Permeability Measurements of Bazhenov Formation Rocks on Plugs and Crushed Core

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Abstract. Laboratory investigations of low and ultra-low permeable rocks of the Bazhenov Formation face serious problems, one of which is the determination of reservoir properties. Currently, there are several methods for measuring the permeability of rocks in range $10^{-3} \ldots 10^{-9}$ mD. All of them include determination of permeability, both on plugs and crushed core. This work is concerned with comparison of results to determine the permeability of Bazhenov Formation rocks on plugs and crushed core. To determine the permeability on plugs, the steady state method, adapted for low and ultra-low permeable core samples, and the pulse decay method were used. The GRI method was used to study crushed samples. It is shown that, the proposed methods give a similar permeability values and can be used to determine permeability of Bazhenov Formation rocks.

1. Introduction

Oil companies in Russia are increasingly paying attention to the development of shale oil, which is mainly confined to the sediments of the Bazhenov Formation (Western Siberia) [1-2]. The Bazhenov Formation has huge resources, but the production of hydrocarbons from it is a difficult task, as rocks are characterized by low and ultra-low permeability.

For dense rocks of the Bazhenov Formation, the use of standard methods for determining permeability leads to a high duration of experiments in time (the order of several weeks). Also, due to the massive natural fracturing of rocks and the formation of artificial fractures during core sawing, permeability values can be overestimated by several times in comparison with permeability of matrix [3]. Currently, there are several methods for determining the permeability of rocks in range $10^{-3} \ldots 10^{-9}$ mD. The purpose of the work was to compare results of permeability determination of Bazhenov Formation rocks on plugs and crushed core by different methods.

2. Sample description and preparation

Investigated samples of the Bazhenov Formation were cored from exploratory well of one of the oilfield in the Tomsk region (Russia). Bazhenov Formation samples are represented by siliceous-argillaceous rocks, with characteristic values of permeability $10^{-3} \ldots 10^{-9}$ mD.

Performance targets in the study involved carrying out experiments on plugs and crushed core with the same reservoir properties. Plugs of Bazhenov Formation rocks were subjected to extraction with an alcohol-toluene mixture in a Soxhlet extractor for several weeks. The extraction time of crushed
samples was 3-5 days. After extraction, samples were dried in a vacuum oven at 105 °C until the weight becomes constant.

3. Methods and equipment

3.1. Steady state method

The steady state method is the standard laboratory method to determine permeability of plugs. This method is highly accurate, reliable, and also has a simple analytical solution (equation 1) [4].

\[ Q = -\frac{k A (P_u^2 - P_d^2)}{\mu L 2P_d} \]  

(1)

where \( Q \) – flow rate of fluid, m³/s; \( k \) – permeability, m²; \( A \) – sample cross-sectional area through which filtration takes place, m²; \( \mu \) – viscosity of fluid, Pa·s; \( L \) – length of sample, m; \( P_d \) – downstream pressure, Pa and \( P_u \) – upstream pressure, Pa.

However, application of this method to very low permeability rocks, such as shale, is typically considered impractical; because the long duration of experiments and the low accuracy of measurements are exist. Still, steady state experiments can be successfully performed for low and ultra-low permeability media and provide reliable results [5-9].

The scheme of steady state experiment set-up is shown in figure 1.

![Figure 1. Scheme of steady state experiment set-up to determine permeability on plugs.](image)

The permeability of Bazhenov Formation samples was determined by using a constant pressure differential technique. This technique involves the use of two piston pumps: one on the upstream end of the sample, and the other on the downstream (figure 1). After system equilibration, the pistons maintain the desired pressure differential by moving in a push (upstream piston) and pull (downstream piston) motion. The displacement of the pistons over time allows determining the fluid flow rate, knowing volume and time, and permeability can then be calculated using equation (1).

3.2. Unsteady state methods

3.2.1. Pulse decay method

The pulse decay technique is based on a method described by Brace et al. [10] and has been further developed by Hsieh et al. [11], Dicker and Smits [12], Jones [13], Cui et al. [14] and Alnoaimi and Kovscek [15]. This method derives its popularity from its shorter experimental run times, and higher resolution for very low permeability measurements, compared with the steady state method.

Experimental set-up of a pulse decay technique is shown in figure 2.
According to pulse decay technique, the cylindrical core sample is placed in Hassler Cell between two reservoirs (figure 2). The gas in the pore space of the sample is kept initially at the same pressure as the gas in the downstream reservoir. The gas pressure in the upstream reservoir is initially slightly higher, thereby creating a pressure pulse. Upon opening the valve V₂ (figure 2), connected at the upstream reservoir, the pressure difference over the sample will decay as the gas flows from the upstream reservoir through the sample to the downstream reservoir. The measured decay curve pressure difference versus time is indicative for the permeability of the sample.

The solution for pulse decay technique can be obtained from the differential equation for a one-dimensional flow of compressible fluid through a porous medium, which is based on Darcy’s law [10]. If the experiment only involves very small pressure changes (i.e. ≤5%), then the experimental dimensionless differential pressure at larger time becomes a single exponential function of time and can be approximated as [12-13]:

$$\ln(\Delta P_D) = \ln(f_0) + s_t t$$

(2)

where the dimensionless differential pressure ($\Delta P_D$) between the upstream and downstream reservoirs is defined as:

$$\Delta P_D = \frac{P_u(t) - P_d(t)}{P_u(0) - P_d(0)}$$

(3)

$$f_0$$ – constant and $$s_t$$

$$s_t = -\frac{k_f A}{\mu L c_g}$$

(4)

where $k$ – permeability, $m^2$; $A$ – cross-sectional area of plug, $m^2$; $V_u$ – upstream reservoir volume, $m^3$; $V_d$ – downstream reservoir volume, $m^3$; $\mu$ – gas viscosity, Pa·s; $L$ – length of sample, m; $c_g$ – gas compressibility (Pa⁻¹); $f_i=\theta_i^2/(a+b)$, where $\theta_i$ is the first solution of the transcendental equation (5):

$$\tan(\theta) = \frac{(a+b)\theta}{\theta^2 - ab}$$

(5)

$a$ and $b$ are gas-storage capacity ratios of sample ($V_p$) to upstream ($V_u$) and downstream reservoirs ($V_d$), respectively.

### 3.2.2. GRI method

The method of the Gas Research Institute (GRI) [16] has established itself as a popular method to determine the matrix permeability of shale formations [17-20]. Because the GRI method has a simple experimental set-up (figure 3) and can significantly shorten the duration of experiments due to core crushing. However, its drawbacks include the lack of confining pressure, the performance of experiments at low pore pressures (~ 50-80 psi), and the fact that the Klinkenberg effect is ignored.

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**Figure 2.** Scheme of set-up to determine permeability on plugs by using a pulse decay technique.
Crushed samples were analyzed in the SMP-200 matrix permeater (Core Lab Instruments, USA) consisting of a reference and a sample cell, valves and a pressure transducer (figure 3b). In the first step, the reference cell is pressurized with gas (~200 psi). When equilibrium is reached, the valve connecting the sample with the reference cell is opened, allowing the gas from the reference cell to expand into the sample cell. After the initial immediate pressure drop in the reference cell, the pressure decays continuously over time as gas penetrates the crushed sample particles, until equilibrium is reached. The experimental data of pressure fall-off are approximated by a theoretical curve, and further if the porosity of the sample is known, the matrix permeability can be calculated [20].

4. Permeability measurement results

4.1. Determination of permeability on plug by the steady state method

The steady state experiments on plugs of the Bazhenov Formation rocks were carried out under the following thermobaric conditions: the pore pressure was 3.0 MPa, the confining pressure was 11.4 MPa, and the temperature was 60 °C. The experiment was designed to filter nitrogen across the investigated sample while maintaining a constant pressure differential. The flow rate of the fluid was determined from the dependence of the pumped out volume of gas by the pump at the downstream end of the sample with time (Fig. 4a.).

In figure 4b shows that the linear dependence of gas flow rate at the downstream end of the sample on the coefficient \((P_u^2 - P_d^2)/2P_d\) (reliability of the approximation \(\chi^2 = 0.995\)). The slope of the straight line was used to calculate the average permeability of the core sample by the steady state method. The permeability of the Bazhenov Formation plug was 3.60·10^{-4} mD.
4.2. Determination of permeability on plug by the pulse decay method

The pore pressure in the Bazhenov Formation plug was balanced with the pressure in the upstream and the downstream reservoirs and was 3.5 MPa. Then, the pressure in the upstream reservoir was increased by 1 MPa, thereby creating a pressure pulse. Further, the pressure fall-off in the upstream reservoir and the growth in the downstream reservoir were recorded as a result of nitrogen filtration through the core sample (figure 5a). Using the slope of the straight line approximating the dependence of the natural logarithm of the dimensionless pressure differential on the time (Fig. 5b), the permeability according to equation (4) was calculated.

The upstream reservoir volume and downstream reservoir volume were 25.8 and 23 cm$^3$, respectively. The pore volume of the sample was determined by the gas expansion method and amounted to 3.36 cm$^3$. All experiments were carried out at the temperature of 60 °C.

To study the influence of microcracking on the permeability of plug, measurements were made at different effective confining pressure (figure 5c). Figure 5c shows that the permeability of the sample is independent of the effective confining pressure. This indicates the presence of undisturbed sample structure.

![Figure 5](image-url)

**Figure 5.** The process to determine the permeability of plug by the pulse decay method: a) – the dependence of pressure in the upstream reservoir and in the downstream reservoir on the time during the process of gas filtration through the sample; b) – the straight line, approximating of experimental data of the natural logarithm of the dimensionless pressure differential versus time; c) – the permeability of the sample at a different effective confining pressure.

4.3. Determination of permeability on crushed core by the GRI method

To determine the permeability of the core sample by the GRI method quantity of crushed core of different fractions 0.5-1, 1-2 mm, 2-5 mm, and 5-10 mm were taken (figure 6).
Figure 6. Permeability determination of the Bazhenov Formation sample on crushed core and plug. Red color indicates the matrix permeability obtained on crushed core by the GRI method. The permeability of the plug, obtained by the steady state method is highlighted in blue. Green color indicates the permeability of the plug, obtained by the pulse decay method.

The permeability, obtained on the plug and the crushed core has a similar values (range from $1.5 \times 10^{-4}$ to $3.5 \times 10^{-4}$ mD) except for the fraction 5-10 mm (figure 6). A high permeability value for a coarse particles fraction is associated with a poor approximation of the experimental data by theoretical curves embedded in the SMP-200.

5. Conclusion
For the first time, a comparison of permeability determination on plugs and crushed core of the Bazhenov Formation rocks was made. It is shown that the steady state method and the pulse decay method for cylinder samples and the GRI method for crushed core give similar results and they all can be used to measure the permeability of the Bazhenov Formation rocks. To correct measure the matrix permeability of the Bazhenov Formation rocks by the GRI method, particles smaller than 5 mm should be used.

To determine the permeability of the Bazhenov Formation rocks, the main emphasis should be placed on thermal stabilization of set-ups, since insignificant temperature changes introduce significant errors in determining the changes in pressure and fluid flow rate.

6. References
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