Permeability Alteration of Carbonate Reservoir Rock Under Cyclic Geomechanical Treatment

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Abstract. The paper presents integral analysis of data obtained on carbonate reservoir rocks of Bashkir and Tournai formations (Republic of Tatarstan, Russia) under specially designed experimental studies for measuring rock permeability alteration under changes of pore pressure with constant triaxial outer (geostatic) stresses. Characteristic hysteretic effects of permeability alteration under cyclic changes of pore pressure are revealed and related to the reservoir and mechanical properties of rock samples, as well as different fluid saturation. It is shown that cyclic geomechanical treatment can promote significant improvements of flow characteristics of a carbonate rock material.

1. Introduction

It is well known that flow (transport) and mechanical properties of reservoir rocks vary significantly under changes of geostatic stresses and fluid pressure in pores (pore pressure). In most applications, it is assumed that the conception of effective stresses can satisfactorily describe these variations \cite{1}. In petroleum applications, the simple Terzaghi relation for the effective stresses is usually adopted \cite{2}:

$$\sigma_{\text{eff}} = \sigma - p,$$  \hfill (1)

with $\sigma$ and $\sigma_{\text{eff}}$ being the geostatic and the effective normal stress along a certain direction, and $p$ being the pore (fluid) pressure. As proposed by relation (1), the pressure depletion typical for oil or gas production from petroleum reservoirs is assumed equivalent to the increase of geostatic stresses. Thus, most laboratory studies of reservoir rock behavior under changing loading (stress-pressure) conditions are performed on rock samples with constant pore pressure and changing confining pressure in the experiment \cite{3, 1}, and even with pore pressures much lower than at actual in-situ conditions. Though this approach has been shown to be appropriate in most situations for conventional sandstones \cite{4}, it is questionable for tighter and brittle rocks like carbonates.

An extended theory describing the effect of pore pressure on effective stresses was developed by Biot \cite{5} with

$$\sigma_{\text{eff}} = \sigma - ap,$$  \hfill (1)
with $\alpha$ being the Biot coefficient, which is close to 1 for highly-porous rocks (like weakly unconsolidated sandstones) and tends to 0 for nearly solid rocks with very low values of porosity. However, evaluation of $\alpha$ for tight rocks is quite tricky, and it turns out to depend on loading conditions [1].

Typically petroleum reservoir rocks demonstrate decreasing permeability (and porosity) values under pore pressure depletion [6]. Hysteresis is also typical, with only partial restoration of initial permeability when pressure is increased to its initial level and under further cyclic changes of pressure [7]. However, for carbonate rocks and some sandstones it was shown that if pore pressure is decreased (effective stress is increased) below a certain level, shear failure can occur in the rock sample with formation of micro fissures, which leads to a significant increase of permeability as pore pressure is restored [8-11]. This process is opposed to hydraulic fracturing which happens when pore pressure is increased above the tensile failure limit [12], but it can also be used as a method for increasing productivity of oil and gas wells [8-10]. Large-amplitude cyclic changes of pore pressure make the process more efficient, especially in tight and brittle carbonate rocks [13]. In this case, it is called the cyclic geomechanical treatment.

The possibility to increase rock permeability and thus productivity of wells by large-amplitude decrease in pore pressure was clearly shown for deep reservoirs (~2.5 km and deeper) with quite high initial fluid pressures and overburden stresses [8-10, 14]. For carbonate rocks at depths of about 1 km with initial fluid pressures ~100 bar it is questionable whether same effects can be obtained. The goal of this study is to investigate possible permeability variations under cyclic changes of pore pressure on rock samples with different reservoir and mechanical properties and fluid saturation from two carbonate oil-bearing formations of Republic of Tatarstan, Russia.

2. Experimental program
In this study, 12 laboratory experiments were performed on 6 rock samples of the Bashkir formation and 6 samples of the Tournai formation. In addition to different flow properties, effect of saturating fluid was also studied. Key parameters of the samples are summarized in Tables 1 and 2.

The experiments were conducted on a certified laboratory setup under triaxial loading conditions corresponding to the actual in situ state of the reservoirs. Axial load, corresponding to vertical overburden stress, was planned to be 21.18 MPa for the Bashkir formation and 26.28 MPa for the Tournai formation. However, due to some technical issues, it was over overstated in most experiments which should be taken into account during interpretation. The confining pressure, corresponding to minimum lateral stress, was estimated by the Eaton’s formula [15] and set to 14.16 MPa for the Bashkir formation and 17.45 MPa for the Tournai formation. The initial pore (fluid) pressure was $P_0$=8.9 MPa for the Bashkir samples and 10.83 MPa for the Tournai samples.

During the experiments on each sample, axial load and confining pressure were maintained, while pore pressure was changed stepwise in the following cycle: decrease – increase – decrease. Each experiment consisted of 14 pressure stages. Fig. 1 shows the typical program of the experiments which was slightly changed for some samples during the study.

| Sample | Rock type | Porosity, % | Gas permeability, $10^{-3}$ μm$^2$ | Saturating fluid |
|--------|-----------|-------------|-----------------------------------|------------------|
| 26     | Limestone | 12.03       | 5.74                              | water            |
| 32     | Limestone | 14.11       | 46.80                             | water            |
| 33     | Limestone | 15.60       | 32.07                             | water            |
| 34     | Limestone | 13.76       | 39.92                             | kerosene         |
| 35     | Limestone | 12.93       | 12.28                             | kerosene         |
| 36     | Limestone | 14.21       | 35.71                             | kerosene         |
Table 2. Parameters of the Tournai samples

| Sample | Rock type | Porosity, % | Gas permeability, $10^{-3}$ μm$^2$ | Saturating fluid |
|--------|-----------|-------------|-----------------------------------|-----------------|
| 1      | Limestone | 15.14       | 179.76                            | kerosene        |
| 2      | Limestone | 14.49       | 129.65                            | water           |
| 3      | Limestone | 13.97       | 75.48                             | water           |
| 4      | Limestone | 12.00       | 35.53                             | kerosene        |
| 5      | Limestone | 13.97       | 31.59                             | water           |
| 6      | Limestone | 16.35       | 80.50                             | kerosene        |

Figure 1. Typical program of the experiments

At each pressure stage, permeability to saturating fluid was measured after stabilization. Also, dynamic Young modulus and Poisson's ratio were measured by the acoustic wave method. It was controlled that changes to elastic properties were in compliance with measured changes in permeability.

3. Results and discussion

Fig. 2 shows the graphs of permeability (for saturating fluid) vs. pressure obtained in the experiments on the Bashkir samples. The following observations can be made.

- Saturation of the sample significantly affects the permeability vs. pressure dependence.

For samples 33 and 32 saturated with water, the primary decrease in permeability is many-fold and irreversible, i.e. permeability is not restored with the subsequent increase in pressure. For sample 26 also saturated with water, permeability practically did not change with decreasing and increasing pressure, and it increased only when pressure exceeded the tensile failure limit of the sample.

For sample 34 saturated with kerosene, the permeability changed nonmonotonically in the pressure decrease-increase cycle. But when the pressure was restored to the initial level, an increase in permeability of about 20% was recorded compared to the initial value. For samples 35 and 36 saturated with kerosene, nonmonotonic changes in permeability were also observed during the decrease and reverse increase in pressure. Nevertheless, a general increase in permeability of about 20% is also observed for these samples after restoration and / or reverse decrease in pressure to the initial values. (Note that in all experiments with Bashkir samples the axial load was overstated if compared to in-situ conditions.)
Figure 2. Experimental graphs of permeability vs. pressure for Bashkir samples. Samples: a – 33, b – 32, c – 26, d – 34, e – 35, f – 36.

Fig. 2 also shows that for all samples saturated with kerosene, in some or other range of pressure values during reduction, an increase of permeability was observed. While for water-saturated samples only an intensive decrease (samples 33 and 32) or preservation of permeability (sample 26) was recorded.

- The nature of permeability vs. pressure dependence is also significantly affected by the internal structure (porosity, presence of microcracks) and associated mechanical characteristics of the samples.
Samples 33 and 32 have the smallest initial values of the dynamic Young modulus (20.73 GPa and 23.03 GPa). This may indicate either the initial presence of microcracks or strong change in mechanical properties (decrease in strength, plasticity) under the influence of water – the so-called water-induced compaction [16]. The initial values of porosity (14.11% and 15.60%) and permeability \((6\times10^{-3} \mu m^2\) and \(8.5\times10^{-3} \mu m^2\)) of these samples are also among the largest. These factors may explain the intense decrease in permeability with a decrease in pore pressure.

In contrast, for samples 26 and 35 having the largest initial values of the dynamic Young modulus (51.63 GPa and 44.14 GPa) and the smallest values of porosity (12.03% and 12.9%) and permeability \((0.3\times10^{-3} \mu m^2\) and \(3.8\times10^{-3} \mu m^2\)), with different saturating fluids, the permeability changed slightly with a decrease in pore pressure.

Among the kerosene-saturated samples, the largest amplitude of permeability variations was observed for samples 34 and 36 having the initial values of the dynamic Young modulus 25.47 GPa and 32.47 GPa, and the porosities of 13.76% and 14.21%, respectively.

For Tournai samples, permeability graphs vs. pressure are given in Fig. 3.

- Similar to the Bashkir formation, the influence of saturation is noted for the Tournai samples.

Samples 2 and 3 saturated with water demonstrated similar trends. A decrease in permeability was recorded for the primary decrease in pressure. With the following increase in pressure, permeability did not significantly increase but remained at approximately the same level or continued to decrease. A relatively sharp increase in permeability was noted in the pressure range of 12-14 MPa, presumably associated with the initial stage of tensile failure (hydraulic fracturing). With the subsequent decrease in pressure, permeability increased by 20-50%.

For sample 5, also saturated with water, similar trends with the samples 2 and 3 were observed starting from the 2nd stage of the initial decrease in pressure and for the subsequent increase in pressure. However, no evidence of tensile failure was noted, which explained no increase and a slight decrease in permeability with the secondary decrease in pressure. The mechanism of the sharp increase in permeability at stage 2 is not obvious.

However, as a common result for the samples 2, 3, and 5, a lesser effect of water saturation on the change of flow characteristics was noted for the Tournai formation in comparison with the Bashkir formation.

For kerosene-saturated Tournai samples, the situation is as follows.

The results for sample 1 are not fully informative because of its destruction at the 3rd stage of pore pressure reduction. However, the fact of destruction under the action of compressive stresses is worth mentioning, because this is the key mechanism of the cyclic geomechanical treatment.

Sample 6 also failed to fully complete the experiment due to technical issues. However, after the initial decrease in permeability, an increase was recorded at stages 3-4 under the action of compressive stresses which corresponds to the expected geomechanical effect of intrinsic shear failure. Unfortunately, since the change in pressure at the subsequent stages did not correspond to the experimental program, it is impossible to quantify the final effect on this sample.

The most interesting results were obtained for sample 4 saturated with kerosene and studied under the correct axial loading conditions corresponding to the actual in-situ overburden stress of the Tournai formation. For this sample, a pronounced tendency was observed of a substantial and almost uniform increase in permeability starting from the 3rd stage of the experiment. This can be explained by the formation of microcracks due to intrinsic shear (compression) failure and their subsequent opening under the influence of increasing pore pressure. At the pore pressure value of about 14 MPa, a sharper increase in permeability can be noted, which is presumably associated with additional tensile failure (hydraulic fracturing). With a subsequent decrease in pressure to 11 MPa, permeability somewhat decreased, probably due to compression of tensile cracks, but remained at higher values than for the same pressures during the previous stage of pressure increase. With the further decrease in pressure, the permeability only increased, which can be associated with the secondary development of microcracks under compression.
Figure 3. Experimental graphs of permeability vs. pressure for Tournai samples.

Samples: a – 1, b – 2, c – 3, d – 4, e – 5, f – 6

Thus, for samples saturated with kerosene, a manifestation of destruction of the internal structure due to compressive stresses was observed, which can lead to the subsequent development of microcracking and an increase in permeability.

An overall increase in permeability for sample 4 compared to the initial value is ~3.5 times, which shows the potential effectiveness of the cyclic geomechanical treatment under the actual stress state of the Tournai formation.
Different trends of permeability behavior with a secondary decrease in pore pressure were recorded. For samples 2, 3, and 4, with evidences of the onset of tensile failure, stabilization or increase in permeability was observed. For sample 5, with no signs of hydraulic fracturing, a decrease in permeability was noted during the secondary reduction of pore pressure.

Similar to the Bashkir samples, one can note a relation between the specifics of variation of the flow characteristics with pressure and the initial values of the elastic moduli for the Tournai samples. The minimum values of the initial dynamic Young modulus are 29.32 MPa for sample 6 and 33.94 GPa for sample 1, and the maximum value is 42.78 GPa for sample 4. Among the samples with a complete experiment, lowest values correspond to samples 5 (34.93 GPa) and 2 (35.88 GPa). It can be assumed that these rocks initially contain microcracks or other defects of the internal structure. This is confirmed by a more intense decrease in permeability, compared to other samples, with a decrease in pressure, especially for sample 2. Also, the initial presence of microcracks with the reduced values of Young modulus can explain the complete destruction of sample 1 and partial destruction of sample 6 at an early stage of the experiment.

The highest values of the initial Young modulus were observed for samples 3 (40.88 GPa) and 4 (42.78 GPa). With a decrease in pore pressure, they demonstrated no significant decrease in permeability. And for sample 4, the mechanism of microcracks creation by the cyclic geomechanical treatment was found to be very efficient.

4. Conclusions
From the presented experimental data and analysis, the following conclusions can be drawn.

- The change in permeability for the carbonate reservoirs of the Bashkir and Tournai formations with a change in pore (fluid) pressure can be significant and depends both on saturating fluid and the initial flow and elastic properties (i.e., on the internal structure) of the rock samples.
- Saturation with water leads to a more intense decrease in permeability than saturation with kerosene. This may be due to the effects known as water induced compaction [16]. However, since fresh water was used in the experiments, non-geomechanical reasons for the permeability reduction due to interaction of water with carbonate rock cannot be excluded. For both the factors, further studies are required. The effect of water is more significant for the Bashkir formation than for the Tournai formation.
- For kerosene-saturated samples, a positive effect of cyclic geomechanical treatment was obtained. For the Bashkir formation, the increase in permeability was about 20% (with axial load overstated). For a Tournai sample studied under the correct loading conditions, 3.5-times increase in permeability was recorded. For several samples, the experimental program was not fully completed due to their destruction, but evidence of microcracking under decrease in pore pressure was also recorded.
- Extra analysis showed that pore pressure required for tensile failure (hydraulic fracturing) is reduced, compared to theoretical estimates, after primary pressure reduction in the experiment. This effect was most pronounced for water saturated Bashkir samples.

The results of the study show that geomechanical effects associated with cyclic changes of pore pressure are significant and can lead to creation of microcracking and increase in permeability in carbonate reservoirs. These effects should be taken into account in petroleum reservoir simulation and can form a basis for treatment methods to improve productivity of oil and gas wells.

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