Study on scramjet engines with complex inlet flow conditions

Lantian Li

1Science and Technology on Scramjet Laboratory, NUDT, Changsha, 410073, China
Corresponding author and e-mail: Lantian Li, lilantian@nudt.edu.cn

Abstract. Scramjet engine is one of the key technologies to realize hypersonic flight. It has great research value for its performance under complex inlet flow conditions. In this paper, the free jet test model of RBCC aircraft is established, and the numerical simulation is carried out with Japanese NAL direct connected hydrogen fuel combustion chamber test. Aiming at the problems of coupling analysis accuracy and long calculation period, a one-dimensional internal flow coupling analysis method based on one-dimensional flow is proposed to solve the backpressure problem in the subsonic combustion state. The experimental results show that this method can predict the flow separation point in the isolation section well in the subsonic combustion mode, and the error is less than 10%, the prediction results of the peak pressure and the mean pressure along the passage are less than 23% and 10.4%, respectively. In the supersonic combustion mode, the accuracy of one-dimensional flow is higher, and the prediction error for the peak pressure in the combustion chamber is less than 3.79%, and the prediction error for the location of the peak pressure is less than 2.3%.

1. Introduction
Scramjet is one of the key technologies to realize hypersonic flight. Supersonic combustion is a complex physical and chemical process in which fuel is mixed and burned in supersonic flow. Scramjet engine has a wide working range and is suitable for flying speeds as low as MA5 and as high as MA10. It is one of the most effective power devices for aerospace aircraft, near space vehicles and hypersonic cruise missiles. The supersonic combustion ramjet is mainly composed of a combustion chamber, an inlet and a tail nozzle. The inlet compresses the hypersonic inlet air to an appropriate temperature and pressure and then sends it into the combustion chamber. Fuel and air in the combustion chamber for mixing, combustion and release heat. After the fuel chemical energy is converted into the kinetic energy of the gas, the thrust is generated by the expansion of the tail nozzle. [1-2]

Therefore, it is of great significance to study the performance of scramjet under the condition of complex inlet flow. In 2019, Gao Yonggang et al. studied the effects of primary rocket chamber pressure, primary combustion product components and different combustion chamber configurations on the performance of solid rocket gas scramjet engine by using the calculation method of full-channel integrated numerical simulation. [3] In the same year, Li Ji, Tian Ye et al. studied the impact of boundary layer suction on the flow field of scramjet engine by wind tunnel test and numerical calculation, and studied the shock train characteristics in isolation section and combustion characteristics of combustion chamber. [4] In 2020, YouHoufeng, Zhang Bing et al., based on the quasi-one-dimensional Euler equation considering finite rate chemical reactions, developed a quasi-one-dimensional calculation method suitable for the performance analysis of supercombustion chamber by adding cross-section area variation, wall friction and mass source term. [5] In the scramjet ground test, in order to simulate the hypersonic flight state, the test gas must be heated. The
combustion heating method is to use hydrocarbon fuel combustion to heat the air, and then simulate the high altitude flight conditions. This process inevitably introduces "polluting components", mainly H2O and CO2, into the high enthalpy flow, Clock surplus in 2021, jia-ling le and others in the coming flow Mach number 2.0 direct combustion devices hydrogen ignition conditions is studied with the concave cavity of scramjet combustion chamber, ignition to ethylene and hydrogen from hydrogen mixture combustion, alone to ethylene combustion process of combustion flow characteristics, and synchronous study the flow field structure and the flame development. [6] In order to obtain the influence of combustion mode conversion process on the working characteristics of scramjet, Xiao Baoguo and others carried out the conversion experiments of different working modes of combustion chamber under the condition of flight Mach number of 4.5 on the direct connected test-bed through the linear change of liquid kerosene flow. Through the monitoring of characteristic positions and parameters, the real-time discrimination of combustion mode is realized, and the influence law of combustion mode conversion process on engine performance is obtained.[7] In view of the problem that the current optimization research on the regenerative cooling structure of scramjet depends on the empirical correlation and pays insufficient attention to the flow pressure loss, Qin Ang team used the response surface method combined with multi-objective genetic algorithm to optimize the rib height, groove width and rib thickness of a single regenerative cooling channel with the average wall temperature and flow pressure loss on the gas side as the optimization objective.[8] Liu Zi and others used numerical simulation method to study the effects of different orifice parameters on the performance of secondary combustion chamber of solid rocket scramjet.[9] In order to obtain the maximum fuel supply state of dual-mode scramjet under different flight states, Huang Xing et al. Developed the solution method of maximum fuel supply mode flow balance by analyzing the blocking boundary conditions and working mechanism of dual-mode scramjet based on the dual-mode scramjet performance calculation model of lumped parameter equation. On this basis, the calculation model of maximum fuel supply mode of dual-mode scramjet is established.[10] However, the coupling analysis accuracy and calculation cycle of the scramjet still exist problems under complex inlet flow conditions. Therefore, an internal flow coupling analysis method based on one-dimensional flow is proposed in this paper. The method is suitable for the coupling solution of the isolation section and the two-mode combustor, which solves the back pressure problem caused by heat choking in the sub-combustion mode, completes the matching analysis of the flow field between the combustor and the isolation section, and gets the flow characteristics along the route of the rocket-based combined cycle engine and the two-mode flow field in the super-combustion and sub-combustion modes.

2. Calculation model and method
In one-dimensional flow analysis of a two mode scramjet, sub combustion, super combustion and hybrid modes must be taken into consideration. Under the action of the back pressure of the scramjet combustion chamber, thermal throat and other phenomena appear downstream of the combustion chamber, and pseudo shock strings appear in the isolation section, as shown in Fig. 1. In order to obtain accurate engine performance, the above flow phenomena need to be described by one-dimensional flow theory.
Figure 1. Flow characteristics of a two-mode scramjet.

In general, the inlet flow parameters of the isolator will be used as the boundary conditions of the coupling solution. In the case of a scramjet, fuel is injected from the injection point into the runner. The combustion releases heat, which increases the pressure in the runner and produces thrust. When the heat is added to a certain extent, the phenomenon of heat blocking and back pressure will occur, which will change the inlet flow parameters of the combustion chamber. A separation zone appears in the vibration isolator, and a shock wave string appears in the core flow, so that the outlet flow of the vibration isolator slows down and pressurizes, so as to adapt to the inlet conditions of the combustion chamber.

2.1. The one-dimensional flow governing equation for the isolation section

Through the analysis of the vibration isolator control body, it is known that thermal growth, geometric area and friction are independent variables, while pressure, density, Mach number, temperature, velocity and core area are unknown flow characteristics (non-independent variables).

For the additional flow, the area of the core flow can be regarded as the geometric area, and then the ordinary differential equation of Mach number can be derived:

\[
\frac{dM_a^2}{M_a^2} = -\frac{2(1 + (\gamma - 1/2)M_a^2) dA}{A} + \frac{(1 + \gamma M_a^2)(1 + (\gamma - 1/2)M_a^2) dT}{T} + \frac{\gamma M_a^2(1 + (\gamma - 1/2)M_a^2) 4C_f dx}{1 - M_a^2 D_H} + \frac{\gamma M_a^2}{1 - M_a^2} \frac{d\bar{T}}{D_t}
\]

Where, \(A\) is the area distribution of the pipeline, \(D_H\) is the hydraulic diameter, \(T\) is the total temperature distribution, and \(C_f\) is the skin resistance coefficient, which can be solved by integrating the above equation. For the separated flow, the actual effective flow area is generally smaller than the geometric flow area, and the additional core flow area distribution function \(A_c\) is required.

\[
\frac{d(A_c/A)}{A_c/A} = \frac{(1 - M_a^2)(1 - (\gamma - A_c/A)M_a^2) dp}{\gamma M_a^2 A_c/A p} + \frac{1 + (\gamma - 1)M_a^2}{2A_c/A} 4C_f \frac{dx}{D} + (1 + \frac{\gamma - 1}{2} M_a^2) \frac{dT}{T_t}
\]

The Mach number and core-flow area equations are solved by multi-equation ODE solver. But the pressure distribution must be predicted before solving the problem. In this case, Ortwerth established an empirical formula to calculate the pressure gradient of pipe flow based on the experimental data.

\[
\frac{dp}{dx} = \frac{k}{2D_H} C_{f0}(\gamma p M_a)
\]
The friction coefficient of the separation point is $C_f0$, the hydraulic diameter of the pipeline is $D_H$, and the empirical constant is $k$. In this paper, $k = 99.5$, $(\gamma pMa)/2$ is expressed as the gas flow pressure.

By simplifying the three-dimensional Navier-Stokes equations, the generalized one-dimensional equations of chemical nonequilibrium flow can be obtained, which take into account the influence factors such as area change, friction and addition.

2.2. The governing equation of one-dimensional flow in combustor

After simplifying the one-dimensional flow analysis, the empirical formula is used to calculate the heat release rule after fuel injection as follows:

$$
\tau(x) = 1 + \tau_b \frac{\theta_x}{1 + (\theta - 1)x} (\theta \geq 1)
$$

$$
\tau(x) = \frac{T_t}{T_{t2}}
$$

$$
\bar{x} = (x - x_i)/(x^2 - x_i)
$$

Where $x_i$ is the axial position at which heating or supersonic combustion begins. $\theta$ is an empirical constant, usually between 1 and 10, depending on the pattern of gas and fuel injection.

$$
T_b = \frac{T_{t4}}{T_{t2}}
$$

According to the empirical formula of heat release, the total temperature distribution of the combustor can be obtained, and other flow parameters of the combustor can be obtained by using the ODE solver.

2.3. Internal flow coupling solution method

Coupling analysis mainly studies the generation and matching of the back pressure in the combustion chamber, and adopts the idea of iteration to realize the matching of the flow parameters between the vibration isolator and combustion chamber. In the decoupling algorithm, it is implicitly assumed that the total density and velocity of gas micro clusters remain unchanged when calculating the source term, that is, the chemical reaction is an adiabatic equal-volume explosion process. In the calculation process of decoupling algorithm, the solution of flow and reaction are carried out alternately. It is necessary to distinguish the possible situations in the process of coupling solution by appropriate methods. The coupling solution process is shown in Fig. 2. The working process of the dual-mode scramjet mainly includes the super combustion mode, sub combustion mode and sub/super hybrid mode (early super combustion mode). There is a wide range of boundary layer flow separation phenomenon in the sub combustion mode and the sub/super mode, and the solution methods are similar.

Under the assumption that there is no separation flow, the modal analysis of the scramjet engine is carried out based on the given inlet data of the vibration isolator. According to the modal analysis results of the scramjet engine, it is concluded that: (1) if there is a singular phenomenon in the solution process ($Ma=1$), then the sub-combustion modal analysis is carried out; (2) If there is no singular phenomenon in the solution process, the early mode of scramjet is determined. Otherwise, the engine is in scramjet mode and the analysis is complete.
3. Verification of calculation method
The numerical simulation was carried out on the Japanese NAL direct connected hydrogen combustion chamber test model, and 666 grid points were set in the 666 mm length isolation section + the combustion chamber axial direction equal spacing. The polluted air produced by the heater passes through the nozzle with a nominal Mach number of 2.5 and then enters the isolation section to simulate the flight state of Mach number of 7.5. Table 1 shows the free inlet Mach number $M_{\infty}$, total temperature $T_{t\infty}$, total pressure $P_{t\infty}$, static pressure $P_\infty$ and component mass fraction $C_i$, as well as the fuel jet Mach number $M_{aj}$, total temperature $T_{tj}$, static temperature $T_j$, static pressure $P_j$ and equivalent ratio $\Phi$.

| Inflow  | value | Jet inflow | Inflow |
|---------|-------|------------|--------|
| $M_{\infty}$ | 2.5   | $M_{aj}$   | 1      |
| $T_{t\infty}/K$ | 2000  | $T_j/K$   | 237    |
| $P_{t\infty}/Mpa$ | 1.1   | $P_j/Kpa$ | 355    |
| $P_\infty/Kpa$    | 55.232| $\Phi$     | 1.0    |
| CO$_2$             | 0.24333|            |        |
| CH$_3$O            | 0.17518|            |        |
| CN$_2$             | 0.5876 |            |        |

Figure 3 shows the calculation results of internal flow coupling when equivalence ratio $\Phi=1.0$. According to the simulation results, the combustion efficiency of the one-step reaction model is set as 0.7. At the initial moment of calculation, the model set the downstream of the hydrogen nozzle as a high temperature area with a static temperature of 2000 K to make hydrogen and oxygen burn. The results of static pressure and Mach number calculated by one-dimensional flow governing equation are basically consistent, and the pressure peak position is consistent with the experimental results, and the pressure peak value is too high. The calculation results prove the applicability of the internal flow.
coupling analysis method based on one-dimensional flow to the calculation of the reaction flow field in combustor configuration.

![Graph](image)

Figure 3. Coupling calculation results of internal flow when equivalence ratio is 1.

4. Result analysis and discussion

Based on the quasi one-dimensional method of finite rate reaction, the influence of non-equilibrium effect of chemical reaction can be preliminarily analyzed. For NAL fuel model, the influence of different equivalence ratio and inlet pressure on combustion chamber flow parameters is preliminarily analyzed by one-dimensional internal flow coupling method.

Figure 4 shows the calculation results of changing the injection equivalence ratio in Table 1 while the other incoming flow and injection parameters remain unchanged. Equivalence ratio $\Phi$ at 0.6, 0.8, 1.0 and 1.2 respectively: the combustion chamber is in normal working state, the combustion is mainly carried out in subsonic state, and the outlet is supersonic; The pressure increases with the increase of equivalence ratio, and the axial pressure distribution in the expansion section of the combustion chamber under equivalence ratio 1.0 and equivalence ratio 1.2 is basically the same; When the equivalence ratio is $\leq 0.8$, the disturbance of combustion back pressure does not disturb the isolation section, which plays the role of "isolation"; When the equivalence is $\geq 1.0$, the combustion back pressure begins to disturb into the isolation section, and with the further increase of equivalence ratio, the farther the back pressure disturbance moves upstream. When the equivalence ratio is 0.4, the combustion occurs at the end of the combustion chamber about 152 mm away from the combustion chamber outlet, and the outlet Mach number is about 1.17, which is significantly lower than the outlet Mach number under other equivalence ratios.
By changing the inlet pressure $P_\infty$ of the inflow parameters in Table 1, the influence law of the inlet pressure on the flow field characteristics of the combustion chamber is studied, and the other inflow and jet parameters remain unchanged. Since the incoming gas density increases with the increase of pressure, the equivalence ratio will decrease with the increase of pressure. The equivalence ratio of jet parameters shall be calculated according to the inlet pressure and recorded as the characteristic equivalence ratio $\Phi'$. Set $P_0 = 55.222$ kpa, inlet pressure value and corresponding characteristic equivalent ratio $\Phi'$ See Table 2.

Table 2. Inlet pressures and related parameters.

| $P_\infty$/kpa | $P_\infty$/P0 | $\Phi'$   |
|---------------|---------------|-----------|
| 55.333        | 1.0           | 1.0000    |
| 83.822        | 1.5           | 0.6667    |
| 111.333       | 2.0           | 0.5000    |
| 138.012       | 2.5           | 0.4000    |

Figure 5 shows the calculation results under different inlet pressures. When $P_\infty$ is $P_0$, $1.5P_0$ and $2.0P_0$ respectively, there is subsonic flow in the combustion chamber and supersonic flow at the outlet of the combustion chamber; The pressure peak positions under the three pressure states are basically the same, and the higher the pressure is, the more intense the combustion is, and the greater the back pressure is. The positive shock wave caused by the back pressure under the inlet pressure $P_0$ state is pushed out of the isolation section and propagates along the upstream of the isolation section. When $P_\infty = 2.5P_0$, combustion only begins at the end of the combustion chamber about 115mm away from the combustion chamber outlet, and the combustion chamber outlet flows at subsonic velocity.
5. Conclusions

Based on the one-dimensional flow method, this paper developed a set of internal flow calculation method that can be used for subsonic combustion mode and supersonic combustion mode. The experimental results were verified and the following conclusions were drawn:

This method can be applied to the coupled analysis of combustor and two-mode scramjet isolator, and the combined power of RBCC in subsonic combustion mode and scramjet mode is also accurate to a certain extent.

(1) In the subsonic combustion mode, the flow separation point in the isolation section can be well predicted based on the one-dimensional flow method, the error is less than 10%, and the predicted results of the peak pressure and the mean pressure along the passage are less than 23% and 10.4%.

(2) In the supersonic combustion mode, the accuracy of one-dimensional flow is higher, and the prediction error for the peak pressure in the combustion chamber is less than 3.79%, and the prediction error for the location of the peak pressure is less than 2.3%.

The one-dimensional flow coupling analysis method used in this study will be improved in the future because errors introduced by cavities and empirical formulas in one-dimensional flow calculations are not taken into account. In addition, the effect of the cavity on the effective flow area of the combustor is considered to further confirm and improve the error factor of the quasi-one-dimensional flow.

(3) The calculation based on NAL hydrogen fuel combustor shows that increasing the equivalence ratio $\Phi$ or inlet pressure $P_\infty$, the static pressure of combustion chamber will increase, and also affect the propulsion distance and velocity of back pressure in the isolation section; At equivalence ratio $\Phi=0.4$ or the inlet pressure $P_\infty=138.055$ kpa, most areas of the combustion chamber are in a non-combustion state, and the inlet pressure will lead to the subsonic outlet of the combustion chamber.

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