

Multiscale Approach for Shaping an Efficient EOR / IOR Field Management, from Lab to Reservoir

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1. Introduction

To improve reservoir simulators' predictive capability, models are needed to calculate petrophysical properties in the reservoir space through interpolation or extrapolation and upscaling of some representative values carefully measured and interpreted in the laboratory. The development of "Pore Network Models" (PNM) corresponds to these three basic problems: the need for predictive physical models to calculate petrophysical properties to feed the reservoir simulators (used in reserves evaluation or recovery forecast), the need to have a tool to extrapolate petrophysical measurements (relative permeabilities, capillary pressures, resistivity index, ...) to uncored wells, and the need to have a tool to interpret and upscale laboratory measurements.

The advantage of this modeling is that it takes into account explicitly pore space geometry/topology and wettability, as well as flow and displacement mechanisms at the pore scale, all known to have a tremendous impact on petrophysical properties relevant for enhanced oil recovery processes. The predictability of such models depends on the accuracy with which the network captures the complex geometric and topological properties of the pore network. High resolution Computed Micro Tomography (μ -CT) appears to be the ideal method to validate these models and improve their predictability in the case of complex geometry media.

In this paper, we present a methodology combining high resolution μ -CT characterisation and a fast and efficient partitioning of the pore space enabling a complete and realistic description of the geometry and topology of the associate large subsets. Relevant parameters are then extracted for pore network simulations. The partitioned volume is directly used to simulate mercury injection which is confronted to experimental HPMI results. The equivalent extracted network is used to calculate absolute permeability using a PNM code. The methodology is applied to a set of real porous media and shows a good agreement between experiments and simulation when the studied volume is representative. A methodology to calculate and upscale transport properties of heterogeneous (vuggy or fractured) rocks is also illustrated.

2. Key Features

The μ -CT equipment installed at IFP is a Nanotom from PHOENIX X-Ray. The source is generated by the impact of a focussed electron beam on a thin target. Spot size varies between 1 and $5\mu\text{m}$ depending on the operating conditions. Generating images using μ -CT starts with the acquisition of a series of 2D projections while progressively rotating the sample step by step through a full 360° rotation at increments of less than 1° . The entire diameter of the sample should remain within the field of view throughout the entire 360° rotation: a 5mm diameter sample will be completely displayed on each projection with a pixel size of $3\mu\text{m}$.

Pore Network Extraction Methodology: The objective is to capture the resolved pore space, partition it into pore bodies, pore throats and channels and describe their connections. This treatment consists in four main steps: binarisation, skeleton extraction, network partitioning and parameters extraction. Figure 1 illustrates in 3D different steps of the pore network extraction on a 12% porosity Fontainebleau sample.

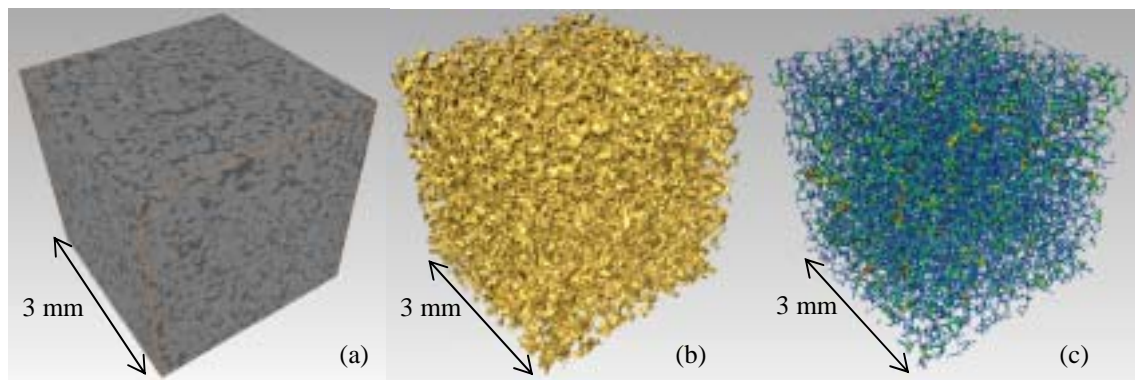


Figure 1: 3D view of three of the main steps of the treatment: (a) acquisition of a 3D block, (b) isolating the

porosity by binarisation, (c) extracting the skeleton marked with minimum distance to the border in each point.

Mercury intrusion Simulation: Once the partitioning is done, a connection matrix is built from which mercury porosimetry can be simulated. To begin the mercury intrusion simulation, the volume is supposed to be surrounded by mercury and the edge pores already full with mercury. At a fixed capillary pressure, all the pores connected to an already invaded pore via a throat greater than or equal to the equivalent pore entry radius are invaded. At each pressure step the non wetting phase saturation is measured from the total invaded volume.

Permeability calculation: Absolute permeability calculation is performed directly on the extracted numerical network. The simulation uses the pore size and coordinates, throat size and channels length between these pores and their neighbours. The procedure has been applied on both sandstones and limestones.

Sandstones: The approach described in the previous paragraph is applied to a subset of 500x500x500 voxels reconstructed with half resolution (6µm) and when necessary to a smaller subset 500x500x500 reconstructed with 3µm resolution. The total porosity of the studied subvolumes is directly deduced from the mean grey level value of the histogram. Measured global porosities are 21.6%, 14.2%, 12.3% and 6.5%. The Pc curves are compared to a mercury invasion experiment conducted on a sister plug of each sample. The matching of experiments is satisfactory for high porosity samples (Figure 2a, $\phi=14.2\%$). For the lowest porosity sample (Figure 2b), the best fit is obtained with a 3µm resolution. The permeability calculations have been performed on all 500³ voxel subset volumes with 6µm resolution. All the simulated points are fitting the reference K- ϕ curve except for the lowest porosity sample. In this sample, at 6µm resolution, the pore network is not represented by a single and continuous cluster but by several clusters among which very few are percolating which explain the low permeability (0.3mD) initially obtained. At 3µm resolution we recover a single percolation cluster and we obtain 18mD in perfect agreement with experimental data.

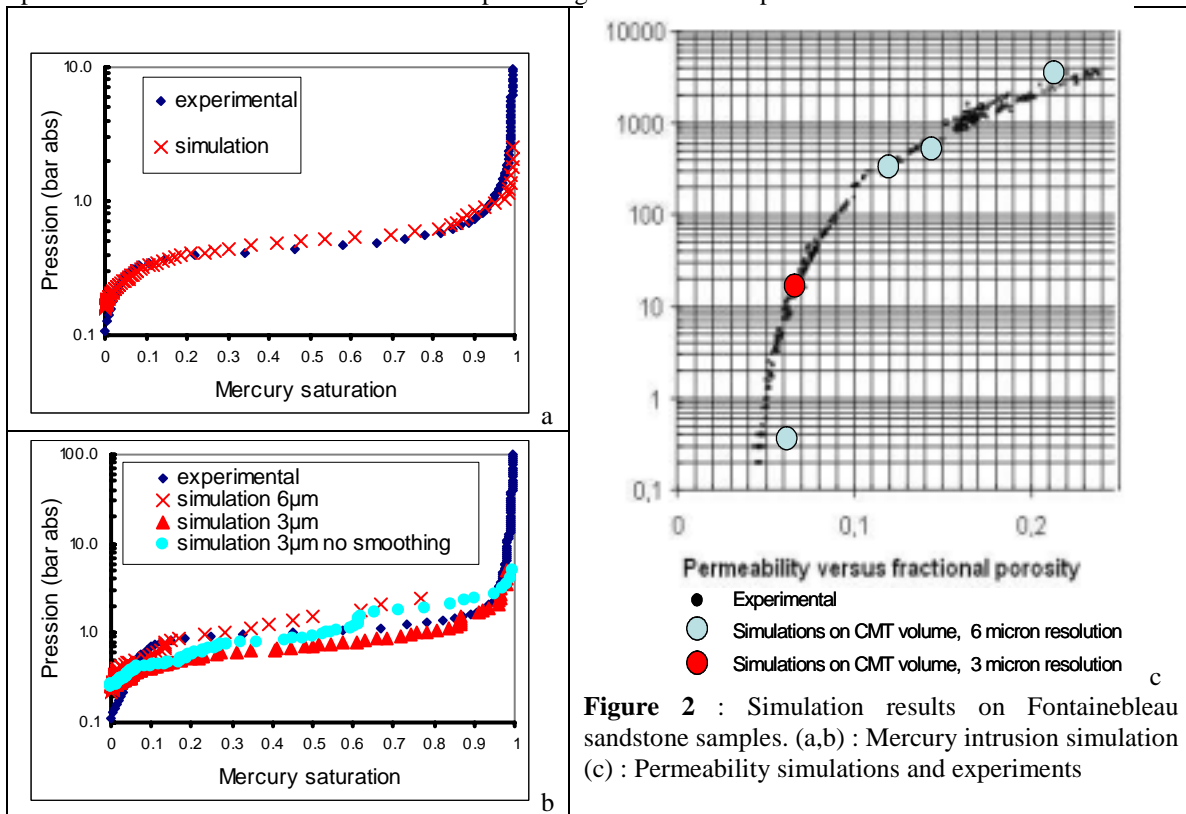


Figure 2 : Simulation results on Fontainebleau sandstone samples. (a,b) : Mercury intrusion simulation (c) : Permeability simulations and experiments

Carbonates: Estailades sample contains microporous algae (intermediate grey level particles in Figure 3a). The binarisation step enables to isolate the macroporous network. In this sample, the macroporosity and microporosity are two independant networks. The mean porosity (deduced from the mean gray level) is 21% and the macroporosity (deduced from the binary image) is 14.3%. In spite of a complex skeleton, the resolved porosity appears to be a single percolating cluster and the treatment leads to a satisfying partitioning. The quality of the partitioning can be appreciated visually and quantitatively via the comparison between simulations and experiments. The fit between experimental and simulated mercury intrusion curves is very satisfactory (Figure 3b). Moreover the permeability simulation conducted on a 800³ block with 3µm resolution, leads to a value of k=80mD while a value of k=130mD is measured on a sister plug.

For vuggy/fractured heterogeneous rocks the network model approach is applied at two (or more) scales as illustrated schematically in Figure 4. The model combines transport properties of the primary porosity (capillary pressure and relative permeabilities of the matrix considered homogeneous) with the pore network modeling approach used to simulate the secondary porosity (macropores, vugs or fractures).

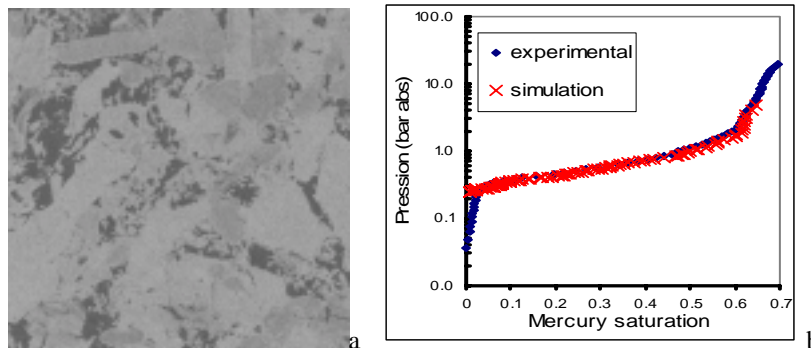


Figure 3: Results on Estailades carbonate: (a) 1000^3 , X-ray density map for $3\mu\text{m}$ resolution (b) Mercury intrusion simulation (1000^3 volume- $3\mu\text{m}$ resolution) and experiment.



Figure 4: Schematic depiction of a dual-network and the gas/oil relative permeabilities for three different contrasts of global to matrix permeability.

3. Conclusions

A methodology combining a high resolution μ -CT laboratory equipment and efficient partitioning of the pore space enables a complete and realistic description of the geometry and topology of the pore network. The methodology has been applied to sandstones and carbonates. A good agreement between experiments and simulations for drainage capillary pressure curve and absolute permeability is obtained as far as the resolved pore space is represented by one single connected cluster. For homogeneous porous media without microporosity this condition guarantees that the numerical pore structure describes the real one in terms of representative elementary volume and critical conductive pore size. In carbonates, because of their multiscale heterogeneity, the representative elementary volume cannot always be reached at high resolution. The challenge of this methodology will be then to increase the volume examined numerically by using discrete representations of the pore space at the relevant scales and combine them in dual (or multiple) porosity networks.

4. References and Bibliography

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Speaker's Biography

Olga Vizika has been working with IFP for 16 years. She has worked on relative permeability modeling for depressurization, gas injection, WAG or gas condensate

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production. Her current research interests also include modeling of the transport properties of carbonate rocks and slightly consolidated porous media. She served as chairman of the Technical Committee of the 2003 Society of Core Analysts Symposium and 2005 President of the SCA. She holds a BS and PhD degree, both in Chemical Engineering. Since October 2006 she is the Director of the Reservoir Engineering Research Division of IFP.