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RESEARCH PAPER

Quantitative characterization of micro forces in shale hydration and field applications

KANG Yili[1], YANG Bin[1,*], LI Xiangchen[1], YANG Jian[2], YOU Lijun[1], CHEN Qiang[1]

1. State Key Laboratory of Oil & Gas Reservoir Geology and Exploitation in Southwest Petroleum University, Chengdu 610500, China;
2. Engineering Technology Research Institute of CNPC Southwest Oil & Gas Field Company, Guanghan 618300, China

Abstract: Shales (illite was the dominant clay mineral) of Silurian Longmaxi Formation in Sichuan Basin and Triassic Yanchang Formation in Ordos Basin were taken as subjects to examine the mechanisms of shale-water interaction, quantitative characterization of hydration force and potential field applications based on micro forces analyses. Mica sheet with composition and property very similar to illite was tested for micro forces between the crystal layers. In electrolyte solution, micro forces between mica-solution-mica system include DLVO (Derjaguin-Landau-Verwey-Overbeek) force and hydration force; when the electrolyte concentration was low, the tested curve agreed with the theoretical DLVO curve; when the electrolyte concentration was higher than the critical value and the distance between mica sheets was less than 5 nm, the tested curve deviated from the DLVO curve completely, and the hydration force became dominant. Quantitative analysis indicated that the hydration force decayed in a rapid double-exponential type with the growth of distance. Field applications indicate that strict control of water invasion and reducing the strength of hydration force are the keys in designing collapse-preventing drilling fluids; meanwhile, during the shut-in period of shale gas wells, shale-water interaction can induce and extend micro-cracks, further improving the stimulation effect of shale reservoirs.

Key words: shale; hydration force; illite; wellbore collapse; well shut-in

Introduction

Shale hydration includes micro chemical-physical interactions between rocks and fluids, in which the dominant micro forces belong to surface forces, including DLVO (Derjaguin-Landau-Verwey-Overbeek) and non-DLVO forces[1–3]. The DLVO force consists of Van der Waals force and double-layer repulsive force. The non-DLVO force mainly indicates the short range solvation force, and when the solvent is water, it refers to the repelling hydration force[4].

The core of clay mineral hydration is shale hydration, and traditional research on hydration mechanism mainly focused on realizing the control of shale hydration and drilling fluid properties through changing the concentration and type of electrolyte to adjust the surface electric potential and double layer thickness of clay mineral[2]. For shale with mainly expansive clay minerals such as smectite and illite-smectite mixed layer, DLVO theory has worked well in guiding the analysis of shale hydration mechanisms and inhibition optimization of drilling fluid[5–6], while the effects of hydration force are usually ignored. For hard-brittle shale with mainly non-expansive clay minerals (illite etc), for example black shale, however, DLVO theory can not offer persuasive explanations to its differences in swelling degree, hydration stress, water uptake from expansive shale, while the hydration force mechanism can provide reasonable explanations to the hydration behavior of hard –brittle shale[1,7]. Israelachvili et al.[4,8] have accomplished some pioneering works in the formation mechanism, measurement and application of hydration force, and pointed out that this force had the characteristics of short range forces, high intensity but declining sharply with the increase of distance.

Field practice shows that wellbore instability in shale reservoir (hereafter referred to as shale) formation had the typical features of hard-brittle shale hydration failure[9–10]. Therefore, taking the shale samples from the Silurian Longmaxi Formation in Sichuan Basin and the Triassic Yanchang Formation in Ordos Basin as example, this study has analyzed hydration mechanisms of shale from the micro-force perspective, investigated the quantitative characterization of hydration force, and combining with results of macro rock mechanics tests, looked into the function of hydration force in the failure of shale, and analyzed field issues by using hydration characteristics.

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*** Corresponding author.** E-mail: cwct2012yb@sina.com
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1. Micro forces in shale hydration

Shale hydration is actually the intercrystalline hydration of clay minerals, which is mainly affected by Van der Waals force, double-layer repulsive force and hydration force. Clay minerals have layer structure with negative charge on the layer surface, so the interaction between crystal layers can be simplified as the interaction of two charged parallel plates[3]:

$$W = W_{\mathrm{V}} + W_{\mathrm{DLR}} + W_{\mathrm{HY}} \tag{1}$$

where the Van der Waals interaction energy:

$$W_{\mathrm{V}} = -\frac{A}{12\pi D^2} \tag{2}$$

Assuming that the intercrystalline charge of every layer is equal and constant, the double-layer interaction energy can be written as:

$$W_{\mathrm{DLR}} = (\kappa / 2\pi) Z \mathrm{e}^{-\kappa D} \tag{3}$$

where $$Z = 64\pi\varepsilon \left(\frac{k_{\mathrm{B}}T}{e}\right)^2 \tanh^2\left(\frac{ze\varphi_0}{4k_{\mathrm{B}}T}\right)$$

$$\kappa = \left(2n_{\mathrm{b}}e^2 / \varepsilon k_{\mathrm{B}}T\right)^{0.5}$$

Both the Van der Waals force and double-layer repulsive force are long range forces. The Van der Waals force exists in all surfaces and is insensitive to pH value and concentration of water phase electrolyte solution, while the double-layer repulsive force depends strongly on surface charge, concentration and pH value of electrolyte, et al. The combined effect of the two forces can be quantitatively characterized with DLVO theory. However, when the distance between surfaces is small enough, the DLVO theory will deviate from the experimental data. One reason is that both Van der Waals and double-layer repulsive forces deviate from the continuum medium hypothesis, and another reason is that the non-DLVO force, the short range repulsive interaction of hydration force, becoming more dominant gradually[3,8]. Due to the complex origin of hydration force, a semi-empirical model is provided to describe the hydration interaction energy[11–12]:

$$W_{\mathrm{HY}} = A_1 \mathrm{e}^{-\frac{D}{\lambda_1}} + A_2 \mathrm{e}^{-\frac{D}{\lambda_2}} \tag{4}$$

In equation 4, the first term from the right side is the primary hydration interaction energy, related to the water molecular layer near the surface or the adsorption enthalpy of the hydrated cation, and the second term is the structure hydration energy which comes from the solvation entropy in a limited space.

2. Samples

This study took shale of the Silurian Longmaxi Formation in Sichuan Basin and the Triassic Yanchang Formation in Ordos Basin as objects. X-ray diffraction analysis shows that both the Longmaxi and Yanchang Formation shale have features of high contents of brittle minerals and clay minerals, in which the clay minerals mainly consist of non-expansive illite, chlorite, kaolinite, and a small percentage of 5%–10% of illite/smectite mixed layers (Table 1). In this study, the illite has been taken as the representative clay mineral to analyze the micro forces between crystal layers during shale hydration.

We took mica instead of illite to analyze the micro forces between the crystal layers in electrolyte solution. Primarily because mica (used to be named hydromica) and illite have very similar elementary composition and crystal structure, they are approximately equivalent physically and chemically[13]. Also, mica is one kind of ideal material for surface force measurement as mica sheet can be easily prepared and the sample surfaces can reach molecular-level smoothness for test.

The surface force apparatus, designed by Israelachvili et al.[3–4], was used to directly measure the surface forces. During the tests, two pieces of mica sheets, of 2 μm thick, were electroplated with 50 nm thick high reflecting silver film on the back. Then the mica sheets were fixed on the surface of two 90° crossed glass cylinders (2 cm in diameter), and the space between the mica sheets was filled with electrolyte solution. The distance control between two surfaces had an accuracy of 0.1 nm by using the multiple beam interferometry technology. The dynamometer between mica sheets is a variable stiffness force measuring spring with a minimum sensitivity of about 10^{-8} N, and the maximum measuring pressure of up to 500 MPa. As the testing surfaces were curve, the measured values can be converted to the interaction between two planes based on the Derjaguin Approximation ($F/R = 2\times10^6\ \pi W$)[3].

Table 1. Shale mineral composition of the Silurian Longmaxi Formation in Sichuan Basin and the Triassic Yanchang Formation in Ordos Basin

Formation	Mineral composition of the whole rock /%							Percentage of different clay minerals/%				
	Clay minerals	Quartz	Orthoclase	Plagioclase	Calcite	Dolomite	Pyrite	Illite	Illite/ Smectite	Interlayer ratio/%	Kaolinite	Chlorite
Longmaxi, Changning	34.0	45.3	4.2	6.7	6.8	2.1	0.9	62.3	17.8	20	5.9	14.0
	36.4	50.4	2.4	8.0	0.4	1.2	1.2	66.5	0.1	5	0	33.4
Longmaxi, Fuling	45.7	29.6	6.5	4.9	4.7	4.6	4.0	68.5	11.1	10	0	20.4
	47.3	26.1	4.6	9.3	3.6	5.0	4.1	85.9	11.7	10	0	2.4
Yanchang, Ordos	48.2	36.2	3.9	4.6	0	2.3	4.8	68.2	5.2	10	16.6	10.0
	54.3	34.6	0.2	4.7	0.9	4.1	1.2	59.4	11.1	15	17.3	12.2

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