Influence of Effective Stress on Absolute Permeability of Ultralow-Permeability Rocks

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Abstract. The great potential of unconventional hydrocarbon resources in the world is realized in shale formations represented by fractured low-permeability and ultralow-permeability reservoirs. The development of shale formations in the energy depletion mode leads to an increase in effective pressure, which has a significant effect on the permeability of low-permeability and ultralow-permeability reservoirs. A laboratory estimation of the influence of effective pressure on the absolute permeability of different litological compositions rocks with permeability from 0.1 nD to 1 mD was carried out. Absolute gas permeability was determined by the pulse decay method and the modified steady-state method under pressure conditions. The results showed that an increase in the effective pressure from 7 to 45 MPa leads to a decrease in the absolute permeability of low-permeability and ultralow-permeability reservoirs by 1.8 – 100 times, depending on the initial permeability of core samples and their lithology. Reliable correlations of absolute permeability and effective pressure for reservoirs of different types have been identified. Correlations can be used to design well flow rates for the entire period of shale formations development.

1. Introduction

The permeability of shale formations is one of the critical parameters that determines both the amount of recoverable hydrocarbon reserves and its production technology. Currently, the development of shale formations is carried out mainly in the energy depletion mode, intensifying production by drilling horizontal wells with multiple hydraulic fracturing [1]. The fall in reservoir pressure during hydrocarbon production increases the effective pressure, which has a significant effect on the filtration properties of shale formations. This fact must be taken into account when designing the shale formations development. The aim of this work is to estimate the influence of effective pressure on the absolute permeability of low-permeability and ultralow-permeability rocks of different lithological composition.

Filtration of compressible fluids (gases) through isotropic porous media obeys the classical Darcy law for laminar flow (1):

$$Q_{\text{mean}} = \frac{K_{\text{g}} \cdot \Delta P \cdot F}{\mu \cdot L} \tag{1}$$

where K_{g} – gas permeability, measured at a given mean pressure in the sample (m^2); Q_{mean} – mean gas volumetric flow rate during filtration through the sample (m^3/s); μ – dynamic viscosity of gas under

filtration condition (Pa·s); L – length of the sample (m); ΔP – differential pressure between sample ends (Pa); F – cross-sectional area of the sample (m^2).

Darcy's law (1) is valid for moderate filtration rates, when pressure losses due to inertial effects of the flow are negligible compared to losses due to the viscosity of the filtered fluid [2]. Meanwhile, many researchers [3-6] indicated that the gas permeability of rock is a variable, depending on the type of gas used and the average pore pressure. To obtain the absolute value of gas permeability, the Klinkenberg correction for gas sliding along pore channels is introduced (2) [7]:

$$K_\text{g} = K_\text{abs} \cdot \left(1 + \frac{b}{P_\text{mean}}\right) \qquad (2)$$

where K_abs – true (absolute) gas permeability, (m^2); K_g – apparent gas permeability (m^2), determined at a given mean pore pressure P_mean (Pa); b – slip coefficient, depending on the type of rock and the filtered gas (Pa).

2. Methods and equipment

2.1. Pulse decay method

The pulse decay method is the most frequently used experimental unsteady-state method to determine the permeability of low-permeable porous media [8-13]. In laboratory practice, permeameters based on the modified pulse decay method proposed by Jones [14], were widely used to determine the permeability of core (Figure 1a).
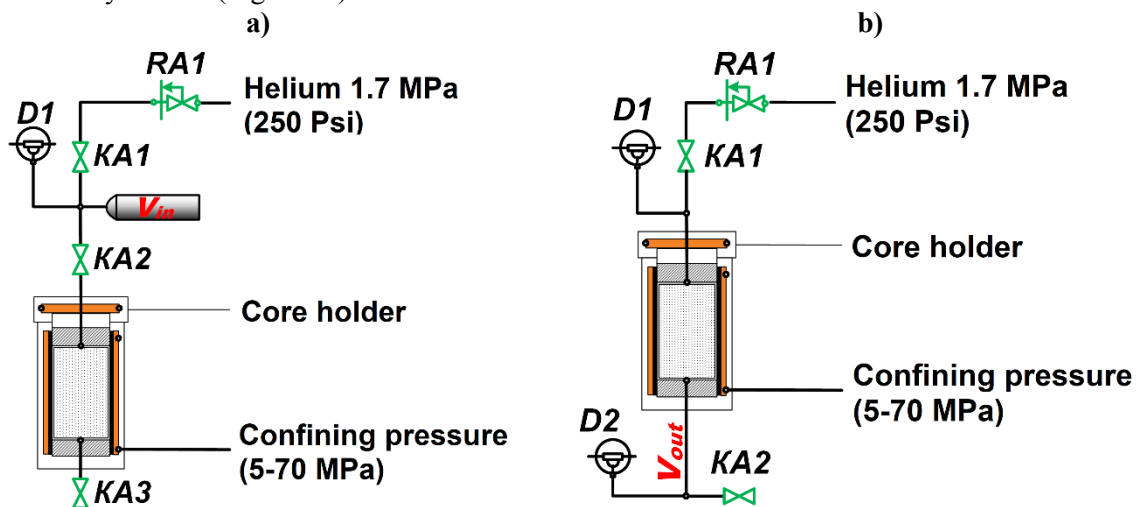

Figure 1. Schematic diagram of the instruments used to determine the absolute permeability of rocks: a) – an automatic analyzer of porosity and permeability PIK-PP (JSC «Geologika», Russia); b) – device for determining permeability by steady-state method PIK-NANO-SF (JSC «Geologika», Russia).

In the Jones modification [14], there is no output tank and the core holder with the sample is connected directly to the atmosphere through the *KA3* valve (Figure 1a). To carry out an experiment, the tank V_in and core sample in the core holder are filled with helium to a certain pressure using the automatic pressure regulator *RA1* and the automatic valves *KA1* and *KA2*. The tank and core sample are initially under pressure of about 240 psi. Then, valve *KA3* opens and the resulting pressure decay in the tank is detected over time using the high-precision pressure sensor *D2* (Figure 1a). If filtration through the core sample obeys Darcy's law, the permeability of porous medium can be determined using equation (3) [14].

$$K_\text{g} = \frac{m \cdot \mu \cdot L}{F} \qquad (3)$$

where K_g – gas permeability, measured at a given mean pressure in the sample (m^2); μ – dynamic viscosity of gas under filtration condition (Pa·s); L – length of the sample (m); F – cross-sectional area of the sample (m^2); m – angle of inclination in the graph of the dependence of y on P_g (4) [14]:

$$y = \frac{V_{tank} \cdot \left(P_g + \frac{i_y}{m}\right)}{(t_2 - t_1) \cdot \frac{i_y}{m}} \ln \left[\frac{Pt_1 \cdot \left(Pt_2 + \frac{i_y}{m}\right)}{Pt_2 \cdot \left(Pt_1 + \frac{i_y}{m}\right)}\right] \qquad (4)$$

where V_{tank} – volume of the tank (cm^3); tank pressure (psi) Pt_1 and Pt_2 (psi) at time t_1 and t_2 respectively (s); i_y – segment cut off by the graph on the y axis depending on P_g, and P_g – geometric mean pressure equal to (5) [14]:

$$P_g = (Pt_1 \cdot Pt_2)^{1/2} \qquad (5)$$

2.2 Steady-state method
The steady-state method is classic to determine the permeability of rocks. It differs in reliability and a simple analytical solution (1).

The use of the steady-state method to determine ultralow permeability is not widespread due to the high duration of experiments and the unsatisfactory accuracy of measuring fluid flow rate. In our previous paper [15] a new method to determine the permeability of low and ultralow-permeability rocks by the modified steady-state method was proposed. This method involves estimating the gas flow through the sample using an automatic low-flow meter.

The essence of the experiment to determine the gas permeability of a core sample using the modified steady-state method is as follows. At the sample inlet, a certain pressure is set using the automatic pressure regulator *RA1* (Figure 1b). The inlet pressure is measured by a high-precision digital pressure sensor *D1* (Figure 1b). During the filtration process, valve *KA2* closes, and the calibrated tube V_{out} is filled with gas filtered through the sample (Figure 1b). The pressure in the calibrated tube is measured by a high-precision digital pressure sensor D2 (Figure 1b). Upon reaching a certain pressure, which is explicitly set in the instrument software, valve *KA2* automatically opens and releases accumulated gas. This cycle of filling the calibrated tube with gas and its output is repeated until the volumetric gas flow rate is stabilized, which characterizes the steady-state filtration mode. The average volumetric gas flow through the sample is calculated based on the outlet pressure using general gas equation [15]. The apparent permeability for helium of the core sample is calculated by the equation (1), knowing the average volumetric gas flow rate through the sample and the differential pressure.

3. Samples description and preparation
To determine filtration characteristics of core, a collection of 10 plugs of tight sandstones, dolomites and siliceous-clay shales (silicites) without visible cracks having a diameter of 30 mm and a length of 15 ... 45 mm was used. Samples were prepared for research (extracted and dried) according to the GOST 26450.0-85 [16].

4. Results of study

4.1 The influence of effective pressure on the filtration properties of low-permeability tight sandstones
Before conducting experiments to determine the absolute permeability of low-permeable ($0.01 < K_{abs} < 1$ mD) tight sandstones, the PIK-PP device was calibrated using porosity calibers to reliably determine the volume of device tanks and the volume of core void space. The volume of the inlet tank after calibration was 7.11 cm^3. Pore pressure was 240 psi in all experiments. The confining pressure evenly increased from 7 MPa to 45 MPa. For each effective pressure, 3 measurements of the reservoir properties of core samples were performed. The arithmetic mean of the last two measurements was

used in the calculation. The results of a study of the influence of effective pressure on the reservoir properties of tight sandstones are presented in figure 2.
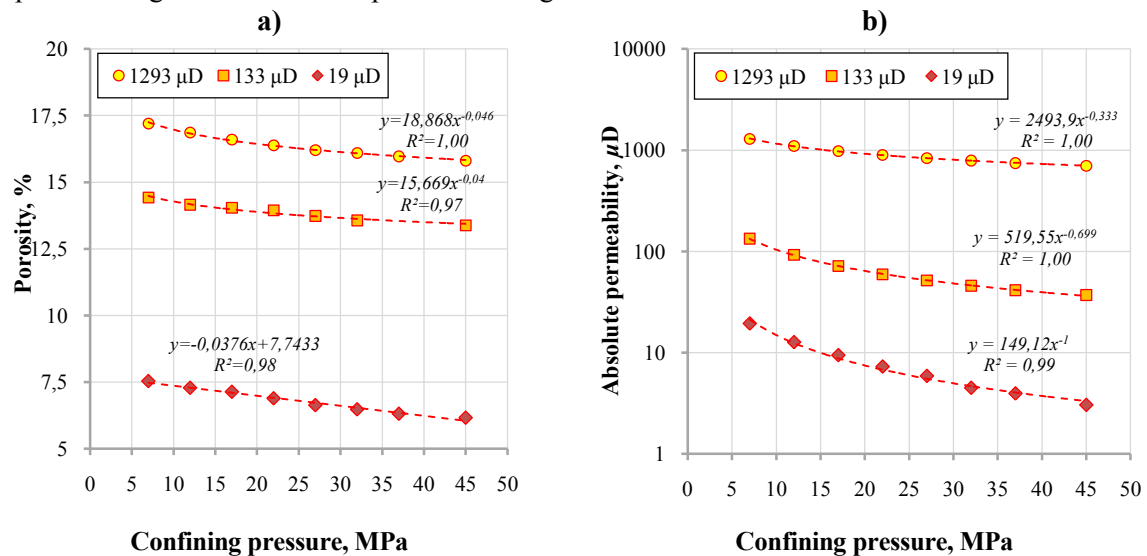

Figure 2. The influence of effective pressure on the reservoir properties of low-permeability tight sandstones: a) – on porosity; b) – on absolute permeability.

It can be seen from figure 2 that the porosity and absolute permeability of tight sandstones is a power law function of the confining pressure (reliability of approximation $R^2 \geq 0.97$) for almost all plugs except for a sample with a permeability of 19 μD (linear function). With an increase in confining pressure from 7 to 45 MPa, the porosity of plugs decreases by $1 - 1.5\%$ for all samples, regardless of their initial porosity at a pressure of 7 MPa (Figure 2a). The initial permeability directly affects the magnitude of the decrease in absolute permeability with an increase in confining pressure, as evidenced by the increase in the degree of function with a decrease in the initial permeability of tight sandstones (figure 2b). With an increase in effective pressure from 7 to 45 MPa, the absolute permeability of the studied samples decreases by $1.8 - 6.4$ times.

4.2 The influence of effective pressure on the filtration properties of dolomites and siliceous-clay shales

The absolute permeability of low-permeability ($0.001<K_{abs}<0.01$ mD) and ultralow-permeability ($K_{abs}<0.001$ mD) rocks was determined using the PIK-NANO-SF device. Before the experiments, the device was thermostated at a temperature of 30 ºC for 24 hours and then calibrated. The pressure at the sample inlet varied from 100 to 1700 kPa, depending on the permeability. The pressure at the sample outlet changed cyclically from 0.25 kPa to 1.25 kPa. The confining pressure evenly increased from 7 MPa to 45 MPa. For each effective pressure, 3 experiments were carried out to determine the absolute permeability of plugs. The arithmetic mean of the last two measurements was used in the calculation.

For all studied samples, linear dependences of gas flow rate on the differential pressure were obtained ($R^2>0.99$, Figure 3a). Its fact indicates validity of the Darcy's law application. Measurement of apparent permeability for helium at $6 - 8$ different mean pore pressures (P_{mean}) were performed to determination the absolute permeability. For each value of mean pore pressure, 3 apparent permeabilities for helium were measured, and then the dependence $K_g = f(1/P_{mean})$ was drawn. The value of absolute permeability K_{abs} was found by extrapolating the dependence by $1/P_{mean}=0$ (Figure 3b).

Figure 3b shows that for all studied effective pressures, a linear dependence is observed between the apparent gas permeability and the inverse mean pressure ($R^2>0.97$), which indicates the applicability of the Klinkenberg theory for samples with ultra-low permeability. It should be noted that other researchers [3, 17-19] came to the conclusion that the Darcy's law and the Klinkenberg effect

still act at gas filtration through ultralow-permeability reservoirs. Similar dependences were obtained for all studied plugs.
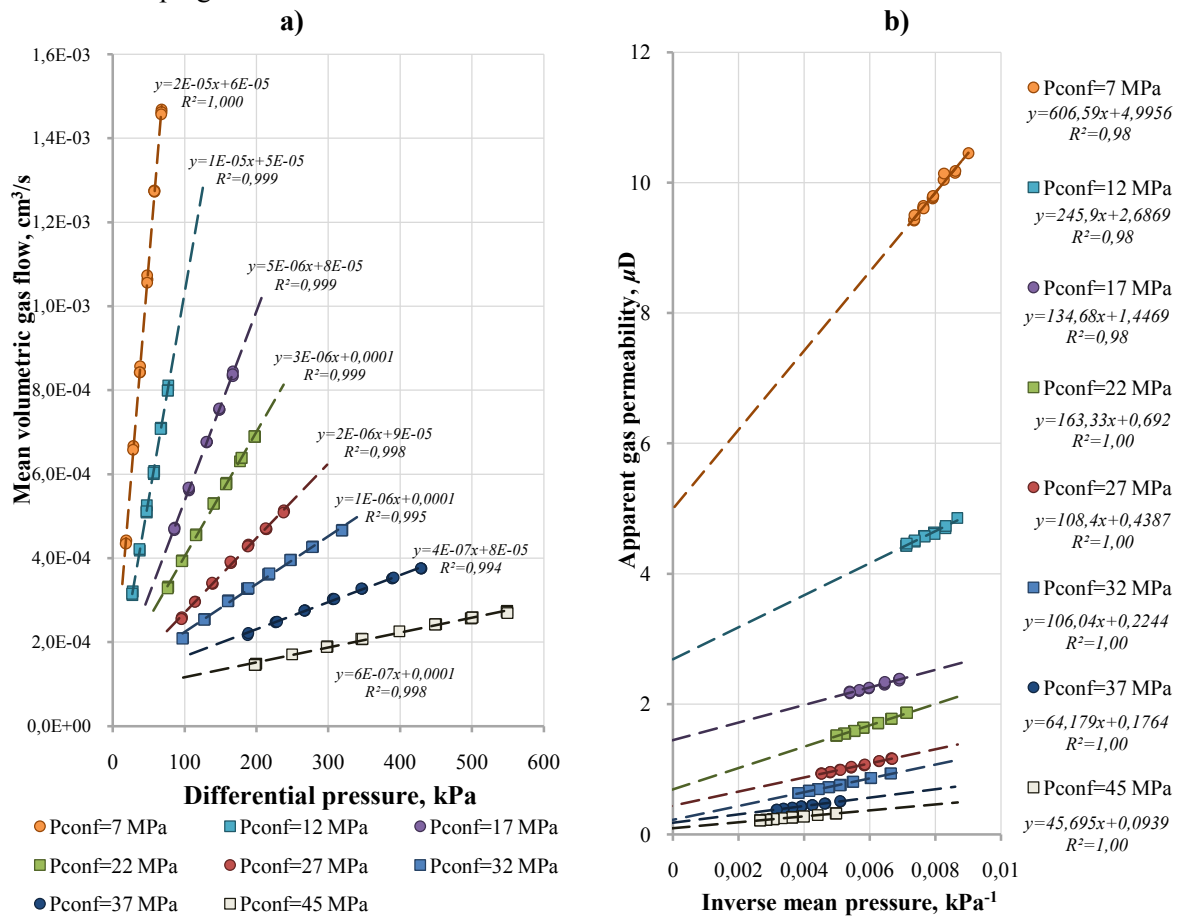

Figure 3. The result of determining the absolute permeability of the Bazhenov Formation silicite at different effective pressures: a) – the dependence of the mean volumetric gas flow through the plug on the differential pressure: b) – the dependence of the apparent permeability for helium on the inverse mean pressure.

The results of the influence of effective pressure on the absolute permeability of tight dolomites and siliceous-clay rocks of the Bazhenov Formation are presented in figure 4.

Figure 4a shows that the absolute permeability of dolomites is an exponential function of the confining pressure ($R^2 \geq 0.94$) for all plugs. The approximation by exponential function of the experimental data is most likely associated with the feature of carbonate rocks pore space. The pore space of carbonates is formed by microcavities and microcracks, which gradually close with increasing effective pressure. And the decrease in absolute permeability with increasing effective pressure is determined by the aperture of microcracks. This assumption is confirmed by the absence of a relationship between the initial permeability and the magnitude of decrease in absolute permeability with an increase in effective pressure (Figure 4a). With an increase in the effective pressure from 7 to 45 MPa, the absolute permeability of studied plugs decreases by 10 – 20 times.

For ultralow-permeability siliceous-clay rocks of the Bazhenov Formation, the correlation of absolute gas permeability and effective pressure has a power law ($R^2 \geq 0.89$), which indicates the pore type of the reservoir. An exception is a sample with an initial permeability of 5.1 μD, which most likely contains a microcrack, as the dependence of absolute permeability on the effective pressure is exponential (Figure 4b). With an increase in effective pressure from 7 to 45 MPa, the absolute permeability of the Bazhenov Formation samples of decreases by 1 – 2 orders of magnitude.
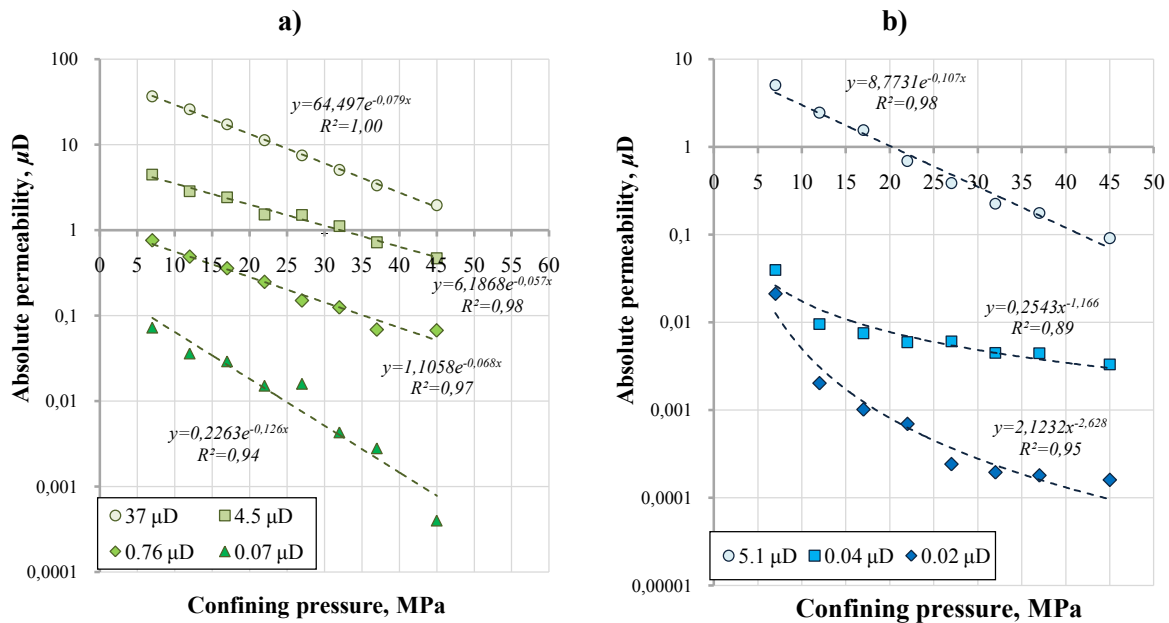
Figure 4. The influence of effective pressure on the filtration properties of low-permeability and ultralow-permeability rocks: a) – tight dolomites; b) – siliceous-clay rocks.

5. Conclusion

In this research the results of laboratory determination of absolute gas permeability of low-permeability ($0.001 < K_{abs} < 1$ mD) and ultralow-permeability ($K_{abs} < 0.001$ mD) different lithological composition rocks depending on the magnitude of the effective pressure are presented for the first time. For the entire studied collection of plugs, the Klinkenberg correction is valid, which must be taken into account to reliably determine the permeability of shale formations.

In the study of tight sandstones, dolomites and silicites of the Bazhenov Formation, a reliable correlation between absolute permeability and effective pressure for all samples studied was found. In addition, the paper shows the relationship between the type of reservoir and the type of dependence of absolute permeability on the effective pressure. For the pore type of reservoir, there is a power law, and for the fracture type of reservoir there is an exponential dependence. Obtained dependencies can be used in design of the shale formations development in energy depletion mode.

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