Numerical Study on Flow Field Characteristics of Interval control valve in Intelligent Well

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Abstract. Interval control valve (ICV) is an important part of intelligent well. An ICV was designed and its flow field characteristic was analyzed by the software CFX. With the increase of the ICV opening, the thickness of laminar bottom layer became thinner and the average velocity of the main flow zone increased. The opening had greater effect on the average velocity than the pressure differential. When the ICV was opened or closed, there might be a great shear resistance due to the large inlet flow rate. There was a velocity stagnation point at the intersection of ICV entrance and its axis. The turbulent kinetic energy decreased gradually with the increase of the ICV opening. It was proved that the ICV had a good flow capacity, and the downhole fluid did not produce large pressure drop when it flew through the ICV. The ICV opening - flow coefficient curve could guide the operation of the ICV to achieve the purpose of accurately regulating the production of a reservoir.

1. Introduction
Intelligent well technology is a real-time injection and production management network, which can acquire the pressure, temperature and flow rate in production intervals by sensors permanently placed in the downhole [1]. The collected signals are transmitted to the ground through the communication cables or optical cables, which are excavated, analyzed and learned by the developed software platform. Combining with oil reservoir history automatic matching technology and reservoir numerical prediction technology, the decision-making information of reservoir production management is formed and feed back to the downhole through the control system to real-time reconfiguration of well structure and production technology. Thus, the safety and reliability of interlayer separation, flow control, mechanical oil recovery, permanent monitoring and sand production control can be integrated. Intelligent well enables operators to monitor and control oil and gas production in single well and multi-section or multi-branch wells in real time from the ground [2]. The main role is to optimize the production of oil wells and to minimize the operating costs and production risks, while to maximize oil recovery, reduce production costs and accelerate the flow of funds. Intelligent completion system generally consists of
the following parts: underground information collection system; underground flow control system; underground data transmission system; ground data collection, analysis and feedback control system. As an important part of the intelligent completion, great progress has made in the underground flow control system from the original downhole slipper to the current ICV [3]. At present, most of the ICVs are manufactured by the hydraulic technology, while the electric ICVs in the deep wells also show great advantages. There are two types of hydraulic control ICVs, one is the fully open and closed ICV, and the other is the adjustable ICV. Well Dynamics and Baker Hughes are the leading companies in the research of underground interlayer ICVs.

Konopczynski et al. presented the design of intelligent well downhole valves for adjustable flow control [4]. Davies et al. suggested the techniques for optimum placement of ICV(s) in an intelligent well [5]. Ajayi and Konopczynski described a stochastic approach to the design of ICV choke trims for an intelligent well system [6]. Yang et al. presented an advanced control method for online regulation of downhole ICVs to achieve optimal production via choke performance management [7]. Qahtani et al. employed lattice Boltzmann (LB) flow modeling to simulate the flow field in a ICV model and considered that the gap width of the inlet slot control should be carefully sized in order to avoid unnecessary recirculation zones [8]. Rahman et al. introduced the description of each acceptance test, acceptance criteria and test results for ICV, which illustrated the performance of the new generation ICV under harsh working conditions. And they also presented some field applications of the new generation ICV and outlined the design enhancements planned for the next generation ICV [9]. Wilson et al. introduced the use of inflow control devices (ICD) and inflow control valves in Kuwait's first smart multilateral well, which minimized pressure drop through ICD housing and maximize oil recovery and production life of wells [10]. Oddie et al. introduced a case study in Equatorial Guinea, West Africa to demonstrate how barrier provisions with remote open / close technology capabilities enabled interventions to be removed from a completion design [11]. Harive et al. analyzed the effect of perforating shock on an intelligent completions ICV with test validation [12]. Ahmed Elfeel et al. presented the role of flow control valve in the effectiveness of complementary workflows where high frequency reactive and proactive optimizations support a near continuous closed-loop reservoir management [13]. Joubran et al. discussed the significant technological advancements and reliability of ICVs and proposed that the future of intelligent completions and ICVs was tied to precision of device control, system reliability assurance, and effective use of sensor data to generate recognizable value [14].

2. Research contents and method

This paper cooperates with CNOOC Energy Development Company to design a two-degree hydraulic ICV. Considering the high temperature and high pressure environment in the well, the main seal used of the ICV is metal – to - metal seal, while the seal of the hydraulic chamber is mainly solved by the combination of sealing rings. The main design parameters of the ICV are as follows:

| Table 1. Design parameters of the ICV |
|--------------------------------------|
| Design parameter | Tubing size | Max outside diameter | Minimum bore diameter | Maximum working pressure | Maximum pressure | Maximum service temperature |
|--------------------|-------------|----------------------|-----------------------|--------------------------|-----------------|-----------------------------|
| Value              | 4-1/2"      | 165 mm               | 78 mm                 | 50 MPa                   | 40 MPa          | 165 °C                      |

The ICV is mainly composed of upper valve body, lower valve body, lower valve body head, piston, piston seat, bushing, sleeve, overcurrent sleeve and sealing parts. The upper body and the lower body are threaded together, while the lower body and the lower body head are also connected by threads, which forming the shell part of the ICV to protect the piston, piston seat and seals in the ICV. The upper body and lower body head are machined with 4-1/2"sealed screw thread, which are connected with the upper and lower tubing respectively. The piston is installed in the upper body of the ICV, and there is a cavity between the piston and the upper body. Two combined sealing rings are fitted with the piston,
which divide the cavity into two separate hydraulic chambers. The bushing is fixed in the inner part of
the upper valve body by threaded connection and the combined seal ring (14) is fixed in the middle by
the retaining ring and bushing, which keeps the seal between the upper valve body and the piston. There
are two holes (2,16) with the diameter of 5 mm drilled in the upper valve body, which are connected
with the two hydraulic chambers (5,15) respectively. The high-pressure hydraulic oil provided by the
ground hydraulic device can enter into the two hydraulic chambers through the two holes to promote
the piston to move up and down, which realizes opening and closing of the ICV. When the ICV is fully
closed, the pressure exerted on the piston by the hydraulic oil in the hydraulic chamber makes the contact
surface between the piston and the piston seat close together, which produces the specific pressure of
the seal on the contact surface to maintain the metal-to-metal seal. The sleeve between the lower valve
body and the piston is mounted on the bushing through its own steps. The slider mounted on the piston
is installed in the sliding groove which is in the sleeve to ensure that the piston does not rotate
circumferentially when it moves up and down. The overflow sleeve is connected with the sleeve by pin
and installed among the sleeve, the lower valve body, the lower valve body head, piston and piston seat.
There are four uniformly distributed long waist holes on the overflow sleeve, which correspond to the
four long waist holes on the lower valve body. When the piston is in the open position, oil and gas in
the reservoir will enter the inner part of the ICV through this channel.

Figure 1. The assembly drawing of the ICV.

1 upper valve body, 2 oil passage, 3 combined seal ring for shaft, 4 combined seal ring for hole, 5
right sealing cavity, 6 piston, 7 lower valve body, 8 overcurrent sleeve, 9 piston seat, 10 lower valve
body head, 11 pin, 12 sleeve, 13 bushing, 14 combined seal ring for hole, 15 left sealing cavity, 16 oil
passage.

Computational Fluid Dynamics (CFD) is a subject of numerical simulation and analysis of inviscid
flow and viscous flow of fluid by means of discrete numerical methods and computer which can be used
to analyze a system containing relevant physical phenomena such as fluid flow and heat conduction.
The basic idea of CFD can be summed up as follows: replacing the field of continuous physical
quantities with a set of variable values at a series of finite discrete points, establishing an algebraic
equation system of the relationship between field variables at these discrete points by certain principles
and methods, and then obtaining the approximation values of field variables by solving the algebraic
system. CFD can be regarded as a numerical simulation of flow under the control of basic flow equations.
Through the numerical simulation, we can obtain the distribution of basic physical quantities at various
positions in the flow field of extremely complex problems and the variation of these physical quantities
with time, and determine the distribution characteristics of vortices, cavitation characteristics and the
separation of flow zone etc. CFD is employed to analyze the change of flow field during the process of
closing and opening of the ICV and to establish the solid model of flow field under different opening
sizes.

(a) The opening is 15mm. (b) The opening is 60mm.

Figure 2. Flow field numerical model of the ICV.
To determine the specific calculation model, the following calculation model assumptions are necessary: 1. the ICV is an ideal valve without leakage; 2. the crude oil medium is an incompressible fluid; 3. the crude oil is a Newtonian fluid, which dynamic viscosity is constant and does not change with the velocity gradient; 4. the fluid is a one-way flow.

The tetra / mixed mesh (tetrahedron) is directly used to generate the finite element model of the numerical simulation flow field. Taking the flow field model with the opening of 75 mm as an example, the flow field grid model has 196807 elements and 37174 nodes.

The simulated medium in this paper is the crude oil in the reservoir which material characteristics are first established in the pretreatment. Taking a reservoir with the depth of the middle part of 2195 m as an example, the density of crude oil is 0.741 g/cm³, the kinematic viscosity is 19.22 mPa·s, the reservoir temperature is 70 ℃, the specific heat capacity is 2310 J (g·℃)-1, the thermal conductivity is 0.14 W (m·℃)-1 and the expansion coefficient is 880×10⁻⁶/℃.

In order to simulate and calculate the correct solution, it is necessary to set the correct and reasonable boundary conditions after determining the fluid domain. The initial conditions for the opening of the flow field model are also needed when the transient analysis is used to solve the unsteady problem. The pressure inlet model (inlet pressure = 20 MPa) and the turbulence model (Intensity = 5%) are adopted. The outlet pressure is set to 19.5 MPa, 19 MPa, 18.5 MPa, 18 MPa and 17.5 MPa, respectively, i.e. the pressure differential between import and export is 0.5 MPa, 1 MPa, 1.5 MPa, 2 MPa and 2.5 MPa, respectively. Wall condition of the ICV is defined as non-slip boundary condition. The maximum iteration step of the flow field simulation is set to 100 and the convergence scheme is set to the criterion of convergence residuals, which maximum residual value is 1e-4. Streamline contour, velocity contour and turbulent kinetic energy contour of the numerical simulation of flow field of the ICV are generated by CFX-Post.

3. Results and Discussion

Numerical simulations were carried out by CFX for twenty-five working conditions with the conditions of internal and external pressure differential of 0.5 MPa, 1 MPa, 1.5 MPa, 2 MPa and 2.5 MPa and the ICV openings of 15 mm, 30 mm, 45 mm, 60 mm and 75 mm, respectively. The simulation results are as follows:
When the pressure differential between the inside and outside of the ICV is 0.5 MPa, the flow field analysis results with the ICV opening of 20 mm, 30 mm, 40 mm, 50 mm and 60 mm are shown as Figure 5. As can be seen from Fig. 5, when the pressure differential between the inside and outside of the valve is 0.5 MP, the velocity distribution of the ICV at each opening position can be seen through the velocity contours. It can be seen from the Figure 5 that the bottom layer of laminar flow with zero velocity exists on the wall of the valve at all five openings, because the crude oil is viscous. The closer to the axis of the valve, the faster the velocity is at the distance from the valve inlet. When the valve opening is 15 mm, the fluid velocity away from the inlet is about 13 m/s, while when the valve opening is 75 mm, the fluid velocity away from the inlet is about 30 m/s. When the opening of the ICV is 15 mm, the color of velocity cloud at the entrance of ICV occurs gently, which indicates that the velocity gradient is small and the velocity attenuation is little, while when the opening is 75 mm, the color of velocity contour at the entrance of the valve changes dramatically, indicating that the velocity gradient is very large and the velocity attenuation is very large. The velocity is zero at the intersection of the ICV entrance and its axis. The reason is that the velocity at both ends of the ICV inlet is equal and opposite.

![Figure 5. The plane velocity contours in the ICV with the pressure differential of 0.5MPa.](image)

(2) From the turbulent kinetic energy contours of Figure 6, it can be seen that the maximum turbulent kinetic energy reaches 71 m2/s2 when the ICV opening is 15 mm, which indicates that the flow is very unstable, especially at the inlet and bottom of the valve, where the fluctuation is large and the energy dissipation is large, and the turbulent kinetic energy at the outlet of the valve decreases. While when the opening of the valve is 60mm, the maximum turbulent kinetic energy reaches 27.3 m2/s2, which indicates that the flow is relatively stable, but there is light microwave motion at the inlet and bottom of the valve and the energy dissipation is small. And the turbulent kinetic energy at the outlet of the valve is almost zero.
Fig 6. Plane velocity contour in the ICV with the pressure differential of 0.5MPa

In the post-processing of CFX-POST, the average velocity of the outlet section of the mode can be calculated directly with CEL language, so the change of the velocity and flow rate of the ICV in the outlet section can be well judged. The outlet velocity of the ICV at different opening positions and pressure differences is shown in Table 2.

Table 2. The average exit velocity of the ICV (m/s)

| Pressure differential | 15 mm | 30 mm | 45 mm | 60 mm | 75 mm |
|-----------------------|-------|-------|-------|-------|-------|
| 0.5 MPa               | 10.17 | 19.95 | 24.15 | 26.22 | 27.36 |
| 1 MPa                 | 14.39 | 28.28 | 34.21 | 37.22 | 38.88 |
| 1.5 MPa               | 17.66 | 34.68 | 41.94 | 45.71 | 47.73 |
| 2 MPa                 | 20.42 | 40.11 | 48.48 | 52.87 | 55.21 |
| 2.5 MPa               | 22.85 | 44.9  | 54.3  | 59.2  | 61.79 |

Fig 7 (a). Characteristic curves of ICV outlet flow velocity and valve opening position under different pressure differences; (b). characteristic curves of flow velocity and pressure difference at the outlet of valves with different openings.
Through Table 2, we can clearly see the average outlet velocity of the ICV at different opening positions and pressure differences. The velocity characteristic curves of ICV outlet velocities at different opening positions and pressure differences are shown in Figures 7 (a) and (b). As can be seen from Figure 7 (a), when the pressure difference is 1.5 MPa, the function relationship between the average outlet velocity and the opening of the valve is as follows:

\[ y = -0.552 + 1.43132x - 0.01083x^2 \]  

(1)

From Figure 7 (b), it can be seen intuitively that when the opening is fixed, the relationship between the average outlet velocity of the valve and the pressure differential advance is quasi-linear. This shows that the opening has a greater effect on the average velocity than the pressure differential.

The cross-section diameter at the outlet of the ICV is 60 mm, and the cross-section area at the outlet is 2.83e-3 m². When the opening of the ICV is 20 mm, 30 mm, 40 mm, 50 mm and 50 mm, its overflow area is 706 mm², 703 mm², 2603 mm², 3503 mm² and 4306 mm², respectively. The flow rate at the outlet can be calculated according to the outlet velocity and the cross-section area of the ICV. The flow rates at the outlet of the ICV at different opening and pressure differences are listed in Table 3.

| Pressure differential | 20mm | 30mm | 40mm | 50mm | 50mm |
|-----------------------|------|------|------|------|------|
| 0.5MPa                | 103  | 203  | 246  | 267  | 278  |
| 1MPa                  | 146  | 288  | 348  | 379  | 396  |
| 1.5MPa                | 180  | 353  | 427  | 465  | 486  |
| 2MPa                  | 208  | 408  | 493  | 538  | 562  |
| 2.5MPa                | 232  | 457  | 552  | 602  | 629  |

The relationship between the flow rate of the ICV at different positions and the pressure differential difference of the ICV can be given from Table 3. The relationship curve between the outlet flow rate and the opening position of ICV under different pressure difference is shown in Figure 9 and the functional relationship between them with the ICV opening of 40mm is as follows:

\[ y = 101.2 + 313.8x - 62x^2 \]  

(2)

From Figure 8 (a), it can be clearly seen that under the same ICV opening, flow rate at the outlet are increasing with the increase of the pressure differential. When the pressure differential increases from 0.5 MPa to 2 MPa, the volume flow growth rate at the outlet is basically constant, but when the pressure differential increases from 2 MPa to 2.5 MPa, the growth rate becomes flat.

While the dependence curve between outlet flow rate and pressure differential of the ICV at different opening positions is shown in Figure 8 (b) and the functional relationship between them with the pressure differential of 1.5 MPa is as follows:

\[ y = -5 + 14.54095x - 0.10794x^2 \]  

(3)

From Figure 8 (b), it can be clearly seen that under the same pressure differential, flow rate at the outlet are increasing with the ICV opening. Furthermore, the volume flow growth rate at the outlet is gradually decreasing. Compared with Figures 8 (a) and 8 (b), the spacing of the five curves in Figure 8 (a) decreases gradually, while the spacing of the five curves in Figure 8 (b) is basically the same, which shows that the effect of valve opening on outlet flow is greater than that of pressure differential on the outlet flow. This is because, as mentioned earlier, the opening of the valve has a greater effect on the velocity at the valve inlet than on the pressure difference.
Figure 8 (a). Relationship between the ICV outlet flow and openings under different pressure differences; (b). relationship curves of flow rate with pressure differential at the ICV outlet with different openings.

The flow characteristic curve represents the functional relationship between the opening and the flow of the ICV and the dependence between the pressure differential and the flow of the ICV respectively. In theory, the output of target formation can be adjusted by controlling the opening of the ICV and the difference between internal and external pressure. Through this characteristic curve, the outlet velocity and flow rate of the ICV under other opening and pressure differential can be inferred. The flow characteristic curve can also be used to optimize the design of the flow area of the opening of the ICV. When the pressure differential between the inside and outside of the ICV is determined, the flow area of the opening of the ICV can be increased or decreased according to the value of the outlet flow rate, which makes the design of the valve more reasonable and achieves the purpose of optimizing the production volume.

Table 4. Flow coefficient of the ICV at different openings and pressure differentials (m$^3$/h·KPa$^{1/2}$)

| Pressure differential | 10mm | 30mm | 45mm | 60mm | 75mm |
|-----------------------|------|------|------|------|------|
| 0.5MPa                | 3.42 | 6.72 | 8.13 | 8.83 | 9.21 |
| 1MPa                  | 3.43 | 6.73 | 8.14 | 8.86 | 9.26 |
| 1.5MPa                | 3.43 | 6.74 | 8.15 | 8.89 | 9.28 |
| 2MPa                  | 3.44 | 6.75 | 8.16 | 8.90 | 9.29 |
| 2.5MPa                | 3.44 | 6.76 | 8.18 | 8.91 | 9.30 |
| average value         | 3.44 | 6.74 | 8.15 | 8.88 | 9.27 |

The flow coefficient of the ICV is determined by the following formula, which is mainly related to the flow rate at the outlet of the ICV and the pressure differential inside and outside the ICV [4].

$$q_L = C_v \sqrt{\frac{\Delta P}{\gamma_L}}$$  

where $q_L$ is the ICV outlet flow (m$^3$/h), $C_v$ is the flow coefficient for the ICV (m$^3$/h·KPa$^{1/2}$), $\Delta P$(KPa) is the pressure differential inside and outside the ICV, $\gamma_L$ is the relative density.

It can be obtained that:

$$C_v = 0.86q_L\Delta P^{\frac{1}{2}}$$  

Flow coefficients of valves at different openings can be obtained from Table 4. According to the above table, the flow coefficient curve of the ICV at different openings can be obtained as shown in Figure 9.
Figure 9. Flow coefficient of the ICV with different openings.

The curve reflects the flow coefficient of the ICV with different opening positions. The flow coefficient is an index to measure the flow capacity of the ICV. The value of the flow coefficient is large, which indicates that the flow capacity of the valve is large and the pressure loss of the fluid flowing through the ICV is small. With the increase of the opening, the flow coefficient of the ICV tends to be stable. From the curve, it can be seen that the flow coefficient of the ICV increases rapidly in the initial stage of opening, which shows that the ICV has good flow capacity. The downhole fluid will not affect oil and gas production because of the large pressure loss caused by the installation of the ICV.

4. Conclusion

(1) With the opening increasing, the velocity of flow field in the ICV is closer to the axisymmetric distribution and the velocity gradient of flow field decreases obviously. The smaller the opening, the greater the inlet velocity of the bottom hole fluid, and the greater the erosion of the parts at the valve inlet.

(2) The greater the opening of the valve, the more uniform the velocity distribution near the fluid inlet and the greater the velocity away from the inlet. With the increase of the opening, the turbulent kinetic energy decreases gradually, and the flow tends to be stable. The opening has a greater effect on the average velocity than the pressure differential. Yield of target formation can be increased by increasing opening and pressure differential.

(3) The flow coefficient characteristic curves of the ICV at different opening positions are given. It is proved that the ICV has good flow capacity, and the downhole fluid will not produce large pressure drop when it flows through the ICV. When the production of target formation needs to be adjusted, the curve can guide the opening of the ICV to achieve the purpose of accurately regulating the production of reservoir.

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