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## Thrust and Drag of a Scramjet Model with Different Combustor Geometries

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### ABSTRACT

Many efforts have been made to improve performance of scramjets<sup>(1-4)</sup>. For this purpose cavities and struts were frequently used as the functions of mixing enhancement and flame stabilization. The present work focused on the effects of different strut and cavities on the thrust and drag of a side-wall compression scramjet model. This model consisting of a side-wall compression inlet, a combustor and a thrust nozzle and fueled by kerosene was tested in a propulsion tunnel that typically provides the testing flow with Mach number of 5.8, total temperature of 1800K, total pressure of 4.5MPa and mass flow rate of 4kg/s<sup>(5)</sup>. A strut was used to increase the contraction ratio and to inject fuels, as well as a mixing enhancement device. Several wall cavities were also employed for flame-holder. The experimental results show that the cavities do not produce significant drag, but improve thrust performance well. It is found that the strut functions as an isolator and also helps the mixing enhancement, resulting in the improvement of the thrust performance. However the strut causes big drag to the scramjet model.

### INTRODUCTION

Due to its high potential in the utilization in the future hypersonic transportations, scramjet engine has been investigated over fifty years<sup>[1-6]</sup>. 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<sup>[7-13]</sup>. However because of the extremely complicated mechanism of scramjet, a complete theory or a design handbook has not been published. Therefore, the accumulation of the scramjet works will make up a database available for engineering design and development.

There are two ways to improve the scramjet engine performance. One is to improve the combustion efficiency, and hence, the thrust performance. Another is to reduce the drag. Therefore, when a device is used for the mixing enhancement and/or for the flame-holder, the accompanying drag increased by it must also be taken into account. The balance of

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merit and demerit becomes an important issue that we should pay more attention on.

Among a lot of techniques for improving the engine performance, the present work focuses on the wall-cavity and the strut. A side-wall compression scramjet model with a variety of cavity and strut was tested in a hypersonic propulsive wind tunnel. The thrust and the drag of the scramjet model were experimentally investigated.

## DESCRIPTIONS OF TEST FACILITY AND SCRAJET MODEL

### 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 consists of a vitiated air generator, a supersonic nozzle, a test cabin, an ejector exhaust and a silence tower, as shown in Fig. 1. Additionally, a computer programmed time sequence control system and a data acquisition system have been developed<sup>(14-15)</sup>. It provides typical test

conditions as Mach number 5.8, total pressure 5MPa, total temperature 2000K 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 uniformity of the facility nozzle flow was validated by a scannable water-cooled pitot rake with 16 pressure ports in 2cm interval driven by a computer-controlled lead screw. The iso-Mach number contour was calculated by using the ratio of the total pressure measured in the heater to the pressure measured by the pitot rake. The Mach number of the core flow was distributed among 5.7 to 5.8 as shown in Fig. 2. The dashed square in the figure shows the inlet entrance projection plane of the typical side-wall compression scramjet model.

### Side-Wall Compression Scramjet Model

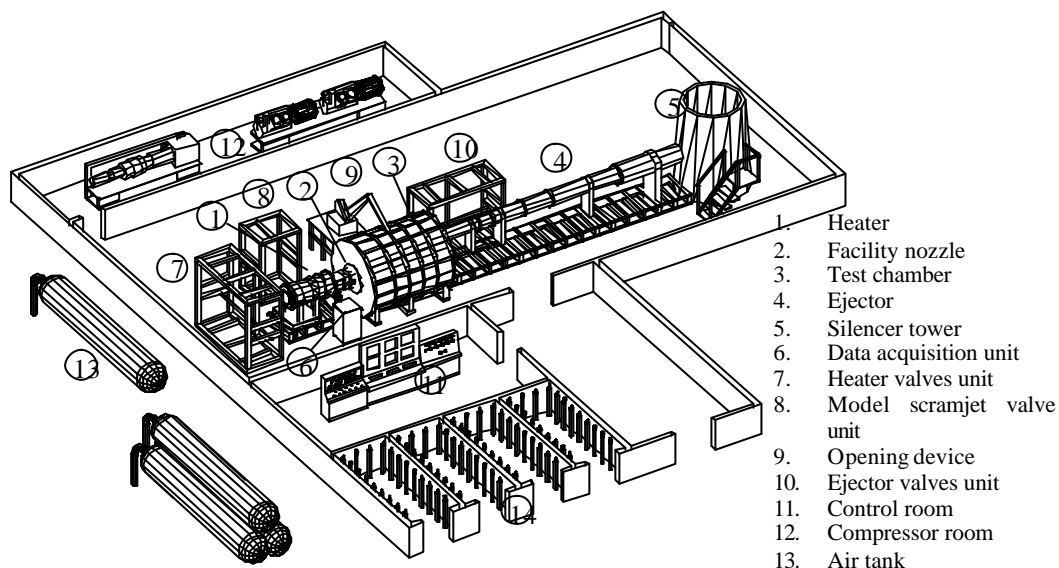


Fig. 1 Schematic of HPTF

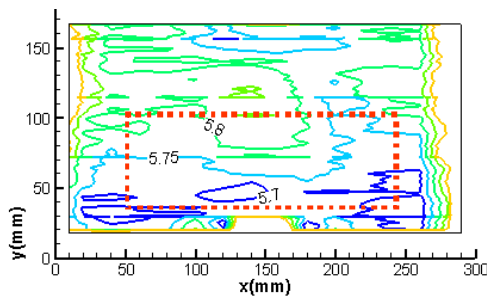


Fig. 2 Iso-Mach number contour at the facility nozzle exit plane

The scramjet model, so-called SCM03, as shown in Fig. 3, used in the tests was designed for testing variable strut and cavities that were considered for mixing enhancement and combustion stabilization. The contraction ratio of the inlet, 474mm in length and 70mm in height, is 6.25 with counting the strut thickness. An isolator following the inlet is 100mm long with 0.5 degree half divergent angle. The combustor is 800mm long with a 1.5 degree half divergent angle. The thrust nozzle is 300mm long and has 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 vortices that help the mixing and combustion process, as well as extending the fuel residence time. The fuel

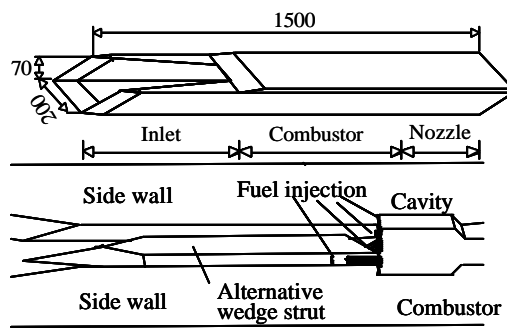


Fig. 3 SCM03 model and strut/cavity details

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.

## RESULTS AND DISCUSSIONS

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.

Table1 Experimental conditions

Test flow	Ma	5.8
	Tt(K)	1650-1750
	Pt(MPa)	4-4.5
	$\dot{M}$ (kg/s)	3.8-4.2
Test Cabin	Ps(kPa)	4
Scramjet	$\phi_{\text{kero}}$	0.5-1.2
	$\phi_{\text{H}_2}$	0.02

## Pressure Distributions along Scramjet Models

Fig. 4 shows the pressure distributions along the scramjet model with different cavities. The open and solid marks in the figure represent the state before and after ignition respectively. LS and D in the figure means the long strut (800mm) condition and the depth of cavities. The length/depth ratio of the cavity was kept at 7.5 when the depth was changed. The numbers following the D are the depth of the cavities in millimeter. Consequently D0 means that no cavity was used. In cases of D12, D6 and D0, the cavities did not show any influence on the inlet flowfield before the ignition. However the pressure distributions along the combustor showed that the different cavities gave some effects on the wave system before the ignition.

The pressure distributions in the figure also showed that kerosene fuel was

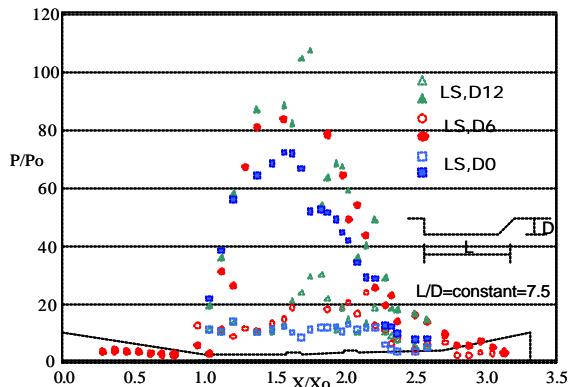


Fig. 4 Pressure distributions along the model before and after ignition

successfully ignited and stably burned for all three cases. It was evident that the deeper cavity makes bigger contribution to the combustion, resulting in the higher pressure distribution. But the cavity is not an absolute necessary condition to burn the kerosene fuel. As shown in the figure, even in D0 case, the combustion still occurred, although the pressure distribution was not as high as the cases with cavity.

### Thrust Measurements

A typical thrust output measured by loadcell under the experimental conditions shown in Table 1 with the long strut and the D12 cavity is shown in Fig. 5. The ejector started to work at  $t=0$ s making a big drag to the model due to its pump effect. Following the air in the test chamber evacuated by the ejector, the drag got a stable level during  $t=2-4$ s. After the facility nozzle working on at  $t=4$ s, the drag was dropped again, corresponding to the establishment of the flow in/out the model. Then an evident thrust was measured at  $t=6$ s, when the model fuel-in. The fuel was shutdown at  $t=8$ s resulting in a big drag due to the facility nozzle flow was still working. The thrust increment was 588N.

### Engine Performance Effected by Strut

As mentioned above, strut produces

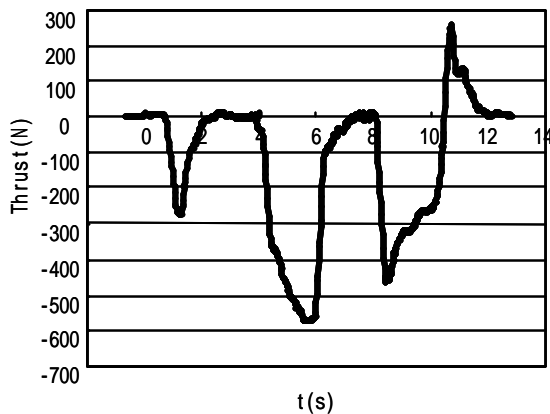


Fig. 5 Time passage of thrust acting on the model

big drag. However it can also improve the thrust performance of a scramjet by its effects on the mixing enhancement and the pressure isolation. Fig. 6 shows the pressure distributions along the scramjet model in cases with and without strut, under the same experimental conditions. There was a pressure jump upstream the engine cowl ( $X/X_0=1$ ) produced by the strut, as shown in the profile before the combustion in Fig. 6(a). The pressure showed slight up along the isolator section from  $X/X_0=1$  to  $X/X_0=1.5$ . Then there was an evident pressure drop 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 1.5 degree half divergent angle. More pressure drop caused by the larger expansion angle was observed along the thrust nozzle.

The pressure along the combustor showed big raise after the fuel ignited, as shown in Fig. 6(a). Fortunately the pressure raise did not transmitted back to the inlet, representing that the strut functioned as an efficient isolator. However, similar pressure raise in the case without strut went back to the inlet, resulting in a big pressure increase there, as shown in Fig. 6(b). It caused the inlet unstated.

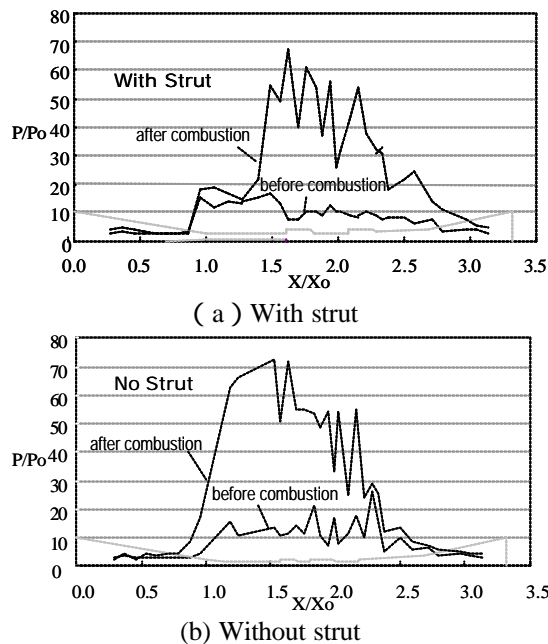


Fig. 6 Pressure distributions along the scramjet model

Fig. 7 shows the thrusts in both cases with and without strut. It's evident that the drag for the model without strut was less than the strut mode. After the fuel-in at  $t=6s$ , thrust was observed in both cases. However, the thrust increment for the strut model was much higher than that for the model without strut. It means that beside the big drag, the strut will help the combustion in the combustor and hence improve the thrust performance. It also can be found by the big oscillation on the curve of no-strut case in Fig. 7 that combustion was not stable without the strut.

### Engine Performance Effected by Location of Fuel Injection

The scramjet model was tested in both cases of fuel injected from the strut and from the wall in the same cross-section, under the same experimental conditions shown in Table 1. During the fuel-off period, the forces acting on the model were almost same as shown in Fig. 8. After the fuel-on, the thrust increment for the case of

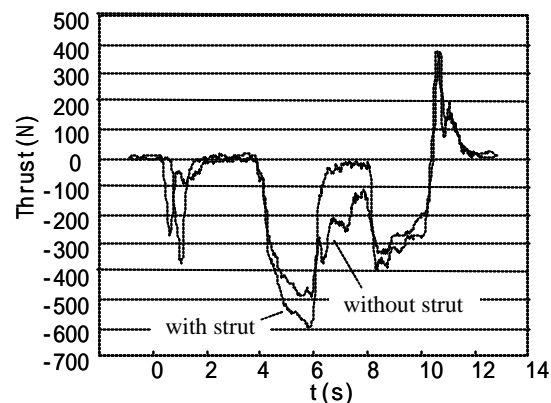


Fig. 7 Thrusts in cases with and without strut

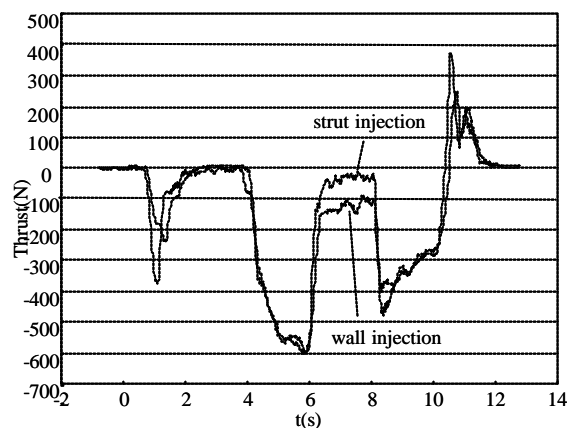


Fig. 8 Thrusts in cases of fuel injected from strut and wall

strut injection was significantly higher than that of wall injection case. This fact could be considered that the fuel injected from the strut was involved into the vortices produced by the alternative wedge of the strut. Hence, the mixing was enhanced that improved the thrust performance. Contrarily in the wall injection case, only a part of fuel was considered to be involved into the vortices.

### Drag Comparisons of Different Cavities and Struts

In order to improve the thrust performance of a scramjet, beside the increasing the combustion performance, the drag reduction also plays an important role. Fig. 9 shows a comparison between the

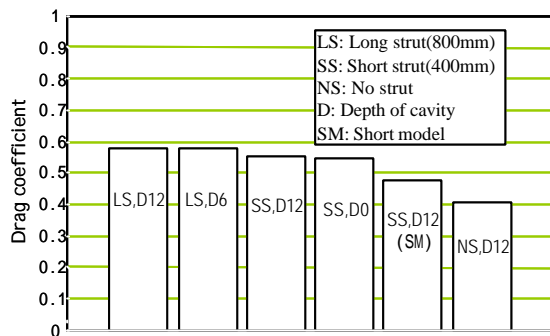


Fig. 9 Comparisons of the drag coefficient

different strut and cavities. SS and SM represent the short strut with length of 400mm and short scramjet model with length of 1.5m, respectively. The drag coefficient in the figure shows the drag measured normalized by the dynamic pressure and the projection area of the model. Comparing the drags of the model with long strut and different depth of cavity, points (LS,D6) and (LS,D12), the drag coefficient of the D12 cavity was only 0.5% higher than D6 cavity. The D12 cavity was also only 0.8% higher than non-cavity case, by comparing the points (SS,D12) and (SS,D0), in same short strut case. These facts mean that the cavity geometry does not effect the drag so much.

On the other hand, the drag coefficient of the longer strut was 5.4% higher than shorter strut case, by comparing the points (LS,D12) and (SS,D12) with same cavity conditions. It is also interesting to compare the points (SS,D12) and (SS,D12(SM)). The drag coefficient of the longer scramjet model with the combustor length of 900mm was 14.5% higher than shorter model with the combustor length of 700mm. It means that the drag from the wet surfaces of the inner duct of the scramjet makes big effect on the scramjet engine performance.

It could be found that the strut causes big drag by comparing (LS,D12) and (NS,D12) in Fig. 9. In the NS case, the side

walls were thickened instead of strut to keep the same contraction ratio. The drag coefficient in NS case decreased about 30% comparing with the LS case, indicating that the strut causes the drag not only by the increase of wet surface but also by the shock wave around the strut.

## CONCLUSIONS

Strut and wall-cavities as effective techniques were used in a kerosene-fueled scramjet that was tested in a propulsion wind tunnel. The scramjet performance was improved by using them. 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 injector to improve the fuel spatial distribution. On the other hand, the wall-cavities showed big influence in the combustion and thrust of the test model. Reasonable cavities could improve thrust performance much than that in case without cavities.

From the drag point of view, beside the thrust improvement, the strut caused big drag by the skin friction and the shock waves. However the merit from the strut in improving the total thrust was obviously bigger than the demerit. The cavities showed almost nothing in the drag increase.

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