

Thermodynamic performance analysis of scramjet at wide working condition

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Abstract

This study is mainly carried out based on a certain geometrical scramjet engine. The primary methods employed in this study are theoretical analysis and setting up physical model. Firstly, some discussion on the selection of burning pattern in the combustor of a scramjet engine is carried out based on the analysis of actual thermodynamic cycle process. Then, discussion on how the performance indexes of the scramjet engine change with the flow condition and how the alteration of dominant factors (air-fuel ratio (f) and combustion efficiency (η_b)) affect the pneumatic thermal performance of the scramjet engine under the fixed flying condition and equivalent dynamic pressure condition are developed respectively. At last, the optimum values of the combustion efficiency (η_b) and the air-fuel ratio (f) of the scramjet model at a fixed work condition ($Ma=10$, $H=30km$) are obtained.

1. Introduction

The concept of ramjet was first proposed by the French engineer Rene Lorin in 1913 [1]. Compared with the traditional turbine aircraft engine, the ramjet owns the advantages of simple structure and light weight as it is constituted just by inlet, combustor and exhaust nozzle. According to the difference of airflow velocity in the combustor, Ramjet is mainly divided into Subsonic Combustion Ramjet (Ramjet) and Supersonic Combustion Ramjet (Scramjet), and there are many influencing factors for the ram-to-scram mode transition [2] [3] [4]. As shown in Fig 1, although the performance of the ramjet engine is good when the flight Mach number is in the range of 3-6, the performance will be deteriorated significantly as the flight Mach number continues to rise and attains hypersonic ($Ma>6$) flight range. This is because that the inlet total temperature will rise constantly when the flight Mach number increases, and within the temperature tolerance limit of the materials, even the injection and combustion of the fuel for a small quantity can lead to the overtemperature of the combustion. Besides, excessive temperature will initiate the decomposition of combustion products, and a considerable part of the heat release in the combustion will be consumed during this process. Accordingly, a lower combustion efficiency must be induced [5] [6].

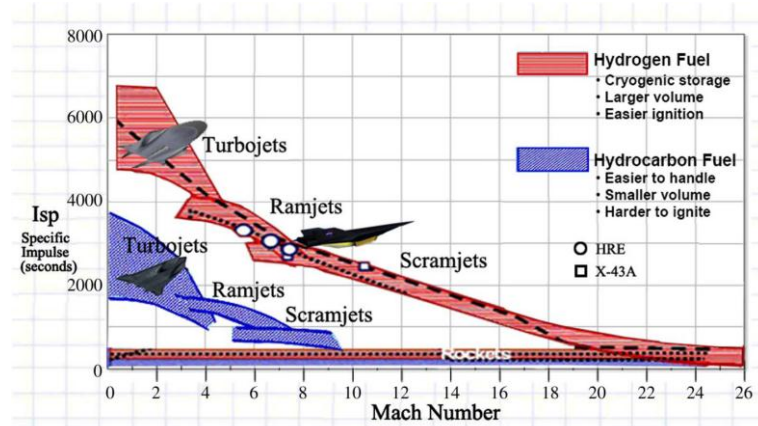


Figure 1: Hypersonic engine specific fuel impulse vs. freestream Mach number [7]

All the factors mentioned above cause a serious attenuation to the performance of the ramjet under the hypersonic condition. Thus, when it reaches hypersonic ($Ma > 6$) flight range, the scramjet engine is believed to be a better choice than ramjet engine [8] [9]. For scramjet engine, the airflow flows into the combustor and burns with a supersonic velocity, which is not only improve the efficiency of the thermodynamic cycle but also avoid the exorbitant static temperature and static pressure, reduce the pressure on the materials of combustor caused by the high temperature and high pressure.

As the optimal dynamical system in hypersonic flight, scramjet engine has the properties of simple structure, large specific thrust and high Mach number cruise. The hypersonic flight vehicle with scramjet engines is well-known as the third aeronautic technological revolution after turboprop and turbo-jet. Besides, the install of scramjet engine in a weapon like fighter plane and guided missile may have a significant influence on war. Recently, scramjet related research has roused wide attention around the world for the outstanding performance and wide application prospects. Scramjet engine is believed to be a promising power system. The operation of the scramjet engine follows the typical open Brayton cycle [7]. Fig.2 demonstrates the temperature entropy (t - s) diagram of actual scramjet thermodynamic cycle. There are four main processes in this cycle system, namely the adiabatic compression in inlet, the supercharged combustion (scram-mode) in combustor, the adiabatic expansion in exhaust nozzle and the isobaric cooling outside the engine.

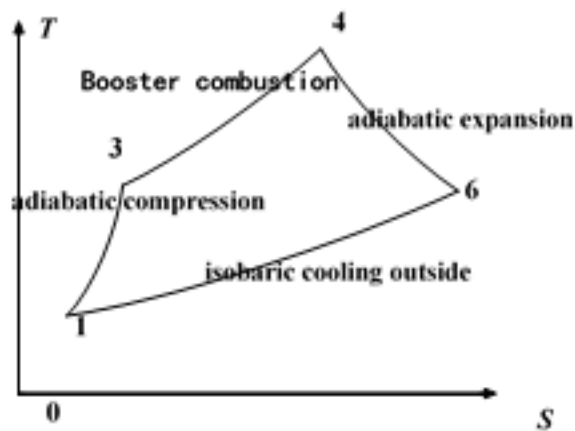


Figure 2: Temperature entropy (t - s) diagram of actual scramjet thermodynamic cycle, 1-Inlet entrance, 3- Combustion chamber entrance, 4- Combustion chamber exit, 6- Tail nozzle exit

The general geometry of a typical scramjet engine is demonstrated in Fig. 3. Similar to the ramjet structure, there is also no mechanical rotating part like compressor and turbine in the scramjet engine. Scramjet engine mainly consists of inlet, separation section, combustor and nozzle. After compressed by the shock wave in the inlet, the supersonic airflow mixes with the fuel and burns in the combustor in a supersonic velocity, and the mixing and combustion process has a great impact on the performance improvement of the scramjet engine [10] [11] [12] [13]. The static temperature and static pressure in the thermodynamic cycle process is in a low level. The high-temperature mixture generated by combustion expands and accelerates in the nozzle. Then, the mixture is pushed out, and the thrust is produced. Compared to ramjet engine, scramjet engine has some special characteristics as following. Firstly, there is only thermal throat but no geometry throat in the inlet and nozzle. Secondly, there is a separation section between the inlet and the combustor, namely the isolator [14], and the separation section has the function of relieving the coupled problem. With the decrease of the effect pressure variation in the combustor on the inlet compression process and shock wave, the stable working range of the inlet will be broadened.

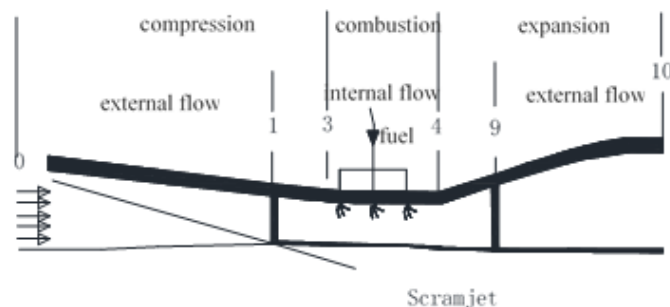


Figure 3: General geometry of a typical scramjet engine

Although scramjet engine can perform stably at high Mach number, there are still some boundedness such as work scope is not wide enough [15] [16] [17]. For example, the American aircraft systems named X-43A and X-51A can only be tested successfully in a single flight Mach number, and the operational capability at wide working condition is not yet to be tested. Before reaching the optimal operating point, the flight Mach number and height of a scramjet engine will go through a massive variable process. The spacing of the flight Mach number is about 3 or 4. The inlet temperature and pressure usually vary dramatically along with it. Therefore, it is significant to study the performance of the scramjet engine at wide working condition.

The United States is one of the earliest countries to begin hypersonic propulsion and scramjet research. Since the end of the 20th century, the United States has conducted dozens of ground and flight tests with several models. The main models include the series of X-43 and X-51. The X-43 is primarily to test the ability of starts and maintain stable flight of the scramjet engine and the vehicle equipped with scramjet engine under a higher Mach number ($Ma=10$ or so). The X-51 is mainly used to test the ability of starts, maintain stable flight and auto acceleration of the scramjet engine and the vehicle equipped with scramjet engine under a lower Mach number ($Ma = 6$ or so). The most noteworthy thing is that the test machine of X-51A has implemented a flight Mach number acceleration from 4.7 to 5.3 in one test. Although the Mach number only changes in a small scope, the test has made a breakthrough in variable conditions working ability of scramjet and hypersonic propulsion [8] [18] [19].

In addition to the United States, there are also many other countries started theoretical and experimental investigation for scramjet engines at the same time. The most representative projects are the PREPHA project and the LEA test program in French, the HOPE-X project in Japan, the HyShot project in Australian, the Sanger conceptual aircraft and the JAPHAR program in Germany. All these projects have made great progress in the field of ramjet and scramjet engines [20] [21] [22].

In the current study, the thermodynamic performance of a typical scramjet model was investigated based on the Brayton cycle, and the influences of the air-fuel ratio and the combustion efficiency on the performance indexes of this scramjet engine were analyzed under the fixed flying condition and equivalent dynamic pressure condition. At last, an optimal fuel injection scheme under the work condition of flight Mach number being 10 and flight height being 30km was obtained.

2. Physical model and analysis approaches

In this article, the core issue is the thermodynamic performance of a scramjet engine at wide working condition. Therefore, the study is carried out based on a typical scramjet model.

The general geometry of a scramjet engine is demonstrated in Fig. 4. The numbers in the figure represent the flow path region, namely "0" is the entry of the inlet, "2" is the entry of the combustor, "3" is the entry of the nozzle, and "4" is the nozzle exit. For scramjet engines, the compression process is completed by a string of oblique shock waves in a convergent inlet. The air flow needs to go through a length of diameter-equivalent isolator before entering the divergent combustor and burning with the fuel at a supersonic speed. At last, the air at high temperature expands in a divergent nozzle and produces thrust [23] [24]. As discussed in the introduction, scram-mode is a better choice than ram-mode when the freestream Mach number is higher than 7 according to the present technical level and engineering experience.

The traditional analysis based on Brayton cycle can also be extended to the scramjet engine although it is not a strict isobaric process in a real scramjet combustor [25] [26] [27]. The characteristic of the scram-mode is the pressure rise combustion in the combustor. The equivalent method is used in this study as it is complicated to fathom the pressure rise combustion out. A pressure ratio is given at the entrance of the combustion chamber, and suppose the isobaric combustion in the combustor. It is crucial to maintain the circulation work equals to that produced in the actual pressure rise combustion [28] [29] [30].

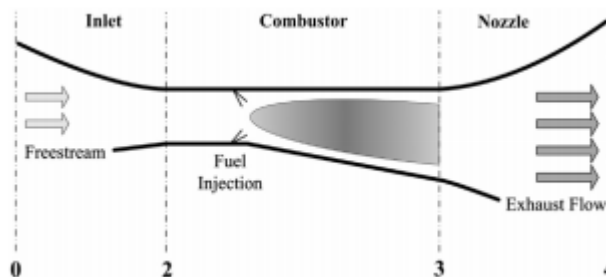


Figure 4: Simplified geometry of a typical scramjet engine

There is a hypothetical pressure rising between the section 2 and 3 according to the analysis before. In order to conform to the actual situation, the geometric model employed in the study has the relative cross-sectional area as follows, see Table.1.

Table 1: Relative cross-sectional area for the geometric model employed in the current study

Characteristic section	A1	A2	A22	A3	A4
Relative area	0.275	0.03	0.015	0.016	1.5

When the input value is $Ma_0 = 10$, $H = 30\text{km}$ and f (air-fuel ratio) = 0.04, the results of the program are as follows, see Table.2.

Table 2: Results for the geometric model employed in the current study

Performance index	Value	Performance index	Value
Specific thrust (m/s)	1044.6	Specific impulse (s)	2662.1
Thermal efficiency	0.6920	Propulsive efficiency	0.9282
Overall efficiency	0.6423	Inlet entropy production (J/K)	17.9
Combustor entropy production (J/K)	1692.1	Nozzle entropy production (J/K)	172.0
Specific fuel consumption (kg/(N h))	0.138		

The obtained result shows that for the work condition of $Ma_0 = 10$ and $H = 30\text{km}$, this scramjet engine can produce positive thrust, and the efficiencies are all in a reasonable scope. Furthermore, the entropy production in the combustor is the main part of the entropy production in the engine. This consequence agrees with David Riggins's opinions as well [31] [32].

The temperature-entropy (T-s) diagram of the scramjet engine is given in Fig.5, and there are two different pressure increasing processes in the thermodynamic cycle diagram. In Fig.5, the green line represents the adiabatic compression process in the inlet, and the yellow line represents the equivalent adiabatic compression process before the entrance of the combustor. The isobaric combustion process in the combustor is represented by the red line, the adiabatic expansion process in the nozzle is represented by the pink line, and the isobaric exothermic process is represented by the blue line. The temperature-entropy (T-s) diagram shows that the entropy production in the isobaric combustion process of the combustor is the main part of the total entropy in the whole process.

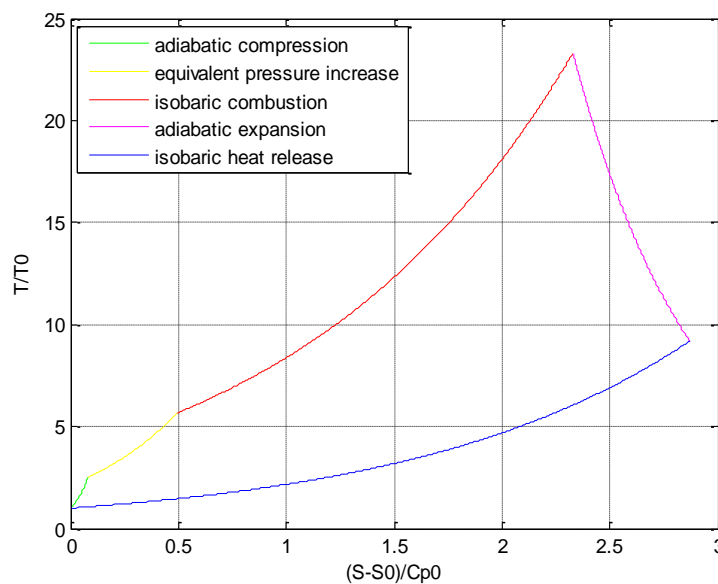


Figure 5: Non-dimensional temperature - entropy curve of the scramjet engine

3. Results and discussion

For ramjet engines, the combustion in the combustor is isobaric process, the thermodynamic cycle can refer to the curve 1-2-3-4-1. However, for scramjet engines, the combustion is booster process, and the thermodynamic cycle can refer to the curve 1-1.2-3'-4'-1, see Fig.6. It can be shown in Fig.6 that the area B-(A+C) represents difference values of the circulation work generated in scramjet and ramjet engines, which means that the scramjet engine can produce more circulation work than the ramjet engine.

If combining the isobaric and booster processes in the scramjet combustor, the thermodynamic cycle can refer to the curve 1-1.2-2'-3'-4'-1. The circulation work generated in scramjet engines is more than the booster combustion (the area C), and the average endothermic temperature is higher, which means the enhancement of the performance of the scramjet engine. According to the analysis mentioned before, the combustion process has a paramount influence on the performance of the scramjet engine. Thus, the main work of this study is analyzing the selection of burning approach in the combustor and how the main factors (the air-fuel ratio (f) and the combustion efficiency (nb)) affect the performance of the scramjet engine.

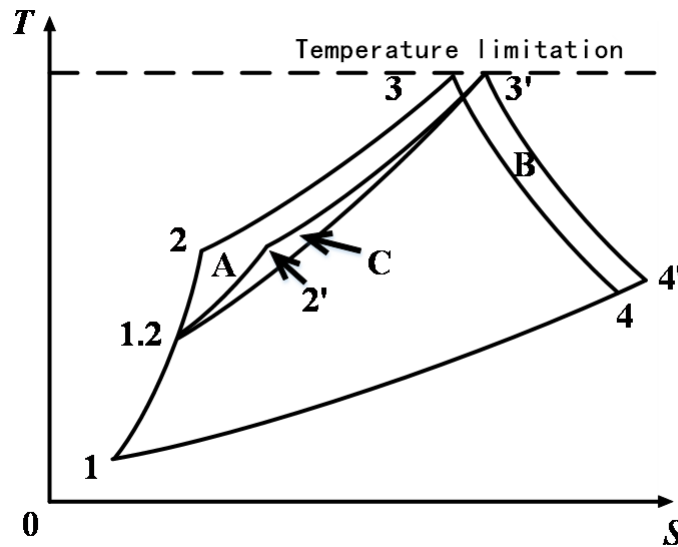


Figure 6: Non-dimensional temperature - entropy curve for different combustion modes

3.1 Burning mode analysis of scramjet engines

The relationship among the radial distance, the Mach number and the total temperature of the airflow in the combustor can be shown in the following equations.

$$\frac{dMa}{dx} = Ma \left(\frac{1 + \frac{\gamma_b - 1}{2} Ma^2}{1 - Ma^2} \right) \left[- \left(\frac{1}{A} \frac{dA}{dx} \right) + \frac{\gamma_b Ma^2 + 1}{2} \left(\frac{1}{T_t} \frac{dT_t}{dx} \right) \right] \quad (1)$$

$$\frac{dT_t}{T_t dx} = \frac{dT}{T dx} + \frac{(\gamma - 1) Ma}{1 + \frac{\gamma - 1}{2} Ma^2} \quad (2)$$

From Eqs. (1) and (2), we can know that as the flow velocity of the airflow in the combustor is high, the heat injected in the combustor is almost independent with the increased amount of the static temperature. This is the biggest specialty the scramjet to the normal aero-engine. In the combustor of normal aero-engine, the heat input almost translates into the static temperature rising of the airflow. While for the combustor of the scramjet engine, the proportion of the effect the heat input on the static and dynamic temperatures can be controlled by using different fuel supply ways and various cross-section areas of the combustor. Thus, the burning velocity can be controlled, and then different combustion modes are obtained. Furthermore, disparate combustion patterns (isothermal combustion/isobaric combustion and so on) can be obtained by regulating the heat input ration.

Fig.7 shows the temperature-entropy diagram of different burning patterns.

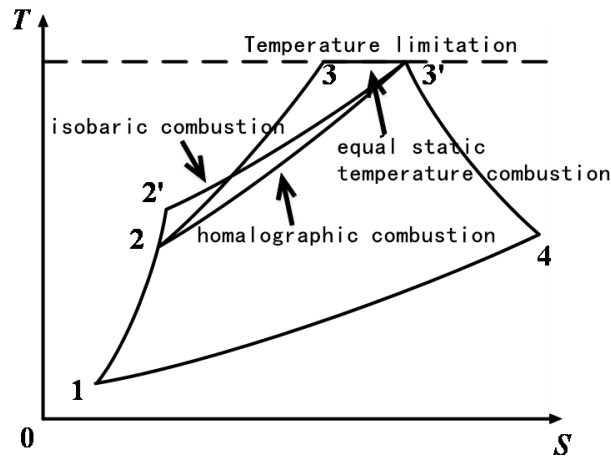


Figure 7: Non-dimensional temperature - entropy curve of the scramjet engine for different burning patterns

When the burning pattern in the combustor is isobaric combustion, the scram-mode has actually been degraded to the ram-mode, complicated profiles are requisite for maintaining isobaric combustion in scramjet engines. Entirely equal static temperature combustion in fact is not possible, and it is only able to realize equal static temperature combustion partly in the combustor after the temperature reaches the material temperature limit. For equal-area combustion, the thermal choking generated by heat release may lead to the velocity of the airflow decreased to subsonic.

Through the analysis above, it can be seen that single burning pattern is difficult to meet the scramjet performance requirements. Therefore, the adoption of the compound burning pattern which combines two or even more kinds of single burning pattern is essential to ensure the performance of the scramjet engine. According to the temperature-entropy diagram, the optimal burning process is booster combustion at first, then transform into equal static temperature combustion when reaching material temperature limit. This burning pattern can produce the largest circulation work, and its temperature-entropy diagram is shown in Fig.8.

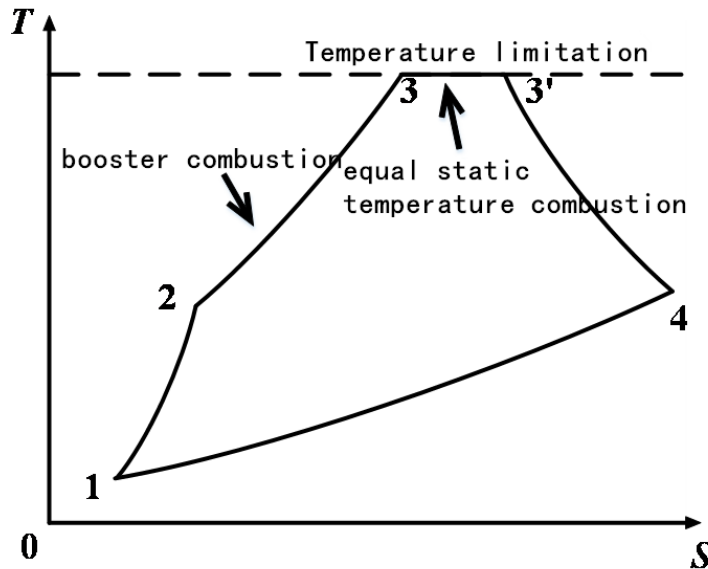


Figure 8: Non-dimensional temperature - entropy curve of the scramjet engine for compound combustion process

From Fig.8, we can see that compared with the traditional onefold booster combustion process, compound combustion process can increase the area of the thermal cycle on the temperature-entropy diagram, which means the enlargement of the circulation work. Therefore, the compound combustion process can enhance the performance of the scramjet engine.

Through designing reasonable area variable rule of the combustor profile and adjusting the gas inject position, disparate burning patterns could be combined, and the best performance of the scramjet engine can be attained. When employing compound combustion pattern, the variation characteristic of parameters along the axial direction of the combustor is show in Fig.9.

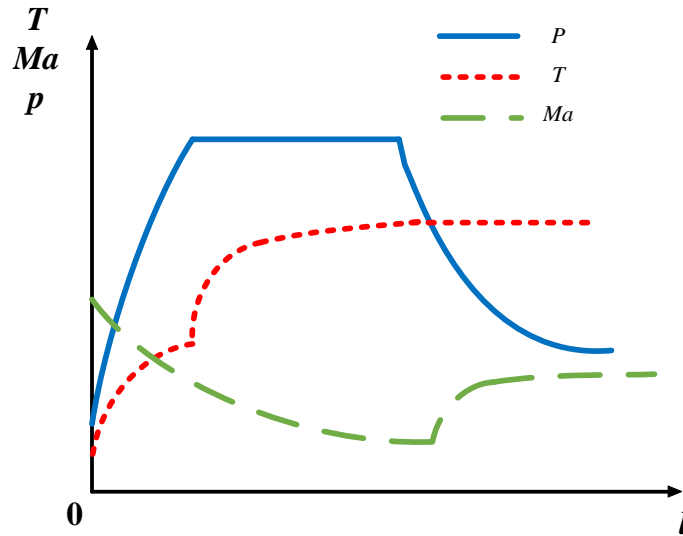


Figure 9: Variation characteristic of parameters along the axial direction of the combustor

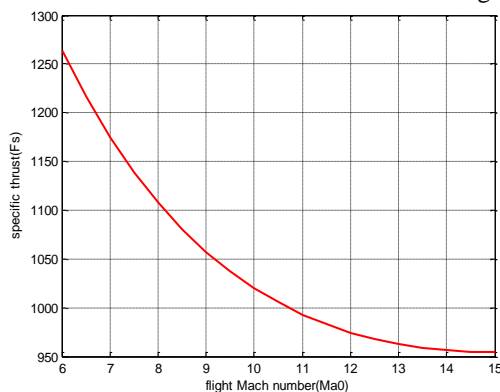
3.2 Pneumatic thermal performance analysis

Along with the variation of flow conditions, the performance characteristics will go through a great variation. On the basis of the combustor characteristic analysis and the previous studies, it can be confirmed that the principle influence factors to the performance indexes for scramjet engines are the combustion efficiency of the combustor (η_b) and the air-fuel ratio (f). The following work is to investigate how these factors affect the pneumatic thermal performances of scramjet engines.

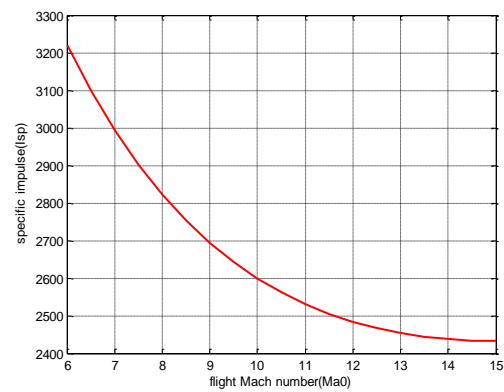
3.2.1 Performance characteristics of scramjet engines under variable flow conditions

Applying the scramjet model mentioned above, the relationship between the flow condition and the performance characteristics are shown in Fig.10.

(1) Performance characteristics with different flight Mach numbers



(a) F_s vs. Ma_0



(b) I_{sp} vs. Ma_0

Figure 10: Performance variations with different flight Mach numbers, (a) F_s vs. Ma_0 and (b) I_{sp} vs. Ma_0

The specific thrust and the specific impulse decreases monotonously with the continuous increase of Ma_0 . This variable rule conforms to the general recognition. For this given geometrical structure scramjet engine, the increase of Ma_0 will cause the decrease of the inlet compression efficiency and then induce the performance reduction of the whole engine. Furthermore, after Ma_0 increases to a certain value, the inlet of the scramjet engine will face the unstart problem. Besides, the loss generated during the working process will raise with the enlargement of Ma_0 , and this will result in a decline in the power capability of the flow and a damping in special thrust. According to the computational formula of specific impulse, namely $I_{sp} = F_s / g / f$, the specific impulse shows a trend of attenuation as well.

(2) Performance characteristics with different flight heights

From Fig.11, a special variable curve can be seen. For this given geometrical structure scramjet engine, when the flying height is lower than 32km, the decline of specific thrust and specific impulse induced by the growth of flight height is not as prominent as the height above 32km. This is because that there is an upper temperature limit in the combustor. The temperature increment induced by the lofty flying height will speed up the attenuation of the performance parameters.

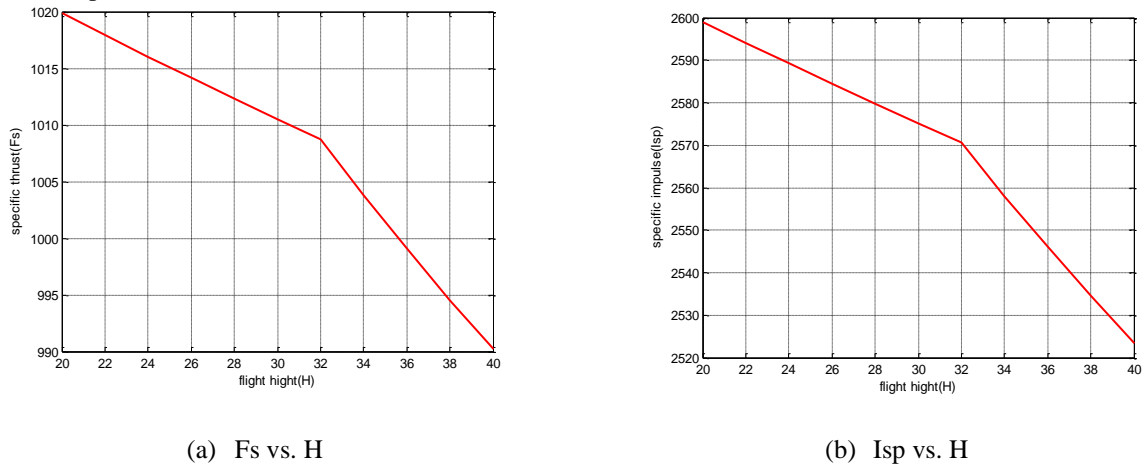


Figure 11: Performance variations with different flight heights, (a) F_s vs. H and (b) I_{sp} vs. H

3.2.2 Pneumatic thermal performance characteristics of scramjet engines under different flight Mach numbers

(1) Scram-mode with different air-fuel ratios

Applying the scram-mode model mentioned above, the specific thrust and the specific impulse of a scramjet engine can be calculated at conditions with different air-fuel ratios (f). The influence of the air-fuel ratio (f) on the scramjet performance under the fixed inlet condition ($Ma_0=10$, $H=30$ km) can be obtained through the Matlab program.

The results of the specific thrust and the specific impulse with different air-fuel ratios are shown in Fig 12. With the continuous increase of the air-fuel ratio (f), there is an increasing trend of the specific thrust of the scramjet engine, while the specific impulse is on a declining curve and the downward trend is slower. The explanation for this phenomenon is that the augmentation of the air-fuel ratio (f) means injecting more fuel oil into the combustor. Absolutely, the specific thrust of the scramjet engine will increase. The formula of the specific impulse is $I_{sp}=F_s/9.81/f$. It indicates that when the increasing rate of the specific thrust is inferior to that of the air-fuel ratio (f), the specific impulse will decrease, and the trend of the diminution will slow down gradually.

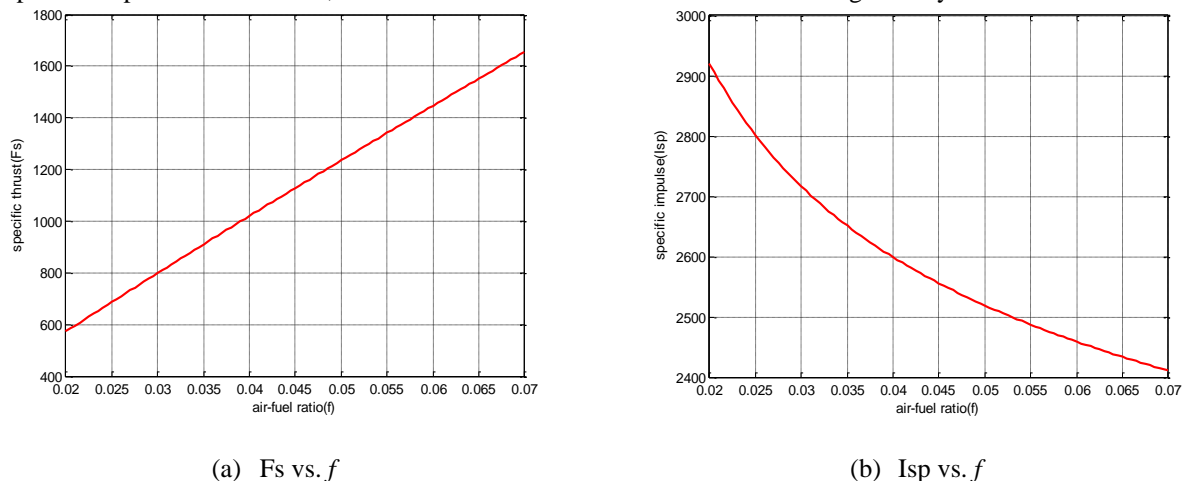


Figure 12: Performance variations with different air-fuel ratios, (a) F_s vs. f and (b) I_{sp} vs. f

(2) Scram-mode with different combustion efficiencies

Repeating the previous work with different assumptions of combustion efficiency, the specific thrust and the specific impulse of a scramjet engine are shown in Fig 13.

From the result of Fig.13, we can see that the combustion efficiency (η_b) has a remarkable impact on the performance parameters of the scramjet engine when the work condition is fixed. With the constantly increase of the

combustion efficiency (nb), the specific thrust and the specific impulse are both have an ascending tendency. That is because of the fuel of equivalent quality, the energy injects into the scramjet will be aggrandized with the enhancement of the combustion efficiency (nb), and the incremental energy will inevitably make the performance parameters such as specific thrust and specific impulse to improve.

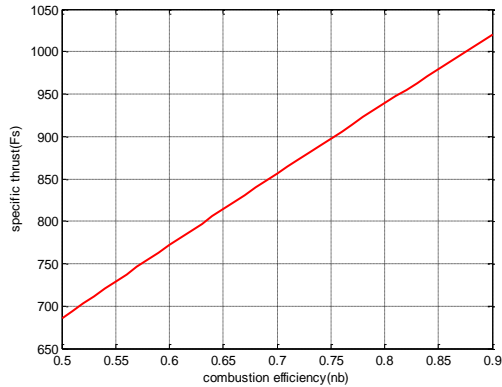
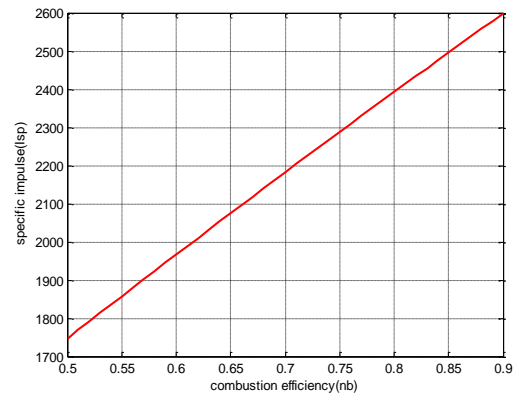
(a) F_s vs. nb (b) I_{sp} vs. nb

Figure 13: Performance variations with different combustion efficiencies, (a) F_s vs. nb and (b) I_{sp} vs. nb

3.2.3 Pneumatic thermal performance characteristics of scramjet engines with the same dynamic pressure

(1) Scram-mode with different air-fuel ratios

For scram-mode, the performance parameters (specific thrust and specific impulse) will vary with the adjustment of the air-fuel ratio (f). The influence of the air-fuel ratio (f) on the scramjet performance under a fixed dynamic pressure can be obtained through the MATLAB program.

Fig.14 shows the variation trend of specific thrust and specific impulse with the variation of air-fuel ratio (f). Under the equivalent dynamic pressure condition, the specific thrust (F_s) has an ascending tendency, while the specific impulse (I_{sp}) is on a declining curve and the downward trend is slower. This result is in accordance with the analysis of pneumatic thermal performance characteristics under different flight Mach numbers.

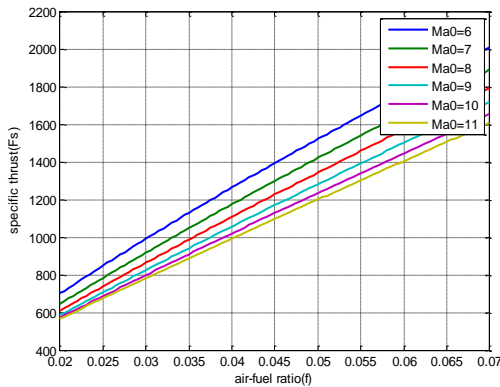
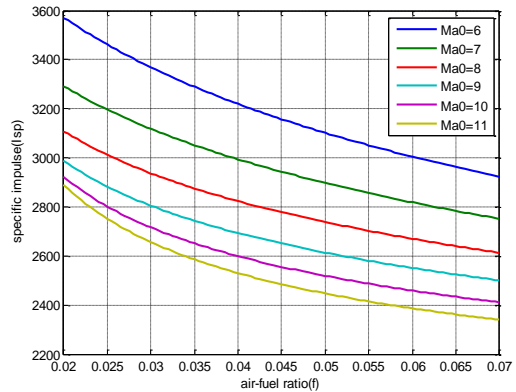
(a) F_s vs. f (b) I_{sp} vs. f

Figure 14: Performance variations with different air-fuel ratios for different flight Mach numbers, (a) F_s vs. f and (b) I_{sp} vs. f

(2) Scram-mode with different combustion efficiencies

Repeating the previous work with variable combustion efficiencies (nb). The affecting law combustion efficiency (nb) to the performance of scramjet engines in a fixed dynamic pressure can be derived. As show in Fig.15, with the continuous increase of combustion efficiency, the specific thrust and the specific impulse of the scramjet engine are taking on a growth trend under the work condition of a given dynamic pressure. The reason for this consequence is that the energy released by the same quality of fuel injection into the scramjet will boost with the augment of the combustion efficiency. Therefore, the performance parameters like specific thrust and specific impulse are on an increasing tendency.

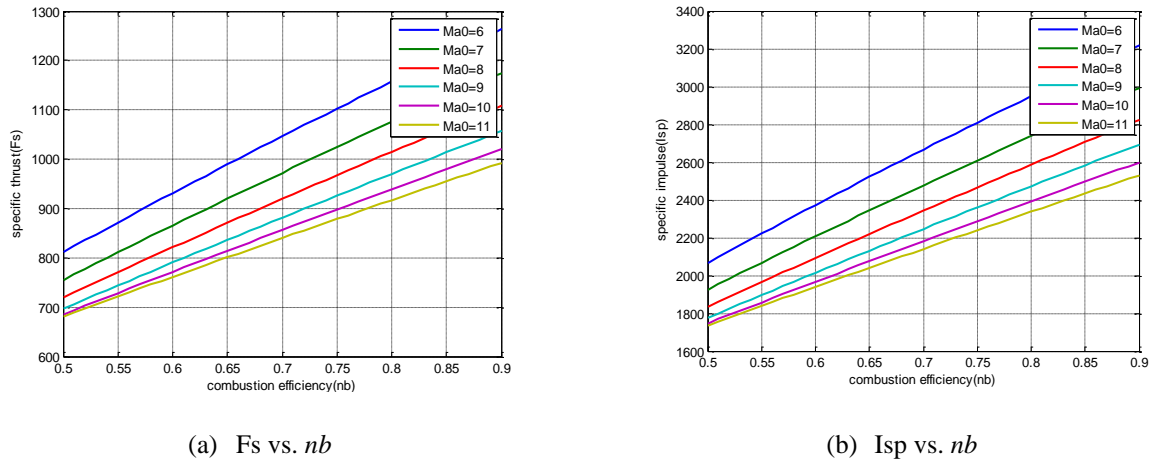


Figure 15: Performance variations with different combustion efficiencies for different flight Mach numbers, (a) F_s vs. nb and (b) I_{sp} vs. nb

3.3 Approach of indexes selection

On the basis of the previous analysis, the performance parameters of scramjet engines are more optimal than that of ramjet in the work condition of high speed flight. For a scramjet engine, the air-fuel ratio (f) and the combustion efficiency (nb) exert great influence on the performance parameters. To investigate the optimal air-fuel ratio (f) and combustion efficiency (nb) of the scramjet engine under a fixed work condition, changing the air-fuel ratio (f) and the combustion efficiency (nb) simultaneously, and the variable characteristics of the performance parameters can be observed. The result is demonstrated in Fig.16.

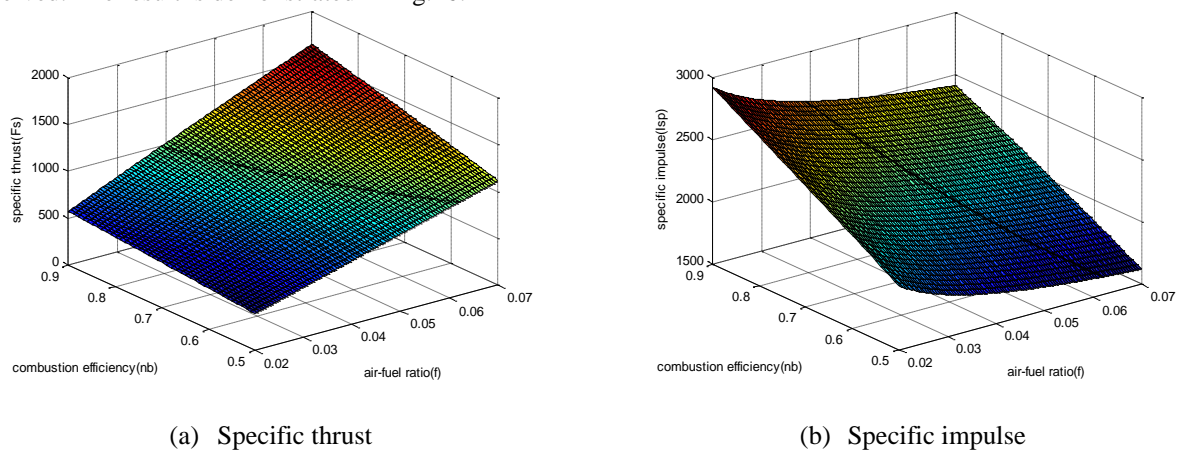


Figure 16: Performance variation with different air-fuel ratios and combustion efficiencies, (a) Specific thrust and (b) Specific impulse

On account of the results show in Fig.16, when the requirement of the specific thrust is $F_s = 1000\text{m/s}$, it can be found clearly that the maximal specific impulse is $I_{sp} = 2607.6\text{s}$. The air-fuel ratio (f) correspond to this situation is $f = 0.039$, and the combustion efficiency (nb) is $nb=0.9$. This is the best fuel injection scheme of a scramjet engine at this work condition. Additionally, the best fuel injection scheme of a scramjet engine at different work conditions can be obtained through changing the inlet flow conditions and repeating the work discussed above.

4. Conclusions

In the current study, the scramjet engine is set as the research object in this article, and the thermodynamic performance analysis of a scramjet engine at wide working conditions was carried out based on the Bryton cycle. We have come to the following conclusions:

- As for scramjet, the compound combustion is the best combustion mode, namely booster combustion at early stage, and convert into equal static temperature combustion when the material temperature of the scramjet reaches the limit.
- The pressure ratio and the temperature ratio have the decisive effect on the performance of a scramjet engine. The entropy production in the compound combustion process of the combustor is the main part of the total entropy in the whole process.
- One of the main factors affect the performance output of scramjet engines are finally determined to be the air-fuel ratio (f). With the continuous increase of the air-fuel ratio (f), there is an increasing trend of the specific thrust (Fs) of the scramjet engine. While the specific impulse (Isp) is in a decline trend, and the trend will slow down.
- The other main factor affects the performance output of scramjet engines is finally determined to be the combustion efficiency (η_b). With the continuous increase of the air-fuel ratio (f), there is an increasing trend of the specific thrust (Fs) and the specific impulse (Isp) of the scramjet engine.
- When the requirement of the specific thrust is 1000 N, the corresponding best air-fuel ratio f is 0.039, and the combustion efficiency η_b is 0.9. This is the best fuel injection scheme of this scramjet engine under the work condition of flight Mach number being 10 and flight height being 30km.

Acknowledgements

The authors would like to express their thanks for the support from the National Natural Science Foundation of China (No.11502291) and a fund for owner of Outstanding Doctoral Dissertation from the Ministry of Education of China (No.201460).

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