Numerical Study on Flow Regulation Characteristics of High Temperature Jet Vortex Valve

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Abstract. The use of a high-temperature jet vortex valve without moving parts for the secondary jet of the vector nozzle can meet the needs of the secondary jet flow regulation of the vector nozzle in a high temperature and high pressure environment. The high-temperature jet vortex valve is a valve device with a certain amplification effect that uses a small cold flow to regulate a large flow of high-temperature gas flow. This paper uses numerical simulation to investigate the flow field distribution and flow adjustment characteristics of the vortex valve in different control pressure ratio when the main gas pressure of the vortex valve is 16 MPa and the temperature is 2500K. The results show that the high-temperature jet vortex valve relies on different radial pressure gradients generated by different control flow pressures could achieve the effect of adjusting the flow rate of high-temperature and high-pressure gas. The results proved the feasibility of the vortex valve in adjusting the secondary jet flow rate of the nozzle; further exploring indicated that the flow adjustment ratio TD will change when the ratio of the control flow port area to the outlet area changes.

1. Introduction
Due to the increasing mobility of weapons in modern warfare, in order to meet the requirements of aircraft higher attack speed and high maneuver, there is an urgent need for engine thrust vector adjustment technology that can adjust the thrust magnitude and direction in real time.

At present, there are mainly two types of thrust vector adjustment schemes: Mechanical Thrust Vector Control(MTVC) and Fluid Thrust Vector Control(FTVC). MTVC scheme is implemented by the mechanical thrust vector nozzle. This scheme adjust the nozzle by directly changing the nozzle mechanical structure to achieve Mainstream deflection. FTVC scheme adjusts the mainstream direction of the nozzle by injecting a secondary flow into the nozzle expansion section to achieve thrust vector adjustment [1]. Among them, there are many problems and deficiencies in the mechanical thrust vector nozzle scheme: there are many moving parts, the mechanical structure is complex, and the weight gain is obvious. In contrast, the fluid thrust vector nozzle has no large servo mechanism, and has a stable surface structure, with the advantages of good sealing performance and simple structure, the fluid thrust vector control technology has gradually become the research hotspot and the development frontier of aircraft thrust vector control. It also has a wider application prospect and engineering value.

The working principle of the FTVC is shown in Figure 1 and Figure 2. In the expansion section of nozzle, the main flow of the nozzle flows at supersonic speed, and a secondary flow is injected into the opening of the nozzle expansion wall to compress the main flow of the nozzle. The oblique shock wave is generated in the flow field, and the main flow of nozzle deviates from the original direction after the
oblique shock wave, and forms a certain angle with the nozzle axis, so that the nozzle generates a certain thrust vector.

According to the source and nature of the secondary flow, the secondary flow supply system is divided into two types: Gas Split type and Cold Air type. As shown in Figure 1, the secondary flow used in the Gas Split-type solution takes the high-temperature gas in the combustion chamber of the engine. However, this solution has the difficulty of developing a flow regulating gas valve in a high-temperature and high-pressure environment and is not suitable for long-term work. The secondary flow used in Cold Air type comes from an independent gas cylinder, as shown in Figure 2. The flow rate is adjusted by adjusting the pressure of the gas cylinder. In this scheme, but the secondary flow comes from the compressed gas in the gas cylinder, so the larger gas cylinder needs to carry more that provides a secondary flow, which undoubtedly increases the negative mass of the engine [2].

Combining the gas split type and cold air type solutions, this paper proposes the application of a high-temperature jet vortex valve to a secondary jet supply system of thrust vectors. As shown in Figure 3, the high-temperature jet vortex valve uses a micro gas cylinder to provide a small amount of control flow for adjusting the high temperature and high pressure gas flow which from the combustion chamber. Compared with the mechanical valve in the gas split scheme, this structure does not require a gas valve under high temperature and high pressure working conditions. At the same time, it can achieve high temperature and high pressure down injection by carrying a relatively small amount of external gas. The secondary jet flow of the tube is adjusted to achieve ‘big and small’. The high-temperature jet vortex valve scheme is completely adjusted by the gas, and has the advantages of fewer mechanical moving parts and compact structure.
The research shows that the flow regulation characteristics of the vortex valve have certain engineering application value. R S Lin [3] performed flow regulation ability analysis on 11 different structures of the vortex valve used in the aero-engine fuel supply system. Results show that when the ratio of the control flow pressure to the mainstream pressure is 1.008, the TD ratio is 2.9, and when the nozzle is increased at the outlet, the TD ratio is increased to 4.2. A Blatter [4-5] applied the vortex valve concept to the variable thrust adjustment of the solid rocket motors, and carried out experimental research by building an axial jet vortex valve platform. The results show that adjusting the combustion chamber pressure through the vortex valve can achieve the thrust control of the engine, and put forward the conclusion that increasing the temperature of the control flow will increase the vortex valve flow adjustment range. R J Woolhouse [6] analyzed the eddy current field in the gas turbine by using numerical simulation and experimental comparison methods, and obtained a turbulence model and a physical model that can be used to calculate the vortex. The results show that the SST model is more suitable for high speed vortex than the model than $k-\omega$ model. Jawarneh [7] established a new method to study the radial pressure distribution of the angular velocity of the vortex chamber using the vortex model with a vortex valve with two supply ports, by using the continuous equation and the energy equation.

This article takes the high temperature vortex valve applied to the secondary jet of the nozzle as the research background, uses CFD numerical simulation to analyze the flow amplification mechanism of the vortex valve under high temperature and high pressure working conditions, and explores the main influence of the control flow pressure, control flow port area, which have the main influence on the flow adjustment characteristics. The purpose of this paper is to provide a reference for the subsequent design of the high-temperature jet vortex valve applied to the secondary jet of the nozzle.

2. Computational models and method

2.1. Vortex Valve Models

This paper uses a high temperature vortex valve structure consisting of a short cylindrical vortex chamber (usually the height of the vortex chamber is less than the radius of the vortex chamber) and three ports. They are the outlet end coaxial with the vortex chamber, the supply gas flow port of the radial jet and the control flow port of the tangential jet, which play a regulating role.

![Figure 4. Structural model of vortex valve.](image)

![Figure 5. Flow regulation characteristics.](image)

Figure 4 shows the basic components of vortex valve. The amplification effect of the vortex valve flow adjustment is reflected in that a larger supply flow rate could be adjusted by a smaller control mass flow. Among them, the supply flow enters the vortex chamber in a radial direction. When there is no control flow, the supply gas flow directly flows out through the outlet, while the vortex valve has the largest flow rate. With the continuous increase of the control flow rate, the angular momentum brought in induces rotation. A pressure gradient is generated in the radial direction of the vortex valve, which increases the flow resistance of the supply flow and reduces the flow of the supply, thereby generating the effect of flow regulation [8].
This paper uses the TD (Turndown Ratio) ratio to measure the effect of the flow regulating characteristics of the vortex valve. The TD ratio is defined as the ratio between the maximum mass flow rate and the minimum mass flow rate of the outlet of the vortex valve. Figure 5 shows the characteristic curve of vortex valve flow regulation under a typical working condition.

Based on the principle of vortex valve flow adjustment by establishing a pressure gradient, this paper mainly explores the characteristics of vortex valve flow adjustment when the pressure of the control flow changes, and also explores the effect of the area of control flow on the vortex valve flow adjustment characteristics.

This paper refers to the vortex valve structure designed by R K Brodersen [9] to design the physical model of the vortex valve. As shown in table 1. The design parameters are: $D_o$ (Vortex Chamber Radius) = 20mm, $D_e$ (Outlet Diameter) = 10mm, $h$ (Vortex Chamber Height) = 10mm, $A_s$ (Supply Flow Area) = 60mm$^2$, $A_c$ (control flow area) = 2mm$^2$.

| Parameter | $\frac{D_o}{D_e}$ | $\frac{A_s}{A_c}$ | $\frac{A_s}{A_c}$ | $h$ |
|-----------|-------------------|-------------------|-------------------|-----|
| Range     | 3~4              | 2.546~9.42        | 0.021~0.254       | 2.0~5.3 |
| This paper| 4 3              | 0.1, 0.15, 0.2    | 4                 |

2.2. Simulation Methods

In order to obtain accurate simulation results, this paper uses ICEM for structured mesh calculation, as shown in figure 6 and figure 7. The meshing quality is a key factor affecting the quality of calculation results. In order to improve the efficiency and quality of numerical calculations, according to the structure of the vortex valve, the calculation domain is divided into three sub-regions, and the meshes are generated and partially encrypted, which stitched by interface. The number of grid nodes of the vortex valve model is $32 \times 10^4$.

![Figure 6. Simplified model of vortex valve.](image)

![Figure 7. Computing meshing of vortex valve.](image)

For the numerical simulation of the fluid condition inside the vortex valve, there are a variety of turbulence models to choose. According to the previous research [5], the lateral dissipation derivative term is added to the SST (Shear Stress Transport) model. The transport process of turbulent shear stress, so the SST turbulence model can better describe the eddy current calculation with backpressure gradient. The SST model combines the advantages of the model calculations in the near-wall region and the features of the model in the far-field calculation. It is calculated by multiplying the two models by the mixing function. In the near-wall area, the mixing function is equal to 1, so the near-wall area is
equivalent to the $k-\omega$ model; the area far from the wall is automatically converted into the $k-\varepsilon$ model.

SST turbulence model transport equation:

$$
\frac{\partial}{\partial t}(rk) + \frac{\partial}{\partial x_i}(rk u_i) = \frac{\partial}{\partial x_i}(\Gamma_k \frac{\partial k}{\partial x_i}) + G_k - Y_k + S_k
$$

$$
\frac{\partial}{\partial t}(r\omega) + \frac{\partial}{\partial x_i}(r\omega u_i) = \frac{\partial}{\partial x_i}(\Gamma_\omega \frac{\partial \omega}{\partial x_i}) + G_\omega - Y_\omega + S_\omega
$$

In the formula, $G_k$ represents the turbulent flow energy; $G_\omega$ is the $\omega$ generated amount; $\Gamma_k, \Gamma_\omega$ represents the effective diffusivity of $k, \omega$. $Y_k, Y_\omega$ represents the dissipation due to $k, \omega$.

In the calculation of this paper, gas is used as the working fluid for the specific vortex valve structure, the changes in the pressure of the combustion chamber caused by the mainstream leading from the combustion chamber are ignored, that is, the parameters of the supply pressure and temperature of the vortex valve do not change with the control flow adjustment process. The calculated gas parameters are as follows: $c_p = 1254 J \cdot kg^{-1} \cdot k^{-1}$ (Specific Heat Capacity), $\lambda_g = 0.3946 W \cdot m^{-1} \cdot k^{-1}$ (Thermal Conductivity of Gas), $\mu = 9.2 \times 10^{-5} kg \cdot m^{-1} \cdot s^{-1}$ (Dynamic Viscosity), $R = 321.943 J \cdot kg^{-1} \cdot k^{-1}$ (Gas Constant).

Under the condition that the supply flow pressure and temperature of the vortex valve are constant, the change of the flow regulating characteristics of the vortex valve is explored by changing the control flow and the mainstream pressure ratio $P_c/P_s$. With reference to the research by Abetter [4], the supply inlet is set to pressure inlet $P_s = 16 MPa$ (total pressure), $T_s = 2500 K$ (total temperature), the control flow adopts the pressure inlet boundary condition, and the wall surface is adiabatic and non-slip wall condition. Each set of calculations is performed until the supply flow is turned off.

3. Results and Analysis

3.1. Analysis of flow field inside vortex valve

Calculating the influence of the pressure change of the control flow on the flow regulation characteristics of the vortex valve to ensure that the supply pressure and temperature remain unchanged. The flow regulation characteristics of the vortex valve are explored by changing the pressure ratio of the control flow to the supply. Flow examples used for the numerical simulations are summarized in table 2.

| Examples | $p_s$ (MPa) | $T_s$ (K) | $T_c$ (K) | $A_s$ (mm$^2$) | $A_c$ (mm$^2$) | $p_c/p_s$ |
|----------|-------------|-----------|-----------|----------------|----------------|-----------|
| 1        | 16          | 2500      | 300       | 60             | 2              | No control |
| 2        | 16          | 2500      | 300       | 60             | 2              | 1         |
| 3        | 16          | 2500      | 300       | 60             | 2              | 1.05      |
| 4        | 16          | 2500      | 300       | 60             | 2              | 1.07      |
| 5        | 16          | 2500      | 300       | 60             | 2              | 1.1       |
| 6        | 16          | 2500      | 300       | 60             | 2              | 1.2       |
| 7        | 16          | 2500      | 300       | 60             | 2              | 1.4       |
| 8        | 16          | 2500      | 300       | 60             | 2              | 1.6       |
| 9        | 16          | 2500      | 300       | 60             | 2              | 1.8       |
Figure 8. Flow characteristic curve of vortex valve.

It can be seen from figure 8 that under the condition that the supply pressure and temperature of the vortex valve remain unchanged, as the control flow pressure increases, the outlet flow of the vortex valve and the supply flow gradually decrease, finally the supply flow is completely cut off. This is because increasing the pressure and flow rate of the control flow increases the angular momentum of the control flow into the vortex chamber, enhances the rotational momentum of the vortex chamber, and increases the radial direction of the vortex chamber. The pressure gradient increasing resists the mainstream flow. It can be seen from figure 8 that when the control flow area ratio $A_c / A_e = 0.1$ and $P_s = 16$ MPa, the vortex valve flow adjustment ratio $TD = 4.6$. During this process, the control flow rate changed little, from 0.04 to 0.21, but the supply flow rate decreased from 0.92 to 0, and the vortex valve outlet flow rate decreased from 0.96 to 0.21, indicating that a small amount of control flow adjustment was used. The feasibility of the large flow main gas flow has verified the amplification effect of the vortex valve flow adjustment, which can use a small amount of control flow change to adjust the large vortex valve outlet flow.

(a) No control  
(b) $P_c/P_s = 1.2$
Figure 9. Cloud diagram of pressure distribution at X = 5mm section.

Figure 10. Y-direction pressure distribution at X = 5mm section.
Figure 11. Streamline distribution of X = 5mm section

Figure 9 and figure 10 show the pressure distribution cloud diagram and the radial pressure distribution curve of the vortex valve X = 5mm section with different pressure ratios. It can be seen from figure 9 that the pressure of the flow field inside the vortex valve is annularly distributed due to the influence of the swirling flow, and the center of the annular pressure distribution gradually approaches the geometric center of the vortex valve with the increase of the force ratio 1.8. Figure 11 shows that the flow separation phenomenon occurs when the pressure ratio is relatively low inside the vortex field, that is, reverse flow occurs inside the vortex field. When the Cut-off state is reached($P_c/P_s = 1.8$), the vortex field is almost in a vortex symmetrical state, and the pressure distribution center is almost at the geometric center of the vortex valve, the internal flow field tends to stabilize. Combining the pressure distribution cloud diagram and curve show that as the pressure ratio gradually increases, the pressure near the wall surface of the vortex chamber gradually increases, and the slope of the pressure distribution curve gradually increases. The pressure gradient inside the vortex field becomes larger, resulting in a smaller pressure drop between the supply inlet and the vortex field. Increased resistance to the supply causes mainstream traffic to gradually decrease. Therefore, by increasing the control flow pressure, the main flow has a certain inhibitory effect. When $P_c/P_s = 1.8$, the resistance caused by the radial pressure gradient is greater than the power of the supply flow to enter the vortex chamber. At this time, the main flow is completely cut off.

Combining figure 8 and figure 10, it is found that the pressure gradient of the radial pressure distribution of the vortex valve suddenly increases at a pressure ratio from 1 to 1.2, the pressure gradient of the process suddenly increases, and the sudden increase in the resistance of the vortex field to the mainstream is the main reason for the sudden decrease of supply flow in the range of 1-1.2. Within the range of pressure ratio 1.2-1.8, the pressure gradient changes little and the mainstream resistance changes slightly, so the supply flow decreases slowly in this range.

3.2. Vortex valve flow regulation performance changes when $A_c/A_e$ changes

In order to investigate the influence of the control flow area on the flow regulating characteristics of the vortex valve, calculation conditions are shown in table 3.

| Conditions | $A_c/A_e$ | $A_e$ (mm$^2$) | $D_o$ (mm) | $h$ (mm) |
|------------|-----------|----------------|-------------|----------|
| 1          | 0.1       | 20             | 20          | 10       |
| 2          | 0.15      | 20             | 20          | 10       |
| 3          | 0.2       | 20             | 20          | 10       |
Figure 12. Result of vortex valve’s flow regulation characteristics ($P_c=16\text{MPa}, \frac{A_c}{A_e}=0.15$).

Figure 13. Result of vortex valve’s flow regulation characteristics ($P_c=16\text{MPa}, \frac{A_c}{A_e}=0.2$).

Combining the flow adjustment characteristic curves with $\frac{A_c}{A_e}$ values of 0.1, 0.15, and 0.2, it can be known that with $\frac{A_c}{A_e}$ values of 0.1, 0.15, and 0.2, respectively, the vortex valve flow adjustment ratios TD are 4.6, 6.4, and 5.7, respectively. As the control flow area becomes larger, the TD ratio increases first and then decreases. It can be known from figure 12 that change the control flow area within a certain range can increase the vortex valve flow adjustment range. When $\frac{A_c}{A_e} = 0.1$, the cutting force ratio is 1.8; when $\frac{A_c}{A_e} = 0.15$, the cutting force ratio is 2.0; when $\frac{A_c}{A_e} = 0.15$, the cutting force ratio is 1.6. This is because as the area of the control flow increases, the tangential speed of the vortex valve becomes smaller and the angular momentum decreases when the same pressure ratio is used. When the cut-off effect is reached, the pressure ratio needs to be increased, and the vortex valve flow adjustment range is also increased. It can be seen from the curve in figure 13 that when $\frac{A_c}{A_e}$ increases to a certain value, the pressure ratio required for cutting becomes smaller, and the flow adjustment process of the vortex valve is more stable. The reason is that as the area of the control flow increases, the flow of the control flow varies with the pressure increase changes relatively slowly, the angular momentum brought by the control flow becomes smaller, and the pressure gradient tends to be smooth, which makes the internal flow field more stable, so the adjustment process is smoother.

4. Conclusions

In this paper, the physical model and mathematical model of the vortex valve are established to mesh the internal flow field. Numerical analysis of the flow regulating characteristics of the vortex valve applied to the secondary jet of the nozzle shows that:

1) When the mainstream parameters of the high temperature jet vortex valve are constant, depending on the radial pressure gradient generated by changing the control flow ratio, the flow rate can be adjusted for the main stream and the outlet, thereby achieving the secondary jet flow adjustment effect of the nozzle, which proves that the high temperature jet is used. The vortex valve is a feasible solution to adjust the secondary jet flow of the nozzle. With the gradual increase of the ratio $P_c/P_s$, the outlet flow of the vortex valve and the main gas flow gradually decrease, which can realize the secondary jet flow of the nozzle. Continuous adjustment, meanwhile, the high-temperature jet vortex valve scheme has the amplification effect of a small amount of control flow to adjust a larger jet flow.

2) By changing the ratio of the area of the control port of the vortex valve to the area of the outlet of the vortex valve ($\frac{A_c}{A_e}$), the flow adjustment range of the vortex valve can be changed. When $\frac{A_c}{A_e}$ is 0.1, 0.15, 0.2 respectively, the flow adjustment TD ratios are 4.6, 6.4, 5.7, and the pressure ratio when the main gas flow is cut off is 1.8, 2.0, 1.6, indicating that when the predetermined flow adjustment range of the vortex valve is reached, At this time, there is an optimal $\frac{A_c}{A_e}$ area ratio. At this time, the
ratio of the required control flow to the mainstream pressure of the vortex valve is the smallest.

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