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Research and Development of Capillary Imbibition Regularity in Ultra-Low Permeability Oil Reservoirs

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Abstract: Nowadays, Chinese economy is growing rapidly, and the petroleum industry is developing swiftly. The demand for oil and gas resources is increasing day by day. As the development process goes deeper, a significant portion of our country's oil fields has entered the stage of high-water content and high recovery. Consequently, the direction of oil and gas exploration is gradually shifting towards unconventional reservoirs. Special low-permeability oil reservoirs in China exhibit characteristics such as low porosity, low permeability, fine pores, and natural fractures. Their recovery rates are low. Hence, the exploration and development of these special low-permeability oil reservoirs have become a critical challenge in today's petroleum engineering domain. The urgent task is to find ways for high-yield, high-efficiency, and sustainable development of such reservoirs. In the development process of these special low-permeability oil reservoirs, capillary action plays a significant role. Capillary action allows the transportation of high-density crude oil within the reservoir, potentially enhancing the recovery rates of special low-permeability oil reservoirs. In recent years, both domestically and internationally, there has been extensive research on the mechanisms and patterns of water injection and capillary action. This paper delivers the research on capillary action in special low-permeability oil reservoirs, summarizes and organizes the progress and achievements in this field, aiming to deepen the understanding of this area and provide insights into future research directions.

Keywords: Ultra-low Permeability Reservoir; Capillary Action Patterns; Research Progress.

1. Introduction

Fractured low permeability reservoir is a dual medium reservoir, which is divided into fracture system and matrix system, wherein fracture system has higher permeability and better percolation capacity, but poor storage capacity, and matrix system is the opposite. Therefore, in dual medium reservoir, pressure difference and gravity are the main driving forces of fracture system, while capillary force is the main driving forces of matrix system. Especially the wettability of the hydrophilic rock, its performance is more obvious. Due to the great difference between the seepage capacity and reservoir capacity of oil and water between the fracture and the rock matrix, there are serious waterflooding and water channeling in the reservoir, which makes it difficult to collect [1] the remaining oil. Therefore, to improve the recovery rate of this kind of reservoir is an important problem to be solved.

Imbibition refers to the phenomenon that under the action of capillary force, the water in the matrix is sucked into the rock and displace the crude oil in the rock. The study has found [2, 3] that the capillary force is the main driving force in the imbibition process. Through the capillary force, the water spontaneously enters the matrix, displacing the crude oil, and the crude oil enters the crack with strong conductivity and is extracted. In essence, it is the process of displacing the non-wetting phase by the wetting phase. Studying imbibition mechanism and exploring imbibition regularity through static and dynamic imbibition experiments is of great significance to waterflood development.

The author investigated and summarized the imbibition oil recovery mechanism and imbibition regularity, sorted out the research results of scholars at home and abroad, analyzed the shortcomings of the current research on imbibition theory, and prospected the future development.

2. Imbibition Mechanism

The discovery and study of imbibition mechanism can be traced back to the 1950s, when Brownscombe and Dyes found that under the action of capillary forces, water in contact with the oil layer will spontaneously enter the matrix rock, and then drive out the remaining crude oil in the matrix. Aronofsky [14] et al. have established Aronofsky's experiential model of imbibition and found that the imbibition efficiency was inversely proportional to time. Babadagli [15] et al. have found that Aronofsky's experiential model of imbibition was not applicable to cores with larger dimensions (diameter and length).

Wei Qing [7] et al. believed that imbibition mainly occurred in small and medium pores. According to the imbibition experiment and the result curve, Wang Junru [8] et al. divided the imbibition pore throat into micro pore, transition pore and large pore. Due to the action of capillary force, the micro-pore has the priority to achieve oil-water displacement and has a high recovery degree, while the large pore has a higher recovery degree than the transition pore, because it is subject to less seepage resistance. Xu Runzi [22] et al. have found that in the initial stage of imbibition, the imbibition process preferentially takes place in small holes, and gradually transitions to medium and large holes. Meanwhile, small holes are the main contributors to the imbibition efficiency of fracturing fluid, and tend to stabilize first. Wang Mengyu et al. [17] proposed the theory of layer imbibition, which divided imbibition into two categories, deep imbibition and surface imbibition. They found that besides capillary force, the difference of injection speed is also the driving force of imbibition. Other studies have found [1] that imbibition can be divided into two types according to the direction of oil-water flow, one is the simultaneous imbibition under gravity control, and the other is the reverse imbibition under capillary force control (Fig. 1). Based on capillary force and gravity in imbibition driving force, Schechter [4] et al put forward the inverse bond number N_B^{-1}, which is equal to the ratio of capillary force to gravity, and put forward the judgment basis: when $N_B^{-1} > 1$, capillary force is dominant, and it is reverse imbibition; When $N_B^{-1} < 1$, gravity is in the dominant position, and it is the same direction imbibition. Based on previous research results, Babadagli [5] et al. analyzed that the final participation rate decreases with the increase of inverse bond number. Yao Tongyu [6] et al. have found that when judging the type of imbibition, in addition to the driving force, the wettability of the rock should also be taken into account. Therefore, the reverse bond number was revised to take wettability into consideration. First, the discriminant was used to discuss whether imbibition could occur. When imbibition could occur, the primary and secondary gravity and capillary force were discussed. Zhu Weiyao et al. carried out dynamic imbibition displacement experiment for heavy water produced from oil [2], and explored imbibition mechanism with nuclear magnetic resonance technology. From the experimental results, it can be seen that in the early stage of water drive, displacement is the main effect, and then the imbibition effect gradually increases. In the whole dynamic imbibition process, displacement and capillary force are coordinated (see Fig. 2).

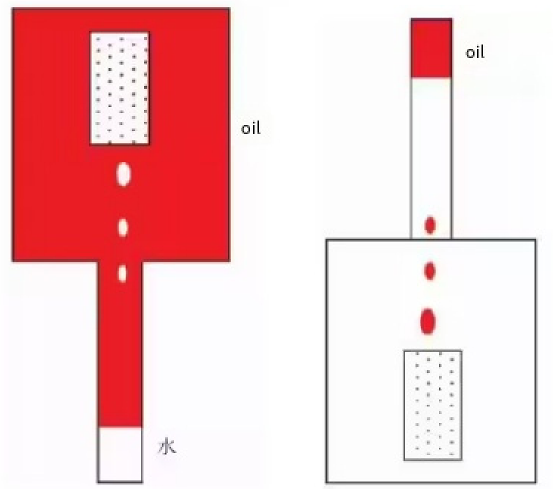

Fig 1. Oil imbibition and drainage water absorption and drainage

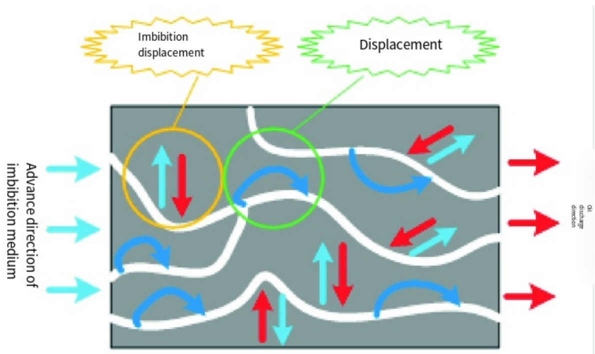

Fig 2. Dynamic imbibition

3. Imbibition Regularity and Influencing Factors

In recent years, according to the imbibition oil recovery mechanism at home and abroad, researchers and scholars have explored and summarized the regularity of imbibition oil recovery through imbibition experiment, nuclear magnetic resonance technology, scanning electron microscopy and other methods, and at the same time, they have analyzed the influencing factors of water imbibition.

3.1. Porous Permeation Structure

The pore structure of the rock has an important influence on spontaneous imbibition. Generally, the increase of porosity, permeability and pore radius will weaken the capillary force and lead to the decrease of imbibition efficiency. However, the specific situation needs to be analyzed according to the specific conditions. Liu Xiangjun [9] et al. found that under pulse pressure, the imbibition recovery efficiency is positively correlated with pore permeability parameters. The reason why the results are different from those under normal temperature and pressure is that the experimental cores are all from ultra-low permeability reservoirs, so the thickness of fine pores and adsorbed liquid film on the rock surface are of the same order of magnitude. Then the capillary force is not enough to overcome the surface viscous force, when the core pore and permeability value are increased, the number of micro-pores increases, so that the recovery rate rises. Wang Yaz [10] hu et al. has found that with the increase of reservoir permeability, pore and throat connectivity increased, and imbibition efficiency increased. Under the same permeability condition, the larger the contact area, the higher the imbibition efficiency; compared with the pure matrix core, the fractured core has a higher imbibition recovery degree. Under the same conditions, the larger the contact area, the better the performance of the core in imbibition. Ma Chao [11] et al. conducted static imbibition experiments combined with nuclear magnetic analysis to explore the law of imbibition. With the increase of permeability, the degree of imbibition recovery showed an upward trend, and the time for imbibition to reach equilibrium was also decreasing. However, when the permeability was close, the increase in the number of pore throat would lead to a slight decline in recovery efficiency. $\sqrt{K/\varphi}$At present, the concept of reservoir quality index (ROI) is generally used to evaluate the reservoir pore structure, and its value is equal to. Wei Qing [7] et al found that the higher the reservoir quality index, the better the reservoir pore structure, the larger the median pore radius and the higher the recovery rate. In the 1960s, foreign scholars [12] conducted comparative experiments between sandstone and limestone, and the experimental results showed that under the same temperature and pressure, the higher the permeability of the core, the faster the imbibition rate. However, He Mengying [13] used the mass method to carry out static imbibition experiment, and came to the conclusion that the higher the permeability of the rock layer, the relative decrease of imbibition rate. Wang Weiying [13] et al. carried out self-imbibition experiments with high permeability sandstone, low permeability sandstone and limestone respectively. From the effects of crude oil composition and reservoir pore structure on spontaneous imbibition properties, they summarized the reasons for the influence of bound water saturation on imbibition rate. The decrease of self-imbibition capillary force, the change of relative permeability, and bound water saturation have a great influence on the imbibition rate of sandstone system. However, it has little effect on the final recovery degree. Secondly, there is a certain linear relationship between the pore structure and the final recovery rate. Due to the difference in pore structure, the final recovery rate of limestone is higher than that of sandstone, and the self-imbibition rate is faster. Blair [14] found that the recovery rate of reverse imbibition increased with the decrease of the original water saturation of the rock.

3.2. Wettability

Wettability is one of the main factors affecting imbibition efficiency. Huang Xing [18] et al. studied the dynamic displacement rule of tight reservoirs by using high-pressure mercury injection and nuclear magnetic resonance technology, and found that the degree of reservoir recovery is negatively correlated with the rock wetting contact Angle. Therefore, the stronger the reservoir hydrophilicity, the higher the dynamic imbibition efficiency. By measuring the wetting contact Angle and interfacial tension, Shen Anqi [19] et al. found that the rule of strong water wet core > medium water wet core > weak water wet core. He Mengying [20] added 0.05%OP-10 surfactant in the process of spontaneous imbibition experiment, and the results showed that the surface activator can promote the imbibition recovery rate, the self-imbibition time is short, the final imbibition recovery rate is high, and the average self-imbibition recovery rate is increased by 2.554%. In recent years, many scholars [1,2,5,19] at home and abroad have explored the law of imbibition from the field of surface activators. Therefore, the surfactant has a good research prospect in the field of reservoir stimulation and efficiency.

3.3. Fluid Characteristics

Factors such as the density and viscosity of imbibition fluid are also important factors affecting imbibition. Li Shiku [1]i et al conducted static imbibition research to explore the influence of different interfacial tension conditions on imbibition efficiency and velocity, and the results showed that the oil-water interfacial tension system could transform residual oil into mobile oil, enhance fluidity, and help improve oil displacement efficiency. Ma Chao [11]'s research found that the interfacial tension decreased, and the recovery first increased and then decreased. By comparison, it was found that the recovery rate when imbibition liquid was used as oil displacement agent was significantly higher than that when water was used as imbibition liquid. Similarly, Li Aifeng [21] et al obtained similar results through spontaneous imbibition experiment, in the range of 0.290~10.439m·N/m, with the increase of interfacial tension, the final water imbibition volume first increased and then decreased. Wang Jing [22] et al. studied the influence of crude oil viscosity on the imbibition process. According to the oil production mechanism and percolation theory, they established a mathematical model and came to the conclusion that the recovery degree decreases with the increase of crude oil viscosity.

3.4. Temperature and Pressure

Ma Chao [11] et al. have found that reservoir confining pressure inhibited the imbibition process and extended the time for the whole imbibition process to reach equilibrium. Yu Hai [23] yang et al. studied the influence of temperature and pressure on the recovery rate of carbonized water flooding. Under high pressure conditions, CO_2 concentration increases, and due to the difference in the solubility of crude oil to CO_2, it diffuses into crude oil, increases the volume of crude oil, decreases the viscosity, and thus improves the efficiency of displacement imbibition. Zhong [24] et al proposed a shale forced imbibition model, from which it is concluded that the greater the pressure, the greater the forced imbibition index, and the imbibition index parallel to the shale bedding direction is greater than that in the vertical direction. Wang [25] et al. evaluated the effects of different confining pressures on spontaneous imbibition based on nuclear magnetic technology and imbibition experiment, and the results were consistent with the forced imbibition results. The recovery degree of spontaneous imbibition was positively correlated with pressure, and it was found that small pores were more strongly correlated with pressure. Relevant studies have shown that temperature cannot directly affect the imbibition efficiency, and with the change of temperature, the viscosity of imbibition fluid changes, which in turn affects the imbibition effect. In recent years, there are relatively few researches on pressure and temperature, and further study on their influence in the microscopic field is an important research direction in the future.

3.5. Water Injection Rate

The influence of displacement speed and water injection speed on imbibition process is an important direction in the study of imbibition law of ultra-low permeability reservoir. Pu Chunsheng [26] et al found that with the increase of water injection speed, imbibition efficiency also increases, but the oil increase range keeps decreasing. Hu Wei [27] et al. studied the influence of water injection velocity on imbibition contribution through two-dimensional flat-rock water flooding experiment, and the results showed that the faster the injection velocity, the higher the imbibition contribution. Liu Xi uchang et al obtained slightly different results, the injection speed increases, the dynamic imbibition efficiency of the core first rises and then falls, at 0.2ml/min to achieve the maximum, this is because the dynamic imbibition process, there is a common influence of capillary force and viscous force, flow rate increases, the proportion of viscous force gradually increases, the influence of capillary force gradually decreases, at this time, The whole process there is an optimal value, making the maximum displacement efficiency, therefore, in the actual production process, reasonable water injection speed, can achieve the best effect. At present, some studies have focused on the influence of displacement velocity on imbibition process, but there are still some challenges and unknown areas that need to be further explored. For example, the imbibition process involves complex fluid-solid interactions, and the mechanism of influence of displacement velocity on imbibition behavior under different conditions still needs to be further studied. In addition, combining experimental and numerical simulations may help to more fully understand the influence of displacement velocity on imbibition processes.

3.6. Other Factors

In addition to the main factors listed above, some scholars have also conducted researches on the content of clay minerals, core size and movable fluid parameters of rocks. Huang Xing [18] et al found that the more complex the composition of clay minerals, the degree of recovery increases first and then decreases. Meanwhile, they also found that the mobile fluid saturation and movable fluid porosity of reservoirs are positively correlated with the degree of recovery. The higher the movable fluid parameters, the better the percolation capacity of the reservoir, the larger the effective storage space, and thus the greater the dynamic imbibition efficiency. Wang Yazhu [10] et al. concluded through experiments that the core length is negatively correlated with the core permeability, and the imbibition rate of short core is faster.

4. Problems and Prospects

With the in-depth study of imbibition mechanism and influence of low permeability reservoir by Chinese and foreign scholars, a lot of achievements have been made in many aspects, but the main controlling factors affecting the degree of imbibition recovery are still unclear. Further quantitative analysis is needed to determine which parameters have a greater impact on imbibition, and then identify the optimal solution.

The imbibition process involves multiple scale phenomena, which may affect imbibition behavior from macro scale to micro scale. Researchers need to conduct in-depth studies at different scales and find the interconnections among them to obtain comprehensive imbibition laws. At the same time, how to study imbibition law under complex conditions remains a challenge. On the other hand, temperature and pressure are important factors that affect the imbibition law. However, there are relatively few studies on imbibition behavior under high temperature and high-pressure conditions, and this aspect needs to be further studied.

In terms of research methods, the current laboratory experiments mainly include static imbibition and dynamic imbibition, which cannot simulate the complex situation inside the actual formation and have limited guidance for field tests. Therefore, it is necessary to update the existing research methods. On the other hand, based on nuclear magnetic resonance technology, CT scanning technology, numerical simulation and other technologies, to strengthen the collaboration of multi-disciplines, and then strengthen the application of other new technologies in imbibition research.

5. Summary

In this paper, the imbibition mechanism and regularity of ultra-low permeability reservoir are investigated, and the research process and progress in this field are summarized. In order to promote the development of imbibition regularity research, interdisciplinary cooperation and the application of advanced technology will be the key direction in the future. With the continuous progress of science and technology, it is believed that the study of imbibition regularity will usher in new breakthroughs and progress, and contribute more wisdom and strength to the sustainable development of the energy field.

References

[1] Li Shikui, Liu Weidong, Zhang Haiqin, et al. Experimental study of spontaneous imbibition in low permeability reservoir. Acta Petrolei Sinica, Vol. 28 (2007) No. 2, p. 109-112.

[2] Zhu Weiyao, Ju Yan, Zhao Ming, et al. Spontaneous imbibition mechanism of flow through porous media and waterflooding in low permeability fractured sandstone reservoir. Acta Petrolei Sinica, Vol. 23 (2002) No. 6, p. 56-59.

[3] Chen Gan, Song Zhili. Imbibition characteristics of matrix rocks in Huoshaoshan oilfield. Xinjiang Petroleum Geology, Vol. 15 (1994) No. 3, p. 268-275.

[4] SCHECHTER D S, ZHOU D Q, ORR Jr F M, et al. Capillary imbibition and gravity segregation in low IFT systems. SPE 22594, (1991) p. 6-9.

[5] BABADAGLI T. Analysis of Oil Recovery by Spontaneous Imbibition of Surfactant Solution. Oil & gas science and technology, Vol. 60 (2005) No. 4, p. 697-710.

[6] Yao Tongyu, Li Jishan, Wang Jian, et al. Mechanisms and optimal conditions of imbibition in naturally fractured low permeability reservoir. Journal of Jilin University (Engineering and Technology Edition), Vol. 39 (2009) No. 4, p. 937-940.

[7] Wei Qing, Li Zhiping, Wang Xiangzeng, et al. Imbibition mechanism and influencing factors of fractured tight sandstone reservoirs: A case study of Chang 8 reservoir in Wuqi Area, Ordos Basin. Petroleum Geology and Recovery Efficiency, Vol. 23 (2016) No. 4, p. 102-107.

[8] Wang Junru, Yang Shenglai, Cao Yujie, Wang Mengyu, Yu Jiayi. Experiment on imbibition mechanism of tight oil core and enhanced oil recovery by surfactant. Science Technology and Engineering, Vol. 20 (2020) No. 3, p. 1044-1050.

[9] Liu Xiangjun, Dai Cen-pu. Experimental study on imbibition and displacement law of low permeability sandstone. Drilling & Production Technology, Vol. 31 (2008) No. 6, p. 110-112.

[10] Wang Yazhu, Yu Feng, Guo Kang. Influence of static imbibition law on enhanced oil recovery of tight reservoir. Petrochemical Technology, Vol. 30 (2023) No. 5, p. 163-165.

[11] Ma Chao, Ren Wendong, Yue Quan, Liu Wei, Huang Xiaoyi. Study on static imbibition law of tight reservoir core. Journal of Yangtze University (Natural Science Edition), Vol. 20 (2023) No. 3, p. 94-100+127.

[12] Handy L I. Determination of effective capillary pressures for porous media from imbibition data. Transaction of the AIME, Vol. 219 (1960) No. 1, p. 75-80.

[13] Wang Weiying, Zhang Gongshe. Effect of bound water saturation and rock properties on imbibition. Acta Petrolei Sinica, Vol. 21 (2000) No. 3, p. 66-69.

[14] Aronofsky J S, Masse L, Natanson S G. A model for the mechanism of oil recovery from the porous matrix due to water invasion in fractured reservoirs. Transactions of AIME. Vol. 213 (1958) No. 1, p. 17-19.

[15] Tayfun Babadali. Selection of proper enhanced oil recovery fluid for efficient matrix recovery in fractured oil reservoirs. Colloid and Surfaces A: Physicochemical and Engineering Aspects, Vol. 223 (2003) No. 1-3, p. 157-175.

[16] Wang Jialv, Liu Yuzhang, Chen Maosheng, et al. Experimental study on dynamic imbibition mechanism of fracture in low permeability reservoir. Petroleum Exploration and Development, Vol. 36 (2009) No. 1, p. 86-90.

[17] Wang Mengyu, Yang Shenglai, Cao Yujie, et al. Imbibition production mechanism of Niudong fractured volcanic tight reservoir. Science Technology and Engineering, Vol. 20 (2020) No. 2, p. 569-575.

[18] Huang Xing, Dou Liangbin, Zuo Xiongdi, Gao Hui, Li Tiantai. Dynamic imbibition and drainage law of fractures in tight reservoirs. Acta Petrolei Sinica, Vol. 42 (2021) No. 7, p. 924-935.

[19] Shen Anqi, Liu Yikun, Qiu Xiaohui, et al. Study on enhancing imbibition recovery efficiency of tight reservoir with surfactant. Oilfield Chemistry, Vol. 33 (2016) No. 4, p. 696-699.

[20] He Mengying. Study on imbibition law of tight sandstone [D]. Jingzhou: Yangtze University, 2017.

[21] Li Aifen, He Bingqing, Lei Qihong, et al. Effect of interfacial tension on spontaneous imbibition of low permeability hydrophilic reservoir. Journal of China University of Petroleum (Edition of Natural Science), Vol. 42 (2018) No. 4, p. 67-74.

[22] Wang Jing, Liu Huiqing, Liu Yuetan, et al. Numerical simulation of imbibition production mechanism in fractured reservoirs. Petroleum Exploration and Development, Vol. 44 (2017) No. 5, p. 1-10.

[23] Yu Haiyang, Chen Zhewei, Lu Xin, Cheng Shiqing, Xie Qichao, Qu Xuefeng. Research progress of enhanced oil recovery by carbonized water flooding. Bulletin of Petroleum Science, Vol. 5 (2020) No. 2, p. 204-228.

[24] ZHONG Ying, ZHANG Hao, KURU E, et al. The forced imbibition model for fracturing fluid into gas shale. Journal of Petroleum Science and Engineering, Vol. 179 (2019) p. 684-695.

[25] WANG Chen, GAO Hui, GAO Yuan, et al. Influence of pressure on spontaneous imbibition in tight sandstone reservoirs. Energy & Fuels, Vol. 34 (2019) No. 8, p. 9275-9282.

[26] Pu Chunsheng, Kang Shaofei, Pu Jingyang, Gu Xiaoyu, Gao Zhendong, Wang Yongdong, Wang Kai. Progress and development trend of injection huff and puff technology for horizontal Wells in tight reservoirs in China. Acta Petrolei Sinica, Vol. 44 (2023) No. 1, p. 188-206.

[27] Hu Wei, Zhang Lei, Shi Lihua, Zeng Jun. Dynamic imbibition experiment and main controlling factors of tight reservoir. Science Technology and Engineering, Vol. 23 (2023) No. 10, p. 4157-4167.