Oil reservoir rock characterization and fluids segmentation using high resolution micro-CT scans

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Objective

Individual 3D analysis (i3D) returns the number, volume and volume-equivalent sphere diameter of the pores in a porous rock sample which is representative of an oil reservoir rock. The cylindrical rock sample has a size of 4 mm in diameter and 6-7 mm in height of which 2.4 mm is scanned in high resolution (1 µm/pixel). The effective pore network at which fluid flow happens is a combination of a huge number of connected pores even in a small sample. i3D returns this connected network of pores as a single object. Due to the pores connectivity, the analysis software, CTAn (2013 user manual⁴), considers the whole network as a single object (Figure 1). In order to have an accurate measurement of pore sizes we need to separate those pores and find the size of all individual pores constituting the network. The other concern is to find the diameter of the channels connecting the pores in the network. This diameter which is also called throat size is an important parameter in petroleum reservoir engineering. Moreover, accurate segmentation of different fluids (oil and water) which exist inside the pore network of the rock is the third objective of this study.

Figure 1: initial i3D analysis; object (pore) #1 is the main pore network including several connected pores
Method

Since permeability of the rock sample is low (around 20 mili-Darcy) and there is substantial amount of clay mineral in the structure of the rock which includes large number of very small pores together with the normal pores, a resolution of 1 µm (1.04 µm) per pixel was chosen in the Skyscan 1172D. The tiny pores are not visible at lower resolutions. The data was reconstructed in NRecon and analyzed by means of CTAn.

First, the data was pre-processed to remove noise and/or the pores that are not connected to the main network of connected pores.

Further analysis was done on the pre-processed data to extract the pore body and throat size distribution. ‘Distance Ordered Homotopic Thinning’ is a method of calculating those parameters. This approach has been used to extract the pore geometry information of an oil reservoir rock sample. Since this method is unavailable in CTAn, it is attempted to use the morphological operations.

![Figure 2: 3D binarised image after opening the objects by 12 pixels, objects A and B can be removed (despeckled) since they are single pores but object C is still combination of two pores connected by a channel and must be kept in the model for further opening.](image)

There are two options under ‘morphological operations’ in ‘custom processing’ to separate the connected pores. ‘Erosion’ is a function to isolate the connected pores; however since it reduces the size and volume of the pores, it is a destructive function. The other option is the ‘open’ function. It includes adding or removing pixels/voxels to or from the surface of all selected binarised objects (Erosion and dilation respectively). Open means erosion followed by dilation. This function isolates the pores and preserves the pores shape and size to a greater extent compared to the erosion function. Open was run successively starting from radius of 1 pixel (=1 µm) and continued with radii of 2, 3, 4, 5… pixel until all the pores are disconnected. After every run of open, all the isolated pores were removed from the model and saved. Finally, all the saved data from separated pores were assembled in a spreadsheet to find the histogram for frequency of pore size distribution. It should be mentioned that porous media in naturally occurring rocks are often heterogeneous; shapes and sizes of the pores and connecting channels are random to a great extent. Thus the application of the procedure of successive open and remove (‘despeckle’) is not straight forward and in some steps (especially the later steps) more than one object is kept for further open in the next steps. For example, in addition to the largest object, the second and/or third largest object after a step of
open may still be a combination of several pores which must be kept in the model for further open until all the pores are disconnected effectively. Therefore, after every step of open before running despeckle to remove and save the disconnected pores, the isolated larger objects must be visually checked in the 3D model to understand whether every one of those objects is a single pore or a combination of some smaller pores (Figure 2). It is adequate to observe the first few large pores. At this point, ‘sphericity’ can be used to distinguish if the object (pore) is a combination of several pores as sphericity of such an object can be much lower than a single isolated pore due to its higher geometrical deviation from a normal sphere. Sphericity of a single isolated pore is much closer to a sphere. This parameter is available in i3D results for every object.

In another study, the open function was used to find only pore body size\(^1\), however we use the same function to estimate size of channels connecting the pores as well as size of the pore bodies. Initially, before running any open, we have a single object (Network of all connected pores); and in every step of open, several objects (pores) are getting disconnected from this network. Since we start the open operation from radius of 1 pixel and continue increasing the open radius by 1 pixel (\(r=1, 2, 3, 4\ldots\)), in every step, diameter of the connecting channels for the separated pores is equivalent to two folds of the open radius in that step (Figure 3).

![Figure 3: After open by radius of 10 (left) and 11 (right); the last open eliminates the connecting throat of pores A and B. Thus the diameter of the channel is greater than 20 pixels (20\(\mu\)m) and equal to or less than 22 pixels (22\(\mu\)m).](image)

The third step is to distinguish between oil and water inside the pores of a saturated rock. The rock sample is initially vacuumed to remove the air out of the pores. Under vacuum water is imbibed into the pores and the sample becomes 100% water saturated. Afterwards the sample is centrifuged with the crude oil so that the oil replaces most of the water. In this condition, the irreducible water exists together with the oil inside the pores. This simulates the initial condition in an oil reservoir before any oil is produced. The sample is scanned at this condition (initial condition). In the next step, to simulate the oil production out of the rock pores, the sample is set inside of a test tube full of water. Therefore water imbibes the pores and replaces some of the oil and pushes the oil out of the rock. This process is called spontaneous imbibition. The sample is scanned after spontaneous imbibition, too (final condition). In order to estimate the efficiency of the oil production process the volume of water and oil must be calculated at initial and final conditions for which segmentation of oil and water phases must be done for 3D model.

It was stated that it is common to apply a filter on the data to enhance the peaks of the histogram\(^3\). Segmentation was facilitated by applying such filter on the data set in CTAn custom processing. Filter with radius of 2 bolds the features (local peaks and troughs) in the histogram of gray scale index (or HU) frequency. Therefore proper segmentation can be
applied on the model; 2D analysis results were saved for all the images at which ‘percent object area’ can give the saturation of oil or water depending on the selected interval for gray scale values on the histogram.

\[ S_o = \frac{A_o}{A_o + A_w} = \frac{A_o}{TA_o + TA_w} \]

\[ S_w = \frac{A_w}{A_o + A_w} = \frac{A_w}{TA_o + TA_w} = 1 - S_o \]

Equations (1 and 2)

\( A_o \) is the area of white pixels in a 2D image while the threshold interval shows oil and \( A_w \) is the area of white pixels while threshold interval represents water. \( S_o \) and \( S_w \) are oil and water saturations respectively. 2D analysis of all images simply returns \( A_o/TA \) and \( A_w/TA \) which are respectively ‘percent object area’ of oil and water. This can give the saturation of oil or water vs. depth of the rock sample. Furthermore average value of the oil saturation for all the 2D images – 3D model – at initial and final conditions can be used to estimate the oil recovery efficiency of the process (Equation 3).

\[ r = \frac{s_{o,f}}{s_{o,i}}, \]

Equation (3)

\( s_{o,i} \) and \( s_{o,f} \) are average oil saturations respectively at initial and final conditions. \( r \) is the recovery.

**Results**

Figure 4 shows the porosity profile of the cylindrical sample along the \( z \)-axis. The average porosity is 12.8%. Object size distribution estimation concluded in average pore body and throat size of 9.9 and 3.7 pixel respectively. Moreover the average pore aspect ratio is 2.8 (Table 1). Histograms of pore, throat and aspect ratio are presented in figure 5. Results of oil/water saturation estimation at initial and final conditions are demonstrated in figure 6. As it is shown, oil saturation after imbibition of water into pores of the rock sample is reduced. The difference in saturations of initial and final states can be used to estimate the amount of recovered oil (Equation 3). Average values of saturations are summarized in table 2. 17.4% of the initial oil has been recovered by the imbibition process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
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</thead>
<tbody>
<tr>
<td>Pore body diameter (D), pixel</td>
<td>184.7</td>
<td>2.3</td>
<td>9.9</td>
</tr>
<tr>
<td>Pore throat diameter (d), pixel</td>
<td>28.0</td>
<td>2.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Aspect ratio (D/d), dimensionless</td>
<td>40.7</td>
<td>0.6</td>
<td>2.8</td>
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<table>
<thead>
<tr>
<th>Phase</th>
<th>Initial saturation (%)</th>
<th>Final saturation (%)</th>
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<tbody>
<tr>
<td>water</td>
<td>31.7</td>
<td>43.6</td>
</tr>
<tr>
<td>oil</td>
<td>68.3</td>
<td>56.4</td>
</tr>
</tbody>
</table>
Figure 4: porosity profile of the cylindrical sample in z direction. Average, max and min values are 12.8, 18.9 and 5.9 percent respectively.
Figure 5: Pore body, throat and aspect ratio size distribution
Conclusion

*Open* is the most appropriate morphological function to simultaneously obtain pore body, throat and aspect ratio size distribution. Also, based on our knowledge, this is the first time throat size has been determined by successive *opening* of pores. Furthermore, *μ-CT* is a good tool for micro-scale characterization of oil reservoir rock and fluid saturation measurement which leads to micro-scale quantification of oil recovery performance of different recovery processes.

Figure 6: Saturation profiles in z direction at initial (red) and final (blue) conditions
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References