Structural Parameter Optimization and Performance Analysis of Autonomous Inflow Control Device

Songyi Guo1 Zhiming Wang1* Quanshu Zeng1 Zhanfeng Dang1 Chengkuan Peng1
1College of Petroleum Engineering, China University of Petroleum, Changping, Beijing, 102249 China
* E-mail: wellcompletion@126.com

Abstract. The Autonomous Inflow Control Device (AICD) adjusts the inflow of the horizontal wellbore by adding additional resistance to the fluid, thereby prolonging the water seepage time and enhancing oil recovery. The performance of AICD mainly depends on structural parameters. The computational fluid dynamics software is used to analyze the influence of structural parameters on the performance of AICD. The results show that the diameter of the variable diameter section, the diameter of the restrictor and the diameter of the outlet are the main factors affecting the performance of the inflow control device. The fluid parameter sensitivity simulation results show that the oil phase viscosity and water content have a great influence on the performance of AICD, while the influence of oil phase density on the performance of the device is negligible; the pressure drop under the pure water condition of this type of AICD is more than twice that of pure oil condition, so it has better water control ability.

1. Introduction
Most of China's onshore oil fields have entered a late stage of development, and the water production of oil wells has risen rapidly. We are facing severe water control problems. The wide application of horizontal well technology, on the one hand, greatly increases the production of oil wells, while on the other hand, leads to early water and gas seepage in the horizontal wellbore due to the "heeling effect" and the heterogeneity of permeability. Early water seepage in oil wells has become a key problem that restricts the application and development of horizontal well technology. The inflow control device is a horizontal well water control technology widely used in recent years [1-3]. It is comprised of an inflow control device (ICD), an autonomous inflow control device (AICD), and an inflow control valve (ICV).

Yang Mingjun et al. studied the performance of AICD based on CFD software, and obtained the distribution of pressure and flow velocity in the device and the influence of pressure drop on anti-erosion performance and viscosity sensitivity [4]. Yang Jinxian et al. used a combination of theoretical analysis and reservoir numerical simulation software to study the optimization method for completion of inflow control devices [5, 6]. Fang Quantang et al. analyzed the factors influencing the early water seepage inflow of inflow control device from the perspective of the reservoir [7]. Tian Xiang et al. studied the types of reservoirs suitable for ICD technology and the actual application of ICD technology [8, 9]. Greci et al. studied the anti-blocking ability of AICD through laboratory experiments [10]. Stone et al. studied the application and optimization of AICDs in reservoirs through reservoir numerical simulation software [11]. Sang Guansen et al. used computational fluid dynamics software to study the sensitivity of fluid parameters of AICD based on expanded rubber [12]. At
present, Halliburton's EquilFlow type AICD is the most widely used one, based on which Yang Mingjun proposed the new AICD [13, 14].

Studies mainly focus on the fluid parameter sensitivity of the inflow control device and the application of the inflow control device in the reservoir, but pay less attention to the optimization of the structural parameters for a single device. This paper adopts the design principle of Halliburton EquilFlow type AICD [15], optimizes the structural parameters of this type of AICD using CFD software, and studies the sensitivity of the fluid parameters of the device based on optimization results.

2. Structural analysis

The structure of this type of inflow control device (AICD) is shown in Figure 1. The device is mainly composed of three parts. The first part is three parallel pipes placed on the left side; the second part is the jet deflection structure corresponding to the outlets of the three parallel pipes; the third part is composed of the radial flow guiding channel, the tangential guiding flow channel and the circular restrictor.

Figure 1 Structural schematic diagram of the AICD

The first part of this type of AICD consists of three parallel lines. The upper one is the current limiting pipeline. The restrictor pipe is composed of a series of short pipes with different diameters. The pressure drop generated when the fluid flows through the pipe is divided into two parts: one is generated when there is friction between the fluid and the pipe wall; the other is caused by the appearance of the vortex zone and the redistribution of the velocity at the sudden change of the pipe diameter, which causes the fluid to rotate, collide, and recirculate irregularly, consuming the energy of the mainstream motion, resulting in large local pressure loss. The middle one is the main channel, whose diameter is larger than that of the restricting pipe and the friction pipe, the pressure drop generated by the fluid flowing through the main channel is small, and the fluid entering the main channel is much more than that entering the limiting pipe and the friction tube. The lower one is the friction circuit, which is significantly longer than the restrictor and main flow channels. Due to the friction between the fluid and the tube wall, a large pressure drop across the path occurs when the fluid flows through the friction tube. The pressure drop along the path is related to the viscosity of the fluid. The larger the viscosity is, the greater the pressure drops along the path, so the friction circuit exerts a greater flow resistance to the high viscosity fluid.

3. Structural parameter optimization

This type of AICD has a complex structure, including multiple branches. The diameter of the pipeline varies greatly, so the pressure drop is difficult to calculate accurately by theoretical analysis. It is time-consuming and labor-intensive to obtain pressure drop data through traditional physical simulation experiments. With the rapid development of computer performance and the computational fluid dynamics, numerical simulation software has been widely used to study the flow laws of fluids in different devices. Fluent software has multiple built-in physical models with wide range of parameters and it is also easy to operate. Fluent software can basically meet the needs of fluid flow simulation. The Laminar model is selected for laminar flow, while the standard k-epsilon model is selected for turbulent flow. When there is multiphase flow, there are three models available: VOF model is suitable for oil-water two-phase stratified flow; Mixture model for oil-water two-phase dispersed flow or
dispersed phase when the volume fraction exceeds 10%; Eulerian model is also suitable for scatter flow, and it is the most accurate one in terms of calculation among the three models. But Eulerian model is computationally intensive and less stable.

Factors affecting the performance of the AICD include: diameter of the variable diameter section, number of variable diameter sections, diameter of the main flow passage, restrictor diameter, and outlet diameter. This paper adopts the single factor analysis method to analyze the specific effects of each factor on the performance of the device. According to Fluent simulation results, this paper selects the optimal value of the first structural parameter, and then optimizes the second structural parameter based on the first selected parameter until the optimization result of all structural parameters is obtained. The specific experiment plan is shown in Table 1.

| Structural parameter                  | Parameter range       | Structural parameter                  | Parameter range       |
|---------------------------------------|-----------------------|---------------------------------------|-----------------------|
| Diameter of the variable diameter section (mm) | 4, 6, 8, 10, 12, 14, 16, 18, 20 | Diameter of the restrictor (mm)       | 30, 40, 50, 60, 70, 80 |
| Number of the variable diameter section (1) | 2, 3, 4, 5, 6         | Diameter of the outlet (mm)            | 10, 20, 30           |
| Length of the frictional channel (mm)   | 600, 700, 800         | Diameter of the mainstream channel (mm)| 10, 15, 20, 25, 30   |

This paper adopts Gambit software to draw two-dimensional images of diameters of 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 14 mm, 16 mm, 18 mm and 20 mm respectively; then divides the grid and sets the boundary conditions; finally imports the grid file into In Fluent, selects the appropriate flow model, sets the simulation parameters, and analyzes the flow of the study fluid in the AICD. The simulation results are shown in Figure 2. It can be seen that the oil and water pressure drop depends on the difference between the diameter of the variable diameter section and the diameter of the inlet of the pipeline, the difference in diameter is the same, and the difference in oil pressure drop is approximately equal. Considering the anti-blocking performance of the pipeline and the influence of the oil-water pressure drop difference, the optimum diameter of the short-length pipe of the variable diameter section is 16 mm.

Based on the optimization of the diameter of the variable diameter section, the influence of the number of short tubes in the variable diameter section on the performance of the AICD is further studied. According to the Fluent simulation results, the pressure drop difference between the oil and water flowing through the AICD with different number of short tubes in the variable diameter section is shown in Figure 3.

![Figure 2](image1.png)  ![Figure 3](image2.png)

It can be seen from the figure that when there are 4 short tubes in the variable diameter section, the difference in pressure drop between the oil phase and the water phase flowing through the device is the largest, so the optimal number of short tubes in the variable diameter section is four.
Similarly, based on the optimization of the diameter and number of the variable diameter section, this paper studies the influence of the length of the frictional passage on the performance of the AICD. Fluent numerical simulation results show that the optimal length of the friction channel is 700 mm.

The diameters of the restrictor and the outlet have a large influence on the performance of the AICD. The simulation results show that the larger the diameter of the restrictor and the smaller the outlet diameter are, the larger the difference in oil-water pressure drop, as shown in Figure 4 and Figure 5. The diameter of the restrictor and the diameter of the outlet are optimized to be 80 mm and 10 mm respectively, taking into consideration the limitation of the overall size of the device and the anti-clogging performance of the outlet.

It can be observed that the pressure drop produced by the oil and water flowing through the device decreases as the diameter of the outlet increases. According to the analysis, as the diameter of the outlet increases, the partial pressure drop generated when the water phase flows through the outlet of the device is significantly reduced, while the pressure drop of the oil phase is less affected. That is, as the diameter of the outlet increases, the pressure drop of the water phase decreases significantly, while the pressure drop of the oil phase remains substantially unchanged, so the pressure drop of the oil and water gradually becomes smaller. For this type of AICD, the optimum diameter of the outlet is 10 mm.

Finally, according to the above optimization results, this paper studies the influence of the mainstream channel diameter on the device performance. It can be seen that when the diameter of the main channel is less than 20 mm, the pressure difference of oil and water changes little with diameter; when the diameter of the main channel is larger than 20 mm, the pressure drop of oil and water decreases with the increase of the diameter of the main channel. Therefore, the optimal diameter of the mainstream channel is 20 mm.

| Structural parameter                              | Optimal value | Structural parameter                              | Optimal value |
|--------------------------------------------------|---------------|--------------------------------------------------|---------------|
| Diameter of the variable diameter section (mm)   | 16            | Diameter of the restrictor (mm)                  | 80            |
| Number of the variable diameter section (Dimensionless) | 4             | Diameter of the outlet (mm)                      | 10            |
| Length of the frictional channel (mm)            | 700           | Diameter of the mainstream channel (mm)          | 20            |

It can be seen from Figure 2 to Figure 5 that the diameter of the variable diameter section, the diameter of the restrictor and the diameter of the outlet have a great influence on the performance of the AICD; the number of the variable diameter section, the diameter of the frictional passage and the diameter of the main passage have a small influence on the performance of the AICD. This means that in the design of this kind of AICD, the main focus is the diameter of the restrictor, the outlet and the variable diameter section. In this way, good results can be achieved.
From the above analysis, the optimal structural parameters of the device are shown in Table 2.

4. Effect of fluid parameters on AICD performance

Based on the optimization results of the structural parameters, the influence of fluid parameters on the performance of the AICD was further studied using Fluent software. Fluid parameters studied included: oil phase viscosity, oil phase density, and moisture content.

The crude oil viscosity ranged from 1 cP to 200 cP. Therefore, the viscosity values of crude oil for analysis were selected as follows: 1 cP, 4 cP, 10 cP, 20 cP, 40 cP, 100 cP, 150 cP, 200 cP. At the same time, with different water content, the change of pressure drop produced by the fluid flowing through the AICD with the viscosity of the crude oil is shown in Figure 6. It can be seen that: (1) When the water content is 0 (or pure oil), the pressure drop generated by the fluid flowing through the device decreases first and then slowly increases. The reason for this change is that at low viscosity, the properties of the oil phase are very close to those of the water phase. The only big difference is the density between the two. If the viscosity of the oil is closer to the viscosity of water (1 cP), the pressure drop generated by the device is higher, that is, as the oil phase increases, the difference between the oil phase pressure drop and the water phase pressure drop increases, that is, the oil phase pressure drop gradually decreases; at high viscosity, as the viscosity increases, the pressure drop along the oil phase increases continuously, the difference between the oil phase pressure drops and the water phase pressure drop gradually decreases. (2) After the water content is greater than the reverse phase, the viscosity of the oil-water mixture no longer changes with the change of water content. It is observed from the figure that when the water content is 50%, the pressure drop generated by the fluid flowing through the device changes with the viscosity. The trend gradually increases, but small in scale, which is probably because the viscosity of the oil-water mixture increases as the viscosity of the oil phase increases, which in turn leads to an increase in pressure drop. (3) When the water content is 100% (all water in the device), the pressure drop is independent of the viscosity of the oil phase, and the pressure drop curve is a straight line parallel to the horizontal coordinate axis. (4) The viscosity range of the device is 20 cP–200 cP. Within this range, the water phase pressure drop is about twice the oil phase pressure drop, and the oil-water pressure drop is significantly different.

The crude oil density of conventional reservoirs ranges from 800 kg/m³ to 1000 kg/m³, so this paper takes the crude oil with oil phase density of 800 kg/m³, 850 kg/m³, 900 kg/m³, 950 kg/m³ and 1000 kg/m³. The relationship between pressure drop and oil phase density at different water contents is shown in Figure 7.

It can be seen from the figure that the pressure drop generated by the fluid flowing through the device hardly changes with the change of the oil phase density, and the relationship curve between the two is approximately a horizontal line. The water content has a greater influence on the pressure drop. In the case of pure water, the pressure drop generated by the fluid flowing through the device is more than twice that of the pure oil. In general, the effect of oil phase density on pressure drop is negligible.

The water content of oil wells in different development stages is different. In order to reveal the
role of this type of AICD in different development stages of production wells, this study takes the crude oil with moisture content values of 0, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 85%, 90%, 100%. The relationship between the pressure drop produced by the fluid flowing through the device and the water content is shown in Figure 8.

Figure 8. the influence of water cut on the performance of AICD

It can be seen that the pressure drop produced by the fluid flowing through the AICD increases as the water content increases. The curve of pressure drop with water content can be divided into three stages: in the first stage, the water content is between 0 and 40%. The pressure drop changes stably with the change of water content, and it decrease first and then increases. In the second stage, the water content is between 40% and 80%. The pressure drop changes significantly with the increase of water content. In the third stage, the water content is between 80% and 100%. The change in the rate tends to be flat, but more significant than the change in the case of low water content. The pressure drop under pure water conditions is 0.075 MPa, and the pressure drop under pure oil conditions is 0.032 MPa. The former is more than twice that of the latter, indicating that the device can produce a distinct pressure drop for oil and water and it good in water control.

5. Conclusion
(1) The performance of this type of AICD is mainly affected by the diameter of the variable diameter section, the diameter of the restrictor and the diameter of the outlet, while it is less affected by the number of the variable diameter section, the diameter of the main passage and the diameter of the friction passage.

(2) The relationship between the pressure drop caused by the oil and water flowing through the device varies with the diameter of the variable diameter section is an approximately symmetrical curve, and the diameter corresponding to the axis of symmetry is equal to that of the friction circuit inlet. The left side of the symmetry axis indicates that the variable diameter section is a shrinkage tube, and the right side of the symmetry axis indicates that the variable diameter section is an expansion tube. The difference between the oil and water pressure drop depends on the difference between the diameter of the variable diameter section and the diameter of the inlet of the pipe, but not on whether the variable diameter section is an expansion pipe or a shrinkage one. When diameter difference is the same, the oil pressure drop is approximately equal.

(3) The difference in pressure drop generated by the oil and water flowing through the device increases with the increase of the diameter of the restrictor, and decreases with the increase of the diameter of the outlet, that is, the larger the diameter of the restrictor and the smaller the diameter of the outlet are, the better the device performance.

(4) The structural parameters of the AICD are optimized by using Fluent software. The optimum results of the structural parameters are: diameter of the variable diameter section is 16 mm, number of variable diameter sections is four, frictional passage length is 700 mm, mainstream passage diameter is 20 mm, the diameter of the current limiting device is 80 mm, and the diameter of the outlet is 10 mm.
(5) The influence of oil phase density on the performance of the device is negligible; the viscosity range of the device is 20 cP~200 cP.

(6) The difference in oil-water pressure drop increases with increasing water content. The pressure drop in pure water is 0.075 MPa, while the pressure drop in pure oil is only 0.032 MPa. The former is more than twice that of the latter.

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Reference
[1] Liu, J.R., Yu, W.Q. (2010) Downhole Inflow Control Technology with ICD/ICV. J. Oil Field Equipment, 04: 35-37.
[2] Zhang, R.X., Wang, J.F., Dong, D.X. (2012) Status And Development Trends of the Water Controlling Completion Technology of Horizontal Well. J. Drilling & Production Technology, 04: 35-37.
[3] Zhao, H.F., Tian, J.C., Mu, E.F. (2017) Developing Situation of Water Control Device in Horizontal Wells. J. Oil Field Equipment, 01: 81-85.
[4] Yang, M.J., Li, H.T., Li, C. (2013) Performance Analysis of Channer-nozzle Type Inflow Control Device Based on CFD. J. Oil Field Equipment, 04: 10-13.
[5] Yang, J.X., Li, H.T., Dong, D.X. (2013) Horizontal Well Completion Optimization with Inflow Control Devices in Bottom Water Drive Gas Reservoir. J. Drilling & Production Technology, 02: 45-47.
[6] An, Y.S., Zhang, N., Zhang, H. (2017) Numerical Simulation Study on the Coupling of Horizontal Wells with ICD Water Control Completion. J. China Offshore Oil and Gas, 02: 109-113.
[7] Fang, Q.T., Zhang, F.L., Duan, Y.G. (2012) Analyses of Influencing Factors and Mechanism of Controlling Bottom Water in Horizontal Well with Inflow Control Device. J. Journal of Southwest Petroleum University (Science & Technology Edition), 06: 107-112.
[8] Tian, X., Li, L., Xie, X. (2012) Application of ICD Completion Technology in Huizhou Oilfield. J. Journal of Oil and Gas Technology, 09: 238-240.
[9] Yang, J.F., Zhao, Y.R., Zhao, L.L. (2013) Technologies and Application for Inflow Control Equipment of Intelligent Well Completion[J]. Oil Field Equipment, 03: 66-70.
[10] Greci, S., Least, B., Aitken L.A. (2014) Plugging Testing Confirms the Reliability of the Fluidic Diode-Type Autonomous Inflow Control Device, In: SPE Deepwater Drilling and Completions Conference. Texas. pp. 1-13
[11] Stone, T.W., Moen, T., Edwards, D.A. (2015) Optimized Design of Autonomous Inflow Control Devices for Gas and Water Coning. In: SPE Reservoir Simulation Symposium. Texas. pp. 1-13
[12] Sang, G.S., Jiang, Z., Zhang, Q. (2014) A Novel Autonomous Inflow Control Device Design Based on Water Swelling Rubber. In: IADC/SPE Asia Pacific Drilling Technology Conference. Bangkok. pp. 1-9
[13] Zeng, Q.S., Wang, Z.M., Wang, X.Q. (2015) A New Type Design of AICD And Its Numerical Simulation [J]. Oil Drilling & Production Technology, 02: 101-106.
[14] Yang, M.J., Li, H.T., Jiang, Rui. (2016) Water Control Principle and Performance Analysis of a New AICD In Bottom Water Reservoir. J. Reservoir Evaluation and Development, 04: 64-68.
[15] Halliburton Company. (2017) EquiFlow® Autonomous Inflow Control Devices. https://www.halliburton.com/content/dam/ps/public/cps/contents/Data_Sheets/web/H/H08364-EquiFlowAICD.pdf.