Experimental Investigation of Fluid Flow Hydrodynamics in Porous Medium Pipeline

Hongsheng Liu¹, Dan Wu², Lin Liu¹

¹.Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian, China;
².Department of Mechanical and Power Engineering Yingkou Institute of Technology, Yingkou, China

lhsh@dlut.edu.cn

Abstract. Porous medium square pipelines with pellet packed bed and cylindrical packed bed are employed to experimentally study the flow characteristics of water. Differences of flow characteristics between the pellet packed bed and cylindrical packed bed, as well as the circular pipe and the square pipe, are discussed by measuring the pipeline pressure drop under different flow rate, and the relationship between the pipe resistance coefficient and flow is analyzed. The results show that the pressure drop per unit length in the square pipe increases with the increase of flow rate and increases with the decrease of pellet diameter. The structure of large diameter pellet packed bed is more advantageous to form a relatively stable flow.

1. Introduction
Flow through porous medium is a common phenomenon in nature and practical engineering applications, such as the hydrology, soil physics, civil engineering, petroleum technology, and so on[1]. As porous medium is a complex geometric system with multi-scale random structure, the flow behaviour in porous medium is extremely complex. The establishment of an accurate geometric model of the porous structure is a prerequisite for the study of flow and heat transfer in porous medium. Up to now, the existing structural reconstruction methods of porous medium include physical method[2], numerical method[3], fractal theory[4], etc. Recently, a geometric structure of randomly packed beds is modeled using the discrete element software LIGGGHTS[5]. Due to the complex structure of porous media, the number of generated grids is often huge and the computational requirements are high[6]. To describe the fluid transport in packed bed, Carman[7] derived an expression of pressure drop under viscous flow regimes, so called Carman-Kozeny equation. Thereafter, Ergun[8] combined the laminar flow Carman-Kozeny equation with the fully turbulent flow Burke-Plumner equation, and proposed a popular semi-empirical equation covering laminar and turbulent conditions. Ergun equation not only took into account the influence of viscous resistance and inertia force, but also considered the influence of porosity of porous medium, which was found to be applicable to a broad spectrum of fluids and packing materials. Since then, scholars proposed various correction for the Ergun equation to make them applicable to specific flow environments. Comiti et al.[9] characterized the Darcy flow regime with different types of particles in terms of the different Reynolds number. Li and Ma[10] examined the applicability of the Ergun equation to flow resistance assessment for packed beds with non-spherical particles. Calis[11] predicted the pressure drop...
characteristics over the full relevant range of Reynolds with a simple two-parameter model, which was obtained from a fully laminar flow and a fully turbulent flow. Li[12] measured the pressure drop of saturated micro-pellet packed bed under different flow rate, and compared the experimental data with the calculation value of Ergun equation in non-Darcy regime. Kundu[13] explored the functional relation of pressure gradient with velocity in terms of friction factor and Reynolds number based on different characteristic length.

Traditional theory and numerical simulation researches generally used the macro simplified method based on the equations of the macroscopic volume average, or simplified the three-dimensional complex structure into a two-dimensional porous structure. However, a two-dimensional porous medium model actually represents a cylindrical stacking bed structure, and the real porous medium is a three-dimensional spherical stacking bed structure. The validity of the two-dimensional model depends on the similarity of the flow characteristics of the two kinds of stacking bed structures. It is necessary to study the difference of the flow characteristics between the spherical stacking beds and the cylindrical stacking beds. In the present work, pressure drop of water flow in porous medium pipeline is obtained through experimental study, and the differences of flow characteristics between square pipe packed bed and circular pipe packed bed, pellet packed bed and cylinder packed bed are discussed, which will provide guidance for the correction of two-dimensional simplified model of the random pellet packed bed.

2. Experimental equipment and procedures

2.1 Experimental equipment
The schematic view of the experimental device is shown in figure 1. The experimental system consists of a mainstream pipe, water tank, water pump, control valve, reflux valve, pressure meter, flow meter, etc. During the experiment, the water is powered by the water pump and the flow is controlled by the control valve and reflux valve. The flow rate of water from below to above in the mainstream pipe is measured by a flow meter and the pressure at the inlet and outlet of the pipe are measured by two pressure meter, respectively.

![Figure 1. Structure schematic of the flow experiment](image)

2.2 The experimental procedures
In the experiment, we first measure the porosity of porous media and then record the pressure in the inlet and outlet to analyze the pressure drop in two types of packed bed pipes with different water flows. Considering the error in the diameter of the pellets, the density method is used to measure the porosity of the porous media. Firstly, twenty pellets with similar diameter are selected to measure the diameters of each one and the total volume of the pellets are obtained. Then, the pellets are weighed by an electronic balance and the average density of the pellets are calculated. Afterwards, the total mass of the pellets in the mainstream pipe is measured and the total volume of all the pellets is calculated by the average density. The porosity of the pellets packed bed can be calculate by the total volume of the mainstream pipe and the volume of the pellets. The porosity of different diameter pellets can be gained by repeating above procedures. The porosity of the pellets with different diameter are shown in table 1. It can be seen from table 1 that the porosity of the pellet packed bed
increases with the increase of the pellet diameter. As the sizes of the quartz cylinders are uniform with each other, the porosity of the quartz cylinder packed bed is easily to calculated by the volume of single quartz cylinder, the quantity of the cylinders and the total volume of the mainstream pipe. It is calculated that the porosity of quartz cylinder is 0.386 for diameter of 8mm and 0.393 for diameter of 10mm in the present experiments.

In the flow character experiment, the control valve and the reflux valve are fully open firstly. Then, the water pump is switched on, and the control valve and the reflux valve are adjusted to the gain the expected flow. When the flow in the pipe keeps constant, the data of each pressure gage at the inlet and outlet of the mainstream pipe are recorded. When a set of experiment is finished, the diameter of the packed pellets or cylinders will be changed and the above experiment steps will be repeated.

Table 1 porosity of different pellets packed bed

| Diameter of each pellet (mm) | Total mass of the pellets(g) | Pellets density(g/cm³) | Total volume of the pellets(cm³) | Porosity of the packed bed |
|------------------------------|------------------------------|------------------------|----------------------------------|---------------------------|
| 3                            | 7731.7                       | 2.4129                 | 3204.31                          | 0.350                     |
| 6                            | 7866.9                       | 2.4292                 | 3238.47                          | 0.365                     |
| 8                            | 7670.5                       | 2.4499                 | 3130.94                          | 0.386                     |
| 10                           | 7671.3                       | 2.4782                 | 3095.51                          | 0.393                     |
| 20                           | 6783.5                       | 2.4423                 | 2777.50                          | 0.455                     |

2.3 Experimental empirical relations
The pressure drop in porous medium can be represented in terms of the particle diameter and fluid velocity as Ergun equation [8], which considered the effects of the viscous force, the inertia force and the porosity:

\[
\Delta p \over L = A \mu v \left( \frac{1 - \varepsilon}{\varepsilon^2} \right)^2 + B \frac{\rho v^2}{d} \frac{1 - \varepsilon}{\varepsilon^3}
\]

(1)

Where \( \Delta p \) and \( L \) are the pressure drop and the length of the experimental section respectively. \( \mu \), \( v \) and \( \rho \) is respectively the viscosity, velocity and density of the fluid. \( d \) is the diameter of the pellets. \( \varepsilon \) is the porosity of the packed bed. \( A \) and \( B \) are constant coefficients. The friction coefficient is calculated by the equation of Montillet [14] (equation 2) in this work, which is compared with the empirical formula given by Carman [7] (equation 3):

\[
f = \frac{-\Delta pd}{L\rho v^2}
\]

(2)

\[
f = (180 + 2.871(\frac{Re}{1 - \varepsilon})^{0.8})(1 - \varepsilon)^2
\]

(3)

Where \( f \) is the resistance coefficient. \( Re \) is the pore Reynolds number in porous medium which can be expressed as: \( Re = \frac{d v d_h}{\mu \rho} \), where \( d_h \) is the equivalent diameter of the porous medium.

3. Experimental results and discussions

3.1 Experimental empirical relations
The comparison of pressure drop per unit length between the square pipe and the circular pipe is shown in Figure 2. The data of the circular pipe is from Li’s experiment [10], where a glass circular pipe with a length of 1000mm, an inner diameter of 50mm are employed and two types of glass pellets with diameter of 3 and 8mm are used. It can be seen that the pressure drop curve of the square pipe is consistent with the circular pipe when the diameter of the pellet is 3mm, and the error is below 5.8%. However, the difference between the square pipe and the circular pipe ranged from 66.7% to 70% as
the diameter of the packed bed pellet is 8mm. It indicates that the flow characteristics of the circular pipe and the square pipe are similar when the diameter of the packed pellets is small.

Figure 2. pressure drop of square pipe and cylindrical pipe

3.2 Analysis of fluid flow characteristic parameters in square pipe
Figure 3 shows the effect of pellet diameter on the resistance coefficient of the pellets packed bed. The square pipe experimental data in this work and the empirical formula results of Carman[7] for circular pipe are presented. It can be found that when the diameter of the pellets is small, such as 6 mm and 3 mm, the experimental results almost coincide with the empirical formula. However, there is a large difference between the square pipe experiment and the empirical formula as the diameter of the pellets are larger than 6 mm. It indicates that the empirical formula for circular pipe can be employed by the square pipe as the diameter of the pellets is small, while the pressure drop need to be corrected when the diameter is large. More detailed study on the critical diameter needs to be done in the following work.

3.3 Contrast of the pressure drop between pellets bed and cylinders bed
Figure 4 shows the differences of flow characteristics between the pellets packed bed and cylinders packed bed. The porosity of the cylinders packed bed is same with the pellets packed bed by adjusting the interval between each cylinder.

Figure 4. Pressure drop in the pellets and cylinders packed bed

It can be found in figure 4 that the differences of pressure drop between the pellets packed bed and cylinders packed bed diminishes gradually as the diameter of the pellets and the cylinder turn large, for instance, the The biggest difference for the diameter of 10mm is 31.5%, while it is 68.9% for the diameter of 8mm. According to the relationship between diameter and porosity, it can be concluded that the the differences between the pellets and cylinders packed bed decreases with the increase of porosity.
For the CFD simulation, the three dimension structure of the pellets packed bed can be expressed as figure 5(a), and the cylinder packed bed can be simplified as a two-dimensional structure such as shown in figure 5(b). To some extent, we can conclude that the two-dimensional strip structure can reflect the flow characteristics of three-dimensional random packed structure which will simplifying the simulation.

4. Conclusions
Experiments on the flow characteristics of single-phase liquid in the pellets packed bed and the cylinders packed bed are presented in this work, and following conclusions can be drawn: The flow characteristics of the circular pipe and square pipe are similar as the diameter of the packed pellets is small. Under the same flow rate, smaller diameter pellets correspond to greater pressure loss, which suggests that large diameter pellet packed structure is more advantageous to form a relatively stable flow. The empirical formula for circular pipe can be employed by the square pipe as the diameter of the pellets is small, while the pressure drop need to be corrected when the diameter is large. The two-dimensional strip structure can reflect the flow characteristics of three-dimensional random stacking

5. References
[1] Mandal D, 2015, Hydrodynamics of particles in liquid-solid packed fluidized bed, Powder Technol. 276, 18-25.
[2] Song Y C, Jiang L L, Liu Y, 2012, An experimental study on CO2/water displacement in porous media using high-resolution Magnetic Resonance Imaging. International Journal of Greenhouse Gas Control. 10, 501-509.
[3] Roozbahani M M, Huat B B K, Asadi A, 2013, The effect of different random number distributions on the porosity of spherical particles, Advanced Power Technology. 24, 26-35.
[4] Miao T J, Yu B M, Duan Y G, Fang Q T, 2014, A fractal model for spherical seepage in porous media, International Communications in Heat and Mass Transfer. 58, 71-78.
[5] Zhao J D, Shan T, 2013, Coupled CFD-DEM simulation of fluid-particle interaction in geomechanics, Powder Technology, 239, 248-258.
[6] Jiang L S, Liu H, Wu D, Wang J S, Xie M Z, 2018, Pore-scale simulation of vortex characteristics in randomly packed beds using LES/RANS models, Chemical Engineering Science, 177, 431-444.
[7] Carman P C, 1937, Fluid flow through granular beds. Trans. Inst. Chem. Eng. 12, 150-166.
[8] Ergun S, 1952, Fluid flow through packed columns, Chem. Eng. Prog. 48, 89-94.
[9] Comiti J, Sabiri N E, Montillet A, 2000, Experimental characterization of flow regimes in various porous media-III: limit of Darcy's or creeping flow regime for Newtonian and purely viscous non-Newtonian fluids, Chem. Eng. Sci. 55, 3057-3061.
[10] Li L X, Ma W M, 2011, study on the effective particle diameter of a packed bed with non-spherical particles, Transp. Porous Media. 89, 35-48.
[11] Calis H P A, Nijenhuis J, Paikert B C, Dautzenberg F M, 2001, CFD modelling and experimental validation of pressure drop and flow profile in a novel structured catalytic reactor packing. Chemical Engineering Science. 56, 1713-1720.
[12] Li Z P, Sun Z N, Liao Y H, 2009, The research on the resistance characteristics of micropellet packed bed porous media in non-Darcy regime, Applied Science and Technology, 36(4), 61-64.
[13] Kundu P, Kumar V, Mishra I M, 2016, Experimental and numerical investigation of fluid flow hydrodynamics in porous media: Characterization of pre-Darcy, Darcy and non-Darcy flow regimes, Powder Technology. 303, 278-291.
[14] Montillet A, Akkari E, Comiti J, 2007, About a correlating equation for predicting pressure drops through packed beds of pellets in a large range of Reynolds numbers, Chem. Eng. Process. Process Intensif. 46, 329-333.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (51576029, 51606176).