Complexity analysis of the connected pore structure in 3D porous medium using meandering parameter and permeability

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Abstract. The complexity of the connected pore structure of porous media samples has been analysed using meandering parameter and permeability. The meandering parameter and absolute permeability was calculated for four porous medium models, which have porosity of 15%. Porous medium samples are generated by depositing grains of varying radius (10, 15, 20, 25 pixels) that are randomly distributed in a 200 × 200 × 200 medium. The fluid flows of the rock models were analysed on the y-direction. To trace the connected pore inside the porous medium, Simple Neurite Tracer was used which then generated the coordinate of the connected pore path for calculating the meandering parameter. Meandering parameter is calculated by using the definition of the ratio between the sum of the curvaceous angles of the connected pore path to the distance between two facing sides of the sample. Absolute permeability is calculated by simulating the Darcy’s experiment by means of Lattice Boltzmann Method. For the four sample models, it was found that meandering parameter is inversely proportional to the permeability.

1. Introduction
Rocks are porous natural objects that have varying degree of complexity. Rock as a porous medium is mainly composed of two different phases, namely the matrix of solids and the pore space [1] which is commonly found in a clastic sedimentary rock. Obtaining the knowledge regarding the characteristics of the rock is important to understand the properties associated with the fact that porous rocks are a reservoir of fossil energy sources (hydrocarbons) in the form of fluid. For example, the content of petroleum can be estimated roughly by analyzing the fraction of the pores of the rock. Furthermore, hydrocarbon fluids (oil and gas) can be easily extracted if interconnected pore structures have simple networks.

Characteristics of rocks as porous media can be described by more detailed rock pore analysis on rock microstructure studies. Studying micro-structures of porous rocks can be done by performing
computer-based modeling, by generating digital models of microstructure porous rock. The development of computer-based rock modeling has been done using various approaches, e.g., by the method of random lattice solid model developed by Mora and Place [2]. Several other studies on porous medium modeling were done by Sun [3] and Teo [4]. The porous rock model with fractal has also been developed by Feranie [5].

Modeling of the microstructure of rocks can help to understand the characteristics of the rock by adjusting the parameters almost with no limits. Natural samples of rocks have limitations in terms of the specific diversity where one cannot always obtain samples in accordance with the required analysis. Simple models can be used to analyze the relationship between various physical quantities with micro parameters so that important physical properties such as porosity, permeability, and tortuosity of rocks can be estimated based on the relation obtained [6].

In various studies on porous media, especially rocks, digital image analysis is used to determine the characteristics of pore structure because experiments in terms of assessment of fluid flow complexity in the porous medium more easily done [7-13]. For example, it is known that tortuosity can be used as a parameter to determine the anisotropic properties of the porous medium from the comparison of tortuosity values in the x, y, and z-direction. Rock models can be constructed to analyze the relation between the grain size distribution of the solid matrix composite to the fluid flow complexity in it. The modeling of porous rock model in this study to analyze whether the physical parameters of tortuosity and permeability of rocks influence each other and whether tortuosity and permeability are influenced specifically by other structural parameters, such as porosity and the grain size distribution of the porous rock model.

2. Methods

3D porous medium samples are arranged by depositing a simple pure spherical grains of four varying radii (10, 15, 20, 25 pixels) that are randomly distributed in a 200 × 200 × 200 medium. The deposition is done such way that it is possible for the deposited spheres to be overlapped to each other, simulating the effect of compaction and cementation. The porosity of the four samples is 15%. Example of 3D porous medium sample can be seen in Figure 1.

![Figure 1. 3D porous medium with a porosity of 15% and a grain size 10 pixels. The blue colour indicates the solid matrix, and the red colour indicates the pore matrix.](image)

The connected pore inside the medium is represented by means of the skeletonization method. Skeletonization is the process of transforming the thickness of the sample image represented by white color in the image (pixel with value 1 in a binary image) into a new 1-pixel image of white color. This method aims to extract features of a form that represents a common form of an object. The skeletonization feature as a method of declaration of the digital rock sample paths is processed in Fiji/ImageJ software.
Figure 2. Skeletonize result of connected pore path from 3D porous medium.

The coordinates of the connected pore path from 3D porous medium samples was traced using the Simple Neurite Tracer method. Simple Neurite Tracer as a method of tracing the coordinates of the connected pore path is implemented in Fiji/ImageJ where it uses 2D as well as 3D visualizations for a more detailed qualitative analysis. In the image processing process, Simple Neurite Tracer traces the white image as a connected pore path.

From each samples, nine sets of entry-exit points of connected pore are selected. The method of calculating meandering parameter is based on the tortuosity as defined by Dougherty [14]. Meandering parameter ($\gamma$) is calculated by using the definition of the ratio between the sum of the curvaceous angles of the connected pore path ($\theta$) to the distance between two facing sides of the sample ($L$) in Equation 1:

$$\gamma = \frac{\sum_{i=0}^{n} \theta_i l_i}{L},$$  \hspace{1cm} (1)

where $l_i$ denotes the length of the $i$-th segment.

From the nine connected pore, nine meandering parameters were obtained and the meandering parameter of the medium was calculated by calculating the average value. The average value is expected to represent the medium’s meandering parameter value for each 3D porous medium samples. Several averaging methods were used to determine the value of medium meandering parameter in 3D porous medium sample, i.e., arithmetic averaging, geometric averaging, and harmonic averaging. The arithmetic averaging (arithmetic mean) is calculated by summing all the data values of a sample group, then divided by the number of samples, using Equation 2

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}.$$  \hspace{1cm} (2)

Geometric averaging (geometric mean) is calculated by multiplying all the data of a sample group, then taking the $n$-th root, using Equation 3

$$G = \left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}}.$$  \hspace{1cm} (3)

The last one is the harmonic averaging, which was calculated by converting all the data into fractions, where the data value serve as the denominator and the numerator is one, then all the fractions are summed and then used as a divisor of the amount of data. The average harmonic is often referred as the opposite of the arithmetic average. The formula of harmonic average is showed in Equation 4

$$H = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}}.$$  \hspace{1cm} (4)
The average value of meandering parameter which represents the meandering parameter of the medium were then plotted against the permeability which was calculated from a simulation using the Lattice Boltzmann method. The Lattice Boltzmann method is one of the methods to simulate and analyze the phenomenon of fluid flow in a porous medium. This method describes the fluid flow as an imaginary particle collision that is much larger in size than the size of the fluid molecule. The collision used is a perfect collision so that the law of conservation of mass and momentum is implemented in the pore space model. The basic concept of permeability is closely related to Darcy's law which describes the fluid flow through a porous medium. The formula of Darcy’s Law is described in Equation 5:

\[
\frac{Q}{A} = -\frac{k}{\mu} \left( P_i - P_o \right). \tag{5}
\]

Where \( Q \) is fluid flow rate in the pore space (m/s), \( P_o \) is fluid pressure on the exit route (Pa), \( P_i \) fluid pressure at the inlet (Pa), \( \mu \) is the viscosity of the fluid (Pa.s), \( L \) is the length of the medium (m), \( k \) is permeability (Darcy), and \( A \) is surface area of the sample (m²). Calculation of permeability in this study uses Parallel Lattice Boltzmann Solver (Palabos) on the 3D porous medium samples. After obtaining the permeability value the relation of meandering parameter with permeability to the distribution of the grain radius can be analyzed.

3. Results and Discussion

After calculating the value of meandering parameter and permeability, plot of the relation between meandering parameter and permeability of the 3D porous rock models was generated, as shown in Figure 3. Based on the graph shown in Figure 3, the general pattern shows that the greater the meandering parameter value, the smaller the permeability value.

![Figure 3. The relation of meandering parameter and permeability using Lattice Boltzmann method](image)

The plot shows that the meandering parameter is inversely proportional to permeability. This relationship is sensible because if the greater the value of meandering parameter, then the complexity of the connected pore path will be more complex so it is difficult to extract the fluid from the pore space, which means the permeability will be smaller. Based on Figure 3, the most consistent average value is the arithmetic average value, so a proper average determination method to determine the meandering parameter of the medium is arithmetic average method.
4. Conclusions
The complexity of the connected pore structure of porous medium samples has been analysed using meandering parameter and permeability parameter. For the four generated models, it was found that meandering parameter value is consistently inversely proportional to the permeability value and the most consistent averaging method is the arithmetic method.

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