Research and Analysis on Cavitation of Different Structures of Cone Valve Ports in Pure Water

Xinjian Zhou\(^1\), Siyu Liu\(^2\), Yongfeng Lu\(^3\), Hongbing Zhang\(^4\), Hongbin Shao\(^5\) and Yan Tian\(^6\)

\(^1\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China
\(^2\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China
\(^3\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China
\(^4\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China
\(^5\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China
\(^6\)School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi,710000,China

\(^*\)Corresponding author’s e-mail: 20205016024@stu.xust.edu.cn

Abstract. In order to study the cavitation problem of the pure water medium hydraulic poppet valve, a three-dimensional model of the poppet control valve under a rated pressure of 31.5MPa was established with the help of Solidworks software, and the poppet valve port model was simplified into a two-dimensional symmetrical model with AutoCAD software. Based on the FLUENT software, the liquid-gas two-phase flow simulation of the cavitation phenomenon in the flow field of the poppet valve is carried out, and the cavitation distribution and intensity change rules of the three valve port structures at three opening degrees are obtained. The results show that for the pure water medium hydraulic cone valve, the cavitation distribution in the new stepped structure is significantly reduced and the strength is significantly reduced under the same opening degree.

1. Introduction

Due to the deterioration of the global environment, all industries are pursuing to be more environmentally friendly. Similarly, hydraulic systems need new and more environmentally friendly media, and pure water media that has been used in various industries in a small range have obvious advantages such as low pollution, wide sources, clean and safe, and are new in the field of hydraulic technology and fluid mechanics research direction.

However, for control valves in hydraulic systems, cavitation is an important factor affecting their service life. Because the flow velocity at the throttle is relatively high, the vaporization pressure of water is relatively high, and it is easy to generate cavitation in the water hydraulic valve. The
damaging effect of cavitation on the surface of the material is called cavitation, which is mainly caused by the pressure wave after the bubble burst has a strong impact on the surface of the part \[1\]. Due to the high density and low compressibility of water, compared with mineral oil, the impact pressure generated by water hydraulic components when the bubble bursts is greater and the destructive force is stronger. This pressure value is the largest or even exceeds 1MPa \[2\].

Scholars conducted two-dimensional visualization experiments and numerical simulations on the control valve to obtain cavitation images intuitively, and verified the simulation methods and models. Then a new control valve structure design, called a convergence model, is proposed for comparison. The original model and the convergence model with different valve lifts are simulated in three dimensions. The results show that sheet-like cavitation occurs on the surface of the sealing cone and steel ball, and then becomes cloud-like cavitation in the downstream area. The cavitation intensity increases with the increase of valve lift. The convergence model can effectively reduce the cavitation intensity near the sealed area. This research can provide a reference for the engineering optimization design of control valves \[3\].

Some people also focused on cavitation luminescence, and conducted simulations and experiments on cavitation in the conical throttle. The finite element method is used to simulate the flow field of the conical throttle valve. In the simulation, the boundary conditions of fluid-solid coupling were applied, and the cavitation model was used to obtain the pressure and cavitation distribution in the conical throttle valve. The simulation and experimental results show that the cavitation in the conical throttle valve is affected by the pressure and opening of the system. With the same valve opening setting, the cavitation phenomenon becomes more obvious as the system pressure increases. Similarly, under the same system pressure, the greater the valve opening, the more obvious the cavitation phenomenon \[4\].

Some scholars have designed a visual experiment method to capture the vibration of the cone valve core and obtain the image sequence of the vibration. The least squares contour fitting method of the valve core is proposed, and the vibration characteristics of the valve core are analyzed, which can eliminate the noise in the vibration signal and improve the accuracy \[5\].

Some scholars are solving the cavitation problems related to fluid flow performance and pitting caused by cavitation luminescence encountered by cone-shaped throttle valves. The author has studied cone-shaped nodes with various valve openings, inlet pressures and outlet back pressures. Flow field in the flow valve group. Through simulation, the flow rate and cavitation distribution of the valve under different pressure conditions are obtained. In order to confirm these results through experiments, a hydraulic cavitation platform was constructed \[6\].

For the cavitation and noise problems of hydraulic poppet valves, based on the radial force analysis of the spool, the radial deviation of the spool valve is considered to obtain the law of cavitation and noise changes \[7\].

In the poppet valve studied this time, cavitation produces two types of damage on the valve core and valve seat of the poppet valve: one is the large pit defect caused by the burst of the bubble, and the other is caused by the weak impact. Smaller pit defects accumulated.

Reasonable structural design is one of the important ways to reduce the cavitation problem in water hydraulic components \[3\]. Therefore, for many years, the two-stage throttling structure in which two throttling ports are connected in series at a throttling position is the main structural method to reduce the cavitation phenomenon of water hydraulic control valves.

2. The problem of cavitation and cavitation
Cavitation is divided into separated cavitation and boiling cavitation. Because the vaporization pressure of hydraulic oil is very low, it is difficult to produce boiling cavitation. Therefore, the cavitation of hydraulic valves is mainly manifested as separated cavitation, and its root is the dissolution in hydraulic oil. The air content is very high \[4\]. Under the same conditions, the solubility of air in water is only 20% of that of hydraulic oil, and the vaporization pressure of water is tens of millions of times higher than that of hydraulic oil. Therefore, the effect of separation cavitation in the pure water hydraulic control valve is small, which plays a leading role. It is boiling cavitation. The
difference in the nature of cavitation in the pure water hydraulic valve and the oil pressure valve determines that the cavitation in the pure water hydraulic valve is more harmful than the oil pressure valve \[5\]. When the pressure at the valve port drops to the vaporization pressure of water, boiling cavitation occurs.

Cavitation has always been a serious problem that often occurs in hydraulic valves. With the development of hydraulic systems to high speed, high pressure and miniaturization, especially the rapid development of pure water hydraulics, the problem of cavitation becomes more prominent\[6\]. Due to the high saturated vapor pressure characteristics of the water medium, the cavitation damage of pure water hydraulic components is hundreds of times stronger than that of hydraulic components. The noise of the components is large, the vibration is severe, and the performance and life are seriously affected. Compared with hydraulic components, the cavitation mechanism of pure water hydraulic components has changed, and the cavitation characteristics of the internal flow field of the components and the degree of material erosion have produced significant differences.

As people pay more and more attention to environmental protection today, the pollution of hydraulic transmission to the environment has become a bottleneck restricting the development of hydraulic technology, especially the development of hydraulic technology to high speed, high pressure and high power, and the pollution of hydraulic system is becoming more and more serious\[7\]. Therefore, it is very necessary to design low-pollution and low-cost pure water hydraulic components to promote the wide application of pure water hydraulic technology.

3. Theoretical analysis of cavitation erosion of two-stage throttle

Although multi-stage throttling can reduce cavitation, too many stages will also lead to complex structure, and it is difficult to guarantee processing accuracy and cost. Therefore, on the whole, it is better to choose a secondary throttling structure. Figure 1 is a schematic diagram of the secondary throttling.

![Figure 1. Secondary throttling schematic.](image)

In the figure,
- \(P_1\) —— Inlet pressure;
- \(P_2\) —— Pressure between the two orifices;
- \(P_3\) —— Outlet pressure.

The vaporization pressure of water is much higher than that of hydraulic oil, so cavitation is more likely to occur in the control valve of the water hydraulic system. The possibility of cavitation can be seen by the critical cavitation index \(k\). The larger the critical cavitation index, the easier it is to occur; on the contrary, the less likely it is to occur. Relatively speaking, the greater the cavitation index of the poppet valve port under a certain working condition, the less likely it is to cause cavitation.

Therefore, the cavitation indexes of the second orifice 1 and 2 are respectively

\[
k_1 = \frac{P_2 - P_v}{P_1 - P_2}
\]
In the formula, \( P_v \) —— the vaporization pressure of water. The conventional first-level throttle cavitation index is

\[
k_0 = \frac{P_3 - P_v}{P_1 - P_3}
\]

Comparing (1) and (3), because \( p_1 \geq p_3 \), so \( p_1 - p_2 \leq p_2 - p_3 \), can be obtained \( k_1 \geq k_0 \). In the same way, compare (2) and (3), because \( p_1 \geq p_2 \geq p_3 \), so \( p_2 - p_3 \leq p_1 - p_3 \), can be obtained \( k_2 \geq k_0 \). It can be seen that the cavitation indexes of the two second-level orifices are larger than those of the first-level orifice under the same working conditions, and the possibility of cavitation will be small.

4. The structure and material of the poppet valve port

4.1. Valve port structure
Now take the CF-PZ200 model, control valve as an example. On the premise of the poppet valve in the pure water hydraulic support control valve with a rated pressure of 31.5MPa, the poppet valve port structure is designed. Based on the Soildworks software, the overall structure of the control valve is designed and drawn as shown in Figure 2.

![Figure 2. The overall structure of the control valve.](image)

Because the poppet valve and the spool assembly are axisymmetric structures, only half of the two-dimensional model needs to be established. In view of the above situation, three poppet valve port structures are designed, as shown in Figure 3. The structures of (a) traditional model one and (b) common model two in Figure 3 are common structures of poppet valves in life, but in the case of pure water media, cavitation will be more serious. According to the principle of two-stage throttling, the optimization model (c) in Fig. 3 is designed on the premise of model (b). Provide a basis for subsequent two-phase flow simulation.

![Figure 3. Poppet valve port structure.](image)

4.2. Cone valve material
The poppet valve material adopts the commonly used polyoxymethylene (IUPAC name Polyoxymethylene, POM). Polyoxymethylene is a kind of engineering plastics with excellent performance, and it is called 'super-steel'. POM has the hardness, strength and rigidity similar to
metals. It has good self-lubrication, good fatigue resistance, and elasticity in a wide range of temperature and humidity. In addition, it has good chemical resistance.

POM has a very low coefficient of friction and good geometric stability, especially with high temperature resistance, so it is chosen as the material of the poppet valve.

5. Simulation and analysis of flow field in poppet valve
This hydraulic flow field simulation uses the Fluent module in Ansys software to simulate and analyze the flow field in the poppet valve. The cone valve structure with a half cone angle of 45° is selected, and the two-dimensional structure models with three different openings are established for each of the three structures. The three models of 0.6mm, 1.0mm and 1.4mm are shown in Figure 4.

![Figure 4. Poppet valve model under different opening degrees.](image)

The two-dimensional model established in AutoCAD software will be exported to the SAT format and imported into the model of Ansys of Fluid Flow (Fluent) module. After the import is successful, the boundary naming and meshing will be performed in the mesh module. Refine the grid at sharp corners and places with high flow velocity and pressure to make the calculation results more accurate. The grid model of the poppet valve flow field after dividing is shown in Figure 5. Import the divided mesh model into Set up, select double precision, set the boundary conditions, set the main phase as water and the auxiliary phase as water vapor, and perform simulation simulation under the Coupled coupling solver.

![Figure 5. Meshing of poppet valve flow field.](image)

5.1. Simulation and analysis of poppet valve port of 0.6mm
Set the inlet pressure to 31.5MPa and the outlet pressure to 1 atmosphere, and iterative calculations are performed through hybrid initialization. The displayed residual curve (shown in Figure 6) observes the convergence, the abscissa is the number of iterations, and the ordinate is the residual value.

![Figure 6. Residual convergence curve.](image)
Figure 6 shows that the simulation results have good convergence. Under the opening degree of 0.6mm, the pressure distribution cloud diagram of the flow field at the interface of the three models is shown in Figure 7.

![Figure 7. 0.6mm Pressure distribution in the flow field of the poppet valve under different structures.](image)

It can be seen from Figure 7 that under the same working conditions, the pressure distributions on the valve ports of the three models are slightly different. Comparing the pressure gradient levels at the valve ports of each model, model three has the most distribution, followed by model two and model one. The least distribution.

Continue to observe the flow field distribution in the poppet valve, and compare it with the cloud diagram of the flow field velocity change under the opening degree of 0.6mm, as shown in Figure 8.

![Figure 8. 0.6mm Velocity distribution of flow field in poppet valve under different structures.](image)

It can be seen from Figure 8 that under the same working conditions, with the gradual change of the structure, there is a large area of vortex flow phenomenon at the valve port of model 1, while the phenomenon of vortex flow in model two and model three is obviously less.

Continue to select the "vapor" item in the "Phases" option to export the volume fraction cloud map of the vapor phase and the enlarged view of the valve port position, as shown in Figure 9.

![Figure 9. Volume fraction cloud map of the vapor phase and enlarged view of the valve port position.](image)
distributed at three corners, the volume fraction of each place is not large compared to model one and two.

It can be seen from the above that, as far as the 0.6mm valve port is concerned, the secondary throttling structure does reduce the vapor phase volume fraction at the valve port a lot compared to the other two commonly used structures, that is, cavitation is reduced, and cavitation occurs. It reduces a lot.

5.2. Simulation and analysis of poppet valve port of 1.0mm

In order to prevent the emergence of special cases, the flow field simulation of the poppet valve under the opening degree of 1.0mm is continued. Similarly, set the inlet pressure to 31.5MPa and the outlet pressure to 1 atmosphere, and perform iterative calculations through hybrid initialization. Under the opening degree of 1.0mm, the pressure distribution cloud diagram of the flow field at the interface of the three models is shown in Figure 10.

It can be seen from Fig. 10 that under the same working conditions, when the opening degree is 1.0mm, the pressure of the three model structures gradually decreases at the valve port, but due to the different valve port structure. Obviously, model three with excessively long valve ports is better.
Continue to observe the flow field distribution in the poppet valve, and compare it with the cloud diagram of the flow field velocity change under the opening degree of 1.0mm, as shown in Figure 11. It can be seen from Figure 11 that under the same working conditions, when the opening degree is 1.0mm, the three models are accompanied by the generation of vortex flow, but the situation of model three is better. However, at the outlet of the valve port of Model 2, an obvious flow suddenly increased and then decreased.

Continue to derive the volume fraction cloud diagram of the vapor phase, as shown in Figure 12. It can be clearly seen from Figure 12 that, under the same working conditions, when the opening degree is 1.0mm, the cavitation of model 1 occurs in the valve body and the valve port of the poppet valve, and the vapor phase volume fraction of the valve body is the largest; model 2 cavitation occurs at the poppet valve port, and the closer to the valve port, the greater the vapor phase volume fraction; model three cavitation occurs on the upper sides of the poppet valve body, 72.04% and 60.05% compared to the first two models of the maximum vapor phase volume fraction, the maximum vapor phase volume fraction of Model 3 is only 47.19%. It can be seen that when the opening degree is 1.0mm, the secondary throttling structure can also reduce the generation of cavitation and reduce the occurrence of cavitation.

5.3. Simulation and analysis of poppet valve port of 1.4mm
Continue to simulate the inner flow field of the poppet valve with an opening degree of 1.4mm. Similarly, after setting the boundary conditions, iterative calculations are carried out through hybrid initialization. Under the opening degree of 1.4mm, the pressure distribution cloud diagram of the flow field at the interface of the three models is shown in Figure 13.
Figure 13. 1.4mm Pressure distribution in the flow field of the poppet valve under different structures.

It can be seen from Figure 13 that under the same working conditions, when the opening degree is 1.4mm, the pressure at the valve port of the three model structures gradually decreases, but due to the different valve port structures, the pressure reduction layer of the first two models exceeds near the valve port, it is better to have a two-stage throttle model with an excessively long valve port.

Continue to observe the distribution of the flow field in the poppet valve, and compare it with the cloud diagram of the flow field velocity change under the 1.4mm opening degree, as shown in Figure 14.

Figure 14. 1.4mm Velocity distribution of flow field in poppet valve under different structures.

It can be seen from Figure 14 that under the same working conditions, when the opening degree is 1.4mm, the overall flow velocity trends of the three models are the same, but the maximum flow velocity is different. The maximum flow velocity of model two is the largest, reaching 218.1m/s; the maximum velocity of model three is the smallest, only 182.2m/s.

Continue to export the volume fraction cloud diagram of the vapor phase, as shown in Figure 15.
Figure 15. 1.4mm Volume fraction of vapor phase in cone valve under different structures.

It can be clearly seen from Fig. 15 that under the same working conditions, when the opening degree is 1.4mm, the three structures have obvious large-scale cavitation. Cavitation in model 1 occurs on both sides of the poppet valve body and behind the valve body, with a maximum vapor phase volume fraction of 94.12%; in model 2, cavitation occurs on both sides of the poppet valve body, behind the valve body and around the valve port. The maximum volume fraction is 94.71%; Model 3 cavitation occurs on both sides of the poppet valve body and behind the valve body, and the maximum vapor phase volume fraction is 97.30%, but the cavitation range is significantly smaller than the former two.

6. Conclusions
1) By analyzing the pressure and velocity distribution of the flow field in the cone valve, it is found that the pressure and velocity decreasing layers of the new structure are significantly increased, and the vortex flow phenomenon is also significantly reduced.
2) Increasing the opening degree can suppress the cavitation strength of the valve port flow field, but when the opening is too large, it will also cause the occurrence of cavitation in the flow field at the outlet position.
3) From the perspective of different working conditions, the new structure of the valve port structure can reduce the occurrence of cavitation and weaken the strength of cavitation.

On the whole, there will be other suitable structures that can reduce cavitation, which requires us to use other methods to further optimize the research, and there will be more research space.

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