Study of Upscaling Permeability from Thin Sections using 3D Pore Space Image and Pore Network Modeling

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Abstract—**Digital rock physics technology has effectively proved in reducing time and cost to predict physical properties of reservoir rocks. However, most of the predictions are at pore-scale level. In this study we address our research on predicting permeability at core-scale. The study carries out numerical simulation on three-dimensional (3D) pore space images to predict permeability at pore-scale. A digital volume required for this numerical simulation is obtained from thin section images. From these images we reconstruct 3D pore space images using multiple-point statistics (MPS). Permeability from several pore space images are used to predict permeability at core-scale by using upscaling methods (arithmetic, geometric and harmonic method). The results from these predictions are expected to match well with the experiment.**

***Index Terms*— 3D pore space image, Multiple-point statistics, Pore network modeling, Permeability, Upscaling.**

I. INTRODUCTION

Porosity and permeability are the key of physical properties in petroleum. These properties usually obtained by applying standard experimental tests on rock samples collected along selected depths of petroleum well. In addition to sampling costs, laboratory routine includes the manufacture of thin plates for petrographic analysis and the measurement of porosity, permeability, which are, presently laborious, time consuming and high cost procedures. Not only are such experiments lengthy and expensive but also there is often a lack of rock material to conduct these experiments i.e. core hardly extracted and the only material left from the well are sidewall plugs and drill cuttings which cannot be measured by experiment. In such situations, digital rock physics can be an alternative (Dvorkin, J., et al., 2008; Touati, M., et.al., 2009).

Numerical simulations of fluid flow through 3D pore space can provide accurate estimations to predict physical properties. A digital volume can be obtained from CT-scan. However, the device still prohibitively expensive and the scanning time is too long to be practically useful in massive numerical experimentation. An alternative is a statistical reconstruction of 3D volume from a 2D image (thin section). Thin sections are relatively easy and cheap to prepare.

The goal of this study is to predict permeability at core-scale (experiment scale) using information from thin sections. Specifically, we carried out simulation of viscous fluid flow through a realistic pore space. A realistic pore space can be reconstructed based on statistical information from two-dimensional (2D) images (thin sections or SEM images) (Keehm, Y., et.al., 2006; Okabe, H. and Blunt, M.J., 2004). MPS was used to obtain 3D pore space images. Once a 3D image is reconstructed, the pore network will be extracted and physical properties will be simulated by solving relevant transport equations from the pore network modeling. The permeability from 3D pore space images are used to predict permeability at core scale using simple upscaling methods.

II. METHODOLOGY

A. *Thin Section Data and Image Processing*

Thin sections saturated by epoxy, so the pore space is clearly distinguishable. From the color image of the thin section, a binary image can be obtained using simple image processing. We converted the true color image into an index image, and selected proper indices for grains and pore space. Then the binary image can be represented by indicator function *f*(r) (Keehm, Y., et.al., 2006),

$$f(r) = \begin{cases} 1 \text{ if } r \text{ belongs to pore space} \\ \quad 0 \text{ otherwise} \end{cases} \tag{1}$$

r denotes a spatial location within the binary image.

B. *2D to 3D Porous Media: Multiple-point Statistics*

Binary images used as an input to reconstruct porous media. In this study, we used MPS to reconstruct 3D pore space images. This method has been used by Okabe, H. and Blunt, M.J., (2004) to reconstruct carbonate rock and has been developed by Tang, Z., et.al., (2010)

First step, a 2D cross section used as an original training image is scanned by 2D multiple-grid data templates to build search trees. From this search trees the conditional probability distribution function (cpdf) information can be stored. Second step, by using the extracting template, sample points are extracted from the training image and then

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these sample points used as original conditional data. Third step, draw a simulated value from the previous cpdf using Monte Carlo Methodology. Then simulated value is then added to the conditional data for the simulation at all subsequent. Fourth step, Loop step 3 until all grid nodes are simulated. Then one simulated image has been generated, which will be used as a new training image for next simulation.

To generate a 3D structure from 2D image, loop step 1-4 until N-1 new 2D simulated images are generated. Stacking the original training image and those N-1 image successively. A 3D image of porous media with N layers is generated. Each pixel in those layers corresponds to a voxel in 3D pore space.

C. Permeability Estimation: Pore Network Modeling

To simulate accurately transport phenomena in porous media, a detailed description of the pore space is needed. In this study, a digital three-dimensional representation of the pore space is constructed by using MPS method. Binarized 3D images (where 1 and 0 represent void and grain respectively) were used as input data for network extraction. From this, a topologically equivalent network model is built with pore sizes, shapes and connectivity based on the three-dimensional representation (Dong, H. and Blunt, M.J., 2009; Oren, P.E. and Bakke, S., 2002).

Permeability, k, in 3D images is computed as the mean of directional permeabilities. This is calculated by applying macroscopic pressure gradient,

$$Q = \frac{K(p_1 - p_0)A}{\mu L} \qquad (2)$$

Q is the volume of fluid flowing per unit time, μ is viscosity of the fluid and A is the cross sectional area in the direction. The fluid flow is assumed to be governed by steady state Stokes equations for an incompressible Newtonian fluid subject to a no slip boundary condition at the solid wall. Permeability is also calculated in the network equation (2); $(p_1$-$p_0/L)$ is then applied macroscopic pressure gradient accross the network while Q is the total single-phase flow rate which is found by solving for pressure everywhere and imposing mass conservation at every pore. From this equation we can calculate the permeability. We used open source software from Imperal College London to calculate the permeability.

D. Upscaling Permeability

(Keehm, Y., et.al., 2006) used simple upscaling methods to predict permeability at core scale. He speculate that the possible reason why the computed permeability values from 3D pore space images overestimated lab-measured permeability values is because its heterogeneity.

To combine the permeability building blocks (each permeability that obtained from 3D pore space images) to arrive at the absolute permeability on the core-plug scale, we used the same upscaling method which the aritmatic mean is used to average permeability values parallel to the bedding (horizontal) direction, while the geometric or harmonic mean is used to average permeability perpendecular to the bedding.

III. CONCLUSIONS

Keehm, Y., et.al., (2006) was using the same concept as we did to predict permeability at core-scale. However, the method to reconstruct 3D pore space image by Keehm has limitation and lacking through-going connectivity. Because of these reasons, this method works best on high porosity clastic rocks. To calculate permeability, Keehm used Lattice Boltzmann Method (LBM), which is robust enough to simulate fluid flow. However, this method is still very computational intensive for single/multiphase flow through porous media.

For these reasons, we use the methods to predict permeability at core-scale (experiment scale). We modify the method to reconstruct 3D pore space image by using MPS (Tang, Z., et.al., 2010). This method was improved and can be used (even) to reconstruct carbonate rock at pore scale (Okabe, H. and Blunt, M.J., 2004). Replacing LBM, we used pore network modeling software from Imperial College London which practical enough to calculate permeability at pore scale (Dong, H. and Blunt, M.J., 2009).

IV. REFERENCES

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V. FIGURE CAPTIONS

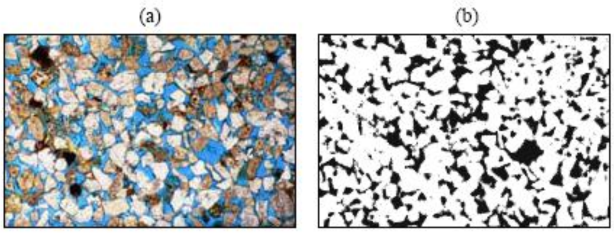

Fig. 1. (a) Scanned image from an epoxy-saturated thin section. Blue color denotes pores. (b) Binary image after image processing. The pore space appears in black. [3]

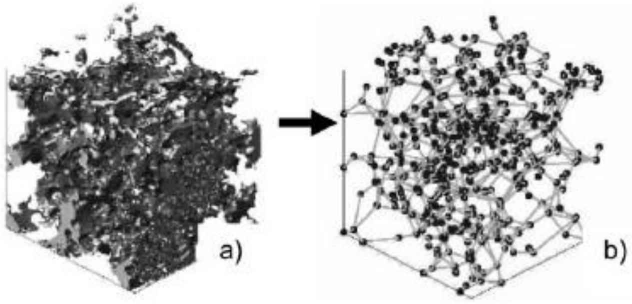

Fig. 2. (a) Binarized 3D image; (b) a topologically equivalent network of pores connected by throats. Each pore and throats has a volume, shape and cross-sectional area derived from the 3D image [1].

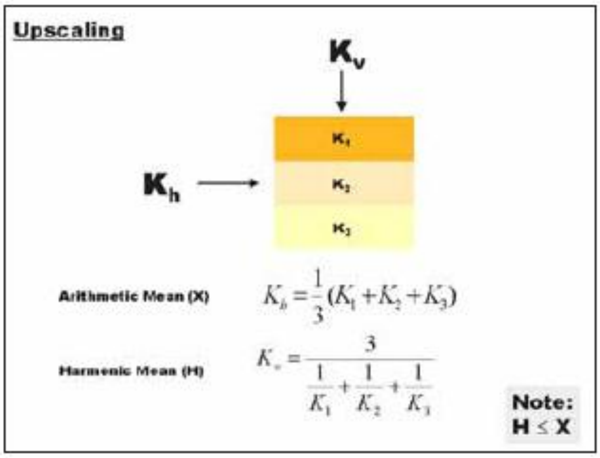

Fig. 3. Schematic figure showing the difference between arithmetic (X) and harmonic (H) mean, which are used to average permeability measurements in the horizontal (parralel to bedding) and vertical (perpendicular to bedding) directions, respectively [3].

VI. WORKFLOW

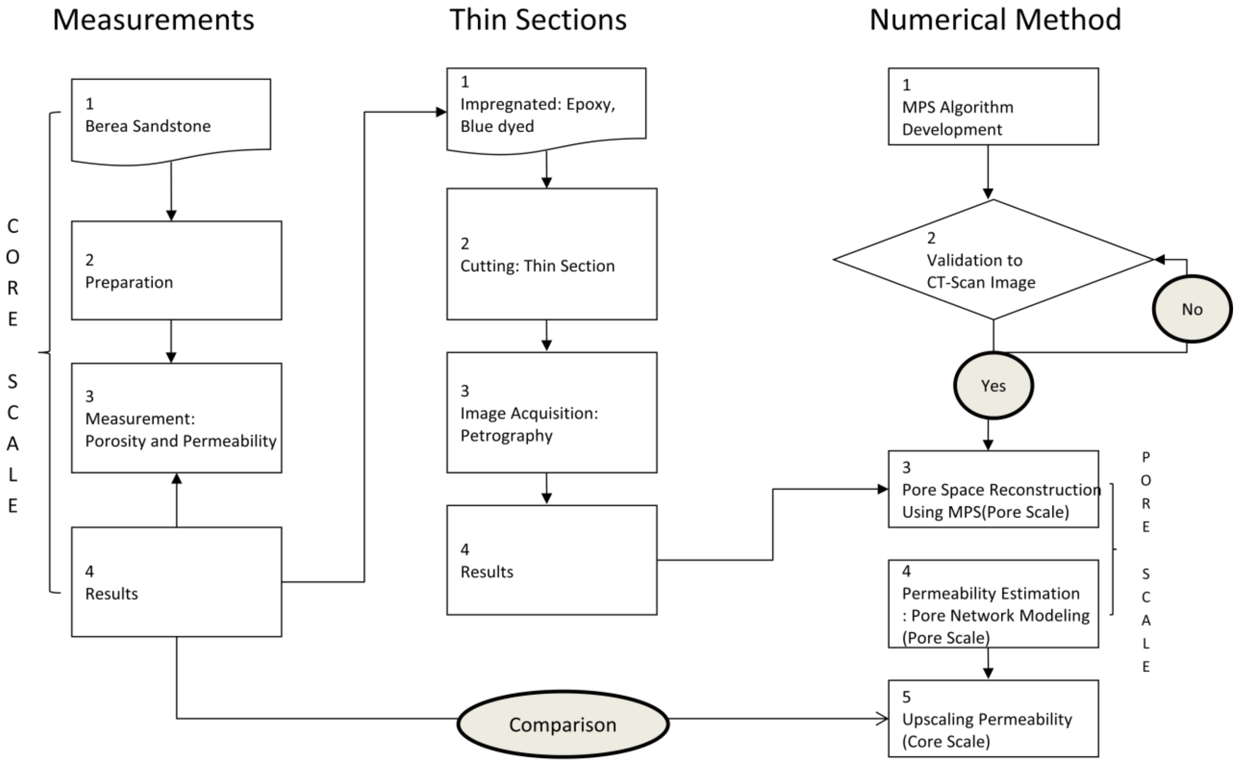

Fig. 4. Integrated workflow to predict permeability at core-scale