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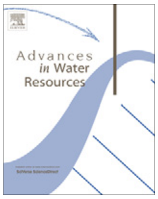

Pore-scale imaging and modelling

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ABSTRACT

Pore-scale imaging and modelling – digital core analysis – is becoming a routine service in the oil and gas industry, and has potential applications in contaminant transport and carbon dioxide storage. This paper briefly describes the underlying technology, namely imaging of the pore space of rocks from the nanometre scale upwards, coupled with a suite of different numerical techniques for simulating single and multiphase flow and transport through these images. Three example applications are then described, illustrating the range of scientific problems that can be tackled: dispersion in different rock samples that predicts the anomalous transport behaviour characteristic of highly heterogeneous carbonates; imaging of super-critical carbon dioxide in sandstone to demonstrate the possibility of capillary trapping in geological carbon storage; and the computation of relative permeability for mixed-wet carbonates and implications for oilfield waterflood recovery. The paper concludes by discussing limitations and challenges, including finding representative samples, imaging and simulating flow and transport in pore spaces over many orders of magnitude in size, the determination of wettability, and upscaling to the field scale. We conclude that pore-scale modelling is likely to become more widely applied in the oil industry including assessment of unconventional oil and gas resources. It has the potential to transform our understanding of multiphase flow processes, facilitating more efficient oil and gas recovery, effective contaminant removal and safe carbon dioxide storage.

1. Introduction

In the last 10 years, pore-scale modelling has developed rapidly from a technique principally devoted to understanding displacement processes with no commercial exploitation, to a predictive tool used in the oil industry with several new companies now providing digital core analysis services. The foundation of this development is the construction of models of increasing sophistication and predictive power that represent both the multiphase flow dynamics and the geometry of the rock [1–11]. This transformation has also been facilitated by the now-routine use of direct three-dimensional imaging of the pore space [12]. This enables predictions to be made on many images of small rock samples, providing data that would be much more difficult – or impossible – to obtain using traditional experimental methods [10,13].

We will first, briefly, mention the imaging methods that are used to produce three-dimensional representations of the pore space of rocks. This topic is the subject of a more detailed review in this issue [14]. We will then discuss the different numerical approaches that are used to compute pore-space properties. These can be divided into two classes: direct simulation, where the governing equations of flow and transport are computed on the image itself; and network modelling, where first a topologically representative network is extracted from the image through which the relevant displacement and transport equations are computed. The strengths and weaknesses of both approaches are presented.

The paper will focus on three applications of imaging and predictive modelling, of interest to the authors, that cover a range of possible application: dispersion in carbonates to elucidate the signature of anomalous transport in highly heterogeneous media; capillary trapping of super-critical carbon dioxide (CO_2) to show that capillary trapping could be an effective and efficient long-term storage mechanism in aquifers; and the relative permeability of mixed-wet carbonates that has implications for waterflood oil recovery in giant Middle Eastern reservoirs. The work builds on the overview of pore-scale modelling published 10 years ago [1], emphasising new developments, particularly the application of pore-scale imaging and the use of predictive approaches to understand carbonates.

We show exemplar applications that illustrate the potential for pore-scale modelling to improve our understanding of different underground flow processes and to help design effective storage,

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clean-up and recovery schemes. This paper is not intended as an exhaustive review of different pore-scale modelling applications. Pore-scale modelling is likely to become a standard and invaluable tool in reservoir management, as well as helping to ensure secure carbon dioxide storage and effective contaminant clean-up. In addition, high-resolution imaging could be used to assess unconventional oil and gas resources. However, not all the problems in this field are solved and the paper will end with an overview of difficulties and challenges: upscaling and representative sampling, the determination of wettability, and use of the results in field-scale simulation.

2. Imaging techniques

2.1. X-rays

The development of modern imaging methods relies on the acquisition of three-dimensional reconstructions from a series of two-dimensional projections taken at different angles: the sample is rotated and the absorption of X-rays in different directions is recorded and used to produce a three-dimensional representation of the rock and fluids. In the 1980s these methods were first applied in laboratory-based systems to measure two and three-phase fluid saturations for soil science [15] and petroleum [16] applications with a resolution of around 1–3 mm. The first micro-CT (micron or pore-scale) images of rocks were obtained by Flannery and co-workers at Exxon Research [17] using both laboratory and synchrotron sources. In a synchrotron a bright monochromatic beam of X-rays is shone through a small rock sample. Several rocks were studied with resolutions down to around 3 μm. Dunsmuir et al. extended this work to characterise pore space topology and transport in sandstones [18–20]. Hazlett was the first to use X-ray images for the direct computation of multiphase flow, including predictions of relative permeability, using the lattice Boltzmann method, which is described later [21]. An excellent overview of these imaging techniques applied to the earth sciences is provided by Ketcham and Carlson [22].

One of the pioneers of the continued development of this technology has been the team at the Australian National University in collaboration with colleagues at the University of New South Wales. They have built a bespoke laboratory facility to image a wide variety of rock samples and then predict flow properties [10,13,23,24]. The base image is a three-dimensional map of X-ray absorption; this is thresholded to elucidate different mineralogies, clays and, principally, to distinguish grain from pore space. We will discuss later the use of similar methods [20] to image multiphase distributions.

The now-standard approach to image the pore space of rocks is to use a laboratory instrument, a micro-CT scanner, that houses its own source of X-rays [10]. Here the X-rays are polychromatic and the beam is not collimated – the image resolution is determined primarily by the proximity of the rock sample to the source. These machines offer the advantage that access to central synchrotron facilities or a custom-designed laboratory is not required, and there is no constraint on the time taken to acquire the image, allowing signal to noise to be improved. The disadvantage is that the intensity of the X-rays is poor compared to synchrotrons while the spreading of the beam and the range of wavelengths introduces imaging artefacts.

Fig. 1 shows two-dimensional cross-sections of three-dimensional grey scale images for eight representative rock samples: several carbonates, including a reservoir sample, a sandstone and a sand pack. Table 1 provides a summary of the rocks analyzed in this paper, their properties and details of the overall image and voxel size. The images were acquired either with a synchrotron beamline (SYRMEP beamline at the ELETTRA synchrotron in Trieste, Italy) or from a micro-CT instrument (Xradia Versa).

The first three images in Fig. 1(a)–(c), are carbonates that will be used in our discussion of network extraction (Section 3) and prediction of multiphase flow properties (Section 6). The second row, Fig. 1(d)–(f), shows samples that will be used in our analysis of dispersion in Section 4. For the quarry carbonates (Estaillades, Ketton, Portland, Guiting and Mount Gambier) a connected pore space is resolved, although the details of the structure are complex and at least two of the samples – Ketton and Guiting – are likely to contain significant micro-porosity that is not captured. Also included is a carbonate from a Middle Eastern aquifer, Fig. 1(g). In this case, while some pores are shown with a voxel size of almost 8 μm, it is likely that there is significant connectivity provided by pores that are below the resolution of the image.

Fig. 2 shows example three-dimensional images of three carbonates where only the pore space is shown; networks (see later) will be extracted from these images for a study of multiphase flow and relative permeability in Section 6. Ketton is a classic oolitic limestone composed of almost spherical grains with large, well-connected pores between them. Estaillades has a much more complex structure with some very fine features that may not be fully captured by the image. Mount Gambier has a very irregular pore space, but it is well connected and the porosity and permeability are very high (Table 1). Overall, while a resolution of a few microns can resolve the pore space for some permeable sandstones and carbonates, many carbonates and unconventional sources, such as shales, contain voids that have typical sizes of much less than a micron. If this fraction of the pore space is ignored, it is possible that the resultant transport predictions are significantly in error.

Typical X-ray energies are in the range 30–160 keV for micro-CT machines – with corresponding wavelengths 0.04–0.01 nm – while synchrotrons have beams of different energies for which those with energies less than around 30 keV are ideal for imaging rock samples. Resolution is determined by the sample size, beam quality and the detector specifications; for cone-beam set-ups (in laboratory-based instruments) resolution is also controlled by the proximity of the sample to the beam, while detecting absorption at a sufficiently fine resolution. Current micro-CT scanners will produce images of around 1000^3–2000^3 voxels. To generate a representative image, the cores are normally a few mm across, constraining resolution to a few microns; sub-micron resolution is possible using specially designed instruments and smaller samples. Developments in synchrotron imaging may allow much larger images to be acquired, but at present most images have an approximately 1000-fold range from resolution to sample size.

In this paper, once the images have been obtained, they are processed and segmented into grain and different fluid phases. The pre-segmentation processing of the images involves two main steps: removing noise and destriping. Noise and ring artefacts may originate during acquisition and must be removed prior to the segmentation phase. Ring artefacts are best removed from the original sinograms, in which they appear as vertical noise stripes, using Fourier–Wavelet filtering [25]. If sinogram images are not available, it is necessary to transform the images to polar coordinates, subsequently remove the vertical stripes, and transform results back to Cartesian coordinates. Salt-and-pepper noise is removed using a two-dimensional, or ideally three-dimensional, anisotropic diffusion filter with a high diffusion limiter along maximal variations for edge preservation [26]. Finally, segmentation is performed based on multi-thresholding based on Otsu's algorithm [27]. In the presence of high density minerals, results are best if the number of segmented domains is increased to capture minerals using a separate threshold [28], and to capture any shadows of contrast-agent dosed media. The quality of the ensuing segmentation will depend on the resolution of the initial data, effective