Research on Flow-Induced Excitation Characteristics of a Four Way Reversing Valve

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Abstract: The four-way reversing valve is a key component determining whether a heat pump air conditioning system can work. Studying the four-way reversing valve is of great significance for improving the performance of the heat pump air conditioning system. In this paper, the control equation of the sliding block movement process is constructed to simulate the reversing process of the four-way reversing valve in fluid mechanics, and a detailed study is carried out from the sliding block speed, sliding block acceleration, sliding block force, refrigerant leakage, and other aspects. Research has shown that optimizing the structure of the slider can greatly improve the working performance of the four-way reversing valve. Increasing the height of the slider not only improves the pressure relief ability of the four-way reversing valve and prevents the slider from being damaged by high-pressure gas impact, but also reduces the leakage of refrigerant during the directional process; When reducing the length of the slider, although it will improve the pressure relief capacity of the four-way reversing valve, it also increases the amount of refrigerant leakage. The research results provide a theoretical basis and improvement direction for designers to improve the performance of four-way reversing valves.

Keywords: Refrigeration and cryogenic engineering; reversing valve; computational fluid dynamics (CFD); performance study

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Nomenclature

P_D	the inlet pressure of D pipe(MPa)
v	the flow rate of fluid in capillary(m/s)
L	the length of capillary(m)
d	the diameter of capillary(m)
Fp	the pressure exerted on the slider(N)
A_1	the cross-sectional area of the capillary(m^2)
A_2	the cross-sectional area of the valve chamber(m2)
u	the fluid viscosity(Pa-s)
m	the mass of moving parts such as slider and bracket(kg)
w	the moving speed of slider(m/s)
t	time(s)
F_t	propulsive force(N)
F_f	frictional force(N)
f	the friction coefficient of capillary
λ	the friction coefficient between the slider and the valve seat
$Cv0$	the flow coefficients of the four-way reversing valve were
$Cv1$	the flow coefficients of the inflow gap
$Cv2$	the flow coefficients of the outflow gap

1. Introduction

With the continuous promotion of green and environmentally friendly travel methods and the pursuit of low travel costs, electric vehicles are increasingly favored by people. However, issues such as thermal runaways often lead to spontaneous combustion in electric vehicles. In order to meet the requirements of safe travel, heat pump air conditioning systems have become the preferred method of thermal management for electric vehicles. However, the use of heat pump air conditioning will significantly reduce the range of electric vehicles. Therefore, finding an efficient heat pump air conditioning system has become a research hotspot for many scholars. Research has pointed out that a large proportion of the total energy loss of heat pump air conditioning systems is caused by throttling elements [1-3]. The COP of the heat pump system is increased from 2.9 to 3.1 only by optimizing the control strategy of throttling components [4]. The pressure drop of the system will be reduced by optimizing the control logic of valve opening speed and valve opening [5] The compressor power will decrease by 7.17% if the corresponding valve opening is adjusted under different working conditions [6]. Under the same flow rate, the pressure loss and pump output pressure can be reduced by 5.51% and 4.38% by optimizing the valve [7]. Therefore, the study of throttling components is of great significance to reduce energy consumption and improve the efficiency of heat pump air-conditioning systems.

As one of the throttling components of the heat pump air conditioning system, the four-way reversing valve has been studied by many scholars for its impact on the heat pump air conditioning system. Some scholars have analyzed the impact of the reversing process of the four-way reversing valve on the heat pump air conditioning system. The results pointed out that the four-way reversing valve may experience frost formation when working in low-temperature environments, requiring additional heat to heat and defrost it. Otherwise, it will cause the four-way reversing valve to fail to reverse [8]. It will increase the reversing time by more than 36% and reduce the system's working efficiency [9]. By optimizing the slider structure of the four-way reversing valve, the pressure on the slider is reduced from 4720N to 3938N, which makes the reversing process smoother and reduces the occurrence of reversing failure caused by friction [10]. In addition, by improving the vibration law and surface shape of the slider, the friction force suffered during the reversing process of the slider can also be significantly reduced, and the reversing failure of the four-way reversing valve can be reduced [11,12].

Some scholars have studied the impact of refrigerant leakage during the reversing process of the four-way reversing valve on the heat pump air conditioning system. The study pointed out that refrigerant leakage in the four-way reversing valve will lead to a 2.5% decrease in COP of the heat pump air conditioning system [13]. And comparing and analyzing the impact of a normally operating four-way reversing valve and a four-way reversing valve with leakage issues on the compressor of the air conditioning system through experiments. The results showed that due to leakage, the input power of the compressor was 58.6% of the normal state, seriously affecting the working performance of the heat pump unit [14]. The study also pointed out that the presence of a four-way reversing valve resulted in an increase of 7.31% in the suction side pressure drop and 0.27% in the exhaust side pressure drop of the compressor, respectively [15].

Some scholars have also studied the impact of the heat transfer process between the high-pressure and low-pressure sides of the four-way reversing valve on the heat pump air conditioning system. The heat loss on the suction side is most affected by the main material of the four-way reversing valve, followed by the connecting material and valve seat [16]. Four-way reversing valves with different thermal conductivity materials have a significant impact on refrigeration systems [17,18]. They analyzed the results of two materials with different thermal conductivity, stainless steel and copper, and pointed out that compared to copper materials, using stainless steel materials with low thermal conductivity can increase energy efficiency by at least 1% [19]. Some scholars studied the effect of heat transfer between the high-pressure and low-pressure sides of the four-way reversing valve on the refrigeration system, and the results showed that heat transfer between high and low pressures can reduce the cooling capacity of the system by about 0.7% [20,21]. The losses caused by heat transfer account for about 60% of the total losses of air conditioning systems, and result in a 1% -5% decrease in system cooling capacity [22,23]. The research analyzed the impact of four-way reversing valves on refrigeration systems from three perspectives: heat capacity, COP, and energy. The research results showed that the presence of partitioning reduced them by 31.86%, 33.59%, and 22.59%, respectively [24].

From the above discussion, it can be found that existing literature mainly focuses on studying the impact of the four-way reversing valve on the efficiency of heat pump air conditioning systems from the entire system level, and there is no in-depth analysis of the reasons for the failure of the four-way reversing valve reversing process and refrigerant leakage. Therefore, this article constructs a motion control equation for the slider to conduct a theoretical analysis of the reversing process of the four-way reversing valve, in order to study the main factors that affect the speed, force on the slider, and refrigerant leakage during the reversing process, providing a clear optimization direction for the four-way reversing valve to have a smoother reversing process and lower refrigerant leakage.

2. Analysis of the Problem in the Reversing Process of the Four-Way Reversing Valve

As shown in Figure 1, the main structures of the four-way reversing valve in the heat pump air conditioning system include a capillary, pilot slide valve, valve chamber, piston, slider, valve seat, and bracket. By controlling the connectivity status of the D, C, S, and E pipes in the four-way reversing valve, the conversion between the cooling and heating states of the heat pump air conditioning system can be achieved. When the air conditioning is in a refrigeration state, the refrigerant in the indoor unit flows into the compressor through the E-S pipe of the four-way reversing valve. After the compressor is discharged, the refrigerant flows into the outdoor unit through the D-C pipe of the four-way valve. At this time, the E-pipe and S-pipe in the four-way reversing valve are connected, and the D-pipe and C-pipe are connected. When the air conditioner is in the heating state, the refrigerant in the outdoor unit flows into the compressor through the C-S pipe, and the refrigerant discharged by the compressor flows into the indoor unit through the D-E pipe. At this time, the C pipe and S pipe in the four-way valve are connected, and the D pipe and E pipe are connected.

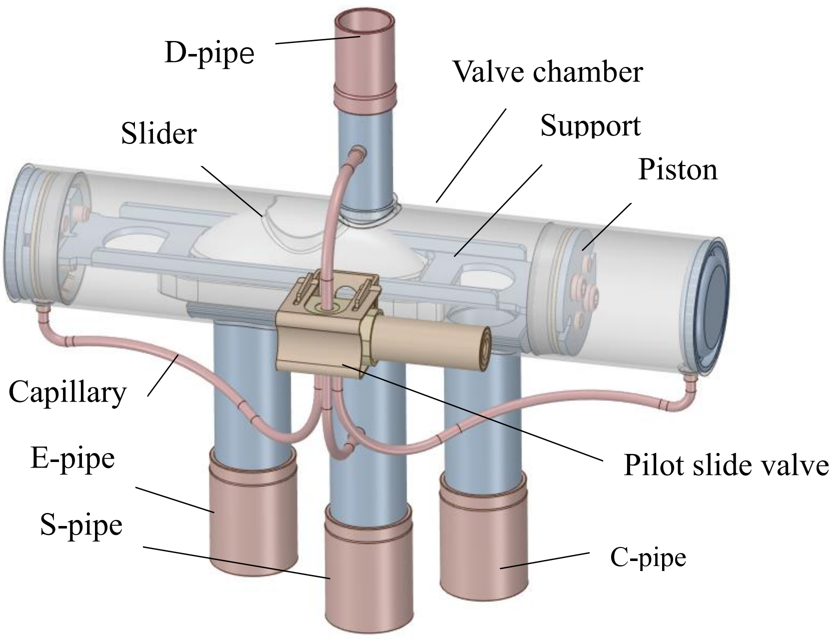

Figure 1. Structure of four-way reversing valve.

The change in the connection status of the D, C, S, and E pipes of the four-way reversing valve requires the driving force to drive the slider movement. Under experimental conditions, block the C and E pipes, apply different pressures to the D and S pipes, and measure the flow coefficient Cv value

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(referred to as the middle flow coefficient) of the four-way reversing valve when the slider is in the middle position. The middle flow coefficient Cv value is generally within the range of 0.2-0.8 to ensure its normal directional change. If the Cv value is too high, there is a possibility of insufficient driving force during the reversing process of the four-way reversing valve, leading to reversing failure; If the Cv value is too low, the high-pressure gas in the four-way reversing valve cannot be discharged in a timely manner, resulting in insufficient pressure relief inside the valve chamber and damage to the slider. Obviously, the experimental method cannot deeply analyze the reasons for insufficient driving force or excessive leakage of the four-way reversing valve. Therefore, establishing the motion control equation for the reversing process of the four-way reversing valve is of great significance for studying and improving the performance of the four-way reversing valve.

In order to study the reversing process of the four-way reversing valve, this article establishes two types of sliders as shown in Figure 2. For the convenience of description in the text, the four way reversing valve model corresponding to slider I is referred to as Model I. The model corresponding to slider II is called model II. Without affecting the calculation results, the four way reversing valve was simplified to generate a high-quality mesh model. The simplified model is shown in Figure 3.

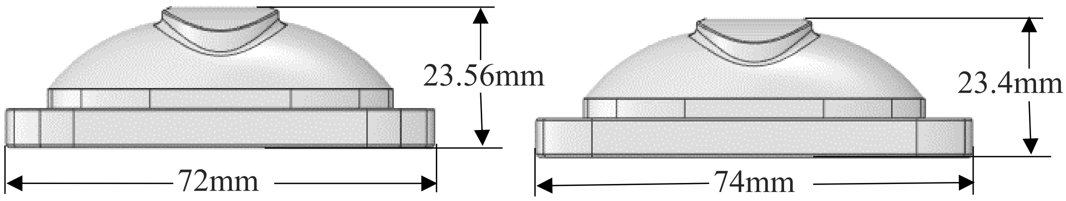
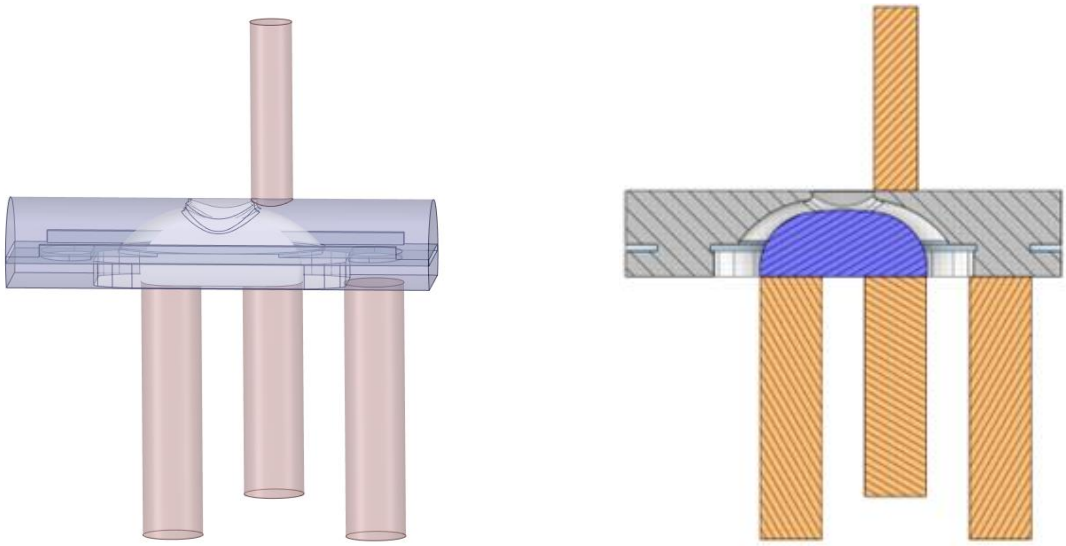


Figure 2. Slider Structure (Slider I on the left and Slider II on the right).



a. Simplified Model b. Fluid Domain Profile

Figure 3. Simplified model of the four-way reversing valve.

3. Establishment of Control Equations for the Reversing Process of the Four-way reversing valve

3.1. Establishment of Mathematical Model for the Motion Process of Sliders

The reversing process of a four-way reversing valve is relatively complex. To facilitate the establishment of a mathematical model, the following assumptions are made,

(1) The physical parameters of air do not change during reversing, that is, the density and viscosity are constant;

(2) During the reversing process, the pressure at the inlet and outlet of the four-way reversing valve is stable;

(3) Ignore the influence of ambient temperature on the four-way reversing valve.

1）Force balance equation of sliding

$$F_t = (P_D - \frac{0.5 \cdot f \cdot \rho v^2 \cdot L}{d}) \cdot A_2 \tag{1}$$

$$F_f = \lambda \cdot F_P \tag{2}$$

$$v \cdot A_1 = u \cdot A_2 \tag{3}$$

$$f = 8 \cdot [\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A+B)^{1.5}}]^{1/12} \tag{4}$$

$$A = \{2.457 \cdot \ln [\left(\frac{7}{Re}\right)^{0.9} + 0.27 \cdot \frac{\varepsilon}{d}]\}^{16} \tag{5}$$

$$B = (\frac{37530}{Re})^{16} \tag{6}$$

$$Re = \frac{\rho \cdot v \cdot d}{\mu} \tag{7}$$

Where, P_D is the inlet pressure of D pipe, f is the friction coefficient of capillary, v is the flow rate of fluid in capillary, L is the length of capillary, d is the diameter of capillary, λ is the friction coefficient between the slider and the valve seat, Fp is the pressure exerted on the slider, A_1 is the cross-sectional area of the capillary, A_2 is the cross-sectional area of the valve chamber, and u is the fluid viscosity.

2）Equation of slider motion

$$m \cdot \frac{dw}{dt} = F_t - F_f \tag{8}$$

Where, m is the mass of moving parts such as slider and bracket, w is the moving speed of slider, t is time, F_t is propulsive force, and F_f is the frictional force.

At the starting time of movement t_0=0s, the slider is located on the left side of the four-way reversing valve, and its speed is 0m/s; When the driving force of the slider is greater than the friction force, the slider starts to move; When the slider moves to the far right, the slider stops moving.

3.2 Establishment of Grid Model for Four-Way reversing valve

The four-way reversing valve is divided into the static area and moving area in the reversing process, and the static area includes the connecting pipe and the valve seat; The moving area includes the valve chamber, slider and support. In the process of reversing, the moving area of the four-way reversing valve is realized by combining the MRF model with expression, and the data transmission between the static area and the moving area is realized by the interface surface. During grid division, model I will generate 2.1 million, 3.37 million, 4.23 million, 5.33 million and 8.23 million grid models respectively for grid independence verification. It can be seen from Fig. 4 that the flow at the middle position of the four-way reversing valve decreases gradually with the increase of the number of grids; When the number of grids exceeds 4 million, the maximum decrease of fluid flow with the increase of grid number is 0.2%. Therefore, when the grid number of the four-way reversing valve reaches more than 4 million, it is considered that the influence of the grid number on the simulation results can be ignored. Finally, the grid parameters of the four-way reversing valve can be set as follows to meet the requirements. The global grid size is 1mm. The slider surface and interface surface are densified with a grid size of 0.5mm.

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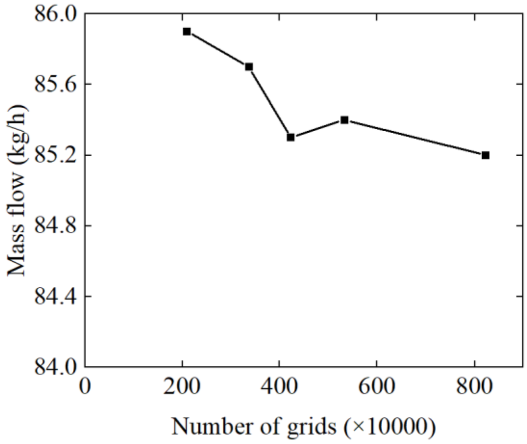

Figure 4. Grid Independence Verification.

3.3. Parameter settings for the transient solution process of the four-way reversing valve

In the numerical solution process, the parameters are set as follows: C-pipe and E-pipe are blocked, D-pipe is the pressure inlet boundary, and the pressure value is 3.1MPa; S-pipe is the boundary of pressure outlet, and the pressure value is 0MPa; SST *k-w* turbulence model is selected as the turbulence model, and the pressure-velocity coupling algorithm is adopted for a transient solution; MRF model is adopted for the moving process of the slider in the reversing process, and the speed change of the slider in the reversing process is realized by the expression method. At the beginning of the movement of the four-way reversing valve, the slider's speed and force are in an unbalanced state. After the slider starts to move, the speed and force of the slider reach a balanced state, and the speed of the slider will not change anymore. At this time, the speed of the slider is the balance speed, and the time required to reach the balance speed is the balance time. In the simulation process, if the time step is set too small, the calculation cycle will be too long, and if the time step is set too large, the simulation process will not correctly reflect the change of the slider speed in the reversing process of the four-way reversing valve. Therefore, the balance time required for the slider to reach the balance speed is taken as the evaluation standard for time step independence verification. The time steps are calculated with 1e-5s, 5e-5s, 1e-4s and 5e-4s respectively, and the results are shown in Fig. 5. It can be seen from the figure that when the time step is less than 5e-5s, the balance time required for the slider to reach the balance speed is less affected by the time step, and it maintains good convergence in the calculation process. Therefore, in the transient simulation calculation of a four-way reversing valve, the time step shall not exceed 5e-5s, and it is considered that the time step meets the calculation accuracy requirements. In the actual simulation, in order to give consideration to the convergence and time period of the numerical solution, when the slider moves to the middle area of reversing, the time step is set to 1e-5s to cope with the sharp change of the flow field and improve the convergence of simulation calculation, and the time step in other moving areas is set to 5e-5s to reduce the calculation period.

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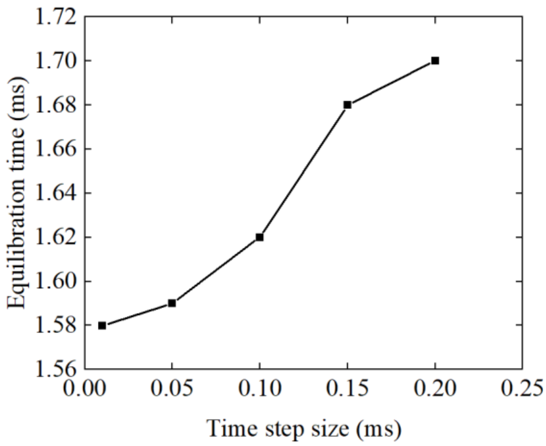

Fig. 5 Time step independence verification

3.4. Model experiment validation

In order to verify the accuracy of the numerical simulation results, a flow and pressure test platform of the four-way reversing valve was built, as shown in Fig.6 and Fig.7. The schematic diagram of the test system is shown in Fig.6. Under the action of the pressure stabilizing pump, the gas tank can output gas with continuous and stable pressure as the air source. Pressure sensor 1 and pressure sensor 2 monitor the pressure at the inlet and outlet of the gas tank and provide signals to the pressure stabilizing pump for operation. The flow in the test system is controlled by controlling the opening of the regulating valve 1, and the flow in the system is monitored by the flow sensor 1; Under the action of the diverter, the flow path in the test system is divided into the tested branch and the auxiliary branch, and the flow and pressure in the tested branch are changed by controlling the flow regulator in the auxiliary branch; Flow sensor 2 monitors the flow in the tested branch, and pressure sensor 3 and pressure sensor 4 respectively monitor the pressure of D-pipe and valve chamber of the measured four-way reversing valve. During the test, the adjustment of flow, pressure and other parameters is realized through the console shown in Fig. 7.

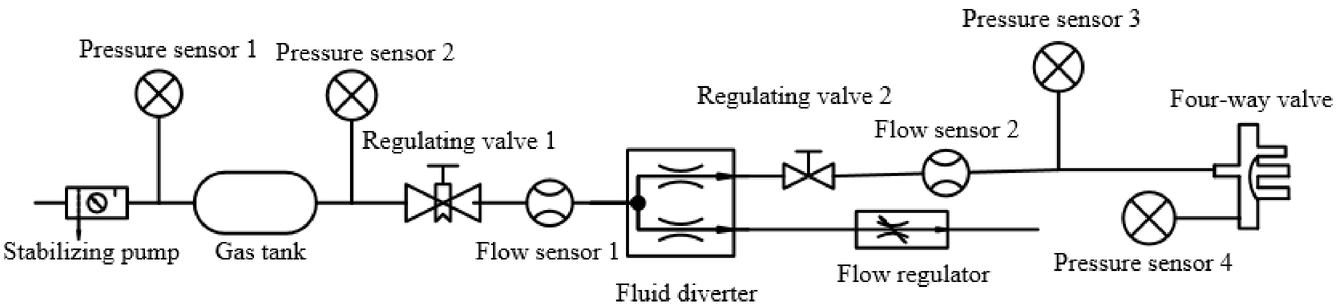

Figure 6. Test system diagram.

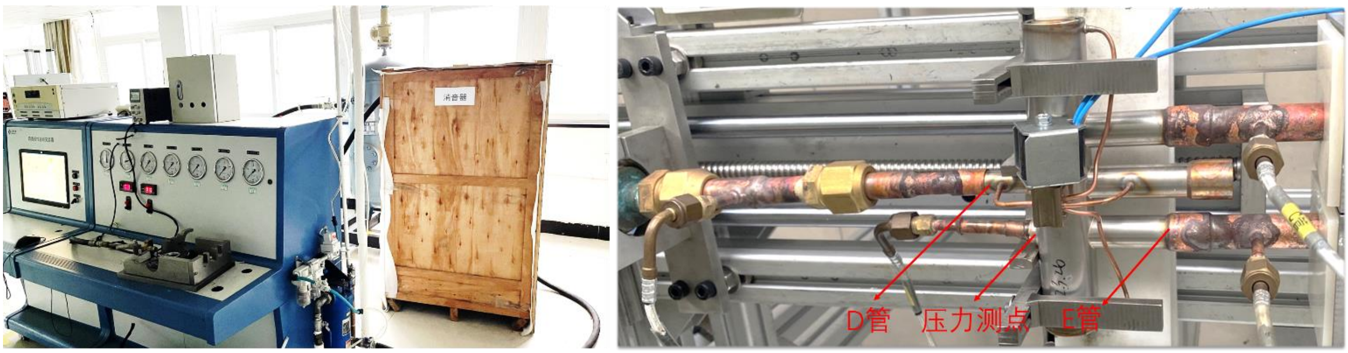

Fig.7 Acquisition experimental platform of flow and pressure.

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During the experiment, the slider is adjusted to the middle position of the reversing, and the pressure in the valve chamber and the flow in the four-way reversing valve are measured, and substitute the measured data into Formula (9) to calculate the flow coefficient Cv. Compare the test results with the simulation results, as shown in Table 1. It can be seen from the table that the maximum error between the simulation value and the experimental value is 12.03%, which is within the allowable error range of the project. Therefore, the simulation results can correctly reflect the changes of various parameters during the reversing process of the four-way reversing valve.

$$Cv = 0.0105 \times q * \sqrt{\rho_0 \times \frac{\Delta P}{\rho}} \tag{9}$$

Where Cv is the flow coefficient, q is the flow of a four-way reversing valve, ΔP is the pressure drop, ρ Is the fluid density, ρ_0 is the density of water.

Table 1. Comparison between numerical simulation results and test results.

	Model I		Model II	
	Pressure (MPa)	Cv	Pressure (MPa)	Cv
simulation	2.12	0.68	2.78	0.50
test	2.41	0.64	3.06	0.49
error	12.03%	6.25%	9.15%	2.04%

The error between the simulation results and the test results may be caused by the following factors: when simplifying the four-way reversing valve model, local geometric features such as chamfer and small clearance are eliminated, which leads to the reduction of pressure loss in the four-way valve; In the setting of the simulation boundary conditions, the pressure boundary is the total pressure and the gauge pressure in the test. When the fluid flows, part of the pressure in the total pressure is converted into kinetic energy, causing the simulation boundary value to be lower than the actual test value.

4. Analysis of Factors Influencing the Reversing Process of Four-way reversing valve

4.1. Transient Characteristics Analysis of Four-Way reversing valve

4.1.1. The variation of velocity and pressure fields inside the valve with the motion process

In order to intuitively observe and analyze the fluid flow field and pressure changes at different positions of the slider during the reversing process, the results of representative positions are selected for display (taking Model I as an example). Figure 8 and Figure 9 show the velocity distribution cloud diagram and pressure distribution cloud diagram of the four-way reversing valve respectively. From Figure 8, it can be seen that when the displacement of the slider does not exceed 11.5mm, the speed in the four-way reversing valve is almost 0, and there is no obvious flow phenomenon between the D pipe and the S pipe; When the displacement of the slider is 12mm, there will be a speed change at the right end of the slider (as shown by the arrow position in the figure); When the displacement of the slider is 14.5mm, there is a significant velocity field distribution in the four-way reversing valve, and at this time, the flow capacity between the D tube and the S tube is the highest; When the slider displacement is 17.0mm, the velocity distribution is only seen at the rear end of the slider. When the slider displacement is 17.5mm, the velocity in the four-way reversing valve is 0. Based on the changes in the velocity cloud map during the comprehensive reversing process, it can be seen that the velocity field between the valve chamber and the S tube changes more significantly, while the velocity field changes between the D tube and the S tube are relatively small. Therefore, during the reversing process, the four-way reversing valve only showed significant refrigerant leakage between 12mm and 17mm, rather than throughout the entire reversing process.

From Figure 9, it can be seen that when the displacement of the slider is less than 12.0mm, the pressure inside the valve chamber of the four-way reversing valve is the same as that of the D-tube, and there is no significant change; When the displacement of the slider is 14.5mm, there is a significant decrease in the pressure inside the valve chamber compared to the pressure inside the D tube; When the displacement of the slider is greater than 17.0mm, there is no significant change in the pressure inside the four-way reversing valve chamber and between the D-tube. Based on Figure 8, it can be seen that when the slider displacement is 12mm, the fluid flow in the four-way reversing valve is relatively small and does not cause a significant decrease in the pressure inside the valve chamber.

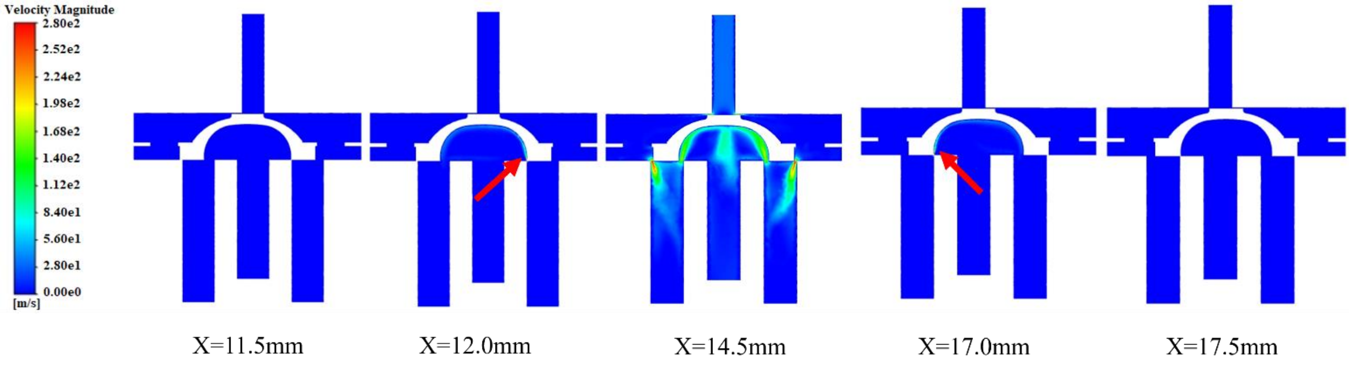

Figure 8. Velocity nephogram of the four-way reversing valve.

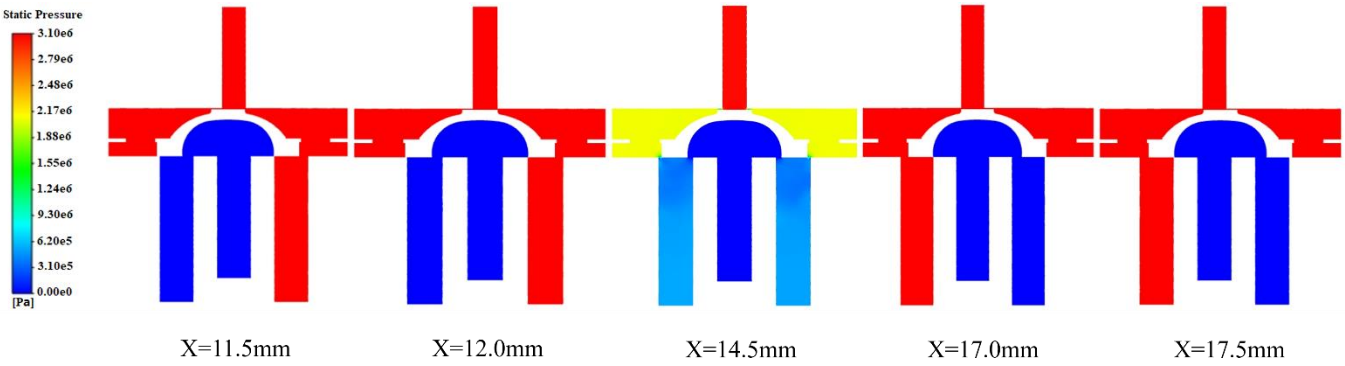

Figure 9. Pressure nephogram of four-way reversing valve.

4.1.2. The variation of pressure in the valve chamber with the reversing process

Figure 10 shows the variation of pressure in the cavity of a four-way reversing valve with displacement. From the figure, it can be seen that when the displacement of the slider is less than 12mm, the pressure inside the valve chamber is independent of the slider position and remains unchanged; When the slider is within the range of 12-17mm, the pressure inside the valve chamber first decreases and then rises. When the slider moves to the middle position of 14.5mm, the pressure inside the valve chamber reaches a minimum value; When the displacement of the slider is greater than 17mm, the pressure inside the valve chamber increases to the initial value and begins to remain unchanged. This indicates that when the sliding block moves at a distance of 12-17mm, the sliding block begins to act as an "upper blockage and lower leakage" to prevent the sliding block from being damaged by high-pressure fluid during the reversing process. From the figure, it can also be seen that the slider pressure relief capacity of Model I is greater than that of Model II. Therefore, reducing the gap between the slider boss and the valve chamber wall and the length of the slider can increase the pressure relief capacity of the slider, ensuring that the slider is not damaged by high-pressure fluid during the reversing process of the four-way reversing valve.

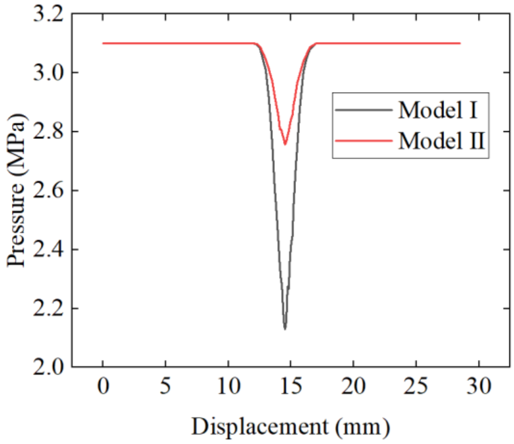

Figure 10. Variation of Pressure in Valve Chamber with Slider Displacement.

4.1.3. Acceleration and velocity changes of slider movement

Figure 11 reflects the change in slider acceleration during the reversing process of the four-way reversing valve. From the figure, it can be seen that the acceleration of the slider undergoes a very short oscillation process at the beginning of the reversal, and then the acceleration stabilizes around 0. At this point, the slider reaches equilibrium speed. When the displacement of the slider is within the range of 12mm-17mm, the acceleration of the slider experiences severe oscillation. This is because during the reversing process, when the slider passes through the middle position of the reversing, the pressure inside the valve chamber suddenly drops, and the pressure and friction force on the slider decreases, resulting in an increase in slider acceleration and velocity, which in turn leads to an increase in fluid velocity and pressure loss in the capillary. In turn, it leads to a decrease in the thrust exerted on the slider, and the changes in thrust and friction cause the acceleration of the slider to oscillate. When the sliding distance exceeds 17mm, the acceleration of the sliding block is maintained at around 0 again. From Figure 11, it can also be seen that when the slider passes through the middle position of the reversing direction, the degree of acceleration oscillation of different sliders varies. The maximum acceleration of the Model I slider can reach 900m2/s, while the Model II slider has a maximum acceleration of 300m2/s. This indicates that the slider acceleration is highly susceptible to the influence of its size parameters during the reversing process.

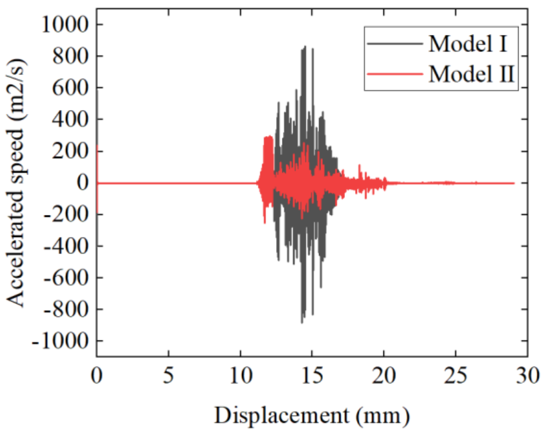

Figure 11. Acceleration of the slider varies with position.

Figure 12 reflects the variation process of slider speed with displacement. From the figure, it can be seen that during the reversing process, when the slider passes through the middle range of 12-

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17mm, the speed of the slider changes first and then decreases. When the displacement is 14.5mm, the speed of the slider reaches its maximum value. From the figure, it can also be seen that the balance speed of the slider in Model II is 0.08m/s, with a maximum value of 0.3m/s; The slider balance speed of Model II is 0.06m/s, with a maximum speed of 0.13m/s. From the figure, it can also be seen that the balance speed of the slider is broken at both 12mm and 17mm, and within this range, the maximum increase in speed of Model I is 2.7 times that of Model II. This indicates that the length and height of the slider do not affect the balance position of the four-way reversing valve, but have a significant impact on the speed of the slider.

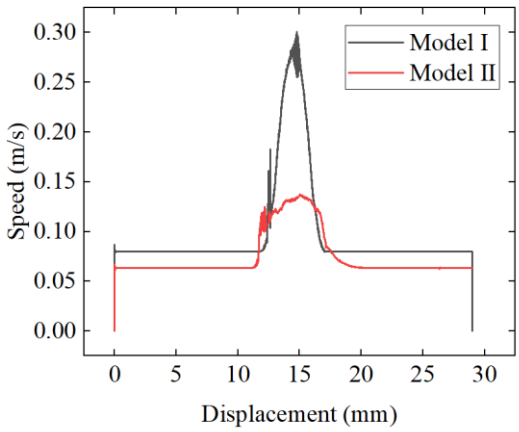


Figure 12. Variation of slider speed with displacement.

Figure 13 reflects the relationship between slider displacement and time. From the figure, it can be seen that during the reversing process, the displacement of the slider gradually increases with time, and the speed increase of the slider suddenly increases in the middle area. Based on Figure 12, it can be seen that this is due to the increase in slider speed. From the figure, it can also be seen that the time required for Model II to complete the commutation is 0.34 seconds, and the time required for Model II to complete the commutation is 0.44 seconds.

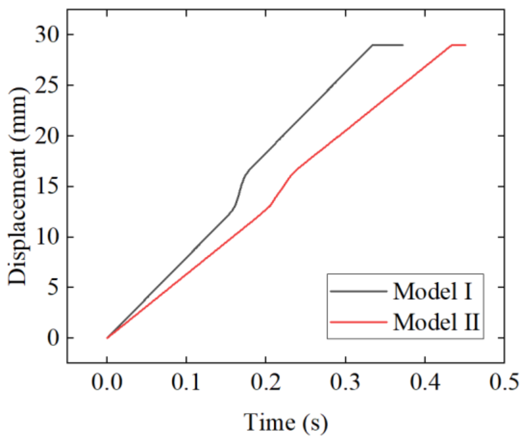


Figure 13. Variation of slider displacement with time.

4.1.4. Change in leakage amount with reversing process

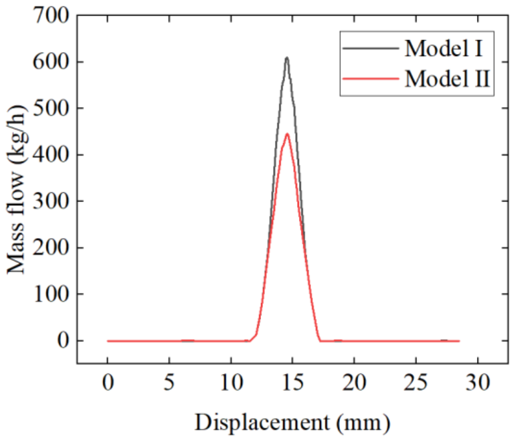


Figure 14. Variation of flow with slide displacement.

Figure 14 shows the flow rate variation of the four-way reversing valve during the reversing process. From the figure, it can be seen that when the slider moves within the range of 12-17mm, fluid begins to flow between the D and S pipes of the four-way reversing valve, and the flow reaches its maximum value when the slider is in the middle position of 14.5mm. From the figure, it can also be seen that the maximum flow rate in Model I of the four-way reversing valve is 610kg/h, and the maximum flow rate in Model II is 446kg/h. In the actual reversing process of the refrigeration system, it is not desired to have a large flow rate between the D pipe and the S pipe, as this will increase the cross-flow phenomenon of the four-way reversing valve and reduce the refrigeration efficiency of the air conditioning system. Therefore, Model II is more optimal from the perspective of reducing the degree of crosstalk.

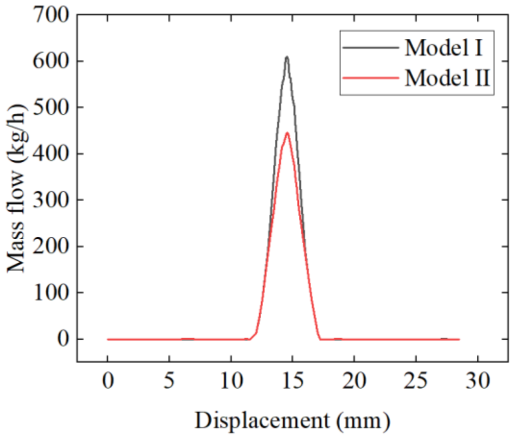


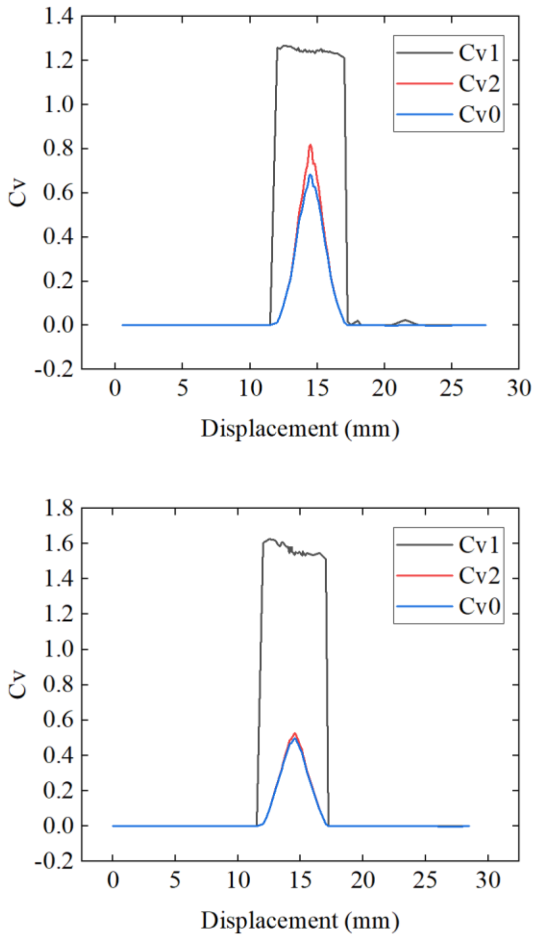
Figure 14. Variation of flow with slide displacement.

4.1.5. Analysis of leakage capacity during reversing process

There are two positions in the four-way reversing valve that cause pressure drop during the reversing process, first between the D pipe and the valve chamber, and secondly between the valve chamber and the S pipe. For the convenience of description in the text, they are referred to as the inflow and outflow gaps, respectively. In order to analyze the impact of the inflow gap and outflow gap on the refrigerant leakage capacity during the reversing process of the four-way reversing valve, the inflow gap flow coefficient Cv1, outflow gap flow coefficient Cv2, and four-way reversing valve flow coefficient Cv0 were calculated, and a detailed analysis was conducted on the three factors.

From Figure 15, it can be seen that when the slider displacement is less than 12mm or greater than 17mm, the four-way reversing valve is in a non-flow state; When the displacement of the slider is between 12mm and 17mm in the middle range, Cv1 shows an instant increase followed by a small decrease, and then an instant change to 0. The variation pattern of Cv2 and Cv0 is first increasing and then decreasing, and a significant peak appears at 14.5mm in the middle position of the commutation. This indicates that in the middle range of the reversing valve, the position of the slider has a small impact on the inflow clearance Cv1 of the four-way reversing valve, while it has a significant impact on the outflow clearance Cv2 and valve Cv0; Meanwhile, the values of valve Cv0 and outlet clearance Cv2 are relatively close, indicating that outlet clearance has a decisive impact on valve Cv0. From the figure, it can also be seen that compared to Model I, Model II has an increase in Cv1 and a decrease in Cv2, while Valve Cv0 ultimately shows a decrease, once again proving that the outflow gap has a significant impact on Valve Cv0.

a. Model I



b. Model II

Figure 15. Variation of Cv value with slide displacement.

4.2. Analysis of the slider structure of a four-way reversing valve

In order to analyze the factors that affect the reversing process and pressure relief ability of the four-way reversing valve, the height and length of the slider was changed based on the two models for analysis.

4.2.1. The Influence of slider height and Length on pressure relief capacity

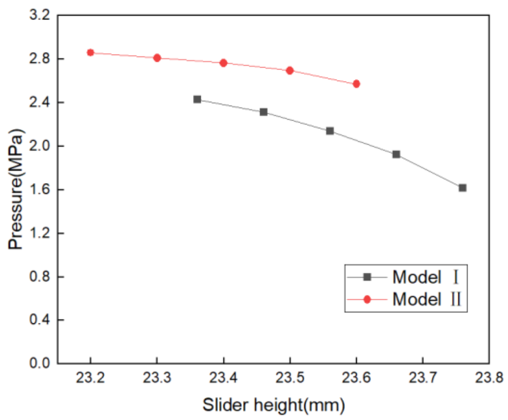


Figure 16. Variation of pressure in valve chamber with slider height.

Analyze the impact of different slider heights on the pressure relief ability of the four-way reversing valve. From Figure 16, it can be seen that as the height of the slider increases, the pressure in the cavity of the four-way reversing valve gradually decreases, and the decrease shows an increasing trend as the height of the slider increases. The main reason for the decrease in pressure inside the valve chamber is the decrease in flow capacity into the gap, and at this time, the flow capacity of the four-way valve itself is not significantly affected. Therefore, increasing the height of the slider can reduce the pressure in the valve chamber of the four-way reversing valve, without causing a significant change in the valve Cv0 value.

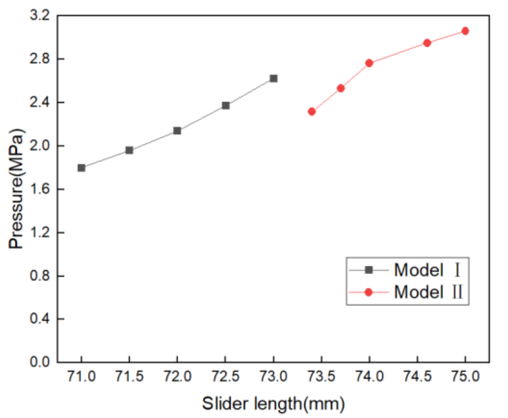


Figure 17. Variation of pressure in valve chamber with slider length.

Analyze the impact of different slider lengths on the pressure relief capacity of the four-way reversing valve. From Figure 17, it can be seen that as the length of the slider decreases, the pressure inside the valve chamber of the four-way reversing valve gradually decreases and the decrease shows a decreasing trend. This is due to the increase in the flow capacity of the clearance of the four-way reversing valve, resulting in a decrease in the pressure inside the valve chamber. In practical refrigeration systems, increasing the flow capacity of the outflow gap will cause more high-temperature gas to flow to low-temperature gas in the four-way reversing valve, thereby affecting the efficiency of the heat pump air conditioning system. Therefore, reducing the length of the slider can reduce the pressure on the slider, but it will lead to a decrease in the efficiency of the heat pump air conditioning system.

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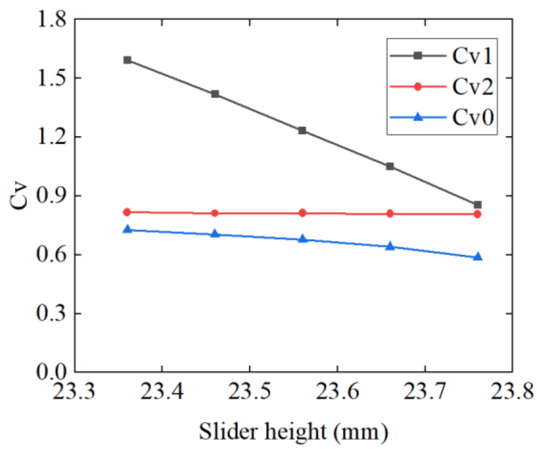
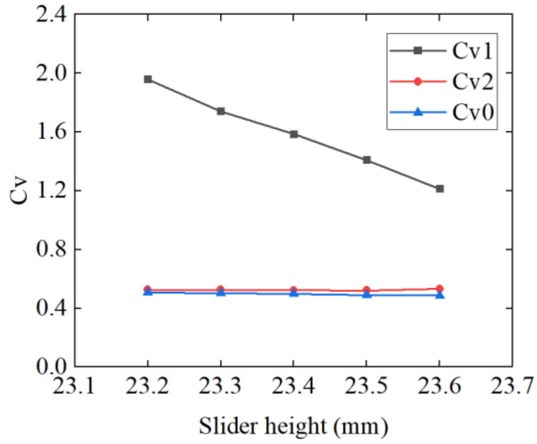
4.2.2. The Influence of slider height and Length on refrigerant leakage capacity

Analyze the impact of different slider heights on the flow capacity of the four-way reversing valve. From Figure 18, it can be seen that in Model I, as the height of the slider increases, the outflow gap Cv2 of the four-way reversing valve hardly changes, while the valve Cv0 decreases slightly with the decrease of the inflow gap Cv1; In Model II, as the height of the slider increases, the valve Cv0 and outflow gap Cv2 in the four-way reversing valve hardly change, while the inflow gap Cv1 shows a significant downward trend. Due to the increase in the height of the slider, it will lead to a decrease in the inflow gap. Therefore, the change in the height of the slider has a greater impact on the Cv1 of the inflow gap, while it has a smaller impact on the outflow gap Cv2 and valve Cv0. From the figure, it can also be seen that there is an upper limit for valve Cv0. As the height of the slider decreases, the inflow gap Cv1 gradually increases, but the valve Cv0 value gradually approaches and is infinitely close to Cv2. This once again proves that the outflow gap plays a decisive role in the refrigerant leakage of the four-way reversing valve.

a. Model I





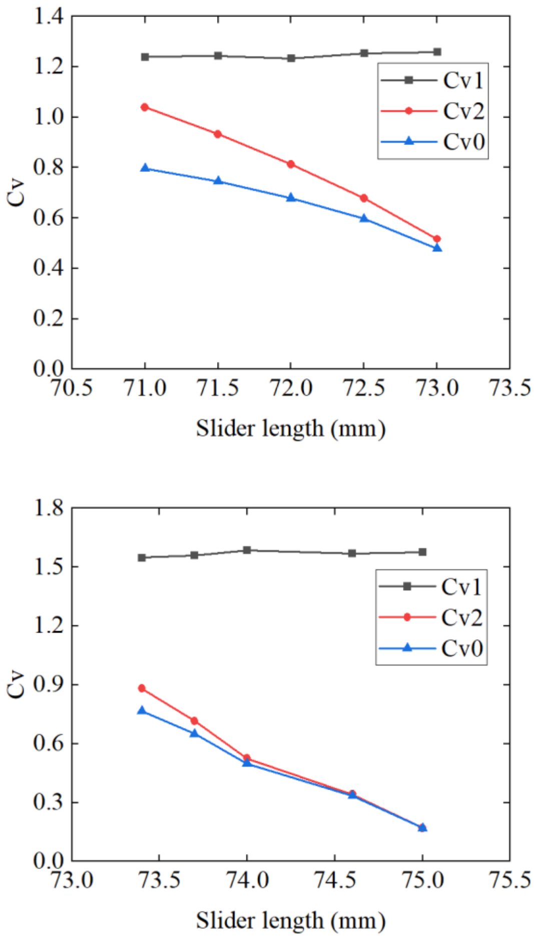
b. Model II.

Figure 18. Variation of Cv value with slider height.

Analyze the impact of different slider lengths on the flow capacity of the four-way reversing valve. From Figure 19, it can be seen that as the length of the slider increases, the inflow gap Cv1 value remains approximately unchanged, while the outflow gap Cv2 and valve Cv0 decrease simultaneously, and Cv2 and valve Cv0 gradually converge with the increase of the slider length. This indicates that the length of the slider has a significant impact on the four-way reversing valve

Cv0, and when the slider length reaches a certain value, the outflow gap Cv2 value is equal to the valve Cv0 value. This also proves that the Cv0 value of the four-way reversing valve is greatly affected by the outflow gap, while the influence of the inflow gap is relatively small or even negligible.

a. Model I



b. Model II

Figure 19. Variation of Cv value with slider length.

5. Conclusion

After verifying the accuracy and reliability of the established mathematical simulation model through experiments, this article analyzed the changes in force, pressure relief process, and refrigerant leakage process of the slider during the reversing process, and analyzed in detail the effects of changes in slider height and length on them.

(1) Based on the analysis of the transient characteristics of the reversing process of the four-way reversing valve, it is shown that the flow field and pressure field in the valve chamber are extremely unstable when the slider is in the initial and intermediate positions during the reversing process of the four-way reversing valve, which can easily induce slider vibration and increase the probability of reversing failure.

(2) Based on the analysis of the impact of slider height on pressure relief capacity and refrigerant leakage capacity, it is shown that increasing the height of the slider is not only beneficial for improving the pressure relief capacity of the four-way reversing valve, protecting the slider from damage caused by high-pressure gas impact, and ensuring the smooth operation of the directional

process. It also reduces the leakage of refrigerant during the directional process, thereby improving the working efficiency of the heat pump air conditioning system.

(3) Based on the analysis of the relationship between the length of the slider and the pressure relief capacity and refrigerant leakage capacity, it is shown that reducing the length of the slider may improve the pressure relief capacity of the four-way reversing valve, but it will increase the leakage of refrigerant and thereby reduce the working efficiency of the heat pump air conditioning system.

CRediT authorship contribution statement

Ke-Peng Zhang: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Investigation. **Da-Zhuan Wu：** Supervision, Methodology, Investigation, Funding Acquisition. **Ya-Dong Yuan:** Software, Methodology. **Jia-Feng Zhu:** Validation, Investigation. **Zhong-Bo Feng:** Supervision, Project administration. **Jian-Jun Li:** Supervision, Project administration. **Li-Hua Xuan:** Validation, Resources.**Yun-Jun Xiong:** Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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