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USE OF MICRO-CT IMAGES TO RECONSTRUCT POROUS MEDIA FOR PORE NETWORK MODEL

Bijoyendra Bera
Department of Mechanical Engineering
University of Alberta
Edmonton, Canada - T6G 2G8

Sushanta K. Mitra*
Department of Mechanical Engineering
University of Alberta
Edmonton, Canada - T6G 2G8

ABSTRACT

The present study is an investigation on the multi-phase flow, specifically oil-water phase flow inside an oil-reservoir using pore network modeling. Pore network model can be effectively used in understanding the transport process of the multi-phase flow within the pores of oil reservoirs, which are typically in the range of 2-5 μm. Pore network model consists of two main components: the description of the pore geometry inside a porous rock material and the simulation of micro-scale processes to calculate various fluid flow properties. In the present study, the realistic description of the pore space is obtained using a Berea Sandstone Core sample. A small core of suitable dimension of this core sample is extracted and micro CT images of this sample are taken at a resolution of 2.1 m. Series of images are obtained in the form of cross-sectional view of individual layers as well as its two-dimensional reconstructions. These images are processed to reveal the exact positions of the void and solid spaces inside the rock-structure according to the pixel-distribution. Maximal ball algorithm is chosen and its extended form is applied to the image data to give the three dimensional reconstruction of the rock sample. In the 3D reconstruction, pores and throats are defined separately in a deterministic way. Thus, realistic complete network is possible to extract from high-resolution micro CT images, instead working with an equi-spaced pore throat system, normally used for such modeling. Pore network model calculations of the physical properties are easier to apply on the well-defined network and the property values such as permeability or capillary pressure are matched well against the experimental data.

INTRODUCTION

Pore network modeling (PNM) has been an active research interest for major part of the twentieth century. The phenomena of flow through the porous media is most suitably represented by this model, and hence has found applications in diverse disciplines like petroleum engineering to medicine and hydrology [1]. Starting from the early works of Fatt [2], the physics behind multiphase flow in the porous media has been gradually developed, through the subsequent contribution by many of his peers. Oren et. al. [3] related PNM with the predictive studies on flow in porous media with the use of thin-section reconstruction algorithm for two-phase flows. Later, they extended the work to three-phase models [4]. Blunt [5] furthered the applications of PNM in oil-recovery with the introduction of wettabillity models [6]. Dijke et. al. [7] [8] have explored the pore-scale properties like relative permeability through network modeling.

But along with the formulation of the physics in pore space, recent decade has seen a quantum of PNM research focused on the proper description of the geometry in which the conservation laws are applied. The main objective of such initiative has been extending the network models to real porous rock materials. Advent of technologies like micro computed tomography (CT) [9] has noticed a great deal of advancement on earlier methods of geometry specification. Previously, Bryant et. al. [10] have de-

*Address all correspondence to this author, Email:sushanta.mitra@ualberta.ca

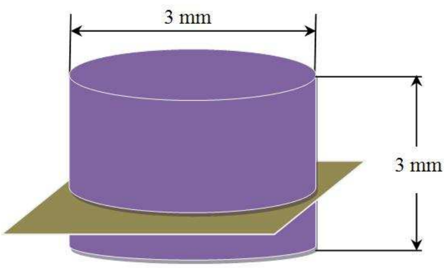

FIGURE 1. A SCHEMATIC OF THE BEREA SANDSTONE CORE AND SECTION SLICING

scribed the sedimentary processes in order to calculate the grain-centres of the void space and define the 3D geometry. Vogel and Roth [11] and Ioannidis and Chatzis [12] and others have extensively used statistical methods like two-point correlation function or Multipoint statistics [13]. The advantage of micro CT over the previous methods is that, it gives sectional images along an axis of the rock material. Hence, the reconstruction allows a direct description of the pore space.

Once the 3D representation of the pore space under consideration is obtained, network is extracted in forms of pores i.e., voids and throats to simulate fluid-flow. Among many state-of-the-art methods of network extraction, Zhao et. al. [14] used multi-orientation scanning algorithm, later exclusively expanded by Ioannidis [12]. Lindquist and Lee [15] suggested medial axis determination of the pore space, one of the first robust methods of network extraction. Later, Sillin et. al. [16] proposed maximal balls to be used in pore space description. The maximal ball algorithm has been extended by Al-Kharusi and Blunt [13] for complex throat situations and for a number of porous rock specimens like fontainebleau and sandstone.

This study reports the micro CT of Berea sandstone at a high resolution (2.1μm) and the subsequent reconstruction into a 3D pore space geometry. The shortcoming of the micro CT images at a few micro level have been analyzed which is to be eliminated in order of a more realistic pore network. Maximal Ball algorithm is adopted for the final network extraction from the pore space.

3D Pore-space Description

The network extraction process from the rock core representing the pore space is divided into several parts. In order the pore space is described, micro CT specific sample is prepared first and with this sample computed tomography is done. From the sectional images, 3D reconstruction is obtained first and maximal balls are created on it.

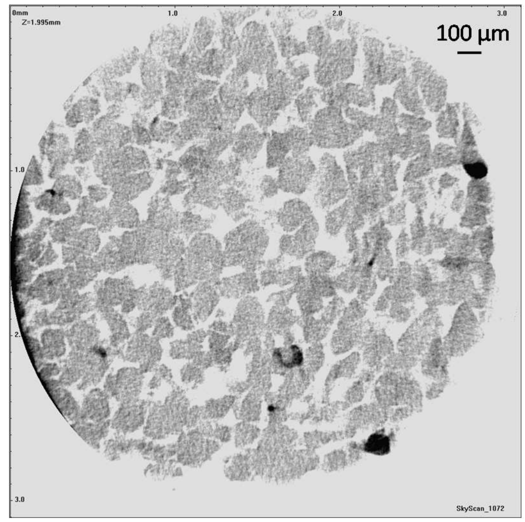

FIGURE 2. A SAMPLE MICRO CT IMAGE, SECTION ALONG THE VERTICAL AXIS, AT A DISTANCE OF 1.995 mm

Sample Preparation

Standard Berea sandstone core (5 *cm* diameter and 5 *cm* length) is taken for the sample preparation. Since, a resolution of 3μm is opted for micro CT operation, the sample is prepared accordingly. The number of pixels in a single image times the resolution provides the sample size. A cylindrical sample of 3 *mm* diameter and 3 *mm* length is prepared in this case. A flat circular piece is cut off the core. Since, standard rounding tools can't be used on brittle Berea sample, an aluminium fixture, circular and flat, is prepared for the purpose. This fixture has a hole of diameter 3 *mm* in the middle. Pressing the flat piece against the fixture and applying pressure, the sample with desired dimension is obtained. Fig.1 shows the method of preparation of sample from original core. Rubbing the sample against sandpaper produces the required surface finish on the sample for the micro CT.

Micro CT Images

The non-destructive imaging procedure of X-ray micro computed tomography was introduced around 1970 and has found innumerable applications in clinical and medical research areas [17] [18]. For the last couple of decades, micro CT has been equally groundbreaking in material science and its research sub-disciplines.

In this study, horizontal cross-section of the sample is exposed to X-rays in a Skyscan 1072 X-ray microtomograph and 3.5 seconds of exposure time is used at 100 kV and 98 μA. Two detectors work simultaneously for the X-raying of the sample, the first exposing horizontal slices and the second one monitoring the rotation of the sample in steps of $.9^0$ until 180^0. A series of images is obtained with the cross-sections approximately 6

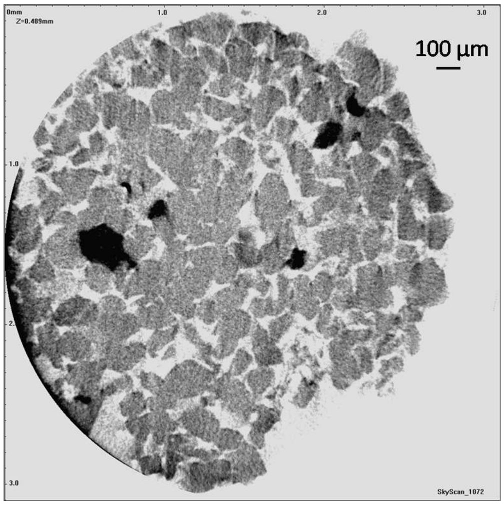

FIGURE 3. SAMPLE MICRO CT IMAGE, SECTION ALONG THE VERTICAL AXIS, AT A DISTANCE OF 0.489 mm

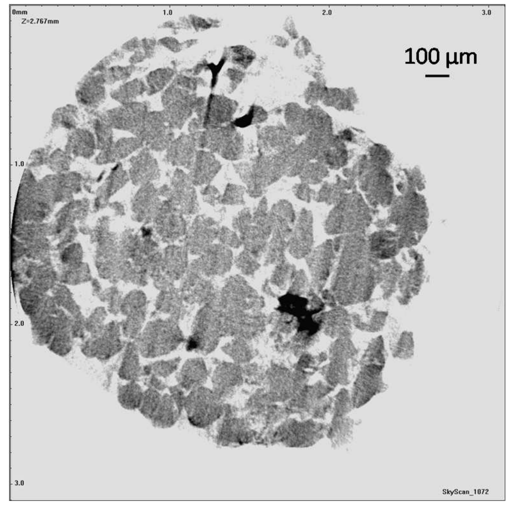

FIGURE 4. TYPICAL FEATURES (GRAINS, X-RAY PATH LENGTH CHANGE AND SCATTERING EFFECTS) AT HIGH RESOLUTION MICRO CT IMAGE, SECTION ALONG THE VERTICAL AXIS, AT A DISTANCE OF 2.767 mm

μm apart. In each of these images, the pixel values vary from 0 (white) and 255 (black). For binary images, the maximum pixel value (black) signifies the solid material in the porous structure, while the minimum pixel value (white) denotes the presence of pores. Sample images are shown in Fig.2 and Fig.3.

In micro CT images, grains are observed which are present in very small-scale, in the order of 2-5 μm or more. These grains are apparent in Fig.3 and Fig.4. Particularly, in Fig.4, a reduction in the diameter than the sample diameter of Berea is noticed. These deviations from an ideal micro CT image occur because of the high resolution used in this study. The polishing material in the sample preparation is sandpaper, which is unable to remove all the roughness from the outer surface. As a result, X-ray path lengths vary frequently, and the final images are of unequal diameter.

Moreover, 2.1 μm is the resolution limit for such micro CT instruments. Thus, detector noise and X-ray scattering effects add to the small-scale grains in the micro CT images. While reconstruction, these effects are removed first and then the images are aligned for 3D description.

Reconstruction

Based on the micro CT Images, the slices are aligned properly with respect to the alignment axis. Arbitrary axis can be chosen based on the solid-void relative distribution in the pore space. The reconstruction for a sample section is shown in Fig.5. Half-section of such similar reconstruction is depicted in Fig. 6. In the sectional reconstruction (Fig.5), the solid and pore space distribution is defined properly. In Fig.6, the alignment axis can be seen as the central line through the sectional images.

Network extraction

The reconstructions obtained provide a description of the pore space of Berea sandstone. But, in order to extract the final network in terms of pores and throats, this geometry has to be defined quantitatively or in terms of 3D voxels. In order to obtain the voxels, the micro CT images are thresholded with a standard number of the pixel value in order to get rid of the detector noises as well as the X-ray scattering effects. Then, the cross-sectional images are converted to grayscale images for efficient comparison with respect to the thresholding value, and a 3D array of the pixel values i.e., the voxel values are calculated along the whole length of the sample. This array is plotted to form the 3D reconstruction of the Berea sandstone core.

These voxel value co-ordinates provide the starting point for applying tree-search-algorithms like Direct search and others, which would separate the solid-voxels and the void-voxels. Once, they are separated, maximal balls mainly identify the boundary between those voxels. Large maximal balls form the pores, and then complex throat systems are analyzed through 'Master-Slave Maximal Balls Hierarchy' [13]. Thus, the complete pore-throat distribution is extracted using maximal balls.

Conclusion and Future work

In this work, description of the pore space of Berea sandstone core, a standard porous rock reservoir material, is investigated through the use of micro CT technique. Micro CT specific sample is prepared from Berea sandstone and the horizontal cross-sections are exposed to X-ray micro CT. Based

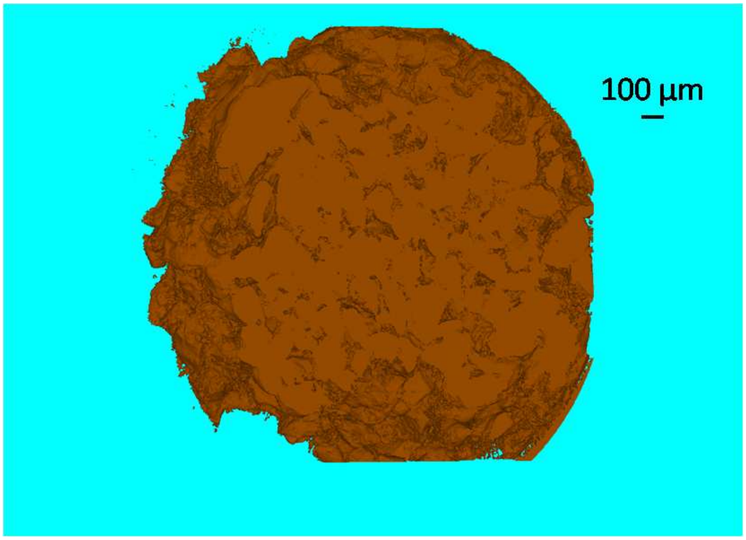

FIGURE 5. RECONSTRUCTION FROM MICRO CT IMAGE, SECTION AT 1.667 mm

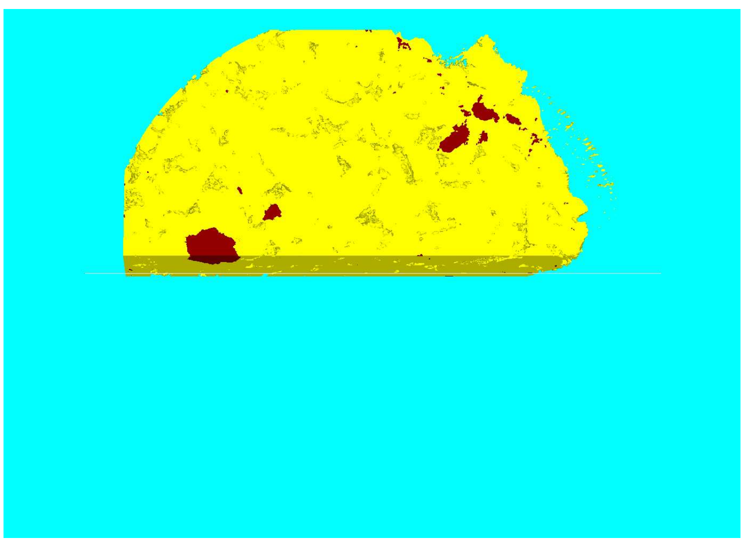

FIGURE 6. HALF-SECTION RECONSTRCUTION

on the sectional images, various features of high resolution images like detector noise or scattering effect are analyzed. The sectional reconstruction has been performed, stacking the images layer by layer. Voxel values have been calculated for the solid and pore spaces.

Further work on the micro CT images would involve the application of maximal balls, to extract the void space and dividing them into larger voids (i.e. pores) and smaller ones (i.e. throats). Throat analysis would be performed on these smaller constrictions, for extracting the robust pore-throat network.

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