Successful New Inhibitive Water-Based Fluid Application, Sulige Gas Field, China

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Abstract

This study developed a new type of shale drilling anti-collapse inhibitor and compounded a set of stable shale water-based drilling fluid for horizontal wells to effectively solve hole shrinkage, collapse, tool sticking, and other complex downhole problems involved in the shale drilling at the horizontal section of the Sulige gas field. Laboratory experimental evaluations indicated that this system had a strong inhibitory effect on shale formation and sound compatibility. After its weight reached 1.20g/cm³, the system exhibited a stable rheology, lubricity, filter loss, high recovery rate of rock debris, and low formation damage. The mud cake was smooth, thin, tough, and compact. The drilling fluid also maintained suitable anti-collapse capability, lubricity, rheology, and highly efficient debris-carrying and well-flushing ability in its field application in the drilling of the shale section of the Sulige gas field. The tripping operation exhibited no clear resistance and sticking. This system achieved significant effects and satisfied the requirements of the drilling construction of a horizontal well in the Sulige gas field.

Keywords: *borehole instability; drilling fluid; anti-collapse inhibitor; Sulige gas field*

1. Introduction

Borehole instability is a common problem in the downhole conditions of drilling engineering and can seriously influence the record of geological data, drilling speed, quality, and cost [1-3]. Shale makes up 75% of drilled formations and causes 90% of wellbore instabilities [4]. Borehole instability occasionally hinders target formation, further delays the exploration and development speed, and influences the economic benefits [5-6]. In recent years, a non-soil phase and low damage temporary-blocking drilling fluid system has been adopted for the exploration of horizontal wells at the horizontal section of the Sulige gas field. This system has achieved success in its application in horizontal wells, given its low density, high acid solubility, high core recovery rate, and small formation damage. However, this system now faces new challenges given the large-scale development of continuous horizontal well extension at the horizontal section of the Sulige gas field. Given that the reservoir formation of the Sulige gas field is characterized by strong heterogeneity, the probability of obtaining shale from the drilling at the horizontal section of the field increases. The improvement of the drilling fluid density has generally been adopted to balance the formation pressure of shale drilling, but this approach can lead to high solid content and high friction of the drilling fluid. It still cannot effectively prevent shale collapses at the horizontal section, drilling sticking, tool sticking, and other accidents, which pose high risks to the construction of the horizontal section.

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2. Shale Formation Analysis of the Horizontal Section

2.1. Conditions of Shale Drilling

According to the investigation of over 20 wells Table 1, it can be known that it is common for shale drilling at the horizontal section in Sulige gas field as well as collapses of different degrees, which causes complex downhole problems, difficult directional drilling, low penetration speed and so on.

Table 1. Statistics of Some Shale Drillings in Sulige Gas Field

Well No.	S5-2H2	S2-9H2	S6-4H1	S1-6H1
Length of the shale section (m)	2864.3-2946.3	2706.95-		3130-
	2977-2996	2813.48		3144
	3054.38-	2916.36-		3270-
	3121.81	2966.45	3582-	3287
	3124.81-3179.9	3031.74-	3600	3416-
	3198.97-	3075.96	3603-	3500
	3247.14	3099.07-	3939	3520-
	3275.89-	3141.52	3948-	3548
	3294.12	3195.24-	3978	3950-
	3304.77-	3335.60		3960
	3330.63	4332-4385		4013-
	3333.59-3412			4061
The cumulative length (m)	394.19	436.65	384	201

2.2. Analysis of Mineral Components

Clay mineral of shale at the horizontal section in Sulige gas field is primarily made of illite/smectite and illite and generally contains kaolinite and chlorite, shown as Figure 1, and Table 2.

Figure 1. Shale Sample at P2sh of Sulige Gas Field

2.3. Analysis of the Physicochemical Properties of the Formation

24h expansion rates at P₂sh of Sulige gas field are over 15%, with maximum of 35.2%; its dispersion is poor and the recovery rate falls between 10-30%, belonging to a formation with high hydration degree. P₂sh is the major collapse formation of Sulige gas field and its mean cation exchange capacities respectively are 14.71 and 23.90 mmol/100g $\pm$. According to Ormghy theory, the cation exchange capacity of illite at non-expansive crystal layer is lower than 15 mmol/100g $\pm$, which indicates

that illite/smectite in the shale at P2sh contains certain amount of expansive crystal layer.

Table 2. Major Mineral Components of the Formation in Sulige Gas Field

Well No.	H(m)	Formation	Petrographic description	Relative mineral contents (%)				
				I/S R>1	I	K	C	lit-par-lit ratio S%
S7-9	2852	P ₂ sh	Sandy mudstone	71	20	4	5	25
S7-9	2899	P ₂ sh	Sandy mudstone	57	27	6	10	25
S7-9	2946	P ₂ sh	Sandy mudstone	56	28	6	10	25
S7-9	2992	P ₂ sh	Sandy mudstone	60	26	7	7	20
S7-9	3039	P ₂ sh	Sandy mudstone	59	33	3	5	20
S5	3115	P ₂ sh	mudstone	69	18	7	6	35
S5	3301	P ₂ sh	mudstone	52	25	15	8	20
S6-4	3306	P ₂ sh	mudstone	84	5	7	4	35
S20	3345	P ₂ sh	mudstone	73	9	11	7	30
S11	2981	P ₂ sh	mudstone	41	31	20	8	20

Table 3. Physicochemical Properties at P2sh of Sulige Gas Field

Well No.	H (m)	Formation	P (g/cm ³)	Recovery rate (%)	Expansion rate (24h)%	CEC (mmol/100g ±)	Soluble salt content (%)	Isothermal adsorption property (p/p=0.5)	Exchangeable cations (mmol/100g ±)	
									Ca ²⁺	Mg ²⁺
S70	3308	P2sh	2.70	90.6	25.2	33.33	0.18	0.70	24.15	431.206
S11	2761	P2sh	2.68	91.7	28.5	14.70	0.21	0.81	14.28	028.246
Q1	3005	P2sh	2.63	92.0	24.2	4.13	0.14	0.61	7.87	612.683
S5	3301	P2sh	2.71	94.3	17.9	11.60	0.41	0.52	6.65	427.829
S64	3306	P2sh	2.67	82.5	35.2	21.13	0.54	0.83	20.44	025.189
S20	3345	P2sh	2.69	90.1	34.9	14.60	0.40	0.40	14.86	918.228

3. Preparation and Performance Evaluation of Stable Shale Inhibitor

The abroad application of anti-collapse organic amine inhibitor is relatively mature while the domestic field application is few [7-8]. The inhibition mechanism of organic amine inhibitor is different from traditional inhibitory drilling fluid and by aid of unique molecular structure of organic amine, this inhibitor can well inlay between clay formations and connect the clay formations tightly [9-11]. Thus, it can decrease the moisture absorption trend of clay and have a strong inhibitory effect on the hydration of shale. Compared with cationic polymer, polymeric alcohol and silicate drilling fluids, this new organic amine not only owns strong inhibitory effect on hydrous disintegration but also has better firm formation function, which can prevent drill bit balling and improve the penetration speed [12-14].

3.1. Synthetic Process

Organic amine polymer is obtained from epoxide (ethylene oxide and / or propylene epoxide) and cationic monomer with catalyst.

3.2. Major Instruments

(1)Polyreactor: 3M³ or larger, including nitrogen charge device, stirrer, temperature regulating device (0-200 °C), cooling device and so on; (2) Aging reactor: 3M³ or larger; (3) raw material storage tank: 20-30 M³; (4) metering pump.

3.3. Main Raw Materials and Dosage

(1)Ethylene oxide: 50-80kg; (2) propylene epoxide: 50-100kg; (3) organic amine: 30-55kg; (4) initiator: 10-15kg; (5) catalyst: 1-3kg; (6) water: 10-20kg.

3.4. Technological Process

Initiator is added in the reactor and then catalyst and organic amine are dropped in under stirring. Later, water of certain amount is added. Replace for 2-3 times by nitrogen charge. It is heated and stirred until 80 °C and epoxide is dropped, with pressure lower than 10MPa and temperature lower than 180 °C. In the reaction process, if the pressure is overly high, charge is stopped feeding in until temperature and pressure decrease. After the drop is over, keep the reaction for 30-40h and cool until the temperature is lower than 50 °C. In this way, colorless or pale yellow viscous liquid is obtained, with trade name of organic amine inhibitor and code name of AI509.

3.5. Performance Evaluation

The reaction product is used as inhibitor, so this paper focused on investigating its inhibition performance and its influences on rheology and filter loss of the drilling fluid.

1) Experiment of expansibility

Experimental data in Table 4, show that the expansibility of core in AI509 test liquid is lower than that in pure water.

Table 4. Experiment Results of Expansibility

Reagent	Dosage (%)	$L_t/8h(mm)$	$H(mm)$	$V_t/8h(\%)$
water	/	3.41	13.13	25.97
	0.05	2.46	11.375	21.63
	0.1	2.57	12.42	20.69
AI509	0.25	2.61	12.27	21.27
	0.5	2.57	12.17	21.12
	1	2.57	12.05	21.33

2)Experiment of flocculation

Experiment of flocculation is the most intuitive evaluation means to evaluate the inhibitory effect of inhibitor on clay hydration. In the experiment, the lower the height of flocculate interface is, the more obvious the inhibitory effect of treating agent is.

Figure 2. Experiment Results of Flocculation

2#:water;3#:7% KCl;4#:1% AI509;5#:0.5% AI509, 6#:0.25% AI509;7#:0.1% AI509;8#:0.05% AI509

It can be seen from Figure 2, that after 24h' standing, with tiny dosage of AI509 (8#), a strong flocculation effect is generated. With the increasing dosage, the flocculation effect gradually strengthens. When the dosage of AI509 is increased to 1%, the height of flocculate is about 11 (scale reading of measuring cylinder), which is twice of that of 7% KCl. Thus, the flocculation effect is good.

Table 5. Experiment Results of the Influences of AI509 on Drilling Fluid Performance

Reagent	Dosage (%)	AV(mPa·s)	PV(mPa·s)	YP(Pa)	FL(ml)	Note
4% Swelling soil	/	12.5	5	7.5	32.8	at room temperature
		6.0	5	1.0	36.6	120°C/16h
	0.05	13.5	6	7.5	24.0	at room temperature
		10.0	6	4.0	28.0	120°C/16h
	0.10	13.5	6	7.5	24.6	at room temperature
		10.5	6	4.5	27.4	120°C/16h
AI509	0.25	12.5	6	6.5	26.2	at room temperature
		9.5	6	3.5	28.0	120°C/16h
	0.5	13.0	6	7.0	25.4	at room temperature
		10.0	6	4.0	28.0	120°C/16h
	1	13.5	7	6.5	26.4	at room temperature
		9.5	6	3.5	29.8	120°C/16h

3) Evaluation of the influences on the drilling fluid performance

It can be seen from the experiment results in Table 5 that at room temperature the influences of AI509 on viscosity and shearing force of drilling fluid are small. After aging at 120°C, filter loss of the drilling fluid caused by AI509 decreases slightly.

4) Comparative evaluation of inhibitory effects

Field rock debris from Sulige gas field is selected for the experiment of the recovery rate. The performances of organic amine inhibitor AI509, inorganic salt

WJ-1, organic salt YJ-B and abroad polyamine are compared. Results are shown as Table 6.

Table 6. Comparative Experiment Results of Inhibitory Effects (120°C×16h)

No.	Test solution	Once recovery rate (%)	Secondary recovery rate (%)	Triple recovery rate (%)
1	Water	40.82	17.74	8.98
2	1.5% polyether	48.04	25.28	13.46
3	0.5% AI509	96.46	96.26	95.34
4	1.0% AI509	96.30	96.18	95.07
5	0.5% polyamine	87.60	83.58	83.40
6	1.0% polyamine	90.62	88.78	86.10
7	7%NaCl	36.06	18.76	11.10
8	7% WJ-1	64.52	34.16	21.86
9	7% YJ-B	75.42	41.26	31.12

It can be seen from the experiment results in Table 6 that with tiny dosage of AI509 (0.5%), the inhibitory effect is good and the recovery rate of rock debris is obviously higher than that of the abroad polyamine products, with over 93% once, secondary and triple recovery rates. Moreover, the secondary and triple recovery rates are far higher than those of other products.

It can be seen from the comprehensive analysis of the above experimental data, organic amine inhibitor AI509 owns good inhibitory effect on shale hydration swelling and at the same time with good compatibility with the drilling fluid, it is an excellent inhibitor to prepare the water-based drilling completion fluid with strong inhibition and high performance. It is suitable for the shale drilling requirements of the horizontal section in Sulige gas field.

4. The Formulation of Drilling Fluid System

4.1. Experiment of Compatibility

Organic amine inhibitor AI509 is a polymer of cation and non-ion. However, cationic polymer usually has compatibility problems with most common anionic treatment agents. Thus, the experiment of compatibility is necessary to carry out and results are shown as Table 7.

Table 7. Experiment Results of Compatibility

Formulation	AV(mPa·s)	PV(mPa·s)
0.3%PAC-H	10.0	3.5
0.3%PAC-H+1.5% AI509	10.0	6.0
0.3% G310-DQT	5.0	4.5
0.3% G310-DQT +1.5% AI509	6.0	4.2
0.3%PAM	4.0	0.5
0.3% PAM +1.5% AI509	3.5	0.7
0.3%KPAM	2.5	1.0
0.3% KPAM +1.5% AI509	2.5	1.0

It can be seen that after the addition of AI509, rheology of the solution basically remains unchanged and the solubility is good, without caking, flocculation and precipitation. It shows good compatibility.

4.2. Experiment of Compound and Dosage

Compounding coat agent with organic amine inhibitor can improve the overall inhibition of the drilling fluid system. KPAM is selected as coat agent and the experiment data are shown as Table 8.

Table 8. Experiment Results of Compound and Dosage

Formulation		AV (mPa·s)	PV (mPa·s)	YP (Pa)	recovery rate (%)		
					Once	Secondary	Clear water
water+ 0.5% AI509+ 0.3%KPAM	Before hot rolling	4.0	3.0	1.0	75.52	69.60	
	After hot rolling	2.5	2.0	0.5			
water + 1.5% AI509+ 0.3%KPAM	Before hot rolling	4.2	2.5	1.7	81.36	78.60	
	After hot rolling	2.5	2.0	0.5			
water + 2% AI509+ 0.3%KPAM	Before hot rolling	3.0	2.0	1.0	80.86	78.80	18.06/ 17.08
	After hot rolling	3.0	2.0	1.0			
water + 2.5% AI509 + 0.3%KPAM	Before hot rolling	2.7	2.5	0.2	81.50	77.62	
	After hot rolling	3.0	2.0	1.0			
water + 3% AI509 + 0.3%KPAM	Before hot rolling	2.7	2.0	0.7	82.80	77.34	
	After hot rolling	3.0	2.0	1.0			

Note: The condition of once recovery rate is 120 °C *16h and the condition of secondary recovery rate 120 °C *4h.

It can be seen from the results when AI509 is added to 1.5%, the recovery rate of rock debris is improved very slightly. Thus, it can be determined that AI509 shall fall between 1~1.5% and can be feasibly adjusted according to the actual field conditions.

4.3. Optimization of Water Loss Agent

G1-JLS and G3-SJS water loss agents are selected for the experiment. When the samples are prepared, the water loss is measured after sufficient hydration. Then hot rolling is kept for 16h at 120°C. To better simulate the filed working conditions, 50g rock debris is added in the process of hot rolling. The experiment results are shown as Table 9.

It can be seen that when 3% G3-SJS and 1% G1-JLS are added in the system, HTHP water loss at 120°C is controlled within 15ml/30min. Mud cake is smooth and tough, satisfying the requirement.

4)Basic formulation

Through the above experiments, the basic formulation of the drilling fluid system is preliminarily determined as

1.0-1.5% AI509+0.2-0.3%KPAM+0.2-0.3%G310-DQT+1%G1-JLS+3%G3-SJS and it can be feasibility applied according to the field requirements.

Table 9. Experiment Results of Water Loss

No.	Experiment formulations	P (g/cm ³)	FL (mL)	FL _{HTHP} (mL)	pH	PV (mPa·s)	YP (pa)
1	1.5% AI509 +0.3%KPAM +0.3%G310-DQT +3%G1-JLS+1%G3-SJS	1.06	5.6	18.0	11	39.0	13.5
	120°C×16h After hot rolling	1.05	4.2	19.0	11	26.0	11.5
2	1.5% AI509 +0.3%KPAM +0.3%G310-DQT +2%G1-JLS+2% G3-SJS	1.07	5.4	16.0	11	39.0	14.0
	120°C×16h After hot rolling	1.07	4.6	16.0	11	25.0	6.0
3	1.5% AI509 +0.3%KPAM +0.3%G310-DQT +1%G1-JLS+3%G3-SJS	1.10	5.2	12.0	12	41.0	15.5
	120°C×16h After hot rolling	1.10	4.4	15.0	11	34.0	15.0

5. Application Examples

1)Example 1

S2-30H2 well was located in the Yishan slope of the Ordos Basin. The target gas reservoir was P2sh section. Its designed well depth was 4,256 m and length of the horizontal section was 1,000 m, but the actual tall depth was 4,730 m and length of the horizontal section was 1,436 m. There were 4 sections of mud rock at the horizontal section, with total length of 318 m. The performance parameters of the drilling fluid in horizontal section are shown as Table 10. In the process of drilling, tripping operation was made twice and the side wall at the mud rock section was stable. The tripping operation was smooth.

Table 10 .The Parameters of the Drilling Fluid in Horizontal Section in S2-30H2 Well

H(m)	ρ (g/cm ³)	pH	FL(ml)	AV(mPa·s)	PV(mPa·s)	YP(Pa)
3330	1.16	8	4.0	30.5	18.5	12.0
3431	1.18	8	3.8	37.0	22.5	15.0
3590	1.20	9	3.6	35.0	22.0	13.0
3662	1.20	9	3.5	37.5	23.0	14.5
3734	1.21	9	3.6	34.5	21.5	13.5
3880	1.19	9	3.0	36.0	29.0	17.0
3956	1.21	9	2.0	46.5	30.5	16.0
4085	1.25	9	2.0	50.0	32.0	18.0
4127	1.25	9	2.0	53.0	34.0	19.0
4250	1.25	9	2.0	56.0	34.0	22.0
4475	1.25	9	2.0	47.0	27.5	14.0
4550	1.25	9	2.0	46.5	25.5	13.5
4640	1.25	9	2.2	50.0	32.0	18.0
4730	1.25	9	2.0	58.5	45.0	23.5

2)Example 2

S3-64H2 well was located in the Yishan slope of the Ordos Basin. The target gas reservoir was P2sh section. Its designed well depth was 4,604 m and length of the horizontal section was 1,500 m, but the actual tall depth was 4,700 m and length of the horizontal section was 1, 545.20 m. There were 7 sections of mud-sandstone

interbedding at the horizontal section, with total length of 278.46 m. The performance parameters of the drilling fluid in horizontal section are shown as Table 11. The side wall at the mud-sandstone interbedding section was stable and the tripping operation was smooth. 6 times of wiper trips were normal and 10 $\Phi 146 \times 1.6$ m packers were smoothly tripped in the horizontal section.

Table 11. The Parameters of the Drilling Fluid in Horizontal Section in S3-64H2 Well

H(m)	$\rho(\text{g/cm}^3)$	pH	FL(ml)	AV(mPa·s)	PV(mPa·s)	YP(Pa)
3161	1.20	9	3.0	49.0	31.0	18.0
3269	1.21	9	3.4	45.5	30.5	15.5
3374	1.20	9	3.2	51.0	31.0	17.0
3457	1.20	9	3.2	48.5	32.0	16.5
3556	1.20	9	3.2	47.5	32.0	15.5
3661	1.20	9	3.2	48.0	32.0	16.0
3757	1.21	9	3.2	51.0	34.0	17.0
3912	1.21	9	3.2	52.5	34.0	18.5
4035	1.22	9	3.2	57.0	37.0	20.0
4183	1.21	9	3.2	47.0	32.0	15.0
4333	1.20	9	3.8	57.5	37.0	20.5
4486	1.21	9	4.0	59.0	41.0	18.0
4608	1.21	9	4.0	60.5	41.0	19.5
4700	1.21	9	3.0	59.0	38.0	23.0

6. Analysis on the Field Experiment Effects

1) High inhibitory effect and obvious anti-collapse effect of drilling fluid

Organic amine drilling fluid from the field experiment was tested, with once recovery rate of 91.6%, secondary recovery rate of 90.4% and triple recovery rate of 89.8%. Its inhibitory effect was high. In the field experiment at the horizontal shale section of Sulige gas field 6 wells, this drilling fluid system had no chipping, collapses or hole shrinkage. Reversing-out rock debris at the mud rock section had clear and obvious edge angles (Figure 3). The borehole was unblocked and the borehole diameter was regular. The cased-hole completion operation was smooth and anti-collapse effect was good.

2) Obvious lubrication and drag reduction effects of the system

The coefficients of friction resistance of the sliding block in the field drilling fluid system were below 0.07, with torque of less than 9 kN·m and tripping friction drag of less than 12T. The tripping process was free from resistance or blocking, which guaranteed the safe and quick drilling at the long horizontal section.

3) Small formation damage

Two cores in the experiment wells were selected and the effects of reservoir temperature and pressure on the drilling fluid system were simulated in the laboratory and evaluations were made. The experiment results are shown as Table 12.

Figure 3. Reversing-Out Shale Drilling Cuttings at the Wellhead

Table 12. Experiment Results of Field Formation Damage

Well No.	Core No.	Formation	Kg ₁ (10 ⁻³ μm ²)	Kg ₂ (10 ⁻³ μm ²)	Damage rate (%)	Mean damage rate (%)
S3-1	216#	P ₂ sh	0.5098	0.4394	13.8	14.4
S3-1	217#	P ₂ sh	0.4668	0.3972	14.9	
S2-18	139#	P ₂ sh	0.5245	0.4512	14.0	
S2-18	140#	P ₂ sh	0.5384	0.4556	14.8	

Note: Differential pressure is 32.5Mpa; time is 48hr; and Kg₁ and Kg₂ respectively represent the permeability before and after damage

Under the simulated downhole conditions, the formation damage rates of the drilling fluid system were only 13.8% and 14.9%, belonging to light damage.

4)Improved drilling rate and complete and smooth tripping in of completion tools

Drilling rate was greatly improved. The footage of single drill bit and single screw at the horizontal section of S2-30H2 well was 722 m, with mean penetration speed of 10.5m/h, which was the currently fastest penetration speed in this region (Table 13). In case of massive mud rock, superior comprehensive performance of the drilling fluid guaranteed the safe drilling of long the horizontal section and the smooth tripping-in of cased-hole completion. Near 1, 436-1, 545.24 m, cased hole completion with open hole packer was safely tripped at the preset position of the horizontal section, which laid foundation for further carrying out staged fracturing and increasing yield and efficiency.

Table 13. Drilling Rate of the Test Wells

Well No.	Length of the horizontal section (m)	Length of the shale (m)	ROP (m/h)	Completion method
S5-56H1	905.0	58.0	9.6	casing pipe
S9-56H1	777.0	181.0	10.0	open hole
S3-64H2	1545.2	278.0	9.4	open hole
S5-65H2	1000.0	56.0	8.2	open hole
S2-30H2	1436.0	318.0	10.5	open hole
S2-38H1	1000.3	339.0	6.9	casing pipe

7. Summary

1) It is common to meet shale in the horizontal section of Sulige gas field. Due to collapse, tool sticking and other complex downhole problems, the directional drilling is difficult and the drilling rate is low.

2) Clay mineral of shale at the horizontal section in Sulige gas field was primarily made of illite/smectite and illite. It belonged to the formation with high hydration degree and was the major collapse formation.

3) This paper developed Organic amine anti-collapse inhibitor AI509, which owned good water solubility, strong inhibitory effect and good compatibility.

4) The prepared anti-collapse drilling fluid system of the horizontal wells owned strong inhibitory effect on shale, high shale recovery ratio, 120 °C temperature-tolerance as well as good rheology.

5) In the Sulige gas field 6 wells, this system manifested good stabilizing capacity of borehole, high purifying capacity of borehole, free of downhole collapse, chipping, sand setting, low formation damage degree and high drilling rate, which solved the prominent problems at the horizontal section. It can satisfy the safe drilling of horizontal wells at the reservoir formation in Sulige gas field.

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