Pore Network Modeling: Analysis of Pore Size Distribution of Arabian Core Samples
Hu Dong, SPE, Imperial College London; Mustafa Touati, SPE, Saudi Aramco; and Martin J. Blunt, SPE, Imperial College London

Abstract
We use X-ray microtomography (micro-CT) to image rock cuttings of poorly consolidated sandstone and vuggy carbonate from Saudi Arabian oil and gas fields. The cuttings are a few mm across and are imaged to a resolution between 3 and 12 microns. The details of the three-dimensional pore space can be clearly seen. A maximal ball algorithm is used to extract a topologically equivalent pore network: the largest inscribed spheres in the pore space represent pores, with throats representing the connections between them. The results are validated through comparison with networks derived by a different method from idealized sphere packings and Fontainebleau sandstone.

The aim of this work is to input the models into pore-scale network models to predict macroscopic properties such as relative permeability and capillary pressure. This acts as a valuable complement to special core analysis, enabling predictions of properties – such as three-phase relative permeabilities and the impact of wettability trends – outside the range of parameters probed experimentally. Furthermore, using microtomography, rock cuttings can be analyzed that are too small for conventional core flood experiments.

Introduction
Pore-scale network modeling can now be used to predict multiphase flow properties as a complementary tool to special core analysis\(^1\).\(^2\).\(^3\). However, the pore structure of the rock and its wettability needs to be determined.

It is possible to image the three-dimensional pore space directly using micro-CT scanning that has a resolution of a few microns\(^4\).\(^5\). However, it is difficult to simulate quasi-static multiphase flow directly through these images. Instead a topologically equivalent network of pores and throats is extracted through which flow is computed. This paper uses a novel method for this network extraction using maximal balls\(^6\), validates it against other methods and applies it to a series of Saudi Arabian reservoir rocks.

At present the networks that are used for predictions are derived from an analysis of two-dimensional thin section images of sandstones\(^7\).\(^8\). From these the grain size distribution is determined. Then packings of these grains with subsequent compaction and diagenesis is simulated. Since the locations of the grain centers is known it is possible to find pores and throats in the void space and from this to extract a topologically equivalent network\(^9\).\(^10\). However, this process-based method is restricted to granular media and does not make use of three-dimensional images if they are available.

Micro-CT imaging
We extract pore networks from micro-CT images. A micro-CT scanner at Imperial College London, Fig. 1, and a synchrotron tomographic scanner at ELETTRA in Italy have been used to image sandstone and carbonate samples. The best spatial resolution obtained so far in our series of experiments is 2.9 \(\mu\)m on a carbonate sample with a diameter of 2 mm.

Fig. 1. The left picture shows the micro-CT scanner at Imperial College London. The right picture shows the X-ray tube in this scanner and the sample stage.
Maximal ball algorithms construct the largest spheres centered on each void voxel that just fits in the pore space. A maximal ball is one of these spheres that is not completely enclosed by another. The concept of maximal balls was used by Sill"in et al. to study the morphology of 3D pore-space images for the identification of pores and throats. A maximal ball that does not overlap any larger sphere defines a pore. Throats are defined as chains of smaller balls that connect pores. The maximal ball method easily and unambiguously identifies pores, but the construction of throats is difficult, since there may be many ways to connect pores by overlapping smaller spheres.

Algorithm validation

In this paper we will apply the maximal ball method to extract a network. The key statistical parameters of the pore networks will be compared with the results of the process-based method. Then the algorithm will be applied to images of Saudi Arabian sandstones.

We test the algorithm on a series of standard, idealized granular systems where it is possible to determine the network using the processed-based method. Fig. 3 compares the number of pores found for a series of simple packings; it can be seen that the maximal ball and process-based algorithms give similar results.

Pore network extraction

Binarized micro-CT images preserve the morphology and topology of the pore space. However, these images cannot be input into pore scale simulators directly. A topologically equivalent network of pores and throats has to be extracted. Then using a series of rules to determine fluid displacements in pores and throats, multiphase flow can be simulated and predictions made.

Two principal approaches have been used to extract a topologically equivalent network from 3D micro-CT images: medial axis analysis and maximal balls. These will be discussed in turn.

Medial axis algorithms use thinning to erode the pore space from grain surfaces until the medial axis – lines with branches denoting the centers of the pore space – is found. Pores are located at branches in the medial axis, while throats connect pores. The size of the pores and throats can be determined by the number of steps of erosion from the surface of the grains. The medial axis mathematically preserves the topology of the pore space. However, the intrinsic sensitivity to the irregularity of pore space makes the unambiguous identification of pores, that may encompass several branches of the medial axis, difficult. Generally, medial axis based algorithms readily capture the interconnectivity of the pore space but pore identification is a problem.

Algorithm validation

In this paper we will apply the maximal ball method to extract a network. The key statistical parameters of the pore networks will be compared with the results of the process-based method. Then the algorithm will be applied to images of Saudi Arabian sandstones.

We test the algorithm on a series of standard, idealized granular systems where it is possible to determine the network using the processed-based method. Fig. 3 compares the number of pores found for a series of simple packings; it can be seen that the maximal ball and process-based algorithms give similar results.

Pore network extraction

Binarized micro-CT images preserve the morphology and topology of the pore space. However, these images cannot be input into pore scale simulators directly. A topologically equivalent network of pores and throats has to be extracted. Then using a series of rules to determine fluid displacements in pores and throats, multiphase flow can be simulated and predictions made.

Two principal approaches have been used to extract a topologically equivalent network from 3D micro-CT images: medial axis analysis and maximal balls. These will be discussed in turn.

Medial axis algorithms use thinning to erode the pore space from grain surfaces until the medial axis – lines with branches denoting the centers of the pore space – is found. Pores are located at branches in the medial axis, while throats connect pores. The size of the pores and throats can be determined by the number of steps of erosion from the surface of the grains. The medial axis mathematically preserves the topology of the pore space. However, the intrinsic sensitivity to the irregularity of pore space makes the unambiguous identification of pores, that may encompass several branches of the medial axis, difficult. Generally, medial axis based algorithms readily capture the interconnectivity of the pore space but pore identification is a problem.

Maximal ball algorithms construct the largest spheres centered on each void voxel that just fits in the pore space. A maximal ball is one of these spheres that is not completely enclosed by another. The concept of maximal balls was used by Sill"in et al. to study the morphology of 3D pore-space images for the identification of pores and throats. A maximal ball that does not overlap any larger sphere defines a pore. Throats are defined as chains of smaller balls that connect pores. The maximal ball method easily and unambiguously identifies pores, but the construction of throats is difficult, since there may be many ways to connect pores by overlapping smaller spheres.

Algorithm validation

In this paper we will apply the maximal ball method to extract a network. The key statistical parameters of the pore networks will be compared with the results of the process-based method. Then the algorithm will be applied to images of Saudi Arabian sandstones.

We test the algorithm on a series of standard, idealized granular systems where it is possible to determine the network using the processed-based method. Fig. 3 compares the number of pores found for a series of simple packings; it can be seen that the maximal ball and process-based algorithms give similar results.

Pore network extraction

Binarized micro-CT images preserve the morphology and topology of the pore space. However, these images cannot be input into pore scale simulators directly. A topologically equivalent network of pores and throats has to be extracted. Then using a series of rules to determine fluid displacements in pores and throats, multiphase flow can be simulated and predictions made.

Two principal approaches have been used to extract a topologically equivalent network from 3D micro-CT images: medial axis analysis and maximal balls. These will be discussed in turn.

Medial axis algorithms use thinning to erode the pore space from grain surfaces until the medial axis – lines with branches denoting the centers of the pore space – is found. Pores are located at branches in the medial axis, while throats connect pores. The size of the pores and throats can be determined by the number of steps of erosion from the surface of the grains. The medial axis mathematically preserves the topology of the pore space. However, the intrinsic sensitivity to the irregularity of pore space makes the unambiguous identification of pores, that may encompass several branches of the medial axis, difficult. Generally, medial axis based algorithms readily capture the interconnectivity of the pore space but pore identification is a problem.

Maximal ball algorithms construct the largest spheres centered on each void voxel that just fits in the pore space. A maximal ball is one of these spheres that is not completely enclosed by another. The concept of maximal balls was used by Sill"in et al. to study the morphology of 3D pore-space images for the identification of pores and throats. A maximal ball that does not overlap any larger sphere defines a pore. Throats are defined as chains of smaller balls that connect pores. The maximal ball method easily and unambiguously identifies pores, but the construction of throats is difficult, since there may be many ways to connect pores by overlapping smaller spheres.

Algorithm validation

In this paper we will apply the maximal ball method to extract a network. The key statistical parameters of the pore networks will be compared with the results of the process-based method. Then the algorithm will be applied to images of Saudi Arabian sandstones.

We test the algorithm on a series of standard, idealized granular systems where it is possible to determine the network using the processed-based method. Fig. 3 compares the number of pores found for a series of simple packings; it can be seen that the maximal ball and process-based algorithms give similar results.
extraction. While the distributions are similar, the maximal ball method implies a better connected network. This test is a particular challenge, since the porosity of the sample is only 13.5% and many of the throats have been completely sealed by diagenesis. Fig. 6 compares the pore and throat size distributions. Again the agreement is good, particularly for the pores that are well captured by maximal balls. For throats some of the discrepancy is due to a random assignment of throat radius about discrete values in the process-based approach.

Fig. 4. The pore network generated from a reconstructed Fontainebleau sandstone image using a modified maximal ball algorithm.

Fig. 5. The coordination number is the number of links connected to one pore, which reflects the spatial connectivity of the pore space. Both the methods find that the distribution peaks at 3. The average coordination number of the network from the maximal ball method is 3.75 while that from the process based method is 3.19.

Fig. 6. Comparison of pore and throat size distributions. The size distributions are in good agreement especially for large pores and throats. Some of the differences are due to dissimilar considerations of boundary pores and the random assignment of radius about discrete values in the process-based method.

Analysis of Arabian rock samples

Ten Arabian samples provided by Saudi Aramco have been scanned and fourteen images have been obtained using industrial and synchrotron micro-CT scanners. To obtain suitable samples for imaging, we drilled cylindrical specimens out of the larger samples before scanning. The resolution of the 3D images varies from 3 to 12 µm corresponding to specimen diameters ranging from 2 to 8 mm. Cross-sections of the images for all the samples are shown in Fig. 7.
Pore networks have been extracted from two sandstones and one carbonate (the first three samples in Fig. 7.) The sandstone sample S1 has a porosity of 16.4% and a measured permeability of 906 mD. We drilled a 10 mm long, 8 mm diameter cylindrical specimen from the core plug and used a subset of the image (1.73 mm$^3$) for our pore network analysis. The image resolution is 8µm. The porosity measured on the image is 16.8% and the permeability computed using lattice Boltzmann simulation is 1400 mD. The subset of the image can be considered a representative elementary volume (REV) of the sandstone.

The second sample is sandstone S2. The image has a resolution of 5.0µm and consists of 150$^3$ voxels representing a volume of 0.42 mm$^3$. The last sample is a limestone L1. The 3D image has a resolution of 3µm. The volume is 0.1 mm$^3$. The 3D images of these samples are shown in Fig. 8.

![Fig. 7. Cross sections and dimensional information of micro-CT images of Saudi Arabian core samples.](image)

![Fig. 8. Transparent view (left) and the cutaway view (right) of the 3D micro-CT images. (a) S1, (b) S2, (c) L1.](image)

We extracted pore networks from these three samples, see Fig. 9, and we list the properties of the networks in Table 1. Since the minimum size of pores and throats is always the resolution value of the image, we don’t list them in the table. We find that the sandstones have average coordination numbers between 4 and 5, which is in agreement with other analyses of granular media. The vuggy carbonate has higher coordination numbers and a wider distribution of pore and throat size than the sandstones.

![Fig. 9. Pore networks generated from micro-CT images using the maximal ball algorithm. From left to right, these are networks of S1, S2 and L1 respectively.](image)
### Table 1 - Properties of the pore networks extracted from Arabian reservoir samples

<table>
<thead>
<tr>
<th>Properties</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>16.8</td>
</tr>
<tr>
<td>Number of pores</td>
<td>442</td>
</tr>
<tr>
<td>Number of throats</td>
<td>1018</td>
</tr>
<tr>
<td>Ave. coordination number</td>
<td>4.71</td>
</tr>
<tr>
<td>Max. coordination number</td>
<td>14</td>
</tr>
<tr>
<td>Ave. pore radius(µm)</td>
<td>25.0</td>
</tr>
<tr>
<td>Max. pore radius(µm)</td>
<td>87.7</td>
</tr>
<tr>
<td>Ave. throat radius(µm)</td>
<td>19.2</td>
</tr>
<tr>
<td>Max. throat radius(µm)</td>
<td>78.5</td>
</tr>
</tbody>
</table>

### Conclusions

Micro-CT scanners provide sufficient spatial resolution to image the pore space of sandstones and some granular carbonates. Other carbonate samples may require sub-micron resolution to image intragranular porosity, which is beyond the capability of current instruments.

We have extracted topologically equivalent networks from 3D micro-CT images. The maximal ball algorithm used was validated by comparing the results with the process-based method for idealized sphere packs and a Fontainebleau sandstone.

The two poorly consolidated sandstone samples had average coordination numbers of around 4.5, representing good connectivity. For the carbonate sample, however, the average coordination was considerably higher – it was more than 8. This is because there is an exceptionally variable pore size distribution with some large pores (vugs) with a very high connectivity.

Future work will focus on using the extracted networks to predict multiphase flow properties, such as relative permeability and capillary pressure.

### Acknowledgments

The members of the Imperial College Consortium on Pore-Scale Modeling (BHP, ENI, JGMEC, Saudi Aramco, Schlumberger, Shell, STATOIL, TOTAL, the U.K. Department of Trade and Industry) are thanked for their financial support. We also thank Pål-Eric Oren and Stig Bakke (Numerical Rocks AS) for sharing the network data with us. The imaging work was partly supported by Stefano Favretto and colleagues at the ELETTRA synchrotron lab. We thank Saudi Aramco for providing the samples and for permission to publish this paper.

### References