

Original Paper

Optimization and application of KCl polymer drilling fluid balancing wellbore stability and logging response accuracy

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ABSTRACT

In Dagang Oilfield in China, the utilization of the KCl polymer water-based drilling fluid (WBDF) in mid-deep exploration/appraisal wells presents a challenge in simultaneously optimizing resistivity logging accuracy and wellbore stability. To address this, it is necessary to conduct geology-engineering integration studies. Based on the formation resistivity, an analytical model was developed to assess the impact of KCl concentration in the WBDF on array induction logging response accuracy. The maximum permissible KCl concentration for the target formations was determined, and technical strategies were proposed to maintain wellbore stability at a reduced KCl concentration. After that, considering the inhibitory, encapsulating, and plugging effects, a low-KCl-concentration WBDF was optimized and applied. Model calculations demonstrate that increasing KCl concentration in the WBDF decreases resistivity, thereby reducing logging accuracy. To maintain a logging accuracy of $\geq 80\%$, the upper limits for KCl concentration in the WBDF are 4.8%, 4.2%, and 3.6% for the 3rd Member of the Dongying Formation, the 1st and 2nd members of the Shahejie Formation, respectively. Cuttings recovery experiments revealed that a minimum KCl concentration of 3% is required to ensure basic shale inhibition. A combination of 3% KCl with 1% polyamine inhibitor yielded cuttings recovery and shale stability index comparable to those achieved with 7% KCl alone, and the shale inhibition performance was further enhanced with the addition of an encapsulator. The optimized WBDF has been successfully deployed in exploration/appraisal wells across multiple blocks within Dagang Oilfield, resulting in superior wellbore stability during operations. Furthermore, the electric logging interpretation coincidence rate improved from 68.1% to 89.9%, providing robust technical support for high-quality drilling and accurate reservoir evaluation in exploration/appraisal wells.

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1. Introduction

In the Dagang Oilfield in China, exploration/appraisal wells exceeding 3500 m in depth predominantly employ the KCl polymer water-based drilling fluid (WBDF). While these fluids effectively mitigate clay shale hydration and promote wellbore stability, their typical KCl content (6%–7%) substantially decreases the drilling fluid's resistivity. This reduction is particularly pronounced in deep, high-temperature environments, significantly

compromising the accuracy of array induction logging. Consequently, array curves exhibit notable separation, diminishing the ability to distinguish between oil and water-bearing strata. The influence of mineralization, specifically salt concentration, in drilling fluids on logging performance remains incompletely understood, and the critical mineralization threshold suitable for the target formations is yet to be definitely established. Attempts to enhance logging accuracy by reducing KCl concentration to 2%–4% in two wells resulted in a higher frequency of wellbore collapse and tripping-related incidents. Therefore, an urgent need exists to resolve the inherent conflict between logging interpretation accuracy and wellbore stability encountered in exploration/appraisal wells within this region when using KCl polymer drilling fluids.

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The influence

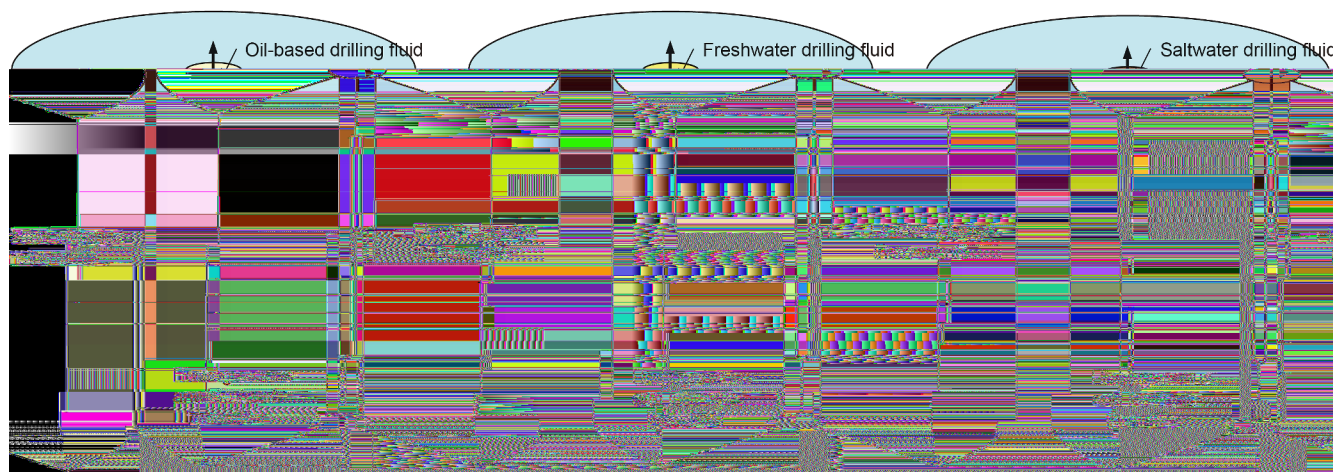


Fig. 1. Schematic diagram of a homogeneous and isotropic formation model.

Using the HDIL (high definition induction logging) array induction logging instrument as an illustrative example, the raw measurement data comprise the real and imaginary components of 7 sub-arrays and 8 frequencies (10, 30, 50, 70, 90, 110, 130, and 150 kHz), yielding a total of 112 logging curves. The processing workflow primarily includes the following three stages: (1) Skin effect correction: To enhance the accuracy of conductivity measurements in heterogeneous formations, the instrument response and the linear relationship between the instrument and formation conductivity were improved. Following depth resampling of the 56 pertinent curves, skin effect correction was initially performed. (2) Borehole effect correction: Typically, geometric factor correction or adaptive correction methods were employed to eliminate measurement errors arising from borehole factors. (3) Standard synthesis focusing processing: Curves characterized by varying resolutions and detection depths were processed utilizing digital filtering to generate synthetic signals with fixed resolution and varying detection depths, thereby improving the resolution of the raw measurement signals and unifying the response characteristics of signals at different detection depths.

2.3. Array induction logging response analysis

2.3.1. Synthetic logging response curves for different formations

To facilitate a comprehensive analysis of the influence of drilling fluid resistivity on logging response, a homogeneous, isotropic formation model was utilized, maintaining a constant borehole diameter of 8 inches and varying the drilling fluid resistivity from 0.01 to 100 $\Omega\cdot\text{m}$. Formation resistivity values for the Dong-3 Member, Sha-1 Member, and Sha-2 Member were set at 3.5, 4.5, and 10 $\Omega\cdot\text{m}$, respectively. Simulation calculations were then performed to generate array induction logging response curves for the three formations at different drilling fluid resistivities, as illustrated in Fig. 2.

The synthetic logging response curves presented are the result of two-inch resolution matching across various spacings (10, 20, 30, 60, 90, and 120 inches). Observations reveal that logging curves corresponding to different source-receiver spacings exhibit varying sensitivities to drilling fluid resistivity, with short-spacing curves being more susceptible and long-spacing curves being less affected. Under consistent formation resistivity conditions, the influence of drilling fluid resistivity on the array induction logging response diminishes as drilling fluid resistivity increases, leading to curve convergence and approximation of the true formation

resistivity value. In practice, the 10-inch curve is typically excluded due to its significant susceptibility to borehole effects. The 60-inch, 90-inch, and 120-inch curves generally exhibit applicability across a range of drilling fluid conditions. Consequently, the primary focus is directed towards investigating the impact of drilling fluid on the 20-inch and 30-inch curves to establish the upper limit of KCl concentration or salinity in the drilling fluid that ensures accurate well logging within the target formation.

2.3.2. The impact of KCl drilling fluid resistivity on logging response accuracy

Based on the results presented in Fig. 2, the logging response accuracy of the 20-inch and 30-inch curves under varying drilling fluid resistivity conditions was analyzed, as depicted in Fig. 3. Logging response accuracy is defined as the ratio of the corrected logging data to the true formation resistivity. Across the three distinct formations, the accuracy of the logging curves exhibits an inverse relationship with drilling fluid resistivity. From a logging performance perspective, the critical drilling fluid resistivity threshold required to maintain a response accuracy of at least 80% is determined by the formation resistivity. For the Dong-3 Member (Fig. 3(a)), where the formation resistivity predominantly approximates 3.5 $\Omega\cdot\text{m}$, a downhole drilling fluid resistivity exceeding 0.018 $\Omega\cdot\text{m}$ ensures a measurement accuracy for the 20-inch and 30-inch curves surpassing 80%, thereby satisfying the requirements for electrical logging curve accuracy. Similarly, for the Sha-1 Member (Fig. 3(b)), characterized by a formation resistivity primarily around 4.5 $\Omega\cdot\text{m}$, a downhole drilling fluid resistivity above 0.021 $\Omega\cdot\text{m}$ guarantees a measurement accuracy for both curves exceeding 80%. For the Sha-2 Member (Fig. 3(c)), where the formation resistivity predominantly measures approximately 10 $\Omega\cdot\text{m}$, a downhole drilling fluid resistivity greater than 0.043 $\Omega\cdot\text{m}$ is necessary to meet the logging curve accuracy criteria.

2.3.3. The impact of drilling fluid KCl concentration on logging accuracy

Based on the computational results presented in Fig. 3, and considering the resistivity of KCl aqueous solutions at varying mass-volume concentrations under surface temperature conditions (18 $^{\circ}\text{C}$), along with the conversion relationship between formation temperature and downhole drilling fluid resistivity at surface temperature, the salinity, or salt concentration, of the drilling fluid in formations at different temperatures was calculated. Subsequently, the influence of drilling fluid salt



Fig. 2. Composite diagram of logging response for different formations.



Fig. 3. Logging response accuracy maps for different formations.

concentration on logging accuracy was analyzed, with the results illustrated in Fig. 4.

The data indicate that as the salt concentration of the drilling fluid increases, resistivity decreases, and the accuracy of the

logging response curve declines. For the Dong-3 Member, characterized by a formation temperature of 120 °C and a resistivity ranging from 1.3 to 19.7 Ω·m, maintaining the KCl concentration in the drilling fluid at $\leq 4.8\%$ ensures that the logging accuracy for all

formations within the Dong-3 Member reaches or exceeds 80%. Similarly, for the Sha-1 Member, with a temperature of 135 °C and a resistivity ranging from 1.9 to 20.4 $\Omega\cdot\text{m}$, a KCl concentration of $\leq 4.2\%$ guarantees a logging accuracy of $\geq 80\%$ for this

on the current application status of drilling fluid shale inhibitors and the research team's prior investigations, a low-molecular-weight polyamine was selected for combined use with KCl as shale inhibitors. The concentrations of these components employed in combination were optimized through experimentation, followed by the further selection of the high-efficiency encapsulator and plugging agent to refine the wellbore-stabilizing drilling fluid formulation.

3.2.2. Shale cuttings recovery rate test with different concentrations of KCl

Given the relatively low clay mineral content in the Dong-3 Member of the target block and the correspondingly high upper limit of KCl concentration (4.8%) permissible for maintaining logging accuracy in this formation, this study primarily focuses on the Sha-1 and Sha-2 members. Experiments on the shale cuttings recovery rate were widely used to evaluate the

increases further, the interlayer spacing decreases slightly before stabilizing at 1.41 nm, demonstrating that polyamine effectively inhibits clay hydration even at low concentrations. Based on the molecular structure characteristics of polyamine (Zhong et al., 2011; Xie et al., 2024), the primary mechanism underlying its inhibition of clay hydration is as follows. Polyamine undergoes partial dissociation in aqueous solution to form ammonium cations, which neutralize the negative charges present on the surface of the clay, reducing the hydration repulsion of the clay. In addition, polyamine molecules can form hydrogen bonds with the surface of the clay crystal layers. The combined effect of electrostatic attraction and hydrogen bonding binds the clay layers together and expels a portion of the interlayer adsorbed water. Furthermore, the adsorption of polyamine on the clay surface enhances its hydrophobicity, preventing water molecules from entering the clay interlayers and further inhibiting clay hydration.

Having confirmed the suitability of polyamine as a non-electrolyte shale inhibitor, further evaluation was conducted to optimize its dosage and assess the shale inhibition performance of polyamine in combination with low-concentration KCl. The objective was to ensure that the shale inhibition effect was maintained despite the reduction of KCl concentration in the drilling fluid from 7% to 3%.

(1) Cuttings recovery experiment

Cuttings recovery experiments were performed on the Sha-1 and Sha-2 members to comparatively analyze the shale dispersion inhibition effect of the polyamine and 3% KCl combination against that of high-concentration KCl. Additionally, the improvement in inhibition performance resulting from the addition of an encapsulator named BYJ, which is a high-molecular-weight acrylamide-based polymer, was also analyzed. The results are presented in Fig. 8. The additives incorporated into each test sample are shown in Table 4.

The results indicate that, for the rock samples from the Sha-1 Member, the addition of 5% KCl and 7% KCl solutions resulted in an increase in the recovery rate from 24.8% to 48.9% and 52.9%, respectively, compared to pure water. The combination of 3% KCl with 1% polyamine yielded a cuttings recovery rate of 48.6%, comparable to that achieved with 5% KCl. Increasing the polyamine concentration to 2% further enhanced the recovery rate to 60.8%, surpassing the performance of 7% KCl. For the rock samples from the Sha-2 Member, the combination of 3% KCl with 1% polyamine resulted in a cuttings recovery rate of 59.3%, exceeding that of 7% KCl.

Table 4
Additives incorporated into each test sample.

Sample No.	Additive concentration, %		
	KCl	Polyamine	BYJ
#1	0	0	0
#2	5	0	0
#3	7	0	0
#4	3	1	0
#5	3	2	0
#6	5	0	0.3
#7	7	0	0.3
#8	3	1	0.3
#9	3	2	0.3

$$SSI = 100 - 2(H_f - H_i) - 4D \tag{1}$$

where H_i is the penetration value of the rock sample prior to soaking, mm; H_f represents the penetration value of the rock sample after soaking, mm; D is the average swelling height or erosion depth of the rock sample after soaking in the drilling fluid, mm.

Using a rock sample from the Sha-1 Member, the SSI experiment was conducted to compare the shale stability effect of 3% KCl combined with polyamine to that of high-concentration KCl. The additives added into each test sample are shown in Table 5. The experimental results are presented in Fig. 9.

Under ideal conditions, where the rock sample does not undergo any hydration in the drilling fluid, for example, an excellent oil-based drilling fluid, the SSI value would be 100 (Mondshine, 1973). However, in practice, drilling fluids cannot completely prevent clay hydration. Following soaking in different solutions, lower SSI values indicate a higher degree of rock sample hydration, more severe degradation of rock strength, and poorer wellbore stability. Soaking the rock sample in pure water (Sample #1) resulted in an SSI value of only 15.9. Following soaking in KCl solutions (Samples #2 to #4), the SSI increased with increasing KCl concentration. The SSI values of the rock samples in 3% KCl, 5% KCl, and 7% KCl solutions were 45.8, 48.9, and 52.6, respectively, demonstrating that KCl significantly inhibited clay hydration, attenuated rock strength degradation caused by clay hydration, and facilitated improved wellbore stability in shale formations. The use of 3% KCl in combination with 1% and 2% polyamine yielded SSI values of 55.5 (Sample #5) and 61.8 (Sample #6), respectively. This indicates that the shale stability effect of 3% KCl combined with 1% polyamine was marginally superior to that of 7% KCl, and increasing the polyamine concentration further enhanced the wellbore-stabilizing effect. The combination of 7% KCl and “3% KCl + 1% polyamine” with 0.3% encapsulator BYJ resulted in SSI values of 73.1 (Sample #7) and 77.5 (Sample #8), respectively. This suggests that the incorporation of polymer encapsulators with

Table 5
Additives incorporated into each sample for SSI experiments.

Sample No.	Additive concentration, %		
	KCl	Polyamine	BYJ
#1	0	0	0
#2	3	0	0
#3	5	0	0
#4	7	0	0
#5	3	1	0
#6	3	2	0
#7	7	0	0.3
#8	3	1	0.3

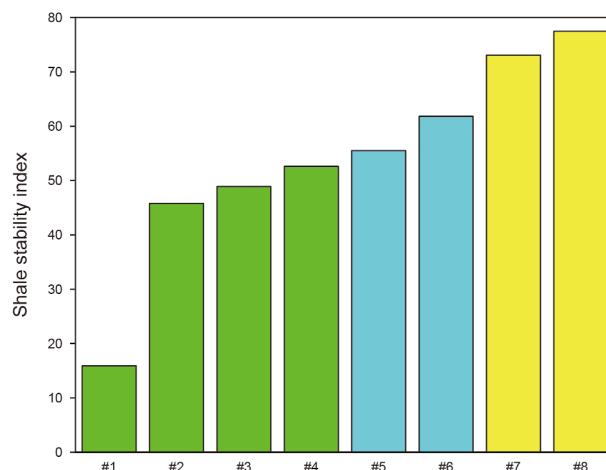


Fig. 9. SSI values for rock samples following immersion in different solutions.

shale hydration inhibitors further improves wellbore-stabilizing performance.

3.2.4. Plugging agent optimization

Enhancing the plugging of formation fractures by drilling fluids is crucial for impeding the transmission of drilling fluid pressure and the invasion of filtrate, which is essential for maintaining wellbore stability (Tchameni et al., 2024; Du et al., 2025). Using a base fluid consisting of “2% bentonite slurry + 0.15% polymer viscosifier (HXC) + 2% poly (alkenyl sulfonate) fluid loss reducer (PAS)”, various types of plugging agents named YFT, FFT, SN, and DFT were added at a concentration of 2.5%. Following 16 h of hot rolling at 150 °C, the API (American Petroleum Institute) filtrate loss (FL_{API}), the high-temperature and high-pressure (HTHP) filtrate loss (FL_{HTHP}) under conditions of 150 °C and 3.5 MPa, along with the rheological parameters of the experimental slurry, including the apparent viscosity (AV), plastic viscosity (PV), and yield point (YP), were evaluated (Huang et al., 2021b; Yang et al., 2024a). The experimental results are presented in Table 6. Triplicate testing was performed for drilling fluid rheology, fluid loss, and pH measurements, with results reported as mean values. The Bingham plastic model was employed to determine the rheological properties of the drilling fluid. The data indicate that, among the four types of plugging agents tested, the asphalt-based plugging agent named FFT exhibited the lowest filtrate volume, measuring 21 mL. Its plugging effect under high-temperature and high-pressure conditions was significantly superior to that of the other three plugging agents, and it also yielded the thinnest filter cake, thereby mitigating the formation of a falsely thick filter cake. Furthermore, among the four plugging agents, FFT also exhibited the lowest API filtrate loss and the thinnest filter cake. In addition, the experimental slurry incorporating FFT did not exhibit significant thickening, indicating that FFT possesses favorable compatibility with the drilling fluid base slurry used on-site and does not induce substantial adverse effects on the rheological properties of

Table 6
Optimization results for plugging agents.

Plugging agent	AV, mPa s	PV, mPa s	YP, Pa	FL_{API} , mL	FL_{HTHP} , mL	pH
YFT	52.5	35.0	17.5	6.6	36.0	8.5
FFT	41.0	29.0	12.0	6.2	21.0	9
SN	42.5	31.0	11.5	6.0	30.0	8.5
DFT	34.0	24.0	10.0	6.6	26.0	8.5

the drilling fluid. Therefore, considering both the plugging performance and the rheological properties, FFT was selected as the optimal plugging agent for the drilling fluid.

3.2.5. Drilling fluid formulation optimization

Based on the shale inhibitors, encapsulator, and plugging agent selection detailed above, the WBDF formulation used on-site was optimized considering the rheological property, filtration property, wellbore stabilizing property, and lubricity. The resulting formulation is

4. Conclusions

- (1) An analytical model was developed to evaluate the influence of KCl concentration in drilling fluids on the accuracy of array induction logging responses. The model's calculations indicate that, under consistent formation resistivity conditions, as the drilling fluid resistivity increases, the influence of drilling fluid resistivity on the logging response diminishes, and the curves progressively converge, approaching the true formation resistivity. Consequently, the critical drilling fluid resistivity threshold required to ensure logging accuracy is governed by the formation resistivity. As the KCl concentration in the drilling fluid increases, the resistivity decreases, and the accuracy of the logging response curve declines. For the target block in the Dagang Oilfield, specifically the Dong-3 Member, maintaining the KCl concentration in the drilling fluid at $\leq 4.8\%$ ensures a logging accuracy of no less than 80% across all layers. For the Sha-1 Member, the KCl concentration in the drilling fluid should be $\leq 4.2\%$, while for the Sha-2 Member, the KCl concentration should be $\leq 3.6\%$ to meet the accuracy requirements.
- (2) As the KCl concentration increases, the shale cuttings recovery rate gradually increases. However, when the concentration exceeds 3%, the rate of increase in recovery diminishes. Therefore, to ensure effective shale inhibition, the KCl concentration should be maintained at a minimum of 3%. The cuttings recovery rate achieved with 3% KCl combined with polyamine at a concentration of at least 1% is close to or reaches that achieved with 7% KCl. Moreover, the shale stability index is marginally

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