of studies investigating the mechanisms of heat and mass transfer, and the flow and pressure drop of the fluid through the bed of solid for the high economic value represented by packed beds, and continue to do so [1].

Although a considerable number of investigations in random packed beds are well presented in literature [2–5], the flow and heat transfer performance of traditional random packed beds may not be optimal [1,6]. The pressure drop in such packed beds is usually much higher than that in other packing forms, and the overall heat transfer performance may be greatly lowered. With the low pressure drop requirements or other specific demands in industries, the development and application of the novel packing and reactors have been increasing over the last decades.

Calis et al. [1] and Romkes et al. [7] investigated the flow and heat transfer characteristics in a variety of composite structured packed beds of spheres with the computational fluid dynamics (CFD) and the experimental method. The results showed that the effects of packing forms on the macroscopic flow and heat transfer characteristics were remarkable. By using composite structured packing, the pressure drop could be greatly reduced. Yang et al. [6,8] and Bu et al. [9] studied the flow and heat transfer characteristics in some novel structured packed beds. It revealed that, with proper selection of packing form, the pressure drop in the structured packed bed could be greatly reduced and the overall heat transfer performance would be improved.

Compared with the structured system, the random packed bed is more convenient for construction due to its simple structure as well as the availability of much accumulated design knowledge. It is thought to be the default catalytic reactor for at least a few decades. If a kind of random packing could be equivalent to the structured arrangement on the pressure drop characteristics, it will be a competitive choice than the structured packed bed to the applications with the low pressure drop requirement.

The emerging packed bed with small tube to particle diameter ratios ($2 < D/d < 3$) could be a promising choice. The radial porosity variations for mono-sized spheres in cylindrical containers have been investigated extensively by using experimental and numerical methods for decades [10–12]. In recent studies, a special packing structure was found in the packed bed with small tube to particle diameter ratios.

Theuerkauf et al. [13] conducted the simulations to the porosity distribution of spheres in packed beds with small tube to particle diameter ratios by the discrete element method (DEM). For most cases, the radial porosity distribution extracted from the DEM simulations matched the correlations in literature quite well. However, with the ratios decreasing to 2.6 and 2.54, a special structure was observed that a straight hole formed along the centerline with the radial porosity value almost to 1. That was compared with the experimental data of Mueller [11] and the simulation tracked the experimental result fair well. Yang et al. [14] used the electrochemical technique to study flow transitions in random packed beds with small tube to particle diameter ratios. In the experiment, the special packing structure was reproduced and it was verified by the DEM method in a good agreement with the real packing structure. Ren et al. [15] carried out a systematic investigation on the porosity and velocity distribution in packed bed by using a combination

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of different Nuclear Magnetic Resonance (NMR) techniques. In their study, a pronounced velocity peak was observed along the centerline of the packed bed at $D/d = 2.7$. In this packed bed, a semi-regular pentagonal arrangement was favored. And a corridor formed at the center where fluid flowed mostly unaffected by obstacles. Huang et al. [16] studied the influence of D/d ratios on the distribution of porosity and velocity in packed beds by optical measurement technique in conjunction with matched refractive index fluid and particles. It showed that the highly ordered ring structure of the packed bed resulted in a channel along the centerline, where significant bypass flow was observed.

Therefore, in the present work, packed beds with a novel structure are proposed, which have very favorable pressure drop characteristics. This kind of packed bed is based on the well-known principle that, in random packed bed, particles in contact with the wall tend to be highly ordered within a particle diameter from the wall. Hence, for the packed bed at $2 < D/d < 3$, most particles in the tube are adjacent to the wall easily and can form a highly ordered ring structure, which lead to a hollow structure of the packed bed with lower tortuosity. Therefore, the pressure drop required to obtain a certain fluid velocity in this packing arrangement is significantly lower than the pressure drop needed to obtain the very same fluid velocity in the conventional packed beds. It is benefit for rapid heat removal and higher reaction rates. To a certain extent, this kind of packed bed can be considered as the hybrid of structured packed bed and random packed bed with small tube to particle diameter ratios ($2 < D/d < 3$).

The pressure drop can be greatly reduced by using the proposed packing arrangement. Therefore, traditional correlations are questionable for predicting pressure drop in the packed bed. Since it is very important for determining the required pumping power in practical applications, an experimental study is conducted to investigate the pressure drop of the novel packing in this work. The result is compared with the predictions by traditional correlations for random packed bed. Then a modified Carman [17] correlation is developed to estimate the pressure drop for the novel packed bed. According to authors' knowledge, almost no attentions have been paid to such packing yet. Some interesting phenomena are obtained. These results can provide some reliable experimental basis for the optimum design in industry applications.

2. Description of experiments

2.1. Test facility

The schematic of the experimental apparatus is shown in Fig. 1. It mainly consists of three parts: water flow loop, test section and measurement equipment. Water is supplied by the centrifugal pump from the reservoir tank to the test tube in most cases. For tests at low flow rate, an elevated tank is used to supply steady and constant water head. The flow rate is adjusted by the inflow valve and the bypass valve. After passing through the test tube, water is collected and back to the reservoir tank. The test section is made of polymethyl methacrylate (PMMA) with the length of 1000 mm. Three pairs of pressure taps are set uniformly to measure the pressure drop at different positions. To avoid the inlet and outlet effects, two pairs of pressure taps are 200 mm away from both ends of the column and another pair of pressure taps in the middle. Each pair of taps makes a 120-degree angle with radial holes 2 mm in diameter to provide an average pressure reading and prevent blockages. At the inlet and the outlet of the test section, two pieces of pore plate are used between the flanges to support the bed and prevent the particles from leaving the bed.

Two Keller differential pressure transmitters with high accuracy are mounted on the test section to measure entire and half pressures drop. The flow rates of water are measured by Endress + Hauser mass flow meter. The temperature is monitored by a thermometer immersed in the reservoir tank. The flow meter and differential pressure transmitters are calibrated prior to the experiment. A Data Acquisition System is realized via National Instruments data acquisition products and a computer program written in LabVIEW.

2.2. Test beds

All experiments are conducted with glass beads. The diameters of spherical beads used as packing material are 14.20 mm, 15.00 mm and 16.20 mm. The diameter of the cylindrical column is 40.90 mm. For each particle size, a sample of one hundred particles is measured. The size of the spheres and tubes is measured using a caliper with a precision of ±0.05 mm.

Although a channel is highly likely to form along the centerline, there are still a few particles located along the centerline. Therefore, in order to get an ideal packed bed without blockages, a small tool – a stainless steel rod – is used in the assembly of the packed bed. In the assembly, after carefully filling the packed bed with 10–20 particles, the rod is inserted into the free channel. Then, the rest of particles is poured into the tube. In order to get a robust structure, the bed is vertically vibrated by hand after the filling process. When the assembly is finished, the rod is pulled out.

The packed bed mean porosity is measured by the water displacement method and weighting method cited in Ref. [18]. The average

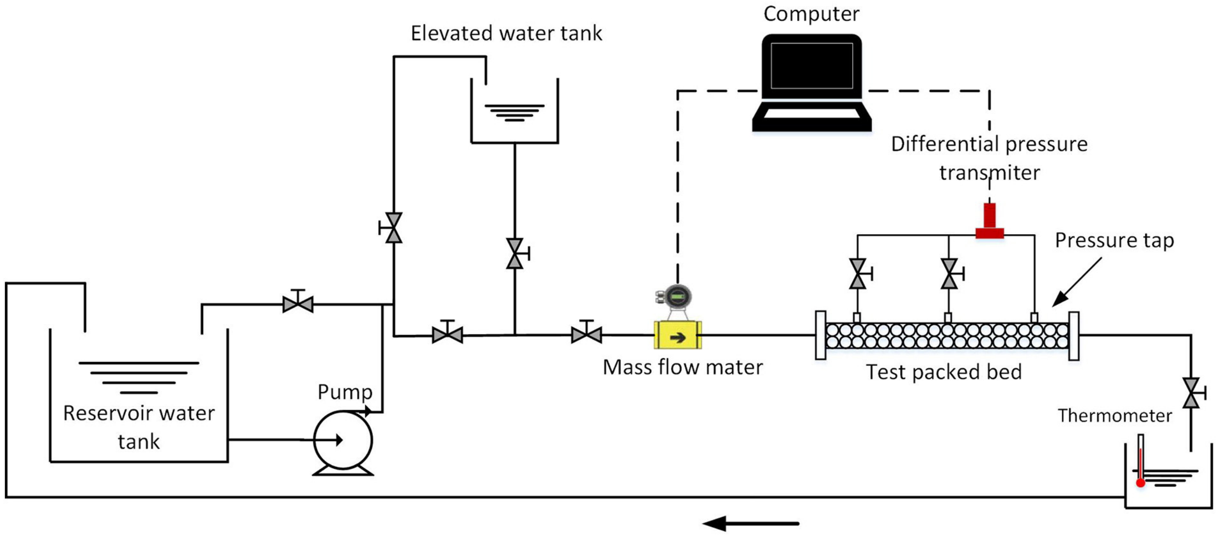

Fig. 1. Schematic of the experimental system.