Research Progress of Enhanced Oil Recovery

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Abstract

With the continuous growth of global energy demand and the depletion of conventional oil and gas resources, enhanced oil recovery (EOR) technology has become the core direction to ensure energy security and achieve sustainable development of oil fields. This paper systematically reviews the mainstream EOR methods such as chemical flooding, gas flooding, thermal oil recovery, microbial oil recovery, micro-nano technology and improved water flooding, and analyzes them from four aspects : action principle, development process, application cases and limitations. Combined with the current research status, the future development direction is prospected, which provides a reference for the selection and innovation of oilfield development technology.

Keywords

Oil Recovery; Chemical Flooding; Gas Drive; Thermal Oil Recovery; Micro-nano Technology; Oilfield Development.

1. Introduction

As one of the world 's major energy sources, the efficient exploitation of oil is crucial to economic development and energy security. Conventional oil recovery technology (primary oil recovery, secondary oil recovery) can only produce 20% -40% of the geological reserves of the oil field, and a large amount of remaining oil is retained in the reservoir. Enhanced oil recovery technology can increase oil recovery by 10% -30% by changing the fluid properties and seepage environment of reservoirs through physical, chemical or biological means, which has become the key support for tapping the potential of old oilfields and developing unconventional reservoirs [1-2]. In recent years, with the increasingly complex reservoir conditions (such as low permeability, high temperature and high salinity, high water cut), EOR technology has been iteratively innovated to form a pattern of multi-technology coordinated development[3].

2. Mainstream Methods for Enhancing Oil Recovery

2.1. Chemical Flooding

Chemical flooding is an EOR technology that changes the physical and chemical properties of the fluid by injecting chemical agents into the reservoir. It mainly includes polymer flooding, surfactant flooding, composite flooding, etc. It is the core oil recovery method for continental heterogeneous reservoirs in China.

2.1.1. Principle

(1)Polymer flooding: By injecting high molecular polymer (such as polyacrylamide) to improve the viscosity of injected water, reduce the water-oil mobility ratio, reduce the fingering of water flow, and expand the swept volume of water flooding.

(2)Surfactant flooding: Surfactants are used to reduce the oil-water interfacial tension (below 10^{-3}mN/m), weaken the adhesion between crude oil and rock, and promote the stripping and flow of residual oil.

(3)Composite flooding: Combined with the synergistic effect of two or more chemical agents (such as alkali-surfactant-polymer ASP), it has the dual effects of expanding the swept volume and improving the efficiency of oil washing.

2.1.2. Development History

In the 1960s, the United States took the lead in carrying out indoor research on polymer flooding ; in 1972, Daqing Oilfield started the pilot test of polymer flooding. In 1996, it was industrialized and popularized. At present, it has formed an annual output of 1000×10^4t. After 2000, in order to solve the problems of scaling in strong alkali compound flooding and difficult treatment of produced fluid, weak alkali ASP flooding and alkali-free binary flooding (SP flooding) have become research hotspots. The ' strong activity and low adsorption ' surfactant system developed by Shengli Oilfield has achieved breakthroughs in high temperature and high salt reservoirs[4-5].

2.1.3. Application Cases

Daqing Oilfield: ASP flooding technology has been applied in the middle and south five blocks of Xing 2, and the recovery rate has increased by 18.6% -26.5%. The recovery rate of the strong alkali compound flooding stage of the second type reservoir in the east of the first fault of the north is 23.5%. Shengli Oilfield: SP binary flooding test in Gudong 7 area,using salt-tolerant surfactant and salt-resistant polymer compound system, the recovery rate is increased by 12.7%, which solves the problem of strong heterogeneity of fault block reservoir[4-5].

2.1.4. Limitations

The cost of chemical agents is high (e.g., the unit price of surfactants reaches tens of thousands of yuan / ton), and it is easily affected by reservoir temperature and salinity (e.g., the polymer is easily degraded at high temperature, and the surfactant fails due to high salt environment) ; strong alkali compound flooding is easy to cause rock scaling and equipment corrosion, and the pump inspection cycle is shortened by more than 50%. The produced liquid is seriously emulsified, and the treatment cost increases by 10% -15%.

2.2. Gas Drive

By injecting gas (such as CO_2, natural gas and nitrogen),gas flooding can improve oil recovery by dissolution expansion and miscible displacement. It is suitable for low permeability, tight and unconventional reservoirs, and has the function of carbon storage, which is in line with the goal of ' double carbon '.

2.2.1. Principle

(1)Miscible flooding: Injected gas (such as CO_2) and crude oil form miscible under reservoir conditions,eliminating interfacial tension and achieving efficient displacement ;

(2)Immiscible flooding: gas expansion is used to supplement reservoir energy and promote crude oil to move to production wells. For example, nitrogen flooding is suitable for high-pressure gas cap reservoirs ;

(3)Gravity differentiation: gas density is lower than that of crude oil, advancing along the top of the reservoir, achieving stable displacement through gravity and reducing gas channeling.

2.2.2. Development History

In the 1950s, the United States carried out CO_2 flooding experiments in the Permian Basin of West Texas ; after 2000, CO_2 flooding technology has been applied on a large scale. At present, the annual oil production of CO_2 flooding in the United States is 1500×10^4t.China started the pilot test of CO_2 flooding in Jilin Oilfield in 2000.After 2020, combined with CCUS (carbon capture, utilization and storage) technology, an integrated mode of " oil displacement-carbon burial " was formed [6-9].

2.2.3. Application Cases

Tanner oilfield in the United States: ASP flooding was implemented in 2000, and 1.0% NaOH +0.1% surfactant +1000mg / L polymer was injected, and the recovery rate was increased by 12.8%. Hei 125 block of Jilin oilfield : In 2024, foam enhanced CO2-WAG (alternating water and gas injection) test was carried out. The gas-liquid ratio was 1:1, the alternating period was 15 days, the gas channeling rate was reduced by 30%, and the stage oil increase was more than 1×10^4t; donghetang reservoir in Tarim Oilfield: top injection of natural gas gravity drive and gas storage collaborative development, cumulative gas injection of 7.6×10^8m^3, recovery rate increased by 30 percentage points, both peaking and supply function [6-9].

2.2.4. Limitations

The gas source is limited, the distribution of natural CO_2 gas reservoirs is uneven, and the purification cost of industrial waste gas is high (about 200 yuan/ton). The problem of gas channeling is prominent, and the gas in heterogeneous reservoirs is easy to break through along the high permeability channel, and the sweep efficiency is reduced. For example, CO_2 miscible flooding requires reservoir pressure higher than the minimum miscible pressure (MMP),which limits the application of low permeability reservoirs.

2.3. Thermal Oil Recovery

Thermal recovery is the dominant development technology of heavy oil and super heavy oil reservoirs by injecting heat energy into the reservoir to reduce the viscosity of crude oil and improve the fluidity. It mainly includes steam huff and puff, steam flooding, in-situ combustion and so on.

2.3.1. Principle

(1)Steam huff and puff: inject high-temperature steam into the oil well, open the well after soaking, and use thermal energy to reduce viscosity and steam expansion to displace crude oil ;

(2)Steam flooding: continuous injection of steam into the reservoir to form a steam front to drive crude oil to move to production wells, which is suitable for thick heavy oil reservoirs ;

(3)In-situ combustion: By injecting air to cause low-temperature oxidation and heat release of crude oil, flue gas is generated to displace crude oil, which is suitable for deep heavy oil reservoirs.

2.3.2. Development History

In the 1960s, Canada first realized the industrial application of steam flooding ; in 1980, China carried out steam stimulation test in Liaohe Oilfield.After 2000, steam assisted gravity drainage (SAGD) technology was developed to break through the bottleneck of super heavy oil development.Since 2020, multi-media synergistic thermal recovery (such as steam+CO_2) and underground in-situ modification technology have become research hotspots[2-3].

2.3.3. Application Cases

SAGD project in Liaohe Oilfield: for super heavy oil reservoir (viscosity 5×10^4mPa·s), horizontal well injection-production mode is adopted, the recovery rate is more than 50%, and the annual oil production is more than 200×10^4t; in-situ upgrading test of Fengcheng Oilfield in Xinjiang: Liquid catalyst was injected to break the chain of heavy components of heavy oil below 300°C, the viscosity of produced oil decreased from 5×10^4mPa·s to 21mPa·s, and the recovery rate increased by 20 percentage points. Thermal recovery of offshore heavy oil in Bohai Sea: Using ' large well spacing, high dryness ' heat injection mode, the cumulative oil production of single well in the first cycle is 2.3×10^4t, which breaks through the space limitation of offshore platform[2-3].

2.3.4. Limitations

The energy consumption is high, the steam consumption per ton of oil in steam huff and puff is 8-10 t, and the carbon emission intensity is 3-5 times that of conventional oil recovery. The heat loss is serious, the steam dryness of the deep reservoir is reduced to less than 30%, and the oil displacement efficiency is reduced. The corrosion of wellbore and equipment is intensified, and the casing life is shortened to 3-5 years due to high temperature steam.

2.4. Microbial Oil Recovery

Microbial enhanced oil recovery (MEOR) uses microorganisms and their metabolites (such as biosurfactants, polymers) to improve the reservoir environment. It has the advantages of green environmental protection and low cost, and is suitable for medium-low permeability and high water cut old oilfields.

2.4.1. Principle

(1)Microbial metabolism produces surfactants to reduce oil-water interfacial tension ;

(2)Microbial degradation of heavy components of crude oil, reducing the viscosity of crude oil ;

(3)The gas produced by metabolism (such as CO_2, CH_4) fills the reservoir energy and promotes the flow of crude oil.

2.4.2. Development History

In the 1980s, the United States carried out microbial-polymer composite flooding experiments in the Bockstedt oilfield; china started microbial huff and puff test in Shengli Oilfield in 2000, and developed a ' probiotic ' oil displacement system after 2020 to achieve a breakthrough in temperature and salt resistance[10-12].

2.4.3. Application Cases

Gudao Block of Shengli Oilfield: From 2019 to 2023, bacterial composite polymer profile control was carried out, and high-temperature hydrocarbon-philic emulsified bacteria SL-1 was injected. The water content decreased from 95.9% to 81.3%, the cumulative oil increase was 3.48×10^4 t, and the predicted oil recovery increased by 9%. Bockstedt oilfield in Germany: The microbial-polymer composite flooding was implemented in 2012. The reservoir temperature was 80°C and the salinity was 18.6×10^4mg/L.After the injection of biopolymer, the rising trend of water content slowed down and the recovery rate increased by 25%[10-12].

2.4.4. Limitations

Microbial activity is limited by reservoir temperature and salinity (e.g., the activity decreases significantly when the temperature exceeds 80°C). The effective period is long (usually 6-12 months), and the effect stability is poor. Uncontrollable metabolites may lead to formation blockage.

2.5. Micro-nano Technology

Micro-nano technology uses the small size effect and surface effect of nanomaterials to improve the reservoir seepage environment at the micro scale, which is an emerging direction of EOR in low permeability and tight reservoirs.

2.5.1. Principle

(1)Nanofluid flooding: Nanoparticles (such as SiO_2, TiO_2) change the wettability of rock (from oil to water) and reduce the adhesion of crude oil ;

(2)Micro-nano bubble flooding: micro-nano bubbles (diameter≤10μm) plug the high permeability channel, expand the swept volume, and reduce the oil-water interfacial tension ;

(3)Nano-intelligent oil displacement agent: It has the characteristics of ' finding oil ', actively adsorbs crude oil and promotes its aggregation and flow.

2.5.2. Development History

In 2010, nano-CT technology was first used in reservoir microscopic research in the United States. In China, the 'nano-water' flooding test was carried out in Changqing Oilfield in 2018.After 2020, nano-oil displacement agents such as iNanoW were developed to achieve breakthroughs in ultra-low permeability reservoirs[13-15].

2.5.3. Application Cases

Changqing Jiyuan Oilfield: In 2018, the ' nano-water ' flooding test (10 injection and 36 production) was carried out, iNanoW nano-oil displacement agent was injected, the injection pressure difference was reduced by 40%, the stage net oil increase was 2428 t, and the cumulative controlled decline oil increase was 8624 t ; xinjiang Mahu Oilfield: Using SiO_2 nanoparticles and surfactant compound system, the oil-water interfacial tension is reduced to less than 0.2mPa·s, and the recovery rate of low permeability core is increased by more than 6 %[13-15].

2.5.4. Limitations

The preparation cost of nanomaterials is high (such as the unit price of modified nano-TiO_2 is more than 100,000 yuan/ton), and the large-scale application is limited. Nanoparticles are easy to agglomerate, resulting in formation pore blockage; the mechanism of action is not deeply studied, and the field effect prediction is difficult.

2.6. Improve Water Flooding

Improving water flooding is a technology to improve the efficiency of secondary oil recovery by optimizing injection-production parameters and adjusting well pattern. It is suitable for old oilfields with high water cut, and has the advantages of low cost and easy promotion.

2.6.1. Principle

(1)Layer subdivision and well pattern encryption: by subdividing the development layer and infilling the well pattern, the utilization degree of the low permeability layer is improved;

(2)Periodic water injection: Alternately change the water injection volume and shut-in time, and use pressure fluctuations to drive and disperse remaining oil ;

(3)Profile control and flooding: injection plugging agent (such as polymer microspheres) plugging high permeability channel, forcing the injected water to low permeability area.

2.6.2. Development History

In the 1970s, the Soviet Union carried out cyclic water injection test in Rome Shijin Oilfield. China implemented three times of well pattern encryption in Daqing Oilfield in 1990, and developed intelligent separate injection technology to realize real-time control of injection-production parameters after 2020[16].

2.6.3. Application Cases

Daqing Oilfield: Through the subdivision and reorganization of strata and the single-layer development of horizontal wells, the recovery rate of the second-class reservoirs is increased by 8 % -10 %, and the annual oil production is stable at more than 1000×10^4t; changqing Oilfield: polymer microsphere profile control and flooding will be implemented in 2024, with a total of 21963 wells, the natural decline rate will decrease by 2 percentage points, covering the production scale of 1100×10^4t[16].

2.6.4. Limitations

Sensitive to reservoir heterogeneity, once the high permeability channel is formed, it is difficult to reverse ; the profile control agent has a short validity period (usually 1-2 years) and needs to be injected repeatedly; intelligent separate injection technology is limited by the temperature and pressure resistance of downhole sensors, and its large-scale application is insufficient.

3. Research Status and Future Direction

3.1. Research Status

The current EOR technology presents a pattern of ' traditional technology optimization and upgrading, new technology gradually landing ': chemical flooding is expanding to high temperature, high salinity and low permeability reservoirs, such as the 120°C betaine surfactant developed by Shengli Oilfield; gas flooding combined with CCUS technology to achieve ' flooding-burying carbon ' synergy, Jilin Oilfield has built a 400×10^4t CCUS-EOR project; micro-nano technology from indoor research to field test, Changqing, Xinjiang and other oil fields have formed a demonstration area; the combination of microbial enhanced oil recovery and chemical agents (such as bio-chemical surfactant flooding) has become a key direction to break through inefficient reservoirs. However, the industry still faces common challenges: poor technical adaptability (e.g., conventional chemical flooding is difficult to adapt to high-temperature and high-salt reservoirs), imbalance of cost and benefit (e.g., high cost of nanomaterials), environmental risks (e.g., groundwater contaminated by chemical agents), and lack of in-depth mechanism research (e.g., micro-mechanism of micro-nano flooding)[17-19].

3.2. Future Direction

3.2.1. Multi-technology Collaborative Integration

The development of ' chemical flooding + micro-nano technology ', ' thermal recovery + CCUS ' and other collaborative models, such as the combination of CO_2 pre-fracturing and nano-fluid flooding, not only improves the fracturing effect, but also improves the efficiency of oil washing. The combination of microorganisms and chemical agents reduces the amount and cost of chemical agents.

3.2.2. Intelligentization and Precision

The closed-loop system of ' monitoring-simulation-decision ' is constructed by using nano-sensor and distributed optical fiber monitoring technology to realize real-time control of reservoir dynamics. Optimize injection-production parameters based on machine learning. For example, Daqing Oilfield uses neural network model to predict remaining oil distribution and improve development accuracy.

3.2.3. Research and Development of Green Low-Carbon Technology

The development of degradable chemicals (such as bio-based polymers), low-energy thermal oil recovery technology (such as electromagnetic heating) to reduce carbon emissions in the EOR process; CCUS-EGR (carbon capture-gas drive-buried storage) technology is promoted to expand new areas of carbon storage in natural gas reservoirs, such as the CCUS-EGR test in Wolonghe gas field in southwest Chongqing, which is expected to increase oil recovery by 10.2 percentage points.

3.2.4. Technological Breakthroughs in Unconventional Oil Reservoirs

For unconventional reservoirs such as shale oil and tight oil, the technology of close cutting uniform fracturing and anhydrous fracturing (such as CO_2 dry fracturing) is developed, combined with early energy supplement (such as CO2 huff and puff) to improve the recovery rate to more than 20%. For example, Changqing shale oil demonstration base adopts CO_2 pre-fracturing, and the initial daily oil production of single well reaches 20.6 t.

4. Conclusion

Enhanced oil recovery technology has developed from a single method to multi-technology collaboration and green intelligence. Traditional technologies such as chemical flooding, gas flooding and thermal oil recovery will still play a leading role in medium-high permeability and heavy oil reservoirs by optimizing formulations and processes. New technologies such as micro-nano technology and CCUS-EOR provide a new path for the development of low permeability and unconventional reservoirs. Microbial oil recovery and improved water flooding have irreplaceable advantages in low-cost and environmentally friendly demand scenarios. In the future, it is necessary to focus on technology collaboration, intelligent upgrading, low-carbon transformation and unconventional reservoir adaptability, break through technical bottlenecks, achieve efficient and sustainable development of oil fields, and provide support for global energy security.

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