Rock stress sensitivity in low-permeability gas reservoirs and its impact on productivity

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Abstract: The relationship between permeability and effective stress could be found using the stress sensitivity test, and the stress sensitivity in the low-permeability gas reservoir was investigated. The productivity model could be deduced and the influences of stress sensitivity on the development of the low-permeability gas reservoirs were also discussed. The results show that the permeability of the core decreases as the effective stress increases and the permeability first quickly declines, then slows. The fitting relationship between permeability and effective stress conforms to the index relationship. The fitting relationship between the stress sensitivity coefficient and permeability accords with the power function relation and the stress sensitivity effect weakens as the original permeability increases. Based on the Darcy flow theory and the original permeability in the reservoir, the productivity model of the well, considering the effect of stress sensitivity, could be presented. The distribution curves of the pressure and permeability in the reservoir are funnel-shaped. The pressure and permeability decline quickly as the original permeability or the gas well productivity increases. The stress sensitivity of the permeability in the conglomerate gas reservoir is obvious, indicating that the fluid pressure must be appropriately controlled and the difference in the production pressure should be maintained at a reasonable value during the development process.

Keywords: low-permeability gas reservoir, stress sensitivity, permeability, effect pressure, productivity model

1 Introduction

Stress sensitivity exists extensively during the progress of oil and gas field development, especially in the low-permeability gas field development. Stress sensitivity usually refers to the decrease in the effective permeability with the increase in the effective overburden pressure.

Based on the methods of experiment, scholars have researched the problem of stress sensitivity in the low-permeability gas reservoir. Fatt and Davis [1] discovered that the permeability of the sandstone reservoir decreases when the confining pressure is rising, deemed the confining pressure should be considered, whereas the permeability of the core is tested indoors. Vairogs et al. [2] did the triaxial compression test and obtained the relationship between the effective stress and porosity of the limestone. Adams [3] found that the formation of pore fluid pressure drops, and the net stress of rock increases when the in-situ stress releases, causing some underground rock physical parameters to change, especially the porosity and permeability, during the process of oil and gas field development.
Holt [4-6] found that the rock first had high effective stress, and then the stress was completely released during the process of coring and taking to the ground. Some changes in the rock pore structure exist, such as the ruptured micropore, the broadened original microfracture, and the new microcracks. Dautriat et al. [7] using the high-confining pressure rock mechanics parameter test and scanning electron microscopy found that the stress released in the micropore during drilling causes new inter-granular microcracks, which significantly increase core permeability. Therefore, when we start the core stress sensitivity test, the core first should be pressurized to the formation pressure for a period, restore its original formation pressure, and then relief to the testing experiment stress to eliminate the interference of stress release caused by the impact of microscopic pore structure during the test.

Walsh [8] found that the stress sensitivity formula can also be applied to low-permeability sandstone gas reservoirs. Dautriat et al. [5] via the igneous rock stress sensitivity test found that the igneous rock core has no relationship between the initial permeability and the loss rate of permeability; it is different from the sandstone. Walsh [8] and Rhett et al. [9] through deep igneous core found that the pore pressure of formation decreases, and the overburden pressure increases during the later period of oilfield development, which could cause rock deformation. Li et al. [10] and Zhang et al. [11] using the stress sensitivity test showed there is less stress sensitivity mineral in igneous rock, the stress sensitivity is the principal factor of reservoir damage, and igneous rock reservoir protection technology is critical. Jones [12] found a relationship between permeability and effective stress in the naturally fractured carbonate reservoir. Li et al. [10] deemed there is a strong stress sensitivity in the fractured carbonate reservoir.

Many experiments have confirmed the stress sensitivity in all types of rock, and there are different degrees of stress sensitivity in different rocks. With the deepening of exploration and development, the gas reservoir will gradually show its advantages. However, detailed research on the stress sensitivity in the low-permeability gas reservoir is not well studied. This study investigates the stress sensitivity in the low-permeability gas reservoir. Numerous stress sensitivity experiments of the full diameter core rock, considering the low-permeability reservoir’s lithology of conglomerate, could be conducted using the method that changes the confining pressure and maintains the internal pressure, establishing the stress sensitivity empirical equation of permeability in the low-permeability conglomerate gas reservoir. This study deduces the stress sensitivity gas well productivity model based on the Darcy flow theory and discusses the influences of stress sensitivity on the development of the low-permeability gas reservoir.

2 Sample and Method

2.1 Experimental sample

In this experiment, 16 full diameter core samples of the gas reservoir were selected. Fig.1 shows the entire core sample. Porosity and permeability were evaluated according to the oil industry’s standard of gas expansion method. Table 1 lists the basic parameters of the test core. The average porosity of the cores is 4.22%, the average gas permeability is $0.373 \times 10^{-3} \mu m^2$, and all the samples belong to low-permeability rock.
Figure. 1. Picture of the entire core sample

Table 1. Basic parameters of test core

| Sample No. | Length/mm | Diameter/mm | Density/g. cm\(^{-3}\) | Porosity/% | Permeability/ \(\times 10^{-3}\)μm\(^2\) |
|------------|-----------|-------------|-------------------------|------------|---------------------------------------|
| 1          | 59.18     | 104.05      | 2.41                    | 3.56       | 0.815                                 |
| 2          | 102.99    | 104.40      | 2.39                    | 3.03       | 0.067                                 |
| 3          | 89.35     | 103.75      | 2.35                    | 5.95       | 0.261                                 |
| 4          | 75.09     | 103.15      | 2.42                    | 5.09       | 0.699                                 |
| 5          | 93.17     | 100.14      | 2.50                    | 4.55       | 0.094                                 |
| 6          | 99.42     | 100.03      | 2.45                    | 2.61       | 0.275                                 |
| 7          | 75.04     | 103.22      | 2.49                    | 2.40       | 0.991                                 |
| 8          | 98.97     | 99.99       | 2.49                    | 4.54       | 0.178                                 |
| 9          | 71.22     | 96.55       | 2.42                    | 2.64       | 0.174                                 |
| 10         | 104.46    | 102.15      | 2.43                    | 4.58       | 0.044                                 |
| 11         | 98.55     | 99.82       | 2.48                    | 5.20       | 0.044                                 |
| 12         | 56.77     | 103.00      | 2.33                    | 10.50      | 0.178                                 |
| 13         | 74.56     | 103.41      | 2.65                    | 4.16       | 0.836                                 |
| 14         | 63.12     | 103.31      | 2.54                    | 1.97       | 0.289                                 |
| 15         | 99.35     | 103.25      | 2.54                    | 2.95       | 0.466                                 |
| 16         | 85.09     | 103.15      | 2.49                    | 3.82       | 0.556                                 |

2.2 Method

Stress sensitivity means that when the net stress of the rock changes, the porosity of the rock changes, and these fractures in the rock will be close or open, changing the seepage ability of
the rock. We consider that the difference between the overburden and pore fluid pressure is the effective stress, and the confining pressure is used to simulate the overburden pressure in this experiment. The study applied 16 full diameter core samples of the conglomerate gas reservoir to test the stress sensitivity test according to China’s oil and gas industry standard SY/T 5358–2002 Formation Damage Evaluation by Flow Test. Dry nitrogen is the working fluid, and the pore pressure is kept lower than 0.3 MPa in this experiment. The displacement pressure is constant, and the effective stress is increased by enhancing the confining pressure. To simulate the conditions of the reservoir, the conventional experiment device was improved (Fig.2).

![Reservoir stress sensitivity test apparatus structure](image)

**Figure. 2.** Reservoir stress sensitivity test apparatus structure

3 Experimental Results

3.1 Characteristics of the stress sensitivity permeability

Fig.3 shows the relationships between permeability and effective stress, and Fig.4 shows the relationships between the normalized permeability and effective stress. Fig.3 and Fig.4 show that the core permeability decreases as the effective stress increases, explaining the strong stress sensitivity in the low-permeability conglomerate reservoir. The change in core permeability is larger at the beginning of the experiment, and then the permeability becomes smaller. Fig.3 and Fig.4 also show that the smaller the original permeability of the sample, the greater the decline of permeability, and the porosity decreases as the effective stress increases. According to the theory of porous media, the permeability or seepage ability of the rock could decline, which could be because some large pores in the primary seepage channel could be compressed, and some small throat could be closed completely.

![Relationships between permeability and effective stress for some samples](image)

**Figure. 3.** Relationships between permeability and effective stress for some samples
3.2 Stress sensitivity coefficient of empirical formula

The permeability stress sensitivity experience formula could be concluded by regression analysis of the data of the stress sensitivity experiment. Fig.5 presents the permeability and effective stress curves, and Table 2 lists the stress sensitivity test fitting data. Fig.5 and Table 2 show that there is a good index relationship between effective stress and permeability. The expression is as follows ($R^2 > 0.98$)

$$K = K_o \exp[-\alpha_i \Delta p],$$

where $K$ is the gas permeability ($10^{-3} \mu m^2$), $K_o$ is the initial gas permeability ($10^{-3} \mu m^2$), $\alpha_i$ is the stress sensitivity coefficient (MPa$^{-1}$), and $\Delta p$ is the differential pressure (MPa).

Because of the influence of diagenesis, different physical parameters in different rocks and different stress sensitivities in different effective stresses exist. Therefore, the sensitivity coefficient of a fitting experience formula in each rock differs. However, for the same block, geological structure background, and sedimentary environment the total trend of the coefficient is consistent. Given this, the permeability stress sensitivity in the conglomerate gas reservoir could be unified into equation (2).

$$K = K_o \exp[-\alpha_i (P_i - P)],$$

where $P_i$ is the initial reservoir pressure (MPa) and $P$ is the pressure (MPa).

The results of the core experiment show that the stress sensitivity coefficient is 0.057–0.173, and the average is 0.105. The reference value of this experience formula is in the same area. Using the stress sensitivity empirical formula, it can determine the gas well productivity equation and region open flow potential.
Table 2. Stress sensitivity test fitting data table

| Sample No. | Regression equation | Stress sensitivity coefficient/MPa⁻¹ | Correlation coefficient (R²) | Sample No. | Regression equation | Stress sensitivity coefficient/MPa⁻¹ | Correlation coefficient (R²) |
|------------|---------------------|--------------------------------------|-----------------------------|------------|---------------------|--------------------------------------|-----------------------------|
| 1          | \( y = 0.815 \exp\{-0.068x\} \) | 0.068 | 0.9990 | 9          | \( y = 0.174 \exp\{-0.108x\} \) | 0.108 | 0.9981 |
| 2          | \( y = 0.067 \exp\{-0.0131x\} \) | 0.131 | 0.9927 | 10         | \( y = 0.044 \exp\{-0.173x\} \) | 0.173 | 0.9999 |
| 3          | \( y = 0.261 \exp\{-0.107x\} \) | 0.107 | 0.9915 | 11         | \( y = 0.044 \exp\{-0.152x\} \) | 0.152 | 0.9905 |
| 4          | \( y = 0.699 \exp\{-0.070x\} \) | 0.070 | 0.9932 | 12         | \( y = 0.178 \exp\{-0.120x\} \) | 0.120 | 0.9895 |
| 5          | \( y = 0.094 \exp\{-0.124x\} \) | 0.124 | 0.9964 | 13         | \( y = 0.836 \exp\{-0.057x\} \) | 0.057 | 0.9990 |
| 6          | \( y = 0.275 \exp\{-0.099x\} \) | 0.099 | 0.9959 | 14         | \( y = 0.289 \exp\{-0.118x\} \) | 0.118 | 0.9939 |
| 7          | \( y = 0.991 \exp\{-0.077x\} \) | 0.077 | 0.9937 | 15         | \( y = 0.466 \exp\{-0.080x\} \) | 0.080 | 0.9919 |
| 8          | \( y = 0.178 \exp\{-0.134x\} \) | 0.134 | 0.9845 | 16         | \( y = 0.556 \exp\{-0.067x\} \) | 0.067 | 0.9909 |

Fig. 6 shows the relationship between the stress sensitivity coefficient and initial permeability. The stress sensitivity coefficient decreases as the initial permeability increases, showing that the greater the initial permeability of the rock sample, the smaller the stress sensitivity coefficient. Furthermore, there is a good correlation (\( R^2 = 0.8618 \)) in the relationship between the stress sensitivity coefficient and initial permeability that can be found from Fig.5. The fitting expression is

\[
\alpha_k = 0.0661 K_0^{-0.296}.
\]
According to the Darcy flow theory, the seepage equation is [13]

$$v = \frac{K}{\mu} \frac{dp}{dr},$$

where $r$ is the length (m), $v$ is the flow velocity (m/s), and $\mu$ is the gas viscosity (mPa·s).

Based on studies on the seepage theory in the low-permeability reservoir, the relationship between the effective stress and permeability accords with the exponential function (equation (2)). Combining equation (2) with equation (4), an equation uniting the stress sensitivity is deduced as

$$v = \frac{K_0 \exp[-\alpha_s (p_i - p)] dp}{\mu}.$$

Changing equation (5) into new deformation, we obtain

$$v = \frac{K_0 \exp[-\alpha_s (p_i - p)] dp}{\mu} = \frac{Q p_e Z T}{2 \pi r h p Z_e T_w},$$

where $Q$ is the production of the gas well (m$^3$/s), $h$ is the thickness of the reservoir (m), $p_e$ is the pressure under the standard state (MPa), $Z$ is the gas compressibility factor, $Z_e$ is the gas compressibility factor under the standard state, $T$ is the temperature of the reservoir (K), and $T_w$ is the temperature of the reservoir under the standard state (K).

If $f(p) = \frac{p \exp[-\alpha_s \pi (p_i - p)]}{\mu Z}$, substituting pseudo-pressure $m(p) = \int f(p) dp$, equation (6) could be simplified as

$$m(p_i) - m(p_w) = \frac{6.455 \times 10^{-4} Q T}{K h} \ln \frac{r_e}{r_w},$$

where $Q_w$ is the production under the standard state (m$^3$/d), $r_e$ is the radius of gas supply (m), $p_w$ is the bottom hole pressure (MPa), and $r_w$ is the radius of the shaft (m).

Equation (7) is the prediction model of the gas well in the low-permeability gas reservoir.
considering stress sensitivity. The calculation process can be simplified by calculating the pseudo-reduced function using numerical integration (Eq. 8). By considering the variation of the real gas PVT parameters in the gas flow process, the natural gas compressibility factor is calculated using the D–A–K relationship [14], and the gas viscosity is calculated using the Lee relationship [15].

\[
m(p) = \int_0^p f(p) \, dp = \sum_{i=1}^n \frac{1}{2} \left[ f(p_i) + f(p_{i-1}) \right] \times (p_i - p_{i-1})
\]

(8)

The productivity prediction model deduced in this study can analyze the effect of stress sensitivity on the production characteristics of the gas well. This study considers a low-permeable conglomerate gas reservoir, of 6 m high, and the initial permeability of the gas reservoir is approximately \(0.5 \times 10^{-3} \, \mu m^2\). The reservoir has a temperature of 365 K and a pressure of 30 MPa, the gas drainage radius is 600 m, and the wellbore radius is 0.1 m. Finally, the stress sensitivity coefficient can be obtained from the initial permeability based on equation (3).

4.1 Influences of stress sensitivity on the distributions of pressure and permeability

We analyze the damage caused by stress sensitivity by setting the gas well production as \(2 \times 10^4 \, m^3/d\). It can calculate the pressure and permeability in the formation under different initial permeability using the gas well production capacity model. Fig.7a shows that the formation pressure distribution curve is funnel-shaped during the process of drilling. Few curves overlap at the border, but all the curves appear differentiated near the bottom. The smaller the initial permeability, the more serious the stress pollution that is caused by stress sensitivity. Fig.7b shows that the distribution of the permeability curve is in the shape of permeability drop funnel. The pressure is constant in the basic border, and the smaller the effective stress, the weaker the effect of stress sensitivity. However, the effective stress is big near the bottom. The larger the stress sensitivity effect is, the faster the permeability declines. The smaller the initial permeability is, the greater the permeability declines. Therefore, the smaller the initial permeability, the more serious the stress pollution that is caused by permeability stress sensitivity.

Fig.8 presents the distribution of pressure and permeability in the formation under different gas well production in the same permeability gas reservoir. Fig. 8(a) shows that the pressure does not change much with the increase in production at the border. However, the pressure decreases rapidly with the increase in production near the bottom. The principal reason for this phenomenon is that the bigger the gas well production capacity is, the greater the need for the production pressure difference, and the larger the decrease in pressure. Fig.8 (b) shows that the bigger the decrease in formation permeability is, the greater the permeability of the formation near the bottom. The principal reason is that the gas well production capacity increases with the increase in the descend range of the bottom hole pressure, and the effective stress increases, finally increasing the descending range of permeability. The decrease in permeability will influence gas seepage, reducing the gas well drilling speed. Therefore, we should pay attention to control gas well production capacity in the production process and
avoid the formation of pressure and rapid permeability decline in the stress sensitivity of the low-permeability gas reservoir.

![Figure 8. Distribution of (a) pressure and (b) permeability in the formation under the different production of gas well](image)

**Figure. 8.** Distribution of (a) pressure and (b) permeability in the formation under the different production of gas well

4.2 Influences of stress sensitivity on the productivity of the gas well

Fig. 9 shows the IPR curves of the gas well that considers the influence of stress sensitivity. The figure shows that the failure of the stress increases gradually with the decrease in the bottom pressure. The stress sensitivity significantly influenced the production of the gas reservoir, which can be analyzed. The analysis of the calculation results shows that the open flow capacity that considers the influence of stress sensitivity was 52.99% less than that without considering stress sensitivity.

![Figure 9. Stress sensitivity influence on the IPR curves of a gas well](image)

**Figure. 9.** Stress sensitivity influence on the IPR curves of a gas well

The greatest concern for oil and gas producers is that the dynamic change of reservoir pore pressure and its effects on the production during the production process. To analyze the effects on production, define a coefficient $\beta$ in the expression as

$$\beta = \left(1 - \frac{Q_{\text{sc}}}{Q_{\text{sc}0}}\right) \times 100\% ,$$  \hspace{1cm} (9)

where $Q_{\text{sc}0}$ is the production without considering stress sensitivity (m$^3$/d).

The dynamic change in the reservoir pore pressure $\Delta p$ and $\beta$ could be obtained by calculation under different initial permeability (Fig. 10). The lower the initial permeability, the greater the stress sensitivity, and the bigger the $\beta$, increasing the decline of productivity. The original reservoir permeability is smaller, the stress sensitivity of the reservoir is greater, and the decline of gas well production is more rapid. Fig. 10 also shows that the stress sensitivity effect gradually increases with the increase in the production pressure difference, namely, the
descending range of productivity increases with the increase in $\beta$. To improve the gas well production, we tend to enlarge the difference in the production pressure that approach to production in the actual production, but the larger the difference in production pressure, the greater the stress sensitivity effect. Eventually, the gas well productivity could be affected by this, and the production of the gas well could be reduced. Therefore, a reasonable difference in production pressure should be selected, the appropriate bottom-flowing pressure should be considered, and the measurable formation pressure should be maintained in the stress sensitivity of a low-permeability gas reservoir during production.

Figure. 10. Relationships between the $\Delta p$ and $\beta$ under different initial permeability

5 Conclusions

(1) A strong stress sensitivity exists in low-permeability conglomerate gas reservoirs. Using the stress sensitivity test, the experience formula conforming to the index of relations could be obtained. The relationship between the original permeability in the reservoir and the stress sensitivity coefficient correlates with the power function. The stress sensitivity coefficient decreases with the increase in the original permeability in the reservoir.

(2) Based on the Darcy flow theory and original permeability in the reservoir as the standard point, the gas well productivity model of stress sensitivity could be presented, which can be used to investigate the influences of the stress sensitivity effect on gas well productivity.

(3) The distribution curves of the pressure and permeability in the reservoir are funnel-shaped. The pressure and permeability increase as the original permeability decreases and the gas well productivity increases. Obvious stress sensitivity exists in the low-permeability conglomerate gas reservoir during the progress of production, indicating that a reasonable difference in production pressure should be selected, the appropriate bottom-flowing pressure should be considered, and the measurable formation pressure should be maintained in the low-permeability gas reservoir.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References
[1] Fatt I, F.: Reduction in permeability with overburden pressure. Journal of Petroleum Technology 4(12), 16-16 (1952).

[2] Vairogs J, F.: Effect of rock stress on gas production from low-permeability reservoirs. Journal of Petroleum Technology 23(09): 1,161-1,167 (1971).

[3] Adams B H, F.: Stress-sensitive permeability in a high-permeability sandstone reservoir-the Kuparuk field. SPE California Regional Meeting. Society of Petroleum Engineers, 1983.

[4] Holt R M, F.: Petrophysics under stress. In 6th Nordic symposium on petrophysics, pp. 15-16. Trondheim, Norway (2001).

[5] Worthington P F, F.: A diagnostic approach to quantifying the stress sensitivity of permeability. Journal of Petroleum Science and Engineering 61(2-4), 49-57 (2008).

[6] Xiong Y, F.: Coupled geomechanical and reactive geochemical model for fluid and heat flow: application for enhanced geothermal reservoir. SPE Reservoir Characterization and Simulation Conference and Exhibition, pp. 16-18. Society of Petroleum Engineers, Abu Dhabi, UAE (2013).

[7] Dautriat J, F.: Stress-dependent directional permeabilities of two analog reservoir rocks: a prospective study on contribution of μ-tomography and pore network models. SPE Reservoir Evaluation and Engineering, pp. 297-310. (2009).

[8] Walsh J B, F.: Effect of pore pressure and confining pressure on fracture permeability. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Pergamon, pp.429-435 (1981).

[9] Rhett D W, F.: Effect of reservoir stress path on compressibility and permeability of sandstones. SPE annual technical conference and exhibition, pp. 4-7. Society of Petroleum Engineers, Washington, D.C (1982).

[10] Li N, F.: A study of laboratory methods of evaluating the stress sensitivity of fractured carbonate rocks. Natural Gas Industry 20, 30-33 (2000).

[11] Zhang H, F.: Deformation theory and stress sensitivity of tight sandstones reservoirs. Natural Gas Geoscience 5(5), 482-485 (2004).

[12] Jones Jr F O, F.: A laboratory study of the effects of confining pressure on fracture flow and storage capacity in carbonate rocks. Journal of Petroleum Technology 27(01), 21-27 (1975).

[13] Xiong J, F.: Analysis of the productivity equation of acid fracturing well in low-permeability gas reservoir with non-linear seepage. Journal of Northeast Petroleum University36(6), 49-53 (2012).

[14] Dranchuk P M, F.: Calculation of Z factors for natural gases using equations of state. Journal of Canadian Petroleum Technology 14(03), (1975).

[15] Lee A L, F.: The viscosity of natural gases. Journal of Petroleum Technology 18(08),
997-1,000 (1966).