Analysis of Stress Sensitivity and Its Influence on Oil Production from Tight Reservoirs

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Abstract

This paper presents a study of the relationship between permeability and effective stress in tight petroleum reservoir formations. Specifically, a quantitative method is developed to describe the correlation between permeability and effective stress, a method based on the original *in situ* reservoir effective stress rather than on decreased effective stress during development. The experimental results show that the relationship between intrinsic permeability and effective stress in reservoirs in general follows a quadratic polynomial functional form, found to best capture how effective stress influences formation permeability. In addition, this experimental study reveals that changes in formation permeability, caused by both elastic and plastic deformation, are permanent and irreversible. Related pore-deformation tests using electronic microscope scanning and constant-rate mercury injection techniques show that while stress variation generally has small impact on rock porosity, the size and shape of pore throats have a significant impact on permeability-stress sensitivity. Based on the test results and theoretical analyses, we believe that there exists a cone of pressure depression in the area near production within such stress-sensitive tight reservoirs, leading to a low-permeability zone, and that well production will decrease under the influence of stress sensitivity.

Introduction

Within the petroleum literature, there are many studies on the sensitivity of permeability to stress fields in tight reservoirs [1–8]. However, most of these studies are carried out in conditions under the low range of effective stress (e.g., generally no more than 7 MPa) as reference stress. Therefore, the extent of “damage” caused by stress or stress sensitivity is found to be very high from such studies. As a result, these studies indicate that low-permeability tight oil reservoirs are inadvisable to be developed under large pressure gradients, because of the formation’s high sensitivity to change in effective stress. In fact, during well drilling and core sampling，the state of stress within core samples will vary from the initial *in situ* state of stress, to a mud-hydrostatic-pressure state inside wellbores and to atmospheric conditions on the surface with stress release. If laboratory experimental conditions are not set approximately to actual *in situ* stress level of reservoirs, experimental results often show substantial changes in core pore-throat structures with changes in effective stress. The resulting stress sensitivity or formation deformation results cannot in general reflect the actual situation in formations. It has been shown in many experiments [9–11] that studies using stress fields lower than those for reservoir conditions overestimate the effects of stress on formation deformation (e.g., the results from laboratory experiments using conventional cores under low effective stress conditions fail to predict realistic changes in pore throats and structures).

This paper presents results and analyses of our recent laboratory experiments, conducted under reservoir stress conditions, to study tight oil reservoir stress sensitivity. The specific objective of this work is to investigate the mechanisms by which effective stress affects rock deformation, formation permeability, and porosity, under relevant reservoir conditions.

Experimental Method

The properties of five core samples used for the experiments are given in Table 1. These core samples are utilized after washing out any oil in the sample and then drying. Dry nitrogen is used as an experimental gas source, a soap-bubble flowmeter is used to measure low-rate gas flow, and a floating-type flowmeter is used to measure high-rate gas flow. Confining pressure is controlled and regulated using a hand pump. The experiments are conducted according to the Reference Standard of China petroleum and natural gas industry, SY/T5358-2002. Minimum effective stress is set at 2 MPa, the original reservoir effective stress is set at 15 MPa, and the maximum effective stress is set at 25 MPa.

Table 1. Permeability and porosity values of core samples

Number	Gas Permeability (10^{-3}ì m^2)	Porosity (□)
1	0.431	14.177
2	0.547	14.162
3	0.327	10.851
4	0.166	8.381
5	0.215	12.941

Result and Analyses

To evaluate formation stress sensitivity, we first normalize the permeability [11]. Figure 1 presents the relationship between effective stress and normalized permeability, with the low effective stress of 2 MPa as starting point, showing the decrease in permeability ratio of K to K_2 (at 2 MPa) versus effective stress. As shown in Figure 1, with the increase in effective stress, the rock permeability initially decreases rapidly. When effective stress reaches 15 MPa, the decrease in permeability becomes less severe. When effective stress increases and reaches 25 MPa, as shown in Figure 1, the change in permeability caused by rock deformation in the 5 core samples is about 87.6□, which is significant. The main reason for such a significant permeability change is that the core samples used in the experiments are in a state of complete stress release compared to the *in situ* reservoir condition. Disappearance in overburden forces and pore pressure causes the core sample 's solid skeletons to release its stress. This leads to changes in core sample pore size, e.g., small throats or microfractures will enlarge or open. When effective stress increases gradually, the rock core skeleton stress is gradually restored to the original reservoir condition. During the recovery buildup period of stress fields, permeability changes are in general too large to be used for estimating stress sensitivity to formation permeability, which suggests that low-effective-stress experiments are not suitable for evaluating the relationship between permeability and stress sensitivity.

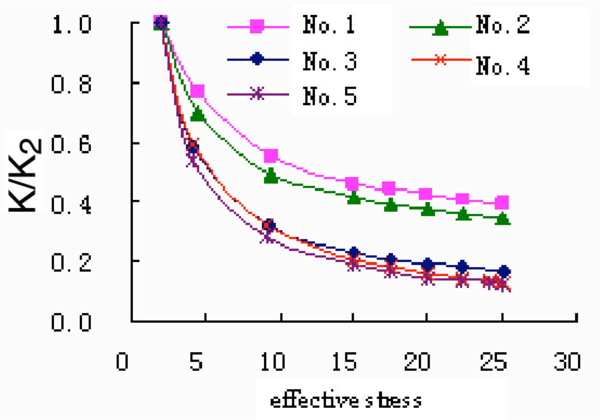

Figure 1. The relation curves between permeability and effective stress (based on 2MPa)

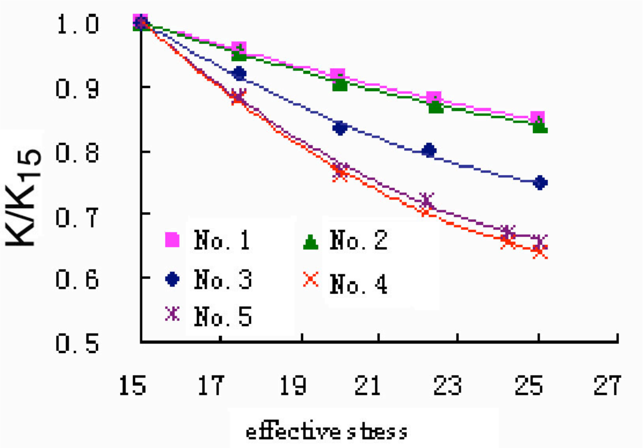

Figure 2. Curves showing the relationship between permeability and effective stress (based on 15MPa)

In order to reflect reservoir stress sensitivity at reservoir condition, we conducted experiments under reservoir effective stress conditions to evaluate reservoir permeability stress sensitivity. In a tight reservoir with a depth of 2,000 m, the *in situ* reservoir effective stress could be approximated as 15 MPa. With a reduction of reservoir pressure to 1 MPa□the effective stress would increase to 1 MPa; when the reservoir pressure drops 10 MPa, then the effective stress is at 25 MPa. As shown in Figure 2, the permeability ratio (permeability K at varying effective stress to permeability K_{15} at the original reservoir effective stress) decreases with the increase in effective stress or decrease in reservoir pressure. Under high, reservoir stress conditions, the core with higher permeability has a smaller percentage of permeability loss (<15), while the core with low permeability has a higher percentage of permeability loss (~35□).

In a deep petroleum reservoir, with thin layers of oil reserves overlain by thick formations, the total stress may be approximated as constant, equal to the weight of the overlain layers. In this case, the effective stress becomes a function of pore pressure only [12]. According to our experimental results, permeability and effective stress are correlated with a quadratic polynomial relation:

$$K/K_{\text{effo}} = c_0 p_{\text{eff}}^2 + c_1 p_{\text{eff}} + c_2 \tag{1}$$

where K is the absolute permeability at varying effective stress (ì m^2)□ K_{effo} is the permeability at original *in situ* reservoir effective stress (ì m^2); c_0, c_1, and c_2 are fitting coefficients; p_{eff} ($p_{\text{eff}} = p_{\text{over}} - p$) is effective stress (MPa); p_{over} is overburden rock stress (pressure) (MPa)□and p is pore pressure (MPa). Fitting results using experimental data show that correlation factors for all curves are larger than 0.99□illustrating that Equation (1) may be useful in describing the stress-permeability relationship for stress sensitivity.

In the process of stress restoration, as effective stress decreases from 25 MPa to 15 MPa, the experimental results show that permeability for Cores #1 and #2 recovers to about 93% of its original value at reservoir conditions, the permeability for Core #3 to about 87□, and the permeability for Cores #4 and #5 to about 78□. This finding indicates that there is elastic-plastic deformation in the reservoir rock, with changes in pores and throats, and that the “damage” to the rock, caused by stress or pressure change, is irreversible and permanent.

Stress-Sensitive Deformation and Mechanism

The primary reason for permeability in tight rock being sensitive to the variations in stress is the significant change in the bearing skeletons, solid particles, and pore throats of porous media, caused by changes in states of stress. Such changes will also have a large impact on flow paths through porous media. Pore structure or space consists, in general, of two parts—pore body and pore throat. When the tight rock of porous media is pressed, compression starts from the pore throats, not from pore bodies [5]. In addition, pore throats are smaller than pore bodies, but provide the majority of flow resistance to fluid flow. Thus, permeability in deformed rock is considered to be subject mainly to throat constraints. This phenomenon is further analyzed below.

Microcosmic Pore Throat Analyses: To intuitively account for effect of pore-throat structure on permeability because of stress sensitivity, we first analyze low-permeability, tight rock cores using electron microscope scanning, at temperature of 22ºC and relative humidity of 40%. Samples of experimental results are shown in Figures 3 and 4. Rock pores consist mainly of intergranular pore space with some fillings. Pores are strong in resistance to stress change when they have smooth walls with polygonal or oval shape. In comparison, pores are more stress-sensitive or easy to deform if they are similar to fractures, with flat shapes or with solid surfaces adsorbed into or connected by substantial clay or chlorite.

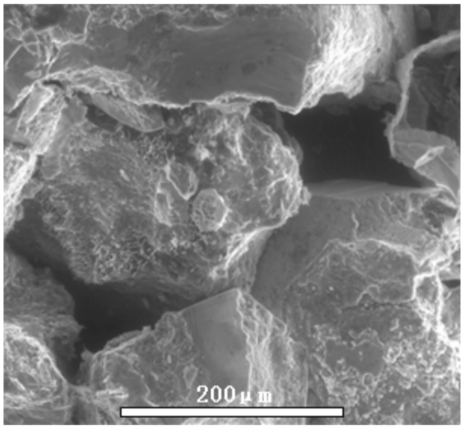

Figure 3. Intergranular pore system of Xi26-25’ s core (magnified 220x)

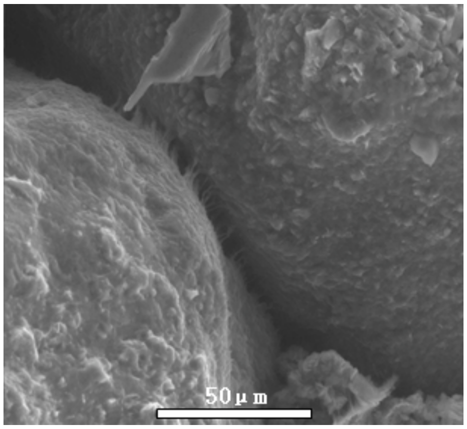

Figure 4. Throat system of Xi31-31 core (magnified 600x)

Throat Analyses by Constant-Rate Mercury Injection Test: Figure 5 shows the throat distribution of constant-rate (volume-controlled) mercury injection tests using reservoir rock. As shown in Figure 5, throat distribution is more homogeneous and approaches a normal distribution for low-permeability core samples, with the peak throat radius at around 0.5 μm . Permeability in such rock is primarily contributed or controlled by small throats with radii less that 1 μm . For relatively large-permeability core samples, the throat radius distribution is wider, with the peak throat radius around 0.6–1.0 μm . With the increase in permeability, throat size can enlarge to 1 μm or more and even as high as 3 μm . As formation pressure decreases, the pores with smaller throats are more sensitive, because there are in general more small-throat pores than large-throat pores. While pressure continues to drop, there are fewer and fewer pores and throats remaining with large openings to close, and the shrinking of pore and throat space reaches its minimum, leading to a decrease in permeability declining rate.

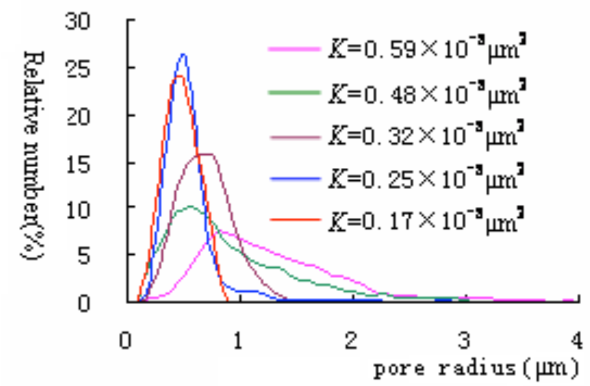

Figure 5. Throat frequency distribution of low permeability cores

Effect of Stress Sensitivity on Oil Production

During oil production from tight oil reservoirs, in addition to pressure decreasing□reservoir rock is subject to elastic-plastic deformation. This in turn changes reservoir permeability (because of the stress-sensitive permeability effect) and directly influences oil-production capacity [5, 13]. To improve production capacity, it is a common practice to reduce bottom-hole pressure. In a stress-sensitive, tight reservoir, however, reducing wellbore pressure would result in larger pressure-depression cones near wells, and could cause serious formation deformation in those zones. It is possible that instead of increasing well production yields, dropping wellbore pressure too much may decrease well production, because of the reduction in permeability. Hence, to maintain appropriate bottom-hole flowing pressure and to improve production capacity the pressure-sensitive permeability effects on oil-field development should be analyzed.

According to the theory of pressure distribution in formation for radial fluid flow into a production oil well, subject to constant-pressure outer boundary conditions as well as Equation (1), permeability distribution in a formation, when considering pressure-sensitive permeability effects, is described by□

$$\frac{K}{K_{\text{effo}}}=c_0\left[p_{\text{effo}}+\left(p_{\text{e}}-p_{\text{w}}\right)\frac{\ln\left(R_{\text{e}}/r\right)}{\ln\left(R_{\text{e}}/r_{\text{w}}\right)}\right]^2+c_1\left[p_{\text{effo}}+\left(p_{\text{e}}-p_{\text{w}}\right)\frac{\ln\left(R_{\text{e}}/r\right)}{\ln\left(R_{\text{e}}/r_{\text{w}}\right)}\right]+c_2 \tag{2}$$

Aternatively, volumetric well production rate in a pressure-sensitive permeability reservoir is given by□

$$\frac{Q}{Q_{\text{effo}}}=\left\{\frac{c_0}{3}\left[p_{\text{ow}}{}^2+p_{\text{ow}}p_{\text{effo}}+p_{\text{effo}}^2\right]+\frac{c_1}{2}\left[p_{\text{ow}}+p_{\text{effo}}\right]+c_2\right\} \tag{3}$$

In Equations (2) and (3), p_{effo} ($p_{\text{effo}}=p_{\text{over}}-p_{\text{e}}$) is the initial reservoir effective stress (MPa); p_{e} is the initial reservoir pressure (MPa); R_{e} is the radius of the formation outer boundary (m); r is the radial distance to production well (m); r_{w} is production-well radius (m); p_{w} is bottom-hole pressure (MPa); Q is the production rate considering pressure-sensitive permeability (m^3/d); Q_{effo} ($Q_{\text{effo}}=86.4\times\frac{2\pi K_{\text{effo}}h\left(p_{\text{e}}-p_{\text{w}}\right)}{\mu\ln\left(R_{\text{e}}/r_{\text{w}}\right)}$) is the theoretical yield of radial fluid flow (m^3/d); h oil layer thickness (m); μ is oil viscosity (mPa.s); and $p_{\text{ow}}=p_{\text{over}}-p_{\text{w}}$.

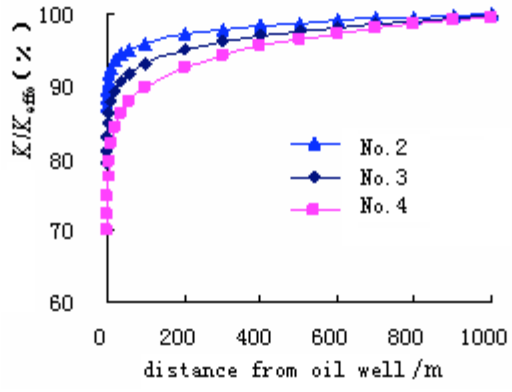

Figure 6. Effect of stress sensitivity on permeability

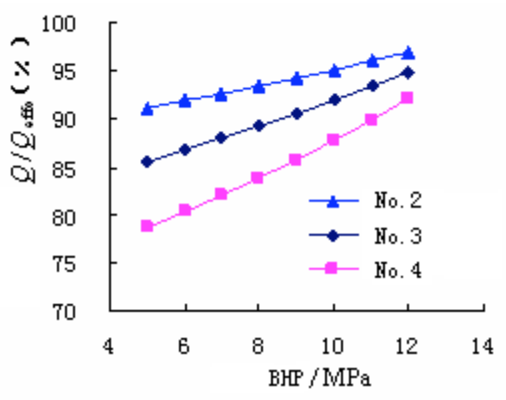

Figure 7. Effect of stress sensitivity on oil production rate

Equations (2) and (3) and experimental data from core samples #2, #3, and #4 are used to fit coefficients, c_0, c_1, and c_2. Figures 6 and 7 show the stress-sensitive permeability effects on both permeability distribution and production rates. At a distance closer to oil production wells, permeability variation is larger and further away from the well, and the change in permeability is small. Near the wellbore, permeability drops to 12.8% in Core 2, to 20.7% in Core 3, and to 30.4% in Core 4. Figure 7 shows the effects of bottom-hole flowing pressure. As this pressure decreases, the production rate is more lost. When bottom-hole flowing pressure decreases to $5\,\mathrm{MPa}$, the production rate drops to about 9% for Core#2, about 14.5% for Core # 3, and about 21.3% for Core #4. These results show that formation-rock stress sensitivity does have a significant impact on oil production rates. Consequently, optimum bottom-hole flowing pressure needs to be determined based on *both* reservoir conditions *and* rock stress sensitivity.

Conclusions

This paper presents a laboratory study of stress-sensitive permeability in reservoir formations, as well as a quantitative method for describing the correlation between permeability and effective stress. Based on our experimental studies and data analyses, we come to the following conclusions:

(1) Studies of stress or pressure-sensitive permeability effects should be conducted at reservoir stress conditions. Otherwise, the results will overestimate the impact of rock deformation induced by change in effective stress.

(2) Permeability and effective stress may follow a quadratic polynomial relation. Stress-sensitive effects resulting

in formation “damage” are of a permanent, irreversible nature.

(3) Pore throat analysis results, using electron microscope scanning and constant-rate mercury injection, shows that tight rock pores are less sensitive pore throats to stress or pressure changes, while throat size and shape are among the major contributors to stress sensitivity.

(4) Theoretical calculations show that formation pressure-sensitive permeability can affect well oil production. Specifically, pressure-sensitive permeability affects both the permeability near wells and the production rates of pressure-sensitive reservoirs.

Acknowledgments

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