Research and Field Application of Adaptive Inflow Control Technology

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Abstract. In view of conventional inflow control completion technique can not control water directly, the valid production period is relatively short, the control water effect become worse after bottom water breakthrough, easily lead to reservoir second damage. Based on problem above, this paper presents an adaptive inflow control well completion technology, that uses adaptive inflow control device and precision sand filtering net control water screen, realizing to adjust the resistance of oil and water automatically, improving inflow profile and oil well recovery, moreover, the adaptive inflow control well completion technology has the features of simple construction, high reliability and strong adaptability. Therefore, from the technological principle and characteristics, key implemental technology, the tool of adaptive inflow control device and screen, construction technology and other aspects of adaptive inflow control well completion technology, adaptive inflow control well completion technology were studied. The technology was applied in horizontal well completion in the B oilfield. After application, the oil production increased by 5 times, the oil production period of low water content was prolonged 400 days, a good effect of controlling water coning and increasing oil was achieved. The application suggests that adaptive inflow control well completion technology can improve the effect of inflow control screen well completion that could be applied in the wells to increase the oil production.

1. Introduction

The inflow control completion technology has been widely used all over the word since it was developed in 1990s, and good application effects have been achieved. With the popularization and application of the inflow control completion technology and the deepening exploration and development of oil fields, the requirement is increasingly high for this technology. How to make the best use of water control and oil stabilization function of inflow control completion technology, and how to realize the intelligent dynamic control of the whole well has gradually become a research hotspot [1-3]. The inflow control screens of “choke type”, “nozzle type” and “spiral channel type” are mainly used in the traditional inflow control completion technology, which belongs to the “passive” inflow control completion technology [4]. When using this technology, the completion parameters need to be accurately designed by means of electrical logging data, and then the inflow control
completion string is run into the hole according to the design; the bottom water coning [5] is indirectly restrained by controlling the formation fluid production. However, the whole technology has high technical requirements, and highly depends on the early stage design; the validity period of water control is relatively short because the inflow control effect is greatly compromised after the local layer is broken through by the bottom water [6]. Therefore, an adaptive inflow control technology and its supporting devices are proposed in this paper, which realizes the goal of equilibrium liquid control in prophase and water-blocking oil recovery in middle and late stage of the oil production process, and meets the technical requirements of controlling water and stabilizing oil production in the whole production cycle.

2. Adaptive inflow control technology

2.1 Composition of tools

The tools used in adaptive inflow control technology include: adaptive inflow control device, special precision sand filter water control screen, expandable packer, top suspension packer, connecting coupling and tubing, etc.

2.2 Technical principle

The figure above shows the overall structure of the adaptive inflow control completion string. The expandable packer is used to divide the reservoir into different segments, and in the middle of the packer, an adaptive inflow control device and a special water control screen (collectively known as adaptive inflow control screen) are installed. From bottom to top, the completion string is composed of guide shoe, isolating valve, adaptive water control screen, expandable packer, others, adaptive water control screen, expandable packer, blank tubing, suspension packer, etc. During the construction, tools and equipment of the completion string are connected at the well head. Then the suspension packer is run into the hole with the adaptive inflow control completion string. After the string is in place, set down and sit the suspension packer. The production test string is run into the hole to obtain production data after the sealing property is checked down, and whether the pumping equipment is needed or not is determined by the liquid producing capacity of the well. After the liquid produced by the well meets the technical requirements, the production string is lifted up, the wellhead is set up and the construction is carried out according to the requirements of the later production string. After the segregated completion of adaptive inflow control screen, the water control module in each section can automatically adjust the additional resistance with the change of the water cut of the produced fluid in the controlled layers. Thus, the purposes of automatically adjusting the oil-water inflow resistance and adaptive inflow control are achieved.

2.3 Technical parameter

The suitable reservoirs are sandstone reservoirs or fractured carbonate reservoirs. The production fluid of the wells is higher than 10m³/d. The formation crude oil viscosity is 3~500 mPa·s. Applicable wellbore inner diameter is 8-1/2”~ 4-1/2”. The self-regulating water / oil pressure drop ratio is 3~20.
3. Key technologies

3.1 Adaptive inflow control device

3.1.1 Structural composition

By investigating the traditional inflow control devices [7-10], the adaptive inflow control device with oil-water self-adjustment function has been designed, which is mainly composed of working barrel, core control part and outer protective sleeve, as shown in Figure 2. This figure illustrates that the core control piece and the working barrel are connected in the form of precision copper lead welding, and the outer protective sleeve and working barrel are connected with thread. As a whole, the device is simple in structure and free of moving parts.

![Figure 2. The structure of adaptive inflow control device](image)

1. Outer protective sleeve; 2. Core control part; 3. Base of core control part; 4. O-ring; 5. Working barrel

3.1.2 Working principle and characteristics

① Working principle

The function of flow adjustment and inflow control is achieved by diverting different fluids into various flow paths. The choice of flow path depends on the geometric characteristics of the inflow control device and the properties of fluid. The most important fluid properties for adaptive inflow control are: density, viscosity, and flow rate. Density and flow rate determine the inertial force of the fluid, and viscosity and flow rate determine the viscous force of the fluid. By adjusting the geometry of the flow path, the inertial force and viscous force of the fluid can be balanced to realize the functions of fluid identification and selective control. The structure of the core control part of this device is shown in Figure 3. The produced fluid passes through the screen, enters the inlet of the core control part, and flows out from a port in the center of the swirl chamber. Once the fluid enters the core control part, it can only exit the center by way of the throttling channel or the throttling nozzle.

![Figure 3. The schematic diagram of the core control part of the adaptive inflow control device](image)

The choice of fluid path is determined by the inertial and viscous forces. When the inertial force dominates, the fluid tends to keep its original direction flowing along the straight path. When the viscous force dominates, the fluid tends to flow toward the branch. Therefore, when oil flows into the core control part, the fluid tends to flow along the throttling nozzle toward the center outlet, and the adaptive inflow control device will give the minimum limit to the produced fluid; when the water flows into the core control part, the fluid tends to flow straight along the throttling channel towards the center outlet, and enters the swirl chamber tangentially at a very high angular momentum. The fluid rotates within the swirl chamber and reaches a high rotary speed before arriving at the center exit. The
The flow limiting function of the core control part is primarily accomplished by controlling the temporal high speed rotation of fluid at the exit. If not considering the gravity, the pressure is related to the square of the flow rate and can be expressed as:

\[ \frac{1}{2} \rho V_1^2 - \frac{1}{2} \rho V_2^2 = \Delta P \]

Where: \( \Delta P \) is the throttling pressure drop, Mpa; \( \rho \) is the density of fluid, kg/m\(^3\); \( V_1 \) is the velocity of fluid swirling at the center exit, m/s; \( V_2 \) is the velocity of fluid movement at the inlet of the core control part, m/s.

The flow rate limiting function of the adaptive inflow control device is mainly determined by the local flow rate of the fluid at the inlet and outlet of the core control part. The flow rate of the fluid is larger at the center outlet than at the inlet, and the transient high speed swirling at the outlet will produce a large additional pressure. When the water cut of produced liquid rises, the proportion of the liquid flowing along the throttling channel increases, and the local rotation speed at the outlet increases as well, resulting in a larger throttling pressure drop; conversely, the adaptive inflow control device will generate a smaller throttling pressure drop.

2 Numerical simulation analysis of fluid flowing

The situation of fluid flowing through the adaptive inflow control device can be calculated by fluid dynamics simulation, and the numerical calculation analysis results are shown in Figure 4:

![Figure 4. Streamline analysis diagram of fluid flowing through the adaptive inflow control device](image)

Figure 4a illustrates the streamline diagram of oil flowing through an adaptive inflow control device. The viscous force of the oil is larger than the inertial force, the oil with high viscosity mostly flows in a straight line along the throttling nozzle toward the central outlet, and the adaptive inflow control device has less restriction on the fluid with high viscosity; when the water flows through the adaptive inflow control device, the inertial force predominates, and most of the fluid will flow into the swirl chamber along the throttling channel. As shown in Figure 4b, the water enters the swirl chamber tangentially and is accelerated while exiting the outlet, thereby generating a larger throttling resistance. Through the design of special flow path, the linear flow and the swirling flow of the oil and water in the adaptive inflow control device can be differentiated, and the purposes of fluid identification, flow conversion and selective restriction can be realized.

3 Performance test and comparative analysis

The performance characteristics of the adaptive inflow control device can be evaluated by measuring the relationship between pressure drop and flow rate of oil and water under different flow rates. By installing pressure sensors at the inlet and outlet of the adaptive inflow control unit, and pumping water (density 1000 kg/m\(^3\), viscosity 0.2 mPa\(\cdot\)s) and oil (density 850 kg/m\(^3\), viscosity 70 mPa\(\cdot\)s) into the adaptive inflow control device with an outlet diameter of 3 mm at different flow rates, the throttling pressure differences of water and oil under different flow rates generated by this device can be measured respectively. The results are shown in Figure 5:
a. Change on oil/water pressure drops at different flow rates

b. Change on oil/water pressure drops at different water cuts

Figure 5. Experimental curves of throttling pressure drop change of the adaptive inflow control device

Figure 5a illustrates that the adaptive inflow control device has a selective control function. Under the same flow rate, the resistance to water is significantly higher than that of the oil, and the water-oil pressure drop ratio increases with flow rate continuously. However, there is also a significant difference on the water-oil pressure drop ratio at a small flow rate. As shown in this figure, at a flow rate of 5 m³/d, the water-oil pressure drop ratio can also be up to 4.64 times. In addition, Figure 5a also shows the relationship between the flow rate and the pressure drop of the traditional “nozzle type” inflow control device under the same outlet conditions. It can be seen from the comparison that the adaptive inflow control device owns the differentiated oil-inflow control function, and it can generate a larger throttling pressure drop at the same flow rate than the conventional “nozzle type” inflow control device, and the throttling resistance of the adaptive inflow control device is more than 20 times that of the nozzle type inflow control device at a larger flow rate.

Figure 5b shows the relationship curves between flow rate and pressure drop of the adaptive inflow control device under different water cuts. This figure suggests that under the same flow rate, the additional resistance generated by the adaptive inflow control device increases with water cut, and as the flow rate continues to increase, the difference on the additional resistance generated by the fluid flowing through the adaptive inflow control device at different water cut increases continuously, which indicates that the established adaptive inflow control device has better oil and water identification characteristics and control performance, and it can automatically control the production of oil wells according to the liquid production conditions of the formation.

3.1.3 Technical features and advantages

(1) Oil and water self-adaption. The additional pressure drop generated by this device can be adjusted automatically according to the condition of formation liquid production; the maximum water-oil pressure drop ratio can be higher than 10, and the inflow control efficiency has been greatly improved.

(2) The flow area is large. The effect of high-throttling resistance of large-diameter nozzles is realized. The large flow area and outlet diameter reduce the risk of blockage and erosion, and provide an overflow space for the bottom hole circulation and acidizing operations.

(3) Good adaptability. The core control part has a small overall dimension and a strong oil-water resistance adjusting ability. It can play a significant adaptive flow adjustment and inflow control function at a lower flowrate (2~5 m³/d).

(4) High reliability. The entire device is free of moving parts, and its integrated design increases the service life effectively. It meets the technical requirements of inflow controlling and oil stabilizing throughout the oil well production cycle, and realizes the low-cost intelligent completion.
3.2 Special inflow control screen

3.2.1 Structural composition

The inflow control technology generally adopts the screen as the filtering and diverting device of formation fluids [11-12]. Combined with the structural characteristics of the adaptive inflow control device, the composite precision sand filtering screen has been developed as the special matching screen. Such screen is mainly composed of the base pipe, wire-wound skeleton, wire mesh, perforated mesh, diffusion mesh, sand filter mesh, outer protective sleeve, docking plug, the intermediate coupling, etc. (Figure 6). Among them, an annular space of 4~5mm is left between the outside of the central pipe and the wire mesh to ensure the lateral inflow of fluids, which satisfies the technical requirements of flow regulation, inflow control and sand blocking in well completion simultaneously.

![Figure 6. Structure of precision composite screen for adaptive flow adjustment and inflow control](image)

1. Base pipe; 2. Quick docking plug; 3. Fixing ring; 4. Modified precision composite sand filtering layer; 5. Intermediate coupling

3.2.2 Working principle and process

In the field application, after the adaptive inflow control completion string is installed and the production starts, the formation fluid first enters the annular space between the screen and formation. The trapezoidal structure design and the side entry mode of the outer protective sleeve of the screen ensure the stability of the fluid entering the screen, which inhibits the direct impact on the screen caused by the high production pressure difference; when the fluid entering the screen passes through the screen, the gravel and impurities in the fluid will be blocked outside the screen, which ensures the high purity of fluid entering the adaptive inflow control device, and reduces the clogging and erosion of the grit or the impurity on the adaptive inflow control device. The diffusion mesh in the inner layer of sand filtering mesh mainly plays the function of protection and support, and the filtration precision of filtering mesh, as well as the layers of filtering mesh and diffusion mesh can be optimized according to the sand producing of formation before entering the wellbore; after the equalization of perforated mesh, the fluid passing through filtering mesh and diffusion mesh enters the wire-wound skeleton channel (i.e., the central annulus channel formed by base pipe and wire mesh) by way of the wire mesh; and then enters the adaptive inflow control at the end of screen by way of the wire-wound skeleton; finally, it enters the completion string after the flow adjustment of this device, thereby achieving the integration of precise filtering and adaptive flow adjustment and inflow control.

3.2.3 Technical features

1. The adaptive inflow control device is connected onto the screen through the docking plug, which facilitates quick abutting and replacement of inflow control device and screen, and enables the on-site replacement of such device.
2. The intermediate coupling is used to connect the inner central flow path of two specialized inflow control screens, which enables the flexible control of fluid;
3. The six-layer filtering screen design is used to alleviate the blockage and erosion of adaptive inflow control device caused by grits and impurities;

4. Field application and effect evaluation

Up to now, the adaptive inflow control technology has been used in three wells. The low water cut oil recovery period in these three wells has been prolonged for 400 days, and the average oil production has been increased by more than 5 times. A comparative analysis of the application of one of these wells is listed below.
4.1 Basic conditions of oil well

The horizontal well, located in B Oilfield, has a total depth of 4981 m with a horizontal length of 240 m. The reservoir thickness is 2.5 m and the water avoidance height is 1.22 m. The lower part of the reservoir has a lot of bottom water, which makes the reservoir a bottom water driving reservoir with sufficient bottom water energy and large water body. The reservoir block in which the horizontal well is located has been developed for 10 years. The average water cut of the producing wells in the block is 82% and the average daily oil production is 6.7 t/d. Controlling and harnessing bottom water and delaying bottom water coning are the main problems faced in the horizontal well completion. The adaptive inflow control technology is used in water control and increasing production completion. The application is very successfully.

4.2 Effect evaluation

After well opening to produce, the production history of the horizontal well is shown as Figure 7.

![Curve of production history](image)

**Figure 7. Curve of production history**

**a. Application well**

Figure 7a shows the productivity change of the application well after well opening. It can be seen from the diagram that the well has been under open flow production since it was put into production, the productivity change has always been stable with a production plateau of more than 600 days and an average daily oil production is 20.2 tons, and the daily water output is always at a low level with an average water cut of 5.4%. Figure 7b shows the production history of an adjacent well developed in the same period of the application well. The flow production days of the adjacent well are only 110 days, and then the mechanical pumping production begins. For the adjacent well, the average daily oil production is 11.4 tons and the average water cut is 56%. Compared with the adjacent well production, the average daily oil production of the application well has increased nearly three times, and the oil recovery period of low water cut has been prolonged for more than 400 days, which has fully embodied the water control and increasing production advantages of the adaptive inflow control completion technology. In addition, it can be seen from the water production variation curve of the application well that, there has been a number of cycles of water production rising and then falling during the production process. In particular, after 110 days of normal production, there was a significant increase in water production and it maintained for some time before the water production began to decline and returned to the production state of low water cut. This shows that because of the small oil layer thickness and the low water avoidance height of the test well, the bottom water coning occurred in the production of the application well. However, due to the application of adaptive inflow control technology, after the bottom water coning occurred in the horizontal section, the adaptive inflow control screen at the bottom water coning generated additional resistance, which restrains the production of water production intervals and promotes the production of oil production sections. Thus, the effect of dynamic water-blocking oil recovery is realized.
5. Conclusion

(1) In this paper, an adaptive inflow control technology is proposed, which realizes the goal of equilibrium liquid control in prophase and water-blocking oil recovery in middle and late stage of the well production process, and meets the technical requirements of controlling water and stabilizing oil production in the whole well production cycle.

(2) The adaptive inflow control device adopts the flowpath regulating mechanism, which realizes the automation of the oil/water self-selection and control water and oil stabilization. With integrated design, unlimited control water, no human intervention and control pipeline.

(3) The special screen is designed with a six-layer precision sand filter screen. The 4~5mm flow passages are left outside the base screen, which meets the requirement of the in-well fluid transversal flow of the adaptive inflow control, and realizes the technical requirement of deep filtration of the fluid entering the wellbore.

(4) To some extent, The adaptive inflow control technology can solve the problem of poor water control pertinence in the conventional inflow control completion technology, and can meet technical requirements of long-term reliable water-blocking oil recovery at the late stage.

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