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The deviation of gas permeability and classical theory in tight reservoir cores with high pressure

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ABSTRACT

Permeability is an important parameter that characterizes fluid flow through porous media. The widely accepted Klinkenberg (1941) slippage theory was proposed to determine permeability. However, for tight reservoir cores, recent studies have shown deviations in lower back pressure (0.1–7 MPa). This study uses the latest gas flow meter, which expands the measurement range from 0.1 MPag to 40 MPag, to identify the changing curve of the steady-state permeability measurements on tight core at high back pressure. Nitrogen gas permeability of different cores with a wide range of dominated throat radius (0.0605 μm–2.15 μm by high-pressure mercury injection experiments) is measured under the condition of the same 0.4 MPag differential pressure and different back pressures. Results show that when the dominated throat radius is more than 1.0382 μm, the permeability curve conforms to the Klinkenberg slippage theory even when the back pressure is between atmospheric pressure and high pressure. When the dominated throat radius is less than 0.7188 μm, the permeability curve measured in ambient back pressure remains in the realm of the slippage theory; by contrast, the high back pressures do not. The deviation initially increases and then stabilizes as the back pressure gradually increases. Moreover, the gap is enlarged when the core is tight.

1. Introduction

Non-Darcy flow occurs when gas flows through conventional porous media. This phenomenon is generally caused by the slippage effect. In their study of gas flow in a circular tube, Kundt and Warburg (1875) proposed the slippage effect for the first time. In this theory, gas molecules on the tube wall are said to be in motion and have sliding speeds, which lead to oversized volume flow.

Based on the theories of slippage effect, Klinkenberg (1941) set up a simple model of parallel capillary porous media and presented the classic Klinkenberg equation.

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

Where b_K is the slip factor and P is the average pressure on core import and export.

Eq. (1) is widely employed in gas measuring permeability experiments and in calculating gas reservoir exploitation. After its emergence, the Klinkenberg slip theory became widely popular.

According to this theory, gas permeability in high pressure is the extension of a linear segment that is based on gas measuring permeability in low pressure (inlet pressure is generally less than 1 MPag and outlet pressure is atmospheric pressure).

Scholars generally believe that the percolation mechanism differs between a conventional core and a tight core with a small throat radius (0–200 nm) (Rahmanian et al., 2010). New methods that use the Knudsen number to determine flow type have been widely investigated (Beskok and Karniadakis, 1999; Civan, 2010; Javadpour, 2009; Karniadakis and Beskok, 2002; Michel Villazon et al., 2011; Sakhaee-Pour and Bryant, 2013; Ziarani and Aguilera, 2012). Fathi et al. (2012) corrected the Klinkenberg slippage theory for gas flow in nano-capillaries by using a lattice Boltzmann method. However, the research focused on the low-pressure area. Studies on direct gas measuring permeability experiments in high pore pressure, especially for tight reservoir cores, remain scarce.

Rushing et al. (2004) found that apparent permeability decreases to below the predicted Klinkenberg permeability (0.0039 mD) when low pressure is applied to the outlet of the core. The deviation widens when the back pressure increases. For example, when the experiment maximum average pressure was

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2 MPag, the apparent permeability was 0.001429 mD; however, the Klinkenberg-predicted permeability was 0.004041 mD. Rushing linked these phenomena to non-Darcy flow effects. Li et al., (2009) conducted a series of gas measuring permeability experiments in tight reservoir cores under different back pressures and obtained similar curves as those obtained by Rushing. Li also found that apparent permeability deviates with a linear trend when 0.35 MPag pressure is applied to the outlet of the core. However, the Klinkenberg permeability measured by Li was 0.034 mD, 10 times larger than that measured by Rushing. When the maximum average pressure of the experiment was 7 MPag, the measured permeability (0.028 mD) was close to the Klinkenberg permeability (0.034 mD), and the slippage factor in high pressure was no longer a constant. You et al. (2013) reported that permeability decreases with an increase in back pressure. When the maximum pressure is 1.42 MPag, gas permeability (0.0026 mD) is less than the Klinkenberg permeability (0.0032 mD). Researchers concluded that the slippage effect cannot depict gas flow in complex micro-nano pores and in the throat of tight cores. A similar deviation was observed by Tanikawa and Shimamoto (2009); however, no explanation for the phenomenon was provided.

One of the previous methods used to measure gas flow rate in high pore pressure is using a back pressure regulator (BPR). This device regulates high-pressure gas to ambient pressure, and then a conventional gas flow meter is employed to measure the flow. A BPR consists of an inlet, an outlet, a controller, and a membrane. The membrane blocks the flow that enters the inlet. In turn, the flow exerts pressure on the membrane. If the flow pressure is insufficient, it accumulates and increases until the pressure set by the controller is reached. Then, the flow goes against the membrane and escapes from the outlet. However, the BPR has two limitations. First, the gas flow range is limited by the use of a back pressure valve. The gas flow velocity, particularly in a tight core, is extremely low; thus, measuring the gas flow rate under high pressure after using the BPR is difficult. The largest back pressure in previous studies is only 7.09 MPag. Second, outlet pressure fluctuations are inevitable and significantly influence the gas measuring permeability experiment.

The gas flow in a tight core under high pore pressure is characterized by ultra-low flow rates. However, the method of measuring the flow with the use of the BPR is unsuitable for gas measuring tight permeability experiments under high pressure.

Therefore, designing a new experimental device is important. The device should be able to measure extremely low flow under high pressure. This study investigates gas measuring permeability in tight core samples under high back pressures by applying a new extremely low flow meter. This study provides an analysis of the difference between the new device and the classical slippage theory. The change in permeability is significant.

2. Experiments and methods

2.1. Experimental setup

The experimental apparatus is divided into three parts, namely, dynamical, core holder, and measurement of fluid flow systems. A schematic of the experimental apparatus is shown in Fig. 1.

The dynamical system consists of a high-precision automatic pump, a high-pressure container, and a high-precision pressure gauge. This part provides a stable pressure nitrogen source for the experiments. The core holder system consists of a high-precision automatic pump, a core holder, and a high-precision constant temperature box. This part provides stable confining pressure and environment temperature.

The flow test system contains a new flow meter and a new back pressure device to measure small flows under high pressure and to provide stable back pressure. The new flow meter has been patented. It uses displacement method to measure the flow rate directly in high pressure and records gas–liquid slug displacement and time by sensors in high-pressure-resistant pipes. When a large flow rate is measured, a constant volume tank is added before the pipe to extend the flow range. The volume of the measuring section is accurately measured thrice with an ISCO pump in atmospheric pressure (error of ±0.14%, ±0.012%, and ±0.002% for three scales). An electronic stopwatch is used to record time (error of 0.1 s).

The tubes for the experiment are resistant to high pressure. The Young's modulus is 77.8 Gpa and the Poisson's ratio is 0.17. For the tube with an inner diameter (D) of 0.5 mm and outer D of 7 mm, the ratio of inner D to outer D is 1:14; thus, the tube can be considered as a thick cylinder. If a tube is only pushed by the inner-spread high pressure, the radial displacement y(r) can be calculated with Eq. (2) (Ming et al., 2014). The maximum inner pressure is 50 MPag and the calculated D change is 0.6 μm. The rate of relative D change is only 0.24%. Therefore, the influence of D change caused by expansion can be ignored. This new flow meter can operate under high pressure (0 MPag to 50 MPag) and can be used to measure small flows (100 nl/min to 0.3 ml/min).

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

The new back pressure device employs a vessel cavity instead of BPR. With the increase in cavity volume, back pressure is kept more stable than when BPR is used. A 3000 ml container was adopted as the back pressure cavity.

In the experimental process, the results can be influenced by the measurement of the volume of measuring section, temperature, time, and pressure. Thus, the influence of a measurement error in experiment flow was analyzed, as shown in Table 1.

2.2. Core samples

Nine Chinese natural sandstone cores were obtained from an area in Shaanxi Province. The pore throat size distribution curve was obtained from high-pressure mercury injection experiments. As shown in Fig. 2, the throat radius of the core was adopted for the x-axis. The permeability contribution was the y-axis. All samples have a unimodal throat size distribution, which indicates that the dominated throat radius of permeability is comparatively concentrated. The dominated throat radius is used to characterize permeability in different cores. The range of dominated throat radius is from 0.0605 μm to 2.15 μm. Table 2 shows the details of the core samples.

2.3. Gas permeability calculations

The calculation formula of gas logging permeability in this experiment is shown in Eq. (3) (You et al., 2013).

$$K_g = \frac{200 Q_1 P_1 \mu L}{A\left(P_2^2 - P_1^2\right)} \tag{3}$$

where A is the core face area, cm^2; L is the length of the core, cm; μ is gas viscosity in outlet pressure, mPa•s; P_2 and P_1 are the inlet and outlet pressure, respectively, MPa; and Q_1 is the gas flow rate in outlet pressure, ml/s. Gas viscosity is significant in gas permeability calculations; consequently, a PVT simulator (CMG WinProp, CMG, 2003) was adopted in this study. According to the literature (Cole and Wakeham, 1985; Kestin and Leidenfrost, 1959; Latto and