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Measuring anisotropic permeability using a cubic shale sample in a triaxial cell

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ABSTRACT

Reservoir rocks for water, oil and natural gas, as well as for CO_2 storage are often anisotropic in permeability, due to different pore or layering structures in different directions. Therefore, anisotropic permeability is an important parameter to measure when analysing fluid flow performance in reservoirs. Permeability is commonly measured using a triaxial cell, and anisotropic permeability is often traditionally measured using subcored cylindrical samples from a recovered core. However, the sample's heterogeneity can significantly affect the test results. Cubic samples can eliminate the effect of heterogeneity when measuring anisotropic permeability, but sealing is a major challenge that limits the use of this technique. In this work, a 3D-printed membrane was made to hold cubic shale sample. The cubic sample and 3D-printed membrane assembly which simulate a normal cylindrical core was then installed in a rubber sleeve for permeability measurement in a triaxial cell. Re-orienting the sample in the triaxial cell enabled permeability measurements along each directional axis. Using helium gas to demonstrate the technique, our results show that the shale sample taken from the Longmaxi Formation in Sichuan Basin, China has strong permeability anisotropy, with permeability perpendicular to bedding about 4% of that parallel to bedding. Through reservoir simulation using different permeabilities, we demonstrate that anisotropic permeability has a large impact on modelling gas production, suggesting that anisotropic permeability should be routinely measured and applied to the modelling of fluid flow in reservoir rocks with high permeability anisotropy, such as shales. Our measurement technique can be readily applied to any existing triaxial rigs and will benefit future reservoir evaluation and characterisation.

1. Introduction

The vertical permeability of reservoir rocks is almost always lower than the permeability in any horizontal direction (Lishman, 1970). Permeability mainly depends on the rock lithology and pore structure (Bolton et al., 2000; Lishman, 1970), and permeability anisotropy correlates well to the presence of bedding (Clavard et al., 2008). The permeability ratio (horizontal vs. vertical permeability) also increases with stress due to greater burial depth (Adams et al., 2013). Because permeability is the key parameter controlling fluid flow in reservoir rocks, measuring and understanding anisotropic permeability is of great significance for modelling oil and gas flow in petroleum reservoirs (Burton and Wood, 2013). It may also be useful for understanding groundwater flow (e.g. Snow, 1969) and CO_2 flow in both the target CO_2 storage reservoir and the sealing rock (Armitage et al., 2011).

Recently, gas shales have become a successful target for petroleum extraction. However, the low permeability of shale gas reservoirs (Soeder, 1988) makes gas production difficult. Although economic shale gas production has been achieved through horizontal drilling and multistage hydraulic fracturing, shale reservoir permeability is still one of the critical parameters in the evaluation of a shale gas play and the understanding of its gas flow and production behaviour. Laboratory measurement using core samples is an important means of obtaining anisotropic permeability information (Burton and Wood, 2013). However, such measurements of shale permeability often use core samples that were drilled vertically, and hence, measure only the vertical permeability of the reservoir. As shale is strongly anisotropic with the presence of bedding, permeability in the vertical direction is often magnitudes lower than in the horizontal direction (Ghanizadeh et al., 2014), and is thus not representative of the true shale reservoir permeability.

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Another problem associated with the direct use of recovered cores is that the core is not perpendicular to the bedding in dipping formations. Hence, the measured permeability lies in between the permeabilities perpendicular and parallel to bedding. It is therefore desirable to measure directional permeability of gas shale samples aligned to bedding directions.

Measurements of the directional permeability of a rock sample are often obtained by subcoring vertically recovered cores in the directions perpendicular and parallel to bedding, and then testing the cylindrical subcore samples in triaxial rigs (e.g. Armitage et al., 2011; Bhandari et al., 2015; Burger and Belitz, 1997; Chen et al., 2009; Farrell et al., 2014; Kwon et al., 2004; Mokhtari et al., 2013; Soeder, 1988). However, the resultant individual subcore samples may not represent the true permeability anisotropy of highly heterogeneous rocks such as shales and muddy sandstones (Chen et al., 2014; Fan, 2014). Subcores can also be sequentially cored in different directions before testing, but because the core becomes smaller at each subcore process, this is also problematic for heterogeneous samples (Chan and Cameron Kenny, 1973). Moreover, subcored samples cannot be preserved for future testing. Thus, indirect measurements of core samples have been developed to avoid different subcores. Shmonov et al. (2011), for example, tested cylindrical rock samples for anisotropic permeability by varying flow patterns of fluid. However, such methods require complex mathematical modelling, and large errors may be introduced by simplifications or assumptions used in the modelling process.

Using cubic rock samples is a seemingly straightforward way to measure permeability anisotropy, because geometrically, each direction is the same. Early attempts to measure anisotropic permeability on a one-inch cubic rock sample were reported by Fettke (1938, as cited in Pettijohn et al., 1972). Other early attempts using cubic compressed soil samples in hydrostatic conditions were proposed by Chan and Cameron Kenny (1973). They placed a rubber sleeve around the sample and fastened it to the end of a square-shaped platen using rubber O-rings held against the membrane by square brass clamps (Chan and Cameron Kenney, 1973). After measuring permeability in one direction, the sample was reassembled and oriented in another direction for a second measurement. This method has not been widely adopted, with only a few applications reported by Bernabe (1992) and Adams et al. (2013). One limitation of this technique may be the difficulty in sealing the cubic sample in the round rubber sleeve. Although the square brass clamps can help seal the sample's surface, its edge could be difficult to seal, leading to flow bypass and thereby affecting the permeability measurement. Another limitation could be the difficulty in preparing cubic samples. Unlike cylindrical cores, which can be prepared using core drill bits with standard diameters, there is no standard method for preparing cubic rock samples, and no standard size. This can make it difficult to prepare a cube to suit the size of the available platens, meaning that new platens have to be made.

Other experimental setups to measure the anisotropic permeability of cubic samples have also been developed. King (2002) developed a polyaxial stress loading system in which the sides of a cubic rock sample were sealed by magnesium plates, while the edge of the sample was chamfered and sealed by room-temperature vulcanisation silicone rubber. The degree of the sealing was up to 3 MPa for pore pressure. Massarotto et al. (2003) developed a true triaxial rig for measuring anisotropic permeability of cubic coal samples. Fixed sample dimensions were required for the experiment, with the biggest challenge being the sealing system at high gas pressures. Meyer (2002) used a probe permeater on a rock block sample, but did not take the permeability measurement under stress, and interpretation of the results was difficult.

From these studies of cubic samples, we conclude that sealing of the cubic sample is a major challenge, especially at high pore pressures. Another challenge is preparing the cubic sample to fixed dimensions. These factors may limit the application of cubic samples in permeability anisotropy measurement, despite their obvious advantages. Hence, developing a technique to use cubic samples of any size in any existing triaxial cell would be extremely beneficial.

In this work, we describe a method to prepare a cubic rock sample and a specially designed membrane to hold the sample. The membrane and cubic sample assembly forms a standard-sized cylindrical core sample, allowing it to be installed in any triaxial rig for gas permeability measurement without modifying the rig. A shale sample from the Lower Silurian Longmaxi Formation in the Sichuan Basin, China, was prepared to demonstrate the methodology. We use the transient method to measure permeability and further examine the calculation method. Lastly, we perform reservoir simulations to demonstrate the importance of measuring and using anisotropic permeability in the modelling and calculation of shale gas production.

2. Experimental

2.1. Cubic rock sample preparation

A diamond wire saw was used to cut an initial sample cube from a cylindrical core sample recovered from the Lower Silurian Longmaxi Formation from Sichuan Basin, which is the main shale gas production formation in China. The Sichuan Basin is located within Sichuan Province and Chongqing Municipality in Southwest China and it is tectonically situated in the northwest of the Yangtze metaplatform and surrounded by the Yunnan–Guizhou–Sichuan–Hubei platform fold zone (Yuan et al., 2014). The sample studied in this work is Lower Silurian Longmaxi shale and commercial shale gas production has been achieved from this formation. The core sample was recovered from an exploration well at about 754 m deep. Mineral content was determined using the offcuts of the sample and the result is listed in Table 1.

The procedure for cutting a cube from a rock block has been described in our previous work (Wan et al., 2015) and similar procedure was used herein. Because it is difficult to create satisfactory parallel surfaces and equal side dimensions using the wire saw, the sample was then lapped in a grinding machine to obtain a cube with sides of 21 ± 0.1 mm. The prepared shale cube is shown in Fig. 1. Other sizes can also be prepared depending on the original core size. As shale samples are often layered, it is easy to identify the original orientations if the original core's layering structure has a dipping angle; thus, the cubic sample can be readily prepared to differentiate two horizontal directions.

2.2. Cubic sample membrane

After the cubic sample was prepared and its dimensions were measured, a membrane was 3D printed using photo polymer to hold the sample (Fig. 2, left). The outer diameter of the membrane is 38.1 mm (1.5 inch), but it can be printed to any other standard core diameters to suit the size of prepared samples. The cubic shale sample was then installed in the membrane (Fig. 2, right) to simulate a standard core sample. It was then installed into a rubber sleeve to fit inside the triaxial cell for permeability measurements. After each measurement, the cubic sample was re-oriented and installed in the triaxial cell to measure permeability along each directional axis.