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Experimental Investigation of Cavity-based Scramjet Model

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Abstract: The configuration of scramjet engine is important to organize combustion with the kerosene fuel. Cavities and struts are usually used to enhance mixing and hold flame. The present work focused on the performance of the model engine with the different inlets and combustors. The models were tested in a free-jet wind tunnel that typically provides the testing flow with Mach number of 5.8, total temperature of 1800K, and total pressure of 4.5MPa and mass flow rate of 4kg/s. Strut as effective techniques were used in a kerosene-fueled scramjet. The integration of strut/cavities also had the important effect to make the combustion more stable than the model without strut. The one dimensional analysis method has been used to analyze the main characteristics of the models.

Key Words: Scramjet, Combustor, Cavity

1 INTRODUCTION

Due to its high potential in the utilization in the future hypersonic transportations, scramjet engine has been investigated over fifty years[1-4]. Although several engine flight tests have been conducted in past few years, the fundamental studies are still focused on revealing the mechanism of the supersonic combustion occurring in a scramjet engine. Because of the high flow speed passing through the engine, hence, short residence time of air and fuel in a limited length combustor, mixing, ignition and flame-holding became dominated issues in scramjet design and development. Many attempts were made by scientists on the optimizations and improvements of the scramjet performance related to mixing enhancement, self and forced ignition, and flame stabilization by using struts, ramps, steps, cavities, plasma touches and their combinations[5-9]. Another obstacle is the fuels for scramjet. Hydrocarbon fuels were selected for their more convenience and stable for storage, but how to organize the combustion remains unsolved.

The combustors with the above structures had been researched for many years. However because of the extremely complicated mechanism of supersonic combustion, the combustor configurations which can satisfy the requirement of thrust under the flight condition have not been published yet.

The strut is a useful structure to improve the scramjet engine performance, but it has shortages of increasing drag and heavy thermal load. Among a lot of techniques for improving the engine performance, the present work focuses on the strut and recessed cavity. The side-wall compression scramjet model (SCM04) and mutishock wave compression inlet model (MCM01) were tested in a hypersonic propulsion wind tunnel. The thrust and the pressure of the scramjet model were investigated experimentally.

2 DESCRIPTIONS OF TEST FACILITY AND SCRAMJET MODEL

2.1 Test Facility

The test facility used in the scramjet experiments is a high-enthalpy free-jet tunnel, so-called HPTF (Hypersonic Propulsion Test Facility). It provides typical test conditions as Mach number 5.8,

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total pressure 4.5MPa, total temperature 1800K and mass flow rate 4kg/s by a rectangular facility nozzle with the exit of 300mm in width and 187mm in height. The pressure of 4kPa inside the test cabin which duplicates the engine entrance pressure condition of 25km altitude can be achieved by a single-stage triple-nozzles air ejector with 40kg/s mass flow rate.

The pressure were measured by PSI 8400 pressure scanner with 128 channels and an accuracy of ±0.05% FS (FS=310.2 kPa), and fuel flow rates measured by the orifice plate and pressure difference transducer.

2.2 Scramjet Model

The scramjet model, so-called SCM04, as shown in Fig. 1, used in the tests was designed for testing variable struts and cavities that were considered for mixing enhancement and combustion stabilization. The contraction ratio of the inlet is 6.25 with counting the strut thickness. The inlet is 474mm in length and 70mm in height. An isolator following the inlet is 100mm long with 1° divergent angle. The combustor is 800mm long with a 1.5° divergent angle. The thrust nozzle is 300mm long and expansion ratio of 1.7. The blockage ratio of the model to the facility nozzle is 31%. The strut having staggered wedge tail serves as compression surface at the inlet as well as a fuel injector in the combustor. Recessed cavities functioning as flameholder in the combustor were used. Both strut and cavity generate variant vortexes that help the mixing and combustion process, as well as extending the fuel residence time. The cowl position is set to front shoulder of 0% and 10% of inlet length. The fuel for scramjet model was kerosene. A small amount of hydrogen was also introduced into the combustors working as pilot flame to help the kerosene ignition.

The model MCM01 was designed without strut and also with three dimensional compression inlet. The combustor has same cavity structure at the baseplate with the SCM04 model and also the same divergence degree, as shown in Fig.2.

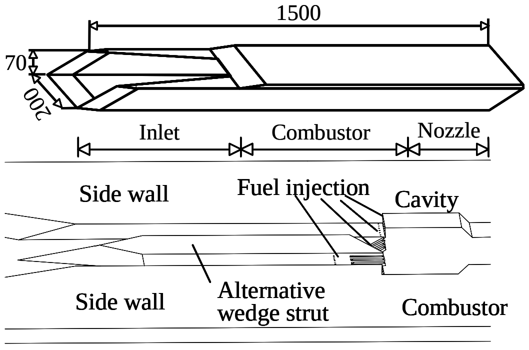

Fig. 1 SCM04 Model and Strut/Cavity Details

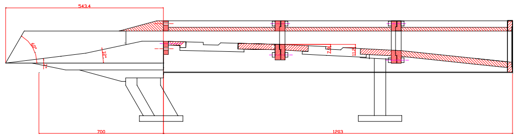

Fig. 2 MCM01 Model without Strut

3 RESULTS AND DISCUSSIONS

3.1 Effect of Combustor Configurations

3.1.1 Combustor with Cavity/Strut of Model SCM04

The typical testing flow conditions for the present experimental series were shown in Table 1. The pressure distributions along the model and the thrust profile were the main data in the performance analysis.

Fig. 3 shows the pressure distributions along the scramjet model SCM04 with strut and two kinds of cavities, one was the cavity with the length to depth ratio L/D=7.5 and depth of 8mm,

Table1 Experimental Conditions

Test flow	Ma	5.8
	Tt(K)	1800
	Pt(MPa)	4.5
	$\dot{M}$ (kg/s)	4
Test Cabin	Ps(kPa)	4
Scramjet	ϕ_{kero}	0.5-1.5
	ϕ_{H2}	0.05

and the other was with the same ratio L/D=7.5 but depth of 12mm. In the figure, the X-coordinate is the dimensionless length by the distance from the leading edge to the cowl. $X/X_0=1$ means the position of the cowl. The Y-coordinate is the dimensionless pressure by the static pressure of the incoming flow.

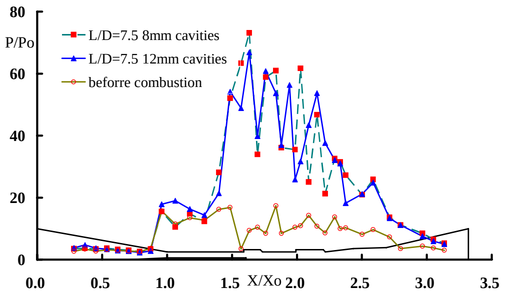

Fig.3 Pressure Distributions along Model

Before the fuel-in, there was a pressure jump due to the shock generated by the strut upstream the engine cowl. Then the pressure increased slightly along the isolator section from $X/X_0=1$ to $X/X_0=1.5$. The evident pressure drop followed due to the expansion at the tail of the strut. In the combustor, from $X/X_0=1.6$ to $X/X_0=2.7$, the pressure showed slight decrease because of the 3° divergent angle. More pressure drop caused by the larger expansion angle was observed along the thrust nozzle.

After ignited, the pressure along the combustor showed high lifting, as shown in Fig. 3. The wavy curves indicated the reflection of the shocks. The two distributions staggered because the shock trains were different due to the different configurations. However, the average pressure levels were almost same, which suggested that the depth of the cavity has a little effect when the depth of the cavity in a certain range.

The results also shown that the pressure raise did not transmit upwards to the inlet, so the pressure distribution along the inlet didn't change during the combustion, representing that the strut functioned as an efficient isolator. Through a series of the tests, the results showed that kerosene fuel was successfully ignited and burned. It is evident that the isolator divided by strut is more effective against the high pressure from the combustor, because there weren't the inlet pressure rises at the fuel equivalence ratio from 0.5 to 1.5.

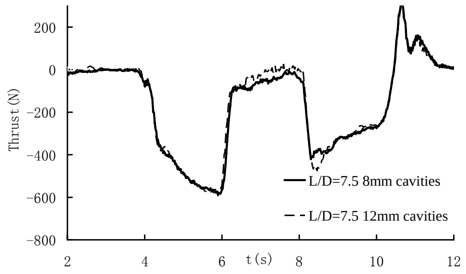

Fig. 4 Thrust of Model SCM04

The thrust measured by the balance under the same experimental conditions. As shown in Fig.4, the drag was obtained at t=6s when the facility achieved the stable hypersonic flow condition. Then the fuel was injected, and the thrust increment can be measured at t=8s. The fuel was shutdown at t=8s resulting in a big drag due to the facility nozzle flow was still working.

Fig. 4 shows the thrusts in both cases with different cavities. Comparing the drags of the model with different depths of the cavities, there was slightly different since the cavities only had little effect on friction and there were not strong shocks before fuel-in. The increment of thrust for model with 12mm cavities was slightly higher than 8mm model. Obviously, the difference was from the different pressure acted on the wall of the model. As shown in Fig.3, although the pressure patterns looked similar, the reflection of the shock waves were quite different, so the integral of the pressure force on the divergent wall shown the difference. However, the difference was quite small, which indicates the depth of the cavity was not the main factor to influence the thrust.

In conclusion, the scramjet model SCM04 with strut/cavity combustor is suitable for supersonic combustion of the hydrocarbon fuel. It can provide the stable combustion and obtain the certain thrust increment. The strut acted as a stable flame holder as well as a successful isolator. However, it brought a bigger drag.

3.1.2 Combustor with Cavity of Model MCM01

As shown in above section, the strut did bring more thrust but the drag was also bigger. To avoid the disadvantage, the model MCM01 was designed without strut. However, the model without strut may encounter the problem of isolating the high pressure of the combustor from the inlet. Therefore, the cross section of the combustor has been changed to enable to withstand higher pressure, as shown in Fig.2. The inlet of the model MCM01 is different from that of model SCM04, which is 3-dimensional compression.

There are two cavities on the baseplate of MCM01 combustor. The fuel injected just before the cavities. Fig.5 shows the static pressure distributions along the sidewall of the model MCM01 under the different conditions of the fuel injection. The shock trains are obviously reflected at the isolator wall and the pressure increasing suddenly at the entrance of the combustor. The static pressure varied with the different injection pressure which indicated that the combustion is controlled by the injection kinetic energy of fuel, which is key characteristic in the mixing process. The higher pressure of the fuel injection caused better mixing then got the higher pressure rise.

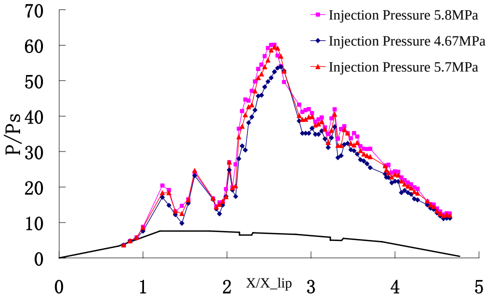

Fig.5 Pressure Distributions along Sidewall

In the model SCM04, the combustion was stable at the fuel equivalence ratio from 0.5 to 1.5 since the strut acted as an efficient isolator. However, the MCM01 model could only maintain stable combustion at a limited range of fuel equivalence ratio, and static pressure oscillated at the entrance of the combustor. There was probably a separation zone near the exit of the inlet due to the 3-dimensional shock wave/boundary layer interaction. Fig. 6 shown the pressure distributions under the different fuel mass flow. The label Φ1 means the fuel equivalence ratio of the first fuel injection, that is the fuel injected just before the first cavity. The label Φ2 is the fuel injected downstream. The upstream fuel injection played the more important role since the source of the combustion instability was mainly from the flow oscillation/separation in the isolator. As shown in Fig. 6, when the upstream fuel equivalence ratio Φ1 is 0.2, the pressure could get little increasing after burning. At Φ1=0.4, the pressure wave transport to the inlet. The most stable combustion condition is around at the Φ1=0.33.

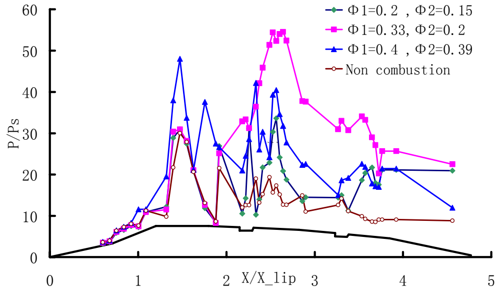

Fig.6 Pressure Distributions along Baseplate

Even though, the model still showed the same level performance of thrust increment as model SCM04 from the comparison of Fig.4 and Fig.7. The reason is that the pressure distribution of the model MCM01 is more rational than that of SCM04 because the pressure was still high at the divergent region of the nozzle.

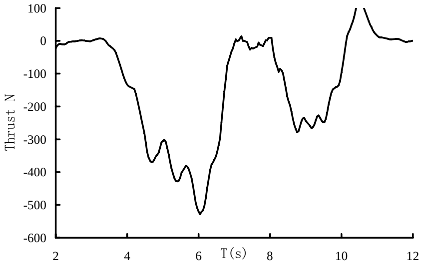

Fig. 7 Thrust of Model MCM01

The thrust increment for both models is shown in Fig.8. The model SCM04 could get stable combustion from equivalence ratio from 0.5 to 1.5, and the thrust increment increased almost linearly with the fuel flow rate. The range of stable combustion for the model MCM01 was very narrow, so there was only one point in Fig.8 to represent the most stable case. From the comparison, the model MCM01 could obtain the same thrust increment with the only half amount of fuel.

In the model MCM01, the fuel was injected at the single side, so there was still extent to improve the combustion by changing the fuel injection, since the combustion is dominated by the fuel mixing.

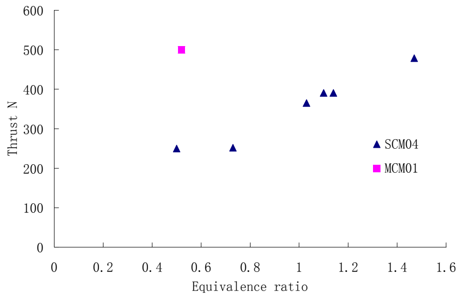

Fig. 8 Thrust vs. Equivalence Ratio

3.2 One Dimensional Analysis

In order to make the main characteristics inside the model scramjet clearer, an analysis method has been developed based on the calculation of quasi-one-dimensional equations. For a given heat release, the other parameters such as pressure, temperature, Mach number etc. can be calculated. Therefore, the possible heat release distribution can be approached from the best matched data of the calculated static pressure distribution with the experimental one.

Fig.9 shown the analysis results for the model SCM04. The solid line is the calculated value, and the dots are from the test. From the comparison of the calculation value and experiment data of the static pressure along the wall, it may be concluded that the heat release mainly occurs in the cavities. The analysis indicated that the combustion efficiency was about 48%, and the corresponding lowest Mach number was about 1.4. In the analysis, if increasing the combustion efficiency, that is more heat release, the flow channel would be choked.

Fig.10 shown the results for the model MCM01. In this case, the calculated data fitted the experiments better. The corresponding heat release was uniform in the cavity region and degressive in the following dilative section. The total combustion efficiency was about 56%. Since the fuel was ejected into the main stream from the two positions, and the main heat release occurred upstream, the efficiency for the first injection would be much higher than this global average value. The lowest Mach number was also around 1.4.

The analysis shown that the better heat release distribution is to release the chemical energy along the whole region, so the energy can be released more but without choking. The more heat release implies more potential thrust. In the model SCM04, the reaction only happened in the local area (the cavity), so the combustion efficiency was quite low. The model MCM01 is better, and the heat release continued downstream, therefore the higher pressure and larger thrust increment have been obtained, as said in above section.

The analysis also shown that the maximum possible combustion efficiency for both models is limited by the configuration. If more heat released, the flow would be choked. Therefore, the configuration should be optimized to ensure more combustion but no choking.

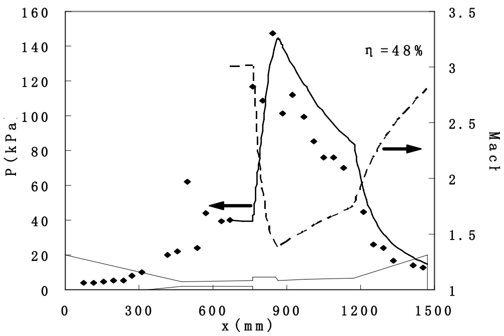

Fig.9 Pressure and Mach along Model SCM04

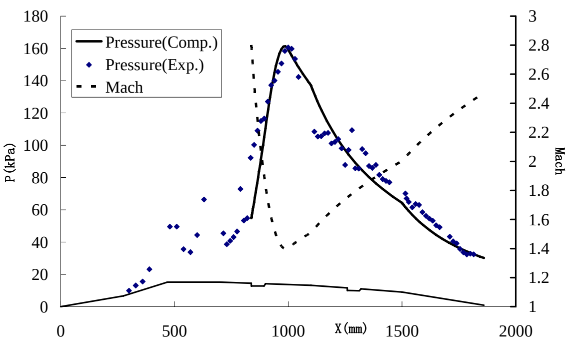

Fig.10 Pressure and Mach along Model MCM01

4 CONCLUSIONS

This study investigated the scramjet model with different configurations, evaluated the cavities and strut effect on the supersonic combustion.

The results can be concluded as the following:

1) Strut is an effective technique for the kerosene-fueled scramjet. The strut functioned not only as a device for the mixing enhancement, but also as an isolator to avoid the pressure raise in the combustor transmitted upstream to the inlet. In addition, the strut could serve as the fuel mixing enhanced way to improve the engine performance. The strut shown the merit to generate more thrust than drag.

2) The integration of strut/cavities also had the important effect to make the combustion more stable than the model without strut.

3) One dimensional analysis show that model MCM01 had more reasonable heat release distribution and higher combustion efficiency. It also indicates that the coupling of fuel injection and flow field is critical to obtain the better performance.

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REFERENCES

[1] Dugger G L. Recent Advances in Ramjet Combustion. *ARS Journal*, 1959, 29: 819~827
[2] Weber R J. A Survey of Hypersonic-Ramjet Conception. American Society, Paper 875-59, 1959
[3] Gross R A, Chinitz W. A Study of Supersonic Combustion. *Journal of the Aerospace Sciences*, 1960, 27: 517-524
[4] Ferri A, Libby P A, Zakkay V. Theoretical and Experimental Investigations of Supersonic Combustion. Proceedings of the International Council of the Aeronautical Sciences, Third Congress, 1962
[5] John M. Seiner,S. M. Dash and D. C. Kenzakowski" Historical Survey on Enhanced Mixing in Scramjet Engines" JOURNAL OF PROPULSION AND POWER Vol. 17, No. 6, November–December 2001
[6] Ben-Yakar, A., and Hanson, R., "Cavity Flameholders for Ignition and Flame Stabilization in Scramjets: Review and Experimental Study," AIAA Paper 98-3122, July 1998.
[7] Gruber, M. R., Baurle, R. A., Mathur, T., and Hsu, K. -Y., 2001, "Fundamental Studies of Cavity-based Flameholder Concepts for Supersonic ombustors," J. Propul. Power. 17_1_, pp. 146–153.
[8] Ferri A. Supersonic Combustion Progress. *Aeronautics and Astronautics*, 1964, 2: 32-37
[9] Sunami T, Analysis of Mixing Enhancement Using Streamwise Vortices in a Supersonic Combustor by Application of Laser Diagnostics, AIAA Paper 2002-5203, 2002.