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Experimental study on the influence of slickwater on shale permeability

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Abstract. There are two diametrically opposite views of the influence of slickwater on shale permeability among scholars at home and abroad. We used the shale outcrops rock samples from the Lower Silurian Longmaxi Formation in Sichuan Basin. The permeability of these dry samples before and after immersion in different solution systems were tested by pulse attenuation method. The experimental results show that the impregnation of different slickwater components and standard salt solution can promote the increase of the permeability of shale samples. The stress sensitivity of shale samples after liquid immersion is medium weak to weak. The sample stress sensitivity is weak after soaked by the synergist solution and Drag reducing agent solution, and the sensitivity of the sample stress is medium weak after immersed by the standard saline solution, defoamer solution and antishwelling solution; The K_i/K_0 of the shale sample after liquid immersion on σ_i/σ_0 is consistent with the exponential stress sensitive evaluation model. With the increase of soaking time, the increase of sample permeability increases first and then decreases.

1. Introduction

There are two diametrically opposite views of the influence of slickwater on shale permeability among scholars at home and abroad. Most of the scholars believe that one of the main reasons leading to the decrease of reservoir permeability is that slickwater retention reservoirs cause clay mineral expansion^[1]. At the same time, due to the small diameter of shale pores, the capillary effect is large, which usually cause serious water lock damage and reduced reservoir permeability^[2], Rimassa et al.(2011) considered that the polymer residue in the slickwater would clog the pores, reduce the effective length of the crack and reduce the gas well production characteristics^[3]. However, Davis B. (2011) proposed the opposite view: both the shale matrix pores and throat size are very small, can not provide the movement of clay particles migration channels, the degree of damage to reservoir from the slickwater is not increase with the clay mineral content^[4]. Liang L et al. (2015) found that hydration stress have a great influence on the increment of shale intensity factor, which is easy to cause shale crack propagation. There are many organic matter in the shale matrix, so that the shale matrix is spotted wet, that is part of the lipophilic, part of the hydrophilic, so the water lock effect is not obvious^[5]. Meanwhile, the intensity factor decreases with the wetting angle, the smaller of the wetting angle is, the larger of the stress intensity factor, the stress concentration of the crack tip is weakened, and the effect on the shale crack propagation is more significant. The larger capillary force can push the slippage into the matrix, reducing the slickwater saturation of contaminated area, thereby



improving the production of gas well^[6]. Although the slickwater contains a small amount of high molecular polymer and additives (content less than 1%), these polymers have less impact on the decrease of gas relative permeability, a greater impact to the decrease of water relative permeability^[7].

In view of the effect of slickwater on the influence of shale permeability, using shale samples collected from Longmaxi Formation, we tested the permeability of shale sample before and after slickwater immersion by pulse attenuation method. Stress-sensitive evaluation method was used to analyze the effect of slickwater on the permeability of shale sample, and the mechanism of slickwater on shale permeability is further discussed.

2. Effects of Slickwater on Shale Permeability

2.1. Experimental Solution

The standard saline solution and four single-component solutions were used to compare the effects on shale permeability with the slickwater of the Fuling shale gas field XX well. The formula for sliding water solution is $\text{CaCl}_2: \text{MgCl}_2: \text{H}_2\text{O} = 175\text{g}: 15\text{g}: 10\text{g}: 1\text{L}$. The formula for Slickwater solution is 0.1% drag reducing agent + 0.3% anti-swelling agent + 0.1% synergist + 0.02% Defoamer. The formula for four single-component solutions is 0.1% Drag reducing agent, 0.3% Antiswellin, 0.1% Synergist and 0.02% Defoamer.

2.2. Experimental Samples

The shale outcrops rock samples were tested, which were selected from the Longmaxi Formation in Sichuan Basin, in accordance with industry standards (SY / T5336-2006 sample analysis method), drilling the rock sample of 25×50mm, drying to constant weight at 60°C conditions (a great change in drying time, generally more than 2 days), cooling into the dryer, until the temperature go to the room temperature, the sample sizes and basic physical properties were tested. The physical properties of the sample are shown in Table 1, the porosity distribution ranged from 1.70% to 2.47%, with an average of 2.22%. Permeability distribution between $(0.0016\sim 0.0026)\times 10^{-3}\text{um}^2$, the average value of $0.0022\times 10^{-3}\text{um}^2$.

Table 1. The date of the sample sizes and basic physical properties

Sample	diameter(cm)	length(cm)	porosity(%)	permeability($\times 10^{-3}\text{um}^2$)
1	2.49	4.02	1.70	0.0016
2	2.51	4.02	1.98	0.0018
3	2.50	3.98	2.21	0.0020
4	2.48	4.01	2.26	0.0022
5	2.47	3.97	2.25	0.0022
6	2.50	4.02	2.45	0.0026
7	2.51	4.00	2.45	0.0026
8	2.49	3.97	2.47	0.0026

2.3. Permeability Test Method of Transient Pressure Pulse

Permeability test method of Transient pressure pulse is based on the unsteady one-dimensional seepage theory. The calculation of the pressure into the mathematical model of the sample at both ends of the pressure and the impact factor data, eventually gain the permeability of test sample^[8]. In the process of pulse attenuation, due to the action of the pressure pulse, resulting in a decrease in the concentration of the system, the gas diffuses from the high concentration end to the low concentration side. The mathematical model of the pulse attenuation is based on the one-dimensional diffusion model of the gas, which takes the resulting function of the pressure Darcy formula^[9].

2.4. Evaluation Index of Reservoir Stress Sensitivity

The stress of the reservoir changes, resulting in rock deformation, which leads to changes in

permeability and thus affect the stress-sensitive of reservoir. The change of reservoir permeability is due to the change of effective stress. Therefore, the study of reservoir stress sensitivity is mainly to study the relationship between permeability and effective stress^[10]. The stress sensitive coefficient S_s is the evaluation index of stress sensitivity, and its formula is^[11]:

$$S_s = (1 - K_i^{1/3} \cdot K_0^{-1/3}) \cdot \lg(\sigma_i \cdot \sigma_0^{-1}) \quad (1)$$

Formula: K_0 —Permeability corresponding to the initial effective stress σ_0 , $\times 10^{-3} \mu\text{m}^2$.

S_s —Stress sensitivity coefficient.

3. Analysis of Experimental Results

3.1. Effects of Slickwater Components on Shale Permeability

The permeability of the shale is measured before and after immersion in 5 different solution systems in one day. The results are shown in Table 2, showing that 5 different solution systems have improved the permeability of the shale samples. Among them, the standard saline solution has the highest degree of impact on the sample permeability, followed by the Defoamer solution, the Drag reducing agent solution, the Antiswelling solution and the Synergist solution have little effect on the sample permeability.

Table 2. Effects of slickwater components on shale permeability

Sample number	Solution systems	Permeability before immersion ($\times 10^{-3} \mu\text{m}^2$)	Permeability after immersion ($\times 10^{-3} \mu\text{m}^2$)	Increased proportion (%)
1	Standard saline solution	0.0016	0.00261	63.13
2	Synergist solution	0.0018	0.00246	36.67
3	Defoamer solution	0.0022	0.00335	52.27
4	Antiswelling solution	0.0024	0.00329	37.08
5	Drag reducing agent solution	0.0023	0.00317	37.83

3.2. Effects of Slickwater Components on Stress Sensitivity of Shale Permeability

Curve of the gas stress sensitivity was shown in Figure 1, and the experimental results of the stress sensitivity was shown in Table 3. The permeability of the shale decreases rapidly with the increase of the effective stress, The stress sensitivity of shale sample after liquid immersion is medium weak to weak. Compared with the sample stress sensitivity is weak after the impregnation of synergist solution and Drag reducing agent solution, the sensitivity of the sample stress is medium weak after immersed by the Standard saline solution, Defoamer solution and Antiswelling solution.

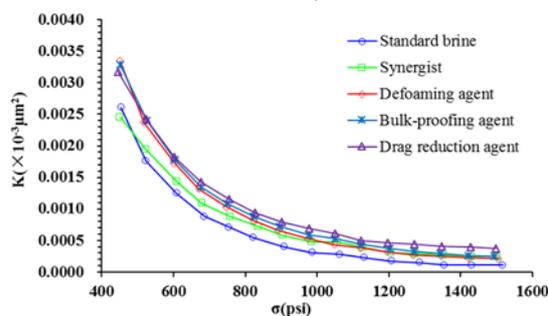


Figure 1. Relation curves between K and σ

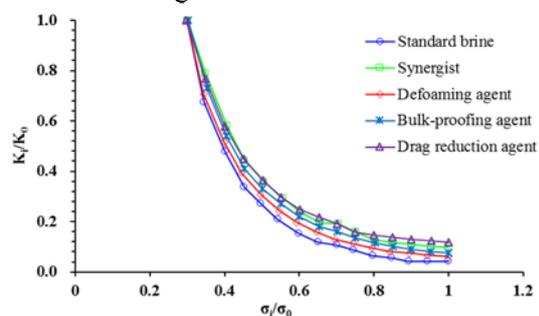


Figure 2. Relation curves between K_i/K_0 and σ_i/σ_0

To facilitate comparison, the permeability and effective stress of the rock sample shall be carried out dimensionless respectively, draw the curve of the relationship between the K_i/K_0 and σ_i/σ_0 as shown in Figure 2. It can be seen that in 5 different solution systems, the dimensionless permeability of the shale sample decreases rapidly with the increase of the dimensionless effective stress. The parameter b,

which is characterized by the sensitivity and intensity of the exponential stress sensitivity evaluation model, is mainly distributed between 3.037 and 4.625. Among them, the fastest and largest decline of the dimensionless permeability is the sample which is soaked by Standard salt water and Defoamer solution. The slower and smaller decrease of the dimensionless permeability is the sample which is soaked by the Defoamer solution and the Antiswelling solution. The slowest and smallest decrease of the dimensionless permeability is the sample which is soaked by synergist solution and Drag reducing agent solution.

Table 3. Experimental results of stress sensitivity evaluation

Solution	Confining pressure (psi)	Permeability ($\times 10^{-3} \mu\text{m}^2$)	S_s	Experimental results
Standard salt water	454.286	0.00261	0.341	Medium weak
	1517.14	0.00011		
Synergist solution	450.867	0.00246	0.281	weak
	1500	0.00024		
Defoamer solution	450.867	0.00335	0.478	Medium weak
	1505.78	0.00021		
Antiswelling solution	450.867	0.00329	0.301	Medium weak
	1494.22	0.00025		
Drag reducing agent solution	445.087	0.00317	0.269	weak
	1497.11	0.00037		

Table 4. Regression results between K_i/K_0 and σ_i/σ_0

Solution	Regression ship between K_i/K_0 and σ_i/σ_0	Parameter a	Parameter b	R^2
Standard salt water	$K_i/K_0 = 2.9175e^{-4.625 \cdot \sigma_i/\sigma_0}$	2.9175	4.625	0.9703
Synergist solution	$K_i/K_0 = 2.1343e^{-3.351 \cdot \sigma_i/\sigma_0}$	2.1343	3.351	0.9604
Defoamer solution	$K_i/K_0 = 2.5175e^{-4.051 \cdot \sigma_i/\sigma_0}$	2.5175	4.051	0.9771
Antiswelling solution	$K_i/K_0 = 2.3136e^{-3.677 \cdot \sigma_i/\sigma_0}$	2.3136	3.677	0.9752
Drag reducing agent solution	$K_i/K_0 = 1.8486e^{-3.037 \cdot \sigma_i/\sigma_0}$	1.8486	3.037	0.9432

3.3. Effects of Soaking Time on Shale Permeability

Test the shale sample permeability soaked by 3 different solution with different time, and draw the relationship curve between dimensionless permeability (K_i/K_0) and soaking time shown in Figure 3. With the increase of soaking time, the sample permeability increase first and then decrease. The effect of three different solutions on sample permeability in one day is basically the same. But the inflection point appeared on the tenth day. In view of the effect of promoting sample permeability, slickwater is the best, followed by standards saline solution, distilled water is the worst.

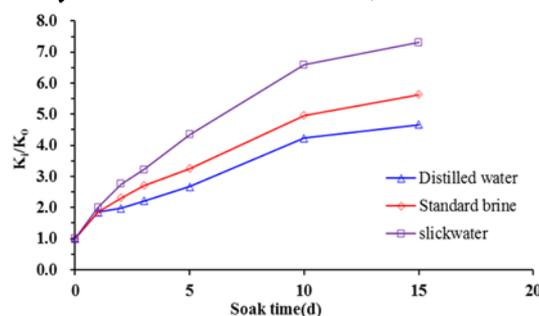


Figure 3. Relation curves between K_i/K_0 and soak time

4. Conclusions

(1) Liquid immersion can promote increase the permeability of the shale sample. Among them, the

maximum increase in permeability is the sample soaked by the standard salt solution, the sample soaked by Defoamer solution followed, and the sample soaked by Synergist solution, Antiswelling solution and Drag reducing agent solution are minimum.

(2)The stress sensitivity of shale sample after liquid immersion is weak to weaker. Compared with the sample stress sensitivity is weak after the impregnation of synergist solution and Drag reducing agent solution, the sensitivity of the sample stress is medium weak after immersed by the Standard saline solution, Defoamer solution and Antiswelling solution.

(3)The relationship between the dimensionless permeability K_i/K_0 and the dimensionless effective stress σ_i/σ_0 of the soaked shale sample conforms to the exponential stress sensitivity evaluation model. Among them, the fastest and largest decline of the dimensionless permeability is the sample soaked by standard salt water and Defoamer solution. The slower and smaller decrease of the dimensionless permeability is the sample soaked by the Defoamer solution and the Antiswelling solution. The slowest and smallest decrease of the dimensionless permeability is the sample soaked by synergist solution and Drag reducing agent solution.

(4)With the increase of soaking time, the rate of increase of the sample permeability increase first and then decrease. The effect of three different solutions on sample permeability in one day is basically the same. But the inflection point of the rate of increase of the sample permeability appeared on the tenth day.

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