Study on dynamic characteristics of a combined air pressure reducing valve

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ABSTRACT

Aiming at a kind of combined high pressure reducing ratio air pressure reducing valve with two stages in series, computational fluid dynamics (CFD) method is used to study the flow field characteristics of the pressure reducing valve. For different pressure reducing states, the dynamic characteristics of the pressure reducing valve are studied through unsteady simulation, and the variation law of characteristic parameters with time in typical processes such as starting, pressurization and decompression is analyzed. The results show that the variation law of the parameters such as pressure of the chamber and flow rate of valve is different in different pressure reducing states and working processes, but the flow field of the pressure reducing valve has reasonable aerodynamic damping characteristics, which can achieve stable operation in the regulation process in a large range of pressure reducing ratio, and has good dynamic characteristics.

INTRODUCTION

Air pressure reducing valve is a common device in the accessories of aeroengine control system, which has an important application in the control system (Tian Zhanqiang, 2014). In addition to meeting the requirements of precision, pressure reduction ratio and regulation range, the air pressure reducing valve is also required to have a fast response when the working state changes and quickly establish a new equilibrium state. The dynamic characteristics is one of the important research directions of air pressure reducing valves.

In some operating environments, the dynamic changes of pressure, flow and other parameters in the process of starting, adding and reducing pressure of pressure reducing valve are also demanding higher requirements. When the working state changes, the volume effect, local separation and even shock wave may occur in the filling process of the airflow in the complex channel, which makes the modeling and analysis of the dynamic characteristics very difficult, and the accuracy of the theoretical analysis is not high, so the experimental method becomes a common method (Gao et al., 2002; Tang et al., 2009; Gao Hong et al., 2002; Tang et al., 1995; Wang et al., 2011; Jiang Yunchun and Wang Haiyan, 2018). However, the test method can only measure limited physical quantities, and it is difficult to analyze the details of the flow field. Moreover, for the high sensitivity pressure reducing valve with short reaction time, its response time can reach the order of several milliseconds, which asks for high requirements for the test device. With the wide application of computational fluid dynamics (CFD) in flow field simulation of hydraulic and pneumatic components, it provides support for the research of pressure reducing valve characteristics. In the research of pressure reducing valve dynamic characteristics, the numerical method has been gradually applied. Chen Yang (Chen et al., 2006) and others used the finite volume method to simulate the dynamic characteristics of a pressure reducer, and analyzed the dynamic response process of the pressure reducer; Zheng Li (Zheng, 2018) used the numerical method to carry out the dynamic simulation of the flow field in a large flow pressure reducer; Zhao Dalei (2010) carried out simulation of static and dynamic characteristics of pneumatic pressure reducing valve; Satoru Hayashi et al. (Satoru et al., 1998; Chen Xiaqiu, 2006; Yang Mingguo, 2010; Zhang et al., 2004) carried out dynamic process simulation based on the numerical method.
to study the dynamic response process of pressure reducing valve according to different structure types and application requirements. These studies show that the numerical method is a feasible way to study the performance of air pressure reducing valve.

Although much work has been done on the dynamic characteristics of pressure reducing valves, there are significant differences in the working principle and structure, flow process and dynamic response of different pressure reducing valves, and the analysis of flow characteristics of specific pressure reducing valves cannot be generalized. In this paper, a two-stage combined air pressure reducing valve which can achieve a large pressure reduction range is studied. Based on the numerical method, the flow field characteristics of the pressure reducing engine are analyzed, and the dynamic response process of the pressure reducing valve under various working conditions is studied. By analyzing the influence law of geometric parameters, it can provide a reference for future design and optimization.

1 COMPUTATIONAL MODE

1.1 GEOMETRIC MODEL

The combined pressure reducing valve is composed of two-stage valve bodies of column valve and needle valve in series. A mixing chamber is set between the two-stage valve bodies. Through the continuous pressure reduction of the two-stage valve body, a larger pressure reduction ratio is achieved for the high-pressure air flow. The geometric model of the valve body is shown in Figure 1.

A is the inlet of the pressure reducing valve. After the high-pressure air enters the valve body, it first reduces the pressure through the column valve. By adjusting the position of the spool 1, the primary cylinder valve forms a gap with the housing2. The gap of Δx1. When the inlet pressure is higher, the air velocity increases, and the high-speed air flow along the axial direction changes direction twice when it passes through the slit, resulting in greater pressure loss, thus reducing the pressure. The reduced pressure air flows through the mixing chamber 3 and then continues to flow into the needle valve. When passing through the annular contraction expansion channel of the needle valve, Just because the large pressure difference between the outlet and the outlet C, the air flow accelerates in the channel. With the increase of the flow speed, the pressure decreases, and the low pressure air flow is bled out at the appropriate position C for gas flow control.

1.2 CALCULATION SETTING

According to the structural characteristics and working principle of the combined pressure reducing valve, the main control parameter is clearance Δx1. In the simulation of dynamic characteristics, the inlet pressure of the pressure reducing valve is 1.0MPa, and the bleed position C (Fig. 1) is 5mm away from the throat of the needle valve, The simulation is carried out under two working conditions of Δx1.

<table>
<thead>
<tr>
<th>working condition</th>
<th>Clearance Δx1/mm</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
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</tbody>
</table>

2 NUMERICAL MODELING

2.1 MESH GENERATION AND BOUNDARY CONDITIONS

According to the geometric channel characteristics of the combined pressure reducing valve, a two-dimensional axisymmetric numerical model is established. A simple topological surface is generated by subdividing the flow channel in the pressure reducing valve geometry. The entrance cavity, mixing cavity and needle valve passage are regular rectangular areas, which are divided into high-quality quadrilateral grids. The meshes in other regions also avoid large distortion, and the quality of the full-flow structured meshes is high. In addition, when meshing, the areas with large
parameter changes, such as the clearance of the cylinder valve, the wall, and the throat of the needle valve, are densified. About 130000 computational grids are generated.

![Computational grid and boundary conditions](image)

**Fig. 2  Computational grid and boundary conditions**

According to the geometry and working conditions of the pressure reducing valve, there are four types of boundary conditions. The inlet of the valve body is the pressure inlet boundary, and the inlet gas pressure and temperature are specified. The outlet of the valve body is determined as the outlet pressure boundary according to the actual working state. Because the dynamic process is very short, the heat exchange between gas and wall is not considered. In addition, the numerical calculation is a two-dimensional model, and the central axis of geometry is the boundary of symmetry axis.

### 2.2 NUMERICAL SOLUTION

Based on the finite volume method, the time-dependent coupled implicit method is used to solve the governing equations. The second order central difference scheme and the second order upwind scheme are used to discretize the diffusion and convection terms in the governing equations. Considering the complexity of no flow regime in the pressure reducing valve, turbulence model RNG κ – ε is selected.

### 2.3 UNSTEADY CALCULATION STRATEGY

In the unsteady calculation, the calculation strategy is different from the steady calculation, mainly reflected in the change of time step. For the unsteady calculation, the choice of time step is very important, and the trade-off between calculation time and convergence is needed. The size of the combined pressure reducing valve body is smaller, the air flow filling process is faster, and the requirement of time step is smaller.

In order to verify the unsteady modeling method and determine the selection principle of time step, the dynamic process of fixed cavity air filling was simulated. The calculation model and main dimensions are shown in Figure 3. The right cavity volume is close to the pressure reducing valve cavity volume. In this model, the left and right sides are respectively the inlet cavity and the stagnation cavity, which are connected by the thin tube in the middle. In the initial state, the pressure in the right chamber is the standard atmospheric pressure, while the pressure in the left chamber is 1MPa. The middle thin tube suddenly opens, and the left air flow is driven by pressure and enters the right cavity through the thin tube. Taking the time step Δt as 1e-6s, 2e-6s and 5e-6s, the variation of the pressure in the stagnation chamber and the flow rate in the middle tube are studied.

![Schematic diagram of calibration model](image)

**Fig. 3 Schematic diagram of calibration model**

FIG. 4 shows the variation of the flow with time, which flows through a φ1mm hole in the center. From the result curve, at the initial time, the flow rate through the middle tube increases rapidly from zero, and stable flow can be achieved in a short time. After that, the flow rate remains unchanged for a period of time. The reason is that the pressure difference between the two sides of the tube is large, which is for the large initial pressure difference, and the sonic flow is achieved in the straight tube. With the increase of gas flow, the pressure of the right stagnation chamber increases gradually. When the pressure ratio reaches a certain value, the flow velocity in the tube decreases gradually from the choked state, and the flow rate also decreases continuously. The change of flow rate with time is consistent with the
theoretic. According to the pressure change process in Fig. 5, the pressure in the stagnation chamber increases linearly with time at the initial stage, and the pressure increase rate decreases gradually with the decrease of flow rate through the middle tube after 8 ms.

Compared with the results of different time steps, the maximum flow condition is maintained for different periods. When the simulation time step is 1e-6s and 2e-6s, the maximum flow state and the change rate of the flow curve have been relatively close. When the time step is 5e-6s, the convergence in each time step is poor, and the change rate of pressure with time is obviously low. From the above analysis, it can be seen that the value 1e-6s of time step Δt is reasonable.

3  SIMULATION CALCULATION AND ANALYSIS

3.1 STEADY FLOW PROCESS

Firstly, for the working condition ΔX1 =0.8mm, the steady-state flow field parameter distribution is calculated, and the Mach number, total pressure and static pressure distribution of flow field in condition 2 are shown in Fig. 6 ~ Fig. 8 respectively. It can be seen from the Mach number distribution in Fig. 6 that the high pressure gas at the inlet has experienced subsonic, transonic, supersonic and other different velocity courses in the flow process of the pressure reducing valve passage. At the gap area a of the first stage cylinder valve, the flow is accelerated to supersonic speed due to the contraction of the flow passage area, and then the shock wave is generated at the gap outlet, which reduces to subsonic speed and flows to the needle valve in the central area of the mixing chamber B. In the contraction expansion channel of the needle valve, the air flow accelerates again to reach the sound speed at the annular throat C, and then the speed increases further to exhaust to the environment. The bleed channel D is located behind the throat, with small amount of bleed air and low flow rate, which is close to the stagnation state.
Fig. 6  Mach number distribution

Combined with the static distribution of the total pressure in Fig. 7 and Fig. 8, the total pressure of the air flow after passing through region A decreases obviously due to the loss of the gap flow and shock wave, and the distribution tends to be uniform in the mixing cavity. In the process of the flow in the needle valve, the viscous loss only occurs near the wall due to the influence of the boundary layer, and the total pressure of the main flow is basically unchanged. The total pressure in cavity D is significantly lower than that in the main flow area. According to the static pressure distribution figure 8, the static pressure gradually decreases along the flow direction. The static pressure in gap A of the cylinder valve decreases significantly due to the large total pressure loss and the acceleration of flow; The static pressure distribution of mixing chamber B is almost uniform. Due to the increase of flow velocity in the needle valve, the static pressure decreases rapidly, and the bleed position is behind the throat, so the pressure is relatively low.

Fig. 7 Total pressure distribution

Fig. 8 Static pressure distribution

The above distribution of flow field parameters shows that the principle of the two-stage pressure reducing principle of the combined pressure reducing valve is different. The first stage cylinder valve reduces the pressure by losing the total pressure, while the second stage needle valve reduces the static pressure at the intake position by increasing the flow rate.

3.2 START UP PROCESS

The unsteady simulation is carried out, and the flow in the starting process of the two conditions is shown in Figure 9. From the change process of flow with time, at the initial stage, because the cavity has a certain volume, and the gas flow through the slit is limited, the filling needs a certain time course, the pressure of flow path and the flow of pressure
reducing valve will change with time, until the equilibrium state is reached. The results show that the flow rate under the two conditions exhibits decaying oscillations, which indicates that the pressure reducing valve has good response characteristics. The time history is divided into two stages: A and B. In stage A, the flow oscillation increases with the time. At stage B, the flow rate changes monotonously and remains unchanged after for case 2, it settles after probably 3ms rather 2 ms. From the comparison of the two working conditions, the clearance of the column valve is smaller under case1 condition, the amplitude and time of flow fluctuation constrained by the clearance of the column valve are smaller than that of case2, and the flow rate is relatively small when the flow reaches the steady state.

Fig. 9 Mass flow time history of the pressure reducing valve

Fig. 10 and Fig. 11 show the pressure change process of mixing chamber and bleed chamber respectively. The pressure is the average of the section in the mixing chamber and the mass at the outlet of the entrain chamber. It can be seen that the pressure of the mixing chamber fluctuates slightly at the initial time of the start-up of the pressure reducing valve, and the pressure increases continuously with the continuous entry and filling of the inlet air. In region A, the pressure rise rate is larger, with the increase of time, when the pressure in the mixing chamber increases, the pressure difference between the two sides of the clearance of the first stage column valve decreases, the flow through the column valve also decreases, and the pressure rise in the mixing chamber slows down, and gradually stabilizes in region B. Under two different working conditions, the clearance When Δx1 is 0.8mm, the pressure of mixing chamber in condition 2 is higher than that in condition 1.

From the pressure time history of the bleed chamber, the pressure time evolution of the two working conditions is similar. After that, with the increase of the flow velocity in the needle valve, the pressure decreases and the pressure in the bleed chamber decreases sharply. After reaching the minimum value, the pressure in the mixing chamber rises again until it reaches a stable state. From the change trend of pressure, The value of the first pressure peak in condition 1 with 0.2mm clearance Δx1 is significantly higher than the steady-state value, and has negative regulation characteristics, and the pressure trough is even lower than the normal pressure. After stable operation, the pressure of condition 1 with 0.2mm clearance is lower, that is, the pressure reduction ratio of condition 1 is greater than that of condition 2.

Fig. 10
Pressure change process of mixing chamber
3.3 PRESSURIZATION PROCESS

When the inlet pressure changes, the original flow equilibrium state changes, and the distribution of flow field parameters will reach a new equilibrium state from a stable state. In this process, the flow parameters will be adjusted dynamically.

According to the given working condition, the parameter dynamic response of pressurization process is calculated. In the calculation process, the stable working state is calculated according to the inlet pressure firstly. On the basis of the initial stable flow state, the 1.5 times step change boundary condition of the inlet pressure is set at 5ms, and the dynamic analysis of the pressurization process is carried out. The change of characteristic parameters is shown in Fig. 12 ~ 14.
Comparing with the parameter change curve in FIG. 12, it can be seen that the change laws of the two different working conditions are consistent. After the increase of inlet pressure, the flow rate has a certain amplitude fluctuation and increases, and the oscillation amplitude decreases rapidly. After about 10 cycles, the vibration is eliminated, and then the flow rate increases monotonously, and reaches a new equilibrium state in about 2ms. The pressure in the mixing chamber fluctuates slightly at the initial time, then increases gradually and reaches a stable state in about 2 ms, and the change process is similar to the start-up state. Compared with FIG. 14 and FIG. 11, the pressure change of the bleed chamber is different from the start-up state. Since there is no flow establishment process, it starts from an equilibrium state, and the pressure of the intake chamber does not fluctuate, but increases monotonously to a new equilibrium state. In addition, the start time of pressure increase in the intake chamber is slightly delayed compared with the sudden change of inlet pressure.

3.4 DECOMPRESSION PROCESS

The decompression process corresponds to the pressurization process. Firstly, the steady state is calculated, and the inlet air pressure step is reduced to 2/3 of the original value at the time of 10ms. The change of pressure reducing valve parameters is shown in Fig. 15 ~ Fig. 17.

When the inlet air pressure decreases, the flow of the pressure reducing valve also decreases. It can be seen from Figure 15 that the flow rate in the initial section still fluctuates and decays rapidly. After about 0.5ms, it begins to decrease monotonously until it reaches a stable state about 2ms. Through the analysis of the specific value, we can see that the flow rate through the pressure reducing valve is basically equal to the inlet air pressure.

From Fig. 16 and Fig. 17, it can be seen that the pressure of mixing chamber and bleed chamber both show a monotonous downward trend. The pressure of mixing chamber fluctuates slightly at the initial time of pressure step, and the pressure of bleed chamber decreases slightly later. The variation law is similar to the pressurization process. In terms of time history, after about 2 ms, the flow rate and characteristic area pressure can approach the new equilibrium state, which indicates that the combined air pressure reducing valve has good dynamic characteristics.
4 CONCLUSIONS

In this paper, the dynamic characteristics of a two-stage combined air pressure reducing valve are studied by unsteady numerical calculation method:

1. Under different working conditions, the change of flow rate can be divided into two stages. At the initial stage, the flow rate shows oscillation characteristics, and the amplitude decays rapidly. At the second stage, the flow rate changes monotonously and approaches the steady value after about 2 ms;

2. The pressure change process of the mixing chamber is basically similar under different working conditions, which changes monotonously after a slight oscillation and stabilizes to a new working state;

3. During the start-up process, the pressure of the bleed chamber changes alternately from increase to decrease to increase, while it changes monotonously after a slight delay in the process of pressurization and decompression;

4. Under two different calculation conditions, the dynamic changes of parameters are similar, and they can work stably in the new state, but the steady-state values are different.

The simulation results show that under different working conditions, the flow rate, pressure and other parameters of the combined air pressure reducing valve can approach the steady-state value in about 2 ms, and there is no long-time large amplitude waveform of the parameters, which indicates that the flow channel of the pressure reducing valve has good dynamic characteristics and working stability.

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