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A new method to reconstruct structured mesh model from micro-computed tomography images of porous media and its application

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A B S T R A C T

Pore-scale modeling of porous media has been emphasized as a platform to study the mechanical properties, fluid storage and transport properties in it. A universal and easy-to-realize approach of structured mesh model is presented in this paper to reconstruct the three-dimensional (3D) pore scale models from the micro computed tomography (micro-CT) images. By substituting the structured hexahedron elements for the voxels in the 3D images, codes are developed to reconstruct the micro structure of porous media. The structured model is tested by the micro-CT images of four rock samples. The advantages of topology and mesh quality of this model is validated by comparisons between the PNM and unstructured mesh models. Then numerical simulations of single- and two- phase flow are conducted in *Fluent* software. The models are validated between the experimental data and simulation results of PNM on the absolute permeability and relative permeability curves under different conditions of sample wettability.

1. Introduction

The porous media is widely used in many aspects of the applied science and engineering, such as material science, geosciences, biology and biophysics [1]. Since the micro structure of most porous media is characterized by disordered, non-transparent, complex in shape and tiny in size, it is difficult to investigate and conduct experiments directly at pore scale. Many scientific efforts have been made to acquire the nano-micron scale inner details of porous media, like NMR, SEM, Micro CT, and so on. Combined with the uniaxial/triaxial test equipment or (and) multiphase flow displacement device, the microscope deformation or fluid flow experiments of porous media have been conducted. Acoustic emission device is employed to monitor the cracking development during the loading process [2]. NMR has been adopted to investigate the movable fluid in this process [3]. However, these two devices cannot be used at the same time. Micro CT is another approach for investigating the status of fluid flow, solid deformation and crack [4,5], but the resolution is limited by the core holder (for pressure or temperature loading) [6]. What's more, it is difficult to conduct real time monitoring according to the time requirements for a full scan. Meanwhile, the equipment with small size and high measuring accuracy is essential to satisfy the requirements of microscopic experiments. The transparent rock-like specimen has been adopted to print the rock matrix and investigate the inner fluid flow and crack development [7,8], but the mechanical properties and micro structures of substitutions are different from the natural rock. Thus, the pore-scale modeling representing the microstructures of porous media has been regarded as a platform for predicting the mechanical properties, fluid storage and flow capacity in it in recent years [9].

In literature, the pore-scale modeling methods can be classified into two categories: pore network model and grids models [10]. The pore network model (PNM) represents the pore space of interconnected pores and throats of simple geometry under the 3D condition [11,12], which is evolved from the capillary tubes model proposed by Purcell in 1949 [13,14]. After that, some scholars have modified the capillary tubes model by using spheres to represent pores and tubes to represent throats [15,16]. The development of PNM based on real rock structures has made enormous progress with the advent of the synchrotron μ-CT for generating 3D data sets at the micron scale [17–19]. Fluid transport calculations initially based upon reconstructions from two dimensional (2D) thin sections [20] or numerical reconstructions have been extended to 3D μ-CT images [21–23]. Yet, regular geometries (for instance, spheres and cylinders) are used to represent pores and throats, in which case the complex shapes of micro structures in porous media are unable to reproduce.

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Some authors construct the pore-scale models through segmenting the images and then extracting the outlines of pore spaces [24,25]. These models can reflect the original porous media images properly, which can be simulated in commercial software after being meshed. However, these models are mostly two dimensional, which are not able to reflect the spatial interconnectivity of the natural porous media. Some scholars have reconstructed the 3D models of porous media using the commercial reconstruction software (*Mimics*, *Amira*, *Simpleware*, etc.) or open source codes (*CGAL iso2mesh*, etc.) [26,27], by which the deformation, cracking of porous material and fluid transport properties in it are simulated [28,29]. However, the shrinking or expanding algorithm has been employed during the generation of the volume mesh, which inevitably leads to deviation of the model size compared to the original sample. What's worse, it is hard to ensure the required mesh quality of models with complex details for commercial simulation codes (see Section 3.2).

This paper proposes a universal and easy-to-realize approach for reconstructing the three-dimensional structured mesh models from natural porous media images. Structured hexahedron elements are employed to represent the voxels in the 3D images of porous media. The structured mesh model is tested on the micro-CT images of four rock samples. Furthermore, single- and two- phase flow simulations are conducted based on the Naiver-Stokes equation in *Fluent* software. The absolute and relative permeability of the models are predicted and validated by comparison between experiments and simulation results of PNM.

2. Structured mesh Modeling method

As is shown in Fig. 1, the work flow of the simulation on the mesh models can be divided into three kinds. NO. ① illustrates the most traditional way to establish the CAD model and then mesh it. NO. ② illustrates the workflow adopting the commercial reconstruction software mentioned in the introduction. The difficulties of these two methods lay in the volume mesh generation process. The model generating algorithm in this paper is numbered by NO. ③ and shown in Fig. 1.

Specifically, the approaches shown in NO. ① of Fig. 1 are explained as follows:

(1) Rock image preparation. The rock samples used in this paper are drilled from the original rock sample and scanned by Zeiss Xradia MICROXCT-400 of the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation in Southwest Petroleum University. The imaging process of rock sample is shown in Fig. 2. A cube of voxels ($300 \times 300 \times 300$ or $400 \times 400 \times 400$ pixels of the sample image) is extracted from the original micro-CT images and used as an input to the reconstructing process. The detailed information of the rock images used in this paper is listed in Table 1.

(2) Image scaling. The modeling method used in this paper is based on the similarity that a voxel in the 3D CT image is replaced with a cubic element of the same size in the 3D mesh models in the same spatial position. For a model with specific sizes, high resolution means more elements. Considering that the computer the authors used in this study is equipped with i7-2600 K and 16 GB RAM, an image scaling process is conducted in order to reduce the elements of the reconstructed mesh models. But this process is not essential for high performance computer to reconstruct the mesh models with the same micro structure as the segmented rock image.
In this way, the original sample image with 200^3 pixels, for example, can be rescaled to 100^3 pixels, to reduce the number of grids in the reconstructed models. The original (200×200 pixels with 8052 pore pixels) and scaled images (100×100 pixels with 1903 pore pixels) are shown in Fig. 3 for comparison, from which it could be found that the images are the same in geometry. Meanwhile, the calculated porosity of the original and scaled image is 20.13% and 19.03%, respectively, the discrepancy of which is acceptable.

(3) Image despeckle and segmentation. Image segmentation is a crucial step in image analysis. It aims to separate the different phases presented in the raw image by assigning to each voxel of the image the corresponding phase depending on its grey level. As a cornerstone of modern image processing, the median filter is employed for smoothing and removing noise in *ImageJ* software. The median filter works by replacing the gray scale value of a voxel with the median value of the nearest 26 surrounding cells, which realizes the process of image despeckle. Then the image is segmented using the OTSU method. The segmented three dimensional (3D) images of *B*1 and *C*1 are shown in Fig. 4(a) and (b), respectively.

(4) Nodes and elements preparation. The reconstructed 3D mesh model with 200^3 pixels contains 200^3 elements and 201^3 nodes, which are composed of the pore space and rock matrix grids. Here, the grid file containing 200^3 elements will be generated in *Abaqus* software and exported as a file with an *.inp* suffix, in which each node or element owns an individual number. The nodes and elements belonging to the matrix and the pore space will be separated in the following step.

(5) Image digitization. Image binarization is employed in this step to convert the color sample images into black and white. And we set the maximum RGB value of the image to 1, which means the value of white and black voxels is 0 and 1, respectively. Then the processed images are converted into digitalized images and stored in a 3D data matrix. Each voxel is represented by a value of 0 or 1 in its

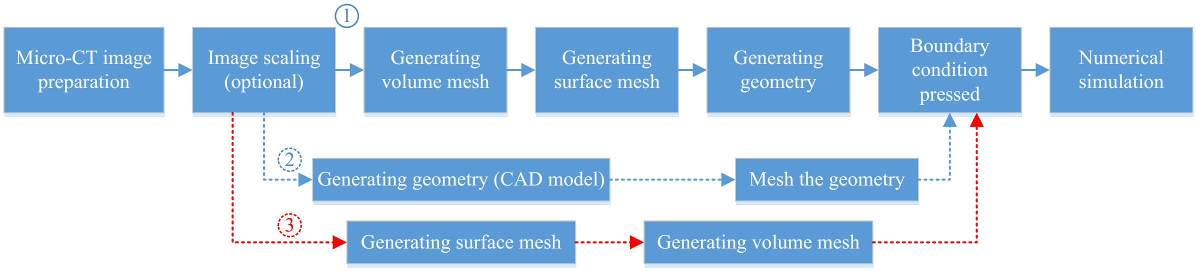

Fig. 1. Work flows of three kinds of mesh model generating.