Experimental study and theoretical analysis of fluid resistance in porous media of glass spheres*

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Porous media have a wide range of applications in production and life, as well as in science and technology. The study of flow resistance in porous media has a great effect on industrial and agricultural production. The flow resistance of fluid flow through a 20-mm glass sphere bed is studied experimentally. It is found that there is a significant deviation between the Ergun equation and the experimental data. A staggered pore-throat model is established to investigate the flow resistance in randomly packed porous media. A hypothesis is made that the particles are staggered in a regular triangle arrangement. An analytical formulation of the flow resistance in random porous media is derived. There are no empirical constants in the formulation and every parameter has a specific physical meaning. The formulation predictions are in good agreement with the experimental data. The deviation is within the range of 25%. This shows that the staggered pore-throat model is reasonable and is expected to be verified by more experiments and extended to other porous media.

Keywords: porous media, random packing, staggered pore-throat model, flow resistance

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1. Introduction

The study of fluid flow in porous media has extensive engineering backgrounds[1] such as, groundwater seepage, oil and gas exploitation, thermal insulation materials, pebble-bed cooling reactors, filters, catalytic fixed bed reactors, absorbers, porous material drying, and biotechnology, among others. Investigations on porous media commonly have the perspective of flow modelling, flow resistance characteristics, transport characteristics of flow, and wall effects. Studies of porous media have a long history, going back to Darcy and Forchheimer, and can be referred to extensively in literature.[2–18] The Ergun equation is the most widely used correlation. Flow resistance through porous media is the result of frictional loss and inertia, characterized by the linear and quadratic dependence on velocity, respectively,

$$\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3 d_{\rm p}^2}\mu v_{\rm s} + 1.75\frac{1-\varepsilon}{\varepsilon^3 d_{\rm p}}\rho v_{\rm s}^2. \tag{1}$$

There are two empirical constants, A and B, in the Ergun equation and the values obtained by Ergun are 150 and 1.75, respectively. Researchers[7,10,13,19–23] derived different values of A and B, as shown in Table 1.[24] There are no specific values of A and B that can be suitable for all porous media; the constants may have different values in different situations and the mechanisms need to be studied further.

In the available literature, most of the efforts are towards the determination of the validity ranges of the Ergun equation. Some researchers proposed a different flow resistance formulation, as shown in Table 2.

Table 1. Values of A and B in Ergun equation.

Source	Forchheimer flow	Turbulent flow
Ref. [7]	$A = 150$, $B = 1.75$	
Ref. [19]	$A = 411\Phi_{\rm s} - 145$, $B = 2.8\Phi_{\rm s} + 0.00698$	
Ref. [20]	$A = 160$, $B = 1.35$	$A = 193$, $B = 1.22$
Ref. [21]	$A = 180$, $B = 9.4$ $(3 \le Re_{\rm p} \le 20)$	$A = 342$, $B = 2.95$ $(Re_{\rm p} \ge 30)$
Ref. [10]	$A = 182$, $B = 1.92$ $(5 \le Re_{\rm p} \le 80)$	$A = 225$, $B = 1.61$ $(Re_{\rm p} \ge 120)$
Ref. [22]	$A = 180$, $B = 0.6$	
Ref. [23]	$A = 180$, $B = 1.8$	
Ref. [13]	$A = 141$, $B = 1.63$	

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Table 2. Formulation of flow resistance.

Source	Resistance formulation	Range of validity
Ref. [5]	$\frac{\Delta P}{L}=(1000Re_{\rm p}^{-1}+60Re_{\rm p}^{-0.5}+12)\frac{\rho u^2}{d_{\rm p}}$	$Re_{\rm p}$ very large
Ref. [6]	$\frac{\Delta P}{L}=(1000Re_{\rm p}^{-1}+125Re_{\rm p}^{-0.5}+14)\frac{\rho u^2}{d_{\rm p}}$	$Re_{\rm p}$ very large
Ref. [7]	$\frac{\Delta P}{L}=150\frac{(1-\varepsilon)^2}{\varepsilon^3 d_{\rm p}^2}\mu u+1.75\frac{(1-\varepsilon)}{\varepsilon^3 d_{\rm p}}\rho u^2$	$1\le Re_{\rm p}\le 2000$
Refs. [8] and [9]	$\frac{\Delta P}{L}=\left[\frac{25}{4\varepsilon^3}(1-\varepsilon^2)\right](21Re_{\rm p}^{-1}+6Re_{\rm p}^{-0.5}+0.28)\frac{\rho u^2}{d_{\rm p}}$	$0.1\le Re_{\rm p}\le 4000$
Ref. [25]	$\frac{\Delta P}{L}=\left(\frac{36.4}{Re_{\rm p}}+0.45\right)\frac{3(1-\varepsilon)\rho u^2}{\varepsilon^3 d_{\rm p}}$	$Re<2000$
Ref. [11]	$\frac{\Delta P}{L}=\left(\frac{150}{Re_{\rm p}}+\frac{4.2}{Re_{\rm p}^{1/6}}\right)\frac{(1-\varepsilon)\rho u^2}{\varepsilon^3 d_{\rm p}}$	$0.35\le\varepsilon\le 0.88$ $10^{-1}\le Re_{\rm p}\le 10^5$
Ref. [12]	$\frac{\Delta P}{L}=\frac{1}{2}\left[\frac{12.5}{\varepsilon^3}(1-\varepsilon^2)\right](29.32Re_{\rm p}^{-1}+1.56Re_{\rm p}^{-n}+0.1)\frac{\rho u^2}{d_{\rm p}}$ $n=0.352+0.1\varepsilon+0.275\varepsilon^2$	$1\le Re_{\rm p}\le 105$
Ref. [13]	$\frac{\Delta P}{L}=2\mu\frac{(1-\varepsilon)^2}{\varepsilon^3}a^2\tau^2u+0.0986\tau^3a\rho\frac{(1-\varepsilon)}{\varepsilon^3}u^2$	Laminar and turbulent flow
Ref. [14]	$\frac{\Delta P}{L}=\frac{\mu^2(1-\varepsilon)^3a^3\tau}{2\rho\varepsilon^3}(Re_{\rm p}+0.0121Re_{\rm p}^2)$	Laminar and turbulent flow
Ref. [15]	$\frac{\Delta P}{L}=6.8\frac{(1-\varepsilon)^{1.2}}{\varepsilon^3}Re_{\rm p}^{-0.2}\frac{\rho u^2}{d_{\rm p}}$	$500\le Re_{\rm p}\le 60000$
Ref. [16]	$\frac{\Delta P}{L}=\left(\frac{117.9}{Re_{\rm p}}+0.63\right)\frac{3(1-\varepsilon)\rho u^2}{\varepsilon^3 d_{\rm p}}$	$Re<800$
Ref. [17]	$\frac{\Delta P}{L}=(\frac{25}{Re}+0.292)\frac{6(1-\varepsilon)}{d_{\rm p}\varepsilon^3}\rho u^2$	$Re<10$
Ref. [26]	$\frac{\Delta P}{L}=a\left(\frac{1-\varepsilon}{\varepsilon^3}\right)\left(\frac{D}{d_{\rm p}}\right)^{0.20}[1000Re_{\rm p}^{-1}+60Re_{\rm p}^{-0.5}+12]\frac{\rho u^2}{d_{\rm p}}$	$10<Re_{\rm p}<2500$ $a=0.061$
Ref. [18]	$\frac{\Delta P}{L}=72\frac{(1-\varepsilon)^2}{\varepsilon^3 d_{\rm p}^2}\tau\mu u+\frac{3\tau}{4}\left(\frac{3}{2}+\frac{1}{\beta^4}-\frac{5}{2\beta^2}\right)\frac{(1-\varepsilon)}{\varepsilon^3 d_{\rm p}}\rho u^2$	

Flow resistance through a 20-mm glass sphere bed is investigated. It is found that the experimentally observed flow resistance data are much lower than the predictions of the Ergun equation. This indicates that the Ergun equation is not applicable to this situation. The staggered pore-throat model is established considering the friction loss and local loss. Moreover, a flow resistance formulation is derived.

2. Experimental study of fluid resistance in porous media

The experimental setup[27] is shown in Fig. 1. The main components of the experimental apparatus are the circulation system, the measurement system, and the test section. The circulation system includes a water tank, pump, flow meter, and valves. The measurement system includes an electronic flow meter and a differential pressure meter. The test section as shown in Fig. 2 is a quartz glass tube with an outer diameter, inner diameter, and height of 110, 100, and 250 mm, respectively. The upper and lower ends of the quartz glass tube are connected by flanges. The measurement points of the differential pressure meter are located in the flanges. Crystal glass spheres with diameter of 20 mm are used as packing materials. The glass spheres are dumped randomly in the quartz glass tube. Flow networks are equipped in the upper and lower ends of the glass tube in order to avoid the entrance and export effects, which also prevent the glass spheres from entering the pipe below. The water tank is equipped with an overflow plate to prevent excessive bubbles and make the flow steady. The fluid used in this experiment is a mixed solution of 65% benzene alcohol and 35% absolute alcohol. The mixed solution's density is 950 kg/m^3, and its viscosity is 3.7×10^{-3} Pa·s.

The main parameters of the experiment are the flow rate and the pressure drop through the test section. They are measured by the flow meter and differential pressure meter, respectively. The differential pressure meter is of the DPG409-10WDWU type (Omega Company), with a measurement range of 0–25 mbar and an accuracy of 0.08%. The flow meter is an explosion-proof electronic flow meter of the HPLWGY-DN15 type, with a measurement range of 0.6–6 m^3/h and an accuracy of 1%. The experiments were carried out twice by two graduate students at different times. The experimental setup, glass spheres, and the fluid were the same for the two experiments. The measurement ranges for the first and second experiments were from 0.095 to 1.675 m^3/h and from 0.091 to 1.554 m^3/h, respectively. The flow rate is de-

creased by a pump frequency converter. The frequency converter reduces the frequency in steps of approximately 0.5 Hz and the corresponding reduction in the flow rate is approximately 0.02–0.03 m^3/h. A set of data are recorded after an interval of 0.02–0.03 m^3/h and when the flow is stable (approximately 1 min later). Each experiment is repeated five times in order to reduce the error. Each reading must be paid careful attention, owing to the high accuracy of the differential pressure meter. The differential pressure meter is very sensitive, with an uncertainty of only 8 Pa per 10000 Pa. Although the data are recorded when the flow is stable, the pressure in the tube is still fluctuating. The reading changes quickly and the frequency of each reading is different, but these different readings will appear to be periodic when the flow is stable. The periodic pressure data should be recorded, and it is necessary to ensure the simultaneous recording of the differential pressure and the flow rate. The range of the modified Reynolds number in the experiment is $1 < Re_p < 600$. The modified Reynolds number is calculated by

$$Re_p = \frac{\rho v_s d_p}{\mu(1-\varepsilon)}, \tag{2}$$

where v_s is the superficial velocity and the porosity of the test section is 0.479.

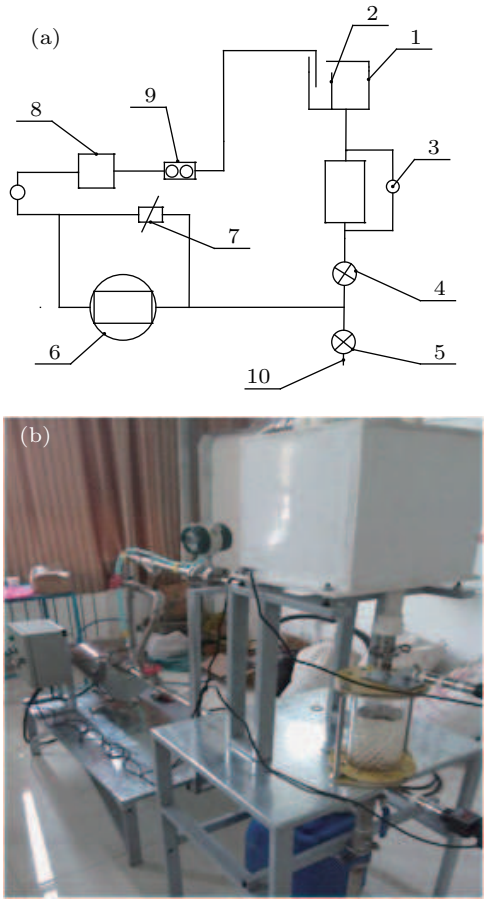


Fig. 1. (color online) Experimental setup and its practical photo. (a) Experimental setup. (b) Photo of the experimental setup. 1. Water tank 2. Overflow plate 3. Differential pressure meter 4. Ball valve 5. Ball valve 6. Pump 7. Gate valve 8. Filter 9. Electronic flow meter 10. Drain.



Fig. 2. (color online) Test section.

A comparison of the Ergun equation and the experimental data of the random porous media with 20 mm glass spheres is shown in Fig. 3. The experimental data in Fig. 3(a) were measured in the first random packing, while the experimental data in Fig. 3(b) were measured in the second random packing.

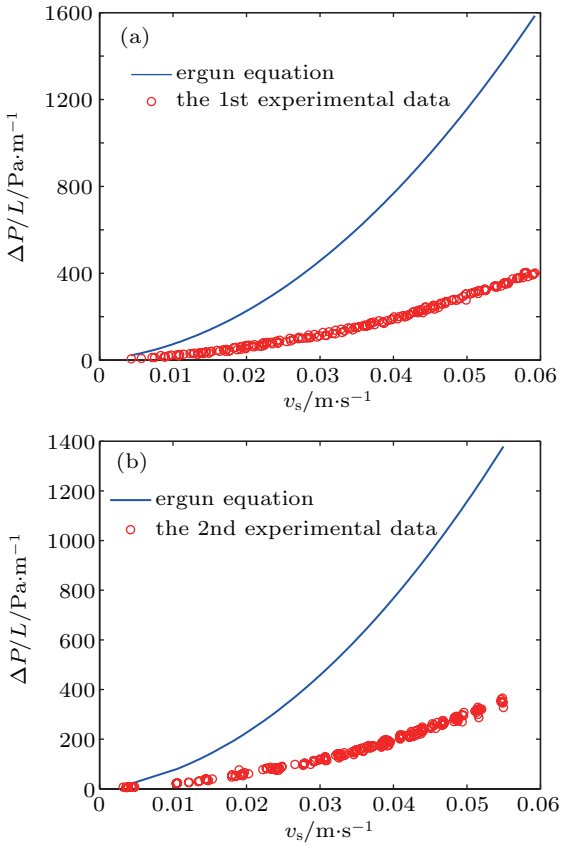


Fig. 3. (color online) Comparison of the Ergun equation with the experimental data.

There is a big gap between the experimental data and the Ergun equation, as seen in Fig. 3. It is obvious that the Ergun

equation is not suitable to describe the flow resistance in this experiment. This prompted the search for a new method for describing the flow resistance.

3. Theoretical analysis of fluid resistance in porous media

The original pore-throat model proposed by Yu and Wu[18] shows that porous media are aligned by equivalent diameter particles. A periodic unit consists of four adjacent particles. However, natural porous media are in fact more randomly staggered. Glass spheres are closer to a staggered arrangement based on the random packing of the test section. Regarding the three adjacent particles as a unit seems more reasonable. The staggered pore-throat model is established as shown in Fig. 4(a) and its geometry parameters are shown in Fig. 4(b). The hypotheses of the staggered pore-throat model are

(i) porous media are packed randomly by spherical particles with equivalent particle diameter d_p;

(ii) the particles of porous media are staggered in a regular triangle arrangement;

(iii) the velocity of the fluid in porous media is the average velocity;

(iv) fluid flows from one inlet and flows out from two outlets, where the radius of each outlet is half that of the inlet.

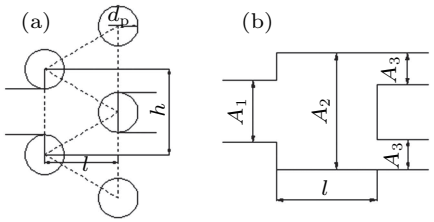


Fig. 4. Staggered pore-throat model and its geometry parameters. (a) Staggered pore-throat model. (b) The geometry parameters of the pore-throat.

The particles in porous media are in a regular triangle arrangement. d_p is the particle diameter and h is the distance between adjacent particles. Namely, the base of the triangle is h. Therefore, the height of the triangle is $l = \frac{\sqrt{3}}{2}h$. The average length of the pore-throat is l, namely the straight length along the direction of the macroscopic pressure gradient. The actual length of the fluid path is $l_t = \tau l$, where τ is the tortuosity. A_1 is the cross-sectional area of the inlet, as shown in Fig. 4, viz., the cross-sectional area of the throat. A_2 and A_3 are the cross-sectional areas of the pore and outlet, respectively.

The area of the particle A is

$$A = \frac{\pi d_p^2}{4}. \tag{3}$$

The unit area, which is the area of the rectangle A_t is

$$A_t = \frac{A}{1-\varepsilon} = \frac{\pi d_p^2}{4(1-\varepsilon)}. \tag{4}$$

A_t can also be expressed as

$$A_t = h \times l = h \times \frac{\sqrt{3}}{2}h = \frac{\sqrt{3}}{2}h^2. \tag{5}$$

The distance between the particles is determined by solving Eqs. (4) and (5) simultaneously. That is,

$$h = \sqrt{\frac{\pi}{2\sqrt{3}(1-\varepsilon)}}d_p \tag{6}$$

and l is

$$l = \frac{\sqrt{3}}{2} \times \sqrt{\frac{\pi}{2\sqrt{3}(1-\varepsilon)}}d_p = \sqrt{\frac{\sqrt{3}\pi}{8(1-\varepsilon)}}d_p. \tag{7}$$

The pore-throat ratio β is

$$\beta = \frac{h}{h-d_p} = \frac{1}{1-\sqrt{\frac{2\sqrt{3}(1-\varepsilon)}{\pi}}}. \tag{8}$$

The pressure drop through the unit is characterised as the flow resistance, which is the sum of the friction resistance and the local resistance, which are calculated below. The fluid channel is considered to be a tortuous capillary, and the pressure drop is the friction resistance loss of the circular pipe. The friction loss is

$$\Delta P_l = \rho g \lambda \frac{l_t}{d_c}\frac{\bar{v}^2}{2g} = \lambda \frac{l_t}{d_c}\frac{\rho \bar{v}^2}{2}, \tag{9}$$

where d_c is the diameter of the pipe and $\bar{v}$ is the mean velocity in the channels.

Nikuradse[28] indicates that the friction resistance coefficient is only related to the Reynolds number in the laminar flow. It is irrelevant to the relative roughness. The friction resistance coefficient is $\lambda = 64/Re$.

The Reynolds number Re is

$$Re = \frac{\rho \bar{v} d_c}{\mu}. \tag{10}$$

The friction resistance loss is

$$\Delta P_l = \frac{64}{Re}\frac{l_t}{d_c}\frac{\rho \bar{v}^2}{2} = \frac{32 \mu l_t \bar{v}}{d_c^2}. \tag{11}$$

The diameter of the channel d_c is calculated as

$$d_c = \frac{(h-d_p)+h}{2} = \left(\sqrt{\frac{\pi}{2\sqrt{3}(1-\varepsilon)}} - \frac{1}{2}\right)d_p. \tag{12}$$

The friction loss per unit length is obtained by substituting $\bar{v} = v_s/\varepsilon$

$$\frac{\Delta P_l}{l} = \frac{32 \mu \tau \bar{v}}{d_c^2} = \frac{32 \mu \tau v_s}{\varepsilon d_c^2}. \tag{13}$$

The tortuosity τ[29] is

$$\tau = \frac{1}{2}\left[1+\frac{1}{2}\sqrt{1-\varepsilon}+\sqrt{1-\varepsilon}\frac{\sqrt{\left(\frac{1}{\sqrt{1-\varepsilon}}-1\right)^2+\frac{1}{4}}}{1-\sqrt{1-\varepsilon}}\right]. \quad (14)$$

The local loss is the sum of one sudden expansion local loss and two sudden contraction local losses. The sudden expansion local resistance coefficient ζ_i is

$$\zeta_i = \left(1-\frac{A_1}{A_2}\right)^2 = \left(1-\frac{1}{\beta^2}\right)^2, \quad (15)$$

and the sudden contraction local resistance coefficient ζ_o is

$$\zeta_o = 0.5\left(1-\frac{A_3}{A_2}\right) = 0.5\left[1-\left(\frac{1}{2\beta}\right)^2\right]. \quad (16)$$

Therefore, the total local resistance coefficient ζ is

$$\begin{aligned}\zeta &= \zeta_i + 2\zeta_o = \left(1-\frac{1}{\beta^2}\right)^2 + 2\times 0.5\left[1-\left(\frac{1}{2\beta}\right)^2\right] \\ &= 2-\frac{9}{4\beta^2}+\frac{1}{\beta^4}. \end{aligned} \quad (17)$$

Each local resistance is calculated twice, considering that the inlet of this unit is the outlet of the former unit and the outlet of this unit is the inlet of the next unit. The local resistance loss coefficient should therefore be multiplied by 0.5 personally. Then, the modified local resistance loss coefficient is

$$\begin{aligned}\zeta' &= 0.5\zeta = 0.5\times\left(2-\frac{9}{4\beta^2}+\frac{1}{\beta^4}\right) \\ &= 1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}. \end{aligned} \quad (18)$$

The local resistance is

$$\begin{aligned}\Delta P_2 &= \rho g\left(1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}\right)\frac{\bar{v}^2}{2g} \\ &= \left(1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}\right)\frac{\rho\bar{v}^2}{2}. \end{aligned} \quad (19)$$

The local resistance per unit length is obtained by substituting $\bar{v} = v_s/\varepsilon$

$$\frac{\Delta P_2}{l} = \left(1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}\right)\frac{\rho v_s^2}{2\varepsilon^2 l}. \quad (20)$$

The total flow resistance is

$$\frac{\Delta P}{l} = \frac{32\mu\tau v_s}{\varepsilon d_c^2} + \left(1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}\right)\frac{\rho v_s^2}{2\varepsilon^2 l}. \quad (21)$$

The dimensionless form of the flow resistance is

$$\begin{aligned}G = \frac{\Delta P}{l}\frac{\rho d_p^3\varepsilon^3}{\mu^2(1-\varepsilon)^3} &= \frac{32\tau\varepsilon^2 d_p^2}{(1-\varepsilon)^2 d_c^2}Re_p \\ &+\left(1-\frac{9}{8\beta^2}+\frac{1}{2\beta^4}\right)\frac{\varepsilon d_p}{2(1-\varepsilon)l}Re_p^2. \end{aligned} \quad (22)$$

The dimensionless form of the Ergun equation is

$$G = 150Re_p + 1.75Re_p^2. \quad (23)$$

4. Results and discussion

Comparison of the experimental data and the model prediction is shown in Fig. 5. The dimensionless pressure drop is shown in Fig. 6. The experimental data in Figs. 5(a) and 6(a) are measured in the first random packing, while experimental data in Figs. 5(b) and 6(b) are measured in the second random packing.

The staggered pore-throat model predictions are in good agreement with the experimental data, as seen in Figs. 5 and 6.

However, the errors between the model prediction and the experimental data must still be compared, as shown in Table 3. The maximum deviation between the model prediction and the first experimental data is 22.92%. The maximum deviation between the model prediction and the second experimental data is 24.83%. The maximum deviation of all the experimental data is less than 25%. Moreover, 89.4% of the data deviate by less than 10% in the first experiment, which increased to 94.0% in the second experiment. It is concluded that the staggered pore-throat model is suitable for this experiment.

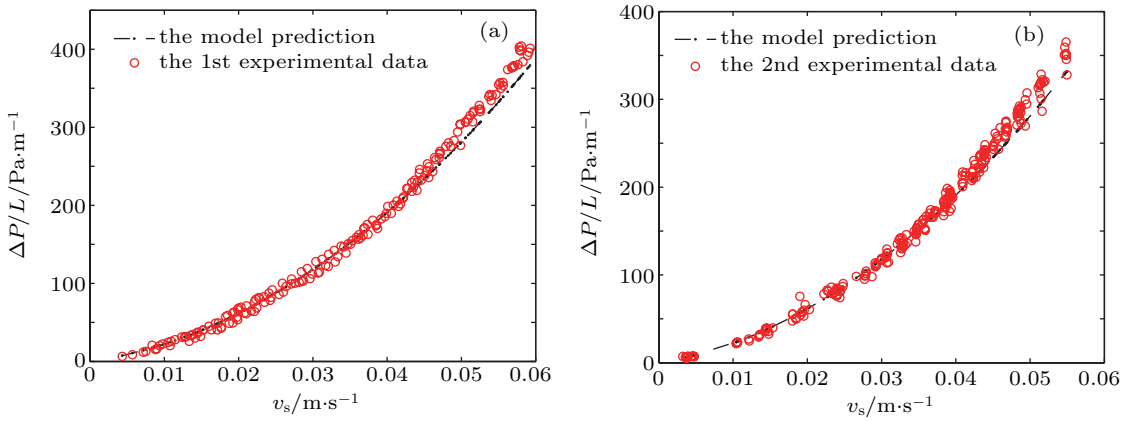


Fig. 5. (color online) Comparison of the predicted value of the model to the (a) first experimental data and (b) second experimental data.

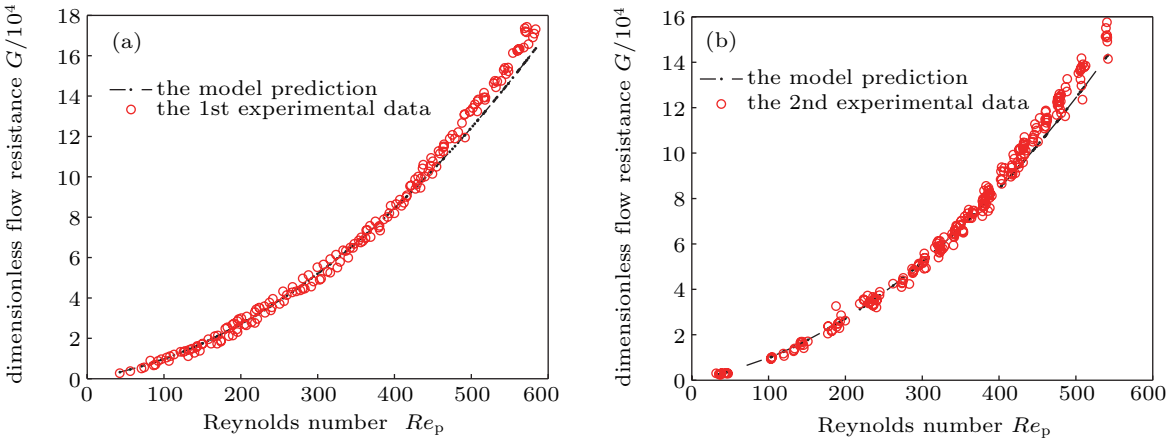


Fig. 6. (color online) Comparison of the dimensionless predicted value of the model to (a) first experimental data and (b) second experimental data.

Table 3. Comparison of the error between the model prediction and the experimental data.

Number of the experiment	Number of the experimental data	Error calculation			
		Maximum deviation	Ratio of deviation between ±20%	Ratio of deviation between ±10%	Ratio of deviation between ±5%
No. 1	180	22.92%	95%	89.4%	50.6%
No. 2	252	24.83%	98.4%	94.0%	55.6%

If the distance between the local resistances is appropriate, and the correction factor is 2.5 instead of 0.5 in Eq. (18), the final analytical formulation is consistent with the Ergun equation. 2.5 is the interference coefficient. This depends on the particle packing state and the particle shape.

5. Conclusions

(i) This experiment studies the flow resistance through random porous media of 20 mm glass spheres. It is found that the Ergun equation deviates strongly from the experimental results, and it is therefore not suitable for this experiment.

(ii) The staggered pore-throat model is established, and a formulation of the flow resistance is derived. The formulation is expressed as a function of the density, viscosity, tortuosity, porosity, pipe diameter, pore-throat ratio, and average pore-throat length. There is no empirical constant in the formulation and each parameter has a specific physical meaning. The model prediction is in good agreement with the experimental data and the maximum deviation between them is less than 25%. This indicates that the model is suitable for this experiment. However, further experimental work is required to determine whether the model can be applied to other types of porous media. Nevertheless, it provides an idea for future work.

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