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An experimental investigation of diffusivity and porosity anisotropy of a Chinese gas shale

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ABSTRACT

Gas shale is fine grained and layered reservoir with strong anisotropy. The permeability of the fractures and diffusivity of the matrix are important flow parameters for shale gas production. Both parameters maintain close ties with shale pore structure and are affected by its anisotropy. Hence, study of anisotropy of shale pore structure and diffusivity is an important aspect in evaluating the production behaviour of shale reservoir. Previous laboratory studies on anisotropy were usually performed on core samples taken from different orientations on the same rock block; however, the sample difference may impact on the results of anisotropy, especially when the rock is heterogeneous. In this paper, a new experimental method is presented to investigate the anisotropy of shale porosity and diffusivity. Instead of using different core samples, cube samples are prepared and used to study the diffusion and porosity anisotropy. A shale sample from early Paleozoic strata in Hunan province, China was studied. Multiple cubes were cut from the shale block. The results show that diffusivity is much higher at the parallel to the bedding direction than that at perpendicular direction. Furthermore, porosity measurement also showed different results measured at different directions, suggesting that there are pores only accessible from one direction and the results suggest more such pores in the parallel to bedding direction. Moreover, different cube samples show different anisotropy even they were cut from the same shale block, suggesting that the shale block is heterogeneous and the cube approach is better to study anisotropy on heterogeneous rocks. Finally, scanning electron microscope (SEM) was used to study the pore structure and the relationship between the SEM observation and the diffusivity and porosity results was discussed.

1. Introduction

Shale gas has become one of the most important unconventional gas resources in recent years (EIA, 2013; NETL, 2013; Stevens and Kuuskraa, 2009; USGS, 2013). The "Shale gas revolution" in North America has greatly expanded worldwide energy supply. This encouraged China and many other countries to invest on shale gas research and development (EIA, 2013). The gas flow in the shale during production has mainly three stages: desorption, diffusion and flow in fractures (Wang, 2014). Although permeability of the fractures is often a more important parameter for gas flow in unconventional reservoirs such as shale, matrix diffusivity has also a significant impact as gas is mainly stored in the matrix and it has to diffuse through the matrix to the fracture system before being produced (e.g., Guo et al., 2012; Jahediesfanjani and Civan, 2006; Pan and Connell, 2015; Rahmanian and Solano, 2010; Zhang et al., 2008). Permeability is the parameter which describes gas flow in natural or hydraulic fractures by pressure difference while diffusivity describes the gas diffusion in the shale matrix by concentration difference, which is also related to pressure difference as gas concentration or density is a function of gas pressure. There are three mechanisms of gas diffusion in porous media: Fickian diffusion, Knudsen diffusion and surface diffusion (e.g., Javadpour et al., 2007). They may all play a role for gas diffusion in shale matrix, as gas is stored as both adsorbed and free gases in the matrix pores with a wide size distribution.

Gas shales or mudstones are fine grained and layered reservoirs (Davis, 1992; Oilfield Review, 2011). The anisotropy of shale was pronounced (Lin, 1978; Young et al., 1964). Different composition

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and compaction history make shale reservoir anisotropic. This may have important implications for modelling gas production from shales. So understanding anisotropy of shale reservoir is an important aspect to evaluate shale formations. Some studies have been focused on permeability anisotropy of shales; a few experiments were carried out (Kwon et al., 2001, 2004). Kwon et al. (2004) reported that permeability measured parallel to bedding are about one order of magnitude greater than those measured perpendicular to bedding on Wilcox shale, United States. Other permeability anisotropy studies were based on seismic or log data (Chemali et al., 1987; Johnston and Christensen, 1995; Safdar et al., 2011). Some other studies were focused on anisotropy of elastic properties (Sayers, 2005) or clay mineral alignment (Kocks et al., 1998; Wenk et al., 2008). Nevertheless, all the experimental studies above mentioned were using cylindrical core samples drilled from different directions of the rock.

Anisotropic diffusion behaviour is closely related to the pore structures of the shale matrix. Chalmers et al. (2012) investigated the nano pore system of gas shale from North America by using field emission scanning electron microscope (FE-SEM) and found that orientations of those macropores are horizontal, sub-horizontal, or parallel to bedding. Loucks et al. (2012) found that organic-matter (OM) pores show alignment controlled by original structure of OM in Barnett Shale and the pores appear to be isolated in two dimensions, but display connectivity in three dimensions. Javadpour et al. (2012) used Atomic Force Microscope (AFM) to characterize nano-pore sizes and shapes and found that distinct phase differences are attributed to organic materials. All these directional pore structures would eventually impact on the diffusion anisotropy. Although the importance of gas diffusion is realized and there are methods developed to obtain gas diffusivities for shales (e.g., Guidry et al., 2002; Luffel et al., 1993; Sinha et al., 2012; Yuan et al., 2014a). All these studies assumed isotropic diffusion and sample used in those studies are often crushed samples. However, the measurement of anisotropic shale matrix diffusion is rare.

In this work, a new experimental method was developed using a single cube sample to investigate the anisotropy of diffusivity and porosity of shale matrix. Measurements on three cube samples cut from the same shale block from Cambrian Niutitang formation in Hunan Province, China, were studied. Then pore structure of the shale was investigated using SEM. Finally, the relationships between pore structure and the anisotropic diffusivity and porosity were discussed.

2. Methods

A commonly used method to measure anisotropic behaviour is drilling cores on the three directions from the same rock block (e.g., Gash, 1991; Gash et al., 1992). However, since natural rocks are more or less heterogeneous, measurement of anisotropic behaviour would be more meaningful on the same sample to eliminate the uncertainties from rock heterogeneity. Thus, using cube samples instead of cylindrical core samples is more sensible for this purpose. Cube samples have been mainly used on anisotropy measurement of mechanical properties (Evans and Pomeory, 1966; Jeremic, 1985). Wooster and Wooster (1944) and Brooks and Hallan (1978) used coal cube to measure the anisotropy of magnetic susceptibility. For fluid transport, Delphine et al. (2004) conducted a study on water diffusion in rocks for nuclear waste disposal purpose using cube rock samples. Alexis et al. (2009), Hu et al. (2004) and Pirkko (2002) also used similar method to study the contaminant transport and weathering of rocks. Massarotto et al. (2003) used true Triaxial Stress Coal Permeameter (TTSCP) to measure the permeability anisotropy of coal reservoir, followed by Gensterblum et al. (2011), Qiao (2011), and Wang et al. (2009). However, no research has been found on porosity and diffusivity of shale reservoir using cube sample yet.

2.1. Geology of the shale sample

The early Cambrian Niutitang Formation was deposited in a marine environment and is widespread in the Middle and Upper Yangtze region of South China. The burial depth of Niutitang shale is about 800–4800 m and the net thickness of black shale is about 20–50 m. Niutitang formation is one of the main target formations for shale gas exploration in China (Wang, 2014).

A shale block was obtained from an outcrop of Niutitang formation at Sangzhi county, Hunan province. This shale has high total organic carbon (TOC = 3%) and high maturity (R_o = 3.6%), suggesting high potential of gas generation. Mineral content is analysed and summarised in Table 1. The shale has high quartz content (40.5%) and relatively low content of clay minerals (15.5%), suggesting that the shale may have high degree of brittleness and may be easily fractured for gas production.

2.2. Sample preparation

Three cubes, named Cube 1, Cube 2 and Cube 3, were cut from the shale block using a wire saw. To ensure stability of the block during cutting, plaster was used to cover its bottom (Fig. 1(a)) to level the block off. Then it was mounted on the platform of the wire saw (Fig. 1(b)). Because water interacts with the shale (e.g., Yuan et al., 2014b), it may lead to shale swelling and degradation. Thus air was used to cool the cutting wire instead of water to avoid these problems. During the cutting, all visible fractures were carefully identified and marked (Fig. 1(c)) so they can be avoided in the cube (Fig. 1(d)) since we aimed to obtain a cube of shale matrix without visible fractures. Moreover, we used vernier caliper, square and mini bar clamps to ensure the final sizes of the cubes were all the same at 21 × 21 × 21 mm with the uncertainty of each length less than 1%.

2.3. Diffusion and porosity measurements

Each cube was first dried in a vacuumed oven at 100 °C before every diffusion or porosity experiment. During the drying process, the sample was weighed periodically until the weight remained constant. Thus all the removable moisture has been removed and moisture should have no impact on the diffusion results.

Fig. 2(a) shows a cube sample used in the experiment. To measure the diffusion at each direction, four surfaces should be sealed and two opposite faces were left open for gas transport. To achieve this, a tight thin membrane was used to wrap the four surfaces of the sample; then four stainless steel plates specially engineered to the size of the cubic sample and three tight O-rings were used to compress the plates and membrane to seal the surfaces of the sample (Fig. 2(b)). After experiment, the O-rings, steel plates and membrane were removed and installed to seal other surfaces for measurement on other directions. Fig. 2(c) and (d) show the photos of the surfaces perpendicular and parallel to bedding, respectively. From Fig. 2(c), bedding planes can be clearly identified, while from Fig. 2(d), the surface looks more visually uniformed. In the experiments, three sets of directional diffusion and porosity measurements were carried out for each sample, with a few runs in each set. The three sets of experiments were for all six surfaces, for surfaces perpendicular to bedding or diffusion parallel to bedding, and for surfaces parallel to bedding or diffusion perpendicular to bedding. Only one direction parallel to bedding for diffusion was tested as the two parallel to bedding directions are