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Measuring permeabilities of Middle-Bakken samples using three different methods

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ABSTRACT

In recent years, petroleum exploration and production from the Williston Basin at the Bakken Formation has garnered great success. Producing hydrocarbons from the Bakken Formation is challenging due to its low porosity and permeability. Investigating the permeability of the Bakken Formation is required in order to better understand the performance of wells that produce hydrocarbons. In addition, permeability is one of the key parameters in modeling fluids flow in reservoir simulation matrices. Unfortunately, the measurement of permeability of tight rocks, such as in Bakken samples, is time consuming and expensive due to their low to extremely low permeability; in addition, sometimes the results from different methods are not in good agreement.

Because of the high uncertainty in measuring the permeability of tight rock, it is worthwhile to investigate permeability through different methods in order to reduce uncertainty. In this study, we measured the permeability of tight rocks utilizing three different methods with the same setup. The investigated methods were the oscillating pulse method, the downstream pressure buildup method, and the radius-of-investigation method. In this way, the comparison provides uncertainty and magnitude and indicates the possible presence of heterogeneities and lamination.

1. Introduction

Hydrocarbon production from the Bakken formation has gained great success at the Williston Basin in recent years through the application of horizontal well and hydraulic fracturing technologies. Because permeability plays an important role in reservoir modeling and production forecast, it is imperative to investigate permeability of the Bakken formation in order to gain a better understanding of reservoir performance.

Based on the experimental work from Darcy (1856), many methods have been presented to improve the accuracy and efficiency of measurement. These methods, based on flow regime, can be classified into two categories: steady-state flow methods and unsteady-state flow methods. Steady-state flow methods measure permeability under steady-state conditions. Aside from low flow rates across the core plug being difficult to measure and control, these tests are quite time consuming. In this case, unsteady state flow is applied to estimate permeability. Brace et al. (1968) introduced a transient flow method to measure the permeability of Westerly granite. From this, many unsteady-state methods have been proposed to measure the permeability of tight rocks. Most of these methods fall into three categories: the pulse decay method, the Gas Research Institute (GRI) method, and the oscillating pulse method.

For the pulse-decay method, the sample has both an upstream reservoir and a downstream reservoir. A pressure pulse, which is applied at the upstream reservoir, will decay over time. The permeability is estimated by analyzing the decay characteristics of the pressure pulse (Brace et al., 1968). Dicker and Smits (1988) improved the pressure pulse-decay method by showing a general solution of the differential equation which describes the pressure decay curve. Based on this solution, they theoretically pointed out that fast and accurate measurements are possible when the volumes of the upstream and downstream reservoirs in the equipment are equal to the pore volume of the sample. Jones (1997) pointed out that the initial pressure equilibration step is the most time-consuming part of the pulse-decay technique. To avoid the equilibrium state, Jones' method utilizes a smooth pressure gradient, which requires smaller upstream and downstream reservoirs. To account for adsorption during pulse-decay measurement, Cui et al.

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(2009) presented their method which can describe gas transport in low permeability reservoir more reliably and accurately. Metwally and Sondergeld (2011) proposed another pulse-decay method by keeping the upstream reservoir pressure constant leading to an infinitely large volume of the upstream reservoir, so that the ratio of upstream reservoir volume to downstream reservoir volume is infinite. Thus, the solution of the pulse-decay measurements can be simplified.

The GRI method differs from the pulse-decay method in that the measurement is carried out on crushed rock samples; a pressure pulse is applies on unconfined crushed rock particles. Permeability is then obtained through the analysis of the pressure decay over time. Cui et al. (2009) developed a late-time method utilizing data from either pulse-decay or GRI experiment to determine the permeability. The GRI method has the advantage of a shorter experimental time as compared with other methods. Unfortunately, permeability measured from crushed samples can differ by 2–3 orders of magnitude among different commercial laboratories (Passey et al., 2010 and Tinni et al., 2012). Another limitation of this method is that the microcracks in the crushed particles essentially violate the GRI assumptions. This leads to an overestimate of permeability (Tinni et al., 2012). To improve the accuracy and consistency of the GRI method, Sinha et al. (2012) developed cylindrical calibration standards based on first principles to calibrate the low permeability measurement apparatus. The GRI method is not used in this study because of large permeability differences between crushed and intact samples.

The oscillating pulse method estimates rock permeability by interpreting amplitude attenuation and phase retardation in the sinusoidal oscillation of the pore pressure as a pressure pulse propagates through a sample. At the beginning of the experiment, the sample pore pressure, the upstream reservoir pressure, and the downstream reservoir pressure are stabilized. Then a pressure wave is generated in the upstream reservoir and propagates through a core plug. The permeability can be obtained by using the information of the amplitude attenuation and phase shift between the upstream reservoir pressure wave and the derived downstream reservoir pressure wave at the downstream side of the sample. Although this method can measure the permeability in a relatively short time without destroying the sample, as the GRI method does, the accuracy of permeability obtained from this method relies on the signal-to-noise ratio and data analysis techniques (Kranz et al., 1990).

Normally, permeabilities measured by the different methods are not in good agreement. Bertoncello and Honarpour (2013) concluded that the steady-state method with critical fluid provides much more consistent and acceptable results after comparing permeability measurements performed at several commercial and research laboratories using four different techniques. However, Bertoncello and Honarpour (2013) did not mention the time of measurement for each method. In fact, the measurement of tight rock permeability, such as in Bakken samples, is time consuming and expensive due to their low permeabilities. In addition, the results given by Lab_1 from transient methods are consistent and acceptable, and Lab_1 is the only laboratory which provides different methods.

In this study, we introduced a testing process to measure the permeabilities of tight rocks with three different methods under the same procedure. These methods are the oscillating pulse method, the downstream pressure buildup method, and the radius-of-investigation method. In this way, not only the comparabilities of the results from these three methods increased, but the difference among the results is also useful for indicating the heterogeneity and/or microcracks of the rock. The theory, development of governing equations, and derivation of solutions for the downstream pressure buildup method and the radius-of-investigation method are shown in Appendices B and C. The experiment procedures and data analyses of these two methods are shown in “Methodology” and “Results and Discussions”.

2. Methodology

2.1. Sampler and equipment

The Bakken Formation, which formed in the Williston Basin with an offshore marine environment, consists of three members: the upper shale, the lower shale, and the lithologically variable middle member. In this study the siltstone Middle Bakken core samples from one well in North Dakota were chosen to represent the tight rocks. The core plugs are cylindrical with dimensions of one inch in diameter and two inches in length.

First, the cylindrical core plug was covered with copper sheeting in order to both form a gas-tight seal on the cylindrical wall of the sample and to apply radial confining pressure. Then the core plug was mounted in a sample holder with flexible rubber sleeves at both ends of the plug (Fig. 1). Finally, the sample holder was put into a vessel flooded with mineral oil, in which the sample could be hydrostatically compressed by hydraulically applying force to the plug. To minimize the volume of the downstream reservoir, a small pocket was implemented inside the downstream end-cap (Figs. 1 and 2). The volume of downstream reservoir was 0.63 cc.

The equipment used to perform the experiments was an AutoLab 1500, which is made by New England Research Inc. Fig. 2 presents a conceptual diagram of the test facility. One temperature transducer (TT1) is used to measure the temperature. Four pressure transducers (PT1, PT2, PT3, and PT4) are used to measure the upstream reservoir pressure, the confining pressure at the flank of the core, the downstream reservoir pressure, and the axial

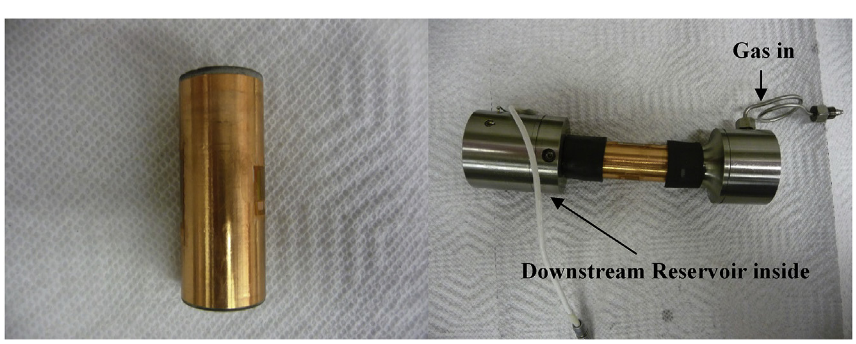

Fig. 1. Core covered with copper sheeting, and assembled on End Caps for a low permeability test system.