Dynamic response analysis of pilot control globe valve focusing on opening and closing time of pilot valve

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Abstract. Pilot control globe valve (PCGV) can use the pressure difference produced by fluid itself to realize the opening and closing states with a pilot valve. In this paper, numerical method is used to investigate the fluid flow characteristics and the valve core movement inside PCGV under different opening and closing times of pilot valve. The result shows that, shorter opening and closing time of valve core results in the shorter vibration of valve core as well as the stronger unstable fluid in main valve and faster opening and closing process of PCGV. Longer opening and closing time of valve core can do less damage to valve body. This work can give some guides for the optimal design work of PCGV and someone who are researching on valves with similar structures.

1. Introduction

As time goes on, a lot of global valves have been used in process equipment and global valve uses a large amount of energy. Because of their high energy consumption, develop a new type of globe valve with less energy consumption is very important. Pilot control globe valve (PCGV) can use the pressure difference produced by fluid itself to realize the opening and closing states with a pilot valve. Since the driving energy of the pilot valve is much less than driving the main valve directly, PCGV can reduce the energy consumption obviously. Thus, PCGV has broad application prospect. Quick response of PCGV can improve the accuracy of valve controlling as well as the flow rate through the main valve. Therefore, it is important to study how to achieve fast response of PCGV in order to improve the industrial intelligences.

Nowadays, many researchers have done a lot of useful work to investigate the characteristics of fluid flow in different valves. Aung *et al.* [1] used CFD to analyze the flow forces and energy loss characteristics in five different flapper–nozzle pilot valve structures with three different null clearances and built verification by experiment. Beune *et al.* [2] analyzed the opening characteristic of high-pressure safety valves by CFD, and the result showed that a large force rise and collapse is caused by a redirection of the bulk flow. E. Lisowski *et al.* [3] designed a body of new directional control valve with four logic type directional valve, which can reduce the pressure losses over 35%. Meanwhile, Lisowski E *et al.* [4] also used CFD to calculate the forces associated with the flow on the spool of solenoid operated directional control valve, and the result were used to design a new valve body, which increased flow range by 45% without having to change springs and solenoids for stronger ones. Chern *et al.* [5] put up forward an approach to design double cages in a globe valve for flow control based on the CFD, and this approach can effectively provide the required control of the flow coefficients for the globe valve. Xie *et al.* [6] presented a design of pilot-assisted load control valve with load velocity control ability and fast opening feature based on static and dynamic modeling. Jin *et al.* [7-8] proposed a new kind of pressure reducing valve with an orifice plate, and explained the mechanisms of pressure reduction and energy conversion in the new valve. Wei *et al.* [9] and Qian *et al.* [10-11] studied the characteristics of flow-induced noise in high pressure reducing valve and provided guidance for noise control with thick perforated plate. Edvardsen *et al.* [12] studied single-phase pressure drop in a downhole shut-in by experiment and numerical analysis, and developed a 1D numerical model suitable for both compressible and incompressible flow.

Dynamical characteristic of fluid caused by interaction between fluid and valve core make the flow in valve more complex. Many researcher focused on dynamical characteristic of fluid in valve . Saha *et al.* [13] used CFD to investigate the flow process inside a pressure regulating and shut-off valve, and developed a special function to calculate force field on the spool and hence predict the dynamic spool position. Hős *et al.* [14] derived a model of an in-service direct-spring pressure relief valve and explained the reason of instability and sudden jumps. Zhang *et al.* and Lu *et al.* [15-16] analyzed open and close characteristic of pilot control cut-off valve using UDFs program and pointed out the main regions that causes a large quantity of resistance lose, which provided theoretical basis for optimal design of the valve. Qian *et al.* [17-20] used CFD to analyze the dynamical flow characteristic and cavitation of in pilot control global valve and summarized the relationship of static inlet pressure and the valve core's displacement, and found that vapor volume fraction reaches its peak point at the valve seat near the outlet tube.

Quick response of PCGV can improve the accuracy of valve controlling as well as the flow rate through the main valve. The stead work of PCGV can extend the life and avoid causing the damage to the whole system. However, there is no research about the dynamic character of PCGV focusing on opening and closing time of pilot valve. Therefore, it is important to study how to achieve quick response and steady work of PCGV in order to improve the industrial intelligences. In this paper, for further research of PCGV, we choose the specific movement of valve core to analyze the typical fluid field. Meanwhile, we also study the effect of pilot valve's opening and closing time on the dynamical characteristic of main valve by observing the valve core movement under different opening and closing times of pilot valve.

2. Numerical model

Establishing a mathematical model and analyzing the force condition of the valve core are needed to simulate the opening and closing process of the PCGV. Grids of model are generated or destroyed with the movement of valve core through the User-Defined-Functions (UDFs) program.

2.1. Working principle

As is shown in Fig. 1, PCGV can use pilot valve to control the open and close state of main valve.

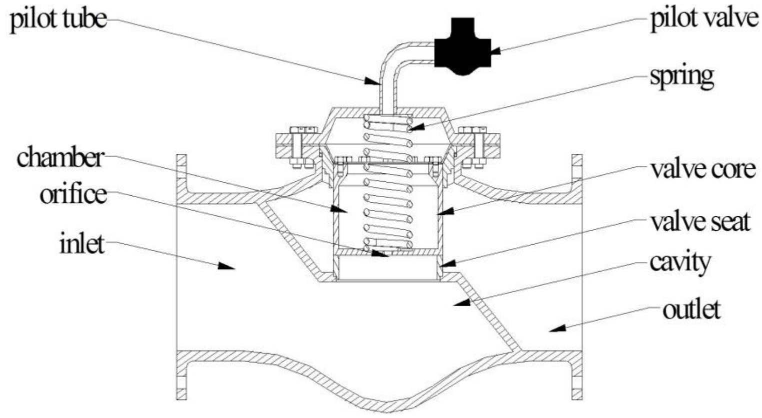


Fig. 1 Pilot control global valve

When the pilot valve is open, the orifice (on valve core) and the pilot tube form an access which let fluid flow through. The change of local fluid shape caused by the fluid through the orifice leads to a pressure difference between upper chamber and cavity of the valve core. As a result, the valve core is pushed up. When the valve core moves upward, the fluid flows to the outlet directly. At the same time, the spring force increases. Finally, the valve core reaches its maximum displacement and stop moving. The PCGV is open.When the pilot valve is closed, the fluid cannot flow through pilot tube, so the former equilibrium will be broken. Meanwhile, the pressure difference decreases and the valve core moves downward because of its gravity and the force of the spring. Finally, the valve core stops until it touch the valve seat. The PCGV is close.

2.2. Mathematical model

In the process of building mathematical model, we make the following assumptions: the gravity of fluid is ignored; the friction between valve core and valve body is constant with upward as the positive direction; there is no leakage between the valve core and the valve seat. So the force of valve core can be described as:

$$F = \int p_1 S_1 - \int p_2 S_2 - k(y + y_0) - mg + F_f \tag{1}$$

In Eq. (1), F refers to the force of valve core, N; p_1 refers to the pressure on the bottle face of valve core, Pa; S_1 refers to the area of the bottle face of valve core, m^2; p_2 refers to the pressure on the upper face of valve core, Pa; S_2 refers to the area of the upper face of valve core, m^2; k refers to spring stiffness, N/m; y refers to displacement of valve core, m; y_0 refers to the internal compression of spring, m; m refers to mass of valve core, kg; g refers to gravity acceleration, m/s^2; F_f refers to the friction between valve core and valve body, N.

As the movement of valve core is determined by the pressure difference, spring force and gravity of valve core, y_0 remains the same during the movement of the valve core, so the friction between valve core and valve body can be ignored and Eq. (1) can be simplified to:

$$F = \int p_1 S_1 - \int p_2 S_2 - ky - C_0 \tag{2}$$

$$C_0 = ky_0 + mg \tag{3}$$

Therefore, the acceleration equation of valve core can be described as:

$$a = \int (p_1 S_1 - \int p_2 S_2 - ky - C_0) / m \tag{4}$$

We can get the speed equation of valve core as follows:

$$v = \int_0^t a dt \tag{5}$$

The displacement of valve core at opening or closing process can be expressed as Eq. (6) ~ (7):

$$y = \int_0^t v dt \tag{6}$$

$$y = y_{\max} - \int_{t_1}^t v dt \tag{7}$$

Where, y_{max} refers to the max and t_1 refers to the time for beginning of closing process of pilot valve.

2.3. Grid and bounding condition

Fig. 2 shows the grid of DN100 PCGV with the valve core displacement 25 mm, and the diameter of orifice is 4 mm. The length of pipe is 100 mm before the main valve and 200 mm after the main valve to enhance the accuracy of simulation. The upper chamber and pipes including pilot pipe are meshed with structured grids, and rest parts are meshed with non-structured mesh because of their complex structure.

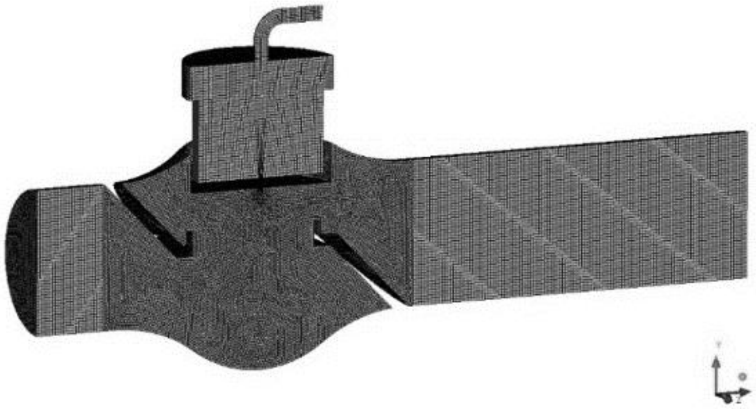


Fig. 2 Grid of PCGV with opening of 15mm

The grid independence check is carried out under the condition that valve core displacement is 15mm. Pressure difference is taken as the judgment parameter, and gridding size ranges from 2 mm to 10 mm. The relative errors of the simulation keep within 2% when the gridding size is smaller than 6 mm. Therefor, 6 mm is gridding size.

The inlet condition of the model is specified as pressure inlet, and the outlet of pilot tube is specified as pressure outlet or wall according to the opening or closing process of PCGV; we choose incompressible liquid water as the liquid phase; the wall function method is adopted in the near wall region by using the finite volume method and first-order upwind scheme; coupling pressure and velocity of liquid are based on SIMPLE.

3. Results and discussion

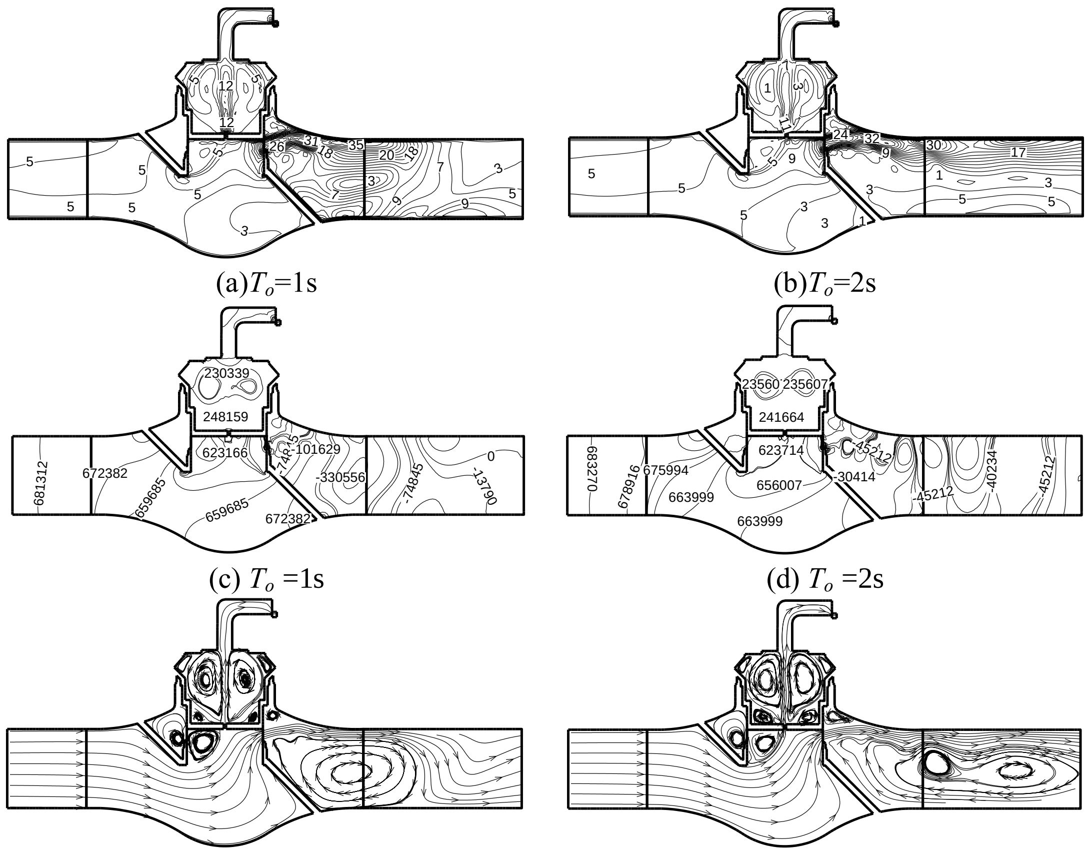
In this part, the effect of opening time of pilot valve on opening process is firstly introduced and the specific flow field under 15mm valve core displacement is presented. Then, the effect of closing time of pilot valve on closing process is also introduced with the specific flow field and the dynamic movement of valve. Furthermore, the dynamic response of pilot control globe valve is summarized.

3.1. Effect of opening time on opening process

To analyze the effect of pilot valve's opening time on opening process of PCGV, we set 1s and 2s with the same spring stiffness K=7700N/m, the inlet pressure is 0.7MPa and the out let pressure is 0MPa.

3.1.1. Flow field analysis. As is shown in Fig. 3, we set the displacement of valve core in main valve is 15mm as an example to analysis the effect of on the flow field in main valve.

It can be easily seen from Fig. 3 that the flow field in main valve at different T_o is similar: the turbulence is formed after the throttle of main valve and in the chamber; the jet is formed after fluid flowing through valve core and valve seat. But there are still some differences. When T_o =2s, the speed of jet is smaller and the strength and thickness of jet is smaller as well; the change of pressure difference is smaller; the turbulence intensity after the throttle of main valve and in chamber is weaker. The reason is that the longer T_o means the slower opening process of pilot valve and it makes the fluid in main valve has enough time to develop, therefore, the pressure in chamber becomes higher and the strength of jet through orifice gets weaker. The pressure difference which is the main motive power of valve core is smaller and the speed of valve core is slower as well. At the same time, the weaker jet and turbulence can also make smaller damage to the chamber. We can draw the conclusion that longer To makes the more stable fluid in main valve and is good to length the life of PCGV.



(a)T_o=1s (b)T_o=2s

(c) T_o =1s (d) T_o =2s

(e) T_o =1s (f) T_o =2s

Fig. 3 Comparison of flow-field at different opening time of pilot valve

3.1.2. Movements of valve core. Fig. 4 shows the movements of valve core with the opening process of pilot valve at different T_o, the process of the movement is similar, and the process can be divided into 3 parts: the upward movement; the vibration; the final static. The opening time of PCGV is almost equal to the half of opening time of pilot valve. But there are still some difference, the longer results in the slower movement of valve core; the smaller acceleration in the upward movement of valve core in main valve; the smaller speed of valve core when reaches the top position. In addition, the smaller speed of valve core makes the less damage to the valve body and the smaller noise. So we can draw the conclusion that the shorter short the time of opening process and does more damage to the main valve.

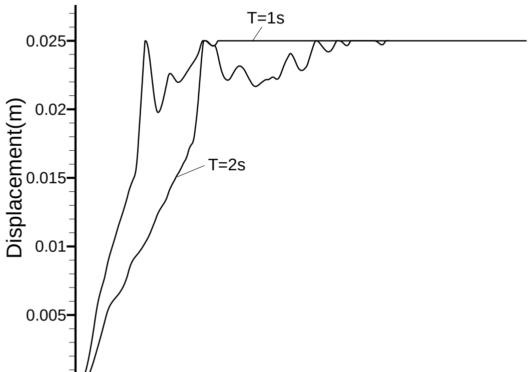
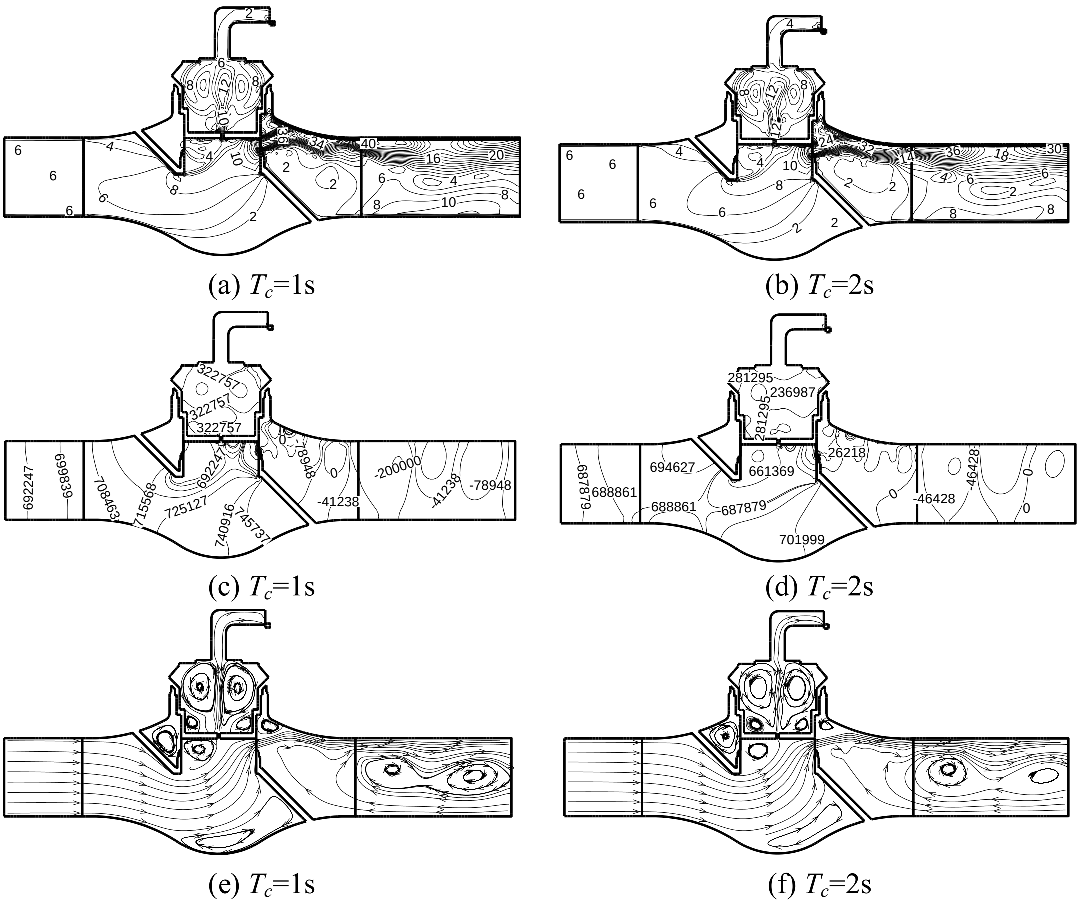


Fig. 4 Displacement of valve core during the opening process at different opening time of pilot valve

3.2. Effect of opening time on closing process

To find the effect of closing of time pilot valve on closing process of PCGV, is set as 0.5s, 1s and 2s with the same spring stiffness K=7700N/m, the inlet pressure is 0.7MPa and the outlet pressure is 0MPa. To make sure the fluid has been fully developed, the fluid has flow for 3s before pilot valve starts cutting off.

3.2.1. Flow field analysis. The valve core displacement of 15mm is selected as an example to analysis the effect of the flow field in main valve. The result is shown in Fig.5. By comparing the flow field in main valve at different closing time of pilot valve in Fig.5, it can be easily seen that the basic distribution of speed field, pressure field and streamlines figure is similar, the turbulence is formed after the throttle of main valve and in the chamber; the jet is formed after fluid flowing through valve core and valve seat. But there are still some differences. When T_c is longer, the speed of jet is faster and the change of jet direction is fewer; the turbulence intensity after the main valve get more stable; the turbulence formed at chamber is also smoother. Longer T_c gives fluid in chamber enough time to develop; the pressure in chamber and the strength of jet through orifice gets weaker; the pressure difference increases and this make the resistance of valve core's downward moving get greater. Thus, longer makes the more stable fluid in main valve.



(a) T_c=1s (b) T_c=2s

(c) T_c=1s (d) T_c=2s

(e) T_c=1s (f) T_c=2s

Fig. 5 Comparison of flow-field at different opening time of pilot valve

3.2.2. Movements of valve core. Here, we set the closing time as 0.5s, 1s and 2s, and the movements of valve core in main valve are recorded in Fig. 6 to study the effect of on movements of valve core. From Fig. 6 we can see that T_c doesn't affect the final position of valve core, it only affects the closing time of main valve. The closing time of PCGV is almost equal to that of pilot valve. The closing process can be divided into 4 parts: the start static, the vibration, the downward movement and the final static. There are still some differences among them. Longer T_c leads to the longer start static and longer vibration with the slower speed of downward movement and the smaller crash of valve core. At the beginning of closing process, the pressure difference is large enough to make the valve core remain the start position. With pilot valve gets closing, the pressure difference gets smaller; the valve core starts to moves down and this phenomenon results in the expanding of pressure difference; the valve core starts to vibrate, and the vibration of valve core is connected with the closing process of pilot valve. When the closing process of pilot valve is large enough, the vibration of valve core stops and it starts to move downward directly until it reaches to the valve seat. We can draw the conclusion that longer T_c makes the closing process longer; longer T_c needs more time to start advanced controlling; longer T_c will makes less damage to the valve seat.

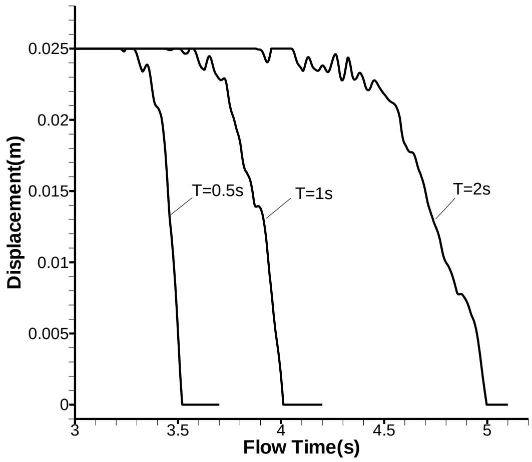


Fig. 6 Displacement of valve core during the closing process at different closing time of pilot valve

4. Conclusion

PCGV can use the pressure difference produced by fluid flow inside the valve to realize the opening and closing states of the main valve with a pilot valve. In this paper, numerical method is applied to investigate the fluid flow characteristics and the valve core movement inside PCGV under different opening and closing times of pilot valve. The results show that the opening and closing characteristics of PCGV are connected with opening and closing time of pilot valve. The opening time of PCGV is almost equal to half of the opening time of pilot valve. The closing time of PCGV is almost equal to it of pilot valve. The shorter opening and closing time of pilot valve can short it of PCGV, but it will cause the larger crush between valve core and valve seat or valve body which will shortens the life of PCGV and makes bigger noise. The longer opening and closing time of pilot valve will enlarge the time of valve core's vibration and this phenomenon may cause the greater vibration of whole system. The longer opening and closing time of pilot valve can make smaller turbulence in chamber and more stable fluid in main valve. It is very needed to make a trade-off when in application. These conclusions can give guide to the further design of PCGV and someone who are researching on valves with similar structures.

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