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FLUID FIELD ANALYSIS OF HIGH PRESSURE THROTTLE VALVE AND IT'S STRUCTURE IMPROVEMENT*

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Abstract: The throttle valves used in Tarim Oil Field have many failure problems, such as valve rod fatigue fracture, valve seat washout, poor linear adjusting, and so on. The fluid field of the throttle valves was studied. The fluid fields of several throttle valves were computed with the PHOENICS CFD software. As a result, the optimum structure of a wedge throttle valve has been obtained. The wedge throttle valve has been further analyzed in details. The curve of its deferent opening and pressure drop has been presented; the fluid resistance coefficient was also calculated. The wedge throttle valve has been adopted by Tarim Oil Field, China and its life is 5~7 times that of the cone valve.

Keywords: PHOENICS CFD, throttle valve, fluid field analysis, optimal design

Introduction

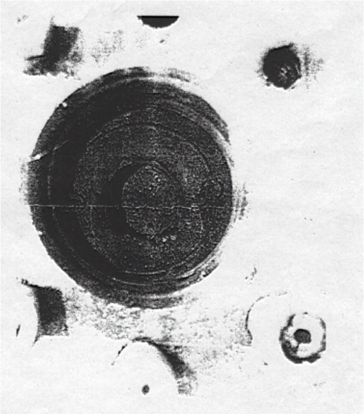
Fig.1 Valve rod fatigue fracture

The throttle valve is one of the numerous valves commonly used in the oil industry. The throttle valves perform various functions according to its application. In the kill-job (shut down well), the throttle valve serves as a flow obstacle that is set at the end of the circulation passage to improve the flow resistance of the annular space. When the fluid flows through the throttle valve, a flow resistance is produced.

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This flow resistance was carried through the bottom hole by the fluid to build up the bottom hole pressure. When the throttle valve is applied to a choke-flow manifold, its function is to control the flow rate so as to maintain the required pressure for the entire oil-gas production system. The throttle valve can also be used in the circulation of the heater by-pass pipe to reduce and control the natural gas pressure.

In Tarim Oil Field, the needle valve, namely the cone valve, was widely used. Through investigation and practice, it has been realized that many problems with the cone valve, such as the noise and valve rod vibration, are disadvantageous to oil-gas production. Even more serious problems are the valve rod fatigue fracture and the valve seat washout. Fig.1 shows the valve rod fracture accident that occurred at Dongqiu well No.8 in Tarim Oil Field in May of 2002. Fig.2 shows the valve body and the double flange spools washout in the kill-job at Wushen well No.1 in Tarim Oil Field. The early pressure-control techniques and the throttle system could no longer meet the demand in production, gathering and transporting. For example, the formation pressure in Dina 2 well, was well above 70 MPa due to the fell-off of the valve flap, the valve could not choke flow in the kill-job, this resulted in disaster accident, and the throttle system was damaged before the kill-job. At Dongqiu well No.8, after replacing three throttle valves, a kill-job was successful, this shows that the quality was poor and the arrangement was improper in the throttle kill system. Imagine that to reduce the formation pressure from nearly 70~100MPa to 1MPa through throttle system, the throttle system must be turn off less, thereby, under a big discharge, the extra high pressure and complex conditions, the failure accidents such as plugging, washout and fracture were easy to take place, even with the imported equipments.

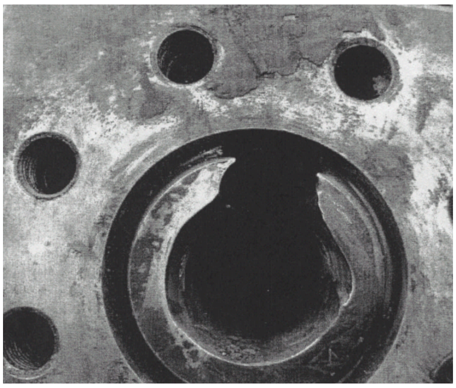


Fig.2 Valve body washout

The companies abroad like Cameron Co., EEC Co., FMC Co., WOM Co., have made a big breakthrough on perfecting related parts in throttling and kill. Mechanically, adopting key techniques, such as balancing forces, improving fluid characteristic, the plasma injecting technique and memory alloy material, these companies have resolved the problem with the low pressure seal, and improved the usage dependability of the throttling-kill system.

The theoretical analysis of throttle valves

1. The flow coefficient

The flow coefficient is an index to measure the pass capacity of the valve. The general formula for calculating the flow coefficient is given by

$$C = Q\sqrt{r / \Delta P} \qquad (1)$$

Where, C is the flow coefficient (m^2), Q is the volumetric discharge rate (m^3/s); r is the fluid density (kg/m^3); ΔP is the pressure loss of the valve (Pa).

The bigger flow coefficient value shows that, when the fluid passes the valve, the pressure loss is smaller. The flow coefficient varies with the size, the type and the structure of valves. For the same structure of the valves, the flow coefficient also varies with the different direction of the valve. The difference is generally produced by the different pressure build-up. What shown in Fig.3 is for a high pressure cone valve. When the valve is nearly closed, the flow coefficient is higher because the diffusion cone in the valve seat causes the pressure of the fluid to build up. The curve of the flow coefficient also differs with the geometry shape of the valve.

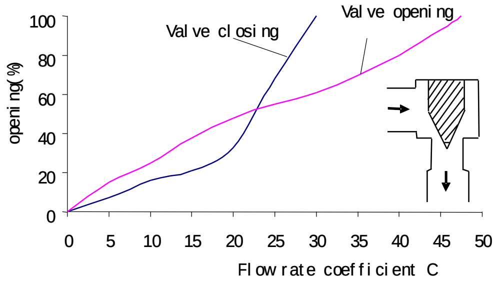


Fig.3 Relation between flow coefficient and opening of the cone valve

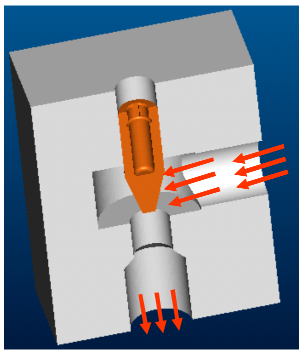


Fig.4 The structure section CAD model of the cone valve

2. The flow resistance coefficient

When the fluid passing through a bent pipe or section saltation, turbulence and stirring occur in these place, consequently, air pocket, swirl and tail flow are formed resulting in bigger energy loss. The partial pressure loss directly relates to the kinetic energy of the fluid, it is generally given by

$$\Delta P = x \cdot \frac{r{v_2}^2}{2} \qquad (2)$$

Where, ξ is the flow resistance coefficient, P_1 is the inlet pressure, P_2 is the outlet pressure, ρ is the density, v_2 is the average flow velocity at the downstream of the partial resistance.

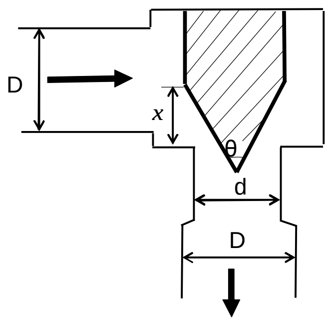


Fig.5 Geometry structure section of the cone valve

The geometry model of the cone valve

Every structure of the throttle valves that studied in this article has some complex changes, the transverse pressure gradient is big and secondary flow is strong. It is obvious three-dimensional in nature. So a three dimensional structure model must be built. In this paper, the CAD model of every valve was built with Pro/E software, and the geometry data have been saved as STL format files, and then imported into PHOENICS software for the CFD modeling. This paper firstly analyzed the flow field and structure of the cone valve. The CAD model and the structure of the middle section of the cone valve are shown in Fig.4 and Fig.5 respectively.

Analysis of the CFD results of the cone valve

As shown in Figure 5, the apical angle θ is 45^0. The diameter of the main passage at the inlet and outlet is 77.8mm and 50mm respectively. In the paper, the flow field has been analyzed with various displacement x, namely under different valve opening.

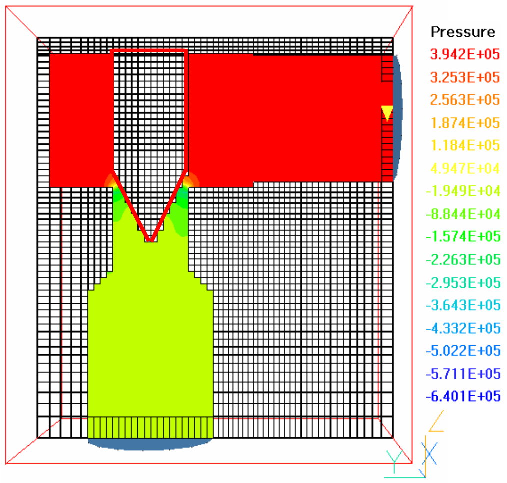


Fig.6 Pressure contours

1. Computation and solution

The PHOENICS built-in k-ε model has been employed. The no gliding condition and the wall function have been applied to solid-walls.

2. Results analysis

The computation result of the flow field for the valve opening, x at 17mm are discussed below.

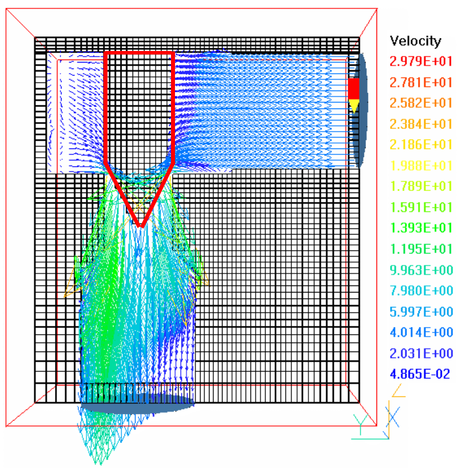


Fig.7 Velocity vectors

Fig.6 shows the pressure contours. At the inlet (upper right), the pressure is higher; the pressure lowers gradually as the fluid flows into the valve port; the pressure is minimum at the minimum flow section of the cone surface of the valve core. Further passing through the valve seat into the expand cavity of the bottom valve, the flow re-attached the cavity wall and the pressure increases. At the starting section of the cone surface of the valve core, the fluid flows downwards; because of inertia, the fluid separates from the cone surface at this region, thus, results in a pressure drop.

Fig.7 shows the velocity vectors. It can be seen, there are two types of flow in the valve cavity: one is the main flow, and the other is a partially rotating flow. At the inlet, the velocity vectors are almost parallel, and this indicates that the fluid flows steadily in this region. When the fluid flows into the valve port with a narrow passage, the magnitude and direction of the velocity also start changing. The velocities at the walls of the valve cavity are greater. Furthermore, where the wall faces the coming fluid, the velocity values are higher than those in other regions, and this has been the reason that the bottom part of the valve cavity was damaged. Flowing further down some distance from the valve port, the fluid reattaches to the wall. For clarity, the arrowheads of the velocity have been magnified in the figure.

The streamlines are shown in Fig.8. We can see that fluid particles at the middle region of the incoming pipe directly flow into the valve port and enter the bottom valve cavity. But majority of the particles bypassed the valve core to its rear or side, and then enter the valve port. This sharp change in flow direction results in a great energy loss.

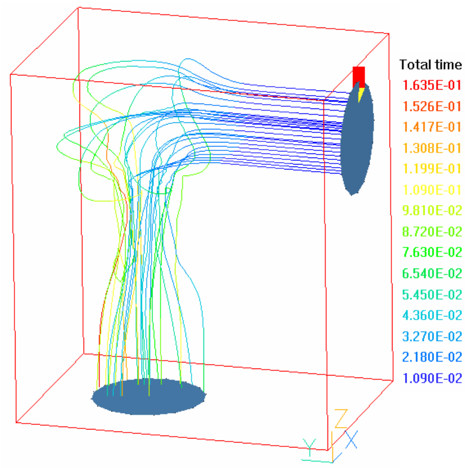


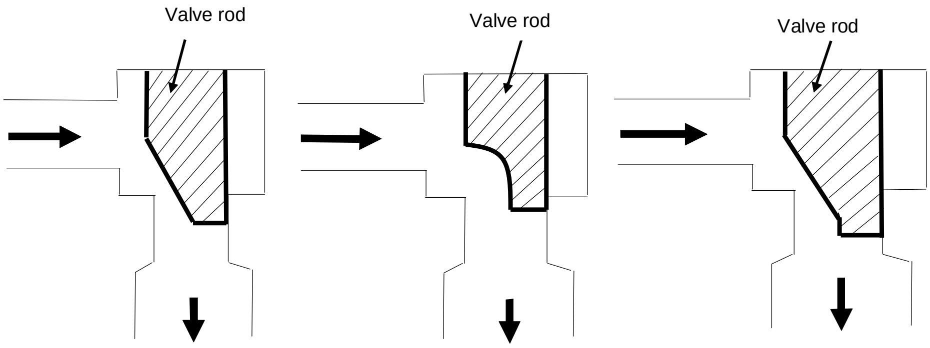
Fig.8 Streamline pattern

Generally speaking, the cavitation occurs at the interface between the highly turbulent main fluid and the relatively stagnant fluid. In the design of the cone valve, the high velocity flow region should, therefore, be avoided. It is expected that a converse angle could avoid the cavitation. In the flow field of the cone valve, the flow separation and reattachment cause a great energy loss and generate flow-induced noises. Mechanically, the reason for the cone valve fracture failure is that when a cantilever beam is under high frequency vibration, fatigue fracture is produced. It is unreasonable in its structure design. The following sections of the paper present the study of the wedge valve that has the quality of a simply supported beam.

The CFD analysis of a wedge valve

1. Geometry

The accidents, such as valve rod vibration, even fracture easily take place in the cone valve, so we begin to recommend using a wedge surface at the end section of the valve core. Based on the structure analysis of the cone valve shown in Fig.5, an improved design on three different designs of the wedge valve is presented as shown in Fig.9a, b, c. Fig.10 shows the three-dimensional CAD model of the structure shown in Fig.9b.



a. one slope surface b. an arc surface c. two slope surface

Fig.9 Schematic diagram of structure of wedge valve

In the paper we only analyzed and studied the instance that the end section of the valve core is an arc surface. Fig.10 shows its CAD structure model. Also, this model was built with Pro/E software, and the data was saved as STL format files and then inputted these files to Phoenics CFD software and analyzed the fluid field. Its meshing, boundary condition and solution control are same as the wedge valve described above.

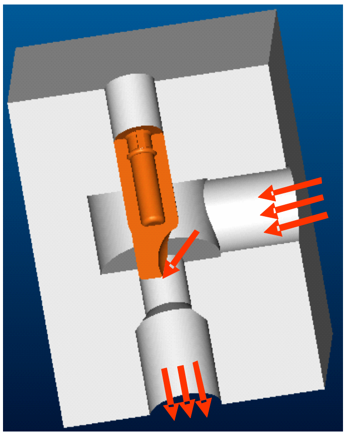


Fig.10 Structure CAD model of wedge valve

2. Result analysis

2.1 Analysis of flow resistance coefficient

Similar to the computation of the cone valve above, computation at different opening of the wedge valve was performed. Under certain discharge, the flow area, the wetted perimeter, the equivalent diameter, the pressure drop, the flow resistance coefficient at

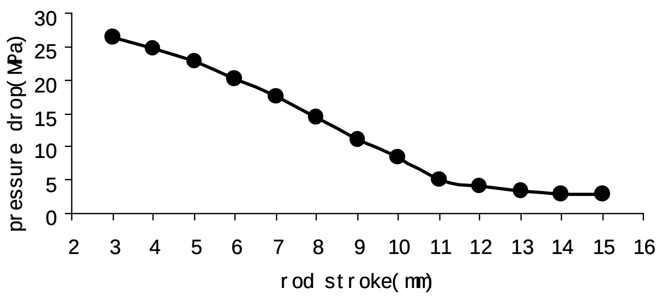


Fig.11 Relation of pressure vs. stroke

different opening were computed and the calculated results are presented in Table 1 from which the curve of the pressure drop vs stroke at different stroke under certain discharge were deduced and is shown in Fig.11.

2.2 Analysis of flow field pattern

The instance with the opening x at 12mm has been studied in this section. As seen from the velocity vector (Fig.12) and the velocity contour (Fig.13), the velocity vectors are almost parallel in the upper cavity of the valve, this shows that the flow is comparatively steady, the velocity value reaches the maximum at the valve port. But in the lower cavity of the valve, the velocity is greater at the middle of the cavity, and the velocity vectors are parallel to the inlet chamber wall, this is advantageous to reducing the erosion to the shell body near the cavity wall. The reflection of the fluid and the swirl are visible in the figure.

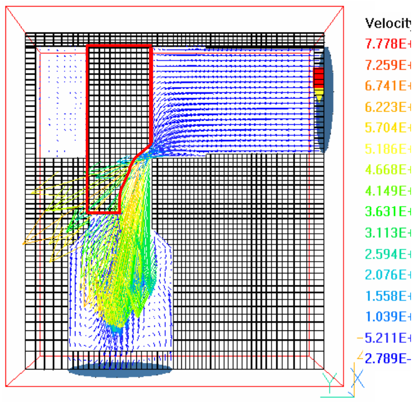


Fig.12 Velocity vector patterns

As seen from Figure 14, the streamlines enter the bottom valve cavity following the arc surface of the valve rod. This shows that the flow direction accords with the structure of the valve core, namely the structure of the valve rod has guided the flow direction. The finding from this study is instructive for the improvement on the structure of the valve rod.

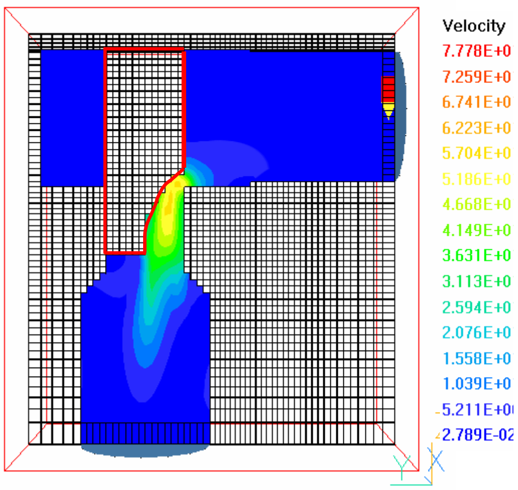


Fig.13 Velocity contour

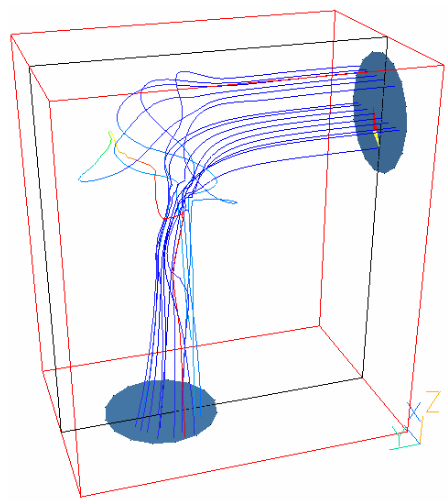


Fig.14 Streamline patterns

Table 1 Pressure drop, flow resistance coefficient of the wedge valve at different opening

Stroke of the valve core (mm)	flowing area (mm^2)	wetted perimeter (mm)	equivalent diameter (mm)	pressure drop(MPa)	flow resistance coefficient ξ
3	92.86	60.26	6.16	26.438	1592.43
4	134.19	68.01	7.89	24.674	1486.18
5	176.61	74.39	9.50	22.789	1372.64
6	219.28	79.85	10.98	20.278	1221.40
7	261.64	84.55	12.38	17.462	1051.78
8	303.35	88.68	13.68	14.347	864.16
9	344.15	92.37	14.90	11.011	663.22
10	383.89	95.68	16.05	8.300	499.93
11	422.44	98.64	17.13	5.058	304.66
12	459.74	101.35	18.14	4.096	246.71
13	495.74	103.81	19.10	3.249	195.70
14	530.44	106.07	20.00	2.919	175.82
15	563.84	108.14	20.86	2.829	170.40

Discussions of structure improvement

Through the CFD study of the fluid field of the cone valves and the wedge valves described above, the improvement of the structure are discussed. Fig.9a shows the general structure of the wedge valve, the valve rod of the wedge valve was shaped by using a slope slicing a column. The throttle valves with such a rod shape are currently widely adopted in oil field. The throttle valve has a simply supported beam, as the bottom of the valve rod clings to the valve seat, the vibration of the valve rod is reduced. The steady operation of the wedge throttle valve in the practice gains its popularity in the oil field. However, at the same time, we discovered that this kind of throttle valve is easy to produce the accident as result of the valve seat washout as shown in Fig.2. Through this study, we have discovered that among many factors contributing to the valve seat washout, there are two main factors. One is the material. The corrosion resistance of the material of the valve seat is poor, and the resistance to the corrosion of the medium such as mud is not strong. Another factor is the fluid field. As described above, the fluid particles rush to the shell body of the valve seat at a high speed and high pressure, constantly impinge the surface of the shell body, and eventually cause flaws appearing at the surface of the shell body, leading to washout.

Because of the danger of the shell body washout, the structure of the slope wedge valve core was improved, shown as in Fig.9b. This structure basically accords with the slope shape, just changing the slope to an arc surface, namely the wedge surface facing the fluid is an arc surface. The aim of using an arc surface is to guide the flow direction of the fluid, and reduce the fluid particle velocity impact on the shell body. Through plentiful fluid field analysis, we know that at some valve position, a jump in the structure pressure occurs, so further improvement to the arc surface wedge valve is required. Changing from the slope to an arc surface is to modify the flow direction, consequently to change the distribution of the fluid field in the valve cavity.

In order to get a better distribution of the fluid field, the paper presented a wedge surface that consists of two slopes, shown as in Fig.9c. From the figure, we could see that the valve core of the wedge valve consists of two slopes, and the bottom slope is parallel to the central axial line, and parallel to the surface of the shell body. It is to avoid the direct impact of the fluid on the wall. Through plentiful fluid field analysis, this structure (shown as Fig.9c) has been the optimum, the production has been applied in the oil field, its life is 5~7 times that of the cone valve.

Conclusions

1. The flow resistance is greater when the fluid flows into the region that abruptly changes its shape than the region that gradually changes its shape. In the design and installation of the throttle valve, the flow passage, that abruptly changed, should be used. With enough flow passage area, the bigger flow resistance is better.
2. The erosion to the valve parts such as valve cavity, valve core, mainly comes from the mud impacting on the valve parts at a high velocity as the mud medium directly rushes to the shell body. The tangent direction of the end section of the valve core should be parallel with the central axial line of the shell body, namely a plane, at the end section of the valve core, parallel with the central axial line of the shell body.
3. The cone valve is equivalent to a cantilever beam; this type of valve easily produces vibration and fatigue damage. The wedge valve is better in the fluid field and the structure. For the high pressure throttle valve, the wedge valve is recommended.
4. The shell body of the bottom valve cavity washout occurred in the use of the slope wedge valve.
5. Changing to an arc surface wedge valve, the erosion damage reduces, but the linear adjusting is poor.
6. After changing the wedge surface of the valve core to two slopes, the lack of the plane wedge valve and the arc surface wedge valve is make up better.
7. For the wedge valve that consists of two slopes, converse angle or circular arc should be adopted at the interface of the two slopes in order to reduce erosion to the slope that parallel with the central axial line of the shell body.

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