Abstract

At present, pore-scale imaging and modeling are becoming routine geoscience techniques of reservoir simulation in the oil and gas industry. The foundation of these techniques is the development of sophisticated three-dimensional models that can represent both the multiphase flow dynamics and the geometry of the rock's pore system. Three-dimensional printing may facilitate the transformation of pore-space imaging into rock models, which can be tested using traditional laboratory methods to provide data that is easily comparable to literature data. Although current methodologies for rapid rock modeling and printing obscure many details of rock geometry, computed tomography data is one route to refine pore networks and experimentally test hypotheses related to rock properties, such as porosity and permeability.

This study uses three-dimensional printing as a novel way of interacting with (a) x-ray computed tomography data from reservoir rocks, and (b) mathematical models of pore systems in coarse-grained sandstones and limestones. These artificial rocks will be used as a proxy to better understand the contributions of various pore system characteristics at various scales to petrophysical properties in oil and gas reservoirs. Pore sizes of typical reservoir sandstone range from 0.1 to 100s of microns. The resolution of three-dimensional digital printing used in the study varied from 16 to 300 microns, therefore, the three-dimensional imaging and especially printing might have lost information on pore geometry. The increase in scale of the pore systems (e.g. from 1 micron in reality to 50 microns in a three-dimensional model) will be a key factor for a precise determination of porosity-permeability relationships as they can be verified against core-scale measurements. The long-term
goal of this study is to focus on testing of petrophysical hypotheses by manipulating digital rock models to determine the resulting changes in artificial rock properties that affect fluid flow. If the pore system models could include tools for adequate measurements of petrophysical properties in “manufactured” rocks in the laboratory conditions, the accuracy of reservoir flow simulations would be increased. Three-dimensional printing offers a great potential to improve our approach to reservoir simulation, facilitating more efficient oil and gas recovery.
The Use of Computed Tomography and 3D Printing Technology to Replicate Reservoir Pore Systems

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Collaborators: Dr. Chris Harding and Dr. Joe Gray
AGENDA

Introduction
  • Definition of Pores in Reservoir Rocks

Importance
  • Challenges of Pore Network Modeling

Hypothesis and objectives

CT scanning
  • Complexities in Porosity-Permeability Scanning

Modeling
  • Reconstruction of CT volume
  • Network Extraction

3D printing
  • Resolution and positioning accuracy
  • Artificial core plugs

Petrophysical Measurements
  • Porosity-permeability of natural and artificial rocks
PORES?

Modified from www.globalccsinstitute.com
IMPORTANCE

- Reservoir core plugs
- Replication of solid materials and pore systems
- Slicing - scale matters!
- Demonstration → research

GeoFabLab, Iowa State University

International Petroleum Technology Conference, Qatar, January 2014
Scanning Limit (Voxel Dimension) 6 µm

Printing Limit (Positioning Precision) 2.5 µm

Not Scanable
Not Printable

Scanable
Printable

Nelson, 2009
WHAT and WHY?

Hypothesis: Textural and petrophysical properties of porous reservoir rocks can be replicated with computed tomography (CT) and three-dimensional (3D) printing technology.

Objectives:
1. Test the extent to which CT and 3D printing technologies can reproduce pore geometries and connectivity of natural porous rocks;
2. Conduct experiments on pore systems of natural and artificial rocks to identify what matters to flow at various scales.

Samples: core plugs

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample</th>
<th>Formation</th>
<th>Porosity, %</th>
<th>Permeability, md</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>Idaho gray</td>
<td>Idaho</td>
<td>29</td>
<td>2200</td>
</tr>
<tr>
<td></td>
<td>Castlegate</td>
<td>Mesaverde</td>
<td>28</td>
<td>750</td>
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<tr>
<td></td>
<td>Berea</td>
<td>Kipton</td>
<td>19</td>
<td>60</td>
</tr>
<tr>
<td>Carbonates</td>
<td>Racine Dolomite</td>
<td>Racine</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Edwards Brown</td>
<td>Edwards Plateau</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Guelph Dolomite</td>
<td>Niagara</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Indiana Limestone</td>
<td>Bedford</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Austin Chalk</td>
<td>Edwards Plateau</td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

Data from Kocurek Industries(2013) and Rovey, 1997
WORKFLOW

1) CT Imaging

2) Modeling

3) Network Extraction

4) Production

5) Rock properties

Artificial vs. Natural Rocks

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Permeability (mD)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho Gray Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castlegate Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berea Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edwards Brown Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indiana Limestone</td>
<td></td>
<td></td>
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<tr>
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<tr>
<td>Austin Chalk</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CT Scanning

Specifications:

1) Imaging

- Resolution of CT system - 6 µm
- Magnification = D/a
  a = distance between source and sample
- Samples: core plugs
- Size of sample: 1x2”
- Exposures: 2º, 5 sec.

Source: Kevex PSX10-16W
- Set energy: 130 keV
- Set current: 100 micro-Amps
- Spot size: approx. 16 µm

Detector: Varian PaxScan 3024I
- Resolution: 2816x3584 pixels
- Pixel Pitch: 83 µm

Center for Nondestructive Evaluation, Iowa State University
1) Imaging

**Racine Dolomite**

- Porosity: 11%
- Permeability: 2 md
- Diameter: 1.75 inches

**Idaho Gray Sandstone**

- Porosity: 22%
- Permeability: 2200 md
- Diameter: 1 inch

Data from Kocurek Industries(2013) and Rovey, 1997
Reconstruction of Idaho Gray Sandstone

Dimensions: pixels, microns, voxels

Modified from Grandin and Gray, 2014
Connected Pores within Idaho Gray Sandstone 10x magnification

1) Imaging ➔ 2) Modeling ➔ 3) Network Extraction !!!

Porosity Extraction Isosurface

Upscaling?

Original size of 3D model: 51x63x52 (mm)

Porosity Threshold

Connected Pores within Idaho Gray Sandstone 10x magnification
1) Imaging ➔ 2) Modeling ➔ 3) Network Extraction !!!

Original size of 3D model: 51x63x52 (mm)

Connected Pores within Idaho Gray Sandstone 10x magnification

Porosity Extraction Isosurface

Porosity Threshold

Upscaling?
3D PRINTING

Makerbot Replicator 2X
- 2 Print heads
- Fused Deposition Modeling
- Filament: Acrylonitrile butadiene styrene (ABS)

10x magnification
5x magnification
### Important parameters of 3D printers

<table>
<thead>
<tr>
<th>Printer</th>
<th>A. XY Resolution (Nozzle diameter)</th>
<th>B/C. Z Resolution (Layer Thickness)</th>
<th>D. XY Positioning Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replicator 2X</td>
<td>400 µm</td>
<td>100 µm</td>
<td>2.5 µm</td>
</tr>
<tr>
<td>Objet30 Pro</td>
<td>42 µm</td>
<td>28 µm</td>
<td>30 µm</td>
</tr>
<tr>
<td>Objet260 Connex</td>
<td>42 µm</td>
<td>16 µm</td>
<td>30 µm</td>
</tr>
</tbody>
</table>

**A. Minimum XY element dimensions** are controlled by aperture of extruder nozzle.

**B. Element thickness** is controlled by positional accuracy of Z stepper motor.

**C. Pore Z-dimension** is controlled by positional accuracy of Z stepper motor.

**D. Pore XY-dimension** is controlled by positional accuracy of XY stepper motors.
Petrophysical Measurements

Pore size distribution
- Nuclear Magnetic Resonance
- Petrography
- SEM mosaic

Porosity, permeability, and pore throat size
- Helium Porosimetry
- High-Pressure Mercury Injection

Comparison of petrophysical properties between data collected from artificial and natural rocks.

Manipulation of properties in 3D models?
Acknowledgements

Dr. J. Gray, Center for Nondestructive Evaluation, Iowa State University
R. Grandin, PhD Candidate, Center for Nondestructive Evaluation, Iowa State University
Dr. C. Harding, GE-AT / Human-Computer Interaction, Iowa State University

References


