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Enhanced Oil Recovery Through Balanced Production Techniques in Horizontal Wells of Bohai A Oilfield

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Abstract: In response to the prevalent high water cut challenge in horizontal wells of the Bohai A Oilfield, this study introduces an innovative approach for pinpointing water production points in horizontal wells. The methodology leverages a comprehensive evaluation that integrates techniques such as curve identification, dynamic analysis, numerical simulation, and seepage model calculations. In conjunction, a novel hydraulic control-based balanced oil production process has been developed. This process utilizes a specialized water plugging string to effectively seal water production points in horizontal wells. Additionally, a hydraulic control system for horizontal well oil production has been implemented, facilitating staged extraction and thus achieving balance in oil production. Field application, particularly in Well X1, demonstrates a marked improvement post-implementation: the comprehensive water cut in Well X1 decreased from an initial 98.1% to 87.3%, and the production pressure differential escalated from 0.55 MPa to 2.01 MPa. This substantial enhancement in reservoir utilization indicates a notable reduction in water cut within the crude oil. The application of this balanced production technology in horizontal wells has led to a decrease in water cut and liquid production, significantly alleviating surface processing pressures. Consequently, there has been an improvement in well productivity and the overall development effectiveness of the oilfield. These findings suggest that the balanced oil production technique offers a promising solution for enhancing oil recovery in horizontal wells, particularly in fields grappling with high water cuts.

Keywords: Horizontal well; Balanced oil recovery; Water-producing point; Enhanced oil recovery

1 Introduction

Horizontal wells, recognized for their capability to enhance oil output and improve the efficiency of oil field development, have been widely adopted across various stages of oil field development. These wells, known for their expansive oil-bearing area, have demonstrated significant advantages in the early stages of oil field exploitation, offering high productivity, swift establishment of production, and rapid cost recovery. As development progresses into the middle and later stages, where the extraction potential of vertical wells declines, horizontal wells play a crucial role. Characterized by extensive drainage areas and minimal production pressure differentials, these wells are adept at suppressing the rise in water cut, enhancing well productivity, and elevating oil recovery rates, thereby presenting a cost-effective approach for maximizing the potential of developed oil fields. In reservoirs with bottom water or gas caps, the deployment of horizontal wells has been instrumental in decelerating the penetration of water and gas cones. This approach effectively prolongs the period of water-free oil extraction, enabling the optimal utilization of reservoir energy, which in turn amplifies well output and recovery rates. The most common completion techniques implemented in horizontal wells encompass open hole completion, casing perforation completion, liner perforation completion, and External Casing Packer (ECP) completion. To address the challenge of excessive water production during the development phase of horizontal wells, a blend of mechanical and chemical water control methods is employed. Mechanical strategies hinge on the application of appropriate mechanical barrier tools for blocking water-producing zones or achieving stratigraphic isolation. On the chemical front, plugging agents such as gels, polymers, expandable agents, water-absorbent polymers, micro-matrix cement, and HWSO series agents are frequently utilized.

In the context of casing perforation completion, which ensures wellbore stability, both chemical and mechanical methods are viable options. When water production is detected at the toe of a horizontal well, either approach can be employed independently. Conversely, in instances where water production is proximal to the heel or along the horizontal section of the well, the use of barrier tools becomes imperative for stratigraphic isolation and targeted layer plugging. In comparison with conventional completion methods, the application of Inflow Control Devices (ICDs) has been shown to markedly enhance the inflow profile of horizontal wells. These devices facilitate a balanced advancement of the water ridge front in the lower part of the reservoir, significantly extending the time to bottom water breakthrough, augmenting the cumulative oil production without water, and enabling horizontal wells to operate effectively under elevated production pressure differentials [1, 2].

Upon the occurrence of water breakthrough in horizontal wells, the effectiveness of ICDs has been observed to diminish. Advancements in ICD technology have led to the development of the Automatic Inflow Control Device (AICD) [3–5], an innovation that intelligently discriminates and restricts unfavorable fluids. Gomez et al. [6]introduced the application effects of five experimental wells in Rubiales and Quifa oil fields undergoing self-expanding AICD device transformation. Youngs et al. [7], Eltaher et al. [8], Ghosh and King [9] and Thornton et al. [10] proposed optimization methods and steps for AICD design using numerical simulation and economic evaluation methods, effectively reducing the construction risk of AICD technology. Hu et al. [11] employed numerical simulation to implement AICD for water control in a specific oil well, attaining notable success in diminishing water production and amplifying oil output. Extending this research, Yan et al. [12] explored AICD and continuous sealing body water control technologies, applying these in over 40 wells across the eastern and western South China Sea and the Bohai Oilfield. This application has resulted in significant improvements in oil production and water reduction, thereby offering vital technical support for the advancement of horizontal wells in offshore oilfields and shaping future development strategies. Yuan et al. [13] used numerical simulation and production dynamic analysis to delineate the production profile of oil wells. By integrating two Annulus Chemical Packer (ACP) slugs within the production layer and segmenting it into three parts, an immediate increase in daily oil production of 98.2 m^3/d was observed, providing foundational support for ongoing water control research in offshore horizontal wells.

Layered oil extraction, serving as an advanced technical support for water control measures, is represented globally by inflow control and intelligent completion technologies. In China, the evolution of layered oil extraction technology has progressed through stages including self-spraying layered allocation, mechanical well plugging for water control, adjustable layer allocation, and intelligent layered oil extraction. Presently, the majority of horizontal wells have not implemented water plugging measures and predominantly utilize generalized oil extraction methods. The integration of layered oil extraction with precision layered water injection, forming an innovative model for the integrated potential development of well groups and blocks, is an area of ongoing research. This research aims to provide effective technical support for the continuous and stable production of high-water-cut aging oil fields, thereby addressing a critical challenge in the industry.

In the Bohai Oilfield, a variety of water control technologies, including variable density screen pipes and ICDs, have been sequentially implemented. Despite these efforts, the overall impact on water control has been limited, characterized by high costs, brief effective durations, and low success rates. This shortfall is primarily attributed to insufficient comprehension and investigation into the patterns, characteristics, and influencing factors of water production in horizontal wells, coupled with a lack of scientifically sound and rational water control methods.

Situated in the western Bohai Sea, the Bohai A Oilfield predominantly comprises lithological structural and layered structural reservoirs. These reservoirs exhibit porosities between 29.3% and 32.7% and permeabilities ranging from 1500 to 8300 mD, classifying them as high-porosity and high-permeability reservoirs [14, 15]. Notably, the reservoirs demonstrate considerable heterogeneity and variability in properties, with prevalent edge and bottom water, primarily in bottom water reservoirs. The prevalent development strategy involves the use of single sand body horizontal wells, which are characterized by high initial productivity, negligible periods of water-free oil extraction, rapid post-commissioning increases in water cut, and swift declines in production. The aggregate water cut in the oilfield has been recorded as high as 95.7%, categorizing it as a typical high-water-cut field in the Bohai region [16, 17]. The high-water content in the produced fluid poses significant challenges, not only impacting production volumes but also intensifying the processing load on offshore platforms. Consequently, the development of a balanced oil extraction technology for horizontal wells is imperative, aiming to attain balance in oil extraction, reduce the water content in the produced fluid, and enhance the overall crude oil recovery rate [18, 19].

This paper focuses on Well X1 in the Bohai A Oilfield as a case study. It addresses the challenges of high water cut and uneven reservoir stimulation in horizontal wells. Through research and field application, a balanced oil extraction technology for horizontal wells has been developed, culminating in the establishment of an intelligent segmented extraction system for bottom water reservoirs in the Bohai A Oilfield. This system is designed to significantly enhance the oil recovery rate.

2 Mechanism of Water Production in Horizontal Wells

In the field of oil field development, horizontal wells have been recognized as an effective technique for enhancing oil production and improving efficiency by expanding the oil-bearing area. This approach is widely applicable across various stages of oil field development. Particularly in the development of bottom water reservoirs, horizontal wells have been observed to increase the contact area between the wellbore and the reservoir. They expand the seepage area and reduce the production pressure differential, which contributes to a measurable coning effect, a distinct advantage over vertical wells. For the evaluation of horizontal well productivity in bottom water reservoirs, researchers globally have predominantly relied on analytical methods for productivity prediction and numerical simulation methods for forecasting [20]. An exemplar of this approach is the analytical method for predicting productivity in offshore oilfield horizontal wells. At the early development stages, these wells are hypothesized to be centrally positioned in the oil layer. This scenario entails a closed boundary above in the vertical direction and an infinitely large boundary in the horizontal direction of the reservoir, with distinct horizontal and vertical permeabilities [21]. Subsequent to considering wellbore storage and skin effects, a dimensionless oil production index is formulated, defined as follows [22]:

$$J_D = \frac{q}{(p_i - p_{wf})} \frac{1.842 \times 10^{-3} \mu \mathrm{B}}{K_h h \sqrt{K_h / K_v}} = \frac{1}{p_{WDS}} \tag{1}$$

where, q denotes the oil production $\left(\mathrm{m}^3\right)$; p_i refers to the original formation pressure MPa; p_{wf} represents the bottom hole flowing pressure (MPa); K_h is indicative of the horizontal permeability (mD) ; K_v signifies the vertical permeability (mD); μ is the formation crude oil viscosity (mpa.s); h is the reservoir thickness (m); P_{WDS} is the dimensionless bottom hole pressure considering well storage and skin effects; B is the crude oil volume factor.

Employing the formula previously described, a theoretical chart is constructed, offering valuable guidance for the production process in horizontal wells. This process incorporates the productivity prediction formula for horizontal wells in bottom water reservoirs, as proposed by Cheng et al. [23]. This methodology facilitates an analysis of productivity and its influencing factors in horizontal wells situated in bottom water reservoirs, as well as an exploration into the elements impacting productivity in such environments. Cheng 's research [23], leveraging the principles of image reflection and potential superposition, focused on the steady seepage in a horizontal well within a bottom water reservoir characterized by a closed top boundary. This investigation resulted in the derivation of a specific productivity formula for horizontal wells:

$$Q = \frac{542.59 \sqrt{k_h k_v} L \Delta P / (\mu o B o)}{\ln \frac{4 \beta h}{\pi r_w} + \ln \tan \frac{\pi z_w}{2h}} \tag{2}$$

where, Z_w represents the distance of the horizontal well from the oil-water interface, measured in meters.

In a parallel study, Yuan et al [24] developed a theoretical approach for wellbore pressure in a reservoir of infinite size with closed top and bottom boundaries under stable conditions. This led to the formulation of a three-dimensional steady-state productivity model for horizontal wells in bottom water reservoirs:

$$Q = \frac{542.59 \sqrt{k_h k_v} L \Delta p / \left(\mu_o B_o\right)}{\ln \left[\frac{4 \beta h}{\pi r_w} \cot \frac{\pi (h - z_w)}{2h}\right] - \frac{2 z_w}{L} \beta} \tag{3}$$

The study reveals that variables such as the length of the horizontal section, reservoir thickness, horizontal and vertical permeabilities, and wellbore radius exhibit a positive correlation with oil production. It is observed that the greater the distance of the horizontal well from the oil-water interface, the lower the resultant production.

During the middle and later stages of development, the progression of bottom water coning emerges as a significant factor influencing the ultimate recovery rate in horizontal wells. This phenomenon is particularly pronounced in heterogeneous and multi-layered reservoirs, where the presence of interlayer contradictions intensifies the challenges of bottom water coning. This exacerbation hinders the exploitation of the full production potential of horizontal wells. In the Bohai Oilfield, the utilization of horizontal wells has been expanding, with their numbers and contribution to total production surpassing 40%. However, an increasing trend in water cut during the development phase of horizontal wells has been identified, which has become a leading cause of reduced productivity and the shutting down of wells in the Bohai A Oilfield. Consequently, the stabilization of oil production and the control of water in horizontal wells have emerged as critical priorities.

3 Analysis of Water Production Characteristics in Well X1 of Bohai A Oilfield

The commencement of production in Well X1 in the Bohai A Oilfield was marked in 2020. Initially, the daily fluid output was documented at 625 m^3/d, characterized by a water content of 93%. Subsequent interventions, such as frequency modulation and enlargement of the oil nozzle, led to a peak in daily fluid production, reaching 2,700 m^3/d. During this phase, water content escalated to 98%, albeit with a relatively stable flowing pressure. The high water content in the well imposed a significant burden on the platform at the wellhead, ultimately necessitating a halt in production in April 2022 due to the excessive water content.

In response to these challenges, a comprehensive analysis of seismic, logging, geological, and development data pertaining to Well X1 was conducted. The findings indicated that the well was notably influenced by interlayers, with a developed interlayer situated below the toe-end, contributing to localized water flooding. As evidenced by logging interpretation (Figure 1), the drilled horizontal section spanned 470.0 m, with the reservoir section measuring 443.9 m and a reservoir encounter rate of 94%. The lowest point of the horizontal section was identified at 13.6 m from the oil-water interface. The resistivity ranged from 4 to 7 $\Omega \cdot m$, natural gamma between 50 to 70 API, and total gas measurements from 3,000 to 6,000 ppm. The presence of fine sandstone containing gravels exhibited fluorescence, emitting a dark yellow fluorescence under direct light, covering approximately $20 - 30\%$ of the area. The logging responses indicated that the heel end of the well, influenced by adjacent well production, displayed characteristics consistent with high water flooding, marked by lower resistivity. In contrast, the middle section showed higher resistivity. Coupled with sedimentation layer distribution and exploratory logging data, this section was not affected by water flooding. The toe-end resistivity generally measured less than 4.5Ω, presenting challenges in stimulation under the existing production pressure differential and indicating a lower degree of water flooding.

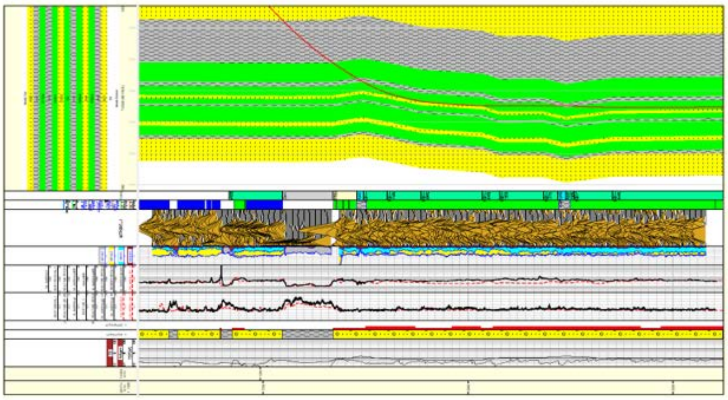

Figure 1. Logging interpretation of Well X1 in Bohai A Oilfield

In the analytical examination of Well X1 in the Bohai A Oilfield, techniques such as curve identification discrimination, dynamic analysis, numerical simulation, and seepage model calculation were employed. These analyses led to the conclusion that the primary cause of water production in Well X1 is attributed to water flooding at the heel end of the horizontal section, which resulted in substantial water production. Conversely, the toe-end of the reservoir exhibited poor stimulation. To optimize the production strategy for Well X1, the horizontal section was divided into three distinct segments, with delineation based on non-permeable and low-permeable layers. The first segment, located at the heel end and identified as the primary water-producing section, was subsequently excluded from the production process. The focus was then shifted to the middle second segment and the toe-end third segment for continued production. The final design approach for Well X1 involved the strategic segmentation of the horizontal well into three parts. This entailed shutting off the main water-producing first section while maintaining production from the second and toe-end third sections. This segmentation strategy is projected to improve the extraction degree by approximately 2.61 percentage points.

4 Balanced Hydraulic Control Oil Extraction Process String

In the reservoir analysis phase, a meticulous process is undertaken for the precise identification of water-producing points within the reservoir. Subsequently, a balanced hydraulic control oil extraction process string is utilized, serving a dual purpose: to plug water-producing points and to segment oil extraction in horizontal wells [25, 26]. This process string is composed of two integral components: the horizontal well water plugging technology and the hydraulic control water control technology for horizontal well extraction [27]. The first component, horizontal well water plugging technology, is dedicated to effectively sealing the water-producing points identified within horizontal wells. The second component, hydraulic control water control technology, is designed to achieve segmented oil extraction in horizontal wells. This is accomplished by implementing hydraulic control measures, thereby facilitating balanced oil extraction.

4.1 Horizontal Well Water Plugging Technology

4.1.1 Composition of the process string

As depicted in Figure 2, the process string for horizontal well water plugging technology is composed of various components. These include tubing, a safety joint, a positioning head, a drain valve, K344 packers, and an injection valve. The primary function of the K344 packers is to isolate and seal the targeted layer segments, ensuring accurate injection of the ACP into the designated location. The injection valve plays a pivotal role in facilitating the injection process of the ACP. The positioning head is instrumental in ensuring the precise placement of the string within the wellbore. Upon reaching the predetermined location, the string is positioned in collaboration with the sand control packer. The elevation of the string subsequently confirms the final position of the injection valve. This strategic use of the positioning head effectively minimizes the cumulative length error of the assembled string. Additionally, the safety joint is designed to allow for the efficient release of the string in instances of sticking, thereby enabling subsequent fishing operations. This technology is characterized by its operational simplicity and the capacity to inject ACP into multiple layer segments through a singular string deployment. Notably, it also encompasses technical features that facilitate the testing of the seal integrity of the plugged segments.

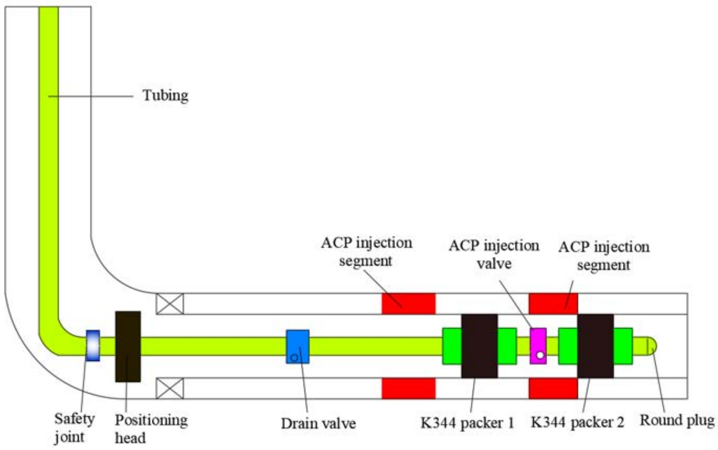

Figure 2. Water plugging process string

4.1.2 Process principle and characteristics

The process commences with the lowering of the injection string to the designated target position. Upon pressurizing through the tubing, the differential pressure inside and outside the string reaches a threshold of 0.5 MPa, prompting the K344 packers to initiate setting. This action achieves effective isolation between the injection valve and the casing annulus both above and below the targeted point. As the pressure incrementally escalates, attaining a differential range between 1.5 to 2 MPa, the injection valve activates, facilitating the injection of ACP into the specified layer segment. Following the completion of the injection in the current segment, the pressure within the center tube is relieved, leading to the unset of the K344 packers, after which the string is elevated for the curing phase of the ACP. Subsequent to this curing process, the string is reinserted into the injected layer segment, and a pressurization procedure through the tubing is conducted to rigorously test the sealing effectiveness, thus verifying the functionality of the ACP's plugging capability. This methodical process concludes the injection phase for one layer segment and prepares the string for subsequent segment injections. The procedure employs a by-pass positioning mechanism on the string to ensure precision in depth correction, effectively minimizing potential errors. After the by-pass positioning, the string undergoes an elevation adjustment for expansion. The upper part of the injection valve, equipped with dual packers, ensures that the chemical bypass back to the tubing channel is securely blocked, significantly reducing the risk of blockage.

4.1.3 Process parameters

Suitable casing size: $139.7\ \mathrm{mm}$; maximum tool outer diameter: $114\ \mathrm{mm}$; temperature resistance: $150°\mathrm{C}$; pressure resistance: $35\mathrm{MPa}$; injection displacement: $5\ \mathrm{m}^3/\mathrm{h} - 25\ \mathrm{m}^3/\mathrm{h}$; ACP unit pressure resistance: $2.0\mathrm{MPa/m}$.

4.2 Hydraulic Control Horizontal Well Oil Extraction Technology

4.2.1 Composition of the process string

The production process string employed for hydraulic control in horizontal well oil extraction is composed of an array of components, as depicted in Figure 3. These include Multi-gear hydraulic control valves, ball-drop sliding sleeves, tracer short joints, Y341 crossover packers, hydraulic control pipeline positioning seals, safety joints, 2.313-inch sliding sleeves, Y-joints, and submersible electric pumps.

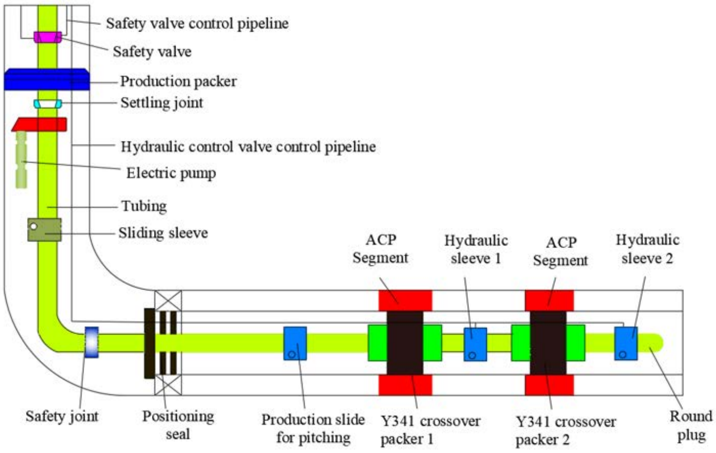

Figure 3. Production process string of hydraulic control horizontal well

In the initial stages of the string design, due to the high water content, the first layer segment is not included in production and is managed using a ball-drop sliding sleeve. This segment can subsequently be opened for production through ball dropping. The second and third layer positions are outfitted with hydraulic control valves and tracer short joints. These hydraulic control valves, which are manipulated via hydraulic control lines, enable the opening and closing of layer positions as well as the adjustment of production allocation. The tracers, collected at the surface, assist in the partitioning of production and in the determination of water cut in the produced fluid. The Y341 crossover packer, strategically positioned at the ACP injection segment, facilitates the segmentation of the subterranean horizontal section. The implementation of this hydraulic control horizontal well balanced oil extraction string proves to be instrumental in blocking high water content segments, thereby achieving balanced extraction and enhancing the ultimate recovery rate of the producing well.

4.2.2 Process principle

The production string, designed for a single-run deployment, is positioned within the well. Following its positioning, pressurization through the tubing initiates the sealing of both the Y341 crossover packers and the cable packers. Wireline operations facilitate the opening of the sliding sleeves, thereby commencing production through the submersible electric pump. The hydraulic control lines play a crucial role in enabling the on-off control of the producing layer segments, thereby contributing to effective water control within the targeted layer segments. Each tracer short joint, equipped with both an oil-soluble and a water-soluble tracer product, aids in the production phase. Tracer testing during production offers insights into the oil and water contributions from each segment, thereby informing the operational strategies for layer segment switches. In scenarios where production from the first segment is resumed, the submersible electric pump is temporarily halted, and the production packer is retrieved through wireline operations. Subsequently, a ball is deployed to activate the No. 1 ball-operated sliding sleeve. Following this activation, the production packer is reinserted, and the submersible electric pump is re-engaged to resume production.

4.2.3 Process characteristics

(1) The balanced oil extraction process string for horizontal wells enables segmented extraction along the horizontal section through a singular string deployment, facilitating layered segment control via hydraulic control valves. (2) The incorporation of tracer short joints, in tandem with surface testing, allows for the monitoring of water content during production in horizontal wells. This setup aids in understanding the contributions of oil and water from each segment, guiding the operation of layer switches. (3) All downhole tools employed in this process are mechanically controlled and hydraulically operated, exhibiting superior temperature resistance and high reliability.

4.2.4 Process parameters

Suitable for sand control size: $120.75\ \mathrm{mm}$; maximum outer diameter: $116\ \mathrm{mm}$; temperature resistance: $150°\mathrm{C}$; pressure resistance: $35\mathrm{MPa}$; daily production per well: $< 2000\ \mathrm{m}^3/\mathrm{d}$.

5 Key Tool Design

5.1 Multi-Gear Hydraulic Control Valve

This underground valve, regulated by surface hydraulics, is a multi-gear valve with various openings. It is designed to enable diverse settings for oil extraction tools, facilitating flexible operational modes.

5.1.1 Structure composition and characteristics

The structure of the Multi-gear hydraulic control valve is depicted in Figure 4. The valve comprises several key components: an upper joint, a central tube, a piston, a guide positioning slot, a guide pin, a nozzle, a lower joint, and hydraulic channels. The piston is securely affixed to the central tube, which is outfitted with a perforated nozzle. In the operational phase, hydraulic oil is channeled into the hydraulic chamber via hydraulic channel 1. This action propels the piston, inducing an upward movement of the central tube. Concurrently, the guide positioning slot, sliding along the guide pin, triggers a rotational motion in the central tube, effectuating a switching mechanism. When elevated to the designated position, pressurization through hydraulic channel 2 drives the piston downward, aligning the guide positioning slot with the guide pin to secure the central tube's position. Thus, a singular axial movement of the central tube accomplishes a complete shift in settings.

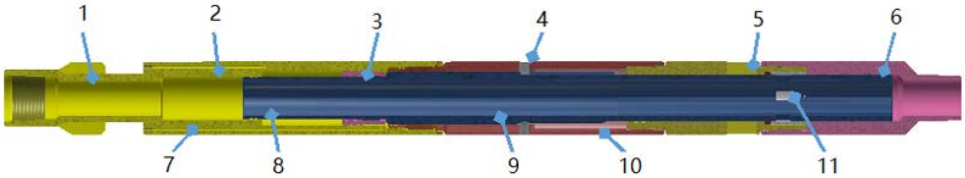

Figure 4. Schematic diagram of multi-gear hydraulic control valve, 1-Upper joint; 2-Hydraulic channel 2; 3-Piston; 4-Guide pin; 5-Outlet hole; 6-Lower joint; 7-Hydraulic channel 1; 8-Central tube; 9-Guide positioning slot; 10-Central cylinder; 11-Central tube nozzle

The multi-gear hydraulic control valve is characterized by the following features:

(1) The tool is constructed with a purely mechanical structure. The shifting of the nozzle is driven hydraulically, ensuring stable and reliable functionality.

(2) The integration of the guide slot and positioning slot into a single, simplified structure enhances the reliability of the switching mechanism.

(3) A rotational shifting design is implemented, enabling the adjustment of four distinct openings.

5.1.2 Technical parameters

Tool length: $1410\ \mathrm{mm}$; outer diameter: $114\ \mathrm{mm}$; internal flow channel diameter: $44\ \mathrm{mm}$; central tube actuation pressure: $3\mathrm{MPa}$; maximum working pressure: $60\mathrm{MPa}$; operating temperature: up to $150°\mathrm{C}$.

5.2 Injection Valve

The injection valve, crucial for providing a passage for liquids to the targeted layer segment, is depicted in its structural configuration in Figure 5.

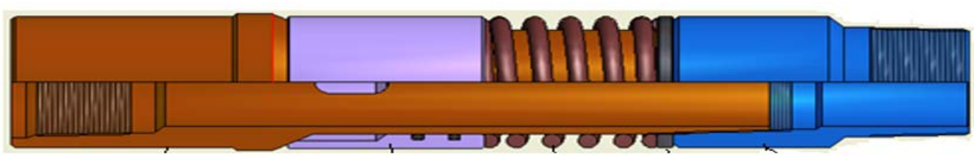

Figure 5. Structural diagram of the injection valve

5.2.1 Structure and working principle

The valve's architecture includes a body, an opening valve, a spring, a spring seat ring, and a lower joint. A conical seal is strategically placed between the body and the opening valve. Upon achieving the opening pressure of the opening valve via pressurization through the tubing, the valve is actuated, causing the spring to shift rightward, thus opening the valve. The injection liquid is then allowed to flow out from the outlet hole located on the body, passing through the annular space between the body and the opening valve. When the pressurization is halted, the spring's force automatically returns the opening valve to its closed position.

5.2.2 Technical parameters

Total length: 570 mm; maximum outer diameter: 114 mm; minimum inner diameter: 62 mm; sealing rating: 35 MPa; opening pressure: 1.6-2.0 MPa.

6 Analysis of Field Application Effects of Balanced Oil Extraction in Horizontal Wells

In December 2022, Bohai A Oilfield's Well X1 witnessed the implementation of balanced oil extraction technology for horizontal wells. The preliminary phase involved leveraging seismic, logging, and geological development data. Techniques such as curve identification, dynamic analysis, and numerical simulation were utilized to comprehensively evaluate the utilization degree of the horizontal section, thereby identifying the water-producing and plugging positions. Utilizing the horizontal well water plugging process string, ACP was injected, segmenting the horizontal section into three distinct parts. Subsequently, the hydraulic control horizontal well balanced oil extraction string was deployed to seal the first layer segment and to exploit the second and third layer segments.

Figure 6 depicts the production dynamic curve of Well X1. The comparison of production data pre-operation and post-operation of the balanced oil extraction technology is shown in Table 1. The field application outcomes revealed that prior to the balanced oil extraction technology's implementation, Well X1 exhibited a fluid production rate of $2855\ \mathrm{m}^3/\mathrm{d}$, accompanied by a high water cut of 98.1%. Following the technology's application, layered exploitation of the second and third segments led to a fluid production reduction to $417\ \mathrm{m}^3/\mathrm{d}$, and the water cut decreased to 87.3%. The production pressure differential experienced an increase from $0.55\mathrm{MPa}$ to $2.01\mathrm{MPa}$, markedly enhancing the reservoir's utilization degree. Field practices have substantiated that the balanced oil extraction technology for horizontal wells efficaciously accomplishes water-producing point identification, water plugging, and segmented exploitation. This technology has emerged as an effective approach for water plugging, water control, and segmented development in oilfield horizontal wells, concurrently reducing fluid production and significantly alleviating surface processing pressure. It has contributed to enhanced well productivity, improved oilfield development performance, and elevated the ultimate recovery rate of the oilfield.

Table 1. Production data comparison of Well X1 pre-operation and post-operation

Well X1	Fluid $(\mathrm{m}^3/\mathrm{d})$	Oil $(\mathrm{m}^3/\mathrm{d})$	Water Cut $(\%)$	Production Pressure Differential (MPa)
Pre-operation	2855	54.2	98.1%	0.55
Post-operation	417	52.96	87.3%	2.01

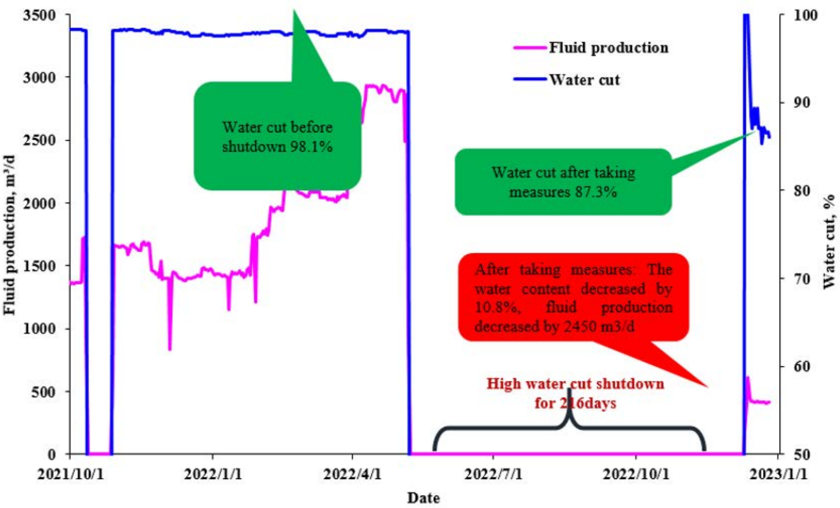

Figure 6. Production dynamic curve of Well X1

The Bohai Oilfield currently encompasses 1,208 horizontal oil wells, accounting for 40.7% of the total well count. This proportion is anticipated to increase with the introduction of new wells. At present, horizontal wells contribute 41% to the oilfield's production capacity, predominantly utilizing generalized extraction methods. The significance of maintaining the productivity of these horizontal wells is underscored by their critical role in augmenting production capacity in offshore oilfields and enhancing reserve additions and output. Preliminary applications of the balanced oil extraction technology for horizontal wells have been conducted in 5 well operations within the Bohai Oilfield. The observed application data is presented in Table 2. Notably, the maximum reduction in water cut reached 22%, with an average decrease in produced fluid water cut of 11.7%. The cumulative reduction in water amounted to 784,000 cubic meters, and an increase in oil production exceeded 1,500 cubic meters. These results substantially alleviated water treatment pressures on platforms, carving a new trajectory for stable oil and water control in horizontal wells. The balanced oil extraction technology for horizontal wells is poised to become a predominant method for stabilizing oil production and managing water control in horizontal oil wells. It is projected to reduce water treatment by over 5 million cubic meters, indirectly enhance oil production by more than 500,000 cubic meters, and is expected to yield economic benefits exceeding one hundred million yuan.

Table 2. Production data comparison of Well X1 pre-operation and post-operation

Well No.	Pre-Operation			Post-Operation			Water Cut	Cumulative Water
	Fluid (m^3/d)	Oil (m^3/d)	Water Cut (%)	Fluid (m^3/d)	Oil (m^3/d)	Water Cut (%)	Reduction (%)	Reduction $(10^4\ m^3)$
X1	2855	54.2	98.1%	417	52.96	87.3%	10.8%	49.6
X2	1470	39.7	97.3%	225	56	75.1%	22.2%	12.1
X3	1717	68.6	96.0%	1541	96.9	93.7%	/	2.4
B1	2700	28	98.3%	355.3	38.9	93.1%	5.2%	12.1
B2	990	33.9	96.6%	532	39.9	92.5%	4.1%	2.2

7 Conclusions and Recommendations

The development of a pioneering compartmentalized water control technology for horizontal wells marks a significant advancement in the industry, showcasing substantial promise for broader application. This study, centered on high water-cut reservoirs in Bohai A Oilfield, has led to the formulation of a novel set of methods for identifying water production in horizontal wells. The implementation of water plugging and hydraulic control segmented extraction processes has facilitated the realization of balanced oil extraction in horizontal wells. Consequently, a technology tailored for large-displacement, hydraulic control, intelligent segmented extraction, specifically designed for horizontal wells in the Bohai A Oilfield, has been established. This technology, incorporating hydraulic control valves for dual-layer production regulation and utilizing tracers for real-time monitoring of water content during production, effectively achieves stable management of oil and water in high water-cut wells. The study yields the following conclusions:

(1) The study proposed a comprehensive assessment technique, based on seismic, logging, geological, and development data analyses. This technique incorporates curve identification, dynamic analysis, numerical simulation, and seepage model calculations.

(2) Research on optimizing the injection process led to the development of a horizontal well drag-type fixed-point water plugging process string. This innovation enables the injection of multiple ACP segments using a single string, achieving external annulus sealing in horizontal wells.

(3) Optimization research on segmented extraction processes resulted in a single-string Y-pipe hydraulic control water control process string. This solution facilitates control of layer segments and monitoring of water content from the surface, thereby achieving internal segmented extraction in horizontal wells.

(4) Field implementation in Well X1 demonstrated significant improvements. The comprehensive water cut decreased from 98.1% pre-operation to 87.3% post-operation. The production pressure differential increased from 0.55 MPa to 2.01 MPa, markedly enhancing reservoir utilization. The balanced oil extraction approach in horizontal wells not only reduced the water content in crude oil but also lowered the volume of produced fluids. This significantly reduced the surface processing pressure, improved well productivity, and enhanced the overall development effectiveness of the oilfield.

Author Contributions

Conceptualization, Q.S; methodology, D.X; formal analysis, J.P. and Z.L.; investigation, C.Z.; resources, Q.S.; data curation, D.X.; writing—original draft preparation, D.X.; writing—review and editing, Z.L.; visualization, C.Z.; supervision, D.X.; project administration, Z.L.; funding acquisition, D.X. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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