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Status and Prospect of Improved Oil Recovery Technology of High Water Cut Reservoirs

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Abstract: The high water cut stage is an important stage of the water injection development of oilfields because there are still more oil reserves available for recovery in this stage. Most oilfields have experienced decades of waterflooding development and adjustment. Although waterflooding reservoirs face the problems of the seriously watered-out and highly dispersed distribution of remaining oil, they remain dominant in waterflood development. This paper investigates the current situation of high-water content reservoirs and the methods available to improve oil recovery and elaborates on the fine reservoir description. Furthermore, it analyzes the main technical measures taken during the high water cut period, namely, secondary oil recovery waterflooding technology (including layer system subdivision, well pattern infilling, strengthening of water injection and liquid extraction, closure of high water cut wells, cyclic waterflooding technology, and water injection profile control) and tertiary oil recovery technology (represented by chemical flooding and gas flooding). In addition, this study reveals the mechanisms and effects of these methods on improving waterflooding development. Finally, this paper summarizes improved oil recovery technology and discusses the key directions and development prospects of this technology in enhancing the oil recovery rate.

Keywords: improved oil recovery technology; high water cut; fine reservoir description; secondary oil recovery; tertiary oil recovery

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1. Introduction

High water cut reservoirs are widespread throughout the world. The high water cut stage is an important stage of water injection development because there are still more recoverable oil reserves in this stage. At the high water cut stage, the water cut can reach 95% in China and more than 80% in other countries [1,2]. As the oil–water ratio increases, costs rise. It is necessary to curb high water consumption, improve the economic benefits, and increase the oil recovery of high water cut oilfields.

According to the analysis of the DAS system database [3,4], 47 oilfields in the world have entered the high water cut development stage. Among them, eight are multi-layer, heterogeneous, medium-high permeability, and large sandstone oilfields. These oilfields are mainly distributed in Russia and the USA. In the East Texas Oilfield of the USA [5] and the Kurisov Oilfield of Russia [6], the water cut has reached 97% [7,8]. These eight oilfields are mainly tectonic and lithological reserves, and the sedimentary phases are mostly river phases. Most of them have edge water or bottom water, and the energy strength is quite different. The physical properties of these reservoirs are relatively good, with an average porosity of between 13–40%, mostly distributed above 20%. The average permeability is over 1000×10^{-3} μm^2 [9].

Although the division of development stages in these oilfields is different, from the analysis of water cut, they have roughly experienced the low water cut stage, medium water cut stage, high water cut stage, and extra-high water cut stage [10]. In the low and medium water cut stages, the water cut rises rapidly, and the peak value is high and appears early. The water cut value corresponding to the peak value is low, and the oil recovery is low, generally less than 20% [11]. However, the production in this stage is constantly rising and reaches the peak output. When the development has entered the high water cut stage, although the water cut still rises rapidly, the increase in the oil recovery rate slows down significantly. This is the late stage of stable production and the early stage of output decline. The decline rate decreases by 10–15% every year [12–15]. To slow down the rate of oil production decline, some oilfields began to develop the non-main oil layer. The extra-high water cut stage lasts for a very long time, often accounting for 70–80% of the whole development time of the oilfield, and the decline in the oilfield production generally slows down [16]. In different water cut stages, the rise speed of the water cut is different. Generally, in the medium and low water cut stages, with the rise in the water cut, the rising rate of the water cut gradually increases. After the medium and high water cut period, the rising rate of the water cut slows down significantly [17]. In another high water cut oilfield, the water cut rose faster than 5%. In the medium and high water cut stages, after the water cut reached 80%, the rise in the water cut slowed down, basically becoming stable within 1%. At this stage, the change in the water cut and production tended to flatten out, mass production wells were closed due to the high water cut, and the geological technical measures were greatly reduced [18]. To improve the waterflooding recovery, the oilfields generally began secondary development [19].

China has more high water cut oilfields than other countries [20], and the development of high water cut reservoir recovery technology has seen many effective innovations. In China, most continental mature oilfields have entered a high water cut or extra-high water cut period. Large areas of the main oil layers are flooded [21]. The movement of the injected water is increasingly influenced by the deposition prosody and inhomogeneity of the fracture and the sedimentary phase zone, resulting in different rules of injected water movement, flooding characteristics, and degree of displacement [22]. This makes the distribution of oil and water more dispersed. Waterflooding is affected by the heterogeneity between the layers and the horizontal surfaces, and fingering occurs along the high permeability layer on the longitudinal and horizontal surfaces, causing the water breakthrough time to be too early [23]. Once the breakthrough time becomes too early, the water cut rises rapidly, the oil–water ratio increases sharply, and oil production decreases year by year. Most of the mature oilfields in China have entered the stage of stable production, and the development situation is becoming increasingly severe. Although the oil saturation is much lower than that of the initial state, the remaining oil saturation is still generally higher than the residual oil saturation, and there are still some remaining oil enrichment areas [24].

In the current development situation, one of the most pressing problems is how to effectively develop the remaining oil of the reservoir. It is of great significance to the production of the oilfield to improve the development effect of the reservoir, raise the displacement efficiency, and increase the economic benefits. Usually we use IOR (improved oil recovery) technology. IOR refers to any practice to increase oil recovery. That can include EOR technology (enhanced oil recovery, meaning the reservoir processes that recover oil not produced by secondary processes), as well as practices to increase sweep such as infill drilling, horizontal wells, and polymers for mobility control or improved conform [25].

Billions of tons of oil remain underground in China. Given the geological characteristics and development characteristics of the complex sedimentary environment, serious formation heterogeneity, long production well section, and a large number of combined mining and injection wells in China [26,27], a comprehensive adjustment technology for subdividing the development layer system [28], injecting water layers [29], infilling well pattern [30], and improving discharge volume [31] has been formed, which has significantly improved the oilfield development effect. To investigate the hydrodynamic adjustment method of external high water cut oilfields, Chinese oilfields have successively conducted research and tests on changing flow direction [32], waterflooding cyclically [33], plugging channels [34], single well puff and huff [35], and depressuring exploitation [36], and the results have been promising. In recent years, tertiary oil recovery technology, especially the polymer flooding technology [37], has been developed rapidly. In addition, binary compound flooding [38], foam compound flooding [39], and microbial-enhanced oil recovery [40] have also seen breakthroughs in theoretical research and mining practice.

The methods of improving high water cut reservoir oil recovery are mainly based on analyzing the remaining oil distribution using fine reservoir description technology and then improving the well injecting and producing profile, regulating deep flow steering, and expanding the volume of water injection by well pattern adjustment, layer segmentation, optimization of injection, and tertiary oil recovery technology. Finally, the recovery rate of the high water cut reservoir can be further improved by realizing refined waterflooding and enhancing the sweep efficiency and displacement efficiency.

2. Fine Reservoir Description Technology of High Water Cut Reservoir

The relationship between oil and water in high water cut reservoirs is very complex. The accurate determination of the remaining oil distribution and the fine description of the reservoirs are both essential to waterflooding, which is also a comprehensive technology [41,42].

In recent years, the development of reservoir description technology can be summarized into two approaches. With the first approach, through establishing a high-precision geological model, the form of multi-information and multi-disciplinary mutual penetration is used to raise the understanding of the complex underground oil and water relationship in the high water cut period [43]. In 2005, the third generation of full oilfield geological model of the Prudhoe Bay Oilfield with dimensions of 142 m $\times$ 142 m $\times$ 5 m, a total grid number of 30,759,582, and an effective grid number of 942,558 was established. Since 2007, seven oilfields, including the Oklahoma Oilfield in the USA, have established a TOP-DOWN intelligent oilfield model (TDIRM) based on the current business model software to conduct a fully intelligent analysis of the entire oilfield [3,44]. With the second approach, the recoverable range of the reservoir is determined by reconstructing the reservoir hole and seepage standards. This new idea is used most commonly in the United States and Russia. In 2005, Romashkino Field reduced the hole and seepage standard of the reservoir according to the differences in the heterogeneous layer types and included the unconventional pore structure permeable rock layer into the development object, thus increasing the balanced ore reserves and the recoverable reserves. According to the new hole and seepage standards, the oilfield geological model was re-established. According to the new geological model, the enhanced oil recovery method can extend the economic exploitation life of the Romashkino Oilfield by 135 years [3].

In China, reservoir description technology mainly includes two aspects: a fine structural description and subdivision of the sedimentary microphase.

The development of the fine structural description requires a structural diagram of the target layers (such as the oil layer top and the sand layer top) with the deepening of the development, which puts forward higher requirements for the description of seismic data [45]. To obtain more accurate results, the seismic data should be processed with a high resolution to lay a good foundation for a fine structural description. Then, the high-resolution fine earthquake data should be interpreted via grid comparison and joint contrast analysis between wells and earthquakes to obtain the hierarchical geological structure map of the oil layer group [46].

Subdivision of the sedimentary microphase is required in the later stage of oilfield development because the characteristics and distribution rules of the sedimentary microphase often control the distribution of the remaining oil [47]. At this time, the research should be based on small layers as units. Especially for the frequently changing continental reservoirs, it is often necessary to further subdivide the sedimentary microphase, because of the large change in lithology in the same microphase zone, which has a great impact on the degree of oil and gas enrichment difference [48–50].

It is critical to predict the enrichment area using a microphase subdivision. The specific approach is to study the single-well phase of the core well, use the acoustic wave, density, and neutron well intersection map to establish the lithology model, and conduct the lithographic study. The research results of the single-well phase and lithographic studies are integrated to divide the sedimentary microphase, providing an important basis for developing the well pattern deployment [51].

3. Secondary Oil Recovery Technologies of High Water Cut Reservoirs

Secondary oil recovery mainly adopts the method of supplementing energy to the formation to make the formation pressure reach a certain balance to improve oil recovery [52]. Secondary oil recovery can greatly improve the sweep efficiency of a reservoir and thus enhance the oil recovery. Secondary oil recovery mainly involves techniques that compensate for the natural energy of the reservoir by injecting fluids, usually water or gas.

3.1. Layer System Subdivision

The most complex fault block reservoirs are multi-layer reservoirs with long well sections and large differences between layers. In addition, the basic well pattern of large well spacing has a low degree of control of reserves. Therefore, after having a certain degree of understanding of the structure, the development layer system should be subdivided in time to improve the utilization degree of reserves [53].

According to the distribution characteristics of the remaining oil in the later development stage of the complex fault block reservoir, the division of the development layer system shall adhere to the following principles [54]:

1. The properties of the crude oil and reservoir layer are similar, and small layers with relatively good crude oil properties and reservoir properties should be classified to the bottom of the layer.
2. The oil content area and oil–water boundary of each small layer of the development layer are not very different. They should be combined according to the distribution characteristics of the longitudinal- and plane-remaining oil and waterflooding characteristics in the period of high water cut development.
3. For a set of development layer systems, the estimated reserves of a single well in the extra-high water cut stage shall be greater than 180,000 t, and the remaining recoverable reserves shall be more than 15,000 t.
4. The thickness of the interlayer between the upper and lower development layers should be more than 2.5 m.
5. Well pattern adjustment of the lower layer is mainly performed to hit new wells, and the upper layer makes full use of the old wells to facilitate the simplified pipe string.

The optimization of the layer system is the basis for the development in the late period of high water cut in complex fault block reservoirs of multiple layers. There are many geological factors and development factors affecting the optimization of the layer system [55]. To ensure the cluster analysis results play a strong role in guiding the division of development layers, according to the difference in producing reserves between layers in a complex multi-layer high water cut block reservoir, the characterization parameters are [56] the permeability, injectivity index, productivity factor, producing thickness, oil viscosity, and remaining recoverable reserves. After transforming the segment data, the distance coefficient of each small layer in the segment must be calculated according to the distance coefficient formula. A smaller distance coefficient indicates that the two small layers are more similar, meaning they can be developed as a set of layers; otherwise, they should be divided into two or even multiple sets of layers. The analysis mainly includes seven steps:

1. Collect raw data.
2. Organize data.
3. Calculate the small layer distance coefficient matrix.
4. Perform the optimal segmentation.

5. Optimize the layer system.
6. Evaluate the economic benefits.
7. Further optimize the layer system [57].

3.2. Well Pattern Infilling

Well pattern infilling is an important method to improve the recovery of reservoirs. The East Texas Oilfield, which is a large sandstone oilfield, has the densest infill well pattern in the world. The development of the infilling well pattern is an important factor for the high recovery rate in the East Texas Oilfield [3]. Well pattern infilling allows the East Texas oilfield to produce more than 70% of its original geological reserves. East Wilmington Field's infilled well pattern density has reached 0.02 km^2/well during its high water cut period. In addition, the type of well pattern and the seepage direction have been changed by reusing old injection wells and changing production wells to injection wells. The implementation of the above measures has greatly increased the production of oilfields [58]. For example, after well pattern infilling, the injection volume and oil production of Ranger group fault block 1 have doubled [59].

According to the specific conditions of the reservoir, the reorganization plan should be formulated, the reorganization time should be determined, and the well pattern should be reorganized to fit the needs of the remaining oil development. For example, in the fastigium faulted reservoir, the development well pattern of injecting in the lower part and producing in the upper part is widely used. The remaining oil is mainly distributed in the upper part of the fastigium line and the interwell retention area, both of which are difficult to develop. Because the reserves are few, there are no conditions for drilling infilling wells. However, the degree of water drive can be improved via the optimization of the well pattern system [60].

There are three reasons the well pattern system would need to be optimized [61]. The first is the reservoir has a small block area, large well spacing, and poor connectivity. The second is the reservoir's development object transferred to layers in class II or III, or the reservoir has poor material properties, or the well spacing needs to be reduced. The third is the original well spacing is large, which is not conducive to the reservoir of the reserves.

In recent years, China has developed complex well technology, including the directional well, horizontal well, and sidetracking well, all of which help realize the effective development of margin reservoirs. These technologies are discussed below.

1. The large-displacement multi-target directional well [62]. The study of remaining oil distribution shows that the high part of the fastigium fault block is one of the main distribution areas of remaining oil. The remaining oil distribution area at the high part is both the remaining oil enrichment area and often the most developed part of the reservoir, and the formation energy is generally high. Drilling a large-displacement multi-target directional well often has a high initial production and a long stable production period. In addition, multi-target directional wells can also include more target layers, with great hole filling potential in the later period, and the investment payback period is shorter than that of straight wells [63]. This technology has been widely used in the development of old oilfields (especially complex fault block reservoirs).
2. The horizontal well [64]. For the small fault block, thick oil layer at the bottom of the oil reservoir edge belt, high-angle multi-layer oil reservoir blocked by fault, or formation whose remaining oil distribution is single and oil thickness is larger (generally greater than 6 m), if drilling straight wells, then the single wells control few reserves, and the economic benefit is poor. In contrast, horizontal wells have a good effect. The cost of a horizontal well is approximately twice that of a straight well, but the production and increased recoverable reserves of a single well are about three-to-eight times greater than those of a straight well [46]. Horizontal wells have the technical advantages of a large drainage area, long production well section, large estimated reserves, and small differential pressure of production, which enable the

remaining oil enrichment well section to be effectively used despite heterogeneities (such as the presence of thin and thick oil layers), to improve the production capacity of a single well, and reduce the production and construction costs [65].

3. The sidetracking well. Sidetracking well technology involves sidetracking old wells (drive pipe damage wells, well accident wells, or high water cut and low-efficiency wells) to the designed target layer so that the old wells obtain a new production capacity [66]. This technology is an important measure to develop remaining oil and improve oil recovery in many old oilfields [67].

3.3. Strengthening Water Injection and Liquid Extraction

Increasing the differential pressure of production and improving the liquid production is an important way to further improve the development effect in the stage of the high water cut period [68]. In the case of little change in production wells, increasing liquid production can be used as the main measure to increase oil production [69]. The Wilmington Oilfield increased liquid production during the extra-high water cut period, producing almost 1.5 times more fluid in 2002 than in 1991. At the same time, the injection volume was increased, and the injection/production ratio was always kept steady to keep the formation pressure at a reasonable level [70].

Increasing liquid production can inhibit the advancement of edge water toward an oil reservoir and prolong the stable production period of an oilfield. At the same time, increasing liquid production can raise the volume of the oil layer affected by water injection [71]. To improve the oil recovery speed and achieve the designed recovery rate of the oilfield, the Romashkino Field has increased the oil well production by 0.5–1 times after the oilfield was put into development, which has increased the oil layer volume affected by water injection by 20%.

3.4. Close High Water Cut Wells

In the development process of high water cut oilfields, according to the production dynamics of production wells and oil layers, a well is generally closed after its water cut reaches 98% [72]. This can effectively control the water–oil ratio, improve production, and save on development costs. In the development process of Romashkino Field, the water cut rises slowly, and the water production is low, partly due to the closure of high water cut wells. In 1976, Romashkino Field closed 1168 high water cut wells, and the total number of wells closed for high water cut had reached 1968 in early 1981. During the development process, the Wilmington Oilfield found that the high water cut wells of the wings of layers had an adverse impact on the production of the upper oil layer. After closing one of the high water cut wells, the oil production levels of two wells of the upper layers more than doubled. After the success of the experiment, nine more high water cut wells were closed. Under the conditions of constant water injection and liquid production, oil production was greatly improved, and excellent economic benefits were obtained [9].

3.5. Cyclic Waterflooding Technology

Cyclic waterflooding technology involves periodically changing the amount of well injection and well production. This causes an unstable pressure field in the layer, which continuously redistributes the fluid in the layer to increase the sweep efficiency. Therefore, it is an effective method to enhance the development of the oilfield in the high water cut period [73].

Romashkino Field has continuously developed a variety of cyclic waterflooding technologies. Currently, most of the injection wells have used this method, so it has become the main means of controlling water cut in the oilfield [74]. Depending on the reservoir property and the type of cyclic waterflooding, the half-cycle of water injection in Romashkino Field typically ranges from 10 days to six months, and it can even reach one year. In the extra-high water cut period of the Azna Keyev Block of Romashkino Field, after 5 years of cyclic waterflooding, the average daily oil production increased, and the water cut decreased. The cyclic waterflooding technology improves the effect of reservoir development and extends the life of oilfield development.

3.6. Water Injection Profile Control

Due to the heterogeneity of reservoirs, layers with high permeability are often flooded first. Plugging the high permeability water flow layer and the water channel section can achieve the purpose of adjusting the water injection profile and raising the water injection sweep efficiency to improve the waterflooding condition [75].

In addition to the mechanical method of wellbore control, chemical methods have become highly valued [76]. Due to its cost advantages, chemical plugging technology has become a strategic measure to improve oil recovery in different reservoir conditions [77].

4. Tertiary Oil Recovery Technologies of High Water Cut Reservoirs

Tertiary oil recovery technologies are implemented to recover the crude oil trapped within the capillaries of reservoir rocks. We also call it EOR (enhanced oil recovery) technology. Tertiary oil recovery technologies are widely used all over the world, mainly in the United States, China, Canada, Venezuela, and other countries. Figure 1 shows the production composition of tertiary recovery technologies for countries around the world (2012) [78]. Tertiary recovery is the process in which different combinations of chemicals, thermal energy, or microbes are infused into the reservoir, which alters the reservoir rock and fluid properties—such as the relative permeability, capillary pressure within the porous medium, interfacial tension, and wettability—to recover crude oil.

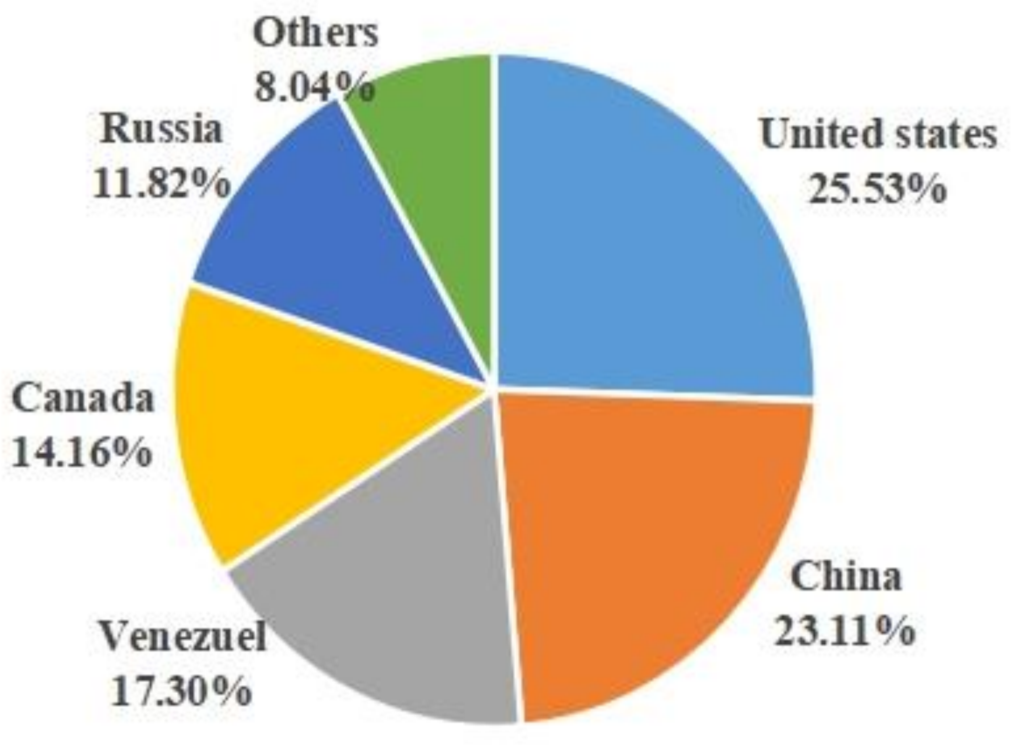

Figure 1. Production composition of tertiary recovery technologies for countries around the world (2012).

4.1. Chemical Flooding

Chemical flooding, an important aspect of improving oil recovery, refers to adding chemical agents to injected fluid to change its physicochemical and rheological properties and thereby improve its interaction characteristics with the reservoir rocks [79]. China's reservoir is characterized by strong continental sediment heterogeneity and high crude oil viscosity, so it is suitable for chemical flooding [80]. The mechanism by which chemical flooding improves oil recovery varies depending on the addition of agents. According to different principles of action, chemical flooding can be divided into five forms: polymer flooding (P), alkali flooding (A), surfactant flooding (S), alkali–polymer compound flooding (AP), and surfactant–alkali–polymer compound flooding (ASP) [81].

Different chemical flooding methods have different modes and displacement mechanisms to improve oil recovery, and the degree of recovery is also different. After analyzing the chemical flooding data and results of chemical flooding simulations, the ranges of various chemical flooding methods for improving the oil recovery rate are shown in Table 1 [81].

Table 1. Potential of chemical flooding for recovery.

Chemical Flooding Method		Increase in Oil Recovery Margin (%)
Polymer flooding	Polyacrylamide flooding	7–15
	Biopolymer flooding	7–15
Alkali–polymer composite flooding		10–18
Surfactant flooding		15–25
Surfactant–alkali–polymer compound flooding		15–25

The same chemical flooding method can have different effects when applied in different reservoirs, because many factors affect the oil recovery effect of chemical flooding, including reservoir geology, formation temperature, fluid environment, well pattern, and remaining oil distribution [82]. According to the field test of chemical flooding and lab research results, the geology of oilfields in China, and the standards of other countries, the screening standards suitable for chemical flooding reservoirs are established in Table 2 [81].

Table 2. Screening standards suitable for chemical flooding reservoirs.

Parameter	Metric	Alkali Flooding	Polymer Flooding	Surfactant Flooding	Multiple Compound Flooding
Oil property	Crude oil viscosity (mPa·s)	<40	<60	<40	<60
	Relative density	<0.9	<0.9	<0.9	<0.9
	Acid value (mgKOH/g)	>0.2	-	-	>0.2
Formation water	Mineralization degree (mg/L)	<10,000	<10,000	<10,000	<10,000
	Hardness (mg/L)	<100	<500	<500	<500
Oil reservoir	Depth (m)	-	<2500	<2500	<2500
	Temperature (°C)	<90	<75	<80	<75
	Permeability (10^{-3} μm^2)	>50	>50	>50	>50
	Coefficient of permeability variation	<0.60	0.60–0.75	<0.70	0.64–0.75
	Lithology	Sandstone	Sandstone	Sandstone	Sandstone
Other	Favorable factor	High acid value	Low temperature, fresh water, and heterogeneous	Low clay content and low mineral degree of water	Low temperature, fresh water, high acid value, and heterogeneous
	Adverse factor	High content of clay and gypsum	Bottom water and high gray matter content	Fracture, bottom water, and heterogeneous	Gas cap and bottom water

4.1.1. Polymer Flooding (P)

Polymer flooding is the most widely used chemical flooding technology. The main mechanism of polymer flooding is to add polymers to the injection water to form high-viscosity displacement fluid [83]. This can increase the viscosity of the displacement fluid and reduce the flow ratio to make the displacement fluid enter the low-permeability layer. Finally, the sweep efficiency is increased to improve the recovery rate [84].

According to the existing theories of polymer flooding, polymer flooding agents can enhance oil recovery mainly by reducing the mobility ratio of the displacement phase and displaced phase. According to the definition of mobility ratio, there are two ways to reduce the mobility ratio: increasing the viscosity of the displacement agent or reducing the permeability of the displacement agent phase. Increasing viscosity is currently the most common method used in laboratories and field sites. Viscosity is an index to evaluate the internal friction force of fluid, which reflects the internal friction force of fluid at a macroscopic spatial scale. At the macro scale, the viscosity of the polymer flooding agent is related to the polymer's relative molecular mass, concentration, molecular aggregate form, and solvent salinity. At the micro scale, the viscosity of the polymer agent is significantly different from that at the macro scale. Studies have shown that [85,86], at the same shear rate, the viscosity of polymer fluid decreases with the decrease in the pore characteristic size; especially at the micro scale and at a low shear rate, the influence of the pore characteristic size is more significant. Therefore, at the micro scale, the viscosity of the polymer flooding agents in porous media will be significantly reduced. The viscosity does not play a leading role in this case, and the additional seepage resistance caused by polymer retention in micropores becomes the main oil displacement mechanism of polymer flooding.

When polymer displacement agents (such as partially hydrolyzed polyacrylamide) enter the porous medium of the reservoir, they preferentially enter the high permeability layer, and will be retained in the high permeability layer due to the chemical adsorption and mechanical capture. Additional seepage resistance will be generated, and the whole well injection pressure will increase under the condition that the injection rate remains unchanged, thus achieving the purpose of increasing the hydraulic pressure and fluid absorption in the middle and low permeability layer. Similarly, polymer displacement agents will also be retained after entering the middle and low permeability layer, resulting in additional seepage resistance, and the increase in seepage resistance is much greater than that of the high permeability layer under the same suction volume. The injection pressure will continue to rise with the increase in displacement agents [87]. In order to avoid a reduction in the sweep volume due to displacement agent inrush caused by reservoir rupturing, the injection pressure generally does not exceed the reservoir rock fracture pressure. As the polymer flooding process continues, the hydraulic absorption difference of each small layer at the injection end gradually decreases, and the performance of the middle and low permeability layer is more significant. Finally, the liquid absorption of the middle and low permeability layer gradually decreases or even does not absorb liquid at all.

Figure 2 shows the changes in the crude oil production rate, polymer injection rate, and water cut over time since a block in Canada started production in 1992. It can be seen that the oil production reached its peak in 2000, and the oil production continued to decrease thereafter. The polymer solution was continuously injected in 2003, and the oil production began to increase continuously after reaching a trough in 2004, from 1.75×10^4 m^3/d to 3.25×10^4 m^3/d [88].

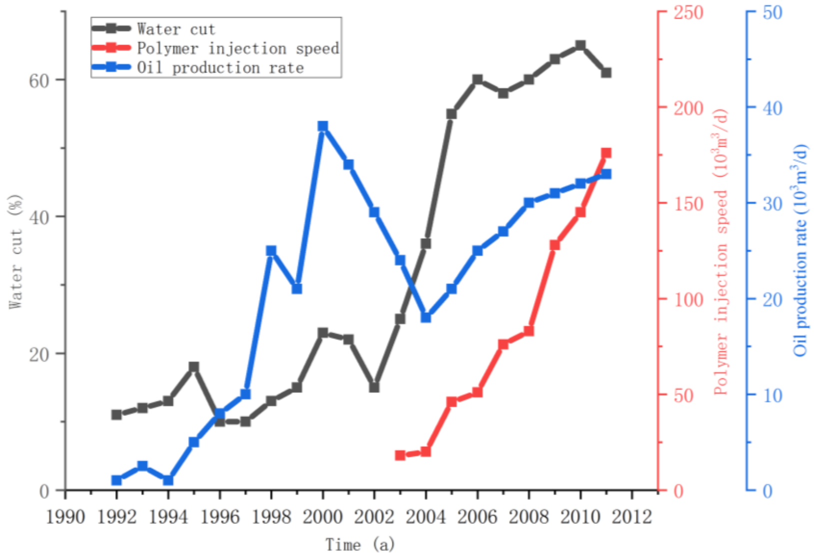

Figure 2. Changes in crude oil production, polymer injection rate, and water cut in A block in Canada over time [89].

As an important tertiary recovery technology, polymer flooding can effectively increase production and improve recovery. However, for the complex situation in the development process, due to the influence of crude oil viscosity, formation heterogeneity, and injection–production parameters, there are other problems after polymer flooding. If polymer flows along a high permeability channel, it will reduce the concentration by adsorbing on the rock surface, which will limit the oil recovery effect. This will lead to a rapid increase in the water cut, thereby worsening the polymer flooding development effect. The single development effect of polymer flooding cannot meet the requirements of production [90].

4.1.2. Surfactant Flooding (S)

The flooding method with a surfactant system as the main agent is called the surfactant flooding method. By examining the action characteristics of surfactant molecules at the oil–water interface, the stress effect of remaining oil after waterflooding, and the influence of surfactant on remaining oil, it is believed that surfactant flooding improves recovery mainly through the following mechanisms [91]:

1. Reduce oil–water interfacial tension. Surfactants can greatly reduce capillary action to improve the displacement efficiency [92].
2. Emulsification. Surfactants can quickly disperse and peel off the crude oil on the rock surface to form an oil-in-water (O/W)-type emulsion, improve the mobility ratio, and raise the sweep efficiency [93].
3. Oil belt formation. Surfactants can gather the oil beads into an oil belt to increase the remaining oil sent to the production well [94].
4. Alter the wettability. The surfactant can increase the wetting angle between the crude oil and the rock and make the rock surface change from a oleophylic to hydrophile form, reducing the adhesion work of the oil on the rock surface [95].
5. Improve the surface charge density. Anionic surfactants can increase the rock charge density on the surface and increase the electrostatic repulsion between the oil and the rock surface. This allows oil to be easily transported by the displacement medium and thus improves the oil displacement efficiency [96].
6. Change the rheology of oil. Some of the surfactants are dissolved into the oil and adsorbed on the bitumen, thereby weakening the mesh structure of the macromolecules in the crude oil, reducing the ultimate dynamic shear stress of the crude oil, and improving the recovery rate [97].

4.1.3. Multiple Compound Flooding (ASP)

Multiple compound flooding is compound flooding with multiple chemical agents such as polymers, surfactants, and alkalis. The main mechanisms of this technology are as follows [98]:

1. Reduce interfacial tension [99]. Alkaline and acidic components in crude oil react to form surfactants, which can combine with added surfactants and polymers to produce ultra-low interfacial tension.
2. Control mobility [100]. Polymers can increase water viscosity, reduce permeability, and expand the sweep efficiency of chemical agents.
3. Reduce the adsorption loss of chemical agents [101]. Alkalis can reduce the adsorption of injected surfactants and polymers and improve displacement efficiency.
4. Emulsification [102], gathering, coalescing, and wetting alteration [103].

Multiple compound flooding can greatly improve oil recovery. Developing various forms of compound flooding technology will be a major direction of future chemical flooding development.

4.2. Gas Flooding

With the development of oilfields and the progress of the process technology, gas injection technology has been continuously developed from secondary oil recovery technology, which maintains the formation energy, to tertiary oil recovery technology, which improves the oil recovery [104]. According to the type of injected gas, the gas flooding technology can be summarized into five categories: hydrocarbon miscible flooding, CO_2 flooding, N_2 flooding, flue gas flooding, and air flooding [105]. Here, we mainly introduce CO_2 flooding.

After 1980, the demand for oil and gas increased and oil prices continued to rise, with the United States government having adjusted its energy policy accordingly. As a new type of gas flooding technology, CO_2 flooding technology in the United States has been gradually promoted on a large scale, with the number of projects increasing year by year and crude oil production rising. As shown in Figure 3, by 2014, the number of CO_2 flooding projects increased from 17 to 137, and the annual production increased from 10×10^4 t to 1371×10^4 t. With the maturity of CO_2 flooding technology in the United States, it has been recognized as an effective method to enhance oil recovery [106].

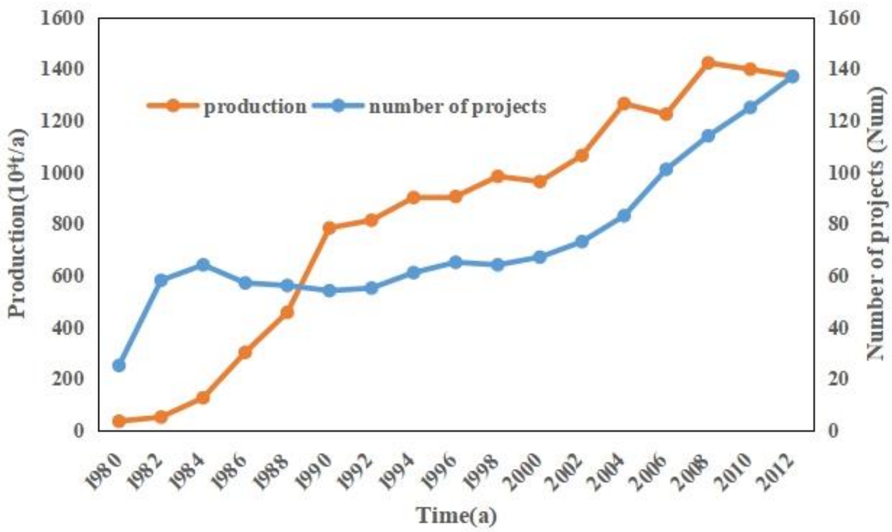

Figure 3. The number of projects and production of CO_2 flooding in United States.

At high-pressure conditions beyond the critical pressure, as the pressure increases, CO_2 becomes a liquid, sticky substance. CO_2 is more soluble in water than general hydrocarbon gas, and its solubility in crude oil is greater than that in water, so CO_2 can be transferred from an aqueous solution into crude oil. The physical and chemical characteristics of CO_2 determine that the main displacement mechanisms are as follows [107]:

1. Reduce crude oil interfacial tension and reduce displacement resistance [108].
2. Reduce oil viscosity.
3. Expand oil volume.
4. Extract and vaporize light hydrocarbons from crude oil [109].
5. Dissolved gas flooding caused by pressure drop.
6. Acidizing improves the injection capacity [110].

Not all reservoirs are suitable for CO_2 flooding for both economic and technical reasons. At present, there are many screening standards for CO_2 flooding. After integrating economic factors, the common screening standards are shown in Table 3.

Table 3. CO_2 screening standards suitable for CO_2 flooding reservoirs [81].

Parameters	CO_2 Miscible Flooding	CO_2 Immiscible Flooding
Formation lithology	Sandstone or carbonate rock	Not critical
Viscosity (mPa·s)	1.5–10	<600
API gravity (°API)	22–36	>12
Oil saturation (%)	20–55	30–70
Crude oil components	C3–C12 content was very high	Not critical
Depth (m)	>800	>600

5. Discussion

5.1. The Limitations of Existing Technologies

The continued use of IOR technology has exposed some of the limitations of existing enhanced oil recovery technologies.

For secondary oil recovery technology [111] they are as follows.

1. Serious water injection contradictions generally occur in the high water cut stage of oilfield development, such as the increase in sand production in the reservoir, uneven distribution of water drive energy, high well pressure which increases the difficulty of water injection, and the increase in impurities in the well leads to the difficulty of development and low injection level.
2. The oil distribution of the reservoir is generally scattered and uneven, and it is affected by the long-term waterflooding development. The waterflooding degree of the high permeability interval is serious, and the water absorption rate of the reservoir in the longitudinal area is uneven.
3. Multiple large-area profile control and drive methods were adopted to improve the development effect. The more rounds, the less significant the effect.
4. The gas permeability of the reservoir is poor, and the water quality of the injection is difficult to guarantee. The water injection pressure of some wells becomes higher and higher, resulting in the decrease in the water injection, which cannot meet the requirements of geological injection.

For tertiary oil recovery technology, the limitations are as follows.

1. A high one-off investment. The investment cost of tertiary recovery technology in some oil fields is very high, reaching tens of millions or even hundreds of millions.
2. A long injection cycle. The injection cycle for tertiary production is usually between 1 and 10 years.
3. The slow separation of oil and water. The high concentration of polymers will seriously slow down the separation speed of oil and water, which will affect the subsequent processing process. Meanwhile, the effect of the crude oil demulsifier will be poor, which will greatly increase the amount of demulsifier used and the cost.

4. Water quality deteriorates. The addition of the chemical flooding agent makes the overall effect of oily sewage treatment worse, and the water quality standard after treatment is difficult to reach the standard.
5. Scaling, accelerating corrosion, and other problems.

5.2. The Future Development Direction of Reservoir Fine Description Technology

The development of reservoir fine description technology is rapid, and its practical application continues to expand. Information integration technologies have gradually become the main development direction of reservoir fine modeling. Therefore, higher requirements are put forward for refined reservoir description. The development trend of reservoir fine description technology mainly includes the following three aspects [112].

The first is high-precision stratigraphy, which is widely used in practice. This technology can better realize the identification and analysis of the data, and it can also be used for the analysis and demonstration of the data, particularly to more accurately reflect the specific conditions of the bottom layer.

The second is a comprehensive analysis and study of a reservoir's physical properties and fluid dynamics. A complete water absorption profile should be provided to ensure a full understanding of the temperature variation within the reservoir. The mechanism of oil–water penetration and other influencing factors should be clarified. A simulation experiment of water injection development should be conducted to obtain an accurate dynamic evolution law of the reservoir.

The third is the construction of a reservoir geological database. A circular model and reservoir geological knowledge prediction and reservoir description should be determined and entered into the database. Then, other data prediction methods should be used to achieve the fine description of the reservoir.

5.3. The Future Development Direction of Improving Oil Recovery Technology

In the process of development in high water cut oilfields, the following problems need to be solved: clarify the distribution of remaining oil, improve the water injection effect, develop low-permeability and super-heavy oilfields, and improve oil recovery in the later development period.

Regarding the development of improving oil recovery technology in the high water cut period, the six following aspects are worthy of further study.

The first is the basic theoretical research of new tertiary recovery techniques.

1. Basic research on chemical flooding. Researchers should deepen the development of multiple compound flooding technology, screen better kinds of polymers, explore the interface chemical flooding mechanism, design and synthesize new molecular structure chemical flooding agents, and study new process control principles. Other future directions are to break the technical bottleneck that polymer flooding is only applicable to class I oil reservoirs and to solve the problems of difficulty in high-temperature and high-salt reservoirs, the difficulty in mining after polymer flooding, and the poor effects of polymer substitutes.
2. Basic research on the new technology of heavy oil development. The problem of the reduction in the production of steam puff and huff in heavy oilfields and the poor effect of heavy oil development both need to be solved. In situ combustion kinetics and its control theory, as well as injection solvent extraction technologies, need to be developed.
3. Theoretical research on microbial flooding. Theoretical research should be conducted on the screening of microbial species, the spread and diffusion of bacteria in the reservoir, the reproduction, colonization, and dissemination of bacteria in the oil layer, and the biochemical metabolism laws of bacteria.

The second is the research and development of new displacement agents. Given the development problems in relation to a high water cut, heavy oil, low permeability, high temperature, high salinity reservoir, and carbonate-fractured vuggy reservoirs, new agents that are economical and effective should be developed.

The third is the efficient integration of new and alternative technologies. Development in new oilfields requires new technologies. An efficient integration of enhanced oil recovery technologies is needed in complex reservoirs. In addition, high water cut reservoirs in the middle and late periods are desperate for alternative technologies.

The fourth is the study of the physical method of oil production. Physical methods such as the mechanical wave, magnetic treatment, electromagnetic wave and microwave, ultrasonic production, layer treatment with low-frequency vibration, hydraulic oscillation plugging, high-energy gas fracturing, and underground low-frequency electric pulse technology need to be thoroughly studied. Physical production processes have the advantages of being simple, highly adaptable, and harmless, and they can improve the oil layer's relative permeability. These technologies have complementary advantages with chemical flooding, so they can be combined to form compound technologies.

The fifth is the in situ modification and transformation technology known as the "underground refinery". In 2019, it was rated as one of the top 10 advances in oil technology. It uses heating to transform organic matter, asphalt, and heavy oil into natural gas and light oil. This technology is not subject to geological restrictions, and it has the advantages of a large scale, high extraction, and low pollution. This is a major exploration area with far-reaching significance to industry stability and development [113].

The sixth is nanotechnology. The application of nano-metal catalysts and intelligent polymer nanocapsules [114] has enhanced the oil recovery of conventional chemistry flooding. The aquathermolysis of heavy oil can be realized after catalysis via nano-metals. Intelligent polymer nanocapsules have a good plugging effect and can reduce pressure, increase injection, and reduce interfacial tension. Capsules can release surfactants upon contact with crude oil to improve the emulsification of crude oil. Nanotechnology has broad prospects in improving oil recovery prospects, so it will be a major future development direction [115].

6. Conclusions

The major oilfields of the world have entered the stage of having high water cuts and decreasing oil recovery rates, and the distribution of remaining oil is also extremely complex. However, there is still great potential to improve oil recovery.

Fine reservoir description of the remaining oil in high water cut reservoirs is the basic mehtod needed to further improve oil recovery. How to improve the oil displacement efficiency, oil recovery rate, and economic benefit of high water cut reservoirs is of great significance to increase the production of oilfields.

Various methods—including the subdivision of layer development, optimization of injection–production well pattern, adjustment of injection–production parameters, and implementation of fine water injection—can effectively improve the waterflooding recovery of high water cut reservoirs.

According to the specific situation of a high water cut reservoir, the reasonable selection of tertiary oil recovery technologies, such as chemical flooding and gas flooding, can further improve the oil recovery rate of the reservoir.

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