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Theoretical research on steady-state and closing value characteristics of liquid level control value

During the refuelling process, the float switch closes when the internal tank liquid level reaches the highest level, but the automatic control valve cannot be closed simultaneously. If the delay time is too long, it may lead to an oil spill accident. In this paper, we analyzed the structure and basic working principle of the liquid level control. In addition, the flow of the automatic control valve, the force condition of the value core, the time required for closing the value, the speed and accelerated velocity of value core movement were theoretically studied according to the fluid momentum theorem and the kinematic equation of the valve closing process, which is of great practical significance for advancing research level of liquid level control valve.

Keywords: *Theoretical research, steady-state, closing value characteristics, liquid level control value.*

1. Introdunction

The liquid level control valve includes an automatic control valve and a float switch, which is a mechanical, high safety, self-contained control device that does not rely on any external power and does not require any manual intervention. What is more, it is entirely dependent on the oil pressure. During the operation of the liquid level control valve, the force condition of the value core directly affects the stability of the valve works. Therefore, it also becomes the important factors in the design of the spring components of the liquid level control valve. During the refuelling process, the float switch closes when the internal tank liquid level reaches the highest level, but the automatic control valve cannot be closed at the same time. If the delay time is too long, there may be an oil spill accident. Therefore, it is necessary to research the force condition and closing characteristics of the automatic control valve, so as to provide scientific basis for the optimization design of the liquid level control valve.

Some scholars have made a meaningful study of this aspect. Eatwell, W. D illustrated the installation of a liquid level control subsurface valve provides a cost-effective means of controlling and protecting well formations (Eatwell, 1988). Khoei, A aimed at presenting a controller for minimizing the movement of the motor valve, at the same time, setting the level of the tank at defined points (Khoei, et al., 2005). Wang, Zhan Yong introduced the working principle, function and characteristic of the oil control valve test system (Wang, et al., 2008). Cao, Fang set up a fluid-structure interaction system model of control valve and analyzed the influences of fluid-structure interaction on fluid velocity and eddy formation (Cao, et al., 2011). Zhang, Zhongzhen emphatically analyzed the causes for the failure of level control valve in absorber to the ammonia purification unit and improved the valve internal structure aiming at the failure causes (Zhang, et al., 2011). Buchtel, Michael E introduced the fluid level control toggle valve device and method (Buchtel, 2012). Since the electronic solution for liquid level control can control the liquid level stable and make sure the plant works in a stable mode with high energy efficiency. Liu, Changfeng introduced a new liquid level sensor with TDR technology and a robust motor valve which will work together to make the refrigeration system running in a safe and energy-saving way with easier service (Liu, 2013). In order to achieve structure improvements of level control valve of water storage tank, Wang, Yaping completed the simulation analysis of internal flow field by the method of numerical simulation that make level control valve of water storage tank better to meet the work requirements (Wang, et al., 2014).

However, little research have been done in respect of steady-state and closing value characteristics of liquid level control value during the usage of oil tank. Thus, these previous results are not so satisfied. In this paper, we theoretically research the flow of the automatic control valve, the force condition of the value core, the time required for closing the value, the speed and accelerated velocity of value core

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movement according to the fluid momentum theorem and the kinematic equation of the valve closing process. It is of great practical significance for advancing research level of liquid level control valve.

Following the introduction, the rest of this paper is organized as follows. Section 2 presents structure and working principle of liquid level control value. Section 3 analysis steady-state analysis on the core of liquid level control value. Section 4 researches the closing value characteristics of liquid level control value. Section 5 concludes the paper.

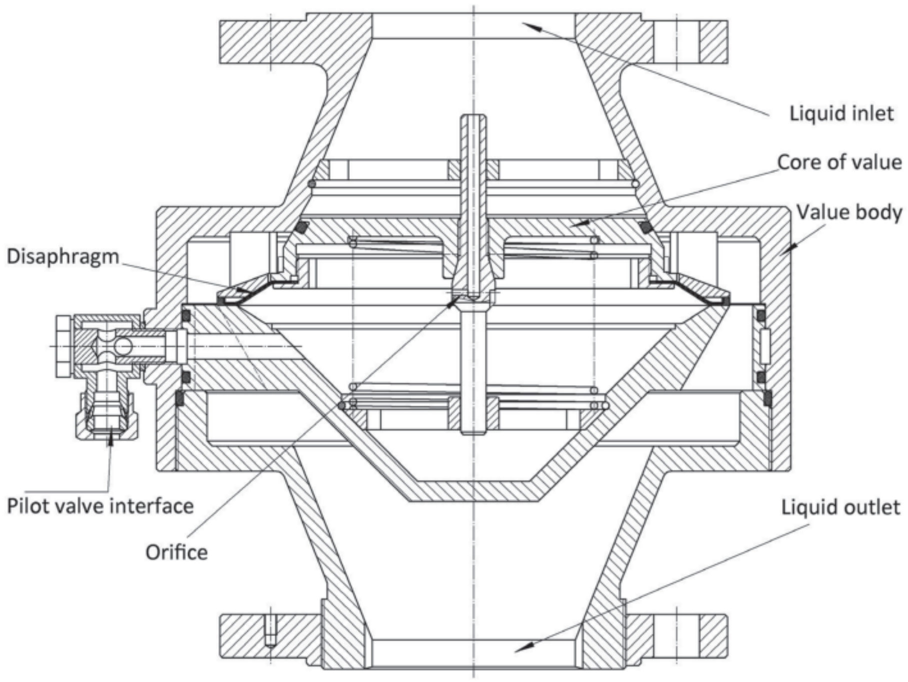

Fig.1 Structure diagram of automatic control valve

2. Structure and working principle of liquid level control value

The structure of the automatic control valve is shown in Fig.1. When oil tank refuelling operation begins, the core of value overcomes the spring force and move downward under the influence of the upper chamber pressure. The valve is opened, and the fuel enters the inner chamber of the valve body through the orifice of value and reaches the float switch through the pilot valve interface. When the liquid level of the oil tank is lower, the float switch opens, and the oil in the inner chamber of the valve enters the oil tank through the float switch. When the liquid level in the tank reaches the set maximum level, the float switch is about to close. The oil flow through the orifice begins to accumulate in the inner chamber of the valve core, and the pressure in the inner chamber of the valve core is raised. When the internal pressure is balanced with the upper chamber pressure, the automatic control valve begins to close under the influence of spring force. As a result, the oil tank refuelling operation closes.

3. Steady-state analysis on the core of liquid level control value

3.1 Momentum equation of incompressible fluid

The momentum equation is the application of momentum theorem of rigid body mechanics in fluid mechanics. The force acting on the solid wall is solved by the momentum equation (Dongchu and Shuhua, 1995), so the momentum equation can also be used to study the force on the core of the value. In order to solve the action force of the liquid flow on the core, the liquid flowing in the valve is selected as the control body, and the momentum equation is applied for research. According to the momentum theory, in time, the momentum increment of a moving body in a certain direction is equal to the sum of the components of the force acting on that object in this direction. That is:

$$d(mv) = Fdt \qquad \dots \quad (1)$$

Then, the sum of all external forces acting on an object are:

$$F = \frac{\mathrm{d}(mv)}{\mathrm{d}t} \qquad \dots \quad (2)$$

The control body is selected as shown in Fig.2. And the momentum increment of the fluid in the control body during the period is listed in equation (3).

$$\mathrm{d}(mv) = d\int_{L_1}^{L_2} \rho Av\mathrm{d}L = \frac{\partial \int_{L_1}^{L_2} \rho Av\mathrm{d}L}{\partial L}\mathrm{d}L + \frac{\partial \int_{L_1}^{L_2} \rho Av\mathrm{d}L}{\partial t}\mathrm{d}t \qquad \dots \quad (3)$$

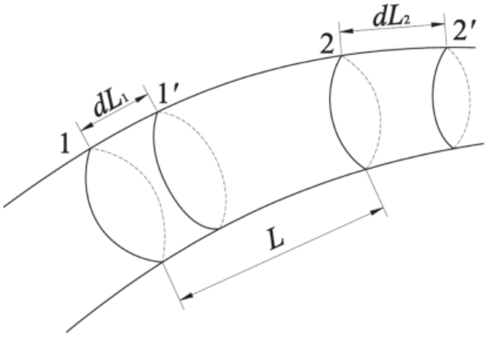

Fig.2 Schematic diagram of control volume

In formula (3), the first item on the right is the position increment of the momentum caused by the change of position in the course of liquid flow. The second item on the right is the time increment of the momentum caused by the time variation. Assuming that the liquid flow rate on dL_1 and dL_2 remains constant and the over-flow cross-sectional area A keeps constant, the position increment of the momentum can be simplified as follows:

$$\frac{\partial\int_{L_1}^{L_2}\rho Av\mathrm{d}L}{\partial L}\mathrm{d}L=\rho A_2v_2\mathrm{d}L_2-\rho A_1v_1\mathrm{d}L_1 \quad \dots \quad (4)$$

At the same time, when adopting the equivalent over-flow cross-sectional area A_D and the equivalent velocity V_D, the time increment of the momentum can be simplified as formula (5):

$$\begin{aligned}\frac{\partial\int_{L_1}^{L_2}\rho Av\mathrm{d}L}{\partial t}\mathrm{d}t&=\rho A_DL\frac{\partial v_D}{\partial t}\mathrm{d}t=\rho A_DL\frac{\partial\left(\frac{Q}{A_D}\right)}{\partial t}\mathrm{d}t\\&=\rho L\frac{\partial Q}{\partial t}\mathrm{d}t=\rho L\mathrm{d}Q\end{aligned} \quad \dots \quad (5)$$

The formulas (3), (4), (5) are substituted into formula (2), and the simplification can be obtained in formula (6):

$$\begin{aligned}F&=\left[\rho A_2v_2\frac{\mathrm{d}L_2}{\mathrm{d}t}-\rho A_1v_1\frac{\mathrm{d}L_1}{\mathrm{d}t}\right]+\rho L\frac{\mathrm{d}Q}{\mathrm{d}t}\\&=\left[\rho Qv_2-\rho Qv_1\right]+\rho L\frac{\mathrm{d}Q}{\mathrm{d}t}\end{aligned} \quad \dots \quad (6)$$

In formula (6), F is the total external force of fluid in the control body.

3.2 CALCULATION OF THE FLOW

The amount of refuelling flow is not only related to the upper chamber pressure but also bore on the opening degree of automatic control valve. As shown in Fig.3, the fuel through the automatic control valve mainly includes two parts, one part gets into the tank through the outer chamber of the core of the valve, and, the other part gets access to the tank via orifice and float switch. The flow can be calculated both by formula (7).

$$Q=C_dA_d\sqrt{\frac{2\Delta P}{\rho}} \quad \dots \quad (7)$$

In equation (7), C_d represents flow coefficient, A_d represents vertical overcurrent area, ΔP represents pressure difference, and ρ represents liquid density. For the flow-path of the outer chamber of the core of the valve, when the opening degree of the core of the value equal X_V, vertical overcurrent area A_d at the 1/2 position of diameter $d = (d_1 + d_2)/2$ can be obtained according the geometric relationship in Fig.3:

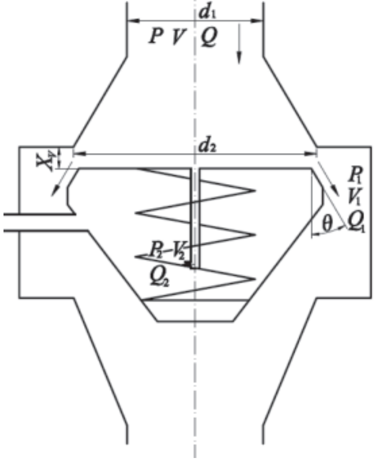

Fig.3 Structure schematic diagram of automatic control valve

$$A_d=\pi dX_V\sin\theta \quad \dots \quad (8)$$

In formula (8), θ represents the cone angle. Setting up the pressure difference ΔP between the internal value chamber and the external value chamber satisfied $\Delta P = P - P_1$. During the whole refueling process, because the fuel that getting into the outer chamber of value through the upper chamber cannot always full-fill it, it could be supposed that the outer chamber pressure $P_1 = 0$. Thus,

$$Q_1=C_{d1}\pi dX_V\sin\theta\sqrt{\frac{2P}{\rho_V}}=C_{d1}\pi\frac{\left(d_1+d_2\right)}{2}X_V\sin\theta\sqrt{\frac{2P}{\rho}} \quad \dots \quad (9)$$

Similarly, for the sake of orifice, for the orifice, the over-flow cross-sectional area A_d is the area of orifice A. That is $A_d = A$. The fuel that getting into the internal chamber through the orifice has entered the oil tank through the floating switch entirely. So, the pressure of internal chamber of core of value can be considered as $P_2 = 0$. Then,

$$Q_2=C_{d2}A\sqrt{\frac{2P}{\rho}} \quad \dots \quad (10)$$

The total flow during the refuelling process Q are derived as equation (11):

$$\begin{aligned}Q&=Q_1+Q_2=C_{d1}\pi\frac{\left(d_1+d_2\right)}{2}X_V\sin\theta\sqrt{\frac{2P}{\rho}}+C_{d2}A\sqrt{\frac{2P}{\rho}}\\&=\left(C_{d1}\pi\frac{\left(d_1+d_2\right)}{2}X_V\sin\theta+C_{d2}A\right)\sqrt{\frac{2P}{\rho}}\end{aligned} \quad \dots \quad (11)$$

In the actual refuelling situation, since $A \ll A_d$, therefore, the flow through the orifice can be neglected compared to the flow through the outer chamber of the valve core. The simplified form of total flow are shown in equation (12):

$$Q\approx Q_1=C_{d1}\pi\frac{\left(d_1+d_2\right)}{2}X_V\sin\theta\sqrt{\frac{2P}{\rho}} \quad \dots \quad (12)$$

From formula (12), it can be seen that the total flow of the automatic control valve is determined by the upper chamber pressure and the opening degree of valve simultaneously.

3.3 STEADY STATE FORCE ANALYSIS OF CORE OF LIQUID LEVEL CONTROL VALUE

When the liquid level control valve is opened, the forces acting on the value core mainly includes the upper chamber hydrostatic pressure, the gravity of core, the steady-state flow force, the spring force and friction force. When the liquid level control valve is running stably, the valve core is under the equilibrium condition of forces. In this paper, the force acting on the valve core due to the change of momentum is called steady-state flow force. As shown in Fig.3, the upper part liquid of the value core is selected as the control body. Assume that the force acting on the control body is F. According to equation (6), the momentum theorem is used to set the momentum equation for the control body along the flow direction when the core is operated stabily, and it was shown in equation (13):

$$P\pi d_1^2/4-F=\rho Q_1 v_1\cos\phi_1+\rho Q_2 v_2\cos\phi_2-\rho Q v\cos\phi \quad \ldots \ (13)$$

In addition, $\varphi_1=\theta, \varphi_2=90^0, \varphi=0^0$, and $Q_1\approx Q$, it can be derived that:

$$F=P\pi d_1^2/4-\rho Q\left(v_1\cos\theta-v\right) \quad \ldots \ (14)$$

In formula (14), the steady-state flow force F_s is satisfied as follows:

$$F_s=\rho Q(v_1\cos\theta-v) \quad \ldots \ (15)$$

When the automatic control valve is operated stabily, the forces acting on the value core are all in the vertical direction, and the force balance equation of the value core can be presented as:

$$PA_0+G_g=F_k+F_s+f \quad \ldots \ (16)$$

In equation (16), P represents the upper chamber hydrostatic pressure, A_0 represents the force area of the value core, G_g represents the gravity of core, F_k represents the spring force, F_s represents the steady-state flow force, f represents the friction force:

$$PA_0+G_g=F_k+F_s \quad \ldots \ (17)$$

Since the friction force is small at this circumstance, so it can be neglected. And, the force balance equation can be simplified as follow. Equation (18) are obtained by substituting the equation (12) and equation (15) into equation (17):

$$PA_0+G_g=F_k+F_s+\rho Q(v_1\cos\theta-v) \quad \ldots \ (18)$$

In above equation,

$$\begin{cases} v_1=\dfrac{Q}{A_d} \\ v=\dfrac{Q}{A_1} \end{cases} \quad \ldots \ (19)$$

Thus, equation (18) can be translated as:

$$PA_0+G_g=F_k+\rho Q^2\left(\frac{\cos\theta}{A_d}-\frac{1}{A_1}\right)=F_k+2C_{d1}^2P\left(A_d\cos\theta-\frac{A_d^2}{A_1}\right) \quad \ldots \ (20)$$

As a result, the spring force can be obtained as:

$$F_k=PA_0+G_g-2C_{d1}^2P\left(A_d\cos\theta-\frac{A_d^2}{A_1}\right) \quad \ldots \ (21)$$

In equation (21), A_1 represents the cross sectional area at the inlet of value, A_d represents the cross section area of the flow, and A_d can be expressed as:

$$A_d=\pi\frac{\left(d_1+d_2\right)}{2}X_V\sin\theta \quad \ldots \ (22)$$

From the formula (21), as the gravity of the valve core remains unchanged, therefore, in the case of a certain valve structure, the spring elasticity is determined by the pressure of the upper chamber of the value.

4. Closing value characteristics of liquid level control valve

When the liquid level of internal tank reaches the set point, the float valve closes. At this time, the fuel entered the internal chamber of valve core cannot be discharged, and began to accumulate in the chamber. When the internal chamber of valve core is full-filled with oil, the pressure in it increases gradually and tends to balance with the upper chamber pressure, leading to the close of automatic control valve under the influence of spring force. As a result, the refuelling process of oil tank ends. After the float valve closed, the closing of the automatic control valve is also divided into two processes. The first process is to fill the internal chamber with the oil from the orifice. At this time, the automatic control valve is still open. The second process is the automatic control valve began to close under the action of the spring force when the internal chamber is full-filled with oil. The delay of the automatic control valve related to the float valve is the sum of the two processes. The time required for the first process is determined by the remaining volume of the internal chamber of the core after the float valve closes. Assuming the remaining volume is V, the time required is:

$$T_1=\frac{V}{Q}=\frac{V}{C_dA\sqrt{2P_1/\rho}} \quad \ldots \ (23)$$

In the second process, when the automatic control valve is about to close, the motion equation of the valve core is:

$$P_2S_2+F_k+F_t+f-P_1S_1=M\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+\beta\frac{\mathrm{d}x}{\mathrm{d}t} \quad \ldots \ (24)$$

In equation (24), P_2 represents the pressure of internal chamber of valve core, S_2 represents the force area of internal chamber of valve core, F_k represents the spring force, F_t represents the transient state flow force, f represents the friction force, P_1 represents the pressure of upper chamber of valve core, S_1 represents the force area of upper chamber of valve core, M represents the quality of the valve core, β represents the viscous damping coefficient, x represents the moving distance of the valve core in the process of closing the valve. The transient state flow force F_t is the force acting on the core of valve by the fluid in the valve chamber due to the change of velocity during the closing procedure of the automatic control valve. This force is usually small, and the proportion of it in all the force on the core of valve is relatively small (chao, 2004). Therefore, it can be ignored. As the closing valve speed is small, the impact of viscous resistance and friction can also be ignored, the above formula can be transformed into equation (25):

$$P_2S_2+F_k-P_1S_1=M\frac{\mathrm{d}^2x}{\mathrm{d}t^2} \quad \ldots \ (25)$$

The flow get into the internal chamber of value core through the orifice is:

$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}} \quad \text{...} \tag{26}$$

In formula (26), C_d represents the flow coefficient of orifice, A represents the cross-section area of orifice, ρ represents the fluid density, ΔP represents internal and external pressure difference of orifice, that is:

$$\Delta P = P_1 - P_2 \quad \text{...} \tag{27}$$

In the time period dt, the moving distance of the valve core in the process of closing is dx. The volume of liquid flowing from the orifice into the internal chamber of value core should be equal to the increase in the volume of the internal chamber of value core. It can be seen from Fig.1, in the closing process of the liquid level control value, the change of the inner volume of the valve core is related to the diameter of the inner chamber. Assume that the average diameter of the internal chamber of the core is d_0, that is:

$$Q\mathrm{d}t = \frac{\pi}{4} d_0^2 \mathrm{d}x \quad \text{...} \tag{28}$$

Therefore,

$$Q = \frac{\pi d_0^2}{4}\frac{\mathrm{d}x}{\mathrm{d}t} \quad \text{...} \tag{29}$$

The spring force is:

$$F_k = K\left(x_1 - x\right) \quad \text{...} \tag{30}$$

In formula (30), K represents the stiffness coefficient of spring, x_1 represents the amount of compression of the spring when the level control valve is fully opened. Simultaneously consider the equations (25), (26), (27), (29) and (30), the simplificated form of results can be obtained as:

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \frac{\pi^2\rho S_2 d_0^4}{32C_d^2A^2}\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + Kx - \left[P_1\left(S_2 - S_1\right) + Kx_1\right] = 0 \quad \text{...} \tag{31}$$

Setting

$$\begin{cases} c_1 = \dfrac{\pi^2\rho S_2 d_0^4}{32C_d^2A^2M} \\ c_2 = \dfrac{K}{M} \\ c_3 = -\dfrac{\left[P_1\left(S_2 - S_1\right) + Kx_1\right]}{M} \end{cases} \quad \text{...} \tag{32}$$

The equation (31) can be transformed as follow.

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + c_1\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + c_2x + c_3 = 0 \quad \text{...} \tag{33}$$

Equation (33) is the second order nonlinear ordinary differential equation. By solving the equation, the closing speed of the liquid level control valve can be obtained as:

$$v = \frac{\mathrm{d}x}{\mathrm{d}t} = \sqrt{\frac{c_2x + c_3}{c_1} - \frac{c_2}{2c_1^2} + \left(\frac{c_2}{2c_1^2} - \frac{c_3}{c_1}\right)e^{-2c_1x}} \quad \text{...} \tag{34}$$

The formula (34) can be deformed as:

$$\mathrm{d}t = \frac{1}{\sqrt{\frac{c_2x + c_3}{c_1} - \frac{c_2}{2c_1^2} + \left(\frac{c_2}{2c_1^2} - \frac{c_3}{c_1}\right)e^{-2c_1x}}}\mathrm{d}x \quad \text{...} \tag{35}$$

The closing time of the liquid level control valve at second process can be obtained by integrating the both two sides of the formula (35). And the result is:

$$T_2 = \int_0^{x_V} \frac{1}{\sqrt{\frac{c_2x + c_3}{c_1} - \frac{c_2}{2c_1^2} + \left(\frac{c_2}{2c_1^2} - \frac{c_3}{c_1}\right)e^{-2c_1x}}}\mathrm{d}x \quad \text{...} \tag{36}$$

The expression of the integrand is very complicated in the formula (36), and it is difficult to obtain the analytical solution by the conventional method. Thus, the numerical methods can be used for approximate calculations. Thus, the total delay time T of level control value after the floating switch is closed can be expressed in equation (37):

$$\begin{aligned} T &= T_1 + T_2 \\ &= \frac{V}{C_dA\sqrt{\frac{2P_1}{\rho}}} + \int_0^{x_V} \frac{1}{\sqrt{\frac{c_2x + c_3}{c_1} - \frac{c_2}{2c_1^2} + \left(\frac{c_2}{2c_1^2} - \frac{c_3}{c_1}\right)e^{-2c_1x}}}\mathrm{d}x \end{aligned} \quad \text{...} \tag{37}$$

The acceleration equation of the liquid level control valve during closing process can be obtained by deriving the formula (37) from time t, which is shown as follow:

$$a = \frac{\frac{c_2}{c_1} - \left(\frac{c_2}{c_1} - 2c_3\right)e^{-2c_1x}}{2\sqrt{\frac{c_2x + c_3}{c_1} - \frac{c_2}{2c_1^2} + \left(\frac{c_2}{2c_1^2} - \frac{c_3}{c_1}\right)e^{-2c_1x}}} \cdot v \quad \text{...} \tag{38}$$

By analyzing the equations (34), (37), and (38), it can be seen that when the main structure of the automatic control valve is determined, the size of the orifice will affect the closing time of the liquid level control valve, the closing valve speed, and the closing speed acceleration. What is more, the larger the diameter of the orifice, the shorter is the closing time.

5. Conclusions

In this paper, the structure and basic working principle of the liquid level control valve are analyzed. According to the fluid momentum theorem and the kinematic equation of the valve closing process, the flow of the automatic control valve, the force condition of the valve core, the time required for closing the valve, the speed and accelerated velocity of valve core movement were analyzed and the following main conclusions were obtained:

(1) When the liquid level control valve is running stably, the forces acting on the valve core mainly includes the upper chamber hydrostatic pressure, the gravity of core, the steady-state flow force and the spring force. In the case of

a certain valve structure, the spring elasticity is determined by the pressure of the upper chamber of the valve.

(2) In the process of closing automatic control valve, the valve core is mainly affected by the pressure difference between internal chamber and external chamber, and the spring force. With the valve closed continues, the pressure difference gradually increases, the spring force gradually reduces. As a result, the movement speed of the core gradually increases, while the acceleration velocity of it gradually decreases.

(3) With the closure of the automatic control valve, the time required for closing the valve, the speed and accelerated velocity of valve core movement have non-linear relationship with the moving distance of the valve core.

(4) When the main structure of the automatic control valve is determined, the size of the orifice will affect the closing time of the liquid level control valve, the closing valve speed, and the closing speed acceleration. What is more, the larger the diameter of the orifice, the shorter the closing time.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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