

Experimental Study on Water - Flooding Development of Horizontal Wells in Tight Oil Reservoirs

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Abstract:

Based on the similarity of pore permeability as well as pore throat structure, nonlinear seepage characteristics and clay mineral content, the outcrop cores are selected to make large-scale physical models. These experiments of staged fracturing horizontal wells are carried out about Madong 2 well area with natural energy exploitation and supplementary energy exploitation. The experimental results show that: (1) the parts of the horizontal well that are easy to water out lie in the wellhead end and the fracture communication area of the horizontal well, the heel end of the horizontal well is easy to water out, and the toe end is difficult to use; (2) The spindle fracture network formed by staged fracturing is easier to control water outflow; (3) For the seven point injection production well pattern staggered by vertical wells and staged fracturing horizontal wells, the heel should be injected early, the middle should be controlled, and the toe should be injected more.

Keywords: Large physical model, Staged fracturing horizontal well, Natural energy exploitation, Supplementary energy exploitation, Water production mechanism.

INTRODUCTION

Water injection development is mainly applied to the development of low permeability and ultra-low permeability oilfields [1,2]. For example, the oil reservoirs with more than 0.5md in Changqing Oilfield and more than 1.5md in Daqing Oilfield are generally developed by water injection. In the process of waterflooding development, the main influencing factors include starting pressure gradient, reservoir water sensitivity characteristics, permeability and other parameters [3-6]; Elastic exploitation development mode is a natural energy development mode. Domestic oilfields will adopt this development mode for oil production when water injection development mode cannot work. Compared with vertical wells, horizontal wells have the advantages of high oil production index, small production pressure difference and long anhydrous oil production period. Especially in recent years, the staged fracturing technology of horizontal wells has made a major breakthrough, making it a powerful technical means to develop ultra-low permeability reservoirs. However, with the development of production practice, the production of horizontal wells has gradually exposed some problems: the water content of horizontal wells rises rapidly after water breakthrough, and the oil production drops sharply. Some horizontal wells even see water just after production, which seriously affects the development effect. In order to ensure the efficient and stable production of horizontal wells, it is necessary to study the mechanism of horizontal well water outflow, find out the causes of horizontal well water outflow, and put forward solutions. The water production mechanism of horizontal wells [7-11] is not limited to the bottom water ridge and fracture burst. Due to the complexity of reservoir conditions, the cause of water production is more difficult to predict. The median permeability of Madong 2 well block is about 1.1md, which makes water injection development difficult. In this paper, the outcrop cores used in the model are screened through similar porosity and permeability, similar pore throat structure, similar nonlinear seepage characteristics, and similar clay mineral content. Outcrop cores are selected to make a large model, and relevant experiments are carried out to try to find a reasonable mining method in this block.

EXPERIMENTAL EQUIPMENT AND METHODS

Introduction to Experimental Equipment

Natural outcrop sandstone, used to make a homogeneous model in large scale physical simulation experiments, can be drilled holes on the model to simulate vertical wells, simulate horizontal wells and hydraulic fracturing fractures respectively by slotting and filling a certain number of quartz sand, and carry out displacement experiments on the model to simulate production under different injection and production methods [5]. On the model, the percolation law of low permeability reservoir produced by staged fracturing horizontal well is studied by detecting the changes of pressure field and pressure gradient field.

The experiment is divided into two parts: high pressure physical simulation and low pressure physical simulation. This paper studies the water production mechanism of natural energy exploitation and supplementary energy exploitation in staged fracturing horizontal wells. The high-pressure large model experimental device can exert confining pressure on the model

through hydraulic pressure, and the maximum confining pressure can reach 25MPa, which can simulate the real formation conditions. The low-pressure device does not consider the confining pressure, so it can qualitatively study the production dynamics of supplementary energy. The experimental device is shown in Figure 1.

In the low-pressure simulation experiment, the confining pressure cannot be applied to the model, the displacement pressure cannot exceed 3Mpa, and the natural energy exploitation cannot be simulated, but the single-phase displacement can be carried out to simulate the supplementary energy exploitation experiment, study the seepage law in the displacement production process, and qualitatively analyze the production characteristics of the block. The low-pressure experimental device includes injection system, pressure acquisition system, velocity measurement system and natural outcrop sandstone model, as shown in Figure 2.



Figure 1. Physical simulation device diagram

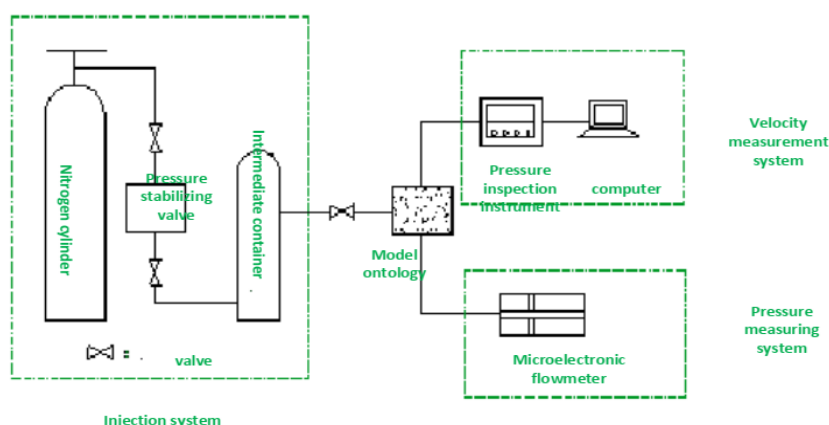


Figure 2. Flow chart of low pressure simulation experiment

Experimental Methods

The water production mechanism of horizontal wells with different fracturing scales in Madong 2 well area during natural energy exploitation is experimentally studied. The confining pressure 10MPa and pore pressure 5MPa were used in the natural energy exploitation experiment. Figure 3 shows the actual schematic diagram of flat model.



Figure 3. Schematic diagram of flat model

The experiment selects 1/2 unit well pattern to make the model, The final selected outcrop core permeability is $1.180 \times 10^{-3} \mu\text{m}^2$, with porosity of 14.50%. The length of the simulated horizontal well is 500m, and three schemes with different fracturing scales are designed: the horizontal well is not fractured, the half fracture length is 100m, and the half fracture length is 150m. Two hydraulic fracturing fractures are arranged, and the fractures are evenly distributed. Multiple pressure measurement points are evenly arranged on the model. The well pattern density, horizontal well section length and fracture length of the model are prepared according to geometric similarity to ensure that the selected units are sufficiently representative. Model size is 40.0cm $\times$ 16.0cm, the length of horizontal well section is 25.0cm, and the half length of fracture of artificial fracturing model is 5.0cm and 7.5cm respectively, representing the half length of 100m and 150m models respectively. According to the well location and fracture location of each model, the pressure measurement points are uniformly distributed on the model, as shown in Figure 4.

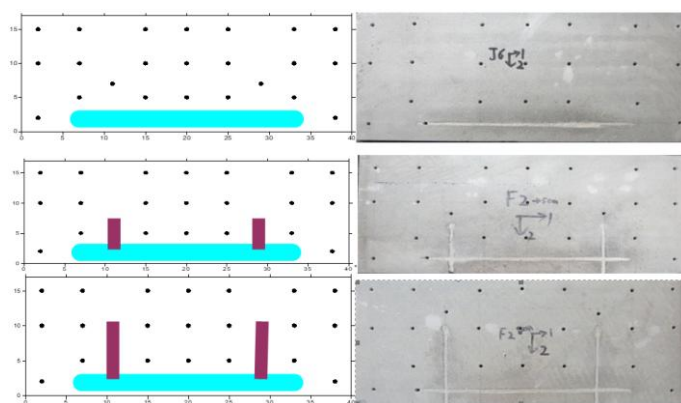
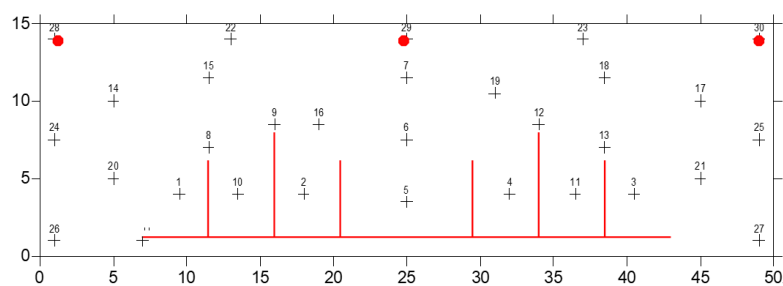


Figure 4. Schematic diagram of natural energy exploitation experiment of horizontal well

The 7-point method of simulating the staggered joint well pattern of vertical and horizontal wells in Madong 2 well area can supplement the water outflow mechanism of horizontal wells for energy exploitation under ideal conditions. Pore pressure of 0.9atm and injection pressure of 0.9atm were used in the supplementary energy exploitation experiment.

The experiment selects 1/2 unit well pattern to make a model, and the outcrop core permeability used in the model is $1.170 \times 10^{-3} \mu\text{m}^2$, with porosity of 14.86%. The length of the simulated horizontal well is 800m, and the spindle shaped fracturing fracture is designed according to the field fracturing mode: the half length of the long fracture in the middle is 140m, and the half length of the short fracture at both ends is 110m. Model size is 50.0cm $\times$ 15.0cm, the length of horizontal well section is 36.4cm, and the fracture length is 5.5 and 7.0cm respectively. The location of model pressure measurement points is shown in Figure 5.



(a) Design drawing of staggered 7-point well pattern model



(b) Physical drawing of staggered 7-point well pattern model

Figure 5. Schematic diagram of horizontal well supplementary energy production experiment

EXPERIMENTAL RESULTS AND ANALYSIS

Experimental Results of Natural Energy Exploitation

The pressure data of the three models at two time points (2min and 60min) in the process of depletion mining are extracted respectively, and the contour map of pressure field is drawn respectively, as shown in Figure 6, in which red represents the high pressure area and blue represents the low pressure area.

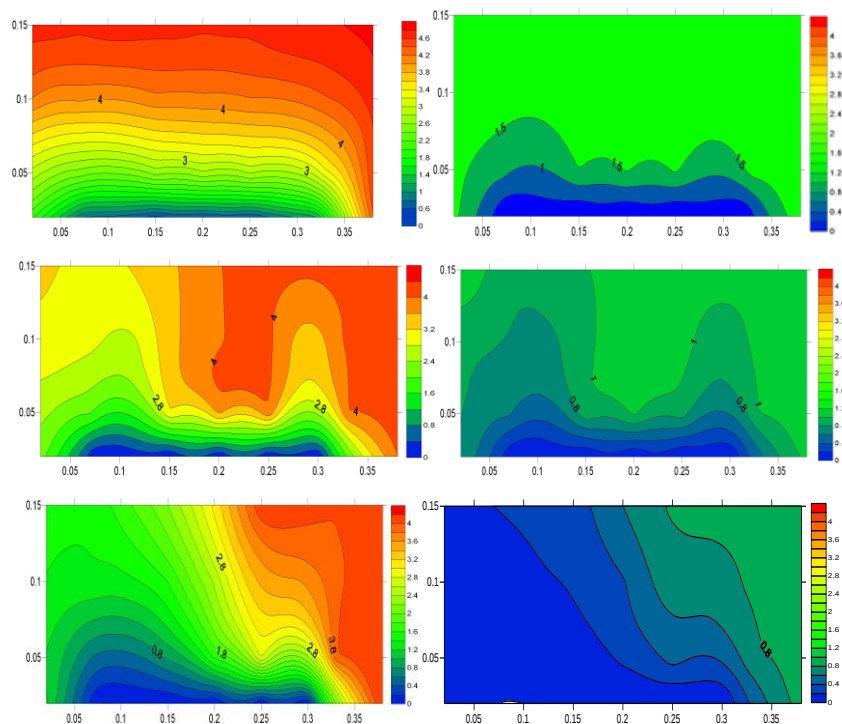


Fig. 6. Pressure field diagram of depleted production of horizontal well

It can be seen from Figure 7 that the overall pressure value of the model decreases during the exploitation of natural energy. Without fracturing model, the pressure decline rate near the horizontal well is fast, among which the wellhead end is the fastest, followed by the toe end, and the pressure decline rate near the wellhead is fast; For the fracturing model, the pressure near the fracture decreases rapidly, and the pressure relief effect of the fracture near the wellhead is obvious, and the pressure decreases faster than that of the fracture far away from the wellhead. At the same time, the model pressure of fractured horizontal well is low, and the model pressure decreases rapidly with the increase of fracture length (the half fracture length of 150m model is 100m longer than the half fracture length). At 60min, the model with large fracturing scale reaches a relatively low pressure value. The pressure decline rate between the two fractures of the fractured horizontal well is slow, and with the increase of the fracture length, the pressure relief effect of the fracture near the wellhead is more obvious. The reason should be caused by the pressure drop of the horizontal well.

According to the pressure field distribution diagram, the pressure between the two fractures and in the area far away from the wellhead of the horizontal well decreases slowly, indicating that under this permeability condition, the control range of the horizontal well is small, the pressure loss near the well zone is fast, and the far end fluid is difficult to supplement it, resulting in the decline of oil saturation, the increase of water phase permeability, and easy water production.

Record the flow velocity of the three model production wells at each time point in the process of natural energy exploitation, and draw the flow velocity curve, as shown in Figure 7.

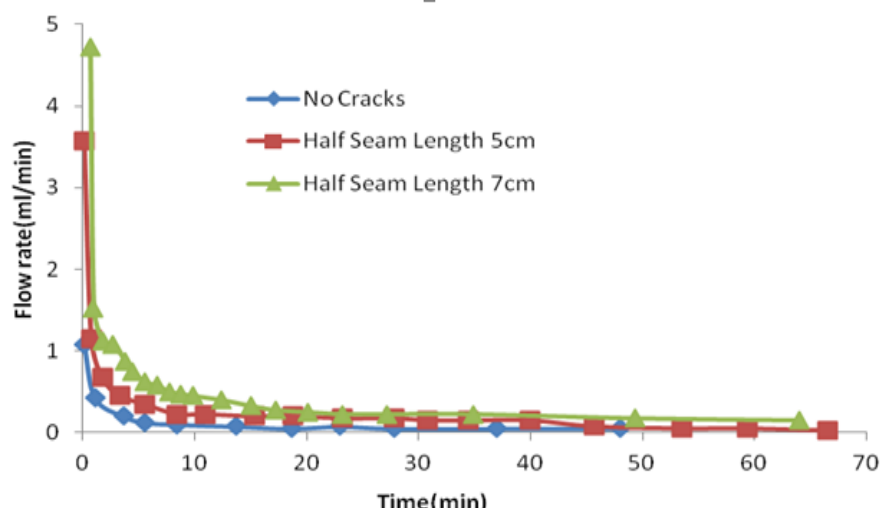


Figure 7. Flow rate curve of depletion mining in horizontal wells

In the early stage of natural energy exploitation, the flow rate of production wells is fast, the flow rate decreases rapidly, and tends to be stable in a very short time. For the horizontal well fracturing model, the initial oil production speed is accelerated, and the initial oil production speed of the half fracture length 150m model is the fastest. The oil production rate of the three block model varies greatly at the initial stage, and the rate is close after it tends to be stable, and the difference is not obvious. For low-permeability reservoirs, the natural energy decreases rapidly in the initial stage of depletion exploitation of horizontal wells and slowly in the later stage, so relatively high productivity can be obtained in the initial stage.

Based on the change of pressure field and flow rate analysis, it is found that appropriately increasing the fracture length is conducive to the oil production rate of natural energy exploitation of horizontal wells, but the control range of horizontal wells is small, which makes it difficult to use the area between fractures and the toe of horizontal wells, and it is easy to have low oil saturation and high water phase permeability near the wellhead and fracture tip of horizontal wells, resulting in water outflow.

Experimental Results of Supplementary Energy Mining

The pressure data of the model at six time points (5, 45, 125, 751, 2852, 3512min) in the process of supplementary energy mining are extracted, and the contour map of the pressure field is drawn respectively, as shown in Figure 8, in which red represents the high pressure area and blue represents the low pressure area.

It can be seen from Figure 8 that in the process of supplementary energy exploitation, first of all, the formation pressure drops rapidly, the pressure drop rate at the wellhead end of the horizontal well is greater than that at the toe end, and the pressure drop rate in the area around the fracture is greater than that in other areas of the well pattern, which is consistent with the process of natural energy exploitation. However, due to the existence of water injection wells, the formation energy is supplemented, and it is more difficult to supplement in areas where the formation energy loss is faster. The pressure around the wellhead of the horizontal well and the three nearby fractures is low, and the water injection wave and effect are poor. The injected water of the water injection well in the upper left corner points in, and the water drive front reaches the fracture, resulting in the water outflow of the horizontal well. At this time, the spindle shaped crack distribution is more conducive to controlling the rise of water content, making the long cracks in the middle easier to be affected and improving the development effect. The pressure sweep range of the middle water injection well is significantly larger than that of the water injection well in the upper left corner. The pressure sweep is more uniform and can be affected by the four cracks in the middle, with a larger control range. However, the length of the two cracks in the middle is too long, the distance between the two spindles is too small, and the injection volume of the middle water injection well is too large, which is also easy to cause water channeling. The injection water of the water injection well in the upper right corner is mainly affected by the two fractures on the right. Because the pressure at the toe of the horizontal well decreases slowly, the energy is relatively easy to be supplemented. Under the same injection conditions, the formation pressure level on the right side is high, which is easy to improve the sweep effect.

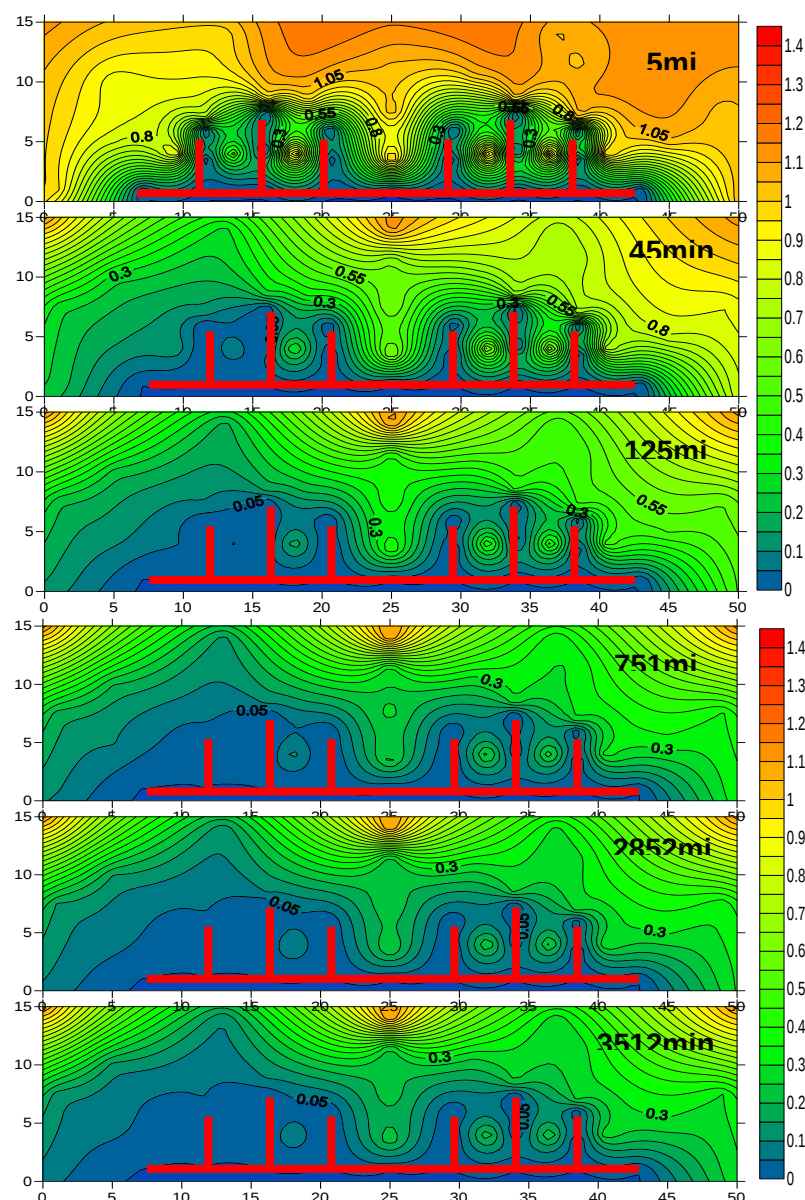


Figure 8. Pressure field diagram of depleted production of horizontal well

RESULTS

1. Using the large model physical simulation experimental system to analyze the production performance of staged fracturing horizontal wells under different development modes can provide experimental guidance for the study of water production mechanism of horizontal wells.
2. The percolation dynamic experiment of natural energy exploitation of staged fracturing horizontal wells shows that the parts of horizontal wells that are easy to produce water lie in the wellhead end of horizontal wells and the fracture communication area. Properly increasing the fracture length is conducive to the oil production rate of natural energy exploitation of horizontal wells, but if the control range of horizontal wells is small, it will make the area between fractures and the toe of horizontal wells difficult to be used, and the situation of low oil saturation and high water phase permeability is easy to occur near the wellhead and fracture tip of horizontal wells, resulting in water outflow.
3. The percolation performance of the seven point injection production well pattern staggered by the vertical well and the staged fracturing horizontal well shows that the part of the horizontal well that is easy to produce water lies in the heel end of the horizontal well, and the injection volume of the water injection well close to the heel end should be increased in the early stage of development, so as to avoid the formation pressure loss near the wellhead is too fast, the crude oil cannot be replenished, and the injected water is directed, resulting in water production; The intermediate water injection well should appropriately reduce

the injection volume, maintain the formation pressure spread range, and prevent the injection water from fingering; The formation pressure of toe end water injection well is relatively easy to maintain, which can increase the injection volume, increase the formation pressure, increase the pressure gradient, and improve the oil production speed without fingering.

ACKNOWLEDGMENTS

This research was supported by the Natural Science Foundation Project of Xinjiang Uygur Autonomous Region (No. 2023D01A65) and the Special Science and Technology Project of Karamay Vocational and Technical College (No. KZY2024 - 05). The authors also would like to thank Langfang Branch of Research Institute of Petroleum Exploration & Development, CNPC for its strong support in providing experimental equipment and the full cooperation of classmate Gao Tianfang.

REFERENCES

- [1] Yikun Li, Pin Hu, Jilei Feng. Background, current situation and development trend of water plugging in horizontal wells, *Journal of petroleum and natural gas*, 27 (5): 757-760, (2005).
- [2] Zhengming Yang, Yingzhi Zhang, Mingqiang Hao. Comprehensive evaluation method of reservoir in low permeability oilfield, *Journal of petroleum*, 27, (2006).
- [3] PermadiP, LeeR L, Kartoatmodjo R ST, et al. Behavior of water crestring under horizontal wells. SPE30743, 431- 434, (1995).
- [4] Fengguo He, Xiangnan Yue, Liangchuan Li, et al. Influence of bottom water reservoir heterogeneity on production characteristics of horizontal wells, *Petroleum drilling and production technology*, 31(4):63-66, (2009).
- [5] Wibowo W, Permadi P, Mardisewojo P, et al. Behavior of water crestring and production performance of horizontal well in bottom water drive reservoir: A Scaled Model Study. SPE87046, 2-4, (2004).
- [6] Tao Wang, Jinyi Zhao. Analysis of influencing factors on water cut change of horizontal wells in bottom water reservoir, *Lithologic reservoir*, 24(3): 103-107, (2012).
- [7] Daiyu Zhou, Tongwen Jiang, Ji Feng, etc. Study on watered-out performance and watered-out model of horizontal wells in bottom water reservoir. *Journal of Petroleum*, 25(6): 73-77, (2004).
- [8] Caili Dai, Fulin Zhao, Yaolin Li. Bottom water ridging control technology for horizontal wells in offshore oil fields. *Journal of Petroleum*, 26(4): 69-72, (2005).
- [9] Yongbin Bi, Mei Zhang, Guizhi Ma, etc. Study on water breakthrough characteristics and influencing factors of horizontal wells in complex fault block reservoir. *Fault block oil and gas field*, 18(1):79-82, (2011).
- [10] chuanfeng Zhao, Jirui Hou, Zhenhua Wu. Study on water-producing mechanism of oil well in reservoir with complex pressure system. *Petroleum geology and engineering*, 25(1): 67 -70, (2011).
- [11] Jialu Wang, Yuzhang Liu, Ruyi Jiang, et al. Physical simulation of water ridges in bottom water reservoir produced by horizontal wells. *Petroleum exploration and development*, 34(5): 590-593, (2007).