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New Completion Technique of " White Oil Fracturing + Deep Acidizing" in Offshore Low-Permeability Oilfield

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Abstract—Aiming at the problems of easy collapse in the Beibuwan Basin and prone to water-lock and water sensitivity in low-pore and low-permeability reservoirs, oil-based drilling fluid is considered to be used for drilling of the target formation and acidizing and stimulating measures to ensure normal production of low-permeability oil fields; however, mud cake generated by the filtration loss of the oil-based drilling fluid, compatibility of the acid with the oil-based drilling fluid and the formation water, and the selection of the acidizing radius will influence the effect of the acidizing. Therefore, this paper takes a low-permeability oil well in Weizhou as an example, and through experimental simulation and mechanism analysis, solves the problem of mud cake breaking after completion drilling of oil-based drilling fluid, and proposes an acid system that reduces reservoir water-lock damage, keeps formation skeleton stable and realizes deep stimulating, and innovatively puts forward the new completion process of "white oil fracturing + deep acidizing" for offshore low- permeability oil fields. This new process was successfully applied in W6 well. This process has been successfully applied in W6 well, and the actual production rate is 223%, and the production has increased 1.4 times. The new completion process of "white oil fracturing + deep acidizing" in offshore low permeability oilfield proposed in this paper has a strong guiding significance for the development of offshore low permeability oilfield.

Keywords—offshore low permeability oil field; completion drilling of oil-based drilling fluid; white oil fracturing; compatibility; deep acidizing

1. INTRODUCTION

Safe and efficient development of offshore low-permeability reservoirs is a hot direction for exploration and development of oil fields in the western part of the South China Sea[1,2]. According to statistics, the development rate of low-permeability reserves in the western oil fields of the South China Sea is only 50%, and the undeveloped part is mainly concentrated in the Beibuwan Basin Liusha Harbor Group, which is characterized by the development of microcracks in the formation, and the

content of clay minerals in the whole-rock mineral analysis accounts for 30%, and some of them are more than 50%, and the clay minerals are dominated by the illite-montmorillonite mixed layer and illite, and the hydration and expansion will take place in contact with the filtrate, which will lead to the uneven force of the mudstone and aggravate the invasion of filtrate and the expansion of microcracks, resulting in hydration and spalling of rocks around the wells. This not only leads to high risk of water sensitivity, but also raises the possibility of wellbore collapse. At the same time, the depth of the target reservoir is large and the compaction is strong, which leads to low permeability of the reservoir, down to 5mD, and the risk of water- lock is elevated.

Considering the characteristics of low permeability oil fields in Beibu Gulf, such as easy collapse of well wall and high temperature of wellbore, the oil-based drilling fluid is mostly used for drilling in the target formation to ensure stable performance under high temperature and to inhibit mudstone hydration and reduce drilling torque[3,4]. Due to the high water sensitivity and water-lock damage in the formation of Liusha Harbor Group, the mud cake generated by the filtration loss of oil-based drilling fluid in the wellbore will further increase the difficulty of reservoir protection, and combined with the low production capacity of low-permeability reservoirs, it is necessary to take measures to stimulate the reservoirs and release the production capacity. The survey found that acidizing is currently an important technical means for reservoir stimulation and capacity release in small-scale, thin-thickness low- permeability oil fields[5]. The Acidizing on reservoir stimulation is mainly realized through two aspects: one is dissolving clay, unblocking the throat, and releasing oil from the clay formation with high porosity; the other is eroding the wall of the throat, lowering the flow friction resistance of the fluid through the throat, and playing the effect of reducing capillary resistance [6-9.]. Overall, acidizing can lift the reservoir injury during the construction of oil and gas wells, unblock the throat, and increase the production of the oil and gas wells. Therefore, reservoir stimulation by acidizing after drilling in oil-based drilling fluid target formation is a better idea for the development of collapse- prone low-porosity and low-permeability reservoirs in Beibu Gulf. However, the breakup of mud cake generated by filtration loss of oil-based drilling fluids will affect the channel of acid seepage into the formation and reduce the effect of acidizing, and in addition, the selection of acid system and its compatibility with drilling and completion fluids and formation fluids are the important factors restricting the effect of reservoir production capacity release after acidizing[10-12]. Therefore, there is an urgent need to carry out research on the design of acidizing process after completion of oil-based drilling fluid.

This paper takes a low porosity and low permeability oil field in Beibu Gulf as an example, through the research on four aspects of oil-based drilling fluid mud cake breaking, acid system selection, acidizing construction design and acidizing effect prediction and evaluation, a new completion process of "white oil fracturing+ open-hole deep acidizing" after drilling with oil-based drilling fluid is formed, which provides a new model for the development of offshore low porosity and low permeability oil field[13].

2. Oil-based drilling fluid mud cake breaking research

Considering the reservoir protection effect of oil-based drilling fluids, oil-based drilling fluids are commonly used for triple-zone or target zone drilling in the development wells of the Beibu Gulf, but oil-based drilling fluids can generate mud cake due to filtration loss at the wellbore, which will cause damage to the reservoir, reduce the effect of reservoir stimulation, and is not conducive to the return of drainage for the later stages of production. Oil-based drilling fluid mud cake is mainly composed of barite, clay and asphalt-based plugging materials, generally more dense, based on the characteristics of the mud cake, combined with the role of dissolution, leakage, dispersion and solubilization, for white oil, acid to carry out experimental research on drilling-based drilling fluids mud cake breaking[14-16].

2.1 Experimental Methods

The mud cake was prepared by simulating the high temperature and high pressure environment at the bottom of the well using a high temperature and high pressure water loss meter, and the mud cake was immersed in white oil and acid at room temperature and water bath of 90℃ for 2h, to compare and analyze the effect of temperature on the ability of white oil to break the mud cake, and at the same time to analyze whether the acid itself can remove the mud cake, in order to evaluate the effect of breaking the emulsion by white oil and acid.

2.2 Experimental materials and instruments

The experimental fluids were appropriate amount of white oil, acid and oil-based drilling fluid configured according to the design. The experimental instruments were a high- temperature and high-pressure water loss meter, an appropriate amount of filter paper, and a 500 mL beaker.

2.3 Experimental results and analysis

From the experimental phenomena in Fig. 1 and Fig. 2, the mud cake was immersed in white oil and acid at room temperature basically has no obvious change before and after the experiment, and the breaking effect is not good; under the condition of 90 ℃, the mud cake immersed in acid still has no obvious change, and the mud cake immersed in white oil is dissolved in less than 2h. Analysis: white oil can dissolve the mud cake generated by the filtration loss of the oil-based drilling fluid is based on the principle of similar compatibility, as the mud cake is generated by filtration at 121°C and 500 psi pressure difference for 30 minutes, under room temperature conditions, the white oil is unable to effectively disperse the solid particles in the mud cake, but the high temperature of 90 ℃ to make the molecular movement speed up, The remaining small amount of white oil in the mud cake separates out due to molecular thermal motion, accelerating the mud cake breaking. The use of acid to break the mud cake is to use the corrosive effect of acid, but the solid-phase aggravator in oil-based drilling fluid is barium sulfate, which is not soluble in any acid, so the effect of acid breaking is not good.



(1)Before the experiment



(2)2 hours later

Fig. 1 Reaction of mud cake in sample solution at room temperature (acid + mud cake on the left, white oil + mud cake on the right)



(1)Before the experiment



(2)1 hours later

Fig. 2 Reaction of mud cake in white oil solution under heating conditions

Compared with the experimental temperature, the downhole formation temperature is much higher than the experimental temperature in practical application, which will be more favorable for white oil to break emulsion. From the fact that acid cannot break the mud cake generated by oil-based drilling fluid filtration loss, while white oil can, under reservoir conditions, it is more evident that in order to ensure that the acid plays its own role well, it is necessary to circulate white oil before pumping the acid to break the mud cake, and establish a channel for the acid to play its role.

3. Acid system selection and compatibility study

Aiming at the water-sensitive damage and water-lock risk of offshore low- porosity and low-permeability reservoirs, we optimize the waterproof locking agent and clay stabilizer of the acid system to reduce water-lock and water-sensitive damage, add pressure reduction assisting agent, and reduce the difficulty of the acid to enter the low-permeability reservoirs, so that we can achieve the goal of deep acidification of the reservoirs[17-19].

Acidification treatment solution: seawater + 20% composite organic acid HWCP+ 2% waterproof locking agent HAR + 2% clay stabilizer HTW + 20% pressure reduction assisting agent + 6% corrosion inhibitor HWCI.

3.1 Main acid selection and deep stimulation mechanism

Considering that the dissolution rate has a large influence on the acidizing effect, for the characteristics of the Beibu Gulf formation, the rock chips drilled and cored in an oil field in Weizhou were used to compare the dissolution rates of 10% HWCA, 10% HWCP, 15% hydrochloric acid and on-site latent acid completion fluid wells after immersing the rock chips at 95℃ for 16h, as well as the pH value of the solution before and after the reaction, and the results show that the dissolution rate of 10% HWCP was also 1.6 times higher than that of 15% hydrochloric acid in the same conditions, so the composite organic acid HWCP was preferred as the acid for this completion process.

In order to maximize the release of reservoir capacity, the simulation evaluation of the deep reservoir stimulating performance of the target acid was carried out, and 8 consecutive dissolution experiments were conducted on the selected composite organic acid HWCP, and the dissolution rate of the acid was judged by comparing the total weights of the rock chips and the filter paper, and the results of the experiments are shown in Fig. 3. The experimental phenomena show that under the same conditions, the dissolution rate of the acid on the rock chips during the 8 experiments did not vary much, which is around 5%, and the selected composite organic acid HWCP has a good performance of deep reservoir stimulating.

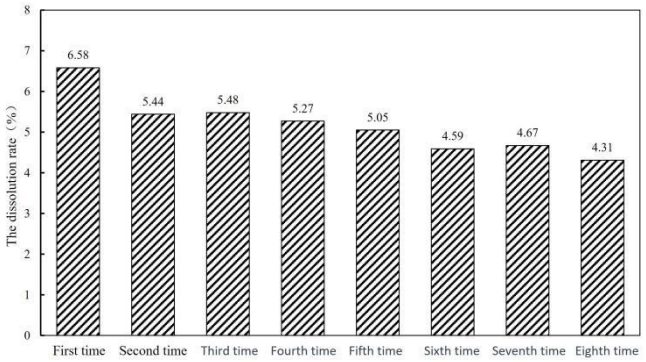


Fig. 3 Variation of dissolution rate of rock chips dissolved by composite organic acids for 8 times

Through the dissolution effect of HWCA, HWCP, hydrochloric acid and latent acid completion fluid on the target rock chips under the same conditions, combined with the dissolution rate of acid solution after many times of repeated acidizing, we get that the composite organic acid HWCP meets the requirements of open-hole deep acidizing, and is able to continue reservoir deep acidizing after lifting the filtrate zone and unblocking the flow channel, and the core shows a porous state after many times of acidizing, like the development of a "root system", and acid in the core for a long time to stay without obvious secondary damage, permeability recovery value with the increase of time has a tendency to improve. So it is confirmed that the composite organic acid HWCP is the main body of the acid.

By analyzing the characteristics of the formation pore throat channel and the drilling and completion operation process, combined with the acid fluid seepage process, the acidized reservoir stimulation process is divided into three stages[6,7]. The schematic diagram is shown in Figure 4: the first stage is to lift the filtrate zone, using its own acid liquid nature to break the emulsion, remove the solid phase particles in the open-hole section, dissolve the sensitive minerals, and improve the permeability of the near- well zone; the second stage is to unblock the flow channel, erode the throat, reduce the liquid flow friction, enhance its own flow ability, reduce the surface tension of the rock, and then dissolve the clay minerals in the throat, unblock the pore throat channel, and achieve the purpose of consolidating the acidized flow channel; The third stage is deep acidification, using the solid acidification flow channel, the acid fluid freely diffuses and infuses into the pores and throats deep in the reservoir, and by immersing the formation, the acid fluid dissolves the clay minerals in the flow channel, and then develops the "root system", connecting the deep reservoir, and realizing the effect of deep acidification.

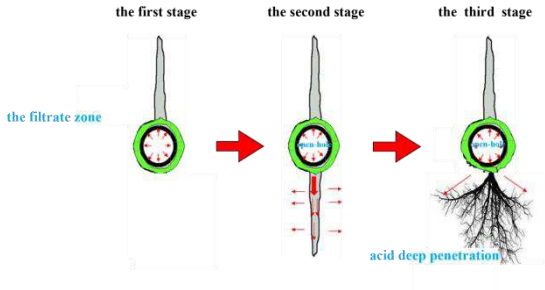


Fig. 4 Schematic diagram of three stages of reservoir stimulation using acid

3.2 Other additive options

Aiming at the high water sensitivity and water-lock damage in the formation of Liusha Harbor Group, we consider adding clay stabilizer and waterproof locking agent to the acid system to increase the reservoir protection effect of the acid system. In order to allow the acid to seep better into the formation and reduce the corrosion of the acid injection column, we consider adding pressure reduction assisting agent and corrosion inhibitor to reduce the corrosion of the column and realize deep acidizing, and preferably select the corresponding concentration.

Clay stabilizers

Through the distilled water, kerosene and clay stabilizer on sodium bentonite reaction 2h after the hydration expansion effect, found that the clay stabilizer HTW can achieve good anti-expansion performance, and clay stabilizer anti-expansion rate with the increase in the amount of additive increases, but when the anti-expansion rate reaches 92%, and then add the clay stabilizer can't make the anti-expansion rate continue to increase. Therefore, adding 2.5% clay stabilizer is considered to effectively reduce the reservoir water-sensitive damage.

Table 1 Evaluation experiment of anti-expansion property of clay stabilizer HTW by centrifugation at 1500r/min for 15min

serial number	name of test solution	Volume of clay after centrifugation(mL)
1	distilled water	8.42
	kerosene	0.43
	2.5%HTW	0.69
2	distilled water	5.98
	kerosene	0.49
	acidizing fluid	0.93

waterproof locking agent

Utilizing artificially fabricated core with a gas permeability measurement of 26.9 mD, the initial oil phase permeability was determined to be 12.68 mD. Following contamination due to aqueous solution intrusion, the oil phase permeability decreased to 7.07 mD. Employing a reverse injection approach, 24 mL of oil field injection water augmented with a 2% waterproof locking agent was introduced for water blockage removal. Post water blockage removal, the oil phase permeability was restored to 10.56 mD, achieving a water blockage removal efficiency of 62.21%, the results of the experiments proved that the 2% waterproof locking agent HAR can effectively reduce the degree of rock water blockage.

pressure reduction assisting agent

The use of optical projection method to determine the rock wetting angle, control the amount of pressure reduction assisting agent HWDA additions to determine the rock wetting angle under different conditions, the experimental phenomenon is shown in Figure 5, with the increase in the amount of HWDA additions, the rock wetting angle gradually decreased, 20% HWDA can make the rock wetting contact angle decreased by 25.72 °.The results show that: the pressure reduction assisting agent can obviously improve the reservoir rock wettability, facilitating pressure reduction and backflow. Under the same seepage pressure difference, the pressure reduction assisting agent can improve the seepage capacity of acid, greatly increase the seepage propulsion speed of acid in the low-pore and low-permeability reservoirs, which is conducive to the release of production capacity to the maximum extent of open-hole deep acidizing.

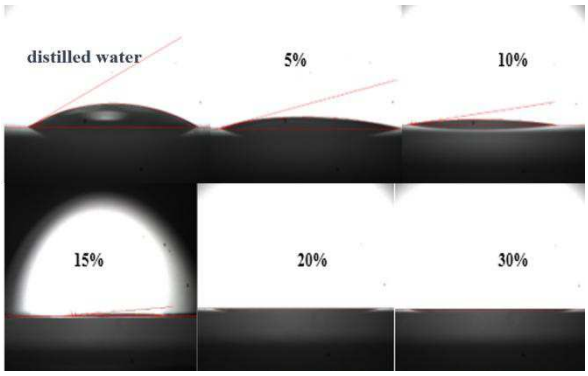


Fig. 5 Experimental phenomena on the effect of pressure reduction assisting agent HWDA addition on rock surface wettability

Corrosion Inhibitors

Based on the industry standard SY/T 5886-2012 "Corrosion Inhibitor Performance Evaluation Method", using size/surface area of 20 N80 material hanging piece at 120 ℃ under the condition of corrosion 72h or corrosion 4h, calculating the weight of hanging piece before and after the corrosion weight loss to calculate the corrosion inhibition effect. Experimental results show that 120 ℃ × 72h and 120 ℃ × 4h corrosion inhibition rate are less than 20g/m2.h, meet the petroleum industry standard corrosion control requirements, so the acid system to add 6% corrosion inhibitor.

Table 2 Clay stabilizer HTW anti-expansion performance evaluation experiment

corrosive medium	Acid + 5% corrosion inhibitor	Acid + 6% corrosion inhibitor	Acid + 6% corrosion inhibitor
corrosioncondition	120℃×72h	120℃×72h	120℃×4h
hanging piece weight loss(g)	1.5009	0.4880	0.0396
Corrosion rate ($g/m^2.h$)	10.4229	3.3889	4.9500

3.3 Acid Compatibility Evaluation

The experiments on the compatibility of acid with oil-based drilling fluid filtrates, completion fluids and simulated formation water under different ratios were designed for the initial mixing, room temperature standing and water bath heating, the experimental phenomena are shown in Fig. 5, and the statistics of the measured NTU values are shown in Table 3. After standing at room temperature, the turbidity of other mixtures basically decreased except that the turbidity of the three groups of acid and oil-based drilling fluid filtrate with the ratios of 5:5 and 7:3 as well as the ratio of acid and simulated formation water with the ratio of 3:7 slightly increased, and the turbidity of the mixtures basically decreased after heating in a water bath, which indicated that

the mixtures had good compatibility. Therefore, the selected acid system has good compatibility with oil-based drilling fluid filtrate and simulated formation water, and best compatibility with completion fluid, which can meet the process requirements of open-hole completion, white oil fracturing and deep acidizing in horizontal section of offshore low porosity and low permeability oil field.

Table 3 Turbidity measurement results for each stage of the mixtures

mix typology	proportions	preliminary mixture (NTU)	average value (NTU)	Room Temperature Standing (NTU)	average value (NTU)	post-bath (NTU)	average value (NTU)
Acid and oil-based drilling fluid filtrate	3:7	252	253	238	238	51	50.8
		254		238		50.6	
	5:5	371	375	467	464	268	268
		379		461		268	
	7:3	453	453	555	554	573	574
		453		553		575	
Acid and Completion Fluids	3:7	81.1	81.4	68.1	67.8	67.3	67.3
		81.7		67.5		67.3	
	5:5	159	156	144	144	20.0	20.1
		153		144		20.2	
	7:3	238	238	189	189	49.9	49.8
		238		189		49.7	
Acid with simulated formation water	3:7	90.7	90.6	111	113	125	121
		90.5		115		117	
	5:5	165	163	156	157	25.9	25.9
		161		158		25.9	
	7:3	262	267	255	259	84.4	84.2
		272		263		84.0	

4. Construction design and application effects

Based on the three stages of acidisation and production enhancement, the well was designed with a long horizontal section open-hole completion to increase the oil drainage area in view of the low porosity and low permeability characteristics of the reservoir; the long open-hole section was fully utilized to carry out large-scale acidizing

by adopting a large acid dosage; and the punching pipe was inserted into the sealing with perforating pipe, and the drill pipe was sent to the bottom to carry out bottom circulation, so as to realize uniform distribution of acid, and turn off squeeze injection of blowout preventer to increase the stimulation rate of the reservoir[20-21]. Considering the high content of clay minerals and strong dissolvability, it is innovative to propose acidizing by "diversion" instead of "injection", gradually leak into the reservoir by immersing the reservoir with acid, and then connect the deep pore space of the formation through diffusion , so as to realize deep acidification and achieve the maximization of reservoir capacity release. The specific operation steps of the field operation design are as follows:

1)Once the perforated pipe is in place, substitute glue breaker white oil to break up the open-hole mud cake;

2)Positively circulate the acid to the open-hole to ensure that the acid is in full contact with the formation before squeezing the acid;

3)Pitch the ball seal the top packer, take off service tool, lift the pipe column, and raise the sealing rod;

4)Positively circulating acid replaces the broken glue in the perforated tube and punch tube;

5)Turn off the blowout preventer and squeeze the acid into the formation;

6)After the end of acid squeezing, react for 2h, relieve pressure, open the blowout preventer, observe the wellbore fluid level stabilisation and then start drilling.

7)punching pipe out of the top packer until the specific gravity of the inlet and outlet is the same, and start drilling.

According to Darcy's radial flow formula, calculate the relationship between the permeability of the treated formation and the treatment radius, the treatment radius is positively correlated with the permeability, combined with the scale and cost of the treatment, the recommended treatment radius of the horizontal well's acidic capacity release measures is 0.6 m. Based on the optimal value of the acidic capacity release radius of 0.6m, the total amount of acid is designed to be 100m3 . The process of the acid preparation is carried out strictly in accordance with the formula of the acid and the requirements of the preparation on site, paying attention to the addition of various chemicals, sampling and testing the pH value after the acid solution is stirred uniformly.

According to the ground leakage experimental data converted formation pressure equivalent density 1.8g/cm3 , the vertical depth of the W6 well is 2950m, completion fluid density is 1.07, using the formula (1) to calculate the construction safety limit pressure is 3796psi.

$$P_{max} = P_f - \rho g h + f \tag{1}$$

In the equation: P_{max} is the maximum pumping pressure, MPa; $_{Pf}$ is the formation fracture pressure, MPa; ρ is the density of the completion fluid, g/cm3 ; h is the vertical depth of the well, m; f is the friction along the course.

The acid fluid is squeezed through the pressure in the drill pipe, and the injection displacement is less than 6.3bpm, and the maximum displacement is adjusted on site according to the construction pressure, so that the injection displacement can be increased as much as possible to shorten the operation time and realize the purpose of

cost reduction and efficiency increase under the condition that the wellhead pressure does not exceed the limiting pressure. Combined with the acidising construction procedure, the designed pump pressure, displacement and total amount of acid in each step of W6 well are shown in Table 4.

Table 4 Schedule of pump injection procedures for well W6

working fluid	Injection method	Pumping Pressure(psi)	Pump Displacement (bbl)	Acid Volume (m^3)
Pre-liquid + treatment liquid + top-off liquid	Orthotropic (bare eye section with perforated pipe loop)	<3796	<6.3	49
replacement fluid	Positive alternation (perforated tube and punched tube annulus)	<3796	<6.3	3
replacement fluid	Positive extrusion (topping to bare eye segment)	<3796	<6.3	48

During the on-site turn off the blowout preventer squeeze acid operation, the maximum displacement reached 1.7bbl/min, the maximum squeezing pressure was 4383psi, and the pressure drop was measured after squeezing, and the pressure dropped from 3982psi to 422psi in 36min, which indicated that the acidising effect was good. By applying the new completion technology of "white oil fracturing + deep acidizing" in the development of low porosity and low permeability oil field of W6 well, the actual production after returning to the drainage is 120m^3/d, with 100% oil content, and the rated production of 50m^3/d, with 240% production rate and 1.4 times of increased production, and the actual production is far more than the rated production.

5. CONCLUSIONS

Considering the importance of acidification in the stimulation of small-scale, thin-thickness low-permeability oil field reservoirs, combined with the use of oil-based drilling fluids in the Beibu Gulf formation to solve the problem of well bore stabilization, and the difficulties in carrying out acidizing after oil-based drilling fluids, this paper proposes a new completion process of "white oil fracturing + deep acidizing" in offshore low-permeability oil fields by using experimental simulation and

mechanism analysis. It has the following three characteristics: the combination of perforated tubular columns is used to realize uniform acid distribution and carry out large-scale reservoir stimulation; acid fluid is immersed first and then squeezed, which not only reduces the injection pressure but also increases the treatment radius; the structure of acidizing tubular columns is simple, and no high pressure is needed for the wellhead and downhole tools.

The new completion process of "white oil fracturing + deep acidizing" in offshore low-permeability oil fields achieves the goal of acidizing reservoir stimulation after drilling with oil-based drilling fluid, and the preferred acid system has good effect on deep acidizing reservoir in practical application, which provides a good model for the safe and efficient development of subsequent offshore low-porosity and low-permeability oil fields.

Data availability statements

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declarations

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