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Water Plugging and Acidizing Combination Technology on Fractured Water Breakthrough Oil Well in Low Permeability Reservoirs

WU Xiongjun[a],*

[a] Drilling Technology Research Institute, Sinopec Shengli Petroleum Engineering Limited Company, Dongying, China.
*Corresponding author.

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Abstract

During the exploration in low permeability reservoirs, oil wells are usually abruptly flooded because of the connection between injection wells and oil wells through fractures and large pore canals, causing the productivity decrease in the integral block. In this research a combination plugging agent consisting of weak gel, strong gel and temporary plugging agent is used to plug fractures and large pore canals and improve formation homogeneity by multi-slug injecting. The basic performances of gel plugging agent and the solubility of the temporary plugging agent in different solvents were determined. Furthermore, the selective plugging ability of combination plugging agent and the feasibility of the new technology were evaluated. The results show that combination plugging agent can reduce the permeability of high permeability core more than 99%, while hardly reduce the low permeability core, and by subsequent acidizing treatment, the permeability of low permeability core was increased more than 30 times, while high permeability core have be increased only a litter. Field application has been conducted in Changqing oil field. All of the three pilot tested wells are getting a good improvement. After the application of the combination technology, oil production is increased by 2.7 t per day of each well. And water content is reduced by 42.9% on average. The effective time is more than 418 days. This technology has increased 3,260.4 tons of oil and obtained an obvious effect.

Key words: Water plugging and acidizing; Low permeability reservoirs; Water breakthrough oil well; Gel plugging agent; Temporary plugging agent; Multi-slug

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INTRODUCTION

Low permeability reservoirs are difficult to be exploited because of the conflict of heterogeneity. Commonly with water flooding at the beginning of exploitation, the methods of fracturing and acidizing are necessary on its starting. As the scale of exploitation gets larger, the method parameter of oil well and the strength of reformation are enlarged, thus deepens the range of the artificial cracks. Meanwhile it is difficult for the conventional acidizing to achieve the desired effects. The heterogeneity of the formation gets more complicated, which leads to the flowing of the injected water within the cracks and even brings out the water. On the exploitation of some oil wells, there are cracks or big pore canals between the injection wells and the oil wells, which brings out the confused swell and the decline of the deliverability of the whole block. It has been a bottleneck problem that the low permeability layer is not liberated which conditions the reasonable and efficient exploitation of the low permeability reservoirs.

Water plugging and acidizing combination technology is an effective measure that improves the heterogeneity of the layers during the intermediary and later stage of the exploitation. This technique was proposed in the 1990s[1]. It has been advanced on the plugging agent system[2-5] as well as the construction method from then on[6-8]. Some techniques of selective plugging up with acidizing are all the progresses that have been made[9-10]. However, with the increase of field applications, a few problems come out, for example, the acid resistance of the plugging agent system is weak, the strength of blockage and the term of validity are insufficient and the low permeability layers are likely to be damaged by the commingled water injection[11]. Therefore, the authors advise that the combination plugging system could be used. The measure of multistage injection is a solution to the fractured canals and the oil soluble diverters play the role of guarders on the water plugging system. With such effects the sequent acidizing could be conducted on the condition that the homogeneity of formations are improved, so that the water is declined while the oil is increased.

1. EXPERIMENTS

1.1 Material

The main reagents used are partially hydrolyzed polyacrylamide (molecular weight 1.8×10^7, degree of hydrolysis 31.25%, marked as $1^{\#}$HPAM; molecular weight 1.0×10^7, degree of hydrolysis 25.06%, marked as $2^{\#}$HPAM), Phenolic resin cross linking agent (effective concentration 87%, liquid of reddish brown, marked as JL-1), Petroleum resin (sagging point 85~90 °C), Hydrocarbon resin (sagging point 130~150 °C).

The cores used are naturally low permeability cores from Changqing oil field. The core Luo33-62 and the core Hua46-39 were put into the core holders separately. The confining pressure applied on the two cores was increased rapidly until the cores were fractured. The confining pressure applied on core Luo33-62 was 12 MPa and the confining pressure applied on core Hua46-39 was 9MPa. Then, the cores were took out and packed with thermoplastic paper. The basic data of the cords is shown in Table 1.

Table 1
Basic Data of the Core Samples in the Studied Oilfield

No.	Core length, cm	Core diameter, cm	Permeability to gas, 10^{-3} μm^2	Porosity, %	Permeability to water, 10^{-3} μm^2	Permeability to water after being pressed for artificial fracture, 10^{-3} μm^2
Luo33-35	6.02	2.51	9.46	16.3	1.03	---
Luo33-62	5.98	2.50	7.62	15.9	0.89	146.71
Hua46-36	6.15	2.50	11.91	17.2	1.25	---
Hua46-39	6.07	2.51	9.27	16.1	0.97	22.15

Note. The symbol "---" in Table 1 denotes that the corresponding core was not fractured.

The water used is simulated formation water from Changqing oilfield. The salinity of the water is 43,923 mg/L, and pH is 7.2. The type of water is $CaCl_2$.

There have been both strong gel and weak gel in the lab. The formula of the strong gel is: 0.30%$1^{\#}$HPAM + 0.40%JL-1 + 0.30%JL-2; the formula of the weak gel is: 0.15%$2^{\#}$HPAM + 0.10%JL-1 + 0.15%JL-2. The gelling time, apparent viscosity and the range of favorite temperature, salinity and pH of the two gels were evaluated separately.

The petroleum resin and hydrocarbon resin were ground into fine powder and sieved by 150 and 200 mesh sieves separately. Then the two kinds of sieved fine powder were mixed of identical mass concentration to be used as temporary blocking agent. Solubility of the temporary blocking agent in different media was measured.

1.2 Method

Plugging effect and the breakthrough pressure gradient of the strong and weak gels were measured, using the pressed fracture cores Luo33-62 and Hua46-39. Specific steps as follows: (a) Pump the core to stimulate formation water and flood the water at the speed of 0.1 mL/min to measure the permeability of water phase. (b) Reversely squeeze into 2 PV of the gel blocking solution, then leave it condensate under constant temperature of 52 °C (strong cold plastic for 3.5 h; weak gel for 18 h). (c) Flood the water at the speed of 0.1 mL/min to water flooding and sharply drop until the pressure at the entrance of gripper reaches its peak. Record the highest injection pressure and calculate the breakthrough pressure gradient while the continuous fluid flows out of the entrance. (d) Flood the water at the constant speed of 0.1 mL/min. Test the water permeability rate K after blocking the water when the core remains stable and calculate the rate of water plugging system. (e) Maintain the water flow rate unchanged and continue the Water flooding. Measure the blocking rate of water plugging system under different volume of water.

With the experiment of double-tube parallel of core flow, the selective blocking rate of the combination plugging system and the feasibility for water plugging and acidizing combination technology were evaluated. The experimental procedure is shown in Figure 1.

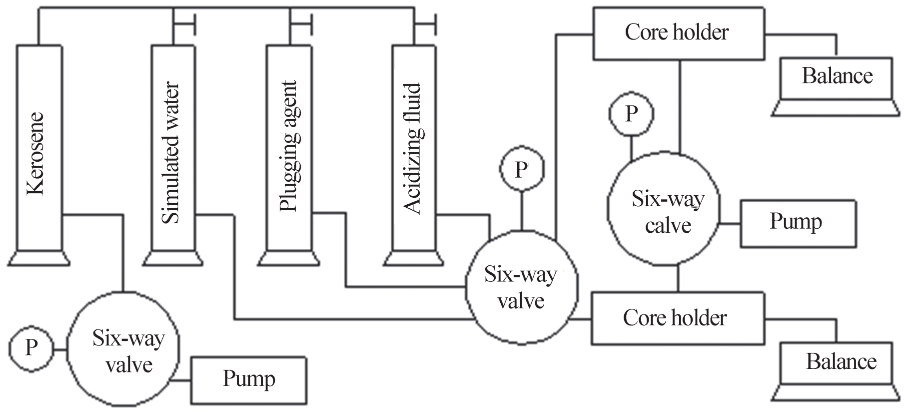

Figure 1
Schematic Diagram of Double-Tube Parallel Connection Core Flow Experiments

Specific steps as follows: (a) Select the core which has naturally low permeability and the artificial core which contains fractures. Evacuate their saturated water separately. Test their permeability at 0.1 mL/min. (b) Then make a reversal procedure to fill in the 2 PV weak gel at 0.1 mL/min, then full in 3/5 PV strong gel to make replacement, later full in the 1/5 PV temporary blocking agent which is oil soluble. Waiting for solidify under a constant temperature at 52 °C. (c) Test the permeability of the two cores at a stable filtering flow at 0.1 mL/min as K'_1 and K'_2, and calculate the plugging rate. (d) Full in the acidizing fluid reversely and then test the permeability of the two cores in a stable filtering flow at 0.1 mL/min.

2. RESULT AND DISCUSSION

2.1 Performance of the Two Kinds of Gel Plugging Agent

The basic performance of the two plugging agent (strong gel and weak gel) were measured in laboratory. The results are shown in Table 2.

Table 2
Basic Performance of the Two Plugging Agent (Strong Gel and Weak Gel)

Plugging agent	Gelling time, h	Apparent viscosity*, mPa·S	Application temperature, °C	Application salinity, mg/L	Application pH
Strong gel	3.5	653,179	40~95	2,000~360,000	6.8~10.3
Weak gel	18	51,296	46~92	2,500~300,000	5.2~9.7

Note. * Apparent viscosity is measured by Anton Paar MCR101 rheometer at 52 °C.

It can be concluded from Table 2 that the two kinds of gel plugging agents have the ability of temperature and salt resistance and they can be applied in a wide pH range.

2.2 Solubility of the Temporary Blocking Agent

The solubility in different medium of the temporary blocking agent at 52 °C is listed in Table 3.

Table 3
Solubility in Different Medium of Temporary Blocking Agent

Medium	Weight of temporary blocking agent, g	Weight of undissolved substance, g	Dissolving rate, %
Distilled water	3.0102	3.0102	0
Simulated formation water	2.9997	2.9997	0
Kerosene	3.0081	0.0035	99.88
Simulated formation oil	3.0116	0.0039	99.87
12%HCl	2.9995	2.9981	0.05
12%HCl+3%HF	3.0002	2.9975	0.09
12%H_3PO_4	2.9986	2.9977	0.03

It can be concluded from Table 3 that the temporary blocking agent has no solubility in distilled water or the simulated formation water; its solubility in three kinds of acid solutions is less than 0.1%, which shows that the temporary blocking agent is insoluble in water and acid. At the same time, its solubility in kerosene and simulated formation oil is more than 99.8%, which shows that in the layers of oil or the layers of oil/water mixture the blocking agent only has a temporary effect, and when well startup it can be cleared out with kerosene, so it will not effect the flow-back with increasing the flow pressure and it has no permanent harm to the formations.

2.3 Plugging Rate and Breakthrough Pressure of the Gels

Two artificial fractured cores (Luo33-62 & Hua46-39) were respectively plugged with the two kinds of gel, and the gradient of breakthrough pressure, permeability, water-flood pressure gradient and plugging rate were measured at 52 °C. The results are listed in Table 4.

Table 4
Plugging Performance of Strong Gel and Weak gel for Different Cores

No.	Crack types	Plugging agent system	Permeability to water, 10^{-3} μm^2	Breakthrough pressure gradient, MPa/m	Permeability to water after plugging, 10^{-3} μm^2	Plugging rate, %
Luo33-62	Wide crack	Strong gel	146.71	1.37	1.937	98.68
Hua46-39	Microcrack	Weak gel	22.15	10.56	0.405	98.17

It can be concluded from Table 4 that: (a) The plugging rate in fractured model of the two gels is more than 98%, which means that the two gels have good plugging effect. (b) When plugged, the breakthrough pressure gradient, and water-flood pressure gradient of the two cores are quite different. The breakthrough pressure gradient of the core with microcrack is 10.56 MPa/m while 1.37 MPa/m in the core with wide cracks. Analyze the results of the two cores: The microcrack model has a coarse surface and low permeability, the plugging mechanism is the same as the pore block-off, and the breakthrough pressure gradient is usually high; but for the wide cracks model, the block-off effect can only depend on the intensity of the gel, so the breakthrough pressure gradient is usually low.

2.4 Erosion-Resistant Performance Evaluation

After testing the plugging effect of the gels in the fractured cores, continue the displacement with flooding at 1 mL/min and test the Erosion-resistant performance of gels in microcrack model and wide crack model. The result is shown in Figure 2.

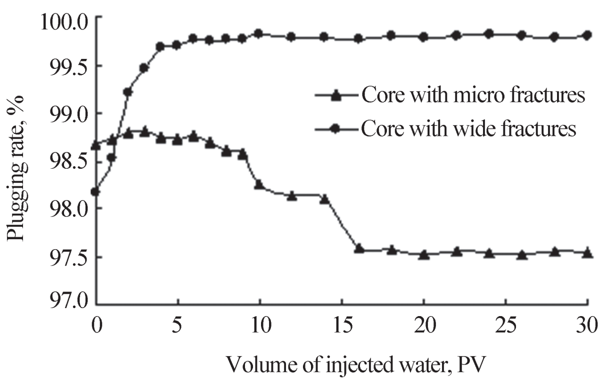

Figure 2
Curve of Plugging Rate and Multiples of Pore Volume of Injection Water in Fractured Core

It can be concluded that: The initial plugging rate of the weak gel in microcrack core is 98.68% and with the increase of sequent flooding, the plugging rate decreases a little, but it is still above 97%; the initial plugging rate of the strong gel in wide cracked core is 98.17% and with the increase of sequent flooding, the plugging rate increases at first, then keeps stable, and finally maintains above 99%.

Result analysis: To the microcrack core, at a stable velocity of flooding in, as the water volume increases, a little gel in the fractures has been squeezed off, so the plugging rate decreases a little; but to the wide cracked cores, the flooding-in pressure gradient is lower, and the gel has little damage, when the water gets into the inner structure of the gel and expands it, the flow channel in the gel gets shrink, and the flow resistance increases, so the permeability of water decreases and the plugging rate of the gel increases; when the inner structure of the gel gets saturated, the permeability of water tends to be stable.

To sum up, the two kinds of gel both have good Erosion-resistant performance and in producing process it will not lose the plugging effect with the sequent water flood-in.

2.5 Feasibility Evaluation of Water Plugging and Acidizing Combination Technology

Separate the gels and acid liquid by using multi-slug, namely, simulated formation water→ weak gel → strong gel→ temporary plugging addictive→constant temperature for condense→ acidizing fluid, as mentioned in Figure 1 above. Bank artificial and natural fractured cores with different permeability ratio to do the dual core parallel flow experiment. The results are listed in Table 5.

From Table 5, it can be concluded that in analog formation conditions, gel system gives priority to go into high permeability core to block it, the ratio is more than 99%, and it also has few influence on the low permeability core. The more different between high and low permeability core, the less influence of plugging agent system on low permeability; after acidizing, the permeability of high permeability core remains the same, but the permeability of low permeability core increases more than 30 times as much, and the greater the differential of acidizing, the better the results.

Based on the experimental results and analysis above, it can be concluded that the multi-slug plugging system is composed of weak gel, strong gel and temporary blocking agent. Weak gel is the pre-slug used to plug the fracture and large pore path in the formation preliminarily.

Meanwhile, the weak gel can also block the subsequent slug (strong gel and temporary blocking agent) partly after being squeezed into the low permeability formation inevitably during injecting process. Because of the poor resistance to acid, the weak gel can easily lose plugging ability while contacting with the acid. It plays a certain function for shielding and temporary plugging. Strong gel is the main slug in the plugging system, which can effectively plug the formation with high permeability after being continuously driven and distributed in the porous media by the subsequent slug. The temporary blocking agent is the sealing plug, which will mainly be squeezed into the high permeability layer following the principle of least resistance. The temporary blocking agent can prevent the strong gel from contacting and reacting with the subsequent acidizing fluids owing to its good acid resistance. So the plugging ability is maintained effectively in high permeability layers while the ability is almost lost in low permeability ones. As a result, the acidizing fluids are apt to be squeezed into the low permeability layer and finally increase the permeability of the low permeability layer after reacting with the matrix and filler[12].

Table 5
Performance of the Water Plugging and Acidizing Combination Technology at 52 °C

Core group	Core number	Initial permeability to water, $10^{-3}\mu m^2$	Permeability ratio	Permeability to water after plugging, $10^{-3}\mu m^2$	Plugging rate, %	Permeability to water after acidizing, $10^{-3}\mu m^2$
1	Luo33-62	146.71	164.8:1	1.24	99.15	1.27
	Luo33-35	0.89		0.81	8.99	52.99
2	Hua46-39	22.15	17.7:1	0.13	99.41	0.27
	Hua46-36	1.25		1.06	15.20	36.73

3. THE FIELD APPLICATION EFFECTS AND ANALYSIS

A pilot application of water plugging and acidizing combination technology on fractured water breakthrough oil well in low permeability reservoirs has been carried out in three oil wells in Changqing oil field. The results are listed in Table 6.

Table 6
Statistics of the Field Applications in Changqing Oilfield

No.		Luo33-35	Hua46-36	Hua46-39
Status before application	Fluid production per day, m^3	5.2	3.9	13.6
	Oil production per day, m^3	0.4	0.2	0
	Moisture content, %	92.3	94.9	100
Status after application	Fluid production per day, m^3	4.7	3.3	10.2
	Oil production per day, m^3	2.3	1.7	3.6
	Moisture content, %	51.1	48.5	64.7
Current status	Fluid production per day, m^3	4.9	3.7	10.8
	Oil production per day, m^3	2.6	1.8	4.3
	Moisture content, %	46.9	51.4	60.2
Incremental oil production per day, t		2.2	1.6	4.3
Cumulative incremental oil production, t		872.5	653.7	1734.2

It can be concluded from Table 6 that after the application of water plugging and acidizing combination technology, the total liquid production per day of each well declined slightly, but the moisture content decreased by about 40%, and oil production increased significantly, by 2.7 t per day of each well.

And water content is reduced by 42.9% on average. All of the three oil wells have got a significant improvement in increasing the amount of oil production and reducing the amount of water. The effective time is more than 418 days. This technology has increased 3,260.4 tons of oil and obtained an obvious effect.

CONCLUSION

(a) The "weak gel + strong gel + temporary plugging agent" combination plugging system can plug fractured outlets in a selectively way, with the plugging ratio above 99%.

(b) Use the multi-plug pattern to inject can solve the problem that blocking agent gel can not stay with acid. Furthermore, based on laboratory experiments, water plugging and acidizing combination technology is feasible.

(c) The field application of the technology obtains an obvious effect in increasing the amount of oil production and reducing the amount of water.

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