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Numerical simulation of plunger valve of colliding energy dissipation in the condition of low backpressure and high pressure difference

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Abstract: The plunger valve of colliding energy dissipation is one of the important parts in pipeline system. In the operation condition of low backpressure and high pressure difference, cavitation phenomenon is easy to come into being, which may result in noise and vibration and even lead to damage to valve. This article aims to decrease and even eliminate the cavitation phenomenon in plunger valve which may occur in this operation condition. Mathematical models including basic control equation, standard k-Ɛ model, equation model of fluid, cavitation model and so on, are used to calculate flow field. Then, the physical model of plunger valve of colliding energy dissipation is built and numerical simulation study on valve's inside flow is conducted in using software on the view of hydraulics. The physical model of plunger valve is built by using Pro/E,ICEM CFD and finally simulation is carried out by using Pumplinx software. Two calculations are performed in this study. One is calculation of monolayer plunger valve and another is double plunger valve in different fluid. The other calculation of double plunger valve under the condition that different structures and different fluids are carried out.

1. Introduction

The plunger valve of colliding energy dissipation is mainly used to reduce pressure and adjust the flow in pipeline system[1]. The valve used in chemical industry, hydraulic and steel plant and so on is one type of general machinery and it is essential in the pipeline system in long distance transportation[12]. Valve in flow transportation pipeline is aimed to be used to adjust resistance. Its operation principle is that the valve achieves the goal of adjusting the flow and reducing the pressure by changing the resistance coefficient of the throttle parts so as to change the effect of resistance. The plunger valve of colliding energy dissipation in the research is mainly used to achieve the goal of adjusting the flow and reducing the pressure by energy dissipation[2].

The plunger valve is generally made up of two cylinders which are different diameters. The small diameter inner cylinder called the sleeve of valve core set many vertical round hole. When the flow reaches the zone between outer cylinder and the sleeve of valve core, the flow is going to get into the sleeve of valve core through the round hole on the sleeve of valve core and then the flow flows along the direction of fluid transportation. Because of existence of the round hole of the sleeve of valve core, the speed and the direction of the flow are changed significantly[7]. When the flow gets into the sleeve of valve core through the round hole on the sleeve of valve core, there is a strong collision in which the high-speed flow and at the same time the changes of local area diminish. It results in head loss[3]. The flow continues to flow towards the direction of downstream with the effects of the reverse plunger valve. As spatial distribution of water resource in our country is unbalanced, in order to meet the water resources utilization in industry, agriculture and city, long distance water transportation projects play a vital role in solving the problem that the spatial distribution of water resources utilization is unbalanced[4]. But in order to meet the requirement of pressure and flow in long distance water transportation projects, some equipment such as energy-dissipation devices, control valve and other pipeline protective devices are widely used. The plunger valve plays an essential role in flow control of water transportation and the performance of the plunger valve is closely related to the stability of the system[5]. This paper carries on the flow field simulation and result analysis of plunger valve, which is based on the plunger valve used in some contingency water transportation system. In order to have a better idea on the inner flow feature of reserve plunger valve, CFD is used to simulate the flow field of monolayer plunger valve and double reverse plunger valve and improve its structure in the operation condition of low backpressure and high pressure difference[15]. This article also has an important reference value for design and improvement of plunger valve.

2. Mathematical models

2.1. Basic control equation

Generally basic control equation has to be obeyed in flow process. This basic control equation is summarized as the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy. The equation made up of the three important laws is used in calculating the problem of classical hydrodynamic and has to be obeyed.

2.1.1. The law of conservation of mass

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

ρ——density; t——time; x, y, z—— component of flow rate in rectangular coordinate system

2.1.2 The law of conservation of momentum

$$\begin{aligned}
\rho(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}) &= \rho f_x+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}+\frac{\partial\tau_{xz}}{\partial z}-\frac{\partial p}{\partial x}\\
\rho(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}) &= \rho f_y+\frac{\partial\tau_{yx}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{yz}}{\partial z}-\frac{\partial p}{\partial y}\\
\rho(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}) &= \rho f_z+\frac{\partial\tau_{zx}}{\partial x}+\frac{\partial\tau_{zy}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}-\frac{\partial p}{\partial z}
\end{aligned} \tag{2}$$

P——hydrostatic pressure of control volume of flow field; f_x 、 f_y and f_z ——force component of control volume

2.1.3. The law of conservation of energy

$$\frac{DE}{Dt}=\frac{D}{Dt}\iiint_V \rho(\mathrm{e}+\frac{1}{2}u\cdot u)dV=Q+W \tag{3}$$

E——energy of control volume; Q——energy from the external; V——volume of control volume; e——energy of per unit mass flow; u——speed of flow.

2.2. Eddy viscosity model

2.2.1. Standard k-Ɛ model. Standard k-Ɛ model which is summarized from lots of experiment phenomenon is reliable and precision-reasonable.

Turbulent energy dissipation rate:

$$\varepsilon=\frac{\mu}{\rho}\overline{(\frac{\partial u_i^{'}}{\partial x_k})(\frac{\partial u_i^{'}}{\partial x_k})}$$

Turbulent viscosity:

$$\mu_T=\rho C_\mu\frac{k^2}{\varepsilon}$$

k equation:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}[(\mu+\frac{\mu_T}{\sigma_k})\frac{\partial k}{\partial x_i}]+\rho P_k-\rho\varepsilon \qquad (4)$$

Ɛ equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_i}[(\mu+\frac{\mu_T}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_i}]+\frac{\rho\varepsilon}{k}(C_{\varepsilon1}\ f_1 P-C_{\varepsilon2}\ f_2\varepsilon) \qquad (5)$$

Parameter values of model:: $C_\mu=0.09$, $C_{\varepsilon1}=1.44$, $C_{\varepsilon2}=1.92$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$。

2.2.2. Equation model in fluid of low Reynolds number

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+\rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}^{*}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (6)$$

2.3. Cavitation model

Lots of studies show that there is better compatibility between turbulence model of standard k-Ɛ model and cavitation model. Beyond that, the accuracy of the result is relatively high and the calculation results are more satisfied. Schnerr-Sauer model is used in this paper:

$$R_e=\frac{\rho_l\rho_v}{\rho}\alpha_v(1-\alpha_v)\frac{3}{r}\sqrt{\frac{2(P_v-P)}{3\rho_l}}\quad P\le P_v$$

$$R_c=\frac{\rho_l\rho_v}{\rho}\alpha_v(1-\alpha_v)\frac{3}{r}\sqrt{\frac{2(P-P_v)}{3\rho_l}}\quad P>P_v$$

$$r=(3\alpha_v/(4\pi n_0(1-\alpha_v)))^{1/3} \qquad (7)$$

$\rho=\alpha_v\rho_v+(1-\alpha_v)\rho_l$ ——mixture density

2.4 Theoretical model of valve's flow adjustment

2.4.1 The equation of conservation of mass. As for incompressible fluid in the condition of a steady flow, the equation of conservation of mass on the pressure pipe is:

$$\rho_1=\rho_2;v_1A_1=v_2A_2=Q=constant \qquad (8)$$

A——cross sectional area of water transportation pipe; v——mean flow rate in pipe;
ρ ——density of flow; Q——volume flow through cross section area within unit time.

2.4.2. Equation of flow.

Flow equation of valve:

$$Q=Av=\frac{A}{\sqrt{\xi}}\sqrt{\frac{2}{\rho}(p_1-p_2)} \qquad (9)$$

A——area of passage,cm^2; p_1——upstream pressure of valve,100kPa;
p_2——downstream pressure of valve,100kPa; ρ——density of flow, g/cm^3.

2.4.3. Working flow model. In the practical work, pressure difference of the valve is going to be changed with the change of water transportation condition, so the ideal flow model curve is changed. Flow model of valve in the practical working is called working flow model.

Working flow model:

$$\frac{q}{Q}=F(\frac{l}{L})$$

The relation between ideal flow model and working flow model:

$$F(\frac{l}{L})=f(\frac{l}{L})\sqrt{\frac{1}{(1-\Delta P_R)f^2(\frac{l}{L})+\Delta P_R}} \quad (10)$$

3. Three-dimensional modeling and numerical simulation

If monolayer plunger valve wants to reach the high pressure difference to throttle effectively and strengthen the effect of energy reduction, it has to decrease the area of passage of valve. Based on relative data and project experience, we have built kinds of monolayer plunger valves to test whether the flow meet the constraint. In this paper, the sleeve diameter of monolayer plunger valve core is 1600mm.The diameter of the outer sleeve of double plunger valve is 1600mm and the diameter of the inner sleeve of double plunger valve is 1000mm.Finally it turns out that fifty round holes with the diameter of 90mm are set up as the area passage of the monolayer plunger valve, the round holes are divided into five rows and there are ten holes per row. The structure of monolayer plunger valve is showed in the figure 1. To reach the same effect of energy reducing as the monolayer plunger valve, many kinds of design structures of double plunger valve are compared. Finally, two kinds of the stricture of double plunger valve are determined. Structure one is showed in the figure 2:at the outer valve core, there are sixty round holes with diameter of 90mm which are set as five rows averagely. On the inner of valve core, there are eighty round holes with 90mm which are set up as five rows averagely. The structure two is showed in the figured 3:at the outer valve core, there are sixty round holes with a diameter of 85mm which are set as five rows averagely. at the inner valve core, there are ninety round holes with 90mm which are set up as five row averagely. Three kinds structure of valve are showed:

Figure 1.

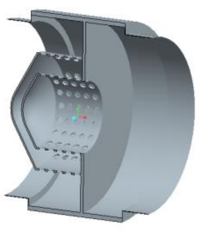

Figure 2.

Figure 3.

After designing the plunger valve which reaches the requirement, Pro/E software are used to constitute a digital watershed model. And then ICEM CFD software is used to mesh and the quality of mesh must meet the requirements. At last, the. mesh file is introduced into Fluent software to examine whether the size of model meets the requirements. After that, turbulence model is set as standard k-Ɛ model and other settings are set as default. The setting fluid medium is set as water and property is set as default. The entrance and the exit of the valve are set as pressure boundary. The water of entrance is set as 100m and the water is set as 5m. The method of steady calculation is set as default and after

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steady calculation the cavitation model is added. Firstly, multiphase flow model is set; and then the first phase is set as liquid water and the second phase is set as gaseous water. The cavitation model setting is set as Schnerr-Sauer model in the condition of transformation from first phase to second phase and other settings are set as default.

4. Flow field analysis

4.1. Flow field analysis of monolayer plunger valve and double plunger valve

The condition is chosen that back pressure is the head 5m and the pr 4. Flow field analysis ensure difference is the head 95m.The result from Fluent is introduced into CFD-Post to be processed.

4.1.1. The results are shown as follows:

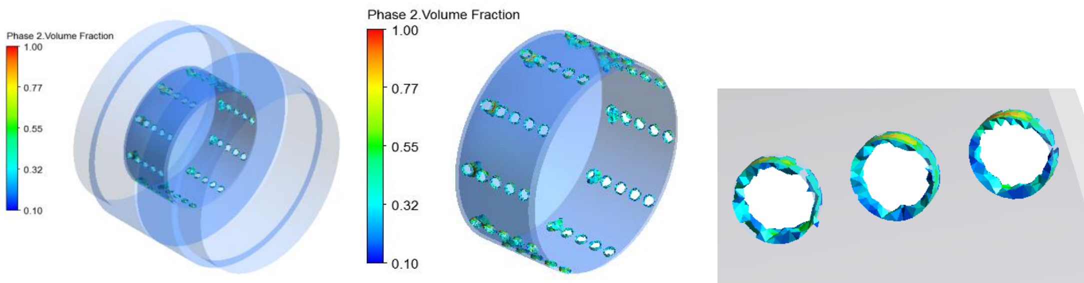
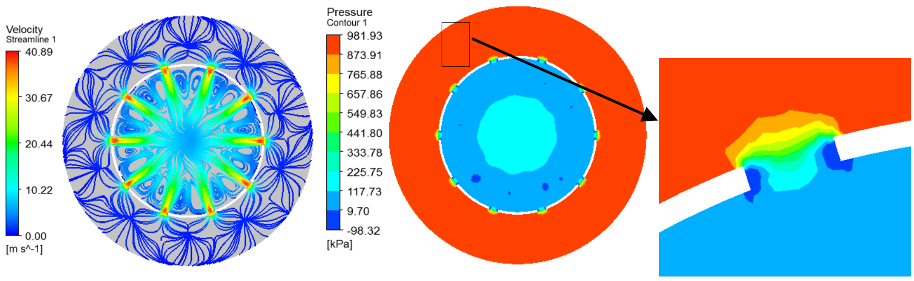


Figure 4. Volume distribution map of gas phase of monolayer plunger valve



（a） Stream pattern （b） Pressure profile

Figure 5. Stream pattern and pressure profile of the last row's section

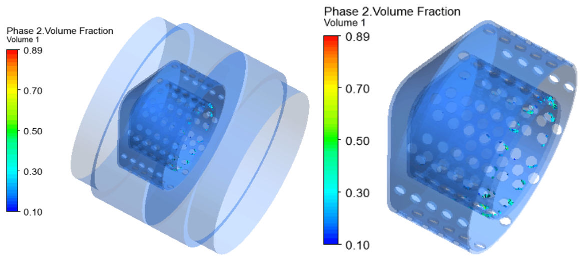


Figure 6. Volume distribution map of gas phase of double plunger valve

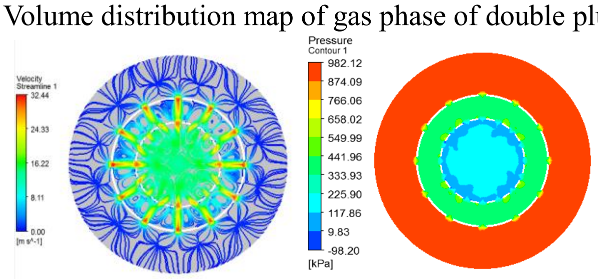


Figure 7. Stream pattern and pressure profile of the last row's section

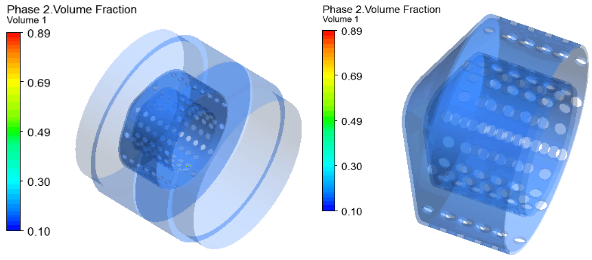


Figure 8. Volume distribution map of gas phase of double plunger valve

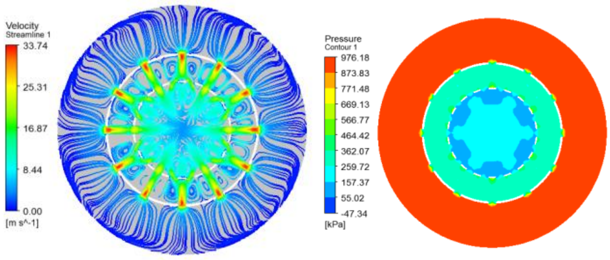


Figure 9. Stream pattern and pressure profile of the last row's section

Based on above the results of numerical simulation, table 1 is made:

Table 1.

	Flow（m^3/s）	Cavitation	Area of cavitation
Monolayer	9.6	yes	All round holes
Structure one	9.3	slightly	The round holes in the inner last row
Structure two	9.3	no	-

This section compares this flow field of the monolayer and double valve and solves the cavitation phenomenon of monolayer plunger valve in the condition of low pressure and high pressure difference with the structural improvement. It can be seen from table1 that the flow of the three structures is basically the same, that is, the conditions of the three kinds of valves are basically the same. From the change of cavitation phenomenon of the three kinds of valves, it is obtained that the capacity of anti-cavitation of valve of structural improvement is strengthened, which can be applied to the condition of low back pressure and high pressure difference.

4.2. Flow field analysis of different structures of double plunger valve

In the condition of the same area of passage, the same number of round holes and the same size of round holes, this section chooses different structures of double plunger valve to compare the effect of energy elimination.

The kinds of double plunger valve are shown in the Table 2:

Table 2.

	diameter of inner layer	diameter of outer layer
structure one	1600	2000
structure two	1600	2200
structure three	1200	1600
structure four	600	1000

The results of Flow field analysis are shown as follows:
Structure one:

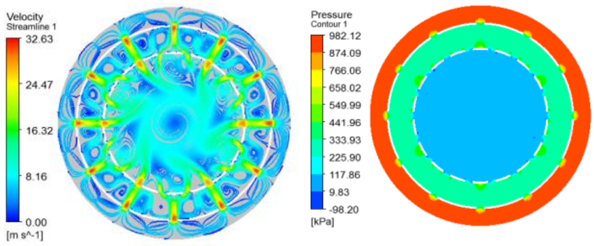


Figure 10. Stream pattern and pressure profile of the second row's section
Structure two:

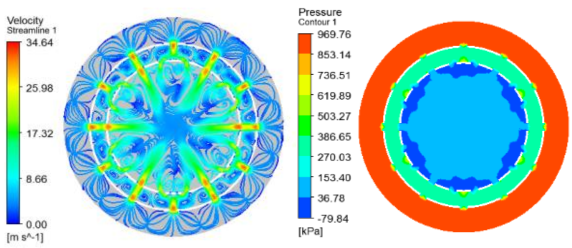


Figure 11. Stream pattern and pressure profile of the second row's section
Structure three:

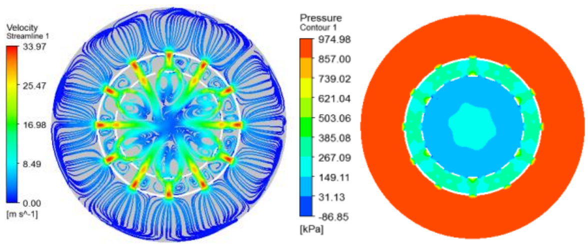


Figure 12. Stream pattern and pressure profile of the second row's section
Structure four:

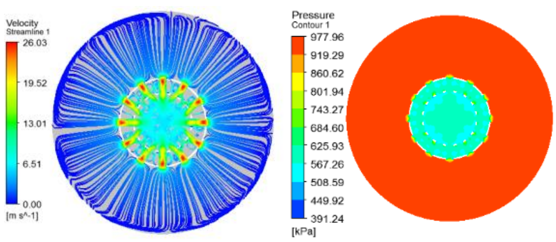


Figure 13. Stream pattern and pressure profile of the second row's section

From the above results of flow field analysis, it is shown that the effect of energy elimination has few changes when the distance between outer valve core and inner valve core is changed and the diameter of inner valve core is not changed. When the diameter of outer valve core does not change and the diameter of inner valve core does not change a lot, the effect of energy elimination has changed a little. But when the diameter of both outer valve core and inner valve core is decreased, the hedging effect of the inner flow is strengthened and then the effect of energy dissipation is strengthened.

5. Conclusion

This paper mainly analyzes the difference of flow simulation calculation of monolayer plunger valve and double plunger valve in the condition of low back and high pressure difference. On the condition of the same pressure boundary conditions at both ends and other settings, the flow of monolayer plunger valve is $9.6m^3/s$ and the flow of double plunger valve is $9.3m^3/s$, which shows that the efficiency of the two valves have the same effect and conditions are basically identical. It is found from visual analysis that in this condition there is cavitation phenomenon coming into being around the round holes of valve core, which is not suitable for this kind of condition. Compared with the monolayer plunger valve, the structure 1 double plunger valve can achieve the effect of eliminating energy and reducing pressure in the condition, but there is a slight cavitation in the valve. The improved structure 2 double plunger valve reaches the effect of eliminating energy and reducing pressure in the condition and there is no cavitation in the valve. Therefore, it can be concluded that in the condition of low back pressure and high difference pressure, the structure of improved double plunger valve is superior to the single plunger valve.

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