Experimental Studies on Scramjet Tested in a Freejet Facility

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Abstract

Two different type scramjet models with side-wall compression and top-wall compression inlets have been tested in HPTF (Hypersonic Propulsion Test Facility) under the experimental conditions of Mach number 5.8, total temperature 1700K, total pressure 4.5MPa and mass flow rate 3.5kg/s. The liquid kerosene was used as main fuel for the scramjets. In order to get fast ignition in the combustor, a small amount of hydrogen was used as a pilot. A strut with alternative tail was employed for increasing the compression ratio and for mixing enhancement in the side-wall compression case. Recessed cavities were used as a flameholder for combustion stability. The combustion efficiency was estimated by one dimensional theory. The uniformity of the facility nozzle flow was verified by a scanning pitot rake. The experimental results showed that the kerosene fuel was successfully ignited and stable combustion was achieved for both scramjet models. However the thrusts were still less than the model drags due to the low combustion efficiencies.

Introduction

Scramjet engine as a high performance propulsive system for hypersonic vehicles has been investigated since last half century[1-6]. Although several engine flight test has been done in past few years, the main studies are still performed on the ground tests.Due to 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 on the optimizations and improvements of such mechanisms related to mixing enhancement, self and forced ignition, and flame stabilization by using struts, ramps, steps, cavities, plasma touches and their combinations[7-12]. Beside the engine characteristic studies, the developments of experimental facility and technique are also important issues for the scramjet research. 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.

In order to study the fundamental phenomena of scramjet, several important issues such as mixing enhancement, ignition, flame stabilization and liquid fuel atomization were experimentally studied with a direct-connected supersonic combustion facility that simulates the combustor of a scramjet since middle of 90s in IMCAS (Institute of Mechanics, Chinese Academy of Sciences) [13-18]. Based on the results obtained, a model scramjet has been designed and tested in a high enthalpy free-jet tunnel that provides nominal Mach number 5.8, total temperature 2000K, total pressure 5MPa and mass flow rate 4kg/s[19-20].

The present work focused on the mixing enhancement and combustion stabilization as well as kerosene fuel ignition with hydrogen

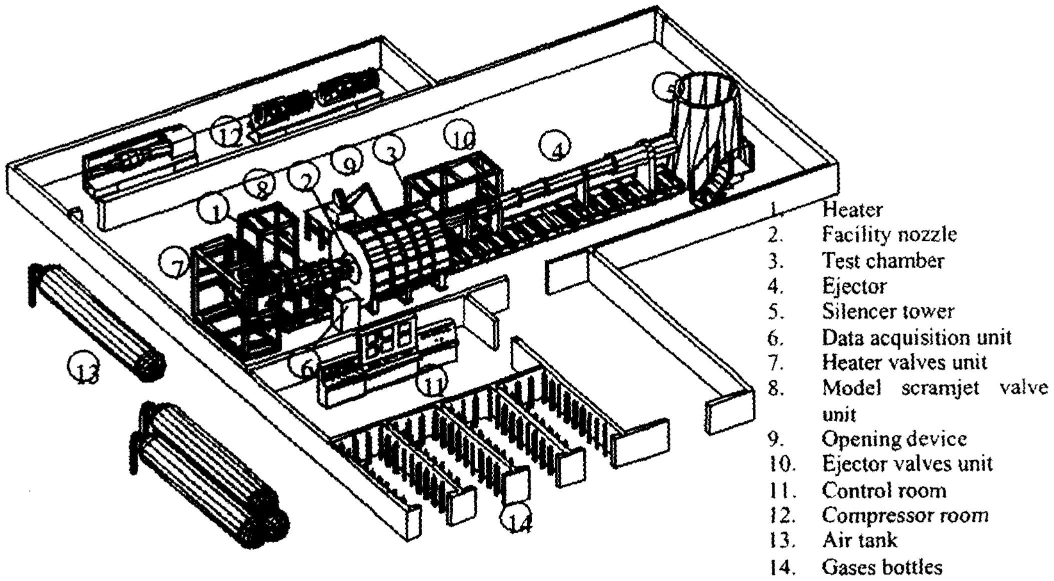

Fig. 1 Schematic of HPTF

pilot flame performed in scramjet models with both side-wall and top-wall compressions.

Descriptions of Experimental Setup and Scramjet Models

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(19-20). 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 scanning water-cooled pitot rake with 16 pressure ports in 2 cm 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.

Scramjet Models

Two scramjet models with different compression manners were used in the tests. One

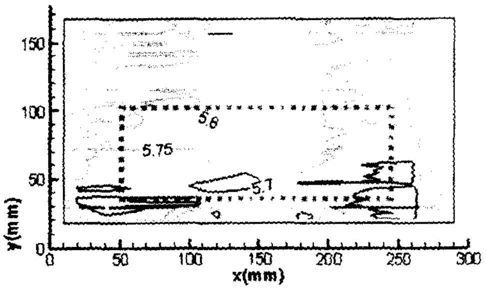

Fig. 2 Iso-Mach number contour at the facility nozzle exit plane

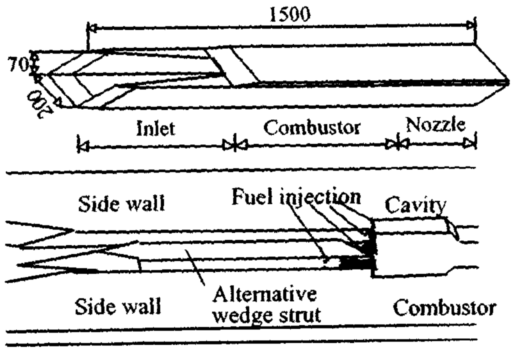

Fig. 3 SCM03 model and strut/cavity details

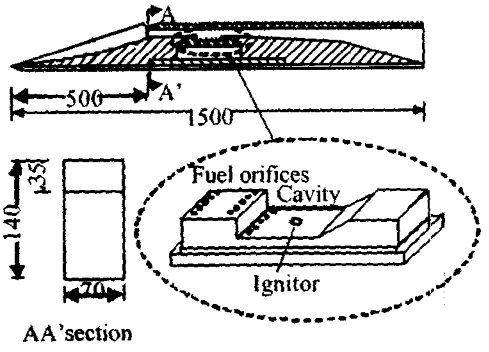

Fig. 4 TCM01 model and cavity details

of them is the model with side-wall compression inlet, so-called SCM03, as shown in Fig. 3. Another is the model with top-wall compression inlet, so-called TCM01, as shown in Fig. 4

The SCM03 model was designed with strut/cavity integrated configuration 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 600mm 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. A pair of recessed cavity functions as a flameholder in the combustor. Both strut and cavity generate variant vortexes that help the mixing and combustion process, as well as extending the fuel residence time.

The inlet of TCS01 model consists of three compression stage, linear, isentropic and linear by taking account of the balance of high compression efficiency and short length. The ramps upstream the cavity generate streamwise vortexes that enhance the mixing of air flow and fuels. The cavity generating recirculation zone and hot spots serves as a flameholder. The plasma ignitor is designed for investigating the difference of self-ignition and forced ignition and its contribution to combustion efficiency and thrust performance. The blockage ratio of TCS01 was 42%.

The fuel for both scramjet models 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 1650-1750K in total temperature, 44.5MPa in total pressure, 3.8-4.2kg/s in mass flow rate, and 5.8 in Mach number, respectively.

Pressure Distributions along Scramjet Models

Three automobile spark plugs were set on each cavity to ignite the fuels. Fig. 5 shows the pressure distributions along the SCM03 model side-wall before and after the fuel ignition. The experimental conditions for this typical run are 1720K in total temperature, 4.1MPa in total pressure, 0.1 and 1.23 in hydrogen and kerosene equivalence ratios, respectively.

Before the ignition, as shown in opened circle marks in Fig. 5, the first value of P/P_0 is 3.5 showing that the oblique shock formed at swept side-wall compressed the flow, where the P and P_0 represent the pressure measured on the model side wall and the static pressure measured at the facility nozzle exit. The slight pressure drop along the inlet must be due to the flow

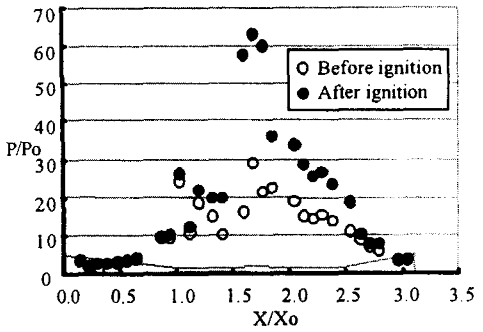

Fig. 5 Pressure distributions along SCM03 model

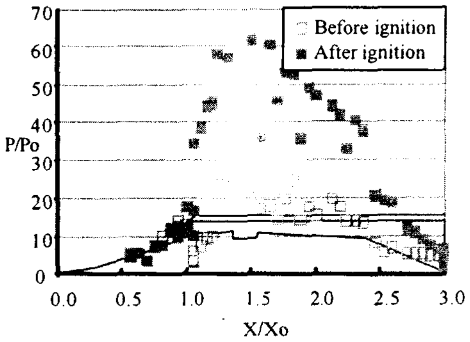

Fig. 6 Pressure distributions along TCM01 model

deflexion caused by the shock. The sudden pressure jump near the cowl shows that the shock reflected on the opposite wall. Then the pressure keeps decrease because of the divergent angle of the isolator, the combustor and the thrust nozzle.

The pressure showed significant change around the combustor after the ignition. In the vicinity of cavity, the pressure ratio, P/P_0, went up to over 60, showing where the combustion strongly occurred. However the pressure dropped suddenly, indicating that less heat release due to the weak combustion. It seems the combustion mainly occurred around the cavity. In another sense, the cavity certainly worked as a flameholder. On the other hand, there was no big change in the pressure distribution along the inlet and most region of the isolator due to the ignition.

Under the almost same experimental conditions, the TCM01 model was tested with the equivalence ratio of 0.96 for the kerosene and 0.1 for the pilot hydrogen. A $2N_2+H_2$ plasma ignitor was mounted at cavity base wall. In this case, the ignition could not be successfully achieved without the plasma ignitor.

It can be seen from Fig. 6 that the pressure increases along the inlet due to the compression for both cases before and after ignition as shown by opened and closed square marks respectively. In the case before ignition, the compression ratio of the inlet was 14. The pressure drop downstream the cowl must be caused by the flow turning around the inlet surface. Then it gradually increases due to the shock train that works as an isolator from the cowl to the beginning of the cavity. In whole combustor the pressure oscillates showing complicated wave system existed there. In the thrust nozzle section, the pressure gradually decreases due to the larger expansion angle. It was a typical pressure distribution along the scramjet model in no combustion case.

On the other hand, when the combustion occurred, the pressure distribution along the model was significantly different, except in the inlet section. In the vicinity of the cowl, the pressure for the ignited case was slightly higher than that for cold case, showing that the backward pressure gradient caused by the combustion in the combustor influenced upstream a little. It was clear that the combustion led the pressure increasing in the isolator. Then the pressure reached high level around the cavity, illustrating the main heat release occurring. The pressure decreased gradually along the combustor from the end of the cavity must be due to the combined effects of less heat release and expansion angle. Finally the burned gas flow exhausted from the thrust nozzle with larger expansion angle, resulting in the pressure decreased and velocity increased.

Combustion Efficiency Analysis

Combustion efficiency is an important parameter in a scramjet performance evaluation. A one-dimensional code based on the static pressure distribution experimentally measured along the combustor was developed for combustion efficiency analysis[21]. Fig. 7 is the results through the isolator to the thrust nozzle in SCM03 test. The parameters appeared in the figure were normalized by the value of the isolator entrance described by subscript 2. The P/P_2 is obtained by curve fitting from the experimental data. Other parameters interested are calculated by the code based on the P/P_2. The Mach number decreased from 3.5 to 2.4 due to the isolator compression by oblique shock system. It further dropped to 1.5 due to the combustion occurred in the combustor. Then it gradually increased by the combustor expansion and finally increased up to 3.2 by the nozzle expansion. The total pressure losses were 37% and 42% in the isolator and the combustor, respectively. The global combustion efficiency was 41% calculated by this code.

Thrust Measurements

The drag and thrust acting on both side and top compression models were measured by a six-component force balance. Fig. 8 and Fig. 9 give the time passages of the heater total pressure, fuel injection pressures and the thrust curves for both models tested.

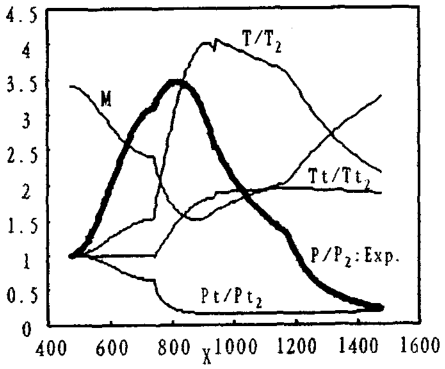

Fig. 7 Parameter distributions calculated by 1-D code

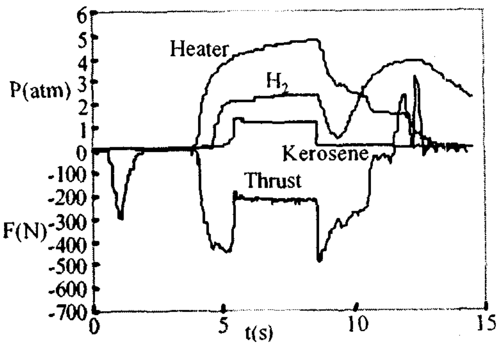

Fig. 8 Thrust measurement for SCM03 model

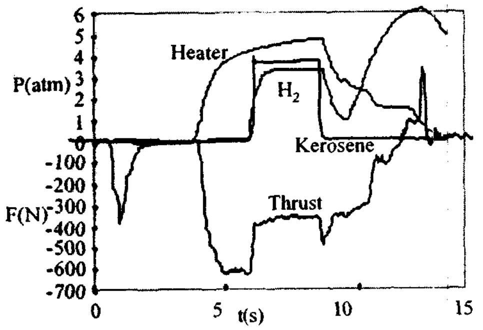

Fig. 9 Thrust measurement for TCM01 model

In the side-wall compression case, as shown in Fig. 8, the drag sharply increased when the ejector started to work. After an overshooting, the drag almost disappeared, showing that the ejector flow achieved at a dynamic balance and the pressure in the test cabin reached the value of the design altitude. When the air heater operated, a significant drag increasing as the heater pressure increases was observed. After the drag increased to 420N, the hydrogen and kerosene were injected into the model and ignited. It caused the drag decreased to around 220N that was maintained stably during the fuel feeding period. When the fuel supply was stopped, the drag suddenly increased again. From the thrust curve it was clear that the drag of model is 420N and that the thrust increment is 200N. It means that the net thrust of the model under present condition is -220N.

In the top-wall compression case, as shown in Fig.9, the thrust curve showed almost same behavior comparing with Fig. 8. It means that the ejector has good repeatability. Because of the blockage ratio of TCM01 as large as 42%, the drag caused by the heater operation was 610N, larger than SCM03 model. The thrust increment was about 250N, higher than SCM03 model case, even the cross-section area of TCM01 was only 70% of that of SCM03. It must be due to the higher pressure distribution along whole combustor for TCM01 model.

Conclusions

A side-wall and a top-wall compression scramjet models with blockage ratio of 31% and 42% have been successfully tested in a high-enthalpy free-jet tunnel. The strut and cavity used in the side-wall compression model showed good effects on mixing enhancement and combustion stabilization. Therefore the kerosene fuel was successfully ignited by electric spark, even self-ignition, with a little amount of hydrogen. On the other hand, a plasma ignitor was necessary to ignite the kerosene fuel even with hydrogen pilot fuel in the top-wall compression model case. The global combustion efficiencies for both model was below 50% calculated by our one-dimensional code. Such low efficiencies resulted in low thrust increments of 200N to 250N. Improving the combustion efficiency and thrust performance is our works in near future.

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