Research Article

A Numerical Study on Gas Flow through Anisotropic Sierpinski Carpet with Slippage Effect

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1. Introduction

Fluid flow through natural and artificial porous media such as soils, rocks, minerals, sludge, ceramics, textile, food, paper, plants, tissues, organs, and fuel cell plays an important role in daily life and practical applications [1–3]. The permeability which represents the capability of a porous medium to permit the flow of fluids through its pore spaces is commonly used to characterize fluid flow through a porous medium. In order to determine the permeability, direct experimental measurement can be performed on a porous medium based on Darcy’s law proposed in 1856 [4–7]. Although the measured permeability is accurate and reliable, it can only be applied to a particular kind of porous material. With the rapid development of computer technology, numerical simulation has become an effective method to estimate the permeability of porous media [8–13]. A few continuous models including finite difference method (FDM), finite element method (FEM), finite volume method (FVM), and Monte Carlo method as well as lattice Boltzmann method (LBM) have been proposed to investigate fluid flow properties in porous media.

As one of the key macroscopic transport properties of a porous medium, the value of permeability depends on the microscopic structures of the medium. Therefore, pore-scale mathematical models on fluid flow through porous media are significant for predicting the permeability and understanding the physical mechanisms of fluid flow through porous media [14]. However, it is difficult to characterize the complex and irregular structures of porous media with traditional Euclidean geometry. Many porous materials are widely accepted to indicate fractal scaling laws, and fractal dimensions such as pore/mass fractal dimension, tortuosity and surface fractal dimensions, Hausdorff dimension, and...
spectral dimension have been proposed to characterize the fractal features governing the transport properties \[15-21\]. For example, Yu and Cheng [22] introduced pore and tortuosity fractal dimensions to characterize the pore structures and presented a fractal capillary bundle model for a single-phase flow through bidispersed porous media. Xu and Wei et al. [23, 24] presented analytical expressions for Kozeny-Carman constant by employing the pore fractal theory. While, Yu et al. and Xu et al. [25, 26] proposed analytical expressions for the relative permeability for the wetting and nonwetting phases with the assumption that pore size distribution follows statistically fractal scaling laws. Xu et al. [27] used fractal scaling laws to characterize the size and topology of the fracture system and presented a fractal network model for fluid flow through fractured porous media. Recently, Cai et al. [28] proposed a three-dimensional fractal model to characterize heterogeneous pore sizes in a shale stratum and presented an apparent permeability for shale. Except for fractal dimensions, Xia et al. [29] proposed two more fractal parameters (lacunarity and succolarity) to characterize the complex and irregular structures of porous media. Among various fractal models, the exactly self-similar Sierpinski carpet model with the flow path of simulating a wide range of pore sizes and configurations has long been used as a model substrate for solving transport problems through natural porous media [30]. This fractal geometry is commonly adopted to model the complex pore space geometries of porous media, and different computational methods can be performed to develop pore-scale mathematical models for fluid flow through porous media [30–33]. However, most of fractal models are limited to isotropic porous media.

Table 1: Parameters of the isotropic Sierpinski carpet models.

| Group no. | \(s\) | \(n\) | \(D_i\) | \(i = 1\) | \(i = 2\) | \(i = 3\) | \(i = 4\) | \(i = 5\) |
|----------|-------|-------|--------|--------|--------|--------|--------|--------|
| S1       | 3     | 1     | 1.893  | 0.889  | 0.790  | 0.702  | 0.624  | 0.555  |
| S2       | 4     | 4     | 1.792  | 0.750  | 0.563  | 0.422  | 0.316  | 0.237  |
| S3       | 5     | 1     | 1.975  | 0.960  | 0.922  | 0.885  | 0.849  | 0.815  |
| S4       | 5     | 9     | 1.723  | 0.640  | 0.410  | 0.262  | 0.168  | 0.107  |
| S5       | 6     | 4     | 1.934  | 0.889  | 0.790  | 0.702  | 0.624  | 0.555  |
| S6       | 6     | 16    | 1.672  | 0.556  | 0.309  | 0.171  | 0.095  | 0.053  |
| S7       | 7     | 1     | 1.989  | 0.980  | 0.960  | 0.940  | 0.921  | 0.902  |
| S8       | 7     | 9     | 1.896  | 0.816  | 0.666  | 0.544  | 0.444  | 0.363  |
| S9       | 7     | 25    | 1.633  | 0.490  | 0.240  | 0.118  | 0.058  | 0.028  |
| S10      | 8     | 4     | 1.969  | 0.938  | 0.879  | 0.824  | 0.772  | 0.724  |
| S11      | 8     | 16    | 1.862  | 0.750  | 0.563  | 0.422  | 0.316  | 0.237  |
| S12      | 8     | 36    | 1.602  | 0.438  | 0.191  | 0.084  | 0.037  | 0.016  |

Table 2: Parameters of the anisotropic Sierpinski carpet models.

| Group no. | \(s\) | \(n\) | \(D_i\) | \(\varepsilon_x\) | \(\varepsilon_y\) |
|----------|-------|-------|--------|---------------|---------------|
| A1       | 3     | 1     | 1.893  | 0              | 1              |
| A2       | 4     | 4     | 1.792  | 0              | 1              |
| A3       | 5     | 1     | 1.975  | 0              | 1              |
| A4       | 5     | 9     | 1.723  | 0              | 1              |
| A5       | 6     | 4     | 1.934  | 0              | 1              |
| A6       | 6     | 16    | 1.672  | 0              | 1              |

Figure 1: A schema for the construction process of the 2D Sierpinski carpet with \(s = 3\), \(n = 1\), \(\varepsilon_x = 1\), and \(\varepsilon_y = 1\): (a) \(i = 1\), (b) \(i = 2\), and (c) \(i = 3\) (white and gray areas represent solid and pore phases, respectively).
Because of the wide range of applications of anisotropic porous materials such as fibrous media, layered media, and rod bundles [34, 35], the discussions on fluid flow through anisotropic porous media are needed.

Recently, gas flow through microscale and nanoscale porous media has attracted increasing interests from science and engineering as it is of great significance for fuel cell, open-cell foams, membrane, microelectromechanical system, low-permeability reservoirs, energy storage devices, etc. [36–43]. When the gas molecule’s mean free path is comparable to the pore size, the gas molecules and their collision with solid wall in the microscale and nanoscale pores takes an important effect on the gas flow [44, 45]. According to Klinkenberg’s effect, the rarefied gas effect should be taken into account for the fluid regime that the Knudsen number is greater than $10^{-3}$. However, the influence mechanisms of slippage effect on the permeability of anisotropic porous media are not clear. Therefore, the present work is aimed at developing a pore-scale model for gas flow through multiscale anisotropic porous media with slippage effect based on the Sierpinski carpet model and exploring the relationship between the macroscopic gas permeability and microscopic structures of porous media.

## 2. Fractal Model

In order to characterize the multiscale structures, an exactly self-similar Sierpinski carpet model is used to generate the geometrical structure of the porous media. The 2D Sierpinski carpet model can be constructed by applying recursive algorithms on a void square with a size of $L$. Then, $n$ square solid particles with size of $C$ located at coordinate $(x_c, y_c)$ are removed. The same procedure is recursively applied to the remaining squares in the next generation. Thus, the pore phase (gray area in Figure 1) in the present Sierpinski carpet model is exactly self-similar fractal, while the solid phase (white area in Figure 1) is nonfractal. That is, the statistical property of the pore size distribution of porous media can be characterized by the 2D Sierpinski carpet model. The pore fractal dimension can be calculated by [15, 46]:

$$D_f = \frac{\log (s^{D_h} - n)}{\log (s)}, \quad (1)$$

where the scaling factor is defined as $s \equiv L/C$, and the Euclidean dimension $D_h = 2$ in a two-dimensional space. The area porosity of the $i^{th}$ generation of the Sierpinski carpet model can be determined by

$$\phi_i = \left(\frac{s^{D_h} - n}{s^{D_h}}\right)^i. \quad (2)$$

The relationship between porosity and pore fractal dimension can be gotten by combining Equations (1) and (2).
Figure 3: A comparison of present numerical results with theoretical models and experimental data: (a) permeability without slippage effect and (b) gas slippage factor vs. absolute permeability.
In order to quantitatively characterize the anisotropic properties of porous media, two anisotropic factors are introduced.

\[ \varepsilon_x = \frac{x_x}{C}, \quad \varepsilon_y = \frac{x_y}{C}. \]  

As shown in Figure 1, the anisotropic factors of \( \varepsilon_x = 0 \) and \( \varepsilon_y = 0 \) represent an isotropic Sierpinski carpet model, while the cases with \( \varepsilon_x \neq 0 \) or \( \varepsilon_y \neq 0 \) denote anisotropic Sierpinski carpet models. Table 1 lists the calculated pore fractal dimension and porosity of isotropic Sierpinski carpet models. The range of pore fractal dimension varies from 1.602 to 1.989, and the porosity value is in the range of 0.016 and 0.960. Due to computer capacity limitations, only five orders of the Sierpinski carpet model were simulated. The parameters of the anisotropic samples are summarized in Table 2. In order to compare the gas flow through anisotropic porous media with that of isotropic porous media, six groups of anisotropic Sierpinski carpet models (A1-A6) with the same pore fractal dimension and porosity as the isotropic Sierpinski carpet models (S1-S6) were used. Figure 2 shows an example of the 3rd order of the isotropic and anisotropic Sierpinski carpet models.

For the gas flow through porous media at very low Reynolds numbers, the inertial term in the Navier-Stokes equations can be neglected. Thus, the governing equations for a steady peristaltic flow of the incompressible Newtonian fluid through the Sierpinski carpet models are the continuity equation for the conservation of mass and Stokes equations for the conservation of momentum.

\[ \rho \nabla \cdot u = 0 \]  
\[ \nabla \cdot (P I + H) + F = 0 \]

where \( \rho \) is the fluid density, \( u \) is the velocity vector, \( P \) is the pressure, \( I \) is the unit diagonal matrix, \( F \) is the volume force vector, \( H = \mu (\nabla u + (\nabla u)^T) \) is the viscous stress tensor, and \( \mu \) is the dynamic viscosity. It was assumed that there are no viscous effects at the slip wall, and hence, the slippage boundary on the solid particles can be expressed by

\[ u \cdot n = 0 \]

\[ H - (H \cdot n) n = 0 \]

where \( n \) is the normal vector of the flow direction. While the fluid velocity relative to the wall velocity is zero for the no-slip boundary condition on a stationary wall, it can be expressed as \( u = 0 \).

The creeping flow module in COMSOL Multiphysics was used to solve the gas flow through the 2D Sierpinski carpet models. Methane (CH\(_4\)) with density \( \rho = 0.648\text{kg/m}^3 \), viscosity \( \mu = 1.1067 \times 10^{-5}\text{Pa} \cdot \text{s} \), and mean molecular free path \( \lambda = 6.22 \times 10^{-4}\text{m} \) was adopted as working gas. The pressure inlet and outlet were settled on the left and right sides of the initial square of the Sierpinski carpet model.
respectively. The pressure difference along the flow direction from left to right was set to be 0.75 Pa. The upper and lower walls of the Sierpinski carpet are symmetrically bordered. The mesh was controlled by a physical mesh in which a free triangle mesh was used. The fluid flow through a porous medium without source terms can be described by Darcy’s law.

\[ \mathbf{u}_{\text{out}} = -\frac{K}{\mu} \nabla P, \quad (9) \]

where \( K \) is the permeability tensor and \( \mathbf{u}_{\text{out}} \) is the flow flux through the porous medium. In most cases, the porous medium is laterally isotropic but vertically anisotropic. If the principal permeability direction is assumed to be along the coordinate axes, the permeability tensor can be expressed as

\[ K = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix}, \quad (10) \]

where \( K_x \) and \( K_y \) are the principal permeabilities along the \( x \) and \( y \) axes, respectively.

3. Results and Discussion

In order to validate the present mathematical model, the predicted permeability of the isotropic Sierpinski carpet models was compared with that of the theoretical models and experimental data. As shown in Figure 3(a), the current fractal model without slippage effect presents acceptable agreement with Kozeny-Carman equation [23] and RTM model [47] as well as available experimental results [48]. It can be seen that the permeability of porous media without slippage effect increases with the increment of porosity. However, the permeability of porous media depends not only on the porosity but also on pore fractal dimension and pore size range [22]. Thus, it is difficult to accurately estimate the permeability of porous media with permeability-porosity relationships such as the Kozeny-Carman equation and its modifications.

Based on the linear correlation for gas permeability of the Klinkenberg equation, the gas slippage factor can be expressed by

\[ b_k = \left( \frac{K_g}{K_l} - 1 \right) \bar{P}, \quad (11) \]

where \( K_g \) and \( K_l \) are, respectively, the gas permeability and equivalent liquid permeability (absolute permeability) and \( \bar{P} \) is the mean pressure. Sampath and Keighin [49] proposed Sampath-Keighin (SK) correlation for gas slippage factor based on ten tight sandstone samples as \( b_k = 13.851 \left( \frac{K_g}{\phi} \right)^{-0.53} \). While Florence et al. [50] presented a general square-root (SR) model as \( b_k = \beta (K_g/\phi)^{-0.5} \), where \( \beta \) is a fitting constant. They obtained an empirical correlation \( \beta = 293.9 M^{-0.586} \) with molecular weight \( (M) \) by fitting the
Figure 6: Continued.
experimental data for hydrogen, helium, air, nitrogen, and carbon dioxide. As can be seen in Figure 3(b), the calculated gas slippage factors by the present Sierpinski carpet model fall within the predicted range of the SK and SR models.

In order to explore the effect of fractal dimension on the permeability, a pore size range (ξ) defined as the ratio of minimum pore size to maximum pore size was introduced. The pore size range of the Sierpinski carpet model can be calculated by ξ = n/12/s’. For example, the pore size range for S1, S2, S5, and S11 are, respectively ξ_{S1} = 13/3, ξ_{S2} = 2/4, ξ_{S5} = 2/6’, and ξ_{S11} = 4/8’. According to Equation (2), the porosity for samples S1 (D_f = 1.893) and S5 (D_f = 1.934) with same order are the same, φ_{S1} = φ_{S5} = (8/9)’. While the porosity for samples S2 (D_f = 1.792) is same as that of S11 (D_f = 1.869) with same order, that is φ_{S2} = φ_{S11} = (3/4)’.

It can be found from Figure 4 that the permeability of the porous medium with the same porosity decreases with increased pore fractal dimension. It can be explained as that the proportion of small pores increases as the pore fractal dimension increases under fixed porosity, which induces the increment of tortuosity (Figure 5).

Figure 6 shows the permeability of the anisotropic Sierpinski carpet models (A1-A6). It can be clearly seen from Figure 6 that the permeability of the anisotropic Sierpinski carpet models is different from that of isotropic cases. As shown in Figure 7, the influence of anisotropy induced by ε_x ≠ 0 on the gas flow along the x axis is not evident. Thus, it can be found in Figure 6 that the effect of anisotropy induced by ε_y ≠ 0 on the permeability K_y is marginal. While the anisotropy induced by ε_z ≠ 0 can significantly enhance the permeability K_z, which can be attributed to the large capillaries formed in the case of ε_z ≠ 0 (Figures 7(c) and 7(d)). Similar results can be found for the relationship between anisotropy induced by ε_x ≠ 0 and the permeability K_x. Therefore, it can be concluded that the anisotropic factor is beneficial to the vertical fluid flow and can enhance the corresponding permeability.

In order to study the slippage effect in microscale porous media, the slippage boundary was performed on the surface of solid particles in the isotropic Sierpinski carpet models. A dimensionless parameter was defined to characterize the gas slippage effect:

$$\tau = \left| \frac{K_{slip} - K_{no-slip}}{K_{no-slip}} \right|,$$

where K_{slip} and K_{no-slip} represent the permeability with and without slippage effect, respectively.

Because the pore fractal dimension decreases with the decrease of porosity, it can be found in Figure 8 that the slippage effect strengthens as the pore fractal dimension decreases. However, the slippage effect is not a monotonically decreasing function with porosity for certain groups of samples with the same pore fractal dimension (D_f = 1.862, D_f = 1.896, D_f = 1.934, D_f = 1.969, D_f = 975, and D_f = 1.989). The reduced pore size by decreasing porosity can enhance slippage effect. While the increased proportion of solid particles by decreasing porosity can increase flow resistance and then lower the slippage effect. Therefore, the slippage parameter τ may decrease when the porosity decrease for the samples with a certain pore fractal dimension because the increased flow resistance takes a dominate effect on gas flow. Therefore, the slippage parameter τ may decrease when the porosity decrease for the samples with a certain pore fractal dimension because the increased flow resistance takes a dominate effect on gas flow.
slippage. It should be noted that only gas slippage effect in the micro- and nanoscale pores has been taken into account in the present work, other microscale effect such as transition flow and free molecular flow may be included when the Knudsen number is larger than 0.1.

4. Conclusions

In this work, a two-dimensional Sierpinski carpet model has been adopted to characterize the multiscale microstructures of porous media. And a pore-scale mathematical model has been developed to study the gas flow through both the isotropic and anisotropic porous media. The influence of microstructures and anisotropy as well as slippage effect on the permeability has been discussed. It has been found that the permeability of porous media depends on the porosity and pore fractal dimension as well as pore size range. The value of permeability increases with increased porosity and decreases as pore fractal dimension increases under fixed porosity. The flow field and permeability of anisotropic
porous media are different from that of isotropic porous media. The anisotropic factor is beneficial to the vertical fluid flow and can enhance the corresponding permeability. For the microscale porous media, gas slippage phenomena show a significant effect on the effective permeability. The numerical results indicate that the slippage effect strengthens as the pore fractal dimension decreases. However, it may be reduced by increased porosity under certain pore fractal dimensions as two competitive factors (pore size and flow resistance) are involved. The proposed fractal model shows advantages in characterizing the complex and irregular microstructures of porous media and provides a conceptual tool to understand the flow mechanisms of gas flow through the porous media. It should be pointed out that some complications such as dead-end pores, contact and overlap of solid particles, pore/particle configurations, and morphology were neglected in the proposed fractal model. As an extension to this study, it would be helpful to investigate randomly a three-dimensional fractal model.

Data Availability

The numerical data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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