Research Article

Influence of Microcracks on Stress Sensitivity in Tight Sandstone

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Stress sensitivity occurs throughout the reservoir development process, especially in the study of low permeability tight reservoir, considering the influence of stress sensitivity is particularly important. When studying stress sensitivity, the current main experimental methods are variable confining pressure and variable fluid pressure methods, but they cannot simulate the stress sensitivity during water injection development. Therefore, in this paper, an experimental stress sensitivity method that can be used to study the depletion mining and water injection development processes is established. In addition, the influence of different degrees of microcrack development on the stress sensitivity of the reservoir is investigated. The results of this study show that under the experimental conditions described in this article, the loading of axial compression plays a role of preloading stress and realizes the whole process of stress sensitivity under the condition that the fluid pressure is lower than the confining pressure. In the experiment, the permeability growth rate of matrix cores does not exceed 20%. For cores containing microcracks, when the axial pressure was less than 30 MPa, the permeability slowly increased with increasing fluid pressure. When the axial pressure was 30 MPa, the permeability changes are mainly divided into two stages. In the first stage, the microcracks are closed under compressive stress. At this time, the microcracks have a limited impact on the seepage capacity. The permeability increases slowly with increasing fluid pressure. In the second stage, the permeability rapidly increases after the microcracks open. These two stages can be described by two straight lines. The slope of the first line has nothing to do with the development of microcracks; the higher the degree of microcrack development, the greater the slope of the straight line of the second stage. For all of the cores, the permeability decreases as the axial pressure increases.

1. Introduction

With the development of the petroleum industry, the recoverable amount of conventional oil and gas is decreasing year by year, and tight oil and gas have become an important energy source to replace conventional oil and gas. Tight reservoirs are characterized by low permeability, low porosity, and strong heterogeneity. During the mining process, the fluid pressure continues to drop, and the effective stress of the reservoir continues to increase, resulting in the closure of pore throats and microcracks in the reservoir and a decrease in the permeability of the reservoir. This change in permeability caused by the change in the effective stress is called stress sensitivity [1–7]. Stress sensitivity also exists in the water injection development process of tight oil. When the water injection pressure increases, the original closed microcracks in the reservoir reopen, resulting in an increase in permeability. Therefore, studying stress sensitivity is important for studying tight reservoirs.

Research on stress sensitivity began in the 1940s when foreign scholars began to explore how permeability and porosity changed with confining pressure. Terzaghi first studied fluid flow in variable saturation media and proposed a conceptual model for the effective stress [8]. Fatt and Davis studied the influence of the relationship between the overburden pressure and the permeability on the oil production process [9, 10]. On the basis of studying the effective stress model considering the nature of the rock, the concept of
the effective stress coefficient was developed [11–14]. After that, various models of the relationship between the effective stress and permeability were proposed, for example, the natural logarithm model proposed by Walsh [15], the power law model proposed by Shi and Wang [16], the exponential function model proposed by Katsube et al. [17], the cubic law model proposed by Kwon et al. [18], and the two-part Hooke model proposed by Zheng et al. [19]. Zhang and Ambastha established a mathematical model of stress sensitivity caused by sandstone deformation to analyze the influence of media deformation on reservoir productivity [20]. Moosavi et al. studied the deformation characteristics of pores under stress and analyzed the relationships between porosity, permeability, and effective stress [21]. On the basis of studying the stress sensitivity model, many scholars began to study the influences of the reservoir’s pore structure on its stress sensitivity, which is mainly manifested as the influence of cracks opening and closing under the action of stress on permeability. In terms of microscopic theory, Hertz proposed an elastic contact model, which mainly solved the contact problem of the crack surface under stress. Subsequently, Yamada et al. studied the relationship between the crack surface and the stress based on the Hertz model and studied the crack stress conditions for closing and reopening [22–24].

The research on stress sensitivity mainly focuses on experimental research and numerical calculation. Archer found that fractured reservoirs, in low permeability stage, have greater stress sensitivity, which is weakened when the effective stress is higher beyond a certain criteria; cracks are the main factor causing stress sensitivity [25]. Cao et al. found that permeability stress sensitivity is more strongly influenced by the fracture system with a larger penetration extent; in the systems with lesser penetration extent, the matrix compression is the leading factor influencing permeability stress sensitivity [26]. Gu et al. analyzed the factors affecting the stress sensitivity of tight sandstone reservoir, including material composition, fracture development, and pore structure of rock, and the stress sensitivity of microfracture cores is higher than that of matrix cores [27]. Tan et al. studied the stress sensitivity of fractured tight carbonate reservoir; the results show that the stress sensitivity of carbonate reservoir is positively correlated with dolomite, salt minerals, and clay content and negatively correlated with quartz and calcite content, and the degree of crack development is positively correlated with stress sensitivity [28]. Gao et al. used nuclear magnetic resonance technology to characterize the change of pore volume under different confining pressures and then studied the sensitivity of the pore structure of tight reservoirs to stress during production; they not only simulated the compression process but also simulated the increase in bottom pressure caused by temporary shut-in or the water injection process; the research results show that during the compression process, the rock with higher permeability contains more larger pores and is easier to be compressed, and the permeability drops more. In addition, the recoverability of the total pore volume after compression is mainly controlled by smaller pores, resulting in lower total pore volume and permeability of core samples with higher permeability [29]. For the study of stress sensitivity, at present, it is mainly aimed at the process of pore compression and closure caused by the increase of effective stress. Few people have noticed the influence of pore structure on fluid flow in the process of increasing fluid pressure during water injection.

In this study, previous studies were reviewed, and it was found that there are few related studies on the influence of microcracks in tight sandstone reservoirs on stress sensitivity, and there are problems with the laboratory methods of studying stress sensitivity. Therefore, on the basis of previous studies, in this study, a stress sensitivity experimental method that can be used to study the depletion mining and water injection development processes was established, and the shortcomings of the traditional experimental methods for studying the insufficient stress range were overcome. Using this experimental method, the influence of microcracks in tight sandstone reservoirs on stress sensitivity was investigated. In reservoirs containing microcracks, the deformation conditions of the microcracks and the matrix under stress are different. Therefore, in this study, the concept of the two-part Hooke’s model (TPHM) was used to describe the relationship between the permeability and stress during the experiments. The results provide important guidance for the development of reservoirs containing microcracks.

2. Theory

2.1. Calculation of the Effective Stress. Reservoir rocks are mainly subjected to the combined action of the overlying formation pressure and the fluid pressure in the vertical direction. The effective stress is equal to the overlying formation stress minus the product of the fluid pressure and a constant, that is,

\[ \sigma_{\text{eff}}^p = \sigma - C \cdot P \]

where \( \sigma_{\text{eff}}^p \) is the primary effective stress (MPa), \( \sigma \) is the overburden pressure (MPa), \( P \) is the fluid pressure (MPa), and \( C \) is a constant with a value range of 0–1.

2.2. The Effect of Axial Stress. The improved experimental method is to increase the axial stress based on the variable fluid pressure experiment in order to realize the stress sensitivity simulation process of the microcracks reopening process in the laboratory. Taking sandstone as an example, the mechanism of the experimental process is analyzed. It is assumed that the sandstone is composed of spherical particles of the same size. The solid source stress of the spherical particles is analyzed using the particle accumulation mode in Figure 1.

In Figure 1, the axial stresses of particles 1 and 2 are equal in size and opposite in direction (\( \delta_1 \)). The radial stresses of particles 3 and 4 are the confining pressure, which is equal in size and opposite in direction (\( \delta_2 \)). Through the combined decomposition of the stresses, the resultant force \( \delta_3 \) in the horizontal direction from particles 1 and 2 to particles 3 and 4 can be calculated. The
direction is opposite to the direction of the confining pressure, and the value is

$$\delta_n = \delta_y \cot \theta$$  \hspace{1cm} (2)

Thus, the loading of the axial stress plays the role of preloading of a tensile stress. Macroscopically, it is equivalent to \( f(\delta_y) \), and the direction is opposite to the direction of the confining pressure. Because the force is transmitted by the solid source with the confining pressure, the effective stress after axial compression can be expressed as

$$\sigma_{eff} = \sigma - f(\delta_y) - C\cdot P$$  \hspace{1cm} (3)

Therefore, the loading of the axial stress can reduce the effective stress, and the corresponding permeability will increase. A schematic diagram of the loading of the axial pressure is shown in Figure 2. When \( f(\delta_y) > \sigma - C\cdot P \), the effective stress is tensile stress, and the microcracks open. The entire process of stress sensitivity is realized when the fluid pressure is lower than the confining pressure, which can simulate the stress sensitivity of microcracks during water injection development.

2.3. Description of the TPHM. In this study, the reopening of microcracks was analyzed. For rock samples containing microcracks, the microcracks are more prone to deformation under stress conditions than the pores; that is, the microcracks have a greater deformation under a low effective stress. Therefore, for low-permeability tight rocks with a low effective stress, we need to separate the roles of the microcracks and pores. In this paper, we describe the concept of the two-part Hooke’s model (TPHM) [30].

The TPHM describes the stress-strain relationship in a rock containing microcracks. A heterogeneous rock containing microcracks is defined as two parts: a “soft” part, which follows the natural-strain-based Hooke’s law, and the “hard” part, which follows the engineering-strain-based Hooke’s law. This concept can be represented by the composite spring system shown in Figure 3, in which the two springs bear the same stress but follow different Hooke’s laws. In order to be consistent with previous studies, we use the subscripts “0,” “e,” and “t” to indicate the “stress free,” “hard” part, and “soft” part.

For the “soft” part, Hooke’s law can be expressed using the real strain [31]:

$$d\sigma_{eff} = K_{s}d\varepsilon_{V,s} = -K_{s}\frac{dV_{t}}{V_{t}}$$  \hspace{1cm} (4)

For the “hard” part, we can use the engineering strain:

$$d\sigma_{eff} = K_{e}d\varepsilon_{V,e} = -K_{e}\frac{dV_{e}}{V_{e}}$$  \hspace{1cm} (5)

where \( \sigma_{eff} \) is the effective stress, \( K_{s} \) and \( K_{e} \) are the bulk moduli of the “soft” and “hard” parts, respectively, \( \varepsilon_{V,s} \) is the real strain of the “soft” part, and \( \varepsilon_{V,e} \) is the engineering strain of the “hard” part.

Under the conditions that the initial \( V_{t} = V_{0,t} \) and \( V_{e} = V_{0,e} \), by solving Equations (4) and (5), we obtain

$$V_{t} = V_{0,t} \exp \left( -\frac{\sigma_{eff}}{K_{s}} \right)$$  \hspace{1cm} (6)

$$V_{e} = V_{0,e} \left( 1 - \frac{\sigma_{eff}}{K_{e}} \right)$$  \hspace{1cm} (7)

When the effective stress is large, the microcracks are closed, and the seepage channel controlled by the “soft” part is almost ineffective. At this time, the permeability of the rock is mainly controlled by the “hard” part.

$$k_{e} = k_{0,e} \exp \left( \beta(\phi_{e} - \phi_{0,e})\sigma_{eff} \right) = k_{0,e} \exp \left( -\beta C_{e}\phi_{0,e}\sigma_{eff} \right)$$  \hspace{1cm} (8)

where \( k_{e} \) is the permeability of the “hard” part, \( k_{0,e} \) is the initial permeability of the “hard” part, \( \beta \) is a constant that represents a stress sensitive coefficient, \( \phi_{e} \) is the porosity of the “hard” part, \( \phi_{0,e} \) is the initial porosity of “hard” part, and \( C_{e} \) is the compression factor of the “hard” part.

When the effective stress is small, the permeability of the “soft” part is expressed as [19]

$$k_{s} = k_{a}\phi_{t}^{m} = \alpha\gamma_{t} \exp \left( -\frac{\sigma_{eff}}{K_{s}} \right)^{m}$$  \hspace{1cm} (9)

where \( k_{s} \) is the permeability of the “soft” part, \( \phi_{t} \) is the porosity of the “soft” part, \( \alpha \) and \( m \) are material constants, and \( \gamma_{t} \) is the volume ratio of the “soft” part to the total volume.

$$k = k_{s} + k_{e} = k_{0,e} \exp \left( -\beta C_{e}\phi_{0,e}\sigma_{eff} \right) + \alpha\gamma_{t} \exp \left( -\frac{\sigma_{eff}}{K_{s}} \right)^{m}$$  \hspace{1cm} (10)

Since the axial stress is introduced in this paper, when the influence of the axial stress on the effective stress is

![Figure 1: Diagram of the particle forces.](image-url)
considered, the new expression for the effective stress in Equation (3) is introduced into Equation (10) to obtain

\[ k = k_0, e \exp \left( -\beta C e \phi_0, e \left( \sigma - C^* P - f (\delta_y) \right) \right) + \alpha \left[ \gamma_i \exp \left( -\frac{\sigma - C^* P - f (\delta_y)}{K_i} \right) \right]^{-m} \]  

The first part of the equation represents the permeability of the “hard” part, and the second part represents the permeability of the “soft” part.

3. Experimental Materials and Methods

3.1. Experimental Materials. Six outcrop cores from tight sandstone reservoirs with diameters of 25 mm and lengths of 50 mm were used in the experiments. The core samples are outcrop cores from the Triassic Chang 8 tight sandstone reservoir in the Huanxian area of the Ordos Basin. Table 1 presents the basic core data. The Ordos Basin is the most important oil producing basin in China, and it is also the main distribution area of tight sandstone reservoirs. The Triassic Chang 8 reservoir is mainly composed of underwater distributary channel sedimentary sand with a large thickness and stable distribution, and it is the main oil bearing series in the study area.

The six cores used in the experiments were all matrix cores. Among them, cores 4–6 were pre-processed to ensure that they contained microcracks using the triaxial stress shear crack-making method. The experimental flow chart for the core crack-making method is shown in Figure 4. During the crack-making process, first, a small axial pressure is loaded first to fix the core position and then load a fixed confining pressure, and it will always remain unchanged; secondly, set a suitable gas drive pressure to test the gas flow rate at the outlet end of the core holder to calculate the real-time permeability of the core; thirdly, set the axial pressure from 0 to 5 MPa, to 10 MPa, to 15 MPa, etc., until the gas permeability growth rate increases rapidly [32]. The degree of microcracks was evaluated using the rate of change of the real-time permeability. A large number of microcracks were generated at the inflection point of the permeability, and cores with a certain degree of microcrack development were obtained by controlling the size of the axial pressure loading. The core data after the crack-making process was conducted are shown in Table 1.

3.2. Experimental Methods. At present, there are two main experimental methods for investigating stress sensitivity in the laboratory: the variable confining pressure method and the variable fluid pressure method [33–36]. In the variable confining pressure method, the confining pressure is...
changed by changing the stress loaded on the rubber sleeve of the core holder to achieve a change in the solid source conduction stress in order to change the effective net stress [37]. In the variable fluid pressure experiment method, the stress is changed by fixing the confining pressure and changing the fluid pressure.

In actual reservoir exploitation, the pressure from the overlying strata is mainly provided by the weight of the strata. Under the same geological conditions, the overlying strata pressure remains unchanged, and the change in the effective stress mainly depends on the change in the fluid pressure during exploitation. Therefore, the simulation process of the variable fluid pressure method is consistent with the stress change in the reservoir development process, and thus, it is more representative than the variable confining pressure experiment method. However, there are still some limitations in the experimental conditions. For example, in the experiments, the fluid will flow from the rubber sleeve of the gripper when the fluid pressure is greater than the confining pressure, and the permeability measured in the experiment cannot reflect the real seepage capacity of the core. When the flow pressure is lower than the confining pressure, the effective stress calculated using Equation (1) is greater than 0, the rock pore is always under compressive stress, and the cracks and microcracks cannot be opened. The cracks and microcracks are the main seepage channels in low-permeability tight reservoirs. If the fluid pressure is always lower than the confining pressure in the experiment, the tensile stage of the cracks and microcracks, which has the greatest impact on the seepage capacity, cannot be reflected by the experiment, and the results cannot reflect the entire stress sensitivity process. Therefore, the experimental method for studying stress sensitivity in this article can be used to simulate the process of pores becoming larger or microcracks restarted when the formation stress increases, and it makes up for the shortcomings of the previous experimental methods.

Therefore, in this study, based on the original variable fluid pressure method, axial stress was added to test the effective stress as the stress changes from compressive to tensile. A flow chart of the experiment is shown in Figure 5. The purpose of this experiment is to obtain conditions closer to the stress change in the formation in order to investigate the entire stress sensitivity process.

The purpose of the variable fluid pressure experiment is to explore the stress sensitivity of cores containing different microcracks and the dynamic opening conditions of the microcracks. The experimental process is shown in Figure 4. The experimental steps used are as follows.

1. Check the tightness of the experimental device, dry the core, vacuum and saturate the core with salt.

| Core number | Length (cm) | Diameter (cm) | Porosity (%) | Initial permeability (mD) | Growth rate of crack permeability (%) |
|-------------|-------------|---------------|--------------|---------------------------|--------------------------------------|
| 1           | 5.01        | 2.55          | 10.46        | 0.48                      | —                                    |
| 2           | 5.00        | 2.56          | 10.52        | 0.46                      | —                                    |
| 3           | 5.16        | 2.55          | 10.59        | 0.42                      | —                                    |
| 4           | 5.02        | 2.48          | 11.36        | 0.45                      | 93%                                  |
| 5           | 5.02        | 2.48          | 11.59        | 0.40                      | 84%                                  |
| 6           | 5.07        | 2.47          | 10.52        | 0.43                      | 79%                                  |

Figure 4: Flowchart of the experimental design for crack creation.
water, and put the core into the experimental apparatus

(2) Load a smaller axial compression to fix the position of the core, and then, increase the confining pressure to 15 MPa. Empty the experimental device

(3) Set the axial compression to 0, 10, 20, and 30 MPa, set the fluid flow rate to 0.1 mL/min, and set the back pressure values to 0, 3, 6, 9, and 12 MPa. Record the inlet pressure and outlet pressure for each pressure setting. The setting of the pressure value follows the following two principles. First, different pressure differences between confining pressure and axial pressure will produce different influence to the pores of rock. Second, the setting of back pressure is to maintain the flow rate and balance the pressure

(4) At the end of the experiment, plot the experimental results

4. Results

4.1. Experimental Results for the Variable Fluid Pressure Sensitivity. The variable fluid pressure sensitivity experiment was carried out according to the experimental method described above. The experimental results are shown in Figure 6. First, as the fluid pressure increased, the permeability of the core increased, and the rates of permeability increase for matrix cores 1–3 were less than 20%. The permeability change in cores 4–6 containing microcrack was divided into two stages. In the first stage, the permeability slowly increased with increasing fluid pressure, and the growth rate does not exceed 25%. In the second stage, it sharply increases after the fluid pressure increased to a certain value. In addition, as the axial pressure increased, the permeabilities of cores 1–6 decreased. When the axial pressure was 30 MPa, the permeability of the core containing microcracks increased rapidly with increasing fluid pressure.

4.2. Analysis of the Relationship between Stress and Permeability. The experimental data for cores 4–6 under an axial pressure of 30 MPa were analyzed separately. The experimental data are shown in Figure 7. In the figure, the discrete data points are the experimental data obtained from the experiments. The experimental conditions were an axial pressure of 30 MPa and a confining pressure of 15 MPa. The continuous curve is a simulated curve based on theoretical Equation (11). The basic parameters of the simulated curve are presented in Table 2.

As can be seen from Figure 8, the permeability is positively correlated with the fluid pressure when the fluid pressure is small (i.e., less than 11 MPa). The dotted line in the figure represents the trend without the influence of microcracks, and the slope of this part of the straight line is determined by $\beta C_2 \phi_0 \sigma_z$ in Equation (11) since the second part of Equation (11) has a limited influence on the calculation results at low fluid pressures. The higher the degree of microcrack development, the greater value of $\beta C_2 \phi_0 \sigma_z$ and the greater the slope of the line [19]. As the fluid pressure increased (i.e., greater than 11 MPa, and 11 MPa is the opening point of the microcracks in the experiment), the effective stress gradually decreased, and the microcracks gradually opened. The main seepage channels in the rock samples were opened, and the permeability increased rapidly [38, 39]. At this time, the permeability of the rock sample was mainly the result calculated using the second part of Equation (11), and the first part of the equation had little effect on the results.

5. Discussion

During the crack formation process, some of the original cementation between the sandstone particles and some of the dead pores rupture under the shear stress and connect with the original pores to form microcracks, which greatly improves the seepage capacity of the core. This part of the microcracks will be closed under pressure [3, 40–42]. For a core with initial microcracks, only the confining pressure was loaded, that is, only the effect of $\delta_x$. Due to the limitations imposed by the experimental conditions, the fluid pressure was always smaller than the confining pressure $\delta_x$, and the effective stress was greater than 0, which is manifested as the compressive stress. The microcracks could not be opened and were always in a closed state. Due to the loading of the axial stress, the tensile stress was preloaded. When the fluid pressure increased to a negative...
Figure 6: Relationship between permeability and fluid pressure.
value of $\sigma_{eff}^2$, the microcracks reopened. This process is shown in Figure 7.

5.1. Analyze the Experimental Results of Variable Fluid Pressure. Based on the above experimental results, the following conclusions can be drawn. First, when the fluid pressure increases, the rock particles can be compressed, the flow space can be increased, and the seepage capacity of the core can be enhanced. However, the degree to which the permeability can be increased due to the expansion of the pore throats’ flow space caused only by increasing the fluid pressure is limited. Therefore, the rates of permeability increase for cores 1–3 were less than 20%, and the permeabilities of cores 4–6 increased slowly in the first stage. When the fluid pressure reached the opening pressure of the microcracks, the permeability increased sharply. Furthermore, for a constant confining pressure, increasing the axial compression will result in compression of the rock particles and a corresponding decrease in the pore flow space, resulting in a decrease in the seepage capacity. The direction of the microcracks in cores 4–6 was mainly 20–27.5° in the horizontal direction. During the experiment, the confining pressure was kept at 15 MPa, and the axial compression was set at 0, 10, 20, and 30 MPa. When the axial pressure was less than the confining pressure, the maximum principal stress direction was parallel to the diameter, and the corresponding principal stress surface was at a small angle to the radial direction. As the axial pressure increased, the tensile stress

Table 2: Basic parameters of the simulated experimental data curve.

| Sample | $k_{0,0}$ ($10^{-3} \mu m^2$) | $\beta$ | $C_e$ (MPa$^{-1}$) | $\phi_{0,0}$ (%) | $\alpha$ | $\gamma_e$ (%) | $k_e$ (MPa) | $m$ |
|--------|-----------------|--------|-----------------|-----------------|--------|---------------|------------|-----|
| 4      | 0.057           | 0.33   | 8.75E-4         | 11.36           | 0.5    | 0.1           | 2.83       | 1.5 |
| 5      | 0.05            | 0.28   | 8E-4            | 11.59           | 0.5    | 0.1           | 2.52       | 1.42|
| 6      | 0.048           | 0.2445 | 8E-4            | 10.52           | 0.5    | 0.1           | 2.52       | 1.42|

Figure 7: Stress structure of the sandstone particles.

Figure 8: Diagrams comparing the experimental data and the simulation curve (experimental data for cores 4–6 are measured under an axial compression of 30 MPa and a confining pressure of 15 MPa).
on the crack surfaces in the core containing initial microcracks with axial directions of 20–27.5° decreased, and the seepage capacity decreased. When the axial pressure was greater than the confining pressure, the direction of the maximum principal stress was axial. This process was anal-

\[ (\sigma - \frac{\sigma_1 + \sigma_2}{2})^2 + r^2 = \left(\frac{\sigma_1 - \sigma_2}{2}\right)^2 \] (12)

5.2. Analyze the Fitting of Experimental and Digital-Analog Results. Since the trend of the curve is mainly divided into before and after the microcracks opened, the change in permeability with fluid pressure can be simplified as two straight lines, and the slope of the straight line describes the degree of microcrack development. The overall composition of the curve can be approximately divided into two straight lines (Figure 2). In the first part, the permeability increases slowly with increasing fluid pressure. During this process, the permeability is positively correlated with the fluid pressure, and the microcracks are in a closed state. According to Equation (14), in this part, the permeability mainly depends on the hard part. The second part of the straight line refers to the permeability curve after the opening of the microcracks, and it can also be approximated as a straight line. The higher the degree of microcrack development, the greater the slope of the straight line. The experimental results after fitting the experimental data are shown in Figure 9.

As can be seen from Figure 9, the slopes of the first part of the fitting lines are 0.0013, 0.0014, and 0.0014, which are not significantly different. Considering the experimental error, it can be concluded that the slope of the curve before the microcracks open is the same; that is, the microcracks have no effect on the process for small fluid pressures. The slopes of the second parts of the fitting lines are 0.0088, 0.0074, and 0.0063, and during this process, the microcracks are open. The higher the degree of microcrack development, the greater the slope of the line. Therefore, the degree of microcrack development can be determined according to the slope of the second part of the fluid pressure sensitivity curve.

6. Conclusions

In this study, the advantages and disadvantages of the traditional stress sensitivity analysis methods were compared, and an experiment method for investigating stress sensitivity with axial compression was designed. The axial compression loading plays the role of the preloading stress, and combined with the variable confining pressure stress sensitivity experiment method, the influence of microcrack development on the reservoir seepage ability was studied. The following conclusions were obtained:

1. In this study, an experimental method for analyzing the stress sensitivity and simulate the opening of microcracks was established, and the entire stress
sensitivity process was simulated when the fluid pressure lower than the confining pressure. The stress sensitivity of the microcracks opening during water injection development can be simulated, and the experimental method for simulating the entire process of stress change is improved. Thus, the experimental process more closely simulates to the development process. Using new experimental method, an effective stress model suitable for the new experimental methods was improved.

(2) In the variable fluid pressure experiments with axial pressure, the permeability increased slowly with increasing fluid pressure, and the maximum rate of permeability increase was less than 20%. For the cores containing microcracks, when the main stress direction is along the microcrack direction, the permeability increases slowly with the increase of fluid pressure. When the principal stress direction is perpendicular to the microcrack direction, the change in permeability was mainly divided into two stages. In the first stage, the microcracks closed under the action of the compressive stress. At this time, the influence of the microcracks on the seepage capacity was limited. The permeability increased slowly with increasing fluid pressure. The second stage involved a rapid increase in permeability after the microcracks opened. For all of the cores, the permeability decreased with increasing axial pressure.

(3) The experimental data of cores with microcracks match well with numerical simulation curves; the permeability is positively correlated with the fluid pressure when the fluid pressure is small (that is less than the reopening pressure of the microcracks). As the fluid pressure increased (when the fluid pressure is greater than the reopening pressure of the microcracks), the effective stress gradually decreased, and the microcracks gradually opened. The main seepage channels in the rock samples were opened, and the permeability increased rapidly.

(4) For the cores containing microcracks, the curve of the change in the permeability with fluid pressure can be approximately described as two straight lines. The slope of the first straight line is not related to the degree of microcrack development, and it is only related to the nature of the core itself. The second straight line is mainly related to the degree of microcrack development. The higher the degree of microcrack development, the greater the slope of the straight line.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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References

[1] K. Liu, D. Y. Yin, Y. H. Sun, and L. Xia, “Analytical and experimental study of stress sensitivity effect on matrix / fracture transfer in fractured tight reservoir,” *Journal of Petroleum Science and Engineering*, vol. 195, p. 107958, 2020.

[2] X. Li, X. Fu, P. G. Ranjith, and J. Xu, “Stress sensitivity of medium- and high volatile bituminous coal: An experimental study based on nuclear magnetic resonance and permeability-porosity tests,” *Journal of Petroleum Science and Engineering*, vol. 172, pp. 889–910, 2019.

[3] Z. W. Wu, L. Dong, C. Z. Cui, X. Cheng, and Z. Wang, “A numerical model for fractured horizontal well and production characteristics: Comprehensive consideration of the fracturing fluid injection and flowback,” *Journal of Petroleum Science and Engineering*, vol. 187, p. 106765, 2020.

[4] Z. W. Wu, C. Z. Cui, G. Z. Lv, S. Bing, and G. Cao, “A multi-linear transient pressure model for multistage fractured horizontal well in tight oil reservoirs with considering threshold pressure gradient and stress sensitivity,” *Journal of Petroleum Science and Engineering*, vol. 172, pp. 839–854, 2019.

[5] W. J. Shen, X. Z. Li, T. R. Ma, J. Cai, X. Lu, and S. Zhou, “High-pressure methane adsorption behavior on deep shales: experiments and modeling,” *Physics of Fluids*, vol. 33, no. 6, article 063103, 2021.

[6] Y. Xue, J. Liu, P. G. Ranjith, X. Liang, and S. Wang, “Investigation of the influence of gas fracturing on fracturing characteristics of coal mass and gas extraction efficiency based on a multi-physical field model,” *Journal of Petroleum Science and Engineering*, vol. 206, p. 109018, 2021.

[7] Y. Xue, T. Teng, F. N. Dang, Z. Ma, S. Wang, and H. Xue, “Productivity analysis of fractured wells in reservoir of hydrogen and carbon based on dual-porosity medium model,” *International Journal of Hydrogen Energy*, vol. 45, no. 39, pp. 20240–20249, 2020.

[8] K. Terzaghi, *Theoretical soil mechanics*, Johnwiley & Sons, New York, 1943.

[9] I. Fatt, “The effect of overburden pressure on relative permeability,” *Journal of Petroleum Technology*, vol. 5, no. 10, pp. 15–16, 1953.

[10] I. Fatt and D. H. Davis, “Reduction in permeability with overburden pressure,” *Journal of Petroleum Technology*, vol. 4, no. 12, pp. 16–16, 1952.

[11] O. Kwon, A. K. Kronenberg, A. F. Gangi, and B. Johnson, “Permeability of Wilcox shale and its effective pressure law,” *Journal of Geophysical Research: Solid Earth*, vol. 106, no. B9, pp. 19339–19353, 2001.

[12] S. Ghabezloo, J. Sulem, S. Guedon, and F. Martineau, “Effective stress law for the permeability of a limestone,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, no. 2, pp. 297–306, 2009.

[13] R. Heller, J. Vermynen, and M. Zoback, “Experimental investigation of matrix permeability of gas shales,” *AAPG Bulletin*, vol. 98, no. 5, pp. 975–995, 2014.
[14] R. Fink, B. M. Krooss, and A. Amann-Hildenbrand, “Stress-dependence of porosity and permeability of the Upper Jurassic Bossier shale: an experimental study,” Geological Society, London, Special Publications, vol. 454, no. 1, pp. 107–130, 2017.

[15] J. B. Walsh, “Effect of pore pressure and confining pressure on fracture permeability,” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 18, no. 5, pp. 429–435, 1981.

[16] Y. L. Shi and C. Y. Wang, “Pore pressure generation in sedimentary basins: overloading versus aquathermal,” Journal of Geophysical Research: Solid Earth, vol. 91, no. B2, pp. 2153–2162, 1986.

[17] T. J. Katsube, B. S. Mudford, and M. E. Best, “Petrophysical characteristics of shales from the Scotian shelf,” Geophysics, vol. 56, no. 10, pp. 1681–1689, 1991.

[18] O. Kwon, A. K. Kronenberg, A. F. Gangi, B. Johnson, and B. E. Herbert, “Permeability of illite-bearing shale: 1. Anisotropy and effects of clay content and loading,” Journal of Geophysical Research: Solid Earth, vol. 109, no. B10, 2004.

[19] J. T. Zheng, L. G. Zheng, H. H. Liu, and Y. Ju, “Relationships between permeability, porosity and effective stress for low-permeability sedimentary rock,” International Journal of Rock Mechanics and Mining Sciences, vol. 78, pp. 304–318, 2015.

[20] M. Y. Zhang and A. K. Ambastha, “New insights in pressure-transient analysis for stress-sensitive reservoirs,” in SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 1994.

[21] S. Moosavi, K. Goshtasbi, E. Kazemzadeh, H. A. Bakhtiar, M. R. Esfahani, and J. Vali, “Relationship between porosity and permeability with stress using pore volume compressibility characteristic of reservoir rocks,” Arabian Journal of Geosciences, vol. 7, no. 1, pp. 231–239, 2014.

[22] T. F. Wong, J. T. Fredrich, and G. D. Gwansmesia, “Crack aperture statistics and pore space fractal geometry of Westerly granite and Rutland quartzite: implications for an elastic contact model of rock compressibility,” Journal of Geophysical Research: Solid Earth, vol. 94, no. B8, pp. 10267–10278, 1989.

[23] Y. Wang, “The effect of a nonlinear Mohr-Coulomb criterion on the stresses and plastic deformation near a circular opening in a poorly consolidated permeable medium,” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 33, no. 2, pp. 197–203, 1996.

[24] S. R. Brown and C. H. Scholz, “Closure of random elastic surfaces in contact,” Journal of Geophysical Research: Solid Earth, vol. 90, no. B7, pp. 5531–5545, 1985.

[25] R. A. Archer, “Impact of stress sensitive permeability on production data analysis,” in SPE Unconventional Reservoirs Conference, Keystone, Colorado, USA, 2008.

[26] N. Cao, G. Lei, P. C. Dong, H. Li, Z. Wu, and Y. Li, “Stress-dependent permeability of fractures in tight reservoirs,” Energies, vol. 12, no. 1, p. 117, 2019.

[27] H. Gao, C. Wang, J. Cao, M. He, and L. Dou, “Quantitative study on the stress sensitivity of pores in tight sandstone reservoirs of Ordos basin using NMR technique,” Journal of Petroleum Science and Engineering, vol. 172, pp. 401–410, 2019.

[28] Y. Gu, W. L. Ding, M. Yin et al., “Study on pressure sensitivity of tight sandstone and its influence on reservoir characteristics,” Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 40, no. 22, pp. 2671–2677, 2018.

[29] Q. G. Tan, Y. L. Kang, L. J. You, C. Xu, X. Zhang, and Z. Xie, “Stress-sensitivity mechanisms and its controlling factors of saline-lacustrine fractured tight carbonate reservoir,” Journal of Natural Gas Science and Engineering, vol. 88, p. 103564, 2021.

[30] H. H. Liu, J. Rutqvist, and J. G. Berryman, “On the relationship between stress and elastic strain for porous and fractured rock,” International Journal of Rock Mechanics and Mining Sciences, vol. 46, no. 2, pp. 289–296, 2009.

[31] Y. Z. Sun, L. Z. Xie, B. He, C. Gao, and J. Wang, “Effects of effective stress and temperature on permeability of sandstone from CO2-plume geothermal reservoir,” Journal of Rock Mechanics and Geotechnical Engineering, vol. 8, no. 6, pp. 819–827, 2016.

[32] Z. K. Wu, X. Z. Li, H. M. Xiao et al., “The establishment and evaluation method of artificial microcracks in rocks,” Energies, vol. 14, no. 10, article 2780, 2021.

[33] X. Y. Zhong, Y. S. Zhu, L. P. Liu et al., “The characteristics and influencing factors of permeability stress sensitivity of tight sandstone reservoirs,” Journal of Petroleum Science and Engineering, vol. 191, p. 107221, 2020.

[34] H. Zhang, Y. Zhong, E. Kuru, J. Kuang, and J. She, “Impacts of permeability stress sensitivity and aqueous phase trapping on the tight sandstone gas well productivity - A case study of the Daniudi gas field,” Journal of Petroleum Science and Engineering, vol. 177, pp. 261–269, 2019.

[35] B. Liu, Y. Q. Yang, J. T. Li, Y. Chi, J. Li, and X. Fu, “Stress sensitivity of tight reservoirs and its effect on oil saturation: a case study of Lower Cretaceous tight elastic reservoirs in the Hailar Basin, Northeast China,” Journal of Petroleum Science and Engineering, vol. 184, p. 106484, 2020.

[36] Z. M. Yan, K. Wang, J. Zang, C. Wang, and A. Liu, “Anisotropic coal permeability and its stress sensitivity,” International Journal of Mining Science and Technology, vol. 29, no. 3, pp. 507–511, 2019.

[37] N. Bo, X. Zuping, L. Xianshan et al., “Production prediction method of horizontal wells in tight gas reservoirs considering threshold pressure gradient and stress sensitivity,” Journal of Petroleum Science and Engineering, vol. 187, p. 106750, 2020.

[38] X. Li, D. Lu, R. Luo et al., “Quantitative criteria for identifying main fluid channels in complex porous media,” Petroleum Exploration and Development, vol. 46, no. 5, pp. 998–1005, 2019.

[39] X. Li, R. Luo, Y. Hu et al., “Main flow channel index in porous sand reservoirs and its application,” Petroleum Exploration and Development, vol. 47, no. 5, pp. 1055–1061, 2020.

[40] W. J. Shen, F. Q. Song, X. Hu, G. Zhu, and W. Zhu, “Experimental study on flow characteristics of gas transport in micron-scale pores,” Scientific Reports, vol. 9, no. 1, pp. 1–10, 2019.

[41] Z. W. Wu, C. Z. Cui, J. P. Trivedi, N. Ai, and W. Tang, “Pressure analysis for volume fracturing vertical well considering low-velocity non-Darcy flow and stress sensitivity,” Geofluids, vol. 2019, Article ID 2046061, 10 pages, 2019.

[42] Z. W. Wu, C. Z. Cui, Z. Wang, Y. Sui, P. Jia, and W. Tang, “Well testing model of multiple fractured horizontal well with consideration of stress-sensitivity and variable conductivity in tight gas reservoirs,” Mathematical Problems in Engineering, vol. 2018, Article ID 1693184, 13 pages, 2018.