Simulation of the water controlling ability of an adaptive inflow control device

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Abstract. Traditional adaptive inflow control device (AICD) has low water control efficiency. Based on adaptive inflow control device, numerical simulation method is used to analyze the internal flow of the device. Influence of relevant design parameters on its water control capacity is studied. Internal structure of AICD is optimized to change internal flow and the flow path of oil flow in the restrictor. Purpose of controlling the flow of oil by using different viscosities of two flow states is achieved. Results show that setting the baffle to distinguish the annular passage and control chamber can improve pressure drop of water flow. The direction and number of flow channels have significant influence on AICD water control ability. Optimizing the shape of flow channel can change entrance speed and entrance angle, improving the water control capacity of inflow controlling device. The AICD achieves the optimal control capacity when it adopts the one transitional flow channel with 45° A angle.

1. Introduction

Horizontal well is an efficient developing tool widely used in fractured reservoirs, heavy oil reservoirs, thin reservoirs, bottom water reservoirs, shallow and deep ocean reservoirs, and unconventional reservoirs [1-4]. Most of the horizontal wells in China are becoming high-water-content wells, and the problem of bottom water ridges is becoming more and more prominent as the water content rises faster. Due to the complicated structure of horizontal wells, it is difficult to find water and water shutoff work, which greatly increases the mining cost. As a result, the research on AICD with high water control capacity is important for oil exploitation [5-8]. In the early 1990s, inflow control device (ICD) was first developed by Norsk Hydro and applied to the Troll field [9]. The AICD technology is more reliable than the inflow control valve (ICV) technology as it does not require cables and infrared [10-11]. This AICD technology has higher water control efficiency compared with traditional methods such as segmental perforation, variable density perforation and central tube completion [12].

The AICD will produce a greater resistance to water than that of oil when they are both exist in the well to achieve the purpose of controlling water flow. Balanced AICD [13] uses the difference in water and gas density to control the opening or closing of the balance, but the device has two disadvantages. First, the movable balance sheet is prone to failure. Second, the device cannot effectively control the water cone. The long-term stability of this unit is critical to the successful development of wells, as wells using ICDs typically require continuous production for more than 5 to 20 years.
2. Introduction to the principle of the new AICD

2.1. Structure of AICD
To solve problems above, this paper proposes a new type of inflow control device, the structure of which is shown in Figure 1. The structure is mainly composed of an inlet, an annular passage, a flow channel, a control chamber and a nozzle. The effect of the current limiting and the diversion is achieved by the interaction of these parts. The pressure drop of the new inflow control device is mainly determined by the minimum flow area and the length of the flow channel. Considering that the inflow control device should have certain anti-erosion and anti-clogging ability, sufficient flow area should be ensured. The structural optimization method adopted in this paper has a good reliability. By using the characteristic that oil and water has different flow states due to the difference in viscosities, an inflow control device with a small oil pressure drop and a large water pressure drop is designed.

2.2. Designing Principle
The nozzle pressure drop is calculated in the same way as the flow channel pressure drop.

By setting the baffle in the AICD and optimizing the flow channel structure to change the flow path of the water in the AICD, it is ensured that the water flow at the nozzle can flow out at a higher flow rate to obtain a higher pressure drop overall. The flow restriction of the AICD inner baffle can effectively increase the inflow velocity of the control chamber inlet and optimize the incident angle. The inertial force is much larger than the viscous force during the flow of water. The incident angle of the water flow directly affects the flow structure of the water in the control chamber, and is most suitable for increasing the pressure drop. The flow path is that the fluid in the restrictor is accelerated at the nozzle by the rotation of fluid. For the oil with high dynamic viscosity, it is not easily rotated and accelerated in the annular passage and the control chamber. The outflow velocity and pressure drop are both small.

2.3. Overcurrent pressure drop model
Due to the internal friction of the fluid and the collision between internal particles, a certain pressure drop occurs after fluid flowing through the device. The pressure drop is generated at the annular channel, the flow channel and the nozzle. As a result, the total pressure drop can be expressed as the sum of the annular channel pressure drop, the flow channel pressure drop and the nozzle pressure drop:

\[ \Delta p = \Delta p_L + \Delta p_N + \Delta p_S \]  

(1)

\( \Delta p \) is the total pressure drop produced by the fluid flowing through the device, \( \Delta p_L \) is the pressure drop produced by the fluid through the annular flow path, \( \Delta p_N \) is the pressure drop produced by the fluid through the flow channel, and \( \Delta p_S \) is the pressure drop produced by the fluid through the nozzle.

2.3.1. Annular channel pressure loss. The annular channel pressure drop includes pressure loss along the path and partial pressure loss:
\[ \Delta p_L = \left( \lambda \frac{l}{d_l} + \zeta \right) \frac{\rho m (Q \cdot f_{DC})^2}{2A_l^2} \]  

(2)

Where \( \zeta \) is the partial pressure loss coefficient, \( \lambda \) is the pressure loss coefficient along the annular channel, \( l \) is the length of the annular channel, \( d_l \) is the hydraulic diameter of the annular channel, \( \rho_m \) is the density of the mixed liquid, \( Q \) is the flow of the automatic phase selection control valve Flow rate, \( A_l \) is the annular flow channel cross-sectional area.

2.3.2. Flow channel pressure drop.

\[ \Delta p_S = C_{DS} \frac{\rho L Q^2}{2A_S^2} \]  

(3)

\( A_S \) is the flow channel cross-sectional area, \( C_{DS} \) is the flow channel pressure loss coefficient.

\[ C_{DS} = K_{Sin} + K_{Sout} + \lambda \frac{l_s}{d_s} \]  

(4)

Where \( l_s \) is the length of the runner and \( d_s \) is the hydraulic diameter of the runner. \( K_{Sin} \) and \( K_{Sout} \) are associated with sudden expansion and sudden contraction of the pipe.

3. Modelling and analysis

3.1. Modelling

The numerical simulation method is used to obtain complex flow structures in a wide range of applications. Therefore, the water control performance of this new type of device was studied with numerical simulation software before its structure was further optimized. The geometric model of the device are completed with CATIA before they are meshed in CFD software. Each model has 1 entry and 1 exit. The entry is set as velocity-inlet, the exit is set as outflow, and the rest parts of the model are set as wall. The internal flow model is then obtained by Boolean operation.

3.2. Structural parameter optimization

In order to improve the water control performance of the device, it is necessary to optimize its structural parameters. The optimized parameters include the flow channel structure, the number of flow channels between the control chamber and the annular channel, and the opening position of the control chamber flow channel.

3.2.1. Flow channel structure. Two types of flow channel structures are proposed, namely a flat-type flow channel and a transitional-type flow channel (see Figure 2). The velocity streamline diagram of water flowing in these two different structures at a flow rate of 5 m3/d is as shown in Figure 3.

![Figure 2. Structure of Two Types of Flow Channel.](image1)

![Figure 3. Velocity Streamline Diagram of Flow Channel.](image2)
It can be seen from the figure that after flowing into the AICD, the water rotates around the annular passage to accelerate before flowing into the control chamber through the flow channel. After that, water continues to rotate and accelerate in the control chamber and the flow velocity reaches a maximum at the outlet. Further analysis of the two types of flow channel is stated below. First, analysis of flat-type flow channel structure revealed that water first hit the side of the outer wall of the control chamber since it did not enter the control chamber from the annular passage in the tangential direction. This phenomenon causes a certain loss in the velocity of the fluid. After the fluid flows into the control chamber, the incident angle has a certain angle difference with the tangential direction, causing the water to hit the inner wall of the control chamber after entering the control chamber. This results in two vortexes in opposite direction, including a larger one and a smaller one. The two vortexes interfere with each other, so that the water cannot sufficiently rotates and accelerates inside the control chamber, making the structure unable to exert the desired effect. For the transitional structure, after the fluid rotating and accelerating along the annular passage, it flows into the interior of the control chamber along the tangential direction, and is accelerated in the control chamber. It has been verified that the pressure drop caused by the device with the transitional structure is about 2.5 times that of the device using the flat head structure. To conclude, the transitional-type flow channel generates better water flow restriction effect compared with the flat-type flow channel.

3.2.2. Number of flow channels between the control chamber and the annular channel. The number of flow channels between the control chamber and the annular passage affects the flow of fluid in the annular passage, and thus affects the velocity of the fluid flowing from the annular passage into the control chamber. In addition, the number of flow channels also affects the flow of fluid in the control chamber. On the one hand, an increase in the number of flow channels makes it easier for fluid to flow into the control chamber as the annular passage accelerates the flow speed, which weakens the flow restriction of the annular passage. As a result, the initial velocity of the fluid is reduced as it flows into the control chamber and current limit effect of the structure is also weakened. On the other hand, when the number of flow channels increases, fluid will enter the control chamber from multiple flow channels simultaneously. Interactions between fluids flowing into the control chamber from different flow channels will cause the fluid to accelerate in the control chamber, which enhances the rotating acceleration effect and the current limiting effect of the structure. Theoretically, there would be an ideal number of flow channels to maximize the current limiting effect of the structure.

Figure 4 shows a velocity streamline diagram of water in a structure with different number of flow channels at a flow rate of 5 m$^3$/d and at a constant flow area. It can be seen that the volume of the fluid flowing into the control chamber through the launder is gradually increased when the fluid flows in the annular channel. When the fluid that accelerates the rotation in the annular passage, a part of the fluid flows into the control chamber through the launder during the rotation. A large velocity gradient is created before and after the flow channel to instantaneously reduce the velocity of the fluid within the annular passage, thereby allowing fluid within the annular passage to more easily flow into the control chamber through the subsequent flow channel, while at the same time the initial velocity of the fluid flowing into the control chamber is reduced, which weakens the flow restriction of the annular passage.

![Figure 4. Streamline Chart with Different Number of Flow Channels.](image-url)
Figure 5. The pressure drop with different number of runners.

The relationship between the pressure drop and the number of flow channels is shown in Figure 5. It can be seen that as the number of flow channels increases, the pressure drop generated by the device is gradually reduced. This phenomenon indicates that increasing the number of flow channels plays a dominant role in the weakening of structural limiting effect. To obtain a higher structural effect, it is better to adopt the design with only one flow chamber in the control chamber.

3.2.3. Opening position of the control chamber runner. The different opening positions of the control chamber chutes affect the flow state between the annular passages and the control chamber, thereby affecting the initial velocity of the fluid as it flows from the chute into the control chamber.

The opening position of the control chamber flow channel is indicated by the angle between the center line of the flow channel and the y-axis (see Figure 6). Figure 7 demonstrates a velocity streamline diagram of water in different control chambers with different opening position of the flow channel at a flow rate of 5 m$^3$/d. It can be seen that different flow channel positions can greatly affect the flow state in the annular channel. When the fluid flows from the inlet into the annular passage, there is a large velocity gradient at the interface between the inlet and the annular passage. The reason is that the fluid that has previously accelerated in the annular passage keeps circulating in the annular passage as new fluid flows in. It could increase the fluid velocity after confluence, resulting in a large pressure drop. As the angle $\alpha$ is increasing, the length of the annular passage capable of accelerating the fluid is gradually shortened. This result has a negative effect on the current limiting effect.

Figure 6. Positions of Runners. Figure 7. Velocity Streamline of Different Angles.
Figure 8. The Law of Pressure Drop with Angles.

Figure 8 is the variation of the pressure drop produced by the whole structure with the angle $a$. It can be seen from the figure that angle $a$ should be set at a proper angle. The pressure drop generated by the structure when $a = 0^\circ$ is less than that when $a = 45^\circ$. The reason is that, when $a = 0^\circ$, the fluid flowing in from the inlet is not able to fully merge with the fluid circulating in the annular passage at the inlet of flow channels, which causes a low initial speed of the fluid and a low pressure drop. When $a = 45^\circ$, the two flow of the fluid can just complete the confluence and then flow from the launder to the control chamber. At this point, the initial velocity of the fluid flowing into the control chamber is the largest. The structure has the best current limiting effect, and the resulting pressure drop is the largest.

4. Conclusion

(1) Different flow channel structures will have a great impact on the water control performance. The transitional-type flow channel has a much better conductive effect on water than the flat-type flow channel, and the resulting velocity loss is smaller. As a result, the transitional-type flow channel could generate a higher pressure drop on water.

(2) In the case that the total flow area of the flow channel is constant, the more the number of flow channels is, the less favourable the acceleration of the fluid in the annular passage would be. More flow channels would result in a lower initial velocity of the fluid and a weakened flow restriction effect of the structure. To conclude, number of flow channels in the control chamber is preferably one.

(3) When the angle of $a$ increases, the pressure drop generated by the device appears to increase first and then decrease. When $a = 45^\circ$, the initial velocity of fluid flowing into the control chamber is the largest, so does the pressure drop. As a result, it has the best current limiting effect when $a = 45^\circ$.

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