Experimental Study on Stress Sensitivity Evaluation and Permeability Anisotropy of Shales in Songliao Basin

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Abstract. Shale oil and gas resources are abundant in Songliao Basin, and shale reservoirs tend to have certain permeability anisotropy with different pore or laminar structures in different directions, and there is no experimental analysis of shale anisotropy and reservoir sensitivity. To solve this problem, this paper tests the shale permeability by pulse decay method, obtains the variation curve of permeability and effective stress, and analyzes the experimental data. The experimental results of permeability show that the permeability of shale in Songliao basin is basically 10^{-4}mD, and the permeability parallel and perpendicular to the laminae shows strong anisotropy, and the permeability perpendicular to the laminae is about 3%-14% The permeability of different rock samples decreases exponentially with the increase of effective stress. It provides basic data support to ensure the development of shale oil in Songliao Basin.

1 Introduction

Songliao Basin is one of the most abundant onshore hydrocarbon-bearing basins in the world. In order to comply with the national dual carbon policy [1-4], various basic studies on shales in the Songliao Basin, such as basic mechanical properties and anisotropy of strength characteristics, have been carried out. Since shales contain a certain amount of clay minerals, tight oil reservoirs are highly susceptible to the influence of foreign working fluids during the construction process, resulting in strong differences in their physicochemical properties compared with conventional sandstones, especially in terms of reservoir sensitivity and anisotropy associated with horizontal well operations. In order to solve the practical problems of shale oil and gas development, it is necessary to analytics and evaluate the experimental results [5-8]. In this paper, the permeability test was conducted by pulse decay method, and the variation curves of permeability with effective stress were obtained for several groups of vertical and horizontal cores under different peritectic and injection pressures, and the experimental data were calculated and analytics[9]. The scientific research work is guided.

2 Experimental

2.1 Experimental sample preparation

The shale sample comes from the Songliao Basin, and its core depth is 2491m-2506.43m, which belongs to the shale type shale with more developed phyllite. According to the whole rock mineral quantitative X-ray diffraction experiment to obtain the mineral composition of the sample, its total clay content is between 42.2-62.8%, because the sampling depth is greater than 1650m, montmorillonite basically disappears, which contains Quartz, calcite, feldspar and other detrital minerals and authigenic minerals, quartz and feldspar such brittle minerals content is usually between 13.1-21.2%, easy to cause reservoir water-sensitive damage, in the drilling and completion of wells and fracturing construction should take appropriate measures. A total of six rock samples of 16 cm in length were taken and numbered 1-6, cut and polished by a wireline cutter into standard rock column samples of 25 mm ± 0.5 mm in diameter and 48 mm in length, which were installed in a rubber sleeve [7] with the appropriate dimensions during the experimental process, and the samples before the experiments (Figure 1).

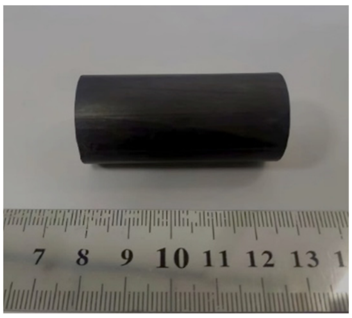

Figure 1. Vertical laminated rock sample

2.2 Permeability testing principle

The shale permeability in Songliao basin is low and the core is relatively dense, so the conventional steady-state method of measuring permeability has a long test time and the experimental changes are not obvious, so the

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pressure pulse decay method is used to measure it. The main principle is to use the pressure difference decay between the upstream and downstream of the ideal gas passing through the rock sample combined with the flow rate through the sample for permeability measurement, and many scholars have subsequently improved this method, while this paper adopts the formula of the pressure pulse decay method for cubic shale permeability measurement by Pan[7] in 2015, the derivation demonstrates that if the upstream and downstream gas cylinders are the same volume and the gas is ideal, Eqs.(1) and (2) can be used to calculate permeability from the pressure decay measurement for any pressure difference. [7] and the detailed process of derivation is shown in the references, and the pressure decay curve can be modelled as:

$$\frac{\left(P_u - P_d\right)}{\left(P_{u,0} - P_{d,0}\right)} = e^{-\alpha t} \quad (1)$$

Where : P_u-P_d -the pressure difference between the upstream and downstream cylinders, MPa;

$P_{u,0}$-$P_{d,0}$ -the pressure difference between the upstream and downstream cylinders at the initial stage, MPa; and α is obtained from the following equation [7]:

$$\alpha = \frac{k}{\mu\beta L^2} V_R \left(\frac{1}{V_u} + \frac{1}{V_d}\right) \quad (2)$$

Where: α – the pressure decay time constant;

A-the cross sectional area of the sample, m^2;

k-permeability, m^2;

L-the length of the sample, m;

μ-gas viscosity, pa·s;

$P_{u,0}$-the initial upstream cylinder pressure, MPa;

$P_{d,0}$-the initial downstream cylinder pressure, MPa;

V_u-the upstream cylinder volume, m^3;

V_d-the downstream cylinder volume,m^3.

The equation for the permeability considering the gas slip effect is [7].

$$k_g = k_a \left(1 + \frac{b}{P_g}\right) \quad (3)$$

Where: k_g-the gas measured effective permeability, μm^2;

k_a-the absolute (equivalent liquid) permeability, μm^2;

b-constant depending on the nature of the gas and the pore structure of the rock, slip factor;

Pg-the average pressure of the core inlet and outlet, Mpa.

The shale formation seam structure is treated as an ideal sheet fracture model[8] (Figure 2).

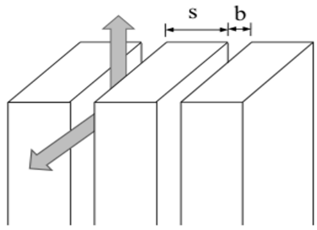

Figure.2 Model of lamellar cracks

Then the shale laminar porosity, fracture spacing s, fracture width b and permeability satisfy the following equation [8]:

$$k = \frac{b^3}{12s} = \frac{s^2\phi_f^3}{12} \quad (4)$$

Define the fracture compression coefficient equation:

$$C_f = -\frac{1}{\phi_f}\frac{\partial \phi_f}{\partial \sigma_e} \quad (5)$$

Deriving (4) for the effective stress and bringing (5) into it yields shale permeability with effective stress and fracture compression coefficient satisfying:

$$\frac{\partial k}{\partial \sigma_e} = -3C_f k \quad (6)$$

Integration of (6) yields [8]:

$$k = k_0 e^{-3C_f\left(\sigma_e - \sigma_{e0}\right)} \quad (7)$$

Considering the effect of gas slippage, equation (3) is introduced, which finally yields.

$$k = k_0 \left(1 + \frac{b}{P_g}\right) e^{-3C_f\left(\sigma_e - \sigma_{e0}\right)} \quad (8)$$

2.3Permeability testing Instruments

The present method of measuring gas flow in dense rock formations by Brace [6] is used to precisely control the pressure and volume using an ISCO gas injection pump and an enclosing pressure pump. The gas in the upstream gas tank flows through the sample to the downstream gas tank. The pressures in the upstream and downstream gas tanks are monitored and used for permeability calculations [7], with the following instrument schematic (Figure 3).

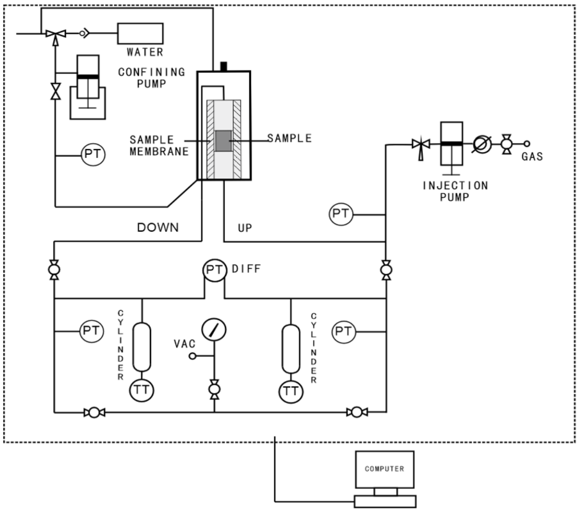

Figure 3. Experimental schematic diagram of permeability testing

The shale samples are subjected to permeability experiments one by one, and the experiments are carried out at 25°C. The surrounding pressure is increased to 5 MPa for compaction and maintained for a period of time before starting the experiments, and to ensure the integrity of the core, the process of applying the surrounding pressure and injection pressure should be loaded in a step-by-step manner, and the nitrogen injection pressure used in the experiments is divided into four groups, the first group is 1 MPa, the second group is 1.5 MPa, the third group is 2 MPa, and the fourth group is 2.5 MPa. The initial surrounding pressure of each group is higher than the injection pressure by 1 MPa, and the pressure is increased by 1 MPa each time.

3 Analysis of test results

3.1 Evaluation of Shale Stress Sensitivity

The experimental results show that the permeability of shales is at the level of 10^{-4} mD, and the permeability of cores in each horizontal direction is approximately the same, while in the vertical direction the permeability reaches the level of 10^{-5} mD (Table 1).The permeability in the parallel and vertical laminae directions shows strong anisotropy, and the permeability perpendicular to the laminae is about 3%-14% of the permeability parallel to the laminae, which is mainly due to the special shale structure, and the pore connectivity is of high quality and there are more large pore throats, resulting in a larger permeability in the horizontal laminae direction.

Table 1. Permeability test results of some core samples

Core NO.	Sampling direction	Length /mm	Diameter /mm	Absolute permeability /10^{-4}mD
4.1	Vertical	46.94	24.75	0.25
4.2	Horizontal	47.34	24.80	1.72
6.1	Vertical	47.65	24.78	0.36
6.3	Horizontal	48.74	24.84	2.73

The data were solved by planning, and the low permeability of the vertical laminated samples and the long experimental time resulted in fewer experimental data points. A comparison of the experimental results of horizontal and vertical rock samples (Figure 4 and 5), and the absolute permeability of shale is obtained to decrease exponentially with increasing effective stress.

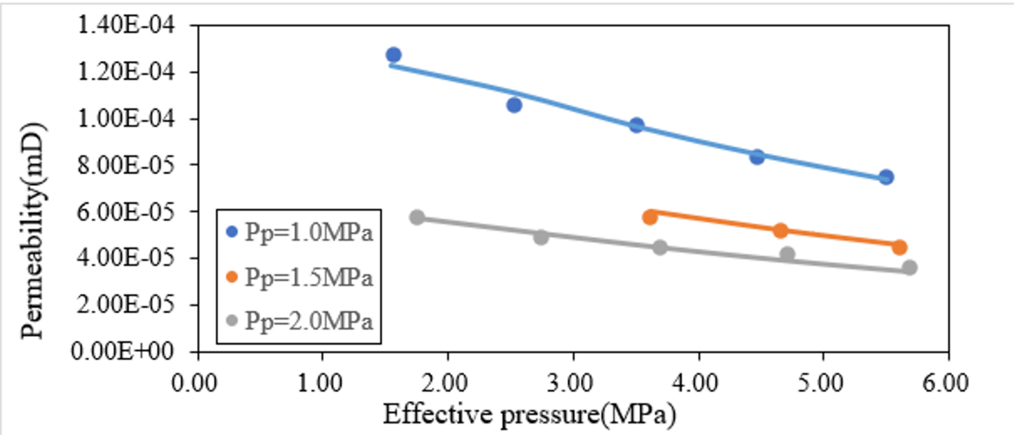

Figure.4 Sample 4.1 fitted/experimental permeability variation curve with effective stress

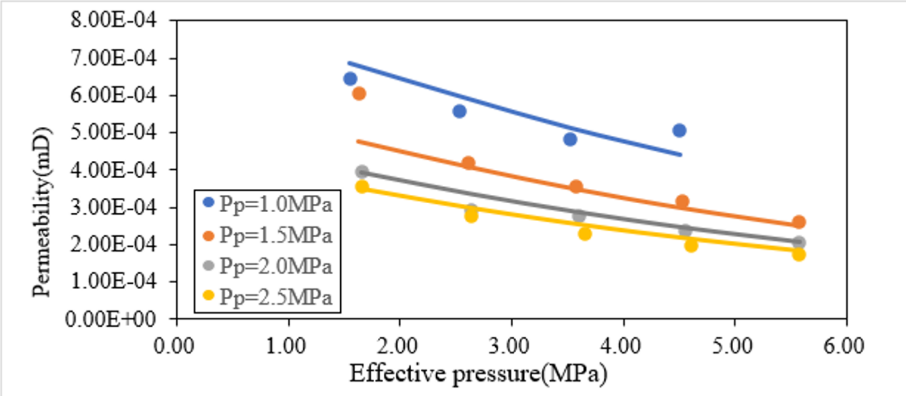

Figure.5 Sample 4.2 fitted/experimental permeability variation curve with effective stress

3.2 Permeability anisotropy analysis

The shale permeability stress sensitivity index β follows the same exponential form [8]:

$$k = k_0 e^{-\beta(\sigma_e - \sigma_{e0})} \tag{9}$$

It can be made $\beta=3C_f$, the experimentally measured data brought into the formula can be calculated with the increase of effective stress, the shale stress sensitivity also decreases, the horizontal direction stress sensitivity is greater than the vertical direction stress sensitivity specific changes (Table 2).

Table.2 Comparison of changes in stress sensitivity coefficients of horizontal and vertical rock samples in the same group

Core NO.	Sampling direction	β	Core NO.	Sampling direction	β
4.1	Vertical	0.165 0.127 0.117 0.109	4.2	Horizontal	0.305 0.187 0.181 0.171

For the shale permeability vertical and horizontal permeability tests, because of its anisotropy, k_0, C_f are not equal in both directions, then under the anisotropic condition, the vertical and horizontal permeability can be expressed as k_v and k_h (Table 3) ,which can be derived after the joint derivation [8]:

$$\begin{aligned} k_v &= k_{v0} e^{-3C_{fh}(\sigma_{eh} - \sigma_{eh0})} \\ k_h &= k_{h0} e^{-3C_{fv}(\sigma_{ev} - \sigma_{ev0})} \end{aligned} \tag{10}$$

Table.3 Permeability of horizontal and vertical rock samples under different effective stresses

Core NO.	Sampling direction	k_v /10^{-5}mD	Core NO.	Sampling direction	k_h /10^{-4}mD
4.1	Vertical	7.58 4.52 3.63	4.2	Horizontal	6.42 2.58 2.02

Defining the degree of shale permeability anisotropy [8] as A_r, since the effective rate of stress change for each group of vertical and horizontal rock samples in the experiments of this paper Δσ is almost equal and approximately equal to 1, the ratio of the two can be simplified as:

$$A_r = \frac{k_h}{k_v} = \frac{k_{h0} e^{-3C_{fv}(\sigma_{ev} - \sigma_{ev0})}}{k_{v0} e^{-3C_{fh}(\sigma_{eh} - \sigma_{eh0})}} = \frac{k_{h0}}{k_{v0}} e^{-3(C_{fv} - C_{fh})} \tag{11}$$

The experimentally obtained data such as C_{fh}, C_{fv}, k_{v0}, k_{h0}, etc. were brought into it, and the experimental data of rock samples 4.1 and 4.2 were calculated to obtain the average A_r=6.58, which was used to evaluate the magnitude of permeability anisotropy. Ar indicates the degree of permeability anisotropy[9], Ar=0 indicates isotropic permeability, Ar=0~0.3 indicates weak permeability anisotropy, Ar=0.3~0.7 indicates strong permeability anisotropy, Ar=0.7~1 indicates strong permeability anisotropy, and Ar>1 indicates super strong permeability anisotropy.

4 Conclusion

(1) The permeability of shales in the Songliao Basin is around 10^{-4} mD in the horizontal direction, while the permeability in the vertical direction is around 10^{-5} mD. The permeability in the horizontal and vertical directions shows a strong anisotropy, and the vertical shale permeability is between 3%-14% of the horizontal shale permeability.

(2) The bedding joints have a positive effect on the horizontal permeability of the shale, and there is a relatively weaker permeability stress sensitivity in the vertical direction, and the permeability stress sensitivity is relatively stronger in the parallel laminated direction. The anisotropy is derived from the corresponding formula, According to the value of Ar falls within the super-strong anisotropy range, it can be seen that the cores in this study have strong anisotropy.

(3) The permeability of different rock samples are exponentially decreasing with increasing effect force, and the production pressure difference should be controlled in the actual production process, otherwise it will damage the reservoir permeability and lead to a decrease in production capacity.

Acknowledgements

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