Performance of 2-D inlets with curved compression surface formed by segments with controllable compression angle

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Abstract. Suppose that curved surface consists of tiny polylines. Two 2-D inlets with curved surfaces formed by equal compression angles of the micro-element segments and a slight increase in the compression angle of the micro-element segments are designed respectively. The numerical simulation method is used to compare the performance of two curved surface 2-D inlets with the reference three-wedge compression 2-D inlet. Select NASA classic test data, in order to determine the turbulence model and calculation method chosen by the numerical simulation Fluent software. Numerical simulation results show: the pressure ratio of the curved compression system at the place corresponding to the wedge compression second shock wave is only 0.55 of the wedge compression pressure ratio, which is much smaller than the critical pressure ratio of the boundary layer separation; at design point, the performance of three inlets is similar; at non-design points, the 2-D inlets with the curved surface have a higher flow coefficient and total pressure recovery coefficient. The configuration of the small segments compression angles is the key to the performance of the curved surface compression two-dimensional inlet.

1. Introduction

The inlet is one of the key components of scramjet engines. Conventional inlets generally have an axisymmetric structure (such as the inlet used by the American scramjet HRE) [1], two-dimensional inlet (such as the inlet of the USA X-43A) [2], sidewall compressed inlet (such as the inlet used by X-43C) [3] etc. The compression method is nothing more than the use of shock compression or isentropic compression.

In recent years, the compression method of the inlet using a curved surface compression system has been extensively studied. Zhang Kunyuan [4] summarized the surface compression technology of hypersonic inlet and proposed the design and reverse design methods of the curved surface compression system. In response to this curved surface compression system, Pan Jin [5] studied the flow field performance of curved surface compressed flow field with equal pressure gradient on the wall surface and verified it by wind tunnel experiment. Zhang Lin [6] studied the flow field performance obtained by inverse design of various forms of wall pressure and Mach number distribution and analyzed the advantages and disadvantages of various parameter distributions. Literature [7] proposed the approximate calculation method of the details and characteristic parameters of the surface compression flow field through the analysis of the wave system interaction.
The curved surface compression system studied in this paper is a curved surface compression system composed of micro element broken lines. It is intended to form a compression system with different compression curvatures by studying the different variation rules of the present microelement fold line compression angle, and apply it to the two-dimensional inlet, and compare the performance with the reference three-wedge compression inlet.

2. Construction of curved surface compression system

It is assumed that the curved surface compression system is formed by a small segment polyline with a given compression angle change law. This special concave 2-D curved surface is constructed using a mixture method of geometric and pneumatic model. By adjusting the geometric parameters, the bending compression surface with different boosting laws and the bending shock with different curvatures are obtained.

As shown in Figure 1, a two-dimensional curved surface compression system with a total compression angle is divided into n tiny compression segments. The compression angle of each small segment is a tiny $\Delta\delta_n$ (n=1, 2, 3...). The supersonic flow starts from the first limited compression angle and deflects successively along n tiny compression surfaces. Every deflection of supersonic airflow at a slight angle $\Delta\delta_n$ produces a weak compression wave that propagates roughly in the direction of the Mach line. These n weak compressive waves must in turn intersect the oblique shock waves generated one after another and force the shock waves to bend upward gradually, thus forming this peculiar bending shock wave generated by the curved surface compression system.

![Figure 1. Sketch of the structure of curved surface compression system.](image)

3. Calculation method verification

In order to explore the possibility of applying this new type of compression system to supersonic/hypersonic inlets, the following will use the hypersonic two-dimensional inlet as a research platform to try to compare this curved compression surface with the plane inclined wedge compression.

Under the condition of super/supersonic flow, we use Fluent software to perform viscosity numerical simulation. The specific calculation method is as follow:

The calculation process uses the coupled compressible N-S equation and the model transport equation to solve implicitly. The molecular viscosity coefficient is calculated using Sutherland formula. Standard wall function is for near wall processing. Proportional encrypted mesh with attached layer near the wall of the calculation model. Specific heat ratio $\gamma = 1.4$. Boundary conditions of pressure far-field, pressure outlet and non-slip adiabatic solid wall are used in the calculation. The calculation convergence condition is that the residual of each index drops to the order of $10^{-3}$ and the inlet and outlet flow balance. Fluent software numerical simulation commonly used turbulence models are S-A model, $k-\epsilon$ model and $k-\omega$ model. In the case of viscous numerical simulation, the appropriate turbulence model can only be used to accurately and accurately describe the problem under study.
In order to evaluate the selected turbulence model for numerical simulation and verify the above calculation method, NASA classic test data [8] was selected to compare with the numerical simulation results of Fluent software. The standard model $\varepsilon - k$ in Fluent software and the calculation method selected above are used in the viscosity numerical simulation in this paper.

4. Performance of 2-D inlets

4.1. Physical models

The above calculation method and standard turbulence model are used to numerically simulate the plane three-wedge compression two-dimensional inlet, the curved surface with small compression lines equal to each compression angle and the curved surface of the small polylines with increasing compression angle two-dimensional inlets. The aerodynamic layout of these three two-dimensional inlets is shown in fig. 2. For simplicity, the reference three-wedge compression 2-D inlet, each compression angle equal and incremental compression angle unconventional curved surface compression 2-D inlet model are represented by $J_1$, $J_2$ and $J_3$.

![Figure 2. Schematic diagram of the two-dimensional inlets.](image)

The initial compression angle of the two unconventional curved surface compression two-dimensional inlets designed is 6°, and the air flow is deflected by 14° on the concave curved surface. Therefore, the total deflection angle of the air flow in front of the inlet lip is 20°. The difference between the compression surfaces of these two unconventional curved surface compression inlets lies in the change law of each compression angle.

Each compression angle and each increment of compression angle of the unconventional curved surface compression system designed in this paper are respectively $\Delta \delta = 1^°$ and $d\delta = 0.15^°$. The compression angles of the three wedge surfaces of the reference wedge compression two-dimensional inlet are respectively 6°, 6.5° and 7.5°. The total deflection angle is also 20°. In addition to the compression of curved surfaces and inclined surfaces, the inlet model also has lip compression. For comparison, the above three inlets have the same lip height and the same lip compression system. The inner lip has a compression angle of 8° to the airflow, and then a circular arc is used to form an isentropic channel to weaken the oblique shock generated by the lip, so as to reduce the separation of the boundary layer at the shoulder of the top plate. Select the design point Mach number $Ma = 5.3^{[6]}$.

The calculation conditions are incoming flow Mach number 5.3, static pressure 2250Pa, and static temperature 221.6K. Using Fluent software, numerically simulate the above three two-dimensional inlets, and analyze their flow field and performance under uniform inflow conditions.
4.2. Results and discussion

Fig. 3 is the pressure contour of the two-dimensional inlet at the design point Mach number 5.3. It can be seen for the conventional two-dimensional inlet $J_1$, the three shock waves generated by them intersect at the lip. For unconventional curved surface compression two-dimensional inlet $J_2$ and $J_3$, the shock wave generated by the initial wedge and compression wave generated by the subsequent curved surface gradually form a bending shock wave. Therefore, the flow coefficients of the three inlets design points are approximately 1.

![Figure 3. Ma 5.3 two-dimensional inlet static pressure contour.](image)

In the design of the conventional three-wedge compression two-dimensional inlet, in order to shorten the length of the inlet, a diagonal wedge with a large compression angle is used, and the shock wave is used to compress the air flow, which may cause separation occurs on the boundary layer.

Of course, the performance of the two-dimensional inlet is also an important indicator to measure its quality. The following study compares the performance parameters of the three two-dimensional inlets at the design point and the non-design point, the total pressure recovery, the outlet Mach number, and the pressure ratio. According to the equal dynamic load, the calculation conditions are: incoming flow Mach number 3, static pressure 8041Pa, static temperature 216.7K; incoming flow Mach number 4, static pressure 4523Pa, static temperature 216.7K; incoming flow Mach number 5, static pressure 2895Pa, static temperature 217K.

Table 1 lists the aerodynamic performance of these three two-dimensional inlet models under design conditions. It can be seen that their flow coefficients are approximately 1. The performance parameters are different due to the different compression surfaces of each inlet. In comparison, the pressure ratio of $J_2$ is maximum and $J_1$ is minimum, and the total pressure recovery of $J_1$ is maximum and $J_2$ is minimum. Under non-design conditions, the aerodynamic performance of each two-dimensional inlet is shown in Table 2 to Table 4.

| Model | Flow coefficient | Total pressure recovery | Outlet Mach number | Pressure ratio |
|-------|------------------|-------------------------|--------------------|---------------|
| $J_1$ | 0.98             | 0.61                    | 2.64               | 12.59         |
| $J_2$ | 0.99             | 0.58                    | 2.61               | 13.70         |
| $J_3$ | 0.98             | 0.59                    | 2.83               | 12.61         |

**Table 2. Performance of 2-D inlets (Ma 3).**

| Model | Flow coefficient | Total pressure recovery | Outlet Mach number | Pressure ratio |
|-------|------------------|-------------------------|--------------------|---------------|
| $J_1$ | 0.56             | 0.72                    | 1.37               | 8.02          |
| $J_2$ | 0.62             | 0.79                    | 1.59               | 6.46          |
| $J_3$ | 0.59             | 0.78                    | 1.66               | 5.71          |
Table 3. Performance of 2-D inlets (Ma 4).

| Model | Flow coefficient | Total pressure recovery | Outlet Mach number | Pressure ratio |
|-------|------------------|-------------------------|---------------------|---------------|
| $J_1$ | 0.75             | 0.65                    | 2.07                | 10.29         |
| $J_2$ | 0.80             | 0.71                    | 2.22                | 8.80          |
| $J_3$ | 0.79             | 0.70                    | 2.32                | 7.89          |

Table 4. Performance of 2-D inlets (Ma 5).

| Model | Flow coefficient | Total pressure recovery | Outlet Mach number | Pressure ratio |
|-------|------------------|-------------------------|---------------------|---------------|
| $J_1$ | 0.95             | 0.62                    | 2.54                | 14.84         |
| $J_2$ | 0.97             | 0.61                    | 2.62                | 12.82         |
| $J_3$ | 0.96             | 0.60                    | 2.74                | 11.15         |

As can be seen from the data in the tables, under non-design conditions, compared with the conventional three-wedge compression two-dimensional inlet, the flow coefficient and total pressure recovery of the unconventional curved surface compression two-dimensional inlet is higher, but the pressure ratio is lower. In two unconventional curved surface compression two-dimensional inlets, the performance of the two-dimensional inlet composed of segments with constant compression angle is better than that of the compression surface with increasing compression angles. It can be seen that how to configure the compression angle of the segments that constitutes the curved compression surface is the key to determine the performance of the unconventional curved surface compression two-dimensional inlet.

5. Conclusion

In this paper, through the evaluation of calculation examples, the turbulence model and calculation method selected for numerical simulation are determined. A method of forming a curved surface compression system using segments is proposed and applied to the two-dimensional curved surface compression inlet.

The following research results were obtained:

(1) By reasonably configuring the segment compression angles that make up the surface compression system, a compression system with different compression efficiency is formed.

(2) At incoming flow $Ma 3$, the flow coefficient of the inlet $J_2$ is 1.07 times that of the inlet $J_1$, and the total pressure recovery is 1.09 times that of the inlet $J_1$.

(3) Unconventional curved compression system formed by constant compression angle segments in this paper is the best for improving performance of 2-D inlets.

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