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A new approach for measuring the permeability of shale featuring adsorption and ultra-low permeability

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ABSTRACT

Based on the critical issues associated with shale permeability measurements, a new experimental approach by modifying the traditional pressure-pulse decay method was developed. In order to reduce the measurement error caused by the pore volumes of the traditional method, we made a new design that the upstream and downstream reservoir volumes can be changed, In addition, we added a by-pass pipe to measure the bidirectional permeability instantaneously, which can reduce the total test time significantly. Except for nitrogen or helium, methane was utilized to measure the shale permeability in this work, which can be more practical and better understand the real gas transport mechanisms in shale. Furthermore, we modified the conventional interpretation model of permeability measurements by incorporating the physical mechanism of gas adsorption. We also performed a series of experimental measurements and data analyses using different cores from pure shale, sand shale, to sandstone, which are from the Ordos basin (Chang 7 section) in China. The results show that: (1) the error caused by the pore volume errors of the traditional method is decreased by nearly half if variable reservoir volumes are used. The total test time is reduced by around 7 h by adding the by-pass pipe on the apparatus. The value of permeability measured with methane is higher than that measured with nitrogen while lower than that measured with helium. (2) The effective gas adsorption porosity increases with the increasing Langmuir pressure and decreasing pore pressure. If without considering gas adsorption, the measured permeability value will be underestimated, especially under lower pore pressure, higher adsorption capacity, and higher Langmuir pressure. (3) The total error is less than 10% using this new apparatus and the modified permeability interpretation method. The measured permeability values are reliable by comparing the measurements using the new apparatus and the standard instrument of ProPDP-200 under the same condition. (4) The influence of gas adsorption on permeability measurement in shale cannot be ignored, and the permeability is underestimated by up to 97% in pure shale while by only 7.5% in sandstone if the gas adsorption is not taken into account.

1. Introduction

Shale permeability is one of the most critical parameters for reservoir characterization and well-performance evaluation in shale gas reservoirs. Accurately measuring the permeability of shale is significant. Currently, most studies related to shale permeability are mainly focused on theoretical calculation (Cheng et al., 2015a) (Cheng et al., 2015b) (Juntai et al., 2013), while there are only very few approaches to measure the permeability of shale in the laboratory. Cui (Cui et al., 2009) defined an apparent transport coefficient to determine the shale permeability and concluded that the apparent transport coefficient will become smaller if the gas is adsorptive to the sample if the gas adsorption is considered. However, the measurement results only represent the apparent permeability of shale, which are not the true permeability. Metwally (Metwally and Sondergeld, 2011) presented a pressure

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transmission technique by creating an infinite storage capacity for the upstream reservoir to keep its pressure constant, which can reduce the permeability measurement error associated with neglecting the gas absorption effect. Firouzi (Firouzi et al., 2014) conducted experimental studies about transport phenomena of a non-adsorptive gas such as helium to investigate gas slippage mechanism in shale.

In general, traditional methods, which are used for testing permeability of tight gas sands, are applied to measure shale permeability. There are three common methods in the laboratory to determine permeability of tight rocks, which are steady-state technique, unsteady-state technique and mercury intrusion. Steady-state technique has been successfully applied in conventional reservoirs for many years (Shreerang et al., 2015) (Shreerang et al., 2014) (Klinkenberg, 1941) (Rushing et al., 2004). However, if the permeability of rocks is ultra-low, this method requires long time to achieve a steady-state flow. Consequently, due to the ultra-low permeability of shale, the steady-state technique has a relatively low efficiency. In oder to overcome the shortcoming of steady-state technique, the unsteady-state technique makes the shale permeability measurement possible by reducing the test time. Pulse decay method is one of the common used unsteady-state techniques, which generally includes the core column method (Bourbie and Walls, 1982) (Chen and Stagg, 1984) (Hsieh et al., 1981) (Jones, 1997) (Dicker and Smits, 1988), core chips or drill cuttings method (Qu et al., 2015), and the degassing method (Luffel et al., 1993) (Guo and Wong, 1996) (Egermann et al., 2002). Brace (Brace et al., 1968) firstly presented core column pulse decay method. Later, many researchers improved this method. For example, Yang (Yang et al., 2015) presented a chamber PPD method. Luffel (Luffel et al., 1993) proposed a method employing the pulse pressure to test the permeability of core chips or drill cuttings with helium. The degassing method (Schettler, 1989) is mainly used to test the permeability of core from sealed coring, but the test precision of this method is low. Washburn (Washburn, 1921) firstly put forward capillary force function and established the relationship between capillary force, interfacial tension and contact angle. After that, the relationship between mercury (Hg) injection curves and permeability had been widely investigated by many researchers in the scientific literatures (Purcell, 1949) (Swanson, 1981) (Rashid et al., 2015).

Despite their usefulness, these methods mentioned above present several shortcomings when measuring the shale permeability. First, the upstream and downstream volumes of traditional pulse decay permeability apparatuses are constant, so errors are difficult to be minimized. Second, the effect of flow direction of measured fluid on permeability is often ignored. Third, the physical properties of test gases, such as helium or nitrogen, significantly differ from those of methane. Accordingly, it might bring a big error if we use the measured permeability by helium or nitrogen to analyze the methane transport in shale. Finally, The clay minerals and organic matter, which are the main components of shale, have net negative electrical charges on their high surface area. It will make shale samples vulnerable to absorb fluid even the inert gases such as helium. Thus, the permeability determined by the traditional interpretation model of permeability without considering gas adsorption might deviate from the intrinsic permeability of shale.

In this study, in order to overcome these problems, we developed a new experimental apparatus by making three significant changes based on the traditional pulse decay instrument. First, upstream and downstream reservoir volumes are variable, which can reduce the permeability measurement error caused by pore volume. Second, a new by-pass pipe is added in the apparatus, which can measure bidirectional permeability instantaneously and reduce the total test time. Third, the gas of methane can be used to measure shale permeability, which can ensure the practical and reliable transport mechanisms of methane in shale. In addition, we modified the traditional permeability interpretation model by fully incorporating the gas desorption effect. Furthermore, we defined an effect adsorption porosity, which is an important parameter for determining the shale permeability. Also, we performed sensitivity studies of the impacts of some uncertain parameters including the Langmuir volume, Langmuir pressure, and pore pressure, and the effect of adsorption on the shale permeability measurements. We used pure shale, sand shale, and sandstone cores from the Chang 7 section of the Ordos basin in China to measure the permeability. Detailed description of the new technique and results analyses will be discussed in the following sections.

2. Measuring apparatus

2.1. Structure of the measuring apparatus

The apparatus is an assemblage of seven components. They are an injection pump, a vacuum pump, a hand pump, a pressure generator, an incubator, a control box, and a data acquisition system. The core holder is made of high-pressure resistant 304 stainless steel with a rubber sleeve and sealing ring. Radial and confining pressures are exerted by a built-in pump, and the inlet and outlet sides are fixed by a core plug; the lateral side is fixed by a piston bushing so that the apparatus can ensure fluid flow along the axial direction. The gas inlet and outlet are equipped with temperature and pressure sensors. The pressure pulse is produced by a pressure generator, and a thermostat is equipped to ensure gas injection at a constant temperature. By using the injection pump, the methane gas can be injected into the core. The data acquisition system records the overburden pressure, temperature, and upstream and downstream reservoir pressures (Fig. 1).

2.2. Improvement of the apparatus

According to the research results of Jones (Jones, 1997), when the ratios of pore volume to the upstream and downstream reservoir volumes are both 0.25, a 65% pore volume error causes less than 2% error in permeability measurement. When the ratios are both 0.5, a 25% pore volume error causes a less than 2% error in permeability measurement. It can be concluded that the lower the ratio, the smaller the error in permeability, but resulting in the longer the measuring time. Hence, in this study, the upstream and downstream reservoir volumes are made variable (Fig. 1). The recommended ratios of pore volume to the upstream and downstream reservoir volumes are equally from 0.25 to 0.5, where we can reduce the errors in permeability measurements and shorten the measuring time. The upstream reservoir volume should also includes the volumes of the connection pipe and pressure monitor. In addition, the upstream and downstream reservoir volumes should be symmetrical in order to reduce errors.

A large amount of time is spent on balancing the temperature and pressure; if the permeability in the reverse direction must be measured after measuring permeability in the forward direction, the pressure and temperature must be balanced once again. The final conditions may not be identical to those used to measure the forward permeability because of human error (e.g., errors caused by loading and unloading of the core). Hence, in this work, we introduced a by-pass line between valves 3 and 8 in the improved apparatus, by which bidirectional permeability can be measured instantaneously. The time spent on loading and unloading cores and repeatedly balancing the pressure and temperature can be reduced and human errors can be eliminated.