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Selective Water Plugging Technology for Horizontal Well with Screen Completion

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Abstract: The SD107 gel system developed has good oil–water phase selective gelation and oil–water phase selective blocking properties. The static gel-forming experiment results showed that the gel water shutoff system formulated with oilfield reinjection water (oil content < 0.05%) has a viscosity of 200 mPa·s after gelation, and the gel water plugging system formulated with oilfield produced fluid (oil content $\geq$ 20.0%) had a viscosity of 26 mPa·s after gelation. Results of the core physical simulation experiment indicated that the enhanced recovery rate was the highest (34.6%) when the resistance ratio of the high-low permeability core was about 10.0 after plugging. As per the fluid volume (Q) of the oil well to be blocked, the maximum production pressure difference (ΔP) was predicted, and on the basis of economic output, the resistance of the oil section, the resistance of the high water cut section, and the resistance of the water outlet section after plugging was used to calculate the plugging depth (re1, the limit water plugging radius), which offers a basis for the design of water plugging process parameters for horizontal wells. The field water plugging test results showed that after using this water plugging technology, the daily oil production increased from about 4 t/d to 20 t/d, the daily oil increase was 16 t/d, and the water cut decreased from 75% to about 25%. The water-blocking construction was a success.

Keywords: screened horizontal well; seepage resistance; selective water plugging agent; water plugging scheme design; field test

Citation: Deng, B.; Jia, Z.; Liu, W.; Liu, X.; Gu, J.; Ye, W.; Wen, H.; Qu, Z. Selective Water Plugging Technology for Horizontal Well with Screen Completion. *Energies* **2021**, *14*, 791. https://doi.org/10.3390/en14040791

Academic Editor: Jens Birkholzer
Received: 28 December 2020
Accepted: 28 January 2021
Published: 3 February 2021

1. Introduction

Casing and perforating completions, screen completions and open hole completions are the three main methods for horizontal well completion [1], and 70% of domestic and 90% of foreign horizontal wells are completed by screen [2]. In the wake of oil fields' development, most of the horizontal Wells have entered the medium and high water cut period, and water plugging has turn into the main method of enhancing oil recovery in the later period of horizontal well development in China.

According to injection technology, water plugging technology in horizontal wells can now be split into mechanical water shutoff and chemical selective water shutoff [3]: mechanical water shutoff includes preset working cylinders, packers, etc., and chemical water shutoff methods include the usual injection plugging agent, ACP seals the well section, etc. Mechanical plugging of water applies to casing well completion [1]. It is effective in the initial stage of pumping. However, the formation water at the outlet is easy to leak from the outside of the pipe to the nearby production well, resulting in short water plugging period and unsatisfactory water plugging measures [4]. Chemical selective water plugging is to use the different chemical properties of plugging agent in oil and water environment to achieve the goal of water plugging without oil plugging or less oil plugging. It applies to horizontal wells with unclear water-producing horizons or physical separation due to wellbore structure or technology [5].

In recent years, the domestic Tahe Oilfield has started selective water plugging of horizontal wells for exceeding 50 well times [6]. The emulsion plugging agent was implemented for 42 well times, with an effective rate of 59.5% and a cumulative oil increase of 2.61×10^4 t. The temperature-resistant organic jelly is implemented for 7 well times, the effective rate is 71%, and the cumulative oil increase is 0.54×10^4 t. The particle and emulsion composite plugging agent is implemented for 2 well times. The efficiency is 100% and the cumulative oil increase is 704.43 t.

Ghosh et al. [7] aimed at the phenomenon that most extended horizontal wells and vertical wells with permeability heterogeneity usually producing water prematurely due to many high permeability stripes and conductive fractures. An optional rig-less water control scheme using the sequential action of three chemical fluids has been developed. The results show that this scheme reduced water permeability by 85–90% and oil permeability by less than 15%. Kadyrov et al. [8] proposed a new technology to control poor water production in the open-hole section of horizontal wells aimed at carbonate reservoirs. The main principle is that the coiled tubing passes through the auxiliary horizontal well parallel to the main horizontal well for water-shutoff treatment and uses polyaluminum chloride and polyacrylamide to form a rigid water barrier. The results showed that the use of tracers (water-shutoff components) on the upper and side of the horizontal wellbore is more important than the previous water-shutoff treatment. Zaripov et al. [9] discussed a method to increase the production of heavy oil by temporarily blocking the under-saturated oil zone in the early stage of steam injection and oil production horizontal well pairing. The comprehensive use of reservoir simulation to design the water plugging gel provides the best choice for plugging the water production area, thereby enhancing the recovery efficiency of steam-assisted heavy oil. Czarnota et al. [10] put forward the optimization method of horizontal well length under the quasi-steady flow condition considering wellbore pressure drop and described the change of reservoir pressure in the production process with the general material balance method. Ghahri et al. [11] developed an in-house simulator to realistically simulate the multiphase flow of gas and condensate around horizontal wells. Based on these simulation results, a new method for predicting the productivity of horizontal wells in gas and condensate system was proposed, so as to do a dynamic prediction of horizontal wells, which greatly facilitated the application of engineering decision-making, and management decision-making to horizontal well technology. Fang et al. [12] optimized the design of particle plugging agents and new interpenetrating network gel composite system and carried out plugging experiments and oil displacement experiments for flawless cores and fractured cores. The results showed that the new type of mutual gel time of the penetrating network gel system could reach 6–7 h at low-temperature conditions (30 °C), and it had strong shear resistance and viscosity retention. Chen et al. [13] aimed at the phenomenon that the traditional model which only considers the gel mechanism can not correctly predict the dynamic performance of horizontal wells, presented a new reservoir wellbore coupling model for horizontal well cementing and water cut prediction. A case prediction of on-site horizontal water interception is carried out, and the results show that satisfactory results of water interception treatment can be provided by the coupling modeling method.

Generally speaking, there are still technical bottlenecks in choosing plugging agents and injection technology for chemically selective water plugging in horizontal wells [14–16]: (1) there is still short of plugging agents with good reservoir applicability and strong oil-water selectivity. In general injection [17–21], the blocking strength of the phase permeability regulator is too low, easy to vomit, and the implementation effect is poor; the gel plugging agent is easy to enter the pay zone and cause productivity damage [22,23]. (2) There is no mature water plugging technology for selective water plugging of slotted screen horizontal wells [24]. In this paper, a new selective water plugging system is developed and evaluated. Based on the equivalent seepage resistance method, the key parameters of water plugging in horizontal wells, including the resistance of the oil section, the resistance of the high water-cut section and the resistance of the water outlet section after plugging are calculated. The new water plugging system have been applied in field tests, which offers a basis for the design of water plugging process parameters for horizontal wells, and improves the pertinence and pertinence of water plugging design in horizontal wells.

2. Development and Performance Evaluation of Selective Water Plugging System

2.1. Water Plugging Mechanism

According to the application effects of different types of chemical agents in domestic oilfields, gel-type plugging agents are preferred to block high-permeability water channeling channels. This type of plugging agent is formed by cross-linking of water-soluble polymers and preferentially enters the water channel with high water content and good physical properties [25]. Moreover, since the gel has a strong oil-water selectivity of "expanding in contact with water and shrinking in contact with oil", even if it enters the same outlet channel of oil and water, it can realize the technology of "blocking water without (or less) blocking oil" through the function of "smart" switch aims.

Selective water plugging not only involves the selective plugging of oil and water by the plugging agent, but also the selective entry of the plugging agent into the formation. Core simulation test results and coring well data show that the water-washed sections of oil layers with large permeability differences are all in high-permeability formations, while low-permeability formations have extremely poor water flooding effects and basically maintain the original oil saturation [26,27]. After long-term research experiments and field applications, many mature selective plugging agents have been studied. With reference to the application effects of different types of chemical agents in oilfields at home and abroad, gel-type plugging agents are preferred to block high-permeability water channeling channels [28]. This type of plugging agent is a water-soluble polymer added with a cross-linking agent to cause the polymer to produce intermolecular or intra-molecular cross-linking. During the water plugging process, the water-soluble plugging agent preferentially enters the high permeability formation and rarely enters the low permeability formation. Because the jelly has a strong oil-water selectivity of "expanding with water and shrinking with oil", even if it enters the same outlet channel of oil and water, it can effectively block the high permeability zone and expand the spread of injected water through the "smart" switch. Coefficient, improving the water injection effect of crude oil in the low permeability zone, achieves the technical goal of "water plugging without (or less) oil plugging", and increasing the oil recovery rate of water injection development.

Polyacrylamide is a water-soluble high-molecular polymer with a linear main chain and active groups on its side chains, which have different effects on oil and water (shown in Figure 1). The mechanism of action is that after the organic silicon enhancer is hydrolyzed, the two groups in the molecular structure diffuse to the surface of similar polarity, and one end of the hydroxyl group on the rock surface undergoes hydrolysis and condensation to form a molecular film with a network structure covering the rock surface. The adhesion; the organic group reacts with the amide group and carboxyl group on the partially hydrolyzed polyacrylamide molecule to form a three-dimensional network structure, thereby realizing the cross-linking process between dissimilar materials and improving the polymer and rock bonding ability of the surface. The flow resistance of water is increased, the water permeability is reduced, and the purpose of reducing water outflow from the formation is achieved. When oil passes through these pores, the polymer molecules shrink and stick to the rock surface. There is no significant increase in the resistance to oil flow, and the damage to the oil phase permeability is small. Limit water production in the well without affecting oil and gas production. There is no need to measure the water source or the barrier section during treatment, and the treatment cost is low.

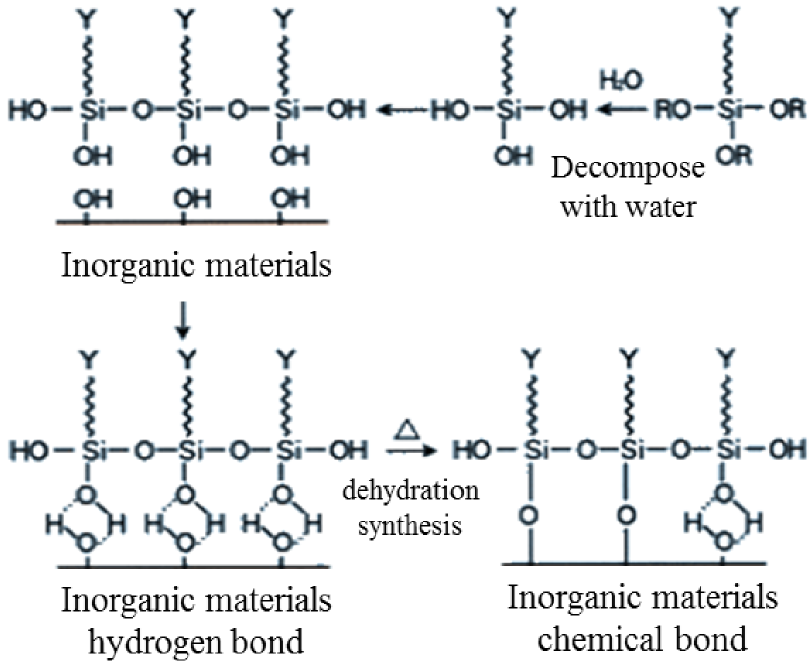

Figure 1. The selective water plugging mechanism of the SD107 gel system.

2.2. Selectivity Evaluation Experiment of Plugging Agent

2.2.1. Evaluation of SD107 Gelling Selectivity

(1) Experimental materials

Oil and water sample preparation: 500 g of Y oilfield produced fluid (20% oil content, 80% water content), and 500 g of Y oilfield produced water.

Selective gel system composition: The polymer was anionic comb polyacrylamide (SD201 molecular weight 18 million). The cross-linking agent was organic carboxylic acid chromium (SD107). The strengthening agent was hydroxyethyl aminopropane triethoxysilane (SD102).

Jelly solution configuration: We used Y oilfield produced fluid and Y oilfield produced water respectively, to prepare 350 mL jelly solution. The formula used polymer concentration of 0.30%; cross-linker concentration of 0.30%; enhancer concentration of 0.25%.

(2) Experimental process

According to the recommended formula, we used Y oilfield produced fluid and Y oilfield produced water respectively to prepare 350 mL jelly solution, pouring it into a container, in a constant temperature water bath set to 50 °C, constant temperature time 48 h, and then remove. Pour the sample into a beaker, observe the gel state of the two samples, and test the viscosity data with a Bush viscometer.

(3) Experimental results

Results of the experiment show (Figure 2) that the produced fluid water plugging system of Y oilfield is in an ungelled state after constant temperature, maintaining fluidity. The gel water plugging system in the produced water of Y oilfield obviously became more viscous, and the water plugging system had a good gelling performance; the Bush viscometer test viscosity data was that the gelled water plugging system prepared by the produced water of Y oilfield had a viscosity of 200 mPa·s after gelling. For the Y oilfield produced fluid prepared gel water plugging system, after a constant temperature of 48 h, the viscosity of the water plugging system was 26 mPa·s, and it could be seen that the SD107 plugging agent had good gelling selectivity.

Figure 2. SD107 water plugging system gelled state in sewage and oil-water mixture.

2.2.2. Evaluation of SD107 Gel Blocking Selectivity

(1) Selection of experimental materials and formulas

Oil and water sample preparation: the Y oilfield produced 2000 g of oil and the Y oilfield produced 5000 g of water.

Selective gel system composition: polymer (SD201), cross-linking agent (SD107), strengthening agent (SD102 (II))

Gel solution configuration: we used the Y oilfield produced water, prepare three kinds of strength gel solution are 350 mL, the formulas used polymer concentration 0.30~0.50% + cross-linking agent concentration 0.30~0.40% + enhancer concentration 0.25~0.35%.

Three different gels were prepared, and the formulation are shown in Table 1.

Table 1. The formulation of three different gel.

Number	Polymer Concentration/%	Cross-linking Agent Concentration/%	Enhancer Concentration/%
1	0.3	0.2	0.25
2	0.4	0.3	0.3
3	0.6	0.3	0.35

(2) Experimental method

The simulated oil displacement device and supporting facilities (shown in Figure 3) were used to conduct experiments to produce a sand-filled core model tube (length 50 cm, diameter 2.5 cm), and the water (oil) measured permeability of the model tube reached 2.5~3.0 μm^2. We measured the pore volume (PV) of the core tube and conducted a simulated plugging experiment at a constant temperature of 60 °C, injecting a selective gel plugging system, and performed water flooding (oil flooding) after a certain constant temperature for a certain period of time to test the core plugging rate and residual resistance.

(3) Experimental results

The experimental results show (Table 2, Figures 4–8) that on 3 cores with similar permeability (2.0~3.0 μm^2), after water flooding, 0.6 PV plugging agent systems of different strengths (1#, 2#, 3#), the water flooding test after the plugging agent was gelled, the plugging rate produced by the core is greater than 98%, and the residual resistance coefficient was 57.19~81.47. On the core with similar permeability (2.0~3.0 μm^2), after oil flooding, 0.6 PV plugging agent system (3#) was injected, and the oil flooding test after the plugging agent gelled, the plugging rate produced by the core was 77.55%, and the residual resistance, the coefficient was 4.45. It can be seen that the SD107 plugging agent has good oil-water phase selective plugging and water phase high-strength plugging performance.

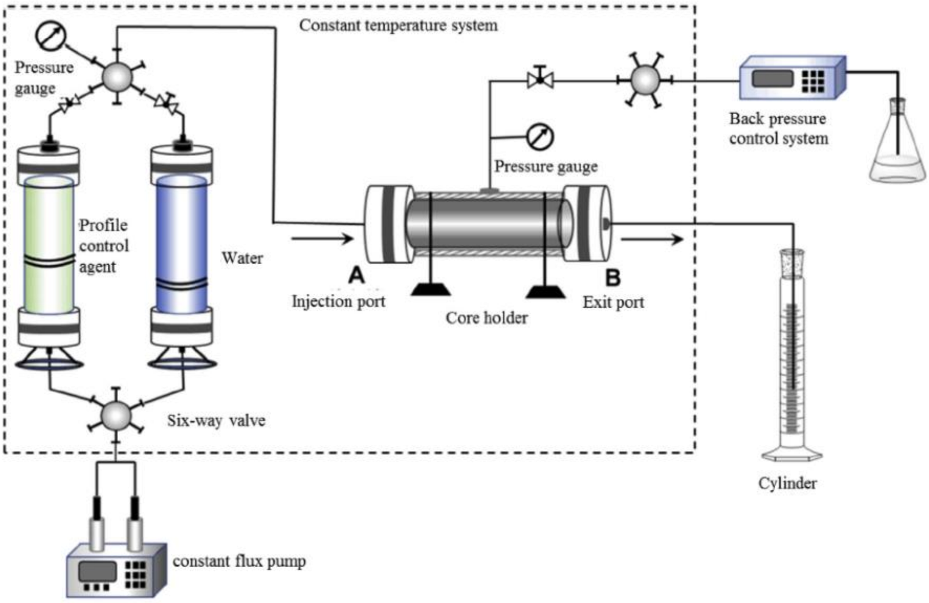

Figure 3. Experimental device.

Table 2. Core parameter data of 1#~3# formulation system before and after plugging.

Medium Types	Jelly Formula/%	System Viscosity/mPa·s	Steady Pressure/MPa	Core Permeability/μm^2	Permeability of Subsequent Flooding 2 PV/μm^2	Follow-Up Drive 2 PV Blocking Rate/%	Follow-Up Drive 2 PV Residual Resistance
Water phase	0.3 + 0.2 + 0.25	140	0.00675	2.514	0.0440	98.25	57.19
	0.4 + 0.3 + 0.30	380	0.0075	2.263	0.0309	98.64	73.33
	0.6 + 0.3 + 0.35	980	0.0075	2.263	0.0278	98.77	81.47
Oil phase	0.6 + 0.3 + 0.35	980	0.072	2.628	0.5900	77.55	4.45

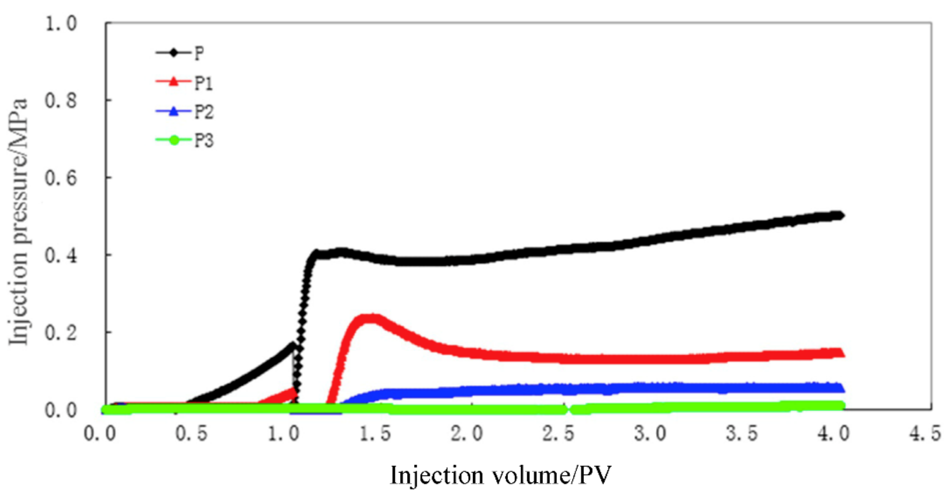

Figure 4. 1# Formula system displacement pressure curve before and after plugging (water phase).

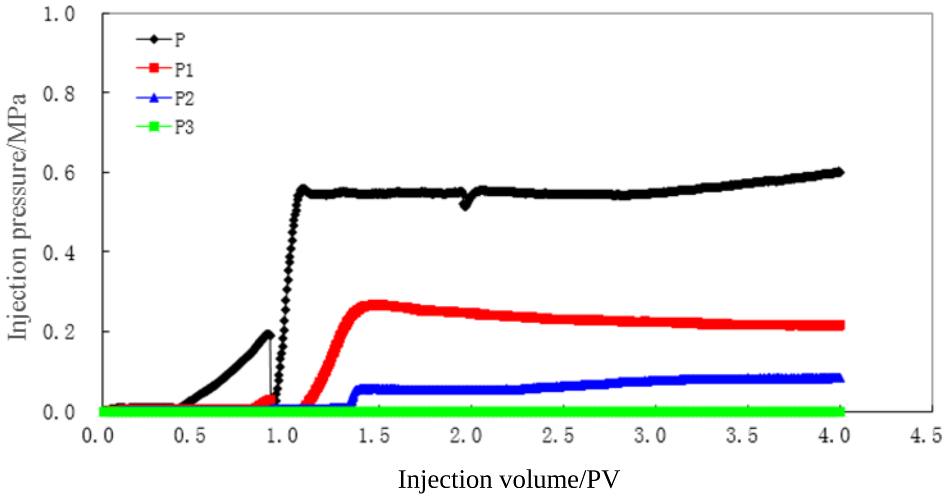

Figure 5. 2# Formula system displacement pressure curve before and after plugging (water phase).

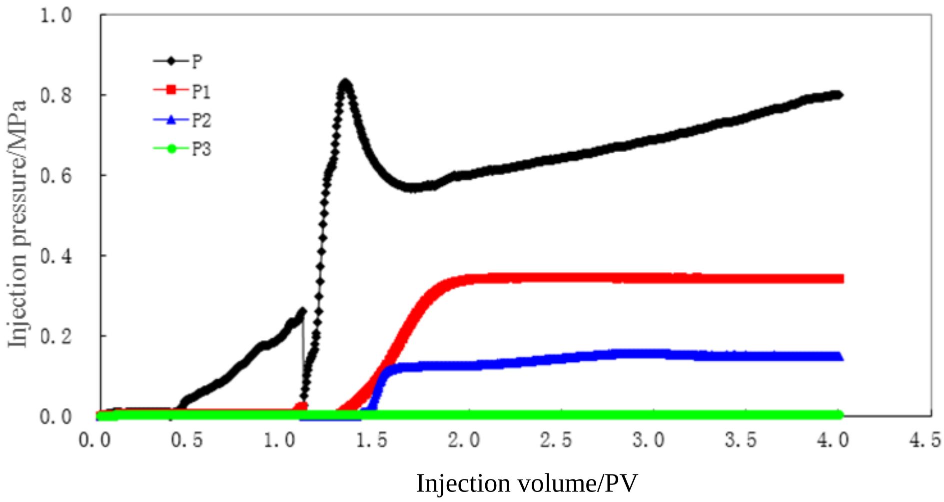

Figure 6. 3# Formula system displacement pressure curve before and after plugging (water phase).

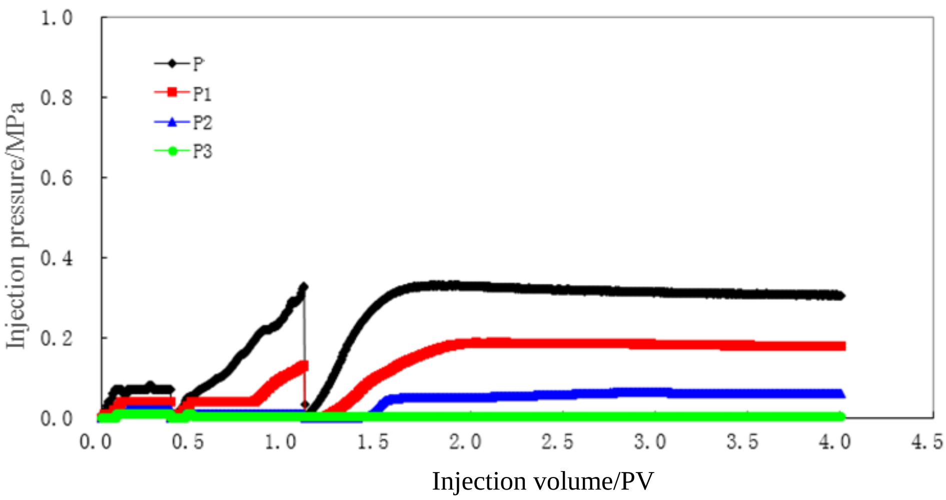

Figure 7. 3# Formula system displacement pressure curve before and after plugging (oil phase).

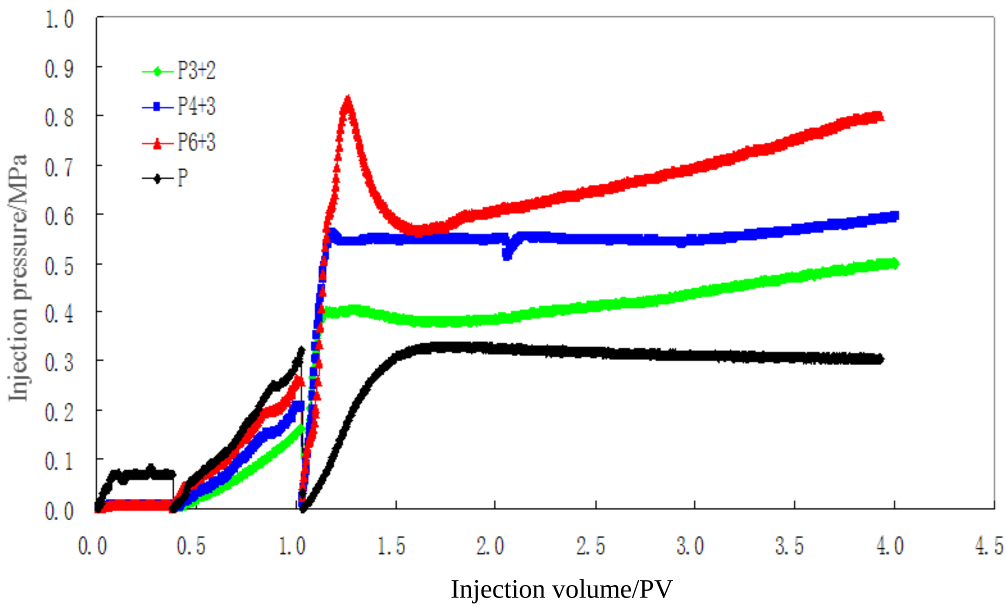

Figure 8. 1#–3# Formula system displacement pressure curve before and after plugging.

2.2.3. Evaluation of SD107 Gel Blocking Effect

(1) Selection of experimental materials and formulas

Oil and water sample preparation: the Y oilfield produced 2000 g of oil and the Y oilfield produced 5000 g of water.

Selective gel system composition: polymer (SD201), cross-linking agent (SD107), enhancer (SD102).

Gel solution configuration: using Y oilfield produced water, the three strength gel solutions are 350 mL, and the formula uses polymer concentration 0.40% + cross-linker concentration 0.30% + enhancer concentration 0.30%.

(2) Experimental methods and procedures

a. Experiments were carried out with simulated oil displacement equipment and supporting facilities (Petroleum Scientific Research Instrument Co., Ltd., Haian County, China), and nine sets of sand-filled core model tubes with low permeability (size: length 50 cm, diameter 2.5 cm) were made. As per the permeability requirements, the permeability of 1.0 μm^2 and 3.0 μm^2 was designed, according to the mass ratio of 80–100 mesh:100–120 mesh:160–200 mesh = 2:2:1 to fill 1.0 μm^2; according to 80–100 mesh:100–120 mesh:160–200 mesh = 3:1.5:0.5 mass ratio of sand filled 3.0 μm^2, after mixing uniformly, fill the core tube model according to a certain degree of compaction.
b. The dry weight of the core was measured as m1, the saturated formation water was evacuated, the wet weight was measured as m2, the pore volume was measured (v = (m2–m1)/p water), and the porosity was calculated.
c. The pipelines were connected in accordance with the experimental procedure and the water permeability was measured. The pressure change range of 30 min was less than 5% or unchanged, and the permeability was calculated as per Darcy's law.
d. At a constant temperature of 55 °C, the high and low permeability cores were saturated with oil, respectively, and the saturated oil was stopped when the outlet oil content was greater than 98%.
e. The high and low permeability cores were connected in parallel and the water flood tests was carried out, and the water flood tests were stopped when the comprehensive water cut reached 98%.

f. On nine sets of parallel cores, plugged the high-permeability cores, and injected the plugging agent system 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0 times the volume of the high-permeability cores, and kept the temperature at 5 °C for 48 h.
g. After the constant temperature process, the resistances of the high- and low-permeability cores were tested, respectively. After the test, the high- and low-permeability cores were connected in parallel for the subsequent water flood experiments, and the water flood experiments were stopped until the comprehensive water cut reaches 98%.
h. After the entire process of the displacement experiment and the high-permeability plugging, the relationship between the ratio of resistance to the flow of high-permeability and low-permeability cores and enhanced oil recovery was analyzed.

(3) Experimental results

On nine sets of parallel cores with low permeability of 1.0 μm^2 and high permeability of 3.0 μm^2, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0 of the high permeability core volume were injected into the high permeability cores. The experimental results showed that (Figure 9), as the amount of plugging agent injected increases, the ratio of high permeability resistance to low permeability resistance gradually increases, and the comprehensive enhanced oil recovery value first increases and then slowly decreases; When the high-low permeability core resistance ratio is 1.2 to 9.8, the enhanced oil recovery value increases with the increase of the plugging dose; when the high-low permeability core resistance rate is greater than 9.8, the enhanced recovery value increases with the increase of the plugging dose. Results of the experiment indicated that when the high-to-low permeability core resistance ratio is about 10.0, the enhanced recovery rate is the highest.

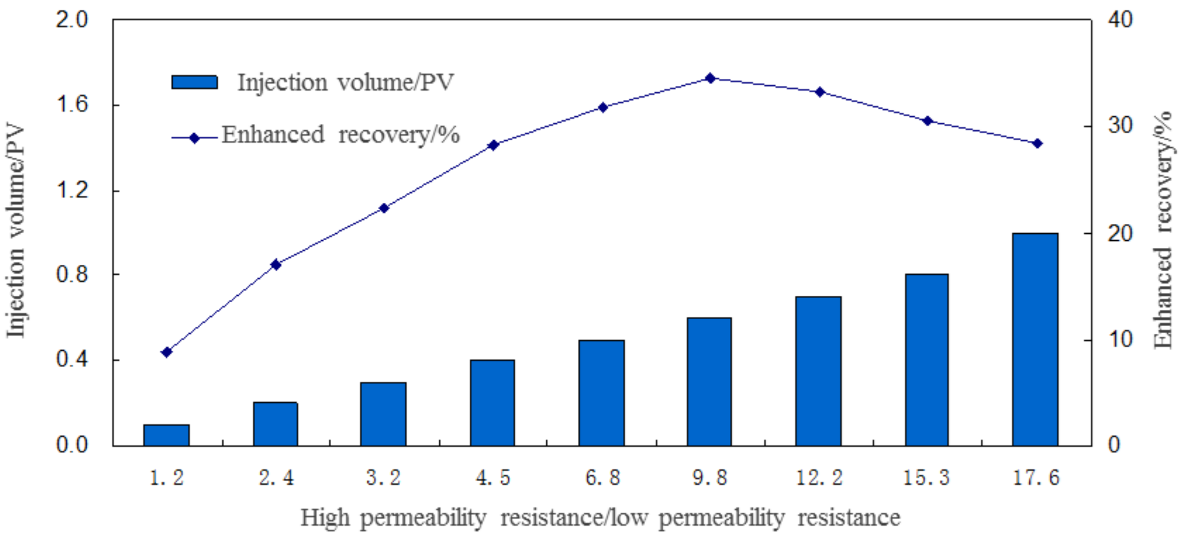

Figure 9. The relationship between the ratio of high permeability resistance to low permeability resistance and enhanced oil recovery after plugging.

The results of indoor system research and development experiments and physical simulation blocking experiments have shown that the main composition of the SD107 jelly system formula developed are: polymer concentration 0.30~0.50% + cross-linking agent concentration 0.30~0.40% + enhancer concentration 0.25~0.35%; SD107 gel system has good oil-water selective gelling performance and oil-water selective plugging performance; when the high-to-low permeability core resistance ratio is about 10.0 after plugging, the enhanced recovery rate is the highest (which can increase the recovery rate by 34.6%).

3. Determination of Key Parameters of Water Plugging in Horizontal Wells

Horizontal well production technology is one of the important technologies to improve the efficiency of oilfield development. At present, a high water cut in horizontal wells is a difficulty that restricts the efficient development of horizontal wells. Research on horizontal well water plugging selective plugging agents and water plugging parameters is the core of horizontal well water plugging technology. These are mainly involved in horizontal well water plugging process parameters such as plugging depth, plugging agent strength, plugging agent dosage, combination mode, and on-site injection pressure control.

3.1. Calculation of Seepage Resistance of Oil-Water Seepage Channels

On the basis of the previous experiment, according to the method of equivalent permeability resistance, the resistance of the oil outlet section and the water outlet section after plugging are shown in Formulas (1) and (2), respectively, and the effective plugging depth and plugging agent are the calculated strength [29].

$$R_0 = \frac{\mu_0}{2\pi K h_0} \ln \frac{r_e}{r_w} \tag{1}$$

$$R_w = \frac{\mu_{gel} R_{ff}}{2\pi K h_w} \ln \frac{r_{e1}}{r_w} + \frac{\mu_w}{2\pi K h_w} \ln \frac{r_e}{r_{e1}} \tag{2}$$

where R_0 is the resistance of the oil outlet section, Pa/(cm^3/s). μ_0 is Viscosity of underground crude oil, mPa·s. μ_{gel} is the viscosity of the gel, mPa·s. μ_w is viscosity of oil-water mixture in water channel, mPa·s. K is the average permeability of the formation, μm^2. h_0 is the length of the oil outlet section, cm. R_w is the resistance of the outlet section, Pa/(cm^3/s). h_w is the length of outlet section, cm. r_e is liquid supply radius, cm; r_w is wellbore radius, cm. R_{ff} is the residual resistance coefficient of jelly and r_{e1} is blocking range of plugging agent, cm.

3.2. Prediction of Water Plugging Depth of Horizontal Wells

The goal of water plugging is to obtain the maximum oil production and the lowest water cut. Nevertheless, the fluid supply capacity of the oil well needs to be guaranteed after the water plugging. Therefore, a reasonable plugging range needs to be studied to ensure the normal production of the oil well after the water plugging. Starting from the principle of fluid percolation, the percolation resistance of oil phase, water phase, and oil-water phase is taken as the research object, and the plugging range is calculated on the basis of the method of equivalent percolation resistance (Equations (1) and (2)).

According to the liquid volume (Q) of the oil well to be blocked, the maximum production pressure difference (ΔP) is predicted, and the plugging depth (re1, the limit water blocking radius) is calculated on the basis of economic production [29].

$$\frac{1}{R} = \frac{1}{R_0} + \frac{1}{R_w} \tag{3}$$

$$Q = \frac{\Delta P}{R} \tag{4}$$

where Q is production, ΔP is production pressure difference, R is section resistance, Pa/(cm^3/s). R—resistance, Pa/(cm^3/s), R_0 is the resistance of the oil outlet section, Pa/(cm^3/s), and R_w is resistance of the outlet section, Pa/(cm^3/s).

3.3. Calculation of Water Plugging Consumption for Horizontal Wells

In general, the amount of plugging agent is related to the length of the plugging section, effective porosity, plugging depth, and other parameters. The statistical data of the on-site water-finding test results of high water-cut horizontal wells show that the length of the water outlet section of a general high water-cut horizontal well accounts for 10–20% of the length of the production well section (the length of the water outlet section hw: the length of the oil-bearing section hO = 1:9~1:4). The water output situation of horizontal wells is relatively complicated, and the amount of water plugging in horizontal wells needs to be combined with the location and shape of the water to conduct a study on the optimization design of the amount [29].

$$Q_p = \pi {r_{e1}}^2 L\phi c \quad (5)$$

where Q_p is the amount of plugging agent, m^3, c is correction factor, L is the length of plugging section, and ϕ is effective porosity.

4. Field Application

4.1. Production Dynamics and Effluent Analysis

Well H2 is a horizontal well in the east section of Yuedong Oilfield. It was completed in February 2011 with a depth of 2356 m and a completion zone of Ed1III1. The effective thickness of Ed1III1 is about 10 m, the oil saturation is about 67%, the average porosity of the reservoir is about 33%, and the average permeability is about 2100 × 10^{-3} μm^2. The viscosity of underground gas-bearing crude oil is estimated to be 800~1000 mPa·s, the salinity of groundwater is about 1500 ppm, the formation temperature is about 55 °C, and the original formation pressure is about 13.5 MPa.

The pump started production on 27 February 2011, with an initial daily output of 30–80 t, basically water-free, and the well was shut down in September of the same year. It started in May 2013 and started normal production in November. Initially, the daily oil production was 45 tons, which was basically free of water; after that, the water content rose slowly and the oil well produced stable fluid production. On 29 December, 2014, the water content rose from 14.8% to 48.2%, the water content rose to 82.3% within 10 days, and the daily oil production was 7 tons. From 9 January to 9 February, 2015, after the well was shut down and heated, the water content of the well opened was above 50% and continued to rise, showing obvious characteristics of water channeling. As of 6 June 2015, the daily fluid production was 20.4 t, the daily oil production was 4.9 t/d, the water content was 76.0%, the cumulative fluid production was 3.47 × 10^4 t, the cumulative oil production was 3.09 × 10^4 t, and the cumulative water production was 0.38 × 10^4 t.

The water content of the H2 well rose shortly after it was put into production; the initial rise was slow, and the later stage was violent flooding, and the recovery was low, indicating that there may have been a small-scale special channel near the well, and the water should be small. During the period, the dynamic liquid level was stable at 100 m, and the oil pressure was stable at 0.5 MPa, indicating that there was a large energy body of water at a long distance.

4.2. Water Blocking Test

The reservoir where the horizontal section of Well H2 was located was continuously developed, with a large effective thickness, and the horizontal section was long (about 600 m). The water channel had just begun to form and the plugging time was good. However, it was a slotted screen completion, and the location and scale of the water outlet point (section) could not be correctly judged. Therefore, the construction of selective water plugging with chemical agents in the H2 well was difficult. On the basis of ensuring the better selectivity of the plugging agent, it was necessary to scientifically design the amount and injection parameters of the plugging agent so that the plugging agent could enter the channeling channel without polluting the oil outlet section.

According to the method of equivalent permeability resistance and the actual reservoir parameters (Table 3), the output section resistance Formula (1) was used to calculate R_0, and the R_w was calculated according to Formula (4). Then the plugging radius re1: 10 m is calculated on the basis of Formula (2) of the resistance of the outlet section after plugging.

Table 3. Value of each parameter.

Parameter	Value	Parameter	Value
Underground crude oil viscosity/mPa·s	800	Residual drag coefficient	15
Length of oil outlet section/cm	5000	Water channel mixture viscosity/mPa·s	120
Liquid supply radius/cm	25,000	Gel viscosity/mPa·s	200
Wellbore radius/cm	5	Average permeability of formation/μm^2	2.1
Porosity/%	35	Length of oil outlet section/cm	1000

On the basis of the judgment of point (segment) effluent, the length of the design plugging section is 50 m, and the number of plugging agent was calculated according to Formula (5), then the amount of major plugging agent was 1055 m^3.

It was predicted that the liquid volume after plugging would be 33 m^3/d, the water content would drop to 27%, and the production pressure difference will be 4.2 MPa. According to Formula (3), the resistance R after water plugging could be calculated as 0.127 Pa/(cm^3/s).

During the on-site implementation (Figure 4), the pressure climbed gently, from 0 MPa to 8 MPa approximately linearly. When the strong slug is injected, the oil pressure rises to a maximum of 8 MPa, and slowly drops to 6.5 MPa at the end of the construction, and the injection ends. Before water plugging, the daily fluid production was 20.4 t/d, the daily oil production was 4.9 t/d, and the water content was 76.0%. After the water plugging, the daily fluid production was 27.3 t/d, the daily oil production was 20.4 t/d, and the water content was 25.3/%; The oil increase was 15.5 t/d, and the water cut decreased by 50.7% (Figure 5). A good water plugging effect was seen.

5. Conclusions

(1) The main composition of the SD107 jelly system developed is: polymer concentration 0.30~0.50% + cross-linking agent concentration 0.30~0.40% + enhancer concentration 0.25~0.35%; the system has good oil-water selectivity Glue and oil-water selective plugging properties; the enhanced oil recovery rate is highest when the high–low permeability core resistance ratio after plugging is about 10.0.

(2) On the basis of the equivalent seepage resistance method, the resistance of the oil section, the resistance of the high water cut section, and the resistance of the water outlet section after plugging are calculated, which are the horizontal well water plugging process parameters (plugging depth, plugging agent strength, plugging agent dosage, combination mode, and on-site injection pressure control, etc.) design provides a basis for improving the pertinence and theory of horizontal well water plugging design.

(3) Results of the field test indicate that the daily fluid production before water plugging is 20.4 t/d, the daily oil production is 4.9 t/d, the water content is 76.0%, the daily fluid production after water plugging is 27.3 t/d, and the daily oil production is 20.4 t/d, Water cut is 25.3/%; daily oil increase is 15.5 t/d, water cut is reduced by 50.7%, a good water plugging effect is seen, and a new successful model for water plugging of horizontal wells with slotted screens of the same type has been established.

(4) The selection of a good oil-water phase selective plugging agent and accurate water plugging process parameter calculation method established a new model and successful experience for water plugging in horizontal wells with slotted screens of the same type, and improved the pertinence and theory of horizontal well water plugging technology.

Author Contributions: Writing—original draft: B.D.; resources: Z.J.; writing—review and editing: W.L.; data curation: X.L.; formal analysis: J.G.; Validation: W.Y.; Funding acquisition: H.W.; Funding acquisition: Z.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China under Grand 2020YFA0711800 and the National Natural Science Foundation of China (Grant No. 51874338).

Institutional Review Board Statement: This paper is not related to ethical problem. We choose to exclude this statement because the study did not require ethical approval.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to its new invention.

Acknowledgments: The authors would like to acknowledge the financial support of the National Key R&D Program of China under Grand 2020YFA0711800 and the National Natural Science Foundation of China (Grant No. 51874338).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

R_0	the resistance of the oil outlet section, Pa/(cm^3/s)
μ_0	viscosity of underground crude oil, mPa·s
μ_{gel}	viscosity of the gel, mPa·s
μ_w	viscosity of oil-water mixture in water channel, mPa·s
K	the average permeability of the formation, μm^2
h_0	length of oil outlet section, cm
R_w	resistance of the outlet section, Pa/(cm^3/s)
h_w	length of outlet section, cm
r_e	liquid supply radius, cm
r_w	wellbore radius, cm
R_{ff}	residual resistance coefficient of jelly
r_{e1}	blocking range of plugging agent, cm
Q	production, m^3/d
ΔP	production pressure difference, Pa
R	section resistance, Pa/(cm^3/s)
R	resistance, Pa/(cm^3/s)
Q_p	the amount of plugging agent, m^3
c	correction factor
L	the length of plugging section, m
Φ	effective porosity

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