Experimental Study on the Effect of Micro Pore-throat Structure on Stress Sensitivity

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***Abstract*—The characteristics of stress sensitivity is the theoretical foundation to determine the formation pressure level in the tight oil reservoir. Therefore many studies focus on it. However, no existing study explains the mechanism of stress sensitivity in nature. Therefore this paper is to solve the problem. In this paper, experiments were conducted to study the characteristics of stress sensitivity in the tight oil reservoir. Then casting thin section, scanning electron microscope and constant-speed mercury injection experiments were performed to study the diagenesis and pore-throat structure. It is found that due to the support of ferrocalcite and quartz, the compressive strength of tinier throats is larger. The gas stress sensitivity is determined by the maximal throat radius. And the relative location of minimal throats for liquid to flow to the peak of pore-throat distribution is the key factor to determine the liquid stress sensitivity.**

***Index Terms*—tight oil reservoir; stress sensitivity; micro pore-throat structure; minimum throats for liquid to flow**

I. Introduction

Stress Sensitivity of petroleum reservoir rock is that its petrophysical parameters change when the effective stress acting on it changes. Permeability stress sensitivity has been a hot topic in the field of petroleum reservoir engineering and geotechnical engineering because permeability with the mutative effective stress has a more direct and important impact on petroleum development.

The development of stress sensitivity research has experienced the following stages.

In 1923, K. Terzaghi studied the flow behavior in the saturated deformable medium and came up with the concept of effective stress (Eq. 1) which laid the foundations of the stress sensitivity research. [1]

$$\sigma_{eff} = \sigma - p \tag{1}$$

where σ_{eff} is effective stress sensitivity, MPa; σ is overlying pressure, MPa; p is formation pressure, MPa;

In 1952, M. Latchie et al used oil to study the stress sensitivity of the cores whose permeability ranged from 3 to $102\times10^{-3}\mu m^2$ and got the k_i/k_o vs σ_{eff} relational graph.[2] And it was found that the irreversible damage for permeability was 4% in the high permeability cores while that reached up to 60% in the low permeability cores indicating that the strain of the cores included both elastic and plastic strain.

In 1958, I. Fatt used gas to study the stress sensitivity of porosity and permeability of the cores whose permeability ranged from 3 to $630\times10^{-3}\mu m^2$. [3] [4] When the confining pressure was 34MPa, the degree of the damage for porosity and permeability were 5% and 25% respectively. According to the experiments, he concluded that the stress sensitivity of porosity could be neglected while that of permeability could not in site.

In 1988, S. C. Jones used gas and the two-point method to determine the relation of permeability and porosity vs net confining stress of cores whose permeability ranged from 10 to $700\times10^{-3}\mu m^2$.[5]

In 1997, G. Jose found the degree of the gas permeability damage is high to 90% in the tight gas reservoir when the cores were compressed.[6]

In 2007, Luo Ruilan used gas to evaluate the stress sensitivity of cores whose Klinkenberg permeability ranged from 0.1 to $3\times10^{-3}\mu m^2$ and came up with a new coefficient (Eq. 2) to show the degree of the stress sensitivity.[7]

$$s_p = \frac{\lg \dfrac{k_{\min}}{k_o}}{\lg \dfrac{\sigma_{\max}}{\sigma_o}} \tag{2}$$

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where s_p is the stress sensitivity coefficient; k_{min} is the permeability when the effective stress is σ_{max} $\times10^{-3}\mu m^2$; k_o is the permeability when the effective stress is σ_o, $\times10^{-3}\mu m^2$; σ_{max} is the maximal effective stress, MPa; σ_o is the initial effective stress, MPa.

In 2013, Sun Junchang compared the differences among the characteristics of the stress sensitivity measured by gas, water and oil and analyzed the reason leading to the differences from the aspect of wettability. [8]

From the preceding part it can be seen that the mechanism of the stress sensitivity was explained from the aspects of permeability and wettability. Although throats are the nature of permeability, there is little studies on the influence of micro pore-throat structure on stress sensitivity.

Therefore, seven experiments were conducted to evaluate the characteristics of the stress sensitivity and advanced technologies such as casting thin section, scanning electron microscope (SEM) and constant-speed mercury injection experiments were performed to reveal the micro pore-throat structure. The mechanism of the stress sensitivity was analyzed by combining these two aspects.

II. Experimental Method

It is studied that the stress sensitivity of permeability is far more serious than that of porosity. [3], [4] Hence the stress sensitivity of permeability was the object of this research. The cores used in the experiments were taken from the tight oil reservoir in Chang 7 Member, Yanchang Formation, Ordos Basin. The basic parameters of the cores are showed in the following Table. I. It can be seen from the table that the porosity of the cores from the tight oil reservoir is ultra low and the permeability ranges from super low to tight. From the results of the analysis assay it is found that the average density of the rock is 2.37g/cm^3 and that of the formation liquid is 1g/cm^3. From the well logging data, it is seen that the average depth of the reservoir is 1800m. According to these parameters, the overlying rock pressure was calculated to be 42MPa and the formation pressure was 18MPa, with the 24MPa initial effective stress. Due to the extremely low permeability, the stabilization time was very long. The accuracy of pressure was so important that the ISCO pump imported from the America had to be used.

A. Gas-measured Stress Sensitivity Experiments

Because the initial formation pressure(15MPa) exceeded the maximum pressure of the pressure reducing valve on the nitrogen cylinder, the displacement pressure had to stay constant and the confining pressure was adjusted to change the effective stress. Considering the application of the advanced water injection technology, the confining pressure was finally determined to be 18MPa. At the same time the displacement pressure was 4MPa and the back pressure was 2MPa with the 3MPa initial formation pressure and the 15MPa effective stress. And then the confining pressure was adjusted to 23, 28, 33, 38, 33, 28, 23, 18MPa successively. The experimental procedure can be seen in Fig. 1. Because of the extremely small flow rate resulted from the extremely low permeability, the stabilization time must extend into 30 minutes and the lather flowmeter was used to measure the tiny flow rate of gas.

TABLE I. BASIC PARAMETERS OF CORES

Number of cores	Length (cm)	Diameter (mm)	Porosity (%)	Gas permeability ($\times10^{-3}\mu m^2$)
1	6.1	25.1	11.7	0.35
2	6.4	25.0	10.6	0.11
3	6.0	25.1	9.3	0.0085
4	5.8	25.2	10.1	0.084
5	6.2	24.9	9.7	0.039
6	5.2	25.1	9.6	0.019
7	5.5	25.0	9.2	0.0085

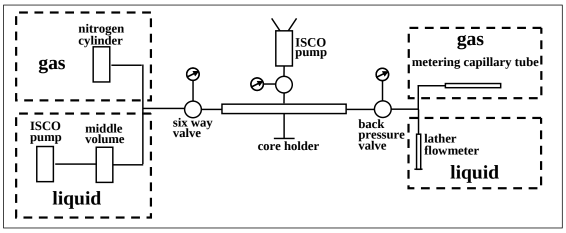


Figure 1. Schematic of stress sensitivity experimental facility

B. Liquid-measured Stress Sensitivity Experiments

In order to simulate the development of the tight oil reservoir realistically, the confining pressure must stay constant and the effective stress was changed by adjusting the flowing pressure in the liquid-measured stress sensitivity experiments. According to the parameters calculated in the preceding part of the paper, considering the application of the advanced water injection technology, the overlying rock pressure, the displacement pressure and the back pressure were 40MPa, 30MPa and 20MPa respectively. The initial formation pressure was 25MPa and the effective stress was 15MPa. Then the displacement pressure was adjusted to 25, 20, 15, 10, 15, 20, 25, 30MPa and the back pressure was adjusted to 15, 10, 5, 0, 5, 10, 15, 20MPa. The experimental procedure can be seen in fig. 1. Kerosene was selected as the experimental fluid to avoid water sensitivity. Because of the extremely small flow rate resulted from the extremely low permeability, the stabilization time had to be as long as 24 hours and the metering capillary tube was used to measure the tiny flow rate of kerosene.

C. Constant-speed Mercury Injection Experiment

Three Constant-speed Mercury Injection Experiments were performed using the cores of No. 1, No. 2 and No. 7. The major experimental facility is ASPE-730 Automated System for Pore Examination imported from America. The software uses Monte Carlo simulation techniques for estimating some of the resulting parameters. The experiments Utilize precision pressure transducers with 0.05% accuracy. Mercury injected volume is measured to <0.000001 cc resolution. Pump injection rate ranges from 0.00006 to 1 cc/min. Pressure Ranges from 0 to 1000 psia.

Volume resolution is 0.000001 cc. Maximum diameter and length of samples are 1cm diameter and 1cm long respectively.

III. RESULTS

A. Gas-measured Stress Sensitivity Experiments

The degree of the permeability damage (Eq. 3) and recovery (Eq. 4) are the evaluation indexes of the stress sensitivity.

$$D = 1 - k_{\min} \tag{3}$$

$$R = k' - k_{\min} \tag{4}$$

where D is the degree of the permeability damage; k_{min} is the relative permeability when the effective stress is the maximum; R is the degree of the permeability recovery; k' is the relative permeability when the effective stress decreases to the minimum.

Fig. 2 shows the gas-measured experimental results of the three cores from the tight oil reservoir, which reveals that with the lower gas permeability, the degree of the permeability damage and recovery are becoming larger.

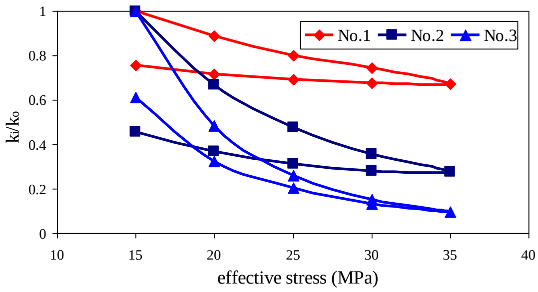


Figure 2. Gas stress sensitivity experimental results

B. Liquid-measured Stress Sensitivity Experiments

Fig. 3 shows the liquid-measured experimental results of four cores from the tight oil reservoir, which reveals that except the No.4 core, the variation regularity of the other three cores from No. 5 to No. 7 is consistent. Namely, along with the gas permeability decreases, the degree of damage for liquid permeability reduces and when the effective stress decreases, permeability recovering does not occur, which means the damage is irreversible. Particularly the permeability recovery happens in the No.4 core but the degree is small.

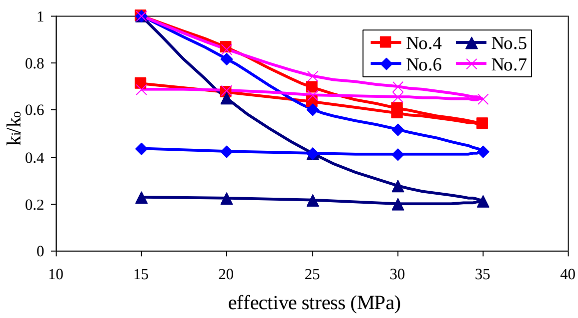


Figure 3. Liquid stress sensitivity experimental results

C. Comparison of Stress Sensitivity Measured by Gas and Liquid

Fig. 4 shows the results of two sets of stress sensitivity experiments using cores from the tight oil reservoir with the approximate gas permeability. It reveals that the degree of damage and recovery for gas permeability are both larger than that for liquid. Moreover, as the gas permeability decreases, the differences in the degree of damage and recovery between gas and liquid permeability increase.

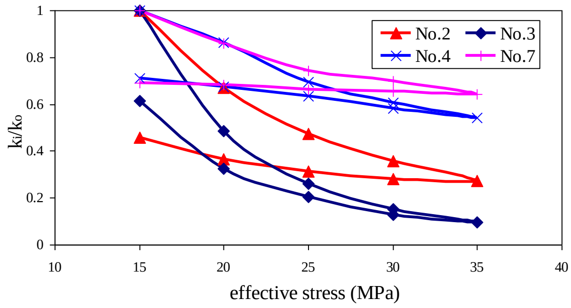


Figure 4. Comparison of gas and liquid stress sensitivity

D. Constant-speed Mercury Injection Experiment

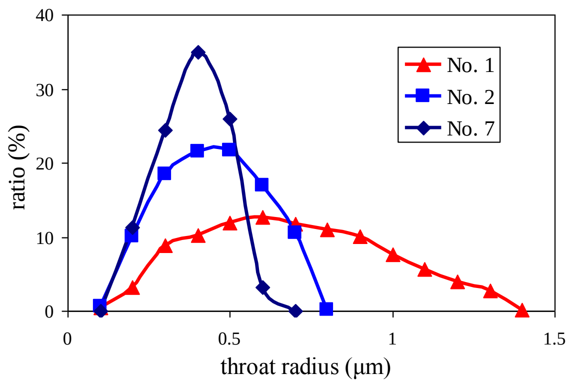


Figure 5. Throat distribution of different permeability cores

Fig. 5 and Fig. 6 show the results of the three Constant-speed Mercury Injection Experiments. It can be seen form Fig. 5 that as the gas permeability decreases, the maximum throat radius reduces obviously and the proportion of the tinier throats becomes higher. As a result the contribution to permeability of the tinier throats is larger (Fig. 6).

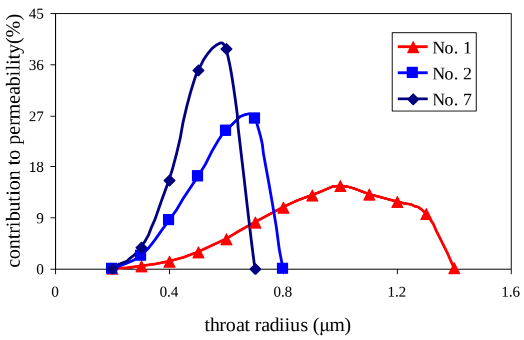


Figure 6. Distribution of throat contribution to permeability

IV. INFLUENCE FACTORS ANALYSIS

A. Analysis of the Influence of the Micro Pore-throat Distribution on the Gas-measured Stress Sensitivity

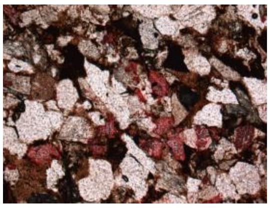
The permeability of cores is mainly controlled by throats, so the strain of throats is the nature of the permeability stress sensitivity.

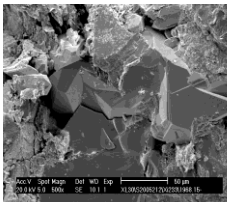
The diameter of nitrogen molecules is 0.304nm. It is so tiny that nitrogen can entry all throats, so gas permeability can reflect the strain of all throats. Through the three constant-speed mercury injection experiments, it is found that when the gas permeability decreases, the throat distribution trends to be negative skewness and the kurtosis value becomes bigger (Table. II) indicating that throats converge to tiny ones (Fig. 5).

TABLE II. THROAT DISTRIBUTION FEATURES OF DIFFERENT PERMEABILITY CORES

Gas permeability ($\times 10^{-3}\mu m^2$)	0.01	0.1	0.3
skewness	-0.097	-0.012	0.070
kurtosis	1.00	0.85	0.67

The second cement function of ferrocalcite and the secondary enlargement of quartz reduced the radii of the throats (Fig. 7) leading to the further diminution of the permeability. It is precisely because of the support of ferrocalcite and quartz for tiny throats that with the same stress, the absolute strain of tiny throats is smaller than that of big throats while the relative strain of tiny throats is larger. So when compressed, big throats which contribute most to permeability are easiest to compress. That is why the rate of the permeability damage is fast in the beginning and then becomes smooth. With the lower gas permeability, the range of the throat distribution becomes smaller and the throats' diameters decrease entirely leading to the bigger ratio of the strain when compressed. Therefore the permeability damage is more serious when the gas permeability is lower.





(a) the cement of ferrocalcite (b) the secondary enlargement of quartz

Figure 7. Diagenesis in the tight oil reservoir

For a core, the rock composition is the same, so the elastic limits of all throats are the same as well. As the absolute strain of the big throats is larger, they reach the elastic limit first and generate plastic strain leading to the fact that when the effective stress decreases, the tinier throats have the higher degree of the recovery. Through the three constant-speed mercury injection experiments, it is found that the contribution to permeability of tiny throats increases as the gas permeability decreases (Fig. 6), which raises the impact of the elastic recovery of the tiny throats. The degree of the permeability recovery increases as the gas permeability decreases with the effect of these two mechanisms.

B. Analysis of the Influence of the Minimum Throat for Liquid to Flow on the Liquid-measured Stress Sensitivity

The gas permeability of the four cores in the fig. 2 is extremely low (less than $0.1\times10^{-3}\mu m^2$). Such cores belong to typical tight oil reservoir cores. Due to the impact of the minimal throat radius for liquid to flow (r_m),[9] the characteristics of the stress sensitivity measured by gas and liquid are totally different (Fig. 4).

The degree of the permeability damage is the accumulation of all damages resulted from each throat (Eq. 5),

$$D = \sum_{r_i}^{r_{\max}} D_{r_i} \cdot \alpha_i \tag{5}$$

where r_{max} is the maximal throat radius, μm; D_{ri} is the damage resulted from the throat whose radius is r_i; α_{ri} is the proportion of the throat whose radius is r_i.

when r_i is the minimal throat radius, D is the degree of gas permeability damage. When $r_i = r_m$, $D_{rm}=1$ and D is the degree of liquid permeability damage. The degree of the permeability damage is mainly controlled by $(D_{ri} \cdot \alpha_{ri})_{max}$. Because $D_{rm}=1>>D_{ri}$, $(D_{ri} \cdot \alpha_{ri})_{max}$ always appears where $r_i=r_m$ all the time. When r_m is on the left side of the throat distribution peak, with the lower gas permeability, α_{rm} is bigger. It leads to larger $(D_{ri} \cdot \alpha_{ri})_{max}$, so D is greater. If r_m is on the right side of the throat distribution peak, with the lower gas permeability, α_{rm} is smaller. It leads to smaller $(D_{ri} \cdot \alpha_{ri})_{max}$, so D is smaller. All these indicate that the key factor to determine the variation regularity is the relative location of r_m to the peak of the throat distribution. However, it is only when the gas permeability is extremely low that r_m is likely to locate on the right side of the throat distribution peak. With the high gas permeability, r_m appears on the left side of the peak always, so the degree of the liquid permeability damage correlates with the gas permeability negatively.

The plastic strain of big throats is more serious than that of tiny throats. As the effective stress decreases, the elastic recovery mostly happens in tiny throats. But the radii of tiny throats are smaller than r_m so the elastic recovery has no contribution to liquid permeability. As a result the liquid permeability cannot recover. However, when the gas permeability is high, the range of the throats distribution is so wide that the elastic recovery can take place where the radii of the throats are bigger than r_m so that the liquid permeability could recovery. Because in this case big throats contribute more to the permeability and the plastic strain mainly happens in them, the degree of recovery for the liquid permeability is small. The mechanism of this phenomena is similar to that of the stress sensitivity of the No.1 core whose gas permeability is high which the throats whose radii are smaller than r_m have little contribution to permeability.

Therefore, as the gas permeability increases, the degree of liquid permeability recovery increases in the beginning and then decreases. What's worst, the process of recovery disappears.

C. Analysis of the Influence of the Minimum Throat for Liquid to Flow on the Difference Between the Stress Sensitivity Measured by Gas and Liquid

The analysis above indicates that due to the influence of the r_m, the liquid permeability cannot reflect the tiny throats' contribution to permeability whose relative strain and elastic recovery are both larger while the gas permeability could. It is the reason why the degree of the gas permeability damage and recovery are larger than that of liquid. As the gas permeability decreases and the range of the throat distribution shrinks, the proportion of throats whose radii are smaller than r_m becomes larger so that the differences between the degree of damage and recovery for gas and liquid permeability are bigger.

V. Conclusions

Because of the support of ferrocalcite and quartz, the strain of tiny throats is smaller than that of big ones, while the relative strain of tiny throats is more serious. Therefore, the degree of damage and recovery for gas permeability in the stress sensitivity increases as the permeability of cores decreases.

The key to determine the variation regularity of the degree of the permeability damage is the relative location of the minimal throat radius for liquid to flow to the peak of the throat distribution. As the gas permeability decreases, the degree of the liquid permeability recovery increases in the beginning and then decreases. What's worst, the process of recovery disappears.

Because of the influence of the minimal throat radius for liquid to flow, the degree of damage and recovery for gas permeability is larger than that of liquid. So with the lower gas permeability, the differences between the degree of damage and recovery are bigger.

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References

[1] K. Terzaghi, *Theoretical Soil Mechanics*, New York, U.S.: Wiley, 1943, ch 2, pp. 11-15.

[2] A. S. M. Latchie, R. A. Hemstick, and L. W. Joung, "The effective compressibility of reservoir rock and its effect on permeability," *Journal of Petroleum Technology*, vol. 10, pp. 49~51, June 1958.

[3] I. Fatt and D. H. Davis, "Reduction in permeability with overburden pressure," *Journal of Petroleum Technology*, vol. 4, pp. 16, Dec 1952.

[4] I. Fatt, "Pore volume compressibilities of sandstone reservoirs rocks," *Journal of Petroleum Technology*, vol. 10, pp. 64-66, Mar. 1958.

[5] S. C. Jones, "Two-point determinations of permeability and PV vs net confining stress," *SPE Formation Evaluation*, vol. 3, pp. 235-241, Mar 1988.

[6] G. Jose, "Numerical simulation of coupled fluid-flow / geomechanical behavior of tight gas reservoirs with stress sensitive permeability," presented at Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, Brazil, Aug 30-Sep 3, 1997.

[7] R. L. Luo, L. S. Cheng, J. C. Peng, and H. Y. Zhu, "A new method of determining relationship between permeability and effective overburden pressure for low-permeability reservoirs," *Journal of China University of Petroleum (Natural Science Edition)*, vol. 31, pp. 87-90, April 2007.

[8] J. C. Sun, Z. M. Yang, and Q. Teng, "Comparative study on stress-dependent permeability of ultra-low permeability sandstone rock using different types of fluid media," presented at International Petroleum Conference, Beijing, China, Mar. 26-28, 2013.

[9] C. N. Zou, R. K. Zhu, B. Bai, Z. Yang, S. T. Wu, and L. Su, "First discovery of nano-pore throat in oil and gas reservoir in China and its scientific value," *Acta Petrologica Sinica*, vol. 27, pp. 1857-1864, June 2011.

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