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Analysis of Influencing Factors of Water Flooding Productivity in Tight Oil Reservoirs

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Abstract: With the continuous development of tight oil resources in China, water flooding has become the main development method of major oilfields. However, due to the influence of formation burial depth, cement type, cementation mode and other factors, the fluid flow is difficult, which affects the flow characteristics of the fluid in the reservoir. Based on the analysis of microscopic pore structure characteristics of different levels of reservoirs, combined with the test results of reservoir fluid physical properties, the macroscopic, microscopic, dynamic and static characteristics of reservoirs are systematically summarized, and the effects of cementation degree, reservoir damage, flow threshold and other factors on single well productivity are classified and evaluated. By analyzing the distribution law of water flooding remaining combined with the characteristics of reservoir microscopic pore structure, the characteristics of current productivity influencing factors are comprehensively analyzed.

Keywords: Tight Oil Reservoir; Water Flooding; Productivity; Analysis.

1. Introduction

At present, with the progress of society, the global economy is also developing rapidly, and the demand for energy is increasing. With the decline of global conventional reservoir production, tight oil has gradually become the focus of oil and gas development [1-3]. The use of water injection development can achieve stable and high yield of oilfield development, and has the ability to maintain reservoir pressure and improve oil recovery, thereby improving oilfield productivity. Water as a displacement agent can save development costs, thereby improving the ultimate recovery of the oilfield [4]. Water injection development is a long-term process. With the increase of water injection time, the water injection pressure will increase relatively, which seriously affects the productivity of oil wells. In the process of water injection development of reservoirs, a variety of factors lead to the blockage of water injection wells, including acid sensitivity, water sensitivity, particle migration, dirty oil, solid particle invasion and formation scaling blockage, resulting in generally low single well productivity. There are obvious different development effects between wells, and the productivity of low permeability reservoirs is affected by many factors [5]. And after the pressure-driven water injection development, it will also be affected by construction and other factors, so that the productivity of different oil wells is different [6]. Therefore, on the basis of previous geological research results, single factor analysis, multi-factor interconnection and full index characterization are carried out. It is necessary to track and evaluate the effect of water injection development test in time, and carry out comprehensive geological research of reservoir. Develop a comprehensive technology to optimize the displacement efficiency of the reservoir, considering the production performance and reservoir performance under different production methods [7]. The comprehensive influence of rock skeleton characteristics, microscopic pore characteristics and fluid seepage characteristics on oil well productivity is clarified, which provides technical support for the efficient development of reservoirs.

2. Water Flooding Characteristic

Water injection development is a secondary oil recovery method, which is the technical means mostly used in domestic reservoirs at present. The domestic research on this is deepening. This technical means has a significant oil recovery effect in the early stage of water injection, but the oil recovery effect gradually decreases in the later stage of water injection. The main reason for the decline of oil production capacity in the later stage of water injection development is that the distribution of remaining oil tends to be discrete. It is difficult to quantitatively describe the remaining oil in the plane and vertical direction. The more accurate the description of the remaining oil is, the better the effect of oilfield adjustment and potential tapping will be [8-9]. In the early stage of water injection development, the continuous oil in the reservoir can be directly displaced by water, which is the " water flooding oil recovery " in water injection development. In the early stage of reservoir development, water flooding is the main method, and the mining effect is good [10]. Reservoir physical properties, pore throat structure, displacement pressure and water injection multiple are the main reasons that affect the efficiency of water flooding. The physical properties of the reservoir are closely related to the water flooding efficiency. The better the physical properties of the reservoir, the more seepage paths of the reservoir, the wider the water flooding area, and the higher the water flooding efficiency. Different pore throat structures have different water flooding efficiency. The difficulty of fluid flow in the reservoir seepage channel is determined by the microscopic pore throat structure of the reservoir, and the microscopic pore throat structure also determines the seepage characteristics. At the same time, the difference of pore throat structure also determines the efficiency of water flooding [11]. The efficiency of water flooding will be improved to a certain extent with the increase of injection pressure or water injection multiple [12-13].

3. Analysis of Comprehensive Influencing Factors

The influencing factors are divided into geological factors and engineering factors. Geological factors include reservoir physical properties, heterogeneity, sensitivity, viscosity, etc., which will lead to different effects of reservoir fracturing and also affect water flooding productivity. Engineering factors include effective horizontal section length and fracturing parameters.

3.1. Geologic Factor

3.1.1. The Influence of Reservoir Physical Properties on Productivity

Reservoir physical property is the total reflection of diagenesis, sedimentation, micro porosity and permeability. Permeability, porosity, sensitivity and throat type are the main factors affecting reservoir physical properties. In 2016, Chengyouyou et al [14] concluded that the degree of reservoir physical properties will have different degrees of interference with the open flow through a comprehensive analysis of various factors. From a macro perspective, as long as the physical properties of the reservoir are better, the yield is higher; the worse the reservoir physical properties, the lower the production. According to the pore throat structure parameters, reservoir displacement pressure, maximum mercury saturation, etc., the physical properties can be judged. From the mercury injection curve, it can be seen that the platform end of the capillary pressure mercury injection curve of the reservoir is not obvious, the capillary curve of different permeability levels is small, the throat distribution is scattered, and there is a certain amount of large pore throat. The overall characteristics are in line with the improvement of water flooding recovery and the increase of single well productivity.

3.1.2. The Influence of Reservoir Heterogeneity on Productivity

In 2015, Xing Bo et al [15] showed that reservoir heterogeneity refers to the comprehensive influence of sedimentary environment, diagenesis and tectonic action in the formation process of oil and gas reservoirs, and there are uneven changes in spatial distribution and internal attributes. In 2016, Yin et al [16] revealed that in the process of oil and gas field development and production, the degree of heterogeneity of reservoirs often leads to different degrees of recovery, residual oil distribution, and single well productivity. In 2022, Deng X et al [17] through physical simulation experiments, it is concluded that the optimized combination system can greatly improve the recovery rate of heterogeneous reservoirs in high water cut stage. Strong heterogeneity will lead to low displacement efficiency, difference in remaining oil distribution and decline in oil well productivity in the study area, which is one of the main factors affecting oil well productivity. The main influencing factors are the change of porosity and permeability, the heterogeneity of particles and fillings.

The strong permeability heterogeneity of the reservoir will seriously affect the oil well production [18]. When the coefficient of variation of permeability is greater than 0.7, it indicates that the permeability of the reservoir is strongly heterogeneous. When the permeability breakthrough coefficient is greater than 3, it indicates that the reservoir permeability is strongly heterogeneous. The larger the permeability difference is, the stronger the heterogeneity of permeability is.

In 2019, Liu et al [19] found that in the rising half cycle of SSC7, the larger the difference in particle size, the easier the pores between large particles will be blocked, causing the heterogeneity of pore throat, resulting in the inability of crude oil to flow and low displacement and sweep efficiency. Therefore, the heterogeneity of particles has a certain impact on the productivity of oil wells. The arrangement direction of particles also affects the heterogeneity of reservoir permeability.

The factors affecting the heterogeneity of reservoir pore throat are: the type, content, occurrence and distribution of interstitial materials. The occurrence of interstitial material in reservoir sandstone can be observed by scanning electron microscope data.

3.1.3. The Influence of Reservoir Sensitivity on Productivity

In 2023, Li Jiangtao et al [20] evaluated the implementation effect, indicating that reservoir sensitivity makes edge water non-equilibrium fingering breakthrough, seepage channel occlusion, and drainage difficulty. Water sensitivity damage is because montmorillonite and illite have strong hydrophilicity and expansibility. Due to the strong hydrophilicity and expansibility, the reservoir pores in the throat are finer, the formation rock particles are unstable, and the fluid flow will be more prone to particle migration and hydration shedding, which will lead to poor permeability performance and damage the reservoir, resulting in a decline in oil well production. Velocity sensitivity refers to the possibility and degree of reservoir permeability decline caused by the migration of particles caused by the increase of fluid flow velocity and the blockage of pores. The reason for the velocity sensitivity is that the intergranular structure of illite and kaolinite is loose, and the particles will be accompanied by their peeling off and migration when they encounter fluid erosion, which is characterized by high critical flow rate and low permeability damage. Therefore, in the area with high content of illite and kaolinite, there will be higher velocity sensitivity and weaker control effect on formation particles. Therefore, in the area with high content of illite and kaolinite, there will be higher velocity sensitivity, weak control of formation particles, and strong accumulation of particles in the pore throat and blockage of the throat, which greatly damages the permeability of the reservoir and has a greater impact on oil well productivity.

3.1.4. The Influence of Crude Oil Viscosity on Productivity

In 2015, in order to improve the accuracy of productivity prediction, Shang et al [21] used the Newton-Raphson numerical method to solve the problem, and the oil well production at any time can be obtained. The results show that when other parameters are constant, under the same production time, the greater the viscosity of crude oil, the lower the oil production of oil wells, and with the production, the influence of crude oil viscosity on oil production will gradually increase. The reason is that the greater the viscosity of crude oil, the fluid cannot flow, the greater the fluid seepage resistance, so the oil production will be smaller.

Heavy oil reservoir is a kind of formation crude oil with high viscosity, which is difficult to be produced from underground, resulting in high development cost. Moreover, colloids, asphaltenes and long-chain paraffins lead to poor fluidity of formation crude oil in reservoirs and wellbores, which makes it difficult for crude oil to flow and seriously affects oil well production. The viscosity of crude oil in the

reservoir rises rapidly, which seriously affects the fluidity of crude oil, increases the seepage resistance, and increases the difficulty of mining. In the case of the same viscosity of crude oil, the logarithm of ultimate recovery is positively correlated with permeability [22]. And some formation crude oil contains a large amount of asphaltene and resin, which also seriously affects the fluidity of crude oil, increases the resistance of seepage, increases the mining cost, and greatly reduces the production of oil wells.

3.2. Engineering Factor

3.2.1. Micro-pore Structure

In 2021, Quan Honghui et al [23] carried out microscopic water flooding experiments, revealing the internal relationship between pore structure and microscopic seepage characteristics of water flooding. The results show that different types of pore throats have different seepage characteristics, which is the main factor affecting the efficiency of water flooding.

In 2022, Lei X et al [24] studied the effects of rock properties, pore structure and oil displacement efficiency by nuclear magnetic resonance and core displacement. The results show that after high-fold water injection, as the particles migrate, the rock permeability increases, the pore volume and the average pore throat radius increase, and the heterogeneity increases. Compared with conventional water injection, high multiple water injection is more effective in improving oil displacement efficiency. Evaluate the influence of pore throat structure on water flooding displacement efficiency and single well productivity, and further reveal the control mechanism of reservoir microscopic heterogeneity on single well productivity [25]. The greater the permeability of the reservoir, the higher the content of the larger pore throat, the higher the single well productivity and water flooding efficiency.

3.2.2. Flowing Characteristics of Fluid

The influence of crude oil viscosity and fluid flow characteristics on water flooding displacement efficiency and single well productivity is clarified, and the control mechanism of fluid properties on single well productivity in unconsolidated sandstone reservoirs is further revealed. In 2020, Liu et al [26] studied the influencing factors of oilfield viscosity change through experiments, and provided corresponding guidance for oilfield development according to the characteristics of flow stages in different periods.

3.2.3. Effective Horizontal Section Length

In 2021, Wu et al [27] speculated the productivity of horizontal sections with different lengths. Under the premise of ensuring certain geological conditions, the production of horizontal wells will increase with the increase of the length of the horizontal section, but the increase in production will gradually decrease after the length of the horizontal section is greater than a certain length. Through the research of scholars, it is found that the production of horizontal wells increases with the increase of the length of the horizontal section. This phenomenon is due to the shallow buried depth of the reservoir in the study area, the low original formation pressure, the longer the length of the horizontal well, the longer the distance of crude oil flowing in the wellbore, resulting in increased resistance and increased energy consumption. With the decrease of formation pressure, the flow of crude oil is relatively slow, and the contribution of the formation to the fluid in the wellbore is reduced, so that the productivity of the oil well is reduced [28].

In 2021, Liu et al [29] conducted numerical simulation through Eclipse to study the influencing factors of horizontal well productivity, and finally proposed that measures such as optimizing the reserve area and increasing the length of the horizontal section should be taken to effectively develop horizontal wells.

In 2021, Xue et al [30] comprehensively analyzed the influence of geological factors on productivity by using grey correlation method and random forest algorithm, aiming at the problem that the main controlling factors of productivity are not clear, according to the obvious difference of oil well productivity affected by geological factors and engineering factors. Based on the experimental results, it can be seen that under the same well spacing conditions, the longer the oil layer is drilled, the larger the horizontal wellbore discharge area is, and the recovery rate is relatively improved. However, the recovery rate increases slowly when the effective horizontal section length is greater than a certain length.

3.2.4. Fracturing Transformation Parameters

In 2021, Xue Ting et al [30] carried out experiments. Based on the results of this work, the results show that by increasing the number of fracturing sections, the amount of fluid entering the ground and the amount of sand added in the 100-meter oil layer, the transformation volume can be expanded, and the fracture conductivity can also be improved to a certain extent. The effect of fracture-making and energy-making will also be significantly affected, and it is positively correlated with the cumulative oil production of the 100-meter oil layer in the first year. Ineffective clusters will be easier to form with the increase of the number of single clusters, and the yield will decrease. There is a negative correlation between non-equilibrium initiation and the degree of extension and the number of segments. The lower the degree of reservoir utilization, the lower the productivity. Therefore, the number of single-segment clusters of subdivided cutting volume fracturing should be appropriate, that is, multi-segment and few clusters.

In 2021, Zhang Yongchun et al [31] studied the wells that were not fully transformed for the first time, optimized the fracturing construction parameters and the fracturing transformation parameters, increased the reservoir reconstruction volume and used the combination of repeated fracturing and formation energy supplement; thus, the oil-water replacement efficiency has been greatly improved.

4. Conclusions and Understanding

At present, the current situation of water injection development in tight reservoirs in China is characterized by high productivity in the early stage of water injection and gradual decline in productivity in the later stage. The comprehensive analysis of the factor's affecting productivity is indispensable, and the fine description of remaining oil is also important. It is the top priority to realize long-term high and stable production in water flooding development of reservoir. In order to analyze the influencing factors of productivity more comprehensively, based on the existing analysis methods, the following suggestions are put forward for better analysis of water flooding development of reservoir in the future:

(1) The greater the reservoir permeability, the higher the content of larger pore throat, the higher the single well productivity and water flooding efficiency. At the same time, the reservoir water sensitivity and speed sensitivity are strong,

which will further reduce the efficiency of water flooding. It is suggested that in the subsequent development stage, we can refer to the indoor experimental results, reasonably control the injection-production parameters, and further reduce the negative impact of sensitivity on single well productivity. And then affect the single well productivity;

(2) The comprehensive analysis of the influencing factors of productivity shows that the viscosity and fluidity of crude oil are the main factors affecting the oil displacement efficiency. It is suggested that some viscosity reducers should be added on the basis of conventional cold-water flooding in the later stage, and the products with good viscosity reduction effect and automatic demulsification and dehydration should be selected. Under the condition of ensuring good compatibility between emulsion viscosity reducer and demulsifier in joint station, the viscosity of crude oil in reservoir can be reduced and the sweep efficiency of water flooding can be increased by applying this type of products, so as to improve the productivity of reservoir.

(3) It is found that reservoir physical properties, micro pore throat structure type, crude oil viscosity and fluidity, reservoir sensitivity, heterogeneity, effective horizontal section length and fracturing parameters are the main controlling factors affecting the productivity of single well. According to the actual geological conditions, the injection-production index should be optimized, and the reasonable development should be carried out to improve the single well productivity.

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