Study on the impact of confining pressure on gas permeability of tight sandstone cores

Jianxiang Tong¹, Hengyang Wang¹, Yuyi Wang¹, Ya Zhang¹ and Xiaohe Huang¹*

¹ School of Petrochemical Engineering and Environment, Zhejiang Ocean University, Zhejiang, 316022, China
*Corresponding author’s e-mail: huangxh@zjou.edu.cn

Abstract: Taking the tight sandstone core of Shengli Oilfield as the experimental sample, this paper studies the permeability variation of the tight sandstone under different confining pressures. The experimental results show that when the pore pressure is constant, the measured gas permeability of core decreases with the increase of confining pressure. Power function is more reasonable to describe the influence of confining pressure on permeability of tight sandstone between power function and exponential function. Analyze the impact of confining pressure on gas permeability of tight sandstone cores by using permeability change rate coefficient D and coefficient S.

1. Introduction

China's natural gas demand has been in a period of rapid growth. If we don't want to over-import natural gas to relieve the pressure of insufficient natural gas, the exploitation of unconventional natural gas is becoming more and more urgent under the premise of conventional natural gas exploitation. Of all the unconventional natural gas, the production of tight sandstone gas reserves can be said to be the largest and most stable production. China's tight sandstone gas reserves are abundant, the technical recoverable reserves of about 9.2 trillion to 13.4 trillion cubic meters [1]. By 2019, China has already produced about 40 billion cubic meters tight sandstone gas annually, with 30 percent of the country's total natural gas production. The production of tight sandstone gas reserve is second only to the production of conventional natural gas reserve, which has become a very important source of natural gas supply in China.

Permeability is one of the most basic parameters of tight sandstone reservoirs and an important factor affecting gas well production [2]. The permeability obtained by conventional core analysis is usually the permeability without stress condition. Under reservoir conditions, the apparent volume and pore volume of the rock decrease due to the compaction of the upper rock, and the porous throat of the rock changes. Thus, the permeability under reservoir conditions is different from that at the ground without stress, and under the compaction of the upper rock the permeability of the reservoirs in different depths are different. Therefore, it is of great significance to study the change law of permeability of tight sandstone under different confining pressure.

2. Experimental materials and devices

2.1. Experimental materials

In this experiment, three tight sandstone cores taken under sealing conditions in Shengli Oilfield are used as experimental samples. The geometrical dimensions of the cores are shown in Table 1.
Table 1. Physical parameters of tight sandstone cores

| Core Number | S-1       | S-2       | S-3       |
|-------------|-----------|-----------|-----------|
| Length (mm) | 51.01     | 49.87     | 52.10     |
| Diameter (mm) | 24.89    | 24.95     | 24.91     |
| Porosity (%) | 13.05    | 14.49     | 15.01     |

2.2. Experimental equipment

The experiment was carried out at 20°C, using high-purity nitrogen as the experimental fluid. The core inlet pressure range is between 0.01 and 5MPa; the outlet pressure is atmospheric pressure. The experimental flowchart is shown in Figure 1.

2.3. Experimental method

1. The tight sandstone core is put into a one-centimeter-thick hose and loaded into the core gripper together with the hose. The confining pressure pump is used to apply uniform confining pressure to the holding ring.

2. The pore pressure is remained in 0.5MPa, confining pressure is 2MPa. Wait until the reading on the soap foam flowmeter fixed, record the inlet pressure and the gas volume flow. Gas permeability under the confining pressure is obtained by equation (1)\(^3\):

\[
K_g = \frac{2Q_0\mu L}{A(p_1-p_2)}
\]

Type: \(K_g\)——gas penetration, \(\times 10^{-3}\)μm\(^2\); \(p_0\)——atmospheric pressure, MPa; \(A\)——core area, cm\(^2\); \(\mu\)——viscosity of the gas, mPa·s; \(L\)——core length, cm; \(p_1, p_2\)——pressure of inlet and outlet, MPa.

3. Repeat the step (2) by increasing the confining pressure to 4MPa, 6MPa, 8MPa.

4. Repeat the step (2) and step (3) by increasing the pore pressure to 1.0MPa, 1.5MPa.

3. Experimental results and analysis

3.1. The results of the experiment

According to Figure 2, under the same confining pressure, the gas permeability increases with a decrease of pore pressure. With an increase pore pressure, a decrease molecular free path leads to lower gas permeability. In this process, the slip effect plays a major role.
Under the same pore pressure, the gas permeability decreases with an increase of confining pressure. With an increase confining pressure, microfractures are closed and pore volume are compressed, which lead to lower gas permeability.

3.2. Data fitting

The curves in Figure 2 are fitted with exponential functions and power functions, respectively, and the exponential function fit equation is as follows:

$$K_a = ae^{-bp_k}$$

The power function fits the following equation:

$$K_a = M p_k^{-n}$$

Among them: $K_a$ —— apparent permeability, mD; $p_k$ —— confining pressure, MPa; $a$, $b$, $M$, $N$ —— Quasi constant.

Table 2 and Table 3 give the fitting results and the correlation coefficient $R^2$ for gas permeability under different pore pressures using exponential and power functions, respectively. It is found that the correlation coefficient $R^2$ of the power function to the gas permeability is higher, indicating that the power function fits the measured value very well.

| Core Number | Pore pressure /MPa | a    | b   | $R^2$  |
|-------------|--------------------|------|-----|--------|
| S-1         | 0.5                | 0.0765 | 0.302 | 0.9708 |
|             | 1.0                | 0.0752 | 0.116 | 0.9528 |
|             | 1.5                | 0.0727 | 0.124 | 0.9832 |
|             | 0.5                | 0.0974 | 0.094 | 0.9201 |
| S-2         | 0.5                | 0.0952 | 0.107 | 0.9137 |
|             | 1.0                | 0.0952 | 0.119 | 0.9098 |
|             | 1.5                | 0.4204 | 0.069 | 0.8662 |
|             | 0.5                | 0.4088 | 0.080 | 0.8104 |
| S-3         | 0.5                | 0.3997 | 0.090 | 0.8138 |
|             | 1.0                | 0.3964 | 0.380 | 0.9820 |
|             | 1.5                | 0.3964 | 0.399 | 0.9884 |
|             | 0.5                | 0.0764 | 0.399 | 0.9884 |

| Core Number | Pore pressure /MPa | M    | n   | $R^2$  |
|-------------|--------------------|------|-----|--------|
| S-1         | 0.5                | 0.0630 | 0.279 | 0.9568 |
|             | 1.0                | 0.0502 | 0.279 | 0.9568 |
|             | 1.5                | 0.0983 | 0.358 | 0.9728 |
|             | 0.5                | 0.0828 | 0.339 | 0.9950 |
| S-2         | 0.5                | 0.0764 | 0.380 | 0.9820 |
|             | 1.0                | 0.0630 | 0.399 | 0.9984 |
|             | 1.5                | 0.0502 | 0.279 | 0.9568 |
|             | 0.5                | 0.0983 | 0.358 | 0.9728 |
| S-3         | 0.5                | 0.0731 | 0.264 | 0.9640 |
|             | 1.0                | 0.3123 | 0.266 | 0.9868 |
|             | 1.5                | 0.3123 | 0.266 | 0.9868 |
3.3. Evaluation of the effect of confining pressure on gas permeability
Analyze the change rule of gas permeability under different confining pressures by using permeability change rate coefficient D and coefficient S.

(1) The change rate of permeability D. The change rate of permeability is defined as the relative change in the permeability caused by the change in the confining pressure at constant pore pressure \[4\],

\[ D = \frac{K_{al} - K_{a1}}{K_{a1}} \]  \hspace{1cm} (4)

Among them: 
- \(D\) — gas-measured permeability;
- \(K_{a1}\) — initial permeability, mD;
- \(K_{al}\) — the permeability of the perimeter pressure change, mD.

This paper only considers the change rate of the permeability at the confining pressure in the range of 2 to 8MPa. The rate of change in the gas permeability of tight sandstone is shown in Table 4. The results show that the change rates of gas permeability are greater than 30% when the confining pressure is in the range of 2 to 8 MPa, indicating that the confining pressure has a big effect on gas permeability of tight sandstone.

Table 4. Rate of permeability change

| Core Number | Change rate of permeability D /% |
|-------------|---------------------------------|
| p=0.5MPa    | p=1.0MPa                        |
| p=1.5MPa    |                                 |
| S-1         | 47.34                           | 51.63                           | 53.20                           |
| S-2         | 45.51                           | 48.86                           | 52.59                           |
| S-3         | 33.88                           | 39.95                           | 43.52                           |

(2) S coefficient

Figure 2 shows that when the confining pressure is greater than 4.0MPa gas permeability is linear to the confining pressure. In order to make the results more obvious, the gas permeability is expressed as the ratio of the permeability measured at 4.0MPa confining pressure. The equation for this relationship is \[5\],

\[ K_a = K_{a0} \left( 1 - S \log \frac{P_a}{P_{a0}} \right)^{\frac{1}{S}} \]  \hspace{1cm} (5)

\[ S = \frac{1 - \left( \frac{K_a}{K_{a0}} \right)^{\frac{1}{S}}}{\log \frac{P_a}{P_{a0}}} \]  \hspace{1cm} (6)

Type:  
- \(K_{a0}\) — the permeability at the confining pressure of 4.0MPa, mD;
- \(S\) — the slope of the straight line. The S coefficient is the slope of the curve made by equation (5).

Table 5. S coefficient under different pore pressure

| Pore pressure /MPa | S coefficient |
|--------------------|---------------|
|                    | Core S-1      | Core S-2      | Core S-3      |
| 0.5                | 0.0261        | 0.0202        | 0.0102        |
| 1.0                | 0.0268        | 0.0213        | 0.0106        |
| 1.5                | 0.0284        | 0.0233        | 0.0122        |

According to equation (5), the greater the S coefficient value is, the greater the impact of the confining pressure is. Generally speaking, the lower the core permeability is, the greater the impact of the confining pressure is, that is the greater the value of S coefficient. Table 5 shows when the pore pressure is constant, the S coefficient of the core S-1 is the largest and the S coefficient value of the core S-3 is the smallest, indicating that the confining pressure has the greatest impact on the core S-1, followed by the core S-2, with minimal impact on core S-3\((K_{S-1}<K_{S-2}<K_{S-3})\). The correctness of the change law of gas permeability with confining pressure is verified.

4. Conclusions

(1) When the pore pressure is constant, the gas permeability of tight sandstone core decreases with the
increase of confining pressure, which is caused by the closing of micro-cracks and the decrease of micropores volume.

(2) Compared with the exponential function, the influence characteristics of the confining pressure on the permeability of tight sandstone are more in line with the distribution law of the power index function.

(3) The change rate of gas permeability at 2 to 8Mpa confining pressure is greater than 30%, indicating that the confining pressure on the permeability of tight sandstone has a great impact.

(4) The S coefficients is calculated, and the correctness of the law of change of gas penetration with circumference pressure is verified.

Acknowledgements
The work is supported by the College Students' Innovation Training Program of Zhejiang Ocean University.

References
[1] Zhang G.S., Zhao W.Z., Yang T., Guo B.C., Deng S.t.. (2012) The potential, distribution and future development status of tight sandstone gas resources in China. China Engineering Science, 14: 87-93
[2] Ran Y.X., Ye B., Cheng Z.R. (2018) Advances in the study of gas slip effects in tight rock media. Journal of Geodynamics, 24:498-504.
[3] Guo Y.X.(1991) Experimental study on the effect of perimeter pressure on the permeability of core gas. Journal of the University of Petroleum (Natural Sciences), 15: 47-52
[4] Duan Z.Q., Fan P., Huang Q.D., Liu Z.H., Bai Y.Q. (2017) Study on the mechanism of low seepage of tight sandstone gas slip-off flow. Broken Oil and Gas Fields, 24: 378-381
[5] Li K., Yang J.S., Chen W.Z., Wang W., Zhou Y., Yu T.H., Zheng Y.L.(2019) The evolution law of the permeability rate of tight coal rock under different stresses and pore pressures. Journal of Taiyuan Polytechnic University, 50: 265-271