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Status and Progress of Enhanced Oil Recovery Technology in Shale Reservoirs

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Abstract: With the continuous exploitation of domestic conventional oil and gas resources, it is urgent to form a new strategic successor force for stable crude oil production, and China's shale oil and gas resources are abundant and rank in the forefront of the world. At present, various cutting-edge technologies such as CO_2 gas injection throughput, horizontal well segmented fracturing technology, and horizontal well synchronous fracturing technology have been applied to the on-site exploitation of shale oil, and numerical simulation methods for shale oil exploitation in various ways are also actively explored. Starting from comparing the current situation of shale oil exploitation at home and abroad and clarifying various development methods and means, this paper summarizes the field application and indoor scientific research of enhanced oil recovery technology in shale oil reservoirs at home and abroad, compares and analyzes the advantages and disadvantages of various methods, and expounds the development trend of shale oil enhanced oil recovery.

Keywords: Shale Oil; CO_2 Throughput; Synchronous Fracturing; Numerical Simulation; Development Trends.

1. Shale Reservoir Characteristics

China is rich in recoverable shale oil resources, ranking third in the world, with 44.1×10^8t [1-3]. Shale oil is mainly derived from organic shale formation systems (high-carbon shale, silty shale, etc.), generally with pores and fractures as storage space, while shale fractures, matrix pores and organic pores are the main forms of fracture occurrence, which is an ultra-low porosity, continuous reservoir [4-5]. Shale oil reservoirs have the characteristics of high brittle mineral content, particularly high pressure, high temperature, high organic matter content, light oil quality, and the production trend is sharp and then slow [6-7]. It is difficult to develop, and it is even more difficult to form an industrial oil flow with commercial economic value using traditional extraction technology. Its development requires the use of horizontal wells, injection throughput and segmented fracturing techniques similar to shale gas [8]. Therefore, in view of the accumulation, enrichment and fluidity of China's continental shale oil, research is carried out, further promoting the exploration and development of China's continental shale oil, and constantly seeking technological innovation, so that China's continental shale oil development can quickly complete the revolutionary process from small-scale breakthrough to large-scale industrial development.

Table 1. Evaluation results of shale oil resources in China by different scholars or institutions

Shale oil geological resources /10^8t	Shale oil technology recoverability /10^8t	R_0/%	References
100	100	>1.0	Zhao (2020) [11]
	700~900	<0.5	
3722	74~372	>0.5	Jin (2021) [12]
200		>1.0	Du (2019) [13]
	700	>0.5	Yang (2019) [14]
	43.7	>0.5	EIA (2013) [15]

At present, the average recovery rate of the discovered shale reservoirs is roughly 1%-2%, and there is still a large amount of crude oil trapped in the formation, which has the potential to continue to be explored, and it is necessary to use enhanced oil recovery technology to increase production. Based on this, this paper summarizes the production enhancement technology methods and numerical model studies of enhanced oil recovery in shale reservoirs in view of the characteristics of shale reservoirs, hoping to provide support for the development of shale reservoirs in China [9-10].

2. Research Status of Gas Injection in Shale Reservoirs Section Headings

In view of the matrix characteristics of ultra-low permeability of shale reservoirs, it is difficult for conventional mining methods to form effective exploitation effects on shale formations. Today, gas injection extraction is the primary way to enhance shale oil recovery. Gas injection production is mainly divided into two types: gas flooding and gas injection throughput, because the matrix permeability of shale reservoirs is extremely low, and under the condition of gas flooding, the pressure drop in the near-well zone is generally obvious, and it still takes a long time for the injection gas to drive crude oil to the near well. Injection throughput is more time-sensitive than gas drive, so most studies are still based on throughput experiments. The gas injected generally includes CO_2, nitrogen, gas mixture (CH_4 and C_2H_6), etc.

2.1. Research Status of CO_2 Injection

In shale reservoir gas injection experiments, CO_2 is a research hotspot, firstly, many experiments show that CO_2 has significant advantages in reservoir exploitation, on the other hand, it can also be large-scale geological storage of CO_2, reduce greenhouse gas emissions, and have economic and social benefits [16]. The mechanism of CO_2 on the recovery of shale reservoirs mainly includes viscosity reduction, improvement of crude oil to water flow ratio, expansion, extraction, and miscibility [17-19].

B Vega et al. in 2010 [20] conducted a microtubule experiment to clarify the minimum miscible pressure between oil sample and CO_2, and on this basis did forward and reverse gas flooding experiments, the experiment showed that the effect of CO_2 miscible flooding is quite good, the forward and reverse oil flooding efficiency reaches 39% and 54%, respectively, and the total oil displacement efficiency reaches an astonishing 93%.

Li et al. 2019 [21] studied the CO_2 throughput test under different conditions, and the results showed that in the immiscible state of CO_2 injection, the recovery rate increased with the increase of injection pressure, and when the injection pressure was lower than 8MPa, the recovery increased with the increase of soaking time, but when the injection pressure was higher than 8MPa, the immersion time had no significant effect on the recovery rate. The miscible state is more conducive to enhanced oil recovery than the immiscible state, because when CO_2 and shale oil reach miscible pressure, the viscosity of crude oil is greatly reduced, so the oil displacement efficiency of the core is continuously improved [22].

In 2023 [23], in order to evaluate the CO_2 throughput and displacement effect of shale feldshire cores and the mobility of crude oil under the holes and throats of different scales, the on-line NMR experiments of felds-core CO_2 throughput and residual oil were carried out based on high temperature and high pressure, and the experiments showed that the mixed-phase throughput spread widely, the pressure gradient was large, the non-miscible throughput and flow effect was poor, the internal pressure of the core did not change significantly, and the mixed-phase oil displacement effect was significantly better than that of the non-miscible phase. The experiment mainly uses nanoscale and submicron fluids in the pores.

Cao Changxiao et al. in 2023 [24] carried out a study on the applicability of CO_2 injection in shale oil reservoirs for Jimsar shale oil through oil and gas phase experiments and reservoir numerical simulation methods, and the results showed that multi-period CO_2 injection throughput can increase recovery by 9.43 percentage points, and under formation pressure and temperature, the dissolved gasoline ratio of CO_2 in crude oil can reach 497.83m^3/m^3, the volume of crude oil can be expanded by 2.05 times, and the viscosity of crude oil can be reduced by 70.65%.

2.2. Research Status of N_2 Injection

In addition to CO_2 being the current hot spot of shale gas injection and exploitation, there are also relevant scholars who have studied other gases, such as nitrogen and mixed gas, but experiments have shown that nitrogen is not effective [25]. During the development process, the injected gas source is mostly associated with oil fields. The main purpose of natural gas injection is to achieve mixed-phase injection.

Wei Y et al. in 2012 [26-27] conducted a study on N_2 displacement in shale injection. The experimental equipment consists of two parts: gas injection device and core saturation device. The experimental results show that when N_2 is injected, the oil displacement efficiency increases with the increase of the displacement time. The higher the displacement pressure, the better the oil displacement effect, but the gas breakthrough time will also accelerate with the increase of pressure.

Sun Yang et al. in 2012 [28] carried out a combination exploration experiment of CO_2 pre-plug + N_2 replacement in order to avoid the problem of excessive CO_2 corrosion of construction pipe columns and equipment, and the experiment showed that the recovery rate of N_2 replacement simple CO_2 plug under a certain pressure could reach 90%, and the displacement efficiency of this method was even higher than that of pure CO_2 injection.

2.3. Research Status of Other Gases Injection

Hoffman et al. conducted gas injection experiments in dozens of wells in Gonzales in 2018 [29] with partial results, but the problem of gas channeling is still insurmountable, and public data show that some wells can increase oil by 17%-20% in two years as a result of natural gas pilot experiments.

Thakur et al. 2019 [30] believe that natural gas injection can play a positive role in reservoir pressurization and production, and can also induce the further extension of matrix fractures in the formation, expand the degree of connection between artificial fractures and natural fractures, and thus play a role in expanding the ripple efficiency.

3. Enhanced EOR Numerical Simulation Study

3.1. Numerical Simulation Study of Gas Injection Enhanced Oil Recovery

Based on the difficulty of shale reservoir exploitation, many uncertainties in field tests, high cost and other reasons, the field application of shale oil enhanced oil recovery technology has certain difficulties, but with the continuous development of computer numerical simulation software, many scholars began to use numerical simulation methods to improve shale oil recovery research, and related demonstration with the production data obtained on site, and achieved ideal results and progress.

Chen et al. 2014 [31] used the UT-COMP reservoir simulator to simulate primary oil recovery and CO_2 throughput recovery in the Bakken block. The results show that the effects of primary oil recovery and CO_2 throughput recovery mainly depend on the permeability characteristics of the reservoir, and the primary recovery rate and CO_2 injection recovery rate are significantly affected by the heterogeneity of the reservoir. It was also found that the use of longer stuffy times did not indefinitely improve the recovery of the production stage, due to the limited migration of CO_2 into the shale matrix.

Zhu et al. 2015 [32] established a " fracture flooding and fracture recovery " model (Figure 1), that is, a "fine-grained" simulation of shale oil extraction, through the modeling of component reservoirs, and considering the effectiveness of the gas injection scheme, indicating that the gas injection scheme has the potential to greatly enhance the recovery of shale-rich oil formations, and pointed out that the injection of mixed gas may be better than CO_2 for enhanced oil recovery in situ.

3.2. Other EOR Numerical Simulation Studies

Ouyang Weiping, 2021 [33], established a numerical model of shale oil fracturing horizontal well water-oil biphasic seepage combining three factors: stuffy well infiltration, fracturing fluid injection and well opening production, and simulated the process of matrix-fracture water-oil displacement under infiltration by using the method of limited control volume, and obtained oil-water-related dynamic change data.

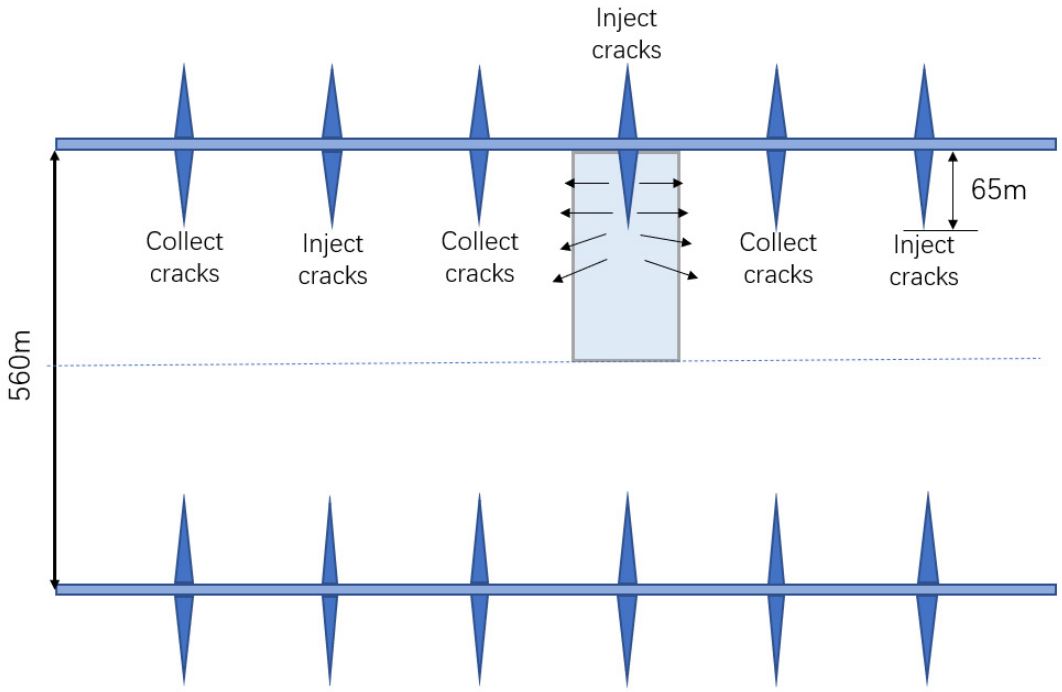

Fig 1. Model of fracture flooding and fracture recovery

In 2022 [34], Zhu Haiyan et al. created a seepage-stress-damage model for the dynamic extension of complex fractures in horizontal well-tight cutting of shale oil, and carried out numerical modeling studies on multiple factors such as the number of perforated clusters, the number, and fracturing construction parameters of specific shale oil reservoirs, and verified its correctness through on-site fracturing construction data.

4. Shale Oil Enhanced Oil Recovery Field Trials

Sheng Xiang et al. proposed in 2015 [35] that the shale oil fracturing process is mainly horizontal well segmental fracturing technology, which includes open-eye packer + slip sleeve partial pressure technology, hydraulic jet segmented fracturing technology, etc. In addition, there is a simultaneous fracturing technique for multiple horizontal wells, which refers to the simultaneous fracturing of two or more wells to form complex network fractures, thereby increasing the seepage capacity of shale oil.

Cote A et al. 2019 et al. [36] conducted a continuous study of wellbore fracturing in the sedimentary basin of Western Canada, which used large-scale densely cut volumetric fracturing to show that widening the fracture width can improve productivity, and using three case studies showing that even if the fracture strength increases due to increasing fracture strength due to increasing fracture strength, production will eventually decline.

Li Guoxin et al. pointed out in 2020 [37] that PetroChina carried out three rounds of capacity evaluation in the Duvanet cooperation project, reaching an annual oil and gas equivalent of 1.77×10^4t, 12.66×10^4t, 39.18×10^4t, respectively, during which the length of the horizontal section of the project increased from 1300m to more than 3000m; The well depth has increased from 5000m to more than 7000m, and the segment spacing of its advanced degradable bridge plug process has been reduced from 89m in 2012 to 49m in 2018, shortening by 45%.

Jiang Tingxue et al. [38] pointed out in 2021 that the YYP1 well and FYP1 well deployed by Sinopec in Jiyang Depression in 2018 produced 93t/d and 117t/d, respectively, with remarkable effects. In addition, shale oil exploration breakthroughs were made in the Shahe Street Formation of Jiyang Depression, the Jurassic system of Sichuan Basin and the second section of Qintong Sag, which verified the feasibility of using close forced sand segmentation fracturing technology for medium and high maturity shale oil in continental facies.

Xie Xin et al. in 2023 [39] took the shale oil horizontal well in Subei Oilfield as the research object, and the depth of the horizontal well in this block can reach 6000m, and the horizontal section length is 2035m. It combines various technologies and processes such as window side drilling technology, wellbore trajectory control technology using the law of formation slope formation, and acceleration technology, and continuously improves the drilling length and process of horizontal wells in on-site construction. The use of old borehole side drilling to develop shale oil can reduce drilling costs and improve economic benefits, which is a new direction for shale oil development.

5. Prospect

In order to accelerate the development of domestic shale oil enhanced oil recovery technology and realize the rapid formation of domestic oil and gas strategic reserve resources, the following two suggestions are put forward: First, introduce a market-oriented mechanism in the field of shale oil exploration and production, give shale oil exploration and development policy tax support in the early stage, and fully authorize and build a closed-loop management system for cyclical projects combining responsibilities and rights; Second, in view of the application technical difficulties of China's continental shale oil potential block exploitation, we

should promote supporting engineering and technical research as soon as possible, form a comprehensive technical system, and increase the intensity of field experiment exploration, integrate the company's strength, achieve breakthroughs in the difficulties of continental shale oil development as soon as possible, and form scale benefit development.

6. Summary

(1) Shale oil development is difficult, heterogeneity is strong, and the total organic carbon content is low. Large-scale hydraulic and multi-cluster fracturing technology is still the main means of transformation and exploitation of continental shale reservoirs, and enhancing the seepage capacity of reservoirs is the basic prerequisite for subsequent multi-production and stable production.

(2) According to the matrix characteristics of shale, gas injection is an important factor to fill the formation energy loss during shale reservoir development, but the feasibility of injecting some gas is not clear in field experiments, and the interaction mechanism between injection gas and reservoir crude oil is still the current research prospect.

(3) There is still a huge difference between the technical level and output of shale oil exploitation at home and abroad, and with the rapid development of shale oil exploration and production in China in recent years, the domestic shale oil development technology system has been basically completed. With the continuous breakthrough and innovation of a variety of technologies, it will promote the coordinated, green and efficient overall development of shale oil reservoir exploitation

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