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Research Article

The Current Status and Development Trend of Water Control Technology for Horizontal Wells

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Abstract

In the advancement of bottom water reservoir development, water breakthrough poses a significant challenge to the productivity of oil and gas wells, underscoring the paramount importance of effective water control strategies. Given the intricate nature of the factors leading to reservoir water breakthrough, a one-size-fits-all approach to water management is non-existent. Rather, tailored water control techniques are necessary to address the diverse causes of this phenomenon. This paper delves into the evolution and application of water control technologies, particularly focusing on the prevalent horizontal well water control methodologies. Horizontal well variable density water control, segmented water control, double horizontal well oil recovery water control, along with advanced solutions such as ICD (Inflow Control Device), ICV (Inflow Control Valve), AICD (Autonomous Inflow Control Device), and AICV (Autonomous Inflow Control Valve) water control systems are comprehensively introduced. Furthermore, center-controlled, mechanical plugging, and chemical plugging water control technologies are also examined in depth, accompanied by a thorough analysis of their respective strengths, limitations, and adaptability to various scenarios. By keeping abreast of both domestic and international trends in horizontal well water control, the future trajectory of this field is forecasted. Emerging as key technologies are novel composite water control systems, dual-purpose water control and sand prevention techniques, and intelligent water control solutions. These advancements promise to revolutionize the management of water breakthrough in bottom water reservoirs, enhancing oil and gas recovery efficiency and sustainability.

Keywords

Horizontal Well, Water Control Technology, Bottom Water, Sand Control, Development

1. Introduction

The use of horizontal well production realize the long distance traversing of oil reservoir, effectively increase the oil drainage area of single well, which can substantially increase the well production and accelerate the cost recovery of oilfield development. Through long-term observation of horizontal well production, it is found that the horizontal well increases single well production, but some horizontal wells have faster water content rise due to the imbalance of production profile, vertical non-homogeneity, active side bottom water and other reasons. The water content of horizontal well production will rise rapidly once water is breakthrough, rising to more than 90% in a short period of time [1], and the oil production drops sharply, and it is very likely that water flooding will eventually be formed. Therefore, for some hor-

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izontal oil wells with bottom water, it is especially important to slow down bottom water coning and control the oil-water interface. At present, a variety of horizontal well water control techniques have been developed at home and abroad, which greatly improve the water control ability of horizontal wells in marginal bottom water reservoirs [2]. According to the time of adopting water control measures, horizontal well water control technology can be divided into first water control and later water control. This paper analyzes the development process, technical status and trend of horizontal well water control technology at home and abroad by summarizing the literature research and on-site construction, and at the same time analyzes and summarizes the advantages and disadvantages as well as the adaptability of water control technology.

2. The Current Situation of Horizontal Well Advance Water Control Technology

Prior water control of horizontal wells means that water control technology is directly adopted to control water in the process of horizontal well completion, so that the wells will have certain water control ability after production. According to the different principles of water control, the process of horizontal well advance water control can be divided into two categories: passive water control and active water control.

2.1. Passive Water Control Methods for Horizontal Wells in the Early Stage

2.1.1. Variable Density Perforation Water Control Technology

Variable density perforation control technology is a water control method proposed in the 1990s, which is based on the permeability difference of sections of horizontal wells, reasonably optimize the perforation density of horizontal well sections as shown in Figure 1, and make use of the change of perforation density to form different resistance, and then adjust the production pressure of different well sections, so as to adjust the fluid production profile of the whole horizontal well section. Variable density shot hole water control technology changes the pressure distribution in the wellbore less, but the inflow characteristics near the wellbore can be changed by this technology. Variable density perforation injection water control technology, which is suitable for reservoirs with good homogeneity, can effectively solve the heel-toe effect of horizontal wells. By decreasing the density of the shot hole at the heel end, increasing the pore density at the toe end, adjusting the inflow pressure difference, and changing the fluid production profile, the rate of bottom water coning in can be reduced to a certain extent. Later, the variable density sieve pipe water control technology appeared, but the variable density sieve pipe produces a small pressure drop due to the large overflow area, and the effect of water control is not obvious.

Figure 1. *Schematic diagram of variable density perforation.*

Variable density perforation technology is simple and mature, and the construction process is efficient, but the water control effect is poor. This technology was partially applied in Bohai Oilfield in the early stage, and later developed into an auxiliary process for other water control methods.

2.1.2. Horizontal Well Segmented Water Control Technology

The idea of horizontal well segmented water control completion technology comes from the optimization of variable density shot hole water control technology [3, 4]. This technology utilizes the packer to segment the reservoir, as shown in Figure 2, according to the change of reservoir permeability, the longer horizontal section with large difference in non-homogeneity can be mined in sections, which can effectively change the non-homogeneity of the reservoir to reduce the along-the-road abrasion resistance in the direction of the horizontal wellbore, and avoid seeing water prematurely in the localized position of the horizontal wellbore [5]. Horizontal well section water control can realize oil recovery in sections, and for the horizontal section with localized water, it can be plugged or the whole section can be abandoned. Producing the sections that do not see water effectively controls the rate of increase of water content in the horizontal section [6].

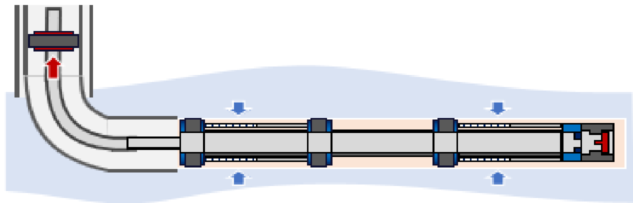

Figure 2. *Schematic diagram of horizontal well segmented water control structure.*

Horizontal well segmented water control technology can be used in conjunction with variable density perforation control technology to carry out perforation injection of different densities in segmented intervals and control the fluid production profile in the segment. Horizontal well section water control technology can also be combined with sand control technology, through the optimization of the hole density of the sand control screen, different flow capacity can be achieved on the same screen tube, combined with the horizontal well section technology to regulate the pressure profile in the wellbore, to balance the production pressure difference, and to reduce the rate of the bottom water coning in.

2.1.3. Double Horizontal Well Oil Recovery and Water Control Technology

Double horizontal well oil extraction and water control technology is to drill a horizontal well for drainage in the lower part of the horizontal well for oil extraction, and carry out oil extraction and drainage at the same time, and its structural principle is shown in Figure 3. Maintaining the equilibrium of the oil-water interface through the separation of oil and water was first proposed by engineer Wojtanowicz A K [7]. Double horizontal well oil extraction and water control technology is mainly applied to horizontal wells with large differences in oil and water densities between the bottom water and the producing oil layer, with a stable demarcation line.

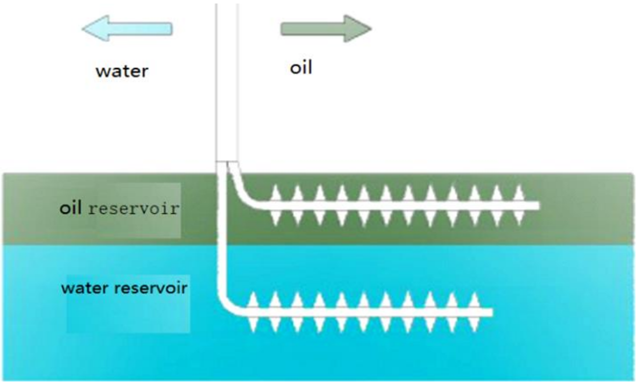

Figure 3. Schematic diagram of the structure of dual horizontal wells for. water control and oil recovery.

The application cost of double horizontal well water-control oil recovery process is high, and there are few reservoir conditions that are suitable for this technology. Although a lot of theoretical research has been done on this technology, its practical application is relatively small.

2.1.4. ICD Water Control Technology

ICD water control technology was devise in the 1990s, by Norwegian engineers first proposed the concept of ICD [8]. This technology mainly installs ICD device on completion tubing columns, which create additional flow resistance to water to control the flow of incoming fluids. The highest developed ICD valve element was the crank-type structure, which was not only overly complex but also could not generate a high overflow pressure drop, and was therefore quickly eliminated. Later and successively developed a nozzle-type, tube-flow-type, spiral-type ICD water control device, the fluid flow channel shown in Figure 4.

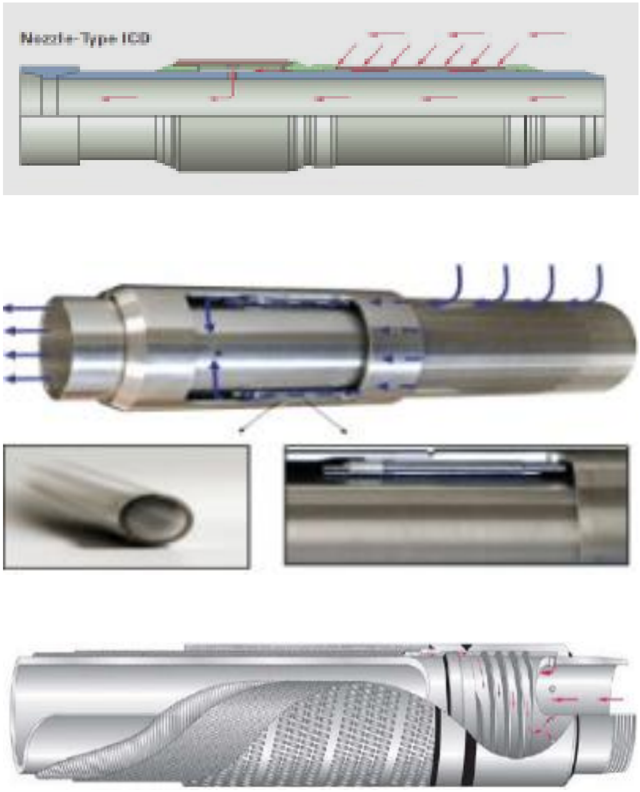

Figure 4. Schematic diagrams of nozzle-type, tube-flow-type, and spiral-type circulation structures.

Through the application of ICD water control technology in the eastern part of the South China Sea, Shan Yankui [9] proved that ICD can effectively balance the well production profile at the early stage of well production, but there is a problem that ICD is easy to be clogged. Since ICD do not have active water control capability, they cannot be adjusted if the oil production program changes after installation [10]. Therefore, in the early program is necessary to consider the later large displacement liquid lift, water plugging, section mining and other factors. ICD water control technology is the earliest popularization of water control technology, the current application of more, the site construction is simple. ICD water control technology in the early production stage of the well may form an effective water control, but in the later production stage of the well especially for the high permeability section of the influx of water can not be effectively identified and blocked.

2.1.5. ICV Water Control Technology

ICV water control technology takes the downhole flow control valve as the main original, is a control valve that can be operated remotely, further developed from the slip sleeve technology [11], and it is one of the core technologies of intelligent completion. ICV valve body is equipped with a movable slip sleeve, and each valve is controlled by multiple tubing lines, and it can be operated on the surface, the use layout is shown in Figure 5. ICV water control technology mainly regulates the flow rate into the wellbore by adjusting the opening size of the valves, and when the bottom water breaks through, it can realize the complete shielding of the bottom water breakthrough area. The ICV valves can realize the flow control function by combated with the packers. According to the type of flow valve parts can be categorized into two-position switch type, multi-position type and infinitely variable speed type. According to the driving method of ICV valve, it can be divided into hydraulic, electric and mixed driving.

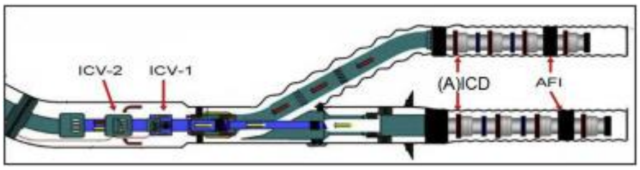

Figure 5. Schematic diagram of ICV valve-controlled water installation location and usage [12].

At present, the application of ICV valve is still in the early stage, ICV tool is not only expensive, but also need to connect the cable from the bottom of the well, liquid control line to the wellhead so as to realize the control, the whole completion tubing column structure is complex, the failure rate is high.

2.2. Active Water Control Methods for Horizontal Well

2.2.1. AICD Water Control Technology

AICD is a new type of water control technology that has been popular in recent years, which is based on the principle of constant fluid dynamic pressure and local pressure loss in Bernoulli's equation, and realizes water control of formation water through active control of fluids with different viscosities. 2006, S. L. Crow et al [13] first designed a density-sensitive AICD. After nearly a decade of development, AICD technology continues to improve and mature, the design ideas and is constantly improving, the current main structure by the clip type, floating plate type, flow channel type, self-expanding type. Among them, the floating plate type and the flow channel type have more applications, and their basic structures are shown in Figure 6.

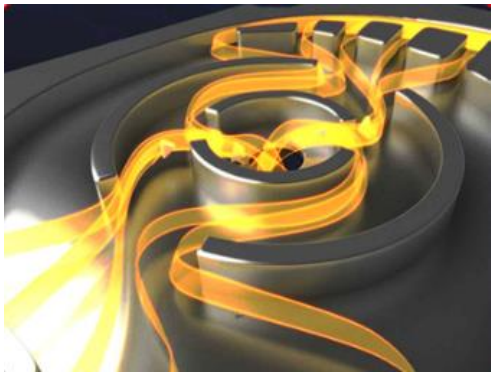

Figure 6. Schematic structure of floating plate type and floating channel type AICD.

CNOOC has been conducting experimental application research in the South China Sea oilfield and Xinjiang oilfield since the end of 2014, and has implemented several wells, but still faces many challenges. The main reason is the complexity and variety of reservoir types in its oilfields, which make it impossible to carry out uniform promotion and application, and it is necessary to carry out targeted design for each well production system, and extraction method to ensure the effect of water control.

AICD water control can be carried out in the middle and late stages of the production well according to the characteristics of the fluid and active water control, especially for the sudden water, can form a high abrasion resistance to reduce the water breakthrough. However, in the early stage of well production, the effect of equalizing the industrial profile is limited, so it is likely to form water flooding in the early stage of production. AICD water control valves are expensive, which is the main obstacle to the promotion of AICD water control valves at present.

2.2.2. AICV Water Control Technology

AICV is a combination of the advantages of AICD and ICV valves, which can realize the automatic adjustment of water encounter, and can completely shut down the breakthrough area of water production, so that the un-breakthrough area will continue to be produced, thus increasing the recovery rate of production.

AICV technology is the core technology of intelligent wells, through controlling the lifting and lowering of the slide sleeve to regulate the opening of the valve, thus affecting the flow rate. AICV is used in conjunction with the packer, and is classified into switching type, inorganic variable-speed type and multi-speed type, which can be driven by either hydraulics or electric power. The AICV water control technology can achieve the maximum degree of water control, but the failure rate is higher, and its high cost and risk also mean that further breakthroughs in this technology will not be achieved until the end of this year. means that it cannot be widely used in the oilfield at present until further breakthroughs in this technology.

3. Water Control Methods During Late Production in Horizontal Wells

Compared with the difficulty of implementing water control technology in the early stage, the difficulty of water control technology in the later stage is even greater. The main reason is that after a long period of production, the tubing column and tools are impacted and corroded by fluids, the structural strength decreases, the channels are blocked, and it is difficult to choose the water control technology. At the same time, if the well is not overhauled, the implementation of water control technology must not move the original completion tubing column to take water control measures, and some processes require the completion of the segmentation or other completion tools, if there is no planning measures in advance, the implementation of water control measures will not be possible.

3.1. Center Tubing Control Water Control Technology

After a period of oil well production, due to the obvious heel-and-toe effect or root-end bottom water surge, resulting in the root-end of the water, for such water out of oil and gas wells can be used to center tubing control water technology. The center tubing water control technology is to lower a smaller diameter center into the original completion tubing of screen, liner tubing or perforated completions, as shown in Figure 7, and then seal the annulus between the center tubing and the original completion tubing with a packer to change the direction of flow at the bottom of the well, so that the fluid at the root end of well will flow to the middle position of well.

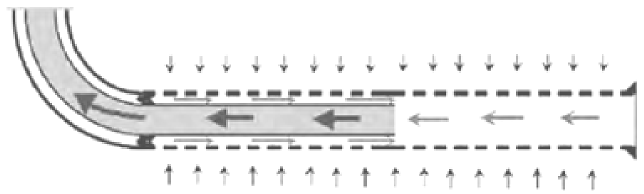

Figure 7. *Direction of fluid flow at the bottom of the center tube control wells.*

Center tube water control technology controls the flow trajectory of high aquifer [14] by inserting tools such as seals, center tubes, and slip sleeves, which can well regulate the wellbore inflow profile and improve the high water content and breakthrough problems at the root end. Zhang Shuqin [15] and others verified the water control effect of the center tube by using the center tube in horizontal wells with high water content, field test and application. However, the center tube water control technology needs to be considered in the pre-completion design, which is difficult to use for some old wells. If the length of the horizontal well is too long, it is also necessary to consider the influence of the trajectory of the well body on the inflow profile. Currently, the center-controlled water control technique is used in conjunction with other water control techniques and can also be used for passive water control in the early stages.

3.2. Mechanical Blocking and Water Control Technology

After serious water breakthrough at the toe end of the horizontal well occurs in the late stage, the water control can be carried out by mechanically blocking the water breakthrough end of the toe end. Mechanical blocking and water control tools are mainly divided into expansion type separation tools and non-expansion type blocking tools. Expansion type isolation tools mainly include expansion tubes, bridge plugs, oil and water expansion isolators [16, 17] and other types of tools with obvious expansion elements. Non-expansion tools mainly use the method of injecting cement to form a cement plug to seal the water outlet location. Mechanical plugging for water control requires out-of-tube segmentation of the horizontal section during pre-completion, and then only after mechanical plugging can water control be realized; otherwise, the original water breakthrough point will also flow into the wellbore from other locations through lateral flow out of the tube.

3.3. Chemical Plugging Water Control Technology

Chemical water plugging is generally divided into generalized water plugging and fixed-point water plugging. Generalized water plugging is also called non-selective water plugging, through the injection of chemical agent non-selective plugging water and oil layer plugging method, generally used for permanent blocking, mainly using chemical agent to seal cracks, large holes, and other permeability and the normal permeability of the reservoir obvious gap between the water point. The advantage of generalized water plugging lies in simple construction and lower cost, the disadvantage is that even if the operation is successful, it will result in loss of production.

Spot plugging, also called selective plugging, injects chemicals to plug the water layer or reduce the permeability of the water phase of the same oil and water layer. The advantage is that it does not plug the oil layer or has less impact on the permeability of the oil layer, but the disadvantage is that it requires the cooperative use of multiple packers, complex configuration of plugging liquid, large liquid volume, and difficult on-site construction.

The advantage of chemical plugging and water control technology is that it has the characteristics of adaptive water search, so there is no need for the preliminary water search process, but chemical plugging and water control has a major drawback is the low success rate and easy to cause the permeability of the reservoir to reduce [18], affecting the oil well yield.

4. Development of Horizontal Well Water Control

From the current development of water control technology, AICD water control technology research has become the main direction of water control research and application at home and abroad, flow channel AICD and floating disk AICD become the main promotion of water control technology. A single use of a water control technology can not realize the water control requirements of the whole life of wells, therefore, the joint use of multiple water control technologies has become the trend of water control technology.

Pan Hao et al. [19] studied a new type of composite water control device C-AICD (Composite autonomous inflow water device, abbreviated as C-AICD) by combining ICD and AICD. Li Xiaobo et al. [20] applied the combination of floating plate type AICD and segmented water control in offshore oilfields, and the effect of water control was remarkable. Zhang Liping et al. [21] through the ACP pipe outside the chemical ring air blocking segmentation + chemical plugging agent fixed-point blocking + center control of water control of the three technologies combined in the way in the application, water control effect is obvious. The composite use of a variety of water control technology has become a new trend of water control technology.

As a new type of well completion technology, water control technology has also been linked with other completion technologies in its own development. To deal with the serious sand problem in loose sandstone, the water control and sand control technology has been formed to better realize the integrated sand control and water control technology and reduce the operation cost. By embedding ICD and AICD into the sand control screen tube, the simple joint operation of hanging filter sand control and water control can be realized. For reservoirs with serious sand discharge, the combination of water control and gravel packing technology has become a hot spot in current research [22].

Although ICV and AICV technologies have more difficulties in promotion at present, from the point of view of intelligent completion, ICV and AICV technologies are bound to become indispensable tools in intelligent completion.

5. Conclusions and Recommendations

(1) The formulation of oil well water control program needs to be considered at the early stage of oil well development, and in the process of completing the well, the relevant measures required for water control in the later stage should be reserved.

(2) Each water control technology has its own advantages and disadvantages, and the selection of water control programs for oil wells can only realize the long-term effectiveness of water control by fully considering the special characteristics of oil well reservoirs and carrying out targeted design.

(3) The comprehensive use of various water control technologies can avoid the shortcomings of a single technology, but not the more water control technology composite water control effect will be better, to prevent the excessive complexity of the tool string.

(4) Active water control and intelligent water control have become the main trend of water control, multi-process joint technology can effectively improve the effect of water control, reduce development costs.

Abbreviations

ICD	Inflow Control Device
ICV	Inflow Control Valve
AICD	Autonomous Inflow Control Device
AICV	Autonomous Inflow Control Valve
C-AICD	Composite Autonomous Inflow Water Device
ACP	Annular Chemical Packer

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Author Contributions

Du Weigang is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

No potential conflict of interest was reported by the authors.

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