

# Research Progress of Enhanced Oil Recovery Technology in Tight Reservoirs

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**Abstract:** With the continuous exploitation of conventional oil and gas resources, its recoverable reserves are gradually decreasing, and the difficulty of exploitation is increasing day by day. Tight oil and gas resources show great development potential and have gradually become new important strategic resources supporting sustainable development. This paper reviews several EOR technologies at home and abroad from the aspects of tight reservoir research status and characteristics, hoping to provide reference for domestic tight reservoir development technology.

**Keywords:** Tight oil; reservoir characteristics; enhanced oil recovery.

## 1. Introduction

In recent years, unconventional oil and gas resources have gradually occupied an important position in the field of oil exploration and development, among which tight oil has attracted much attention due to its abundant reserves and unique occurrence conditions [1]. Tight oil mainly occurs in tight clastic rock or carbonate reservoirs, which are usually characterized by low permeability, small porosity and extensive micro-nano porosity development, making the production process extremely challenging. Although horizontal wells and multi-stage fracturing techniques have been applied to tight oil development at present, they are still faced with problems such as low recovery factor [4] and rapid production decline of single well. In view of these problems, researchers at home and abroad have been exploring how to enhance the recovery of tight oil. This paper summarizes the distribution, reservoir characteristics and development status of tight oil resources, and analyzes the technical progress of EOR. By comparing different technologies, it provides reference for efficient development. At the same time, the application prospect of multifunctional fracturing fluid imbibition flooding technology in EOR is prospected, so as to promote the high efficiency and low cost development of tight oil resources.

## 2. Present Situation of Tight Reservoir Research

Tight oil reservoirs are divided into broad and narrow categories [6]. Broadly speaking, it covers all oil resources in low porosity and low permeability reservoirs. These reservoir characteristics make it difficult to apply traditional production methods. Therefore, it is often necessary to learn from advanced technologies in shale gas production, such as

horizontal wells and volume fracturing, to enhance oil recovery. In a narrow sense, tight oil refers to petroleum resources in non-shale reservoirs with the same characteristics of low porosity and low permeability. The exploitation of these reservoirs also depends on the above advanced technologies. Chinese scholars usually define tight oil in a narrow sense, emphasizing the characteristics of tight reservoir and low permeability. Professor Zou Caineng[7] thinks tight oil is sandstone, limestone and other reservoir oil layers with permeability less than or equal to  $0.1 \times 10^{-3} \mu\text{m}^2$ , while Professor Jia Chengzao [8] points out that tight oil is oil existing in tight sandstone, carbonate rock and other source rocks or adjacent source rocks without large-scale migration. These definitions highlight the geological characteristics and genesis of tight oil and provide theoretical support for efficient exploitation.

### 2.1. Distribution of tight reservoirs at home and abroad

With the large-scale commercial exploitation of tight oil resources in the United States, the world traditional energy pattern has changed, which has caused a global upsurge in tight oil exploration and development. Affected by this, many countries have devoted themselves to the exploration and development of tight oil resources, and most of them have made positive progress. According to statistics, the total reserves of tight oil resources in the world are as high as  $66220 \times 10^8$  barrels, of which the United States, China, Russia and other countries occupy the main share. However, under the current development technology, the average recovery factor of tight oil resources is only 4.97%, see Table 1[9]. This situation highlights the urgency and importance of enhancing tight oil recovery technology.

**Table 1.** Distribution of Geological Reserves and Recoverable Reserves of Global Tight Reservoir

country	Geological reserves( $10^8$ barrels)	Recoverable reserves( $10^8$ barrels)	Average recovery(%)
Russia	12430	746	6.00
US	9540	477	5.00
China	6440	322	5.00
Libya	6130	261	4.26
Argentina	4800	270	5.63
Australia	4030	175	4.34
other regions	22850	1023	4.56
Total/Average	66220/	3274/	/4.97

China is rich in tight oil resources. Although it started later than western countries in exploration and development, it has achieved remarkable development results. In Ordos Basin, Songliao Basin, Sichuan Basin, Turpan-Hami Basin, Zhunger Basin and other important areas, 100 million tons of tight oil areas have been discovered [10], which fully demonstrates the huge potential of tight oil resources in China.

## 2.2. Tight reservoir characteristics

Tight oil are one of the unconventional hydrocarbon resources. Its characteristics are mainly reflected in the following aspects:

1. Tight oil reservoirs are characterized by low porosity and low permeability, which makes it difficult to apply traditional production methods. Typically, tight reservoirs have a porosity of less than 10%, a matrix overburden permeability of less than 0.1 mD, and a pore throat diameter of less than 1 $\mu$ m. This property makes it difficult for the oil in the reservoir to flow, thus increasing the difficulty of production.

2. The tight oil mainly exists in source rocks in a free or adsorbed state or in tight sandstones and carbonates interbedded with source rocks or other reservoirs. It has not been migrated on a large scale and over long distances, so tight reservoirs have no distinct fixed trap boundaries compared to conventional reservoirs.

3. Tight reservoirs usually have a symbiotic relationship with source rocks, which makes tight reservoirs different from conventional reservoirs in geological characteristics. Due to the existence of symbiotic relationship, the oil quality of tight reservoirs is usually light, the density of crude oil is generally greater than 40°API or less than 0.8351g/cm<sup>3</sup>, and the fluidity is good.

4. Tight oil is generally distributed in sag or slope, and its structure is relatively simple, which is favorable for large-area oil bearing. In addition, the formation of tight reservoir also needs sapropelic and high quality source rock with high maturity and continuous distribution of tight reservoir.

## 2.3. Development Status of Tight Reservoir

With the continuous updating of staged multi-stage fracturing technology for horizontal wells, the upsurge of exploration and development of tight reservoirs in the world is heating up, especially in North America, especially in the United States and Canada. As early as 2006, the tight oil production of Bakken Formation in Williston Basin of the United States exceeded 50,000 barrels per day; subsequently, the United States continuously strengthened its investment in tight oil resources, and the tight oil production increased significantly in 2010, and the proportion continued to rise; by 2014, the number of tight oil and gas wells drilled increased significantly; by 2015, the tight oil production exceeded half of the total crude oil production of the United States [11]. Canada, as the world's fifth largest oil exporter, is also rich in tight oil resources, which began to be developed in 2005. Canada's tight oil production has steadily increased from 19,600 tons per day in 2010 to 48,300 tons per day in 2016, and production has stabilized in recent years, remaining at 46,900 tons per day in 2018.[13]

At present, China has learned from foreign successful experience in tight oil reservoir development and made remarkable progress through exploratory research. In 2012, Shengli tight oil field adopted horizontal well staged fracturing technology, and the production reached 4008t in the first year and decreased to 2455t in the next year [14]; the first annual production of North China tight oil field was 2071t, and decreased to 1087t in the next year. PetroChina established four tight oil demonstration areas in Chang 7 Member of Ordos Basin at the end of 2015, with a total production capacity of 115 $\times$ 10<sup>4</sup>t[15]. However, the production of tight oil areas developed at present declines rapidly, for example, the decline rates of Shengli and Huabei oil areas in the first year are as high as 50% and 65% respectively, failing to achieve stable high production. Therefore, on the basis of understanding the characteristics of tight oil in China, it is the key to develop tight oil resources efficiently and stably by using foreign technology for reference reasonably and adopting technical measures suitable for domestic reservoir development.

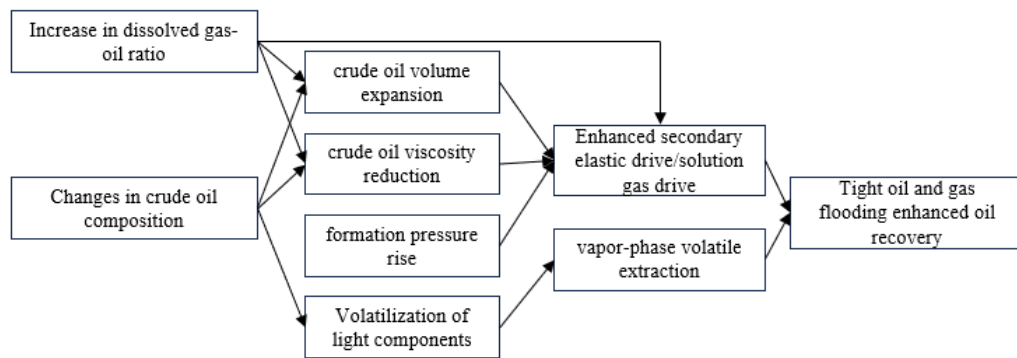
## 3. Enhanced Oil Recovery Technology for Tight Reservoirs

After horizontal well staged fracturing, a fracture network with conductivity is formed in tight oil reservoir, thus realizing commercial production. However, only natural energy depletion development, its production will decline rapidly, a recovery factor is often only 3%~10%. Therefore, it is particularly critical to improve the recovery efficiency of tight oil reservoirs [16]. At present, many kinds of EOR techniques have been widely used in tight oil reservoirs, and their effects have been verified by field tests, including gas injection development, water injection development and imbibition displacement.

### 3.1. EOR Technology of Gas Injection Development

#### 3.1.1. huff and puff

Gas injection huff and puff technology in tight reservoirs can significantly enhance oil recovery through multiple mechanisms synergy. These mechanisms mainly include volume expansion, viscosity reduction, reservoir pressurization and volatilization of light components. The comprehensive effect of these processes strengthens the secondary elastic drive and solution gas drive effect in the reservoir, and promotes the gas phase volatile extraction at the same time, thus realizing the goal of improving the recovery efficiency of tight oil gas injection huff and puff technology, as shown in Figure 1. The enhanced recovery mechanisms involved in gas injection huff and puff in tight reservoirs include oil volume expansion, oil viscosity reduction, reservoir pressurization and volatilization of light components. As shown in Figure 1, the enhancement of these mechanisms can enhance secondary elastic flooding/solution gas flooding in the reservoir, and gas phase volatile extraction occurs, thus achieving the purpose of tight oil gas injection huff and puff to enhance oil recovery [19].



**Figure 1.** Logic diagram of enhanced oil recovery by gas injection and huff and puff in tight oil

In 2008, a huff and puff test was conducted in the Bakken Formation of North Dakota, and the test did not achieve the expected results although the gas injection rate was 1.0 MMscf/d for 30 days. The main problem is that the gas is rapidly breaking through the reservoir, causing oil production to decline instead of increase. Later that year, however, huff and puff tests in the Montana Bakken Formation in Richland County, USA, yielded different results. The test was conducted at a gas injection rate of 1.5 - 2.0 MMscf/d for 45 days and shut in for the next 64 days. By March 2010, the well was producing 44 bbl/d, a significant stimulation [21]. Jiangsu Oilfield has also made active exploration for low permeability and tight reservoirs. The workers carried out 12 well-times of CO<sub>2</sub> huff and puff field test, and injected 2926 tons of CO<sub>2</sub> accumulatively. These efforts resulted in a significant increase in oil production, with a total of 3348 tons of oil added, with an average single-well oil increase of 304 tons and an average oil change rate of 1.14 tons per ton of CO<sub>2</sub> [22]. This series of experiments proved the effectiveness of CO<sub>2</sub> huff and puff technology in enhancing the recovery factor of low permeability tight reservoir.

In addition, Mahu tight reservoir is famous for its low porosity and low permeability, and its production declines rapidly after fracturing. In order to improve oil recovery, CO<sub>2</sub> huff and puff test has been carried out for 3 well times in this area. In these tests, well X721 increased oil by 2161 tons with an oil change rate of 1.07; well X92 increased oil by 1768 tons with an oil change rate of 0.44; and well M1114 increased oil by 1452 tons with an oil change rate of 0.33 [23]. Although the oil change rate of each well is different, on the whole, these tests have achieved certain stimulation effect, which further verifies the application potential of CO<sub>2</sub> huff and puff technology in tight reservoir development.

### 3.1.2. continuous gas injection

Gas injection flooding shows significant application potential and advantages in tight reservoir development [24]. Especially the injection of CO<sub>2</sub> and other gases can not only effectively supplement formation energy, but also significantly improve oil recovery by reducing oil viscosity and improving its mobility. However, the low porosity and low permeability of tight reservoirs also bring some challenges to gas injection flooding technology. Due to low permeability, too high injection pressure may cause gas to fail to enter the reservoir smoothly, thus affecting the oil displacement effect. Therefore, in practical application, it is necessary to comprehensively consider the geological characteristics of the reservoir, the physical and chemical properties of the crude oil, and the types and properties of the

injected gas to accurately control the injection parameters to ensure that the gas can smoothly enter the reservoir and exert the best oil displacement effect. MANSOUR et al. [13] simulated tight reservoir, and when formation permeability is higher than 0.01 mD, EOR effect of gas injection development is better.

Viewfield Bakken Formation in Saskatchewan, Canada has specific geological characteristics, such as average porosity of 9%~10%, average permeability of 0.01~0.1 mD and pore throat size of 0.1~0.2 μm. In December 2011, 9 production wells in the area were retrofitted with gas injection stimulation, and by operating at a gas injection rate of 300 Mscf/d and an injection pressure of 3.45 MPa, production was significantly increased to 295 bbl/d, while the annual production decline rate was reduced to 15% [25], showing significant stimulation effects. Similar gas injection stimulation practices exist in the Bakken Formation in North Dakota, USA. In 2014, 4 production wells were injected with gas at an injection rate of 1.6 MMscf/d and an injection pressure as high as 24.13 MPa. After 55 days of gas injection, the production of these 4 wells increased somewhat [21]. At home, Fuyang Formation in Daqing Oilfield Placanticline periphery and CO<sub>2</sub> flooding pilot test area in Gao 89-1 block of Shengli Oilfield have also been tried. The formation of Daqing Oilfield has an average porosity of 12% and permeability of 0.79 mD. From 2007 to 2015, a total of 204000 t CO<sub>2</sub> was injected and 9000 t oil was produced [26].

These field test results show that oil production and recovery efficiency can be significantly enhanced by accurately controlling gas injection parameters and applying advanced gas injection flooding technology for reservoirs with different geological characteristics, whether abroad or at home.

## 3.2. Enhanced oil recovery by water flooding

As an important method to realize high efficiency development of conventional reservoir, water flooding also shows a certain application prospect in the development of tight oil resources. Continuous water injection (water drive) and water injection stimulation are two main modes of water injection development [27], which have different characteristics and applicable conditions respectively. A lot of scholars at home and abroad have studied and tested it.

FRIESEN et al. [28] conducted in-depth study on Cardium formation (permeability: 0.35~0.85 mD) in Pembina Oilfield, Alberta, Canada, and demonstrated the feasibility of water flooding development in this formation. HUSTAK [29] predicts oil recovery in the range of 15% to 25% for the

Bakken Formation in the Western Canadian Sedimentary Basin through refined water drive simulation and history fitting analysis. YU et al.[30] systematically carried out experimental study on water injection stimulation under indoor environment. The research results show that injection pressure is the key factor affecting oil recovery, and soaking time (i.e. field shut-in stage) plays an important role in improving oil recovery. However, compared with gas injection stimulation, water injection stimulation has relatively limited effect on enhancing oil recovery in tight reservoirs. In addition, a waterflood stimulation field test was conducted in the Bakken Formation in North Dakota in 2012. The test uses a water injection rate of 1200 barrels per day for one month, followed by a shut-in of two weeks and a production phase lasting three to four months. Although the water injection process did not encounter difficulties, the oil production rate did not achieve the expected increase [21]. In the tight reservoir of Chang 7 of Well A in Ordos Basin, water injection exploration test has also made progress. An innovative combined well pattern development model was used in the area, including 20 horizontal wells as producers and 36 vertical wells as water injection wells. However, at the beginning of the test, although the production of single horizontal well reached 10.2t/d, serious water flooding occurred afterwards, resulting in water breakthrough in as many as 13 wells and forced shut-down of most injection wells. In April 2014, the water injection stimulation test of Well B8 in Ordos tight reservoir achieved remarkable results. During the injection period of 22.5 days, an average injection rate of 80m<sup>3</sup>/d was achieved. After 15 days of shut-in immersion, the daily oil production after well opening significantly increased to 12.45t, which increased by 78.3% compared with that before stimulation [31], which preliminarily verified the effectiveness of water injection stimulation technology in tight reservoir development.

### 3.3. Imbibition flooding enhanced oil recovery technology

Conventional EOR methods, such as water flooding, immiscible CO<sub>2</sub> flooding and surfactant flooding, have little effect on enhanced oil recovery in tight reservoirs, especially in heterogeneous reservoirs with permeability lower than 0.01mD. Most laboratory studies focus on core samples with relatively uniform permeability, which differs significantly from the heterogeneity of actual reservoirs. In tight reservoirs, heterogeneity becomes one of the key factors affecting recovery efficiency [32]. Because of the extensive micro-nano pores, strong heterogeneity and remarkable capillary force in tight oil reservoirs, imbibition flooding technology has become an important measure to enhance tight oil recovery. The imbibition process involves the working fluid infiltrating into the oil-bearing matrix from the fracture under the action of capillary force, and driving out the crude oil in the matrix through the displacement of oil and working fluid [33]. For imbibition displacement mechanism, scholars at home and abroad have carried out in-depth research.

The imbibition effect of tight core is affected by many factors, including rock wettability, porosity, permeability, fluid viscosity, interfacial tension, fluid mineralization, rock mineral composition, temperature and pressure.[34]. The results show that wettability of rock has significant influence on imbibition effect. Wei Zhijie et al.[35] showed that the lipophilic core could hardly imbibe spontaneously, while the imbibition effect was significantly improved after the change

from lipophilic to hydrophilic rock, and the recovery ratio could reach 15%~25%. This is mainly due to the hydrophilic change which makes capillary resistance change into oil displacement power. Gu Xiaoyu et al.[36] took the tight sandstone of Chang 8 member of Yanchang Formation in Fu County area of Ordos Basin as the research object, and found that submicron to micron pores played a leading role in the process of imbibition and oil displacement, and the spontaneous imbibition recovery ratio of cores could reach 5.24%~18.23%. This indicates that micro-nano pore structure in tight sandstone has an important influence on imbibition effect. In addition, JAVAHERI et al.[37] conducted research by double core imbibition method, and found that the imbibition effect of water-wet core is stronger than that of oil-wet core, and the imbibition effect is greatly affected by porosity. When porosity is less than 2.5%, imbibition displacement effect is limited. This further proves that petrophysical properties and pore structure play a key role in imbibition effect. Large volume fracturing is a common technique in the development of tight oil resources. However, the retention of fracturing fluid in the formation should not be neglected. Generally, more than 70% of fracturing fluid is difficult to be returned, which causes certain damage to the reservoir. But on the other hand, the retained fracturing fluid can not only supplement energy for the formation, but also play an oil displacement effect through imbibition. Statistical data show that wells with low flowback rate tend to produce more after well opening, while wells with high flowback rate produce less. Therefore, the combination of fracturing fluid and imbibition flooding technology has multiple advantages of reducing formation pollution, reducing operation cost and improving production. In future tight reservoir development, this technology combination should be further explored and optimized to enhance recovery efficiency and economic benefits.

## 4. Conclusion

This paper deeply discusses the exploration and development status of tight oil resources, and combs the main technologies studied in enhancing oil recovery at home and abroad, and then draws the following important conclusions:

At present, gas injection development technology, especially gas injection huff and puff method, is generally better than water injection development in improving recovery efficiency. However, continuous water flooding has higher risk. In contrast, the effect of water flooding is better than pure water flooding. However, it is worth noting that for specific tight reservoirs, in-depth research and field tests are still needed to determine which development method is more suitable.

Tight oil reservoirs exhibit strong imbibition due to the wide distribution of micro-nano pores, strong heterogeneity and remarkable capillary force. Therefore, imbibition flooding technology has become one of the key means to enhance oil recovery. In addition, fracturing fluid imbibition flooding technology can not only effectively reduce the potential damage to the formation, but also significantly improve the production of production wells, providing a strong support for the efficient development of tight reservoirs.

In view of the fact that a large amount of fracturing fluid is consumed in the fracturing process of tight reservoirs, it is particularly important to improve the functionality of fracturing fluid. By enhancing the function of fracturing fluid, such as supplementing formation energy, changing rock

wettability, reducing friction resistance of fracturing fluid and improving permeability and oil displacement effect, it not only helps to realize formation protection, but also significantly improves tight oil recovery, which has great practical significance for sustainable development of tight reservoirs.

## References

- [1] LIN Senhu, ZOU Caineng, YUAN Xuan jun, et al. Status quo of tight oil exploitation in the United States and its implication [J]. *Lithologic Reservoirs*, 2011, 23 (04): 25-30.
- [2] YANG Hua, LI Shixiang, LIU Xianyang. Characteristics and resource prospects of tight oil and shale oil in Ordos Basin [J]. *Acta Petrolei Sinica*.2013,34(1):1-11.
- [3] WEI Haifeng, Fan Zheyuan, Yuan Xiangchun. Review on new advances in foreign tight oil development technology and their enlightenment [J]. *Petroleum Geology and Recovery Efficiency*,2013,20(02):62-66.
- [4] ZHOU Qingfan, Yang Guofeng. Definition and application of tight oil and shale oil terms [J]. *Oil & Gas Geology*, 2012, 33(04): 541-544.
- [5] LI Quanshu, XING Huilin, LIU Jianjun, et al. A review on hydraulic fracturing of unconventional reservoir [J]. *Petroleum*, 2015,1(1):8-15.
- [6] WANG Ning, GAO Dong. Development characteristic and technique analysis of tight oil reservoir [J]. *Petrochemical Industry Application*, 2016,35(03):15-18.
- [7] ZOU Caineng, ZHU Rukai, WU Songtao, et al. Types, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: taking tight oil and tight gas in China as an instance [J]. *Acta Petrolei Sinica*,2012,33(02):173-187.
- [8] JIA Chengzao, ZOU Caineng, LI Jianzhong, et al. Assessment criteria, main types, basic features and resource prospects of the tight oil in China [J]. *Acta Petrolei Sinica*,2012,33(03):343-350.
- [9] Zhang Junfeng, Bi Haibin, Xu Hao, et al. New progress and reference significance of overseas tight oil exploration and development [J]. *Acta Petrolei Sinica*,2015,36(2):127-137.
- [10] HU Zegen, MA Yuben, LI Mingfeng, et al. Research progress on enhanced oil recovery technology of tight oil [J]. *Petrochemical Industry Application*, 2023,42(03):5-11.
- [11] SHENG J J. Critical review of field EOR projects in shale and tight reservoirs [J]. *Journal of Petroleum Science and Engineering*,2017,159(9):654-665.
- [12] LIU Xin, AN Fei, XIAO Xuan. Potential Of the tight oil resource and its current situation of exploration and development in Canada [J]. *Petroleum Geology and Oilfield Development in Daqing*,2018,37(06):169-174.
- [13] MANSOUR A G, KHALIL R, GAMADI T. Compositional simulation evaluation of miscible gas injection performance in tight oil formation [C]. *SPE Western Regional Meeting*,2017.
- [14] SUN Longde, ZOU Caineng, JIA Ailin, et al. Development characteristics and orientation of tight oil and gas in China [J]. *Petroleum exploration and development*,2019,46(6):1015-1026.
- [15] DU Jinhu, Yang Tao, Li Xin. Oil and gas exploration and discovery of PetroChina Company Limited during the 12th Five-Year Plan and the prospect during the 13th Five-Year Plan [J]. *China Petroleum exploration*,2016,21(02):1-15.
- [16] MANSOUR A, EMADIBALADEHI H, WATSON M. Limitation of EOR applications in tight oil formation [C]. *SPE Kuwait Oil&Gas Show and Conference*,2017.
- [17] DU Jinhu, LIU He, MA Desheng, et al. Discussion on effective development techniques for continental tight oil in China [J]. *Petroleum Exploration and Development*,2014,41(2):217-224.
- [18] ZHOU Fujian, SU Hang, LIANG Xingyuan, et al. Integrated hydraulic fracturing techniques to enhance oil recovery from tight rocks [J]. *Petroleum exploration and development*,2019,46(5):1007-1014.
- [19] OROZCO D, Fragoso A, Selvan K, et al. Eagle ford Huff-n-Puff gas injection pilot: comparison of reservoir-simulation, material balance, and real performance of the pilot well [J]. *SPE Reservoir Evaluation&Engineering*,2020,23(1):247-260.
- [20] HOFFMAN B T, Reichhardt D. Quantitative evaluation of recovery mechanisms for Huff-n-Puff gas injection in unconventional reservoirs [C]. *Unconventional Resources Technology Conference (URTEC)*, 2019:147-MS.
- [21] TODD H B, EVANS J G. Improved oil recovery IOR pilot projects in the Bakken Formation [C]. *SPE Low Perm Symposium*, 2016.
- [22] ZHOU Zhengping, QIAN Weiming, LANG Chunyan. Analysis on CO<sub>2</sub> puff-and-tuff effect in low permeable reservoirs [J]. *Petroleum Geology and Oilfield Development in Daqing*, 2003, 22(5):53-54.
- [23] SHI Leiting, ZHANG Yulong, YE Zhongbin, et al. Field test effect analysis of CO<sub>2</sub> huff and puff for EOR of horizontal wells in tight glutenite reservoir of Mahu Oilfield [J]. *Reservoir Evaluation and Development*,2021,11(6):871-877,883.
- [24] REN Bo, ZHANG Liang, HUANG Haidong, et al. Performance evaluation and mechanisms study of near-miscible CO<sub>2</sub> flooding in a tight oil reservoir of Jilin oilfield China [J]. *Journal of Natural Gas Science and Engineering*, 2015, 27(11):1796-1805.
- [25] LUO Peng, LUO Weiguo, LI Sheng. Effectiveness of miscible and immiscible gas flooding in recovering tight oil from Bakken reservoirs in Saskatchewan, Canada [J]. *Fuel*, 2017, 208(7): 626-636.
- [26] JIANG Hongfu, LEI Youzhong, XIONG Xiao, et al. An CO<sub>2</sub> immiscible displacement experimental study aiming at Fuyang Extra-low Permeability Layer at Peripheral of Daqing Placanticline [J]. *Geoscience*,2008,22(4): 659-663.
- [27] WANG Hongwei. Application of integrated large-scale fracturing and water flooding development technology in extra low permeability oil reservoirs [J]. *Oil drilling & production technology*, 2018, 40(1):102-106.
- [28] RIESEN O J, DASHTGARD S E, MILLER J, et al. Permeability heterogeneity in bioturbated sediments and implications for waterflooding of tight-oil reservoirs, Cardium Formation, Pembina Field, Alberta, Canada [J]. *Marine and Petroleum Geology*,2017,82(1):371-387.
- [29] HUSTAK C, DIEVA R, BAKER R, et al. Waterflooding a multi-layered tight oil reservoir developed with hydraulically fractured horizontal wells [C]. *SPE Unconventional Resources Conference*,2017.
- [30] YU Yang, SHENG J J. Experimental investigation of light oil recovery from fractured shale reservoirs by cyclic water injection [C]. *SPE Western Regional Meeting*,2016.
- [31] LI Zhongxing, Qu Xuefeng, Liu Wantao, et al. Development modes of Triassic Yanchang Formation Chang 7 Member tight oil in Ordos Basin, NW China [J]. *Petroleum exploration and development*,2015,42(2):217-221.
- [32] SINGH H, CAI Jianchao. Screening improved recovery methods in tight-oil formations by injecting and producing through fractures [J]. *International Journal of Heat and Mass Transfer*,2018,116(9):977-993.

- [33] LI Shikui, LiuWeidong, Zhang Haiqin, et al. Experimental study of spontaneous imbibition in low-permeability reservoir [J]. *Acta Petrolei Sinica*, 2007, 28(2): 109-112.
- [34] SHEN Anqi, LIU Yikun, QIU Xiaohui. Improvement of Spontaneous Imbibition Oil Recovery in Tight Oil Reservoir by Surfactants [J]. *Oilfield Chemistry*, 2016, 33(4): 696-699.
- [35] WEI Zhijie, KANG Xiaodong, LIU Yuyang, et al. Key Impact Factors of Spontaneous Imbibition EOR in Tight Oil Reservoirs [J]. *Chongqing university of science and technology*, 2018, 20(2): 39-43.
- [36] GU Xiaoyu, PU Chunsheng, HUANG Hai, et al. Micro-influencing mechanism of permeability on spontaneous imbibition recovery for tight sandstone reservoirs [J]. *Petroleum exploration and development*, 2017, 44(6): 948-954.
- [37] JAVAHERI A, DEGHANPOUR H, WOOD J. Imbibition oil recovery from tight rocks with dual-wettability pore-network a montney case study [C]. *SPE Unconventional Resources Conference*, 2017.