Flow Resistance Characteristics of Power Low Fluid Flow Through the Structured Porous Media

Xingwang Tian, Ao Li, Feng Liu*, Dianguang Zhang and Lin Xu

ABSTRACT

The flow characteristics of power law fluid in finite wall three-dimensional structured packed beds of spheres was investigated experimentally. The packed beds of spheres was in Simple Cubic configuration and enclosed in square cross-section duct, and the Partially Hydrolyzed Polyacrylamide (HPAM) solutions with different concentrations and temperatures was chosen as the working fluids (a power-law type non-Newtonian fluids). The relationships between the friction factor and Reynolds number was verified by the modified Ergun type equations. And found that the coefficients $A_e'$ and $B_e'$ had certain relations with the power index and would vary for different concentrations and temperatures of the fluids. However, the results showed that the existing Ergun correlations for random porous media failed to predict the resistance factor for finite wall structured beds, and the new modified Ergun correlation was proposed and verified to be valid for power law fluid. At last, the study highlighted the need for pinpointing of the different flow regimes.1

INTRODUCTION

The flow characteristics of non-Newtonian fluid in porous media is a universal physical process in nature, industry and agriculture. Such as ceramic processing, liquid composite molding, food processing, enhanced oil recovery etc. Reviews of many theoretical and experimental studies can be found in the works[1-6]. Here, the widely-used semi-empirical modified Ergun equation of power law fluid is given:

1Xingwang Tian, Feng Liu*, Dianguang Zhang Dalian Ocean University, Liaoning, China
Ao Li, China Construction Second Engineering Bureau Co., Ltd., Beijing, China
Lin Xu, Dalian University of Technology, Liaoning, China
\[
\frac{\Delta P}{L} = A \cdot \frac{\mu u^n}{d_p^{n+1}} \cdot \frac{(1-\varepsilon)^{n+1}}{\varepsilon^{2n+1}} + B \cdot \frac{(1-\varepsilon)}{\varepsilon^3} \cdot \frac{\rho u^2}{d_p} 
\]

(1)

where A and B are empirical constants, \( \Delta P \) is the pressure drop, Pa, \( L \) is the bed length, m, \( u \) is the flow velocity, m/s, \( \rho \) is the fluid density, kg/m\(^3\), \( \mu \) is the viscosity of fluid, Pa/s, \( d_p \) is the particle diameter, m, \( \varepsilon \) is the average porosity.

However, Limited information is available concerning the wall effects on the pressure drop of non-Newtonian fluids for structured packed beds in the published literatures. This work will present new experimental data of flow resistance characteristics for HPAM solutions flow in Simple Cubic configuration of packed spheres in square cross-section duct, as shown in Figure 1.

**EXPERIMENTAL MODEL**

The experimental system, procedure and data reduction, can be refer to the previously published work[7]. The dimensionless friction factor \( f_p \) and Reynolds number \( Re_p \) for power-law fluids in modified Ergun equation can be defined as:

\[
f_p = \left( -\frac{\Delta P}{L} \right) \frac{d_p}{\rho u^2} \left( \frac{\varepsilon^3}{1-\varepsilon} \right) = A_e / Re_p + B_e , \quad Re_p = \frac{\rho(u/e)^{2-n}}{\mu} \left( \frac{d_p e}{1-e} \right)^{2-n} 
\]

(2)

In order to accurately describe the pressure drop behavior in the real finite packed beds, one need modify the Ergun equation according to the average hydraulic radius and the wall friction factor.

\[
R_p = \frac{\varepsilon d_p}{6(1-\varepsilon) + 4(d_p/D)} = \frac{\varepsilon d_p}{6(1-\varepsilon) \cdot M}, \quad M = \frac{1 + 2d_p}{3D(1-\varepsilon)} 
\]

(3)

Using formula (3), equation(1) can be modified as follows:

\[
\frac{\Delta P}{L} = A_e \cdot \frac{\mu u^n}{d_p^{n+1}} \cdot \frac{(1-\varepsilon)^{n+1}}{\varepsilon^{2n+1}} - M^{1+n} + B_e \cdot \frac{(1-\varepsilon)}{\varepsilon^3} \cdot \frac{\rho u^2}{d_p} \cdot M 
\]

(4)

Figure 1. Schematic of finite wall structured packed beds \((D_s / d_p = 4)\).
RESULTS AND DISCUSSION

Relationship Between Friction Factor And Reynolds Number

In Figure 2, friction factor is plotted as a function of Reynolds number by experimental data, which addresses the effects of the confining wall. As depicted in Figure 2, with low Reynolds number, the experimental data follow linear, which can be named as Darcy flow, with the Reynolds number increase, experimental data gradually deviated from the Darcy flow, which can be named as non-linear flow. It showed that the ratio of \( \frac{A_E' \cdot \text{Re}_p}{\text{Re}_p} \) is not a constant but gradually decreased, and the higher concentration and the lower temperature of HPAM solution, the higher value of friction factor.

Verification of Different Models

Using the modified hydraulic diameter, the modified resistance factor \( \Lambda'(\equiv f_p \cdot \text{Re}_p) \) can be defined as a linear function of Reynolds number:

\[
\Lambda' = A_E \cdot M^{1+\eta} + B_E \cdot M \cdot \text{Re}_p = A_E + B_E \cdot \text{Re}_p
\]  

(5)

As can be observed from Figure 3, Figure 4, at lower Reynolds numbers, the existing Ergun correlations under predict the Resistance factor significantly. Actually, the Resistance factor in structured packing should be lower compared to the random beds, however, the apparent viscosity of HPAM solution is larger and viscous effects dominates at small Reynolds numbers range, which makes the total Resistance factor be larger than predicted by the existing theoretical models. As Reynolds number increases, the channeling effect is stronger than the wall friction in structured beds, and hence the Resistance factor are decreased even at higher Reynolds numbers. So it can be seen that Resistance factor are only compared well to the random packing correlations over a certain Reynolds number regime.

Figure 2. Friction factor changing along porous Reynolds number.
Therefore, it is necessary to match the experimental data with new correlation by the method of nonlinear regression curve fitting, which can be expressed as:

Figure 3. Resistance factor changing along porous Reynolds number (T=293K).

Figure 4. Resistance factor changing along porous Reynolds number (C=1.5 g/L).

Figure 5. Comparison between experimental data and fitting correlations.
Figure 5 illustrates the comparison between the correlation and experimental data. As depicted in Figure 5, the overall anastomosis of the experimental data and the proposed correlation is better, and the maximum deviation is within ±15%.

The Flow Regimes Transition

Understanding different flow regimes and the pressure drop behavior in porous media is important. The format of Figure 6 is more suitable for such purpose, resistance factor versus porous Reynolds number is plotted for different mass concentrations at 293K. Various flow regimes may be ascertained by the clear changes of the slope, which was similarly performed by Fand et al. [11].

It can be observed from Figure 6, the Darcy regime ends at about 0.85, 6.68, 13.1, 20, respectively. There are a transitional regime which lead to the Forchheimer regime starting at about 4.02, 12.6, 19.7, 166.4, and end at about 20.2, 30.7, 56.2, 241.8. Beyond the Forchheimer regime, there is a narrow transitional regime followed by likely a turbulent flow regime starting at about 25.5, 54, 78.1, 118.5. The resistance factor of turbulent flow is to be a linear with Reynolds number.

\[
\Lambda' = 7.42 \cdot 3^{n+1} \cdot \left(\frac{3n+1}{n}\right) + (0.167 + 1.6n)^{-1} \cdot Re_p
\]

\hspace{1cm}(7)
CONCLUSIONS

The characteristics of flow pressure drop of HPAM solutions flowing through three-dimensional structured packed beds of sphere have been investigated experimentally. Successful representation of the pressure drop and its dependence on velocity as expressed in the modified Ergun equations was demonstrated. The results showed that the pressure drop increased with the fluid velocity increased or the power index decreased. However, for non-Newtonian fluids, it was found that the existing correlations for predicting modified resistance factor in finite wall random beds were unsuitable for structured beds, and the new modified Ergun correlation was proposed and verified to be valid for power law fluid. Various flow regimes of Darcy, Forchheimer and turbulent flow regimes, along with transitional regimes were identified. More investigation was still expected for the non-Newtonian fluids in different structured configurations.

ACKNOWLEDGEMENTS

Project supported by Provincial Education Department Project (Grant No.L201627) and Dr. initial funding (Grant No.HDBS201801).

REFERENCES

1. 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. Chemical Engineering Science, 55:3057-3061.
2. Shenoy A. V. 1993. Darcy-Forchheimer natural, forced and mixed convection heat transfer in non-Newtonian power-law fluid-saturated porous media. Transport in Porous Media, 11:219-241.
3. Woudberg S., Du Plessis J. P.,2006. Smit G. J. F., Non-Newtonian purely viscous flow through isotropic granular porous media. Chemical Engineering Science, 61: 4299 – 4308.
4. Tang G. H., Lu y. B., 2014. A resistance model for newtonian and power-law non-Newtonian fluid transport in porous media. Transport Porous Media, 104:435–449.
5. Sabiri N. E., Comiti J.1995. Pressure drop in non-Newtonian purely viscous fluid flow through porous media. Chemical Engineering Science, 50(7):1193–1201.
6. Machac I., Caki J., Comiti J., Sabiri N.E., 1998. Flow of Non-Newtonian Fluids Through Fixed Beds of Particles: Comparison of Two Models, Chemical Engineering and Processing, 37: 169–176.
7. Tian Xingwang Xu Shiming Wang Ping. 2018. Experimental study on flow and heat transfer of power law fluid in structured packed porous media of particles. Experimental Thermal and Fluid Science, 90: 37-47
8. Christopher R H, Middleman S. 1965. Power-law flow through a packed tube[J]. I & EC Fundamentals, 4: 422-426.
9. Kemblowski Z, Michniewics M. 1979. A new look at the laminar flow of power law fluids through granular beds[J]. Rheologica Acta, 18 (6): 572–739.
10. Pascal H. 1983. Non steady flow of non-Newtonian fluids through a porous medium[J], Int. J. Engg. Sci., 21: 199-210.
11. Fand, R.M., Kim, B.Y.Y., Lam, A.C.C., Phan, R.T., 1987. Resistance to the Flow of Fluids Through Simple and Complex Porous Media Whose Matrices are Composed of RandomlyPacked Spheres. J. Fluids Eng, 109: 268–273.