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Non-Klinkenberg slippage phenomenon at high pressure for tight core floods using a novel high pressure gas permeability measurement system

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ABSTRACT

Klinkenberg slippage theory has been widely used to predict the percolation rules at high pore pressure for conventional core floods. However, recent studies have shown deviations to applications of Kinkenberg slippage theory at low back pressure for tight cores. A novel phenomenon of deviation to apparent gas permeability by Klinkenberg slippage theory as pressure differential increase for tight core is reported. To overcome problems of measuring apparent gas permeability for tight core accurately, a system of three novel equipment is invented composed of a high pressure micro flow meter, a high pressure micro flow experimental pressure control system, and a high pressure dynamic micro differential pressure gauge. Nitrogen permeability as a function of pressure gradient in tight core at high pressure differed than that at atmospheric pressure where nitrogen permeability varied inversely with pressure gradient according to Klinkenberg slippage theory. A novel phenomenon observed in this study was that as pore pressure increased passed an inflection pressure point, nitrogen permeability became directly related to pressure gradient contrary to the trend predicted by Klinkenberg slippage theory. As pore pressure became greater, the magnitude of nitrogen permeability enhancement is enhanced.

1. Introduction

In the development of tight gas reservoirs, gas slippage characteristics in the reservoir are a key issue to be studied first. When gas flows in conventional porous media, non-Darcy gas flow attributed to gas slippage occurs. This slippage effect was first proposed by Kundt and Warburg (1875) in the study of tube gas flow. Klinkenberg (1941) proposed a model that incorporates the slip effect that has been widely recognized and applied for low pressure condition.

$$K_g = K_\infty\left(1 + \frac{b_K}{p}\right) \tag{1}$$

In the formula, b_K is the slippage factor that reflects the strength of slippage, K_∞ is the absolute permeability, and P is the average pressure at core inlet and outlet. For high pressure condition, apparent gas permeability is simply achieved by extension of that calculated with Klinkenberg gas slippage at atmospheric back pressure. But a few scholars have recently obtained different results in tight core permeability experiments that consider back pressure. Li. et al. (2009, 2004) discovered through an experiment that the gas slippage effect in the core weakened with increasing back pressure. Finally, in the case of a high back pressure (7.16 MPa), the effect of slippage can be completely ignored.

You et al. (2013) conducted permeability experiments with different tight sandstone cores with application of back pressure, he found that gas slip effect can be eliminated when the backpressure reaches a limit pressure. Dion Salam (2015) conducted gas permeability experiments on eight different cores with permeability of 0.0076 × $10^{-3}\mu m^2$~182 × $10^{-3}\mu m^2$ with back pressure. He obtained results similar to those of Li et al. (You et al., 2013; Li. et al., 2009; Li. et al., 2004).

Tight reservoirs in comparison to conventional reservoir have lower matrix permeability, higher reservoir pressure, lower fluid velocity, etc. These special characteristics of tight reservoirs have placed a higher requirement for the experimental method, technology, and equipment necessary in its studies. All the experimental tight reservoir core permeability tested under high pressure with back pressure no higher than 8 MPa resulted in differential pressure greater than 0.2 MPa. This is mainly attributed to the mechanical limits of the three primary experimental equipment used in testing.

1. Large measurement error measuring low pressure differential in high pore pressure system for conventional differential pressure transducer- Conventional differential pressure transducer has higher

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accuracy tested at low pressure, but at higher testing pressure (greater than 25 MPa), its error is very large (0.1 MPa). Currently, routine method is to use large experimental pressure differential to minimize measured pressure differential error. However, whether the seepage characteristics modeled under large differential pressure in the lab accurately depicts seepage in real tight oil reservoir remains a question.

2. Experimental back pressure control problem- The main method of fluid measurement systems in most previous research employed the use of a back pressure regulator (BPR) to maintain a constant back pressure and the use of a conventional flow meter to measure the gas at the outlet of the BPR. BPR consists of inlet pressure, set pressure, and a membrane. Fluid enters the BPR from the inlet but is blocked by its membrane, exerting pressure on the membrane as the pressure at the inlet builds. If the fluid pressure is inadequate, then the pressure will continue to accumulate. When the pressure reaches the set pressure, the membrane is pushed open and fluid escapes through the outlet. However, this back pressure control method has two disadvantages. First, gas flow range is limited when applying the BPR to maintain constant pressure. Particularly in case of the tight cores, the gas flow rate is extremely small, especially as more pressure leads to a low gas flow rate. Measuring the significantly low gas flow rate in high pressure is difficult using BPR. This reason may explain why the highest back pressure in Li's data is not over 8 MPa. Second, BPR causes evident pressure fluctuations in the injection pressure. The injection pressure fluctuations will significantly affect experiments, especially those in the study of gas slippage in a tight reservoir. The outlet volume fluctuations also seriously affect the results.
3. Error greater than 50% in permeability measurement with use of conventional flow meter and differential pressure transducer under real reservoir pressure and ultra-low flow condition.

The gas permeability measurement for tight cores at high pressure aims to study gas flow property at a high pore pressure and ultra-low flow rate. Thus, a new and reliable system of apparent gas permeability measurement is invented.

2. Experiments and methods

2.1. Experimental setup

For the purpose of studying gas seepage in tight cores under high pore pressure and low differential pressure setting, the authors devised a new experimental setup (Fig. 1). This experimental setup differs with conventional gas permeability measurement setup in that there is a novel high pressure gas permeability measurement setup composed of a high pressure micro flow meter in combination with a high pressure micro flow experimental pressure control system at the outlet end of the coreholder, and a high pressure dynamic micro differential pressure gauge measuring the differential pressure at the two ends of the coreholder. High pressure micro flow meter, high pressure micro flow experimental pressure control system, and high pressure dynamic micro differential pressure gauge are all novel experimental equipment developed by authors' research group.

High pressure micro flow meter can realize very small flow measurement (4 nl/min~1 ml/min) at high pressure condition (Atmospheric pressure ~50 MPa) with high accuracy (error <1%). Its working principle is based upon the displacement method measuring the speed of fluid displacement in a pressure-resistant capillary tube. One concern of this new high pressure micro flow meter used in this study is the extent of expansion of the capillary tube at high pressure and the error it introduce to the measurement. According to the pressure-resistant capillary tube data provided by the manufacturer, the Young's modulus is 77.8 GPa, Poisson's ratio is 0.17, and in–out diameter ratio is 1:14. The radial displacement of the inner diameter is calculated as 0.6 μm under the highest working pressure (50 MPa) by Eq. (2). Therefore, the relative radial displacement of the inner diameter is 0.24% at 50 MPa. This shows the measurement error caused by tube expansion in high pressure can be ignored.

$$y(r) = \frac{D_{\text{inner}}^2 p}{E\left(D_{\text{outer}}^2 - D_{\text{inner}}^2\right)}\left[\frac{(1+\nu)D_{\text{outer}}^2}{r} + (1-\nu)r\right] \tag{2}$$

High pressure dynamic micro differential pressure gauge can continuously log dynamic differential pressure in the order of 10^{-6}MPa under a system pressure up to 80 MPa, with error controlled to within 0.1%. Its working principle is based upon the micro differential pressure measurement under high system pressure through digitized reading of fluid level in a pressure resistant U-shaped tube (pressure resistant manometer).

Micro flow experimental pressure control system employs an end-point large capacity cylinder (3000 L) to provide steady pressure conductance. With it the pressure spikes are reduced to smaller than 10^{-2}MPa. A new back pressure control is designed. The tight cores for experiment have small permeability, and the gas flow rate is very low at a specific experimental pressure. Thus, a large pressurized tank is devised

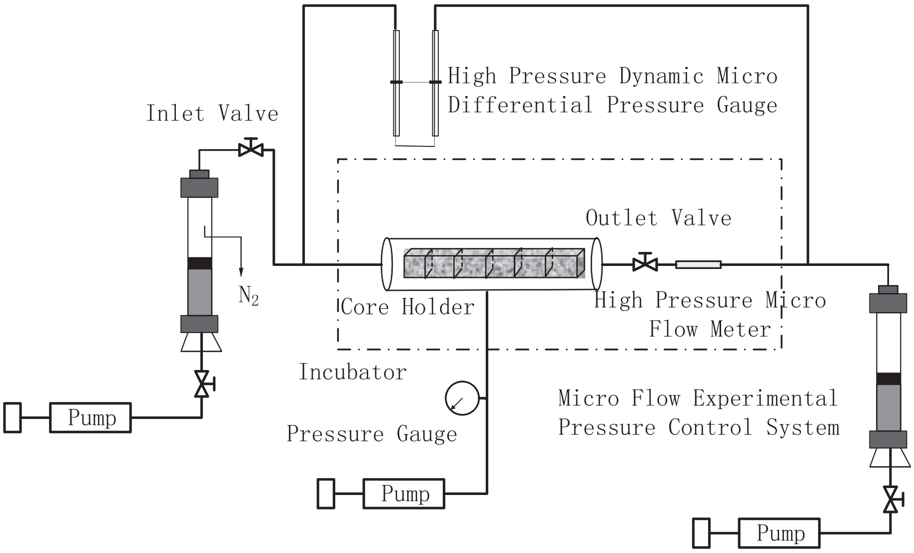

Fig. 1. Schematic diagram of the experimental setup.