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CFD OPTIMUM DESIGN OF SUPERSONIC EJECTOR SYSTEM STRUCTURE OF TEST CELL

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Abstract

In order to study the test requirements of vectoring nozzle aeroengine in high altitude simulation test bed, and the matching between the vectoring nozzle and the exhaust ejector of the test bed in the supersonic working state. Numerical simulation method is used to determine the straight section inner diameter, length diameter ratio and injection ratio of the exhaust ejector of the test bench, and the relative position of the vectoring nozzle and the exhaust ejector, and the aerodynamic structure of the ejector of the test bench under the condition of vectoring nozzle test. Using the typical working points of vectoring nozzle to check the applicability of the ejector aerodynamic structure, The results show that the aerodynamic structure of the ejector meets the test requirements of the vectoring nozzle.

Keywords: aerodynamic design; test bed; exhaust ejector; vector nozzle; numerical simulation

1. Introduction

The high-altitude simulation test bed strives to be able to truly and safely evaluate the engine performance and function within the aeroengine envelope [1]. The exhaust ejector system of test bed is composed of the aero-engine exhaust nozzle and the test bed ejector, the ejector decelerates and pressurizes the high-temperature and high-speed gas flow under aero-engine operating conditions, and exhausts the gas from the test bench. The working efficiency of the exhaust ejector is characterized by the pressurization ratio, and the matching between the exhaust ejector and the exhaust nozzle is determined by their size, distance and injection ratio. The temperature and velocity of the high-speed gas at the exit of the aero-engine nozzle and the low-speed gas around it exchange violently in the exhaust ejector, and the ejected gas flows back on the wall of the ejector. Under the condition of airflow oscillation, the high-temperature backflow of the ejector wall flows back into the test bench from the exhaust ejector. The high-temperature airflow causes ablation to the equipment and aeroengine in the test bench, which affects the normal operation of the engine under serious conditions.

With the development of the fourth-generation computers in the world, as the research of aero-engine with vectoring thrust is popular, it is of great significance to carry out the research of test bench with vectoring thrust test capability. When the axisymmetric nozzle aeroengine is tested in the test bed at low altitude and high Mach number operating point, If the design of the ejector system is not ideal, the phenomenon of high temperature gas backflow in the ejector is easy to occur; Under normal vectoring nozzle test conditions, it is easy to produce high temperature gas backflow due to the eccentric injection system in the test bench. In this paper, CFD method is used to simulate the phenomenon of high temperature gas backflow in the injection system of the test bench, at the same time, in order to meet the test requirements of vectoring nozzle aero-engine, the aerodynamic structure of exhaust ejector is optimized in order to realize the normal test of vectoring nozzle aeroengine on the test bench.

2. Ejection system of test bench

This paper mainly analyzes the air flow in the ejector system of the test bench composed of axisymmetric nozzle, vectoring nozzle and ejector. The flow situation of axisymmetric nozzle jet in exhaust ejector is shown in Figure 1, and that of vectoring nozzle jet in exhaust ejector is shown in Figure 2. In Figure 1, some of the secondary flow lines form a closed annular recirculation zone, and stagnation points with zero front and back velocity are formed on the walls at both ends of the recirculation zone. The whole exhaust ejector consists of high temperature and high-speed jet zone, secondary flow zone and mixing zone. The high-temperature and high-speed flow carries the ejected flow for mixing under the viscous shear force. In the mixing process, the high-temperature and high-speed jet exchanges energy with the low-temperature and low-speed ejected flow, a recirculation zone is formed at the inlet of the exhaust ejector, and the temperature and pressure of the air flow gradually increase after mixing. In Figure 2, when the high temperature and high speed vectoring flow is injected by the vectoring nozzle, a counter vortex recirculation zone is formed in the exhaust ejector, high temperature and high speed vector jet impinges on the wall of exhaust ejector to form jet impingement zone, the impinging jet and the low-temperature and low-speed air flow are strongly mixed in the ejector, the mixing flow forms a recirculation zone under counter vortex flow, after mixing, the temperature and pressure of the gas flow downstream gradually increase.

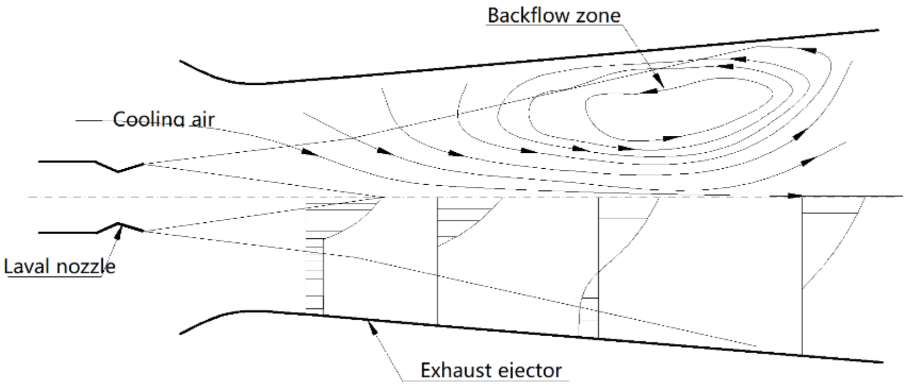


Figure 1 -Axisymmetric nozzle ejection system

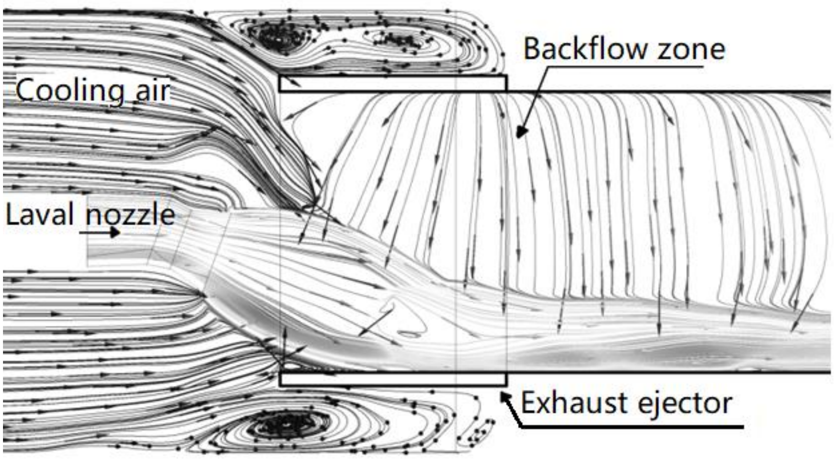


Figure 2 -Vector nozzle ejection system

3. Gas reflux phenomenon

As mentioned above, high temperature gas is easy to return in the high-altitude test chamber, this phenomenon is easy to appear under the condition of low altitude and high-speed flight test or the mismatch of the nozzle and the exhaust ejector. In order to verify the existence of this phenomenon, the unsteady CFD method is used to reproduce the gas recirculation of axisymmetric Laval nozzle under the test conditions in the high altitude cabin, Figure 3 shows the temperature field distribution at the inlet of the exhaust ejector at different times, as time goes on, the high temperature gas moves successively at the inlet of the exhaust ejector, then it flows back to the nozzle until it reaches the outer surface of the nozzle, then proceed to the next cycle. In the same way, American aero-engine test technicians also detected the high-temperature gas backflow phenomenon of axisymmetric Laval nozzle at the inlet of exhaust ejector by using thermal imaging technology [1].

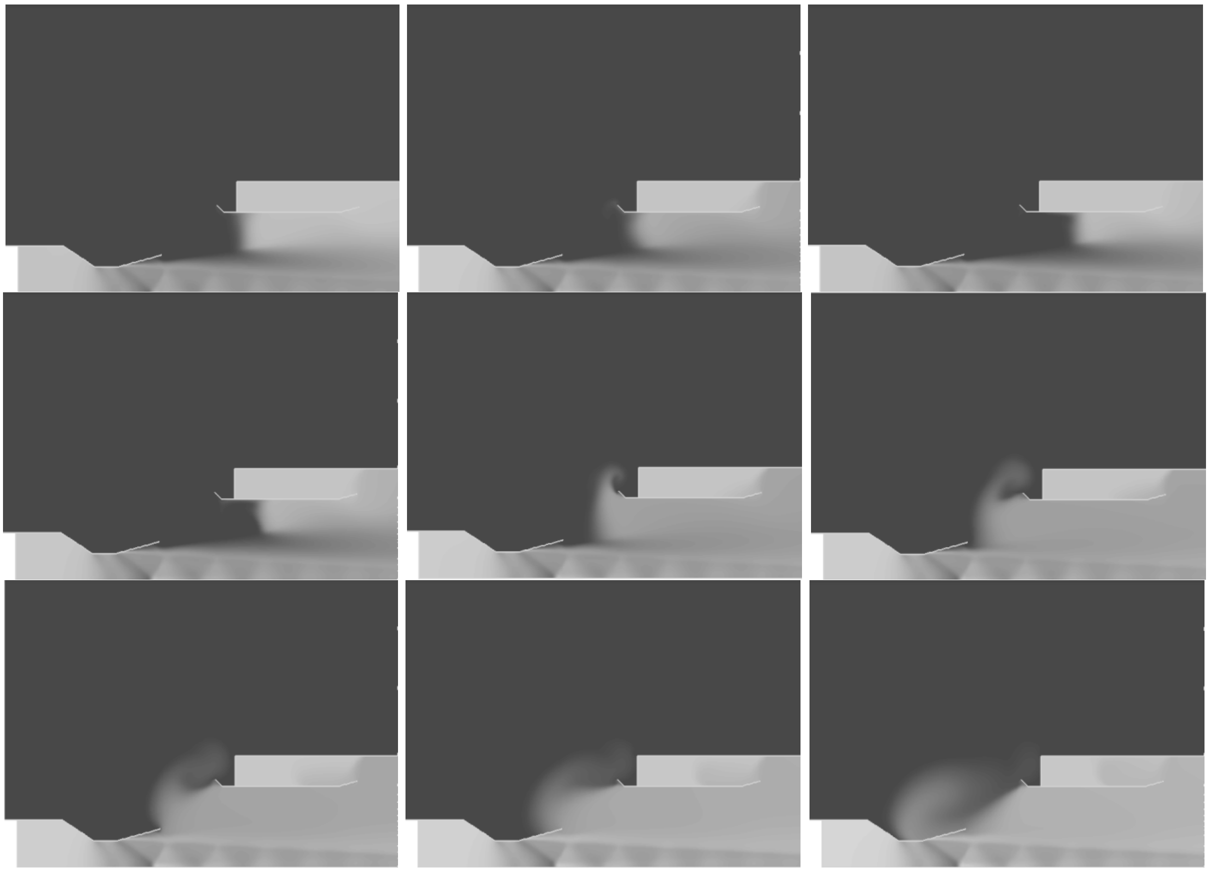


Figure 3 -Simulation result of gas backflow

It can be seen that there is gas backflow near the nozzle in the high-altitude test of axisymmetric Laval nozzle, of course, this is not expected in the test chamber. High temperature gas is easy to cause fire in the high-altitude chamber, it is also a burning threat to the surface pipeline of aeroengine. However, in the experiment of vectoring Laval nozzle, the area and intensity of gas recirculation produced at the inlet of exhaust ejector are larger than those in the experiment of axisymmetric Laval nozzle, and the flow field is more complex. It is necessary to avoid or reduce this phenomenon in high altitude test of vectoring Laval nozzle or two-dimensional vectoring nozzle engine. In this paper, CFD method is used to analyze the phenomenon of high temperature gas backflow in the high-altitude cabin, so as to avoid high temperature gas backflow in the high-altitude test.

4. Numerical Simulation

4.1 Physical model

The axisymmetric CFD method is used to simulate the aerodynamic characteristics of exhaust ejector in the test of axisymmetric Laval nozzle engine, Taking the test chamber and the central axis of the engine as the axisymmetric boundary, Ignore the structural influence of the high-altitude cabin platform and other accessories, as shown in Figure 4.

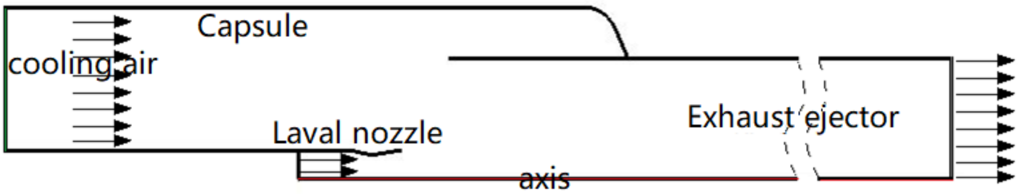


Figure 4 -Domain of axisymmetric nozzle engine test

Aerodynamic simulation of exhaust ejector for vectoring Laval nozzle engine test, the structure and flow are symmetrical, the half model is taken as the aerodynamic analysis model, similarly, the structural influence of the platform and other accessories in the high-altitude cabin is ignored, as shown in Figure 5.

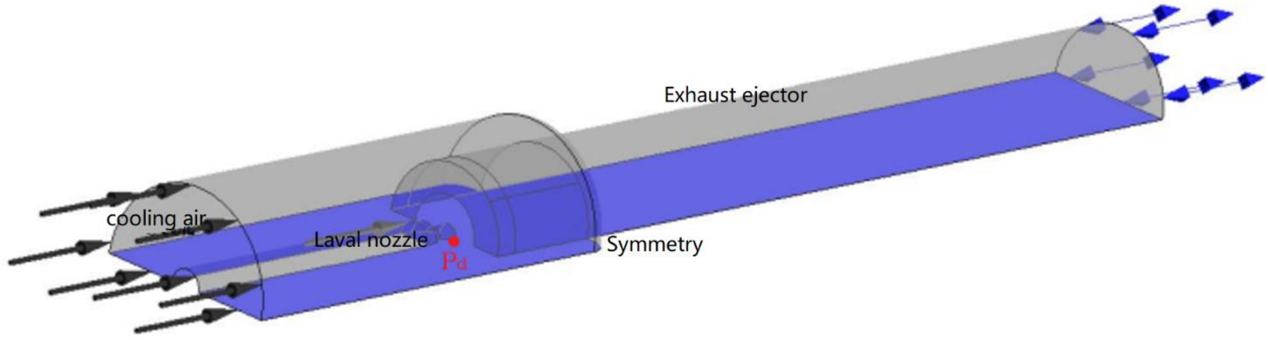


Figure 5 -Domain of vector nozzle engine test

4.2 Boundary Settings

There are two entrance boundaries and one exit boundary in the computational domain, a symmetrical boundary and other solid boundary. The interface between the inlet plenum of the high altitude test chamber and the test chamber is taken as the inlet boundary of the cooling gas in the test chamber, the mass flow rate and temperature are given according to the injection ratio; taking the nozzle inlet of the engine as the mainstream inlet boundary, given mass flow rate and temperature (according to the working state of engine); The outlet of exhaust ejector is taken as the outlet boundary, the pressure value is given according to the pressure in the test chamber (simulating the working altitude of the engine);The meridian plane is taken as the boundary of symmetry plane; The nozzle, test chamber and exhaust ejector are adiabatic solid wall boundaries.

4.3 Grid division

In this paper, two kinds of grids, two-dimensional axisymmetric structure and three-dimensional symmetric structure, are involved. The two-dimensional axisymmetric grid model corresponds to the test bench structure of axisymmetric non vectoring nozzle in high-altitude simulation test chamber, the three-dimensional symmetrical mesh model corresponds to the test bench structure in the high-altitude simulation test cabin of the axisymmetric vectoring nozzle, the quadrilateral and hexahedral elements are used for mesh generation, the mesh is locally refined near the nozzle.

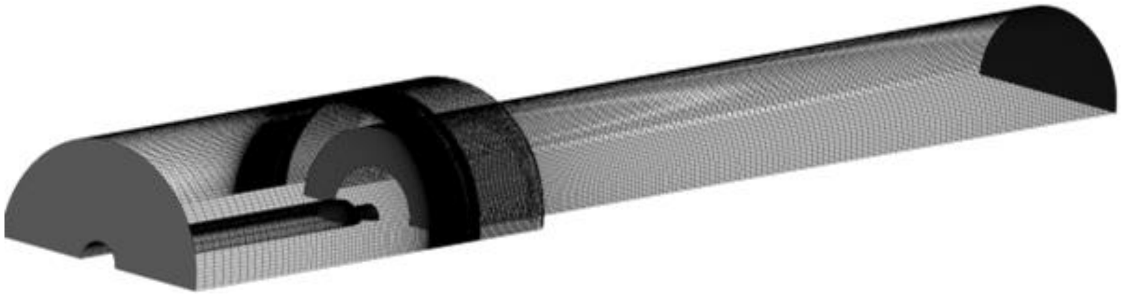


Figure 6 -Mesh of vector nozzle engine test

4.4 Grid independence

In order to obtain the ideal number of discrete elements in the computational domain, three grids with different number of discrete elements are calculated, the number of coarse grid cells is 1.1 million, the number of medium grid cells is 3.1 million, the number of fine grid cells is 5 million. Figure 7 gives the results in SST K- ω, the results of different number of grids in turbulence model [2,3], the velocity distribution along the axis is shown in the figure. It can be seen that the data of medium grid is basically consistent with that of fine grid, so medium grid is selected for subsequent calculation and analysis.

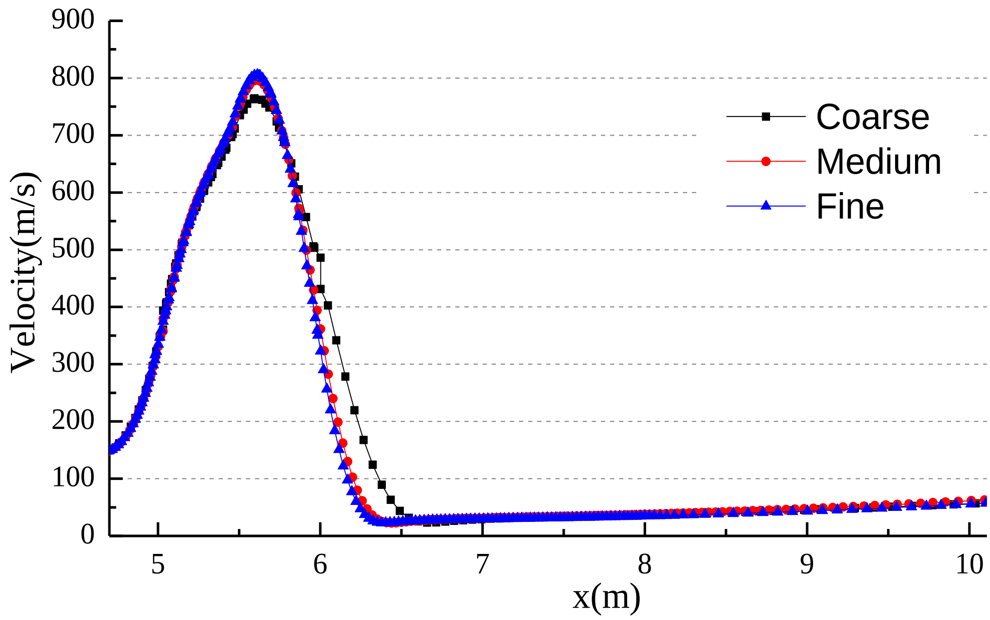


Figure 7 -Grid independence

5. Determine of the parameters of exhaust ejector

5.1 the diameter of exhaust ejector

In the case of vectoring nozzle test, the jets axis intersects with the inner wall of the exhaust ejector, the flow field is transformed into impinging jet. In the vectoring jet state of the nozzle, the geometric center line of the flow does not coincide with the aerodynamic center line, and the deflection angle of the aerodynamic center line is generally 3°～ 4°. In the case of positive impact, the basic flow field of impinging jet is divided into three parts: free jet zone, impinging zone and wall jet zone. The flow field structure of oblique impact is similar to that of normal impact, the difference is that on the side near the wall, the free jet zone will shorten to varying degrees according to the impact angle, and the velocity and pressure distribution will change accordingly, the stagnation point will deviate from the geometric intersection of the axis for a certain distance, and the whole flow field shows obvious asymmetric characteristics [4].

In the book "jet theory and application", Ping-Jun expounded the formula for the distribution of the initial section of circular jet [5].

$$\frac{r_1}{r_0} = 0.95 - 0.097\frac{x}{r_0} \tag{1}$$

Where x is the distance between the studied section and the nozzle, r0 is the exit radius of the jet nozzle, r1 is the radius of the core region of the jet. The section with r1 = 0 is the end section of the core area, and the corresponding x value of the section is the length of the core area. By substituting r1 = 0 and the known value of r0 into the formula, the core length S0 can be obtained.

The calculation method of the length of the core region is described in the ejector [6] by Sokolov et al.

$$s_0 = 6r_0 \tag{2}$$

The meaning of the formula is that the length of the core area is equal to 6 times of the nozzle radius. The results show that the core length of the latter method is 38% smaller than that of the former method. In this paper, the mean value of the two methods is taken.

5.2 Aerodynamic simulation of axisymmetric retractor-expansion nozzle test

An important index for designing exhaust ejector is the critical expansion ratio of exhaust ejector (i.e., the nozzle pressure drops ratio of the ejected flow in the exhaust ejector under critical conditions). The envelope should cover the pressure drop ratio envelope of the tested nozzle. Taking the nozzle outlet inner diameter as D and the exhaust ejector inner diameter as 2.2D, the simulation analysis is carried out with the test point parameters of larger nozzle expansion ratio.

Figure 8 gives the calculation results of exhaust ejector inner diameter 2.2D. It is difficult to determine the outlet pressure of exhaust ejector in calculation, when the pressure is adjusted to the set range, the engine nozzle will expand excessively and block the exhaust ejector. When the ambient pressure near the nozzle outlet is stable at a certain value, the jet still overflows into the back cabin of the test chamber. With the increase of pressure near the nozzle, although the exhaust ejector can work normally, the nozzle pressure drop ratio has deviated from the working point.

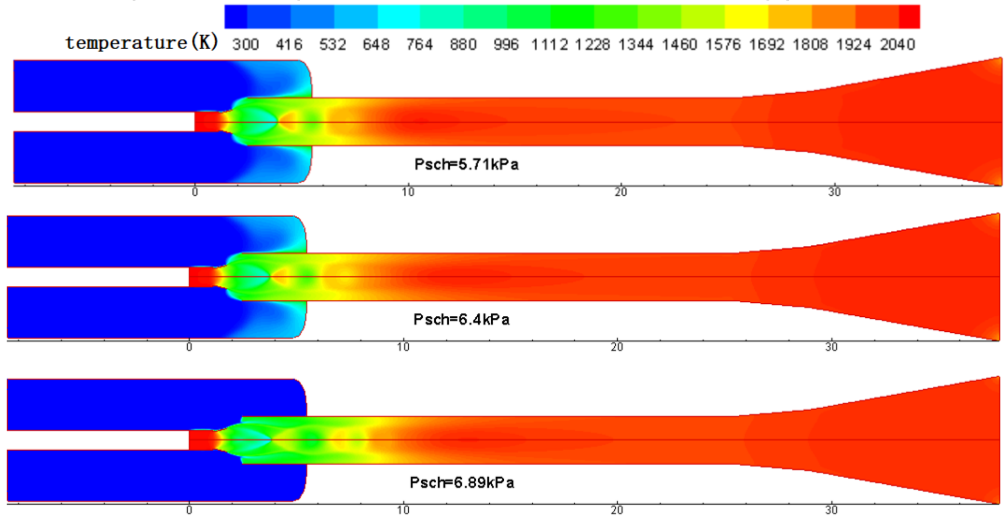


Figure 8 -Simulation results under different environmental pressure conditions

As a result, 2.2D inner diameter of exhaust ejector is not enough to contain the flight envelope of the tested nozzle, the diameter of exhaust ejector should be increased. According to the theoretical calculation of critical expansion ratio, the exhaust ejector with 2.4D inner diameter can meet the demand, at the same time, the inner diameter of 2.6D and 3D exhaust ejector were simulated, the nozzle drop pressure ratio works within the range of exhaust critical expansion ratio, and there is no gas return in the cabin, as shown in Figure 9.

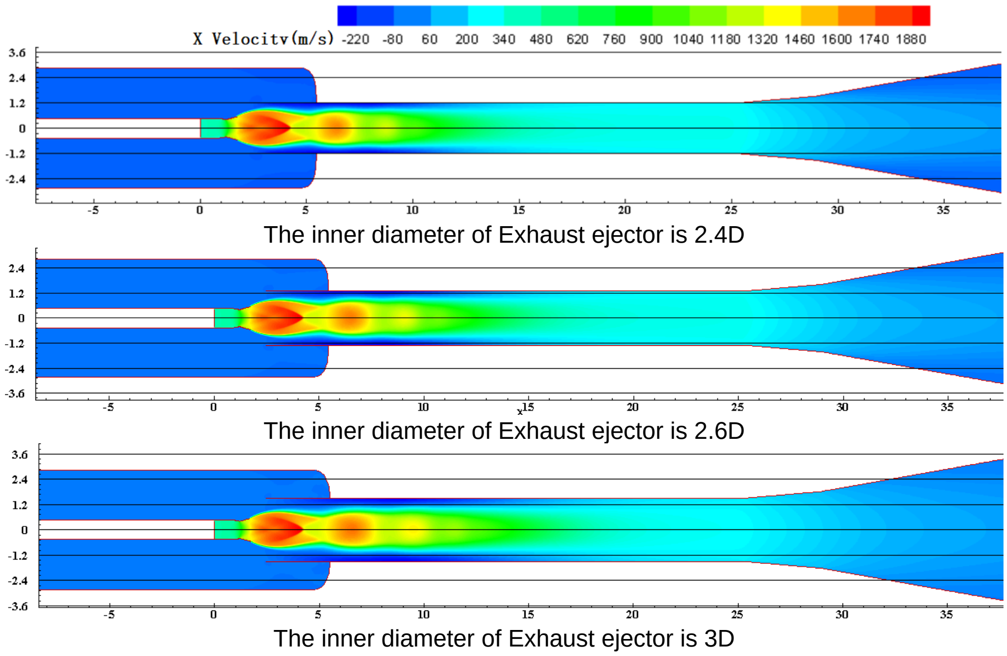


Figure 9 -Velocity distribution of different diameter exhaust diffuser

To sum up, the simulation results at the working point with large expansion ratio show that the nozzle has a high expansion ratio, to meet the test requirements of full envelope test point of axisymmetric convergent divergent nozzle with outlet inner diameter D, the inner diameter of exhaust ejector should not be less than 2.4D

5.3 Simulation of axisymmetric retraction-expansion vector nozzle free jet flow

As the same as above, the point with larger drop pressure ratio of nozzle is used to calculate the air flow under the condition of free jet. When the outflow velocity is set to zero, the ambient pressure of the vectoring nozzle is given, the jet parameters of the nozzle are given according to the working parameters of larger drop pressure ratio. Figure 10 shows the Mach number distribution of the meridional flow under the condition of free jet, and the velocity variation curve in the cross section of the jet core region, taking the center of nozzle inlet as the origin, the mixing region of jet and atmospheric environment is about 3D~3.6D in the direction of nozzle deflection, therefore, the inner diameter of the exhaust ejector should not be less than 3.6d during the high-altitude simulation test with exhaust ejector. During the vectoring nozzle test in the test chamber, the air flow in the core area should not impinge on the wall of the exhaust ejector.

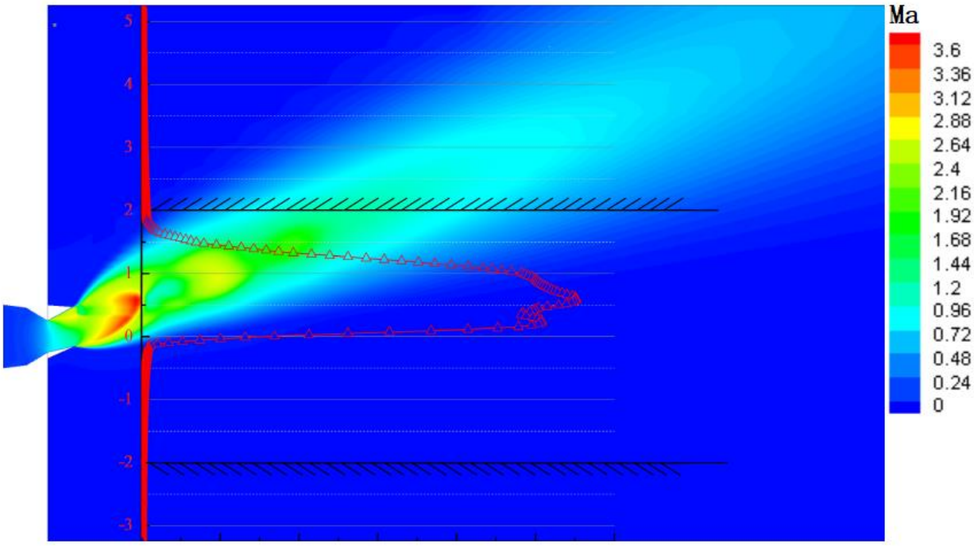


Figure 10 -Free jet simulation result of a vectorial nozzle engine

5.4 Straight length

Sokolov et al thought that the ratio of length to diameter of cylindrical mixing chamber is recommended to be 6~10[6]; Russia suggested that the length diameter ratio of exhaust ejector should be 5~6; The length diameter ratio of exhaust ejector is recommended to be 5 in the United States; The length diameter ratio of the exhaust ejector in a Chinese high-altitude cabin is 8. According to the above conclusion, the inner diameter of the exhaust ejector is 2.4D, and the length diameter ratio of the mixing section is 6, the Mach number distribution on the axis of the exhaust ejector at different working points is obtained as shown in Figure 11. The red vertical line is the inlet edge of the exhaust ejector, and the red horizontal line is the contour line with Mach number equal to 1.

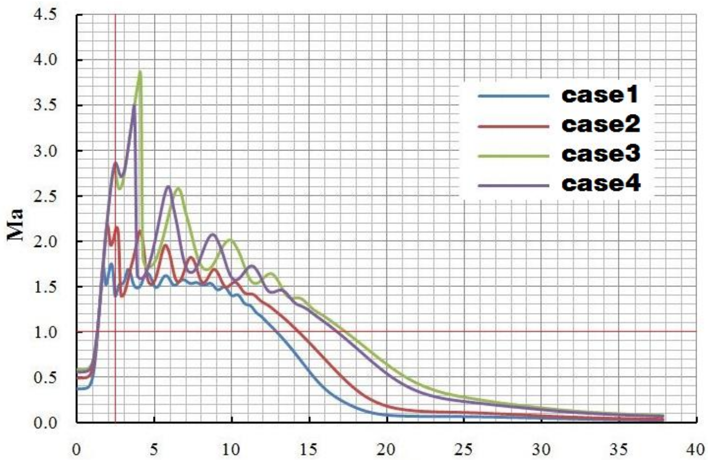


Figure 11 -Mach number distribution on the axis line of the exhaust ejector with aspect ratio of 6

In case 1(Nozzle pressure ratio, NPR=1.3) and case 2 (NPR=2.1) of Figure 11, the Mach number begins to fall below the red line at about 7.5 of the length diameter ratios of the exhaust ejector in the straight flow direction; In case 3 (NPR=4) and case 4(NPR=3.5), the Mach number begins to fall below the red line when the aspect ratio of the exhaust ejector is about 8.75.

In order to obtain a better structure size of the exhaust ejector and have a full understanding of the design of the length diameter ratio of the exhaust ejector, the straight section of exhaust ejector with aspect ratio of 4 is considered again for calculation, and the results are shown in Figure 12.

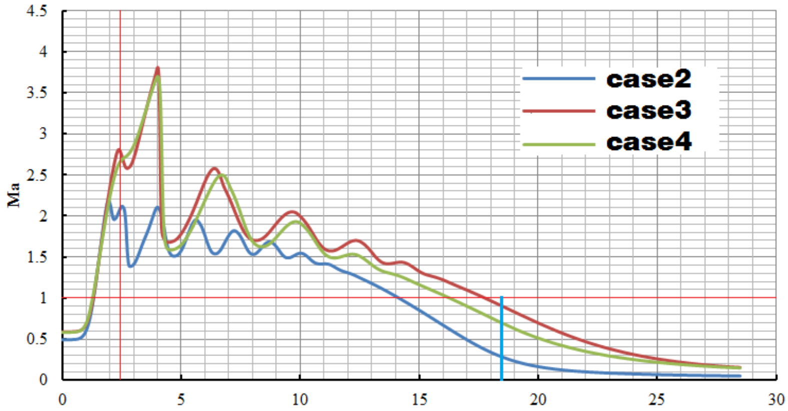


Figure 12 -Mach number distribution on the axis line of the exhaust ejector with aspect ratio 4

In Figure 12, the Mach number on the axial line of the straight section outlet has all decreased to below the red line, that is, the maximum air velocity at the straight section outlet is less than the local speed of sound, the main flow velocity of case 3 and case 4 at the exit of cone section is about 120m/s and 140m/s respectively, which is acceptable for downstream equipment.

To sum up, it is necessary to design the exhaust ejector matching with the nozzle, combined with engineering application, considering enough allowance, it is suggested that the length diameter ratio of exhaust ejector should not be less than 4.5.

5.5 Determination of entrance structure

5.5.1 Conventional entrance structure analysis

Based on the above exhaust ejector design and analysis results, the vectoring nozzle structure shown in Figure 13 is used to simulate the air flow in the inlet structure of the conventional exhaust ejector. Due to the eccentric injection of vectoring nozzle, the flow characteristics of the jet are different from those of axisymmetric nozzle. Under the action of eccentric injection of main stream, the secondary flow of cooling gas cannot flow regularly along the flow direction, but presents a chaotic shape. The jet from the vectoring nozzle is directly injected into the wall of the exhaust ejector, and part of the high temperature air is reflected upward, forming a large recirculation zone at the inlet of the exhaust ejector, after mixing with the jet, part of the cooling gas flows back to the cabin under the action of the recirculation zone.

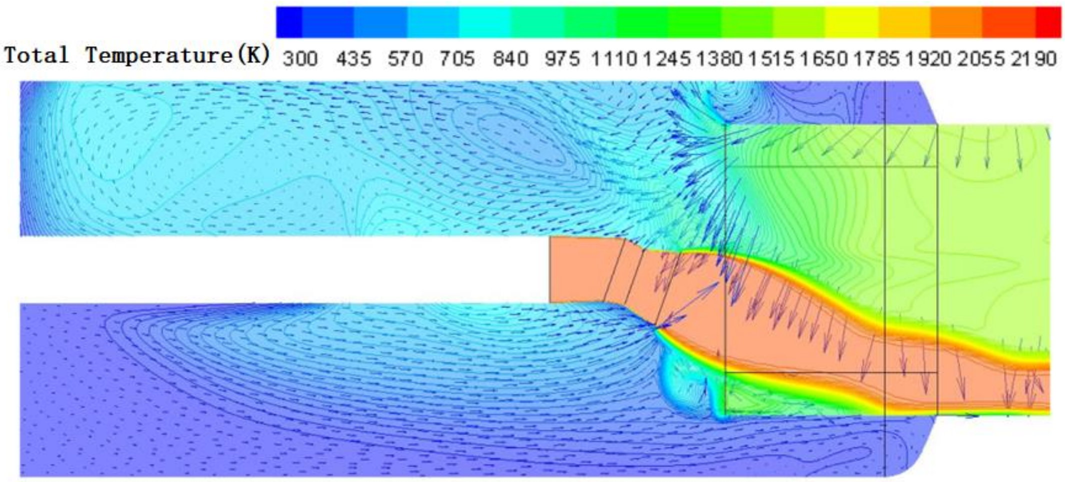


Figure 13 -Calculation results of conventional exhaust ejector inlet structure in vector nozzle test

As mentioned above, the backflow of high temperature gas in the test chamber needs to be avoided or suppressed. The gas backflow in the vectoring nozzle test is also not allowed, in the case of backflow, the maximum temperature of air flow in the test chamber should not exceed 120 ℃. In

Figure 13, the air temperature in the test chamber is as high as 770K. The method of directly increasing the injection ratio of the test chamber is used to suppress the backflow of high temperature gas, at the same time, the phenomenon of high temperature gas backflow in vectoring nozzle test is more serious than that in axisymmetric nozzle test, which is obvious. If we only use the method of increasing the injection ratio of cooling air flow, we will need to pay additional continuous air extraction source as the cost, which is very uneconomic [1].

5.5.2 Analysis of flow baffle inlet structure

Refer to F119 engine altitude simulation test, the experiment of two-dimensional vectoring nozzle is not completely dependent on the increase of injection ratio, instead, a movable rectangular baffle was installed at the inlet of the exhaust ejector, and the ejection ratio was increased appropriately, which made the high-altitude simulation test of F119 engine go smoothly.

The vectoring nozzle test cannot meet the test requirements under the conventional exhaust ejector inlet configuration, the temperature in the high-altitude cabin is too high, and the cabin, test instruments, thrust bench and the outer surface of the engine do not have normal working conditions, which has been mentioned above. For this reason, the simulation technology is used to obtain the air flow situation of the exhaust ejector inlet with a baffle structure, as shown in Figure 14. Under the action of baffle, the gas return at the inlet of exhaust ejector cannot continue to move into the test chamber, it is forced to flow along the baffle in the direction of the vector jet, at the same time, the axial velocity component decreases, Under the action of the secondary flow of the engine exhaust main flow, it returns to the exhaust ejector and flows downstream of the exhaust ejector after mixing with the main flow.

The secondary cooling gas in the test chamber is no longer affected by the high-intensity gas return in the exhaust ejector, under the action of high-speed exhaust of vectoring nozzle, from the front cabin, it flows into the exhaust ejector through the baffle plate, where it begins to mix with the nozzle jet and high temperature gas return, this is illustrated by the vector diagram of secondary flow in the cabin shown in Figure 14. Compared with the conventional exhaust ejector inlet structure, Under the condition of the same injection ratio, there are more airflow vortices in the inlet of the baffle exhaust ejector. The vortex is easily affected by the working state of the engine and flows into the test chamber, the temperature in the test chamber is increased, especially in the back area of the vectoring nozzle.

By changing the injection ratio, the appropriate orifice area of the baffle and the distance between the exhaust nozzle and the baffle, the gas backflow in the exhaust ejector can be restrained.

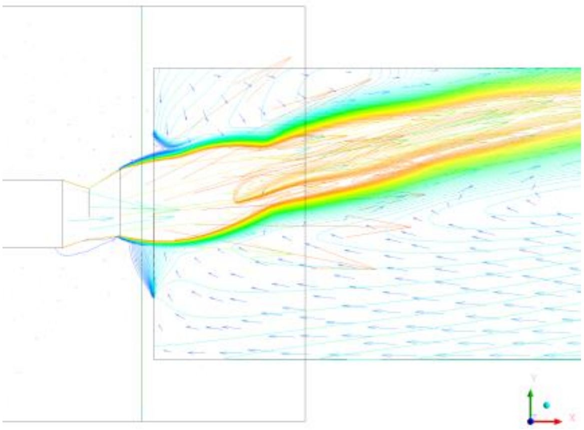
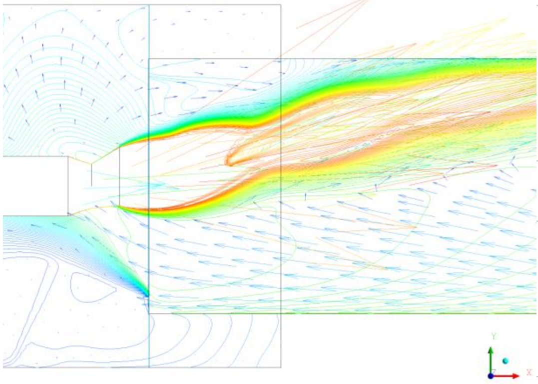


Figure 14 -Simulation result of vectorial nozzle engine in exhaust diffuser with baffle plate

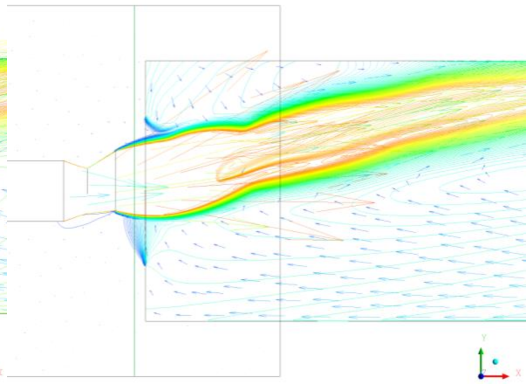
5.6 Determination of ejection ratio and inlet structure size

With other parameters unchanged, the critical expansion ratio of exhaust ejector will decrease with the increase of injection ratio; To ensure the critical expansion ratio of exhaust ejector, it is necessary to increase the inlet area of the exhaust ejector in order to leave enough circulation channels for the secondary flow of cooling gas [7,8,9].In the previous paper, the inlet structure of the baffle exhaust ejector was used to carry out the vectoring nozzle test, the relationship between the injection ratio and the orifice area of the baffle (diameter is defined as D1) and the distance between the nozzle outlet and the exhaust ejector inlet (L) is monotonic. L is 0.3D and 0.5d, D1 is 2D, 2.2D and 3.4D, Ejection ratio(n) is 02、0.3 and 0.4 respectively, Figure 14 shows the calculation results of three parameters under five combined conditions.

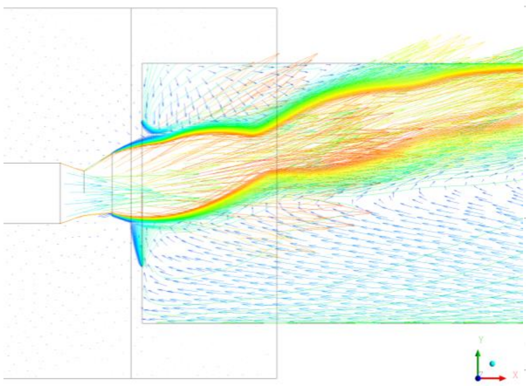
The diameter of the baffle (D1) is 3.4D, the simulation results show that the vectoring flow can completely flow into the exhaust ejector, and the ejection ratio has reached 0.3, but there is still a large range of high temperature gas backflow in the cabin. There is obvious backflow in the inlet area of the exhaust ejector, and the area is small in Figure 15(b). The maximum temperature at the inlet section of the exhaust ejector is about 500K, from the vector diagram, it can be seen that the high temperature gas return zone in the exhaust ejector does not enter into the test chamber. When the injection ratio is increased to 0.4 in Figure 15 (c), the phenomenon of gas backflow at the inlet of exhaust ejector is obviously reduced. Figure 15 (d) and Figure 15 (e) are the calculation results of the distance between the nozzle and the inlet of the exhaust ejector, the 2D layout of the orifice, and the injection ratio of 0.3 and 0.2, from the temperature distribution of the inlet section of the exhaust ejector, there is no high temperature gas reflux under the condition of 0.3 injection ratio, when the injection ratio is 0.2, part of the high temperature gas lingers at the inlet of the exhaust ejector, the maximum temperature of the inlet section of the exhaust ejector is about 700K, and the high temperature gas in the exhaust ejector does not return into the test chamber.



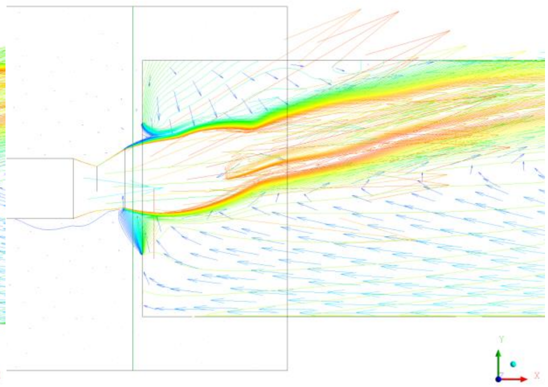
(a) L= 0.5D, D1= 3.4D, n=0.3



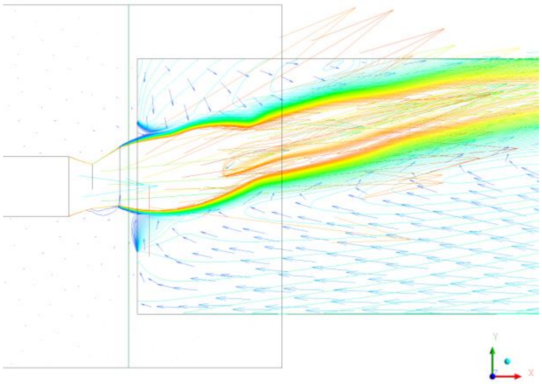
(b) L= 0.5d, D1= 2.2D, n=0.3



(c) L=0.5D, D1=2.2D, n=0.4



(d) L=0.3D, D1=2D, n=0.2



(e) L=0.3D, D1=2D, n=0.3

Figure 15 -Simulation result of vectorial nozzle engine in exhaust diffuser with baffle plate

In conclusion, in this paper, under the working condition of vectoring nozzle, the orifice diameter of the baffle should be in the range of 2.2D~2.4D, the injection ratio should not be less than 0.3, the distance between the tail nozzle and the exhaust ejector inlet should not be more than 0.5D.

6. Structural design suitability evaluation

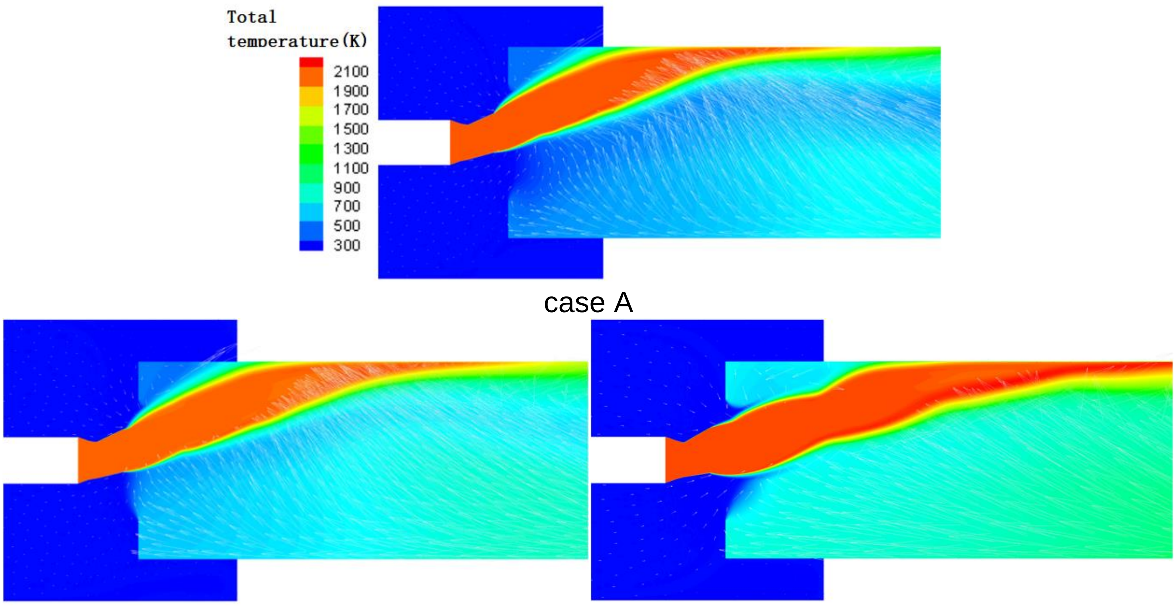
So far, the structural parameters of exhaust ejector have been basically determined. But for the vectoring nozzle test, the ability of exhaust ejector is to meet the requirements of the whole flight envelope. In order to verify the applicability of exhaust ejector structure at other working points, according to the nozzle vectoring flight envelope, three working points are selected to check the structure design results of the exhaust ejector.

Table 1 calibration test point

case	supercharging ratio (Exhaust diffuser)
A	1.09
B	1.14
C	1.29

When checking calculation, L is 0.3D, D1 is 2.4D, n is 0.3. The calculation results are shown in Figure 16, the ambient temperature in the test chamber is the temperature of the secondary flow of the cooling gas, and the pressurization ratio of the exhaust ejector is about 1.1~1.3.

There is no gas backflow phenomenon in the high-altitude simulation test of vectoring nozzle under three check conditions, the exhaust ejector can work normally, which shows that the design results of the exhaust ejector meet the design requirements.



case A

case B

case C

Figure 16 -Simulation result of calibration rest point

7. Conclusion

In this paper, the numerical simulation method is used to study the exhaust characteristics of vectoring and non-vectoring nozzle, the structure of the exhaust ejector in the test bed is designed pneumatically, the conclusion is as follows:

1. When vectoring nozzle is not vectoring, according to the working envelope of nozzle, the minimum inner diameter of exhaust ejector is determined, to ensure that there is no critical phenomenon of cooling gas in the exhaust ejector, that is to say, the inner diameter of exhaust ejector should not be less than 2.4 times of nozzle outlet diameter; under the condition of nozzle vectoring, the inner diameter of exhaust ejector should not be less than 3.6 times of nozzle outlet diameter.

2. The Mach number distribution of the jet mixing in the exhaust ejector should be considered in the design of the straight section of the exhaust ejector, the Mach number should be reduced to subsonic flow in the straight section of the ejector, and the outlet flow parameters of diffuser meet the requirements of downstream equipment, generally, the length diameter ratio is not less than 4.5.

3. In the vectoring test of the vectoring nozzle, a baffle plate can be installed at the inlet of the exhaust ejector to restrain the gas backflow, the orifice diameter of the baffle plate is determined according to the nozzle pressure drop ratio; it is suggested that the opening diameter of the baffle should be 2.2~2.4 times of the nozzle diameter, the injection ratio should not be less than 0.3, the distance between the nozzle outlet section and the inlet of the exhaust diffuser should not be more than 0.5 times of the nozzle outlet diameter.

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9. Copyright Statement

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