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Analysis and Possible Improvements of Scramjet Engines: The Effective Thrust and the Combustion Stability Problems

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Abstract. The scramjet is the representative of the future jet engine, and it has irreplaceable advantages in terms of working performance and service life. Although it has been developed more than fifty years, there are many problems in the driven system of the scramjet engine. This paper mainly focuses on the problems of the effective thrust and the combustion stability. The research shows that how the pressure ratio affects the positive thrust and the combustion stability. Furthermore, this paper also shows that the elements which can affect the pressure ratio. The lower inlet air temperature is beneficial to enhance the thrust. According to the relevant research which apply the CJ detonation theorem to find the possible reason for the combustion instability. For the possible improvements, the research found that the engine thrust at different speed and the allowable maximum speed. The type of fuel and the reactivity of the fuel can influence the thrust.

Keywords: Scramjet engine, Combustion, Thrust, CJ detonation.

1. Introduction

The structure of the scramjet engine was firstly come up in the 50s last century. The basic operating principle in scramjets is converting the significant kinetic energy of the incoming air into pressure energy. Unlike the traditional turbojet engine, it has only three simple components: the compression part, the combustion part, and the expansion part. That leads the scramjet engine has several features including the simple structure, light. Besides, the scramjet engine does not need the oxidizing agent because the engine can take the abundant surrounding air in the supersonic work environment. The hypersonic air flow can be compressed easily because the change of the cross-section area in the compression part. Thus, the scramjet engine does not need the rotational components such as the turbine and compressor and the main shaft. The super simple structure be considered as a reliable design [1].

There are several future applications of scramjet engines, including civil supersonic aircrafts, space exploration as a stage for access to Earth orbit, and military hypersonic weapons. As the author said, "Despite many impressive achievements obtained in the field since the early sixties, still today there are no scramjet engines being used in practical devices: many developments including experimental flights and ground-based tastings are currently in progress" [2].

The design of scramjet engine is a very complex engineering program including the fluid mechanics, thermodynamic, physics of gas, combustion fluid field and so on. The combustion at supersonic or even hypersonic field will become very different. The combustion flow field is full of shock waves, mixing, turbulence, and boundary layer. All of these enable the work mechanism very complex. Thus, many

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problems as above prevent the development of the scramjet engine. The most two important problems are how to maximize the positive thrust and how to enable the combustion stable. Because the drag force in the hypersonic flight for the aircraft is extremely big, the engine should produce a big thrust to gain a positive net drive force. For the combustion instability problem, that is a common phenomenon with the high combustion pressure. Thus, how to find a proper pressure ratio become a vital problem [3].

This report focuses on the analysis of the above mentioned two problems: the effective thrust and the combustion stability. Besides, the low thermal efficiency of the scramjet engine is also a problem. This research also gives a possible way to improve the efficiency of scramjet engine: use a kind of fuel with high combustion product pressure and low momentum, control the fuel reactivity. To gain a more real result, the report analyzes the possible maximum speed of aircraft equipped with the scramjet engine.

All the experiment data and simulation methods come from the previous literatures, this report just gives a reasonable analysis and integrate the conclusions based on the results.

2. Research Methods and Physical Models

2.1. The Approach of Simulation

Using the H2/Air mixed gas, according to the work process of scramjet engine, to do the simulation which take the combustion pressure ratio as a result by changing the inlet flow temperature and the speed. Because of the complex working process of real scramjet engine, here the author used the theoretical model of CJ detonation engine to simulate combustion process which is the core process of the scramjet engine as shown in figure.1 [4]. To find the reason of the combustion instability, the author did a comparison between the wave caused by CJ detonation and the nonreactive shock. Here the CJ detonation represent a detonation process with combustion whereas the nonreactive shock represents the detonation without combustion. According to the CJ detonation theorem hypothesis: flow is one-dimensional, regardless of the heat conduction, heat radiation and viscous friction dissipation effect; the detonation wave as strong discontinuity; after the detonation wave through chemical reaction and discharge instantaneous chemical reaction heat, reaction products in the thermal chemical equilibrium and thermodynamic equilibrium state; detonation wave front propagation process is stationary [5].

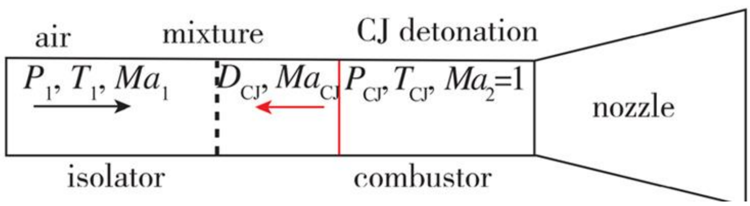

Figure 1. Theoretical model of CJ detonation engine as a simulation of the scramjet engine.

2.2. The Optimization for Scramjet Engine

To find possible improvements of scramjet engine, this report shows a kind of more efficiency fuel to drive the engine. Furthermore, there are previous literatures shows “a concept of controlling the self-starting characteristics and propulsion performance of a scramjet via fuel reactivity modification” [6]. The other simulation shows that the specific thrust and maximum speed of the aircraft with different area ratio between the hypersonic vehicle reference area to the inlet capture area of scramjet engine. The aerodynamic data process shown as followings [7].

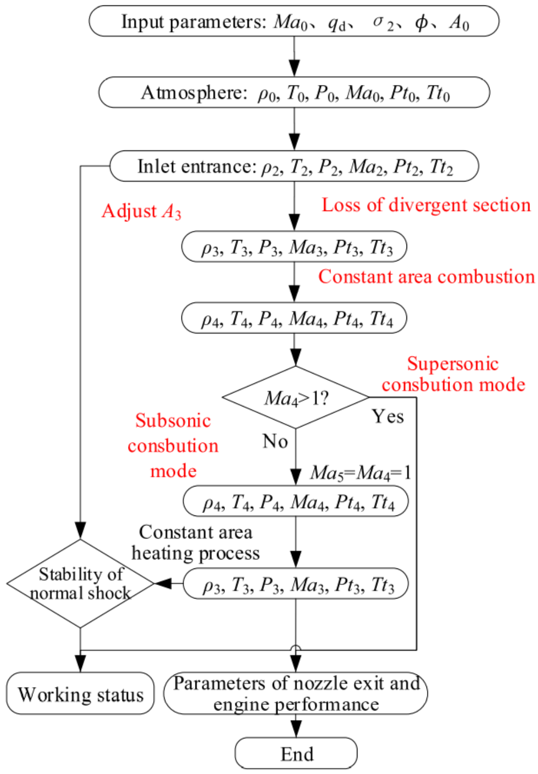

Figure 2. Performance calculation process of scramjet engine.

The method of aerodynamic data process has shown as following,

$$D = \frac{1}{2}\rho_0 u_0^2 C_D S \tag{1}$$

$$T = \frac{1}{2}\rho_0 u_0^2 C_T S \tag{2}$$

$$C_T = \frac{T}{\frac{1}{2}\rho_0 u_0^2 S} = \frac{I_{sp} f \rho_0 u_0 A_0 \varphi g}{\frac{1}{2}\rho_0 u_0^2 S} = \frac{2 I_{sp} f A_0 \varphi g}{u_0 S} \tag{3}$$

$$a = \frac{T cos\alpha - D}{m} - g sin(\theta - \alpha) \tag{4}$$

$$\dot{\alpha} = \frac{-T sin\alpha - D}{m} + \dot{\theta} + \frac{g cos(\theta - \alpha)}{u} \tag{5}$$

$$L = \frac{1}{2}\rho_0 u_0^2 C_L S \tag{6}$$

$$\dot{\alpha} = 0, \dot{\theta} = 0 \tag{7}$$

$$\frac{T sin\alpha + L}{m} = g \tag{8}$$

$$T cos\alpha - D = 0 \tag{9}$$

3. Result and Discussion

Experiments have shown that the pressure of combustion products in the combustion chamber is up to about 4.4 times the inlet pressure, and most of them are about 2.4 times the inlet pressure at a static temperature of about 950 K and a Mach number of about 2.6. The ability to generate high pressure gas by exothermic combustion at supersonic speed is very limited [8]. The pressure in the combustion chamber is not enough at this state, that can also lead the thrust is too small. The final simulation result also shows that.

The simulation result shows the data of incoming flow temperature varies from 300 K to 1,500 K with an initial pressure of 1 atm. Table 1 gives the Mach number, pressure and burst velocity of the CJ blast wave at different isolated incoming flow temperatures [4].

Table 1. Parameters of stoichiometric H2/air CJ detonation under different initial temperatures.

T_1/K	$M_{a_{CJ}}$	P_{CJ}/P_1	$D_{CJ}/(m/s)$	$P_2/P_1(shock)$
300	4.85	15.08	1979.3	27.85
400	4.18	11.28	1976.3	20.55
500	3.72	9.02	1955.6	16.18
600	3.39	7.49	1943.9	13.43
700	3.13	6.42	1932.2	11.41
800	2.92	5.61	1920.4	9.88
900	2.75	4.96	1908.4	8.74
1000	2.59	4.46	1896.3	7.72
1100	2.46	4.04	1883.8	6.85
1200	2.35	3.71	1871.1	6.32
1300	2.24	3.41	1857.8	5.72
1400	2.15	3.15	1844.3	5.25
1500	2.06	2.93	1830.1	4.73

For the data row of 1000K, the results roundly correspond to the experiments mentioned in the first paragraph of the current part. This result can prove the low thrust at this state again and shows the correctness of this simulation experiment. Furthermore, the higher inlet temperature brings the lower pressure ratio. That will cause the sharp decline of the thrust of scramjet engine. In other words, the engine thrust can be improved by lowering the static temperature of the combustion chamber inlet air. The low pressure ratio maybe cause the work instabilities or stalls or even hard to start.

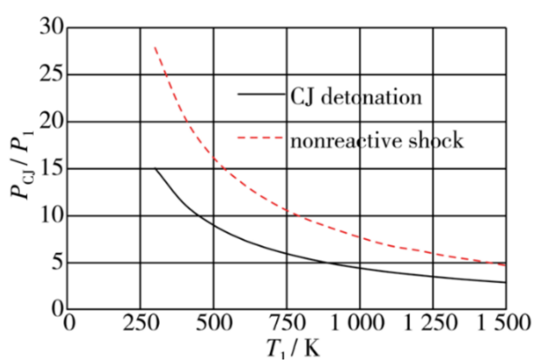

Figure 3. Pressures of stoichiometric H2/ air CJ detonation under different initial temperatures.

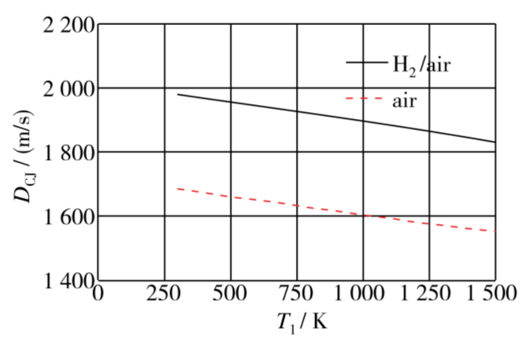

Figure 4. Velocities of stoichiometric H2/air CJ detonation under different initial temperatures.

Previous research shows that the combustion instability does not due to the high back pressure from the combustion chamber [9]. Figure 3 shows the pressure ratio comparison of the CJ detonation and the nonreactive shockwave. The results of CJ detonation represent the situation with combustion. It is obvious that, the back pressure of nonreactive shockwave even higher than the combustion situation. That can prove the above research and show the correctness of the experiment data.

Excitation and compression waves can be propagated upstream, that may be a reason about why the combustion become instability at high pressure ratio. “The detonation wave generated in the combustion chamber propagates into the air in the isolation section. Since the velocity of detonation wave is higher than that of incoming air as figure 4, the detonation wave is not stationary, but propagates upstream” [4]. The shock wave will decay continuously during the upstream spread. When the velocity of the shock wave decays to less than the velocity of the incoming air, it will be transmitted down into the combustion chamber to generate oscillating shock waves.

The hydrocarbon fuel can provide much big thrust than the traditional hydrogen fuel. The hydrocarbon can product high combustion pressure with low momentum. Besides, “Fuel reactivity modification is an effective way to control the self-starting characteristics of jet burners. By reducing the activation energy of hydrogen, the characteristic ignition length is significantly reduced at low flight Mach number conditions. The minimum flight Mach number required for self-start was reduced from 6.2 to 5.1 when the activation energy was reduced by 50%” [6]. That is a good way to improve the start difficulty and the combustion instability. Just from the fuel perspective, both two problems can be optimized.

For the aerodynamic simulation experiment, the biggest thrust occurs around 3.5 Mach as shown as figure 5. However, the lowest start speed of scramjet engine must more than a very high speed [10]. That needs more than 5 Mach around. That has no real meaning. Nevertheless, lower speed in the scramjet speed range means longer travel life. Because of the high start speed of the scramjet engine, the area ratio must smaller than 7 at least to gain a stable work speed range as shown as figure 6. The influence of the area ratio to the maximum speed is very big. Low area ratio can even own the ability to accelerate more than 10 Mach.

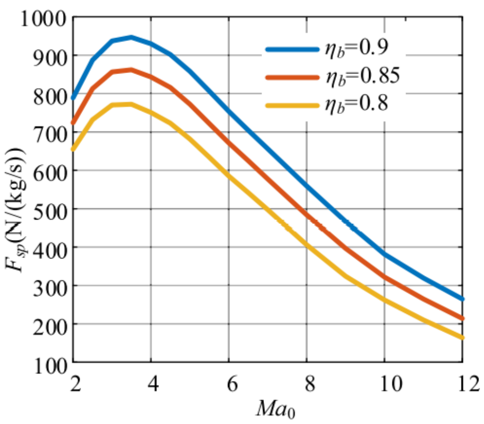

Figure 5. Specific thrust vs. freestream Mach number under different combustion efficiency.

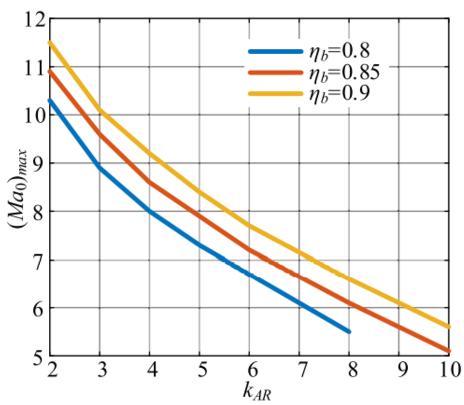

Figure 6. Maximum flight Mach number at different combustion efficiency and k_AR when the angle of attack is 10°.

4. Conclusion

Too low pressure in the combustion chamber causes the low thrust and too high pressure causes the combustion instability. It is important to find a proper combustion pressure.

The higher inlet temperature brings the lower pressure ratio. The engine thrust can be improved by lowering the static temperature of the combustion chamber inlet air

From the pressure ratio comparison of the CJ detonation and the nonreactive shockwave, the high back pressure is not the reason of combustion instability.

The oscillating shock waves in the combustion chamber which caused by the spread of shockwave upstream and downstream may be a reason why the combustion is instable in high pressure.

Hydrocarbon fuel can help to improve the thrust and the activity control of the fuel can help to solve the start difficulty and combustion instability problems.

At around 3.5 Mach, the scramjet engine has biggest thrust. The area ratio between the hypersonic vehicle reference area to the inlet capture area of scramjet engine must less than 7 to ensure the engine can work.

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