Numerical Study of Shock Train in the Isolator of Scramjet Engine

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Abstract: The isolator of scramjet engine has to separate the combustor from the inlet so that the scramjet can keep working stably. The steady-state flow field structure, the shock train shape and the starting position of the symmetrical model of isolator under different backpressure ratio are obtained by numerical simulation of commercial software fluent. Using the user-defined function to simulate the pressure fluctuation caused by the irregular heat release in the combustion chamber, the motion of the shock train in the isolation section is obtained. It is found that the start position of the shock train is larger than that of the steady state simulation, which provides a reference for the design of the combustion chamber.

1. Nomenclature
\[ P \quad = \quad \text{pressure} \]
\[ T \quad = \quad \text{temperature} \]
\[ C_p \quad = \quad \text{pressure coefficient} \]
\[ L \quad = \quad \text{length} \]
\[ H \quad = \quad \text{height} \]
\[ \rho \quad = \quad \text{density} \]

subscripts
\[ b \quad = \quad \text{background} \]
\[ in \quad = \quad \text{inlet} \]
\[ 0 \quad = \quad \text{total} \]

2. Introduction
The isolator is an important part of the scramjet engine, which is located between the inlet and the this document, combustion chamber. The isolator mitigates the mutual interference between the inlet and the combustion chamber and prevents the inlet does not start. It is very important for the stability of engine. However, there are complex flow phenomena such as the interference of the shock wave boundary and the formation of the shock train in the isolation section under the back pressure[1]. Due to the complexity of the internal flow in the isolation section, it is still not possible to accurately calculate the length of the shock train according to the conditions of flow and back pressure.

Many researchers have done a lot of research in this area. Billig and Waltrup [2],[3] experimentally study the shock wave structure in a circular tube and give the fitting formula between shock train length L and back pressure Pb, the Mach number of flow and the thickness loss \( \theta \) of the momentum
loss near the wall. Hoeger [4] used VULCAN software to provide back pressure gradually or instantaneously at the outlet section of two-dimensional supersonic flow, and analyzed the relationship between the final position of the shock train and the back pressure ratio [5]. Peek used a ramp device to artificially provide backpressure and studied the effect of backpressure on the leading edge position of the shock train [6]. Hutzel established a dynamics model that correlates the leading edge position of the shock train in the isolation section with backpressure [7].

Therefore, it is very important to study the influence of the back pressure on the shock train structure of the isolation section. And it is of great significance for the study of the engine components and their overall performance.

In this paper, the flow field of the two-dimensional symmetrical model of isolated section is simulated by the commercial software Fluent. And it obtained the change of the starting position of the shock train in the isolator under different backpressure.

3. Numerical simulation Method

3.1 Physical model.
The mesh of the model shown in Figure 1. The length to height (L/H) is 6[8], and the height is 35mm. The inlet Mach number considered at the entry of the isolator was 2.5. The total pressure \( P_0 = 310000 \text{ Pa} \), static pressure \( P_{in} = 16535 \text{ Pa} \), total temperature \( T_0 = 289K \). And the outlet pressure of the isolator is 3 to 7 times of the static pressure of the inlet. The mesh of the model adopts ICEM professional grid generation software, which adopts structured meshing and refines the grid near the wall to improve the accuracy. The total number of grids is about 100,000.

3.2 Calculate model
In this paper, the commercial software Fluent is used, which uses the finite volume method to solve the Reynolds-averaged Navier-Stokes equations. The solver to choose the second order implicit scheme and the Gauss-Seidel iteration method. The turbulence model to choose the RNG k-\( \varepsilon \) model and the wall using unbalanced wall function method. The details of the numerical method are given in [9]. The solution is considered to have converged when the following conditions are met:

- Residuals of each control equation are less than 0.00001;
- With iteration, there is no change or little change in the distribution of wall static pressure;
- The quality of inlet and outlet is less than 0.0001;

And there is some basic assumptions:

- Gas is the ideal gas, subject to the ideal gas state equation;
- Do not consider the impact of gravity and other body force;
- Wall is no slip and adiabatic, and the entire flow field with the outside without heat exchange;

4. Results and Discussion

4.1 Shock train under different backpressure ratio
The outlet pressure \( (P_b) \) is set to 4 to 7 times the static pressure \( (P_{in}) \) of the inlet to study the evolution of the shock train and the variation of the exit parameters of the isolator with the backpressure ratio.
increase. Figure 2 shows the pressure cloud at different backpressure ratios. It can be seen from Figure 2 that when the backpressure ratio \( P_b/P_m \) is 4.0, a more obvious shock train structure has been formed in the flow field. As the backpressure ratio increases from 4.0 to 6.0, the starting position of the shock train continues to move forward, the length increases, and the number of shock waves increases. When the backpressure ratio rises to 7.0, the shape and shock wave number of the shock train are not changed obviously, but the length of the mixing zone is longer and the starting position of the shock train has a large forward, close to the entrance. It can be seen that the rise of the backpressure ratio will gradually move forward position of the shock train, the area affected by the backpressure in the isolator is expanded.

Figure 3 shows the distribution of the Mach number of the axis of the isolator. It can be seen that when the backpressure ratio is 4, the Mach number of the outlet (combustor inlet) of the isolation section is still greater than 1. This shows that the engine is in supersonic combustion mode. When the pressure ratio is greater than 5, the Mach number of the outlet of the isolator (combustor inlet) is less than 1, the outlet gradually transitions from partial subsonic areas to the complete subsonic area, this shows that the engine is in the subsonic combustion mode. It can be seen that with the increase of backpressure, it is possible to realize the modal conversion of the scramjet engine. It can be further analyzed that when the outlet pressure is high enough, the structure of the shock train will no longer change. With the further increase of the outlet pressure, the intensity of the shock train is gradually increased, and the oblique wave is transformed into the positive shock wave strain, \( \lambda \) positive shock wave, and the position of the shock train continues to move forward until the isolation section enters the inlet. It can affect the normal operation of the inlet, and even cause the inlet does not work.

Captions should be typed in 9-point Times. They should be centred above the tables and flush left beneath the figures.
4.2 Shock train under outlet pressure of sine wave.

The outlet pressure $P_b$ is set to change according to the sine wave law to ensure that the back pressure ratio also has the same variation. The method is that the user-defined function is written into the Fluent. Set the calculation of the combustion environment pressure is 8.9MPa, the pressure ratio is 5. The time at which the pressure disturbance begins to be added is 0.01 ms; and the dimensionless pressure is defined as 0.2. Figure 4 shows a periodic of the pressure distribution at different time under a sine wave. It can be seen from the figure that the length and the location of the shock train in the tube will also change periodically. In contrast to the pressure cloud at backpressure ratio of 7.0 in Figure 2 and the pressure cloud at the 1/4T in Figure 4, it can be seen that the starting position range of the shock train is larger than that of the steady state simulation due to the hysteresis. When it is at 3/4T, the starting position of the shock train is large, close to the outlet of the isolation section.

4.3 Shock train under outlet pressure of saw tooth wave

In the same way, the backpressure of the outlet is set to the law of saw tooth variation. Figure 5 shows the saw tooth wave change, and this saw tooth wave is a 1000-order Fourier transform of the previous
sine wave. Figure 6 shows the change of the start position of the shock train near the wall in the corresponding time interval of Figure 5. Analysis of Figure 5 and Figure 6, in a saw tooth wave cycle, the isolation section of the shock position has also been cyclical changes, but in a cycle there have been three shock changes. In Figure 6, some of the slope of the curve is very large where the shock wave movement speed is fast, and some slope is small where the shock wave movement speed is slow. According to the Fourier transform formula of the saw tooth wave, it is found that the frequency of the shock string position is the same as that of the third order Fourier transform.

![Figure 5. Saw tooth image](image)

![Figure 6. The start position of the shock train](image)

Figure 7 shows the pressure cloud of the minimum and maximum moments of the coordinate position on the axis of the shock train in the isolation section. Compared with Figure 4, it can be seen that the minimum location of the shock wave of the back pressure ratio under the saw tooth wave is smaller than that under the sine wave. It can be seen that when the back pressure ratio changes to the saw tooth wave, the shock string in the isolation section will appear many oscillations. The change position range is almost the same as the position of the shock string when the back pressure ratio is sine wave. The results provide a reference for the design of the combustion chamber.
5. Conclusion
The isolation section can effectively isolate the impact of periodic dynamic backpressure pulsations on the inlet of different waveforms. The increase in the back pressure ratio will cause the shock train to move forward step by step, and the area affected by the back pressure in the isolation section is also enlarged. And for a dual-mode engine, the back pressure lift is usually accompanied by a change in the operating mode. When the back pressure ratio is under the sine wave or saw tooth wave, the length of the shock train in the isolator will change periodically. But there are multiple change cycles of the shock train under the back pressure of the sine wave. The reason needs to further study.

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