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EXPERIMENTAL STUDIES ON METHANE-FUEL LABORATORY SCALE RAM COMBUSTOR

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Abstract

The laboratory scale ram combustor test program has been investigating to obtain fundamental combustion characteristics of a ram combustor which operates from Mach 2.5 to 5 for the super/hypersonic transport propulsion system. In our previous study, combustion efficiency had been found poor, less than 70 %, due to a low inlet air temperature and a high velocity at Mach 3 condition. To improve the low combustion efficiency a fuel zoning combustion concept was investigated by using a sub-scale combustor model first. Combustion efficiency more than 90 % was achieved and the concept was found very effective. Then a laboratory scale ram combustor was fabricated and combustion tests were carried out mainly at the simulated condition of Mach 5. A vitiation technique was used to simulate a high temperature of 1263 K. The test results indicates that ignition, flame stability and combustion efficiency were not so significant but the NOx emissions are a critical problem for the ram combustor at Mach 5 condition.

Nomenclature

B.R.	blockage ratio,	%
E.I.	emission index,	g/kg fuel
P	total pressure,	MPa
PLR	total pressure loss ratio, %	
Mn	inlet air Mach number	
T	total temperature, K	
U	inlet air velocity, m/s	
ϕ	equivalence ratio	
ηb	combustion efficiency, %	

subscripts

p	pilot
6	ram combustor inlet
7	ram combustor exit

Introduction

The Super/Hypersonic Transport Propulsion System Research Project (HYPR Project) has been undertaken since 1989 in Japan. The propulsion system is a combined cycle engine (CCE), which consists of a turbojet engine for the lower speed range from take-off to Mach 3 and a ramjet engine for the higher speed range from Mach 2.5 to 5. The liquid methane or liquid natural gas contained high purity methane was selected as its fuel. Though it is challengeable to use the novel fuel, it has many advantages. The fuel is superior to help deal with the high temperatures created by high speed flight and it is available in large quantities also it offers the possibility of reducing fuel costs.

The ramjet engine for a commercial hypersonic transport will need achieving low fuel consumption for superior economy and low emissions for environmental quality. However there are many technical problems that must be overcome to develop the ram combustor. The operating conditions of the ram combustor such as inlet air temperature, pressure and velocity chang largely during a flight mission (Watanabe et al., 1993) . For example, relatively low temperature air, T_6=603 K, flows into the combustor at a high speed, U_6=98 m/s, at Mach 3 condition, then it is difficult to perform reliable ignition, stable flame, high combustion efficiency and low pressure loss. On the other hand, extremely high temperature air, T_6=1263 K, flows into the combustor at a relatively low speed, U_6=40 m/s, at Mach 5 condition. Therefore it becomes important to establish technologies on efficient cooling for the combustor liner and flameholder also on the reduction of NOx emissions. The objective of this study is to establish the combustion technology mentioned above and to obtain design data for the development of the ramjet engine combustor.

Mullen and Fenn conducted experimental research on ramjet combustor by using a small scale V-gutter flameholder(1951). Longwell and Frost investigated fundam-

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flame stabilization characteristics on V-gutter flameholder system[3][4]. Gregory, et al examined the effects of inlet air temperature on the flame stabilization also on combustion efficiency up to 920 K on the afterburner system[5], and Branstetter, et al examined the effect up to 1255 K[6]. However these researches were executed by JP fuel and there was few on a ram combustor that used methane as a fuel.

Authors have been investigating combustion characteristics on the laboratory scale ram combustor (LSC) using natural gas as a fuel. In the early stage of our work, fundamental flame stabilization and combustion characteristic tests were conducted at the simulated conditions of flight Mach number 3. The results indicated that there were some difficulties on flame stabilization but an acute problem was poor combustion efficiency about 70 %[7]. To settle the significant problem a series of fundamental combustion test on a fuel zoning combustion concept was conducted with a sub-scale ram combustor. A fuel zoning combustion concept means an idea of making active chemical reactions by creating a locally stoichiometric premixture around the flameholder. The test results proved it to be valid for improvement of combustion efficiency. As s next step, a Laboratory Scale Ram Combustor (LSC) test was conducted with a rectangular ram combustor. The combustor was a sub-scale part model but its dimensions were near to those of an actual ram combustor. A series of combustion test was carried out at the simulated conditions of Mach 3 and 5. Useful data for the design of the Mach 5 ram combustor were obtained.

This paper presents the experiment and the test results of the fundamental combustion test on a fuel zoning combustion concept first, then it refers on the laboratory scale ram combustor test results.

Experimental Apparatus and Measurements

Fuel Zoning Combustion Tests

A sub-scale ram combustor was used to examine whether the fuel zoning combustion method was effective for improvement of combustion efficiency. A sub-scale ram combustor was much smaller than an actual combustor and it may be difficult to predict the actual combustor performance from its test results. However, it is considered proper to assess the feasibility and potential of the fuel zoning combustion concept.

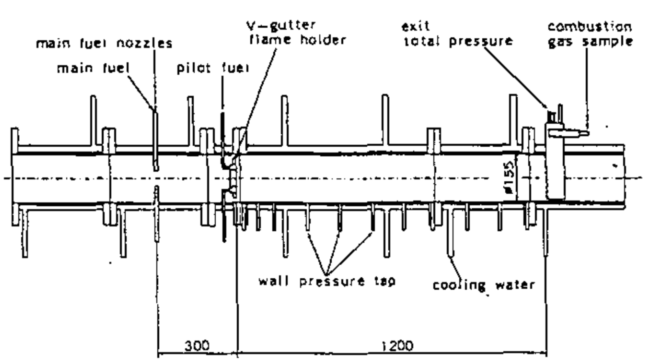

Figure 1 A schematic of a sub-scale combustor for a fuel zoning combustion concept.

Combustor Description

A schematic of the sub-scale combustor is illustrated in Figure 1. The combustor was 155 mm in diameter and 1500 mm in length. The combustor consisted of three major parts: main fuel injection system, a flameholder and a heat pipe. The combustor was cooled by water.

The main fuel injection system was located 300 mm upstream of the flameholder. Sixteen fuel injectors were spaced circumferentially around the injection plane. Two types of fuel nozzles, that is shown in Figure 2, were used in this test. One was a premixing fuel nozzle and the other was a zoning fuel one. The premixing fuel nozzle placed twelve injection holes of 0.6 mm diameter at relatively long intervals on the body and was expected to achieve better mixing performance. On the other hand, the zoning fuel nozzle placed eight injection holes of 1 mm diameter at short intervals and this fuel nozzle was expected to make a locally fuel rich mixture around the flameholder. To make the fuel zoning effective, the zoning fuel nozzle with a flow separator was also investigated. Fuel was delivered perpendicularly to the air flow for both fuel injectors.

The flameholder was employed the configuration cf an annular V-gutter with eight radial segment gutters as shown in Figure 3. A pilot fuel nozzle was installed inside the gutter to perform reliable ignition and to sustain stable combustion. Eight injection holes of 3 mm diameter was equispaced inside the annulus V-gutter.

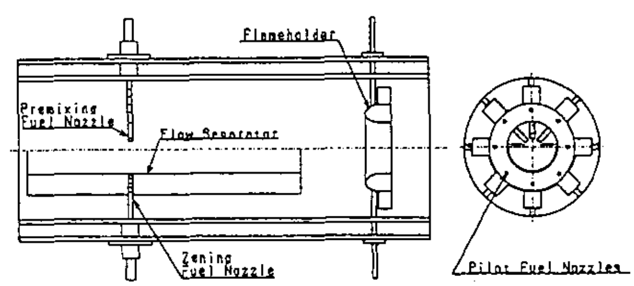

Figure 2 Main fuel injection system and a flameholder of the sub-scale combustor.

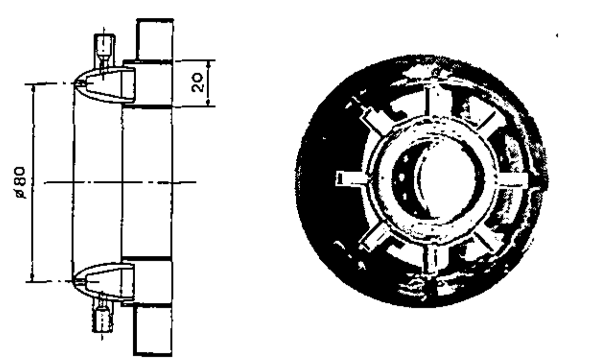

Figure 3 A schematic of the flameholder of the sub-scale combustor.

blockage ratio of the flameholder was 35 % and the dimensions of the annulous gutter were 20 mm in width, 90 mm in center diameter and 45° in gutter angle.

Measurements

Combustion tests were conducted at the simulated conditions of Mach 3, namely T_6=600 K, P_6=0.14 MPa and U_6=98 m/s. Combustion gas was sampled by a water cooled gas sampling probe mounted on the exit plane of the ram combustor and was cooled rapidly by the water. Therefore it is considered that proper quenching of reaction was occurred within the probe. Products of combustion were analyzed by a flame ionization detector for total unburned hydrocarbon (THC), non dispersive infrared instruments for CO and CO_2, a paramagnetic analyzer for O_2 and a chemiluminescence analyzer for NOx. Combustion efficiency was calculated from measured exhaust gas compositions.

A flame stability test was carried out at the inlet temperature of 600 K and being varied the inlet air velocity. Equivalence ratio of lean blow out was measured when the pilot flame extinct by reducing the pilot fuel flow rate. Equivalence ratio of rich blow out was also measured when the main flame blow out by increasing the main fuel flow rate and the pilot fuel flow rate was kept constant, ϕ_p=0.085, in this test.

Laboratory Scale Ram Combustor Test

The laboratory scale ram combustor (LSC) used in this study was a rectangular model and a part of a practical scale ram combustor. Configuration of the flameholder and fuel injection system was originally drafted by SNECMA and designed by KHI. The purposes of this LSC test were to obtain combustor performance, especially combustion efficiency and NOx emissions, at Mach 3 and 5 conditions and to make problems clear for the ram combustor of the combined cycle engine.

Combustor Description

A schematic drawing of the LSC is illustrated in Figure 4. Dimensions of the combustor were 130 mm in width, 180 mm in height and 1279 mm in length. The inner wall of the combustor was made of refractory cement and there was water jacket outside the wall.

Two types of main fuel nozzles were designed and fabricated. One was a premixing fuel nozzle and the other was a zoning fuel nozzle just the same as the sub-scale combustor. The main fuel injection system, that is shown in Figure 5, was located 79 mm upstream of the flameholder. Pairs of the premixing fuel nozzle were mounted on 30 mm both sides of a vertical centerline of the injection plane. Fuel was delivered perpendicularly to the air flow through ten equispaced holes of 1 mm diameter on the body of injectors and this premixing fuel nozzle was expected to show better mixing ability by the result of CFD analysis that was carried out by SNECMA. The zoning fuel nozzle was single injector, which was mounted between the two premixing fuel nozzles and had thirty injection holes of 1 mm diameter on its body also trailing edge.

The flameholder, that is in Figure 6, consisted of a vertical main V-gutter and two horizontal arm V-gutters. The height and the width of the flameholder were respectively 153 mm and 32 mm for the main V-gutter and 90 mm and 36 mm for the arm V-gutters. The blockage ratio of the flameholder was 30 %. This flameholder was cooled by an auxiliary air (shop air). A tube was inserted inside the flameholder and cooling air was supplied into it. The cooling air was injected to the inner surface of the flameholder through small holes on the tube. The cooling air was exhausted to the atmosphere not to effect combustion phenomena in the combustor. A pilot fuel nozzle was also put inside the V-gutter as shown in Figure 6.

Measurements

Combustion tests were carried out at the simulated conditions of Mach 3 and 5. These are the representative operating conditions of the combined cycle engine: Mach

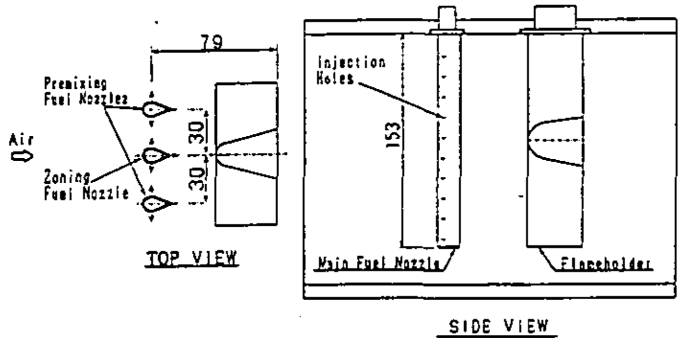

Figure 5 Main fuel injection system and a flameholder of the LSC.

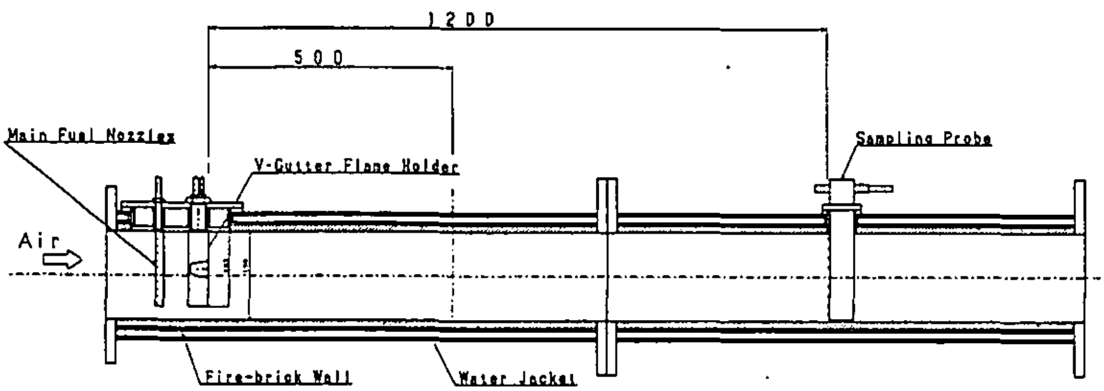

Figure 4 A schematic of a laboratory scale ram combustor.

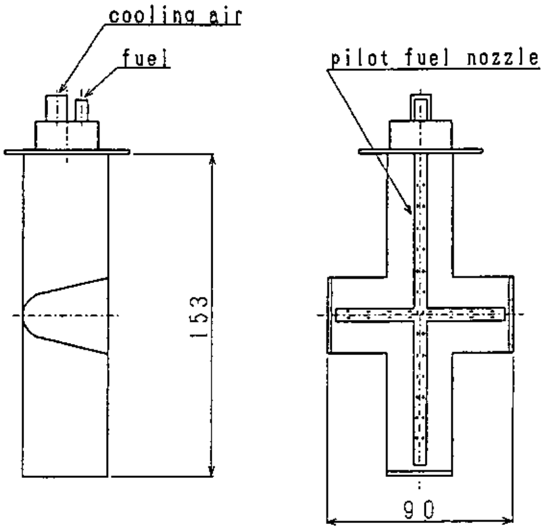

Figure 6 A schematic of the flameholder of the LSC.

3 is a starting point of ramjet single mode and Mach 5 is a high speed cruise condition. Test conditions at Mach 3 were these: T_6=600 K, P_6=0.14 MPa, U_6=98 m/s, ϕ_p=0.085 and ϕ=0.3. At Mach 5 they were, T_6=1263 K, P_6=0.2 MPa, U_6=40 m/s, ϕ=0.43 and 0.35. To simulate such a high temperature at Mach 5 condition a vitiation technique was used in this study.

A water cooled gas sampling probe with 9 holes of 2 mm diameter just as the one used in the fuel zoning combustion test was installed at the exit plane of the combustor. The probe was moved to three locations on the plane and the locations of sampling point are shown in Figure 7. Measuring the average performance of the combustor, e.g., average combustion efficiency and average emission index of NOx, combustion gas was sampled through all holes of the probe then it was gathered and analyzed. Moreover the spatial measurement was also carried out by individual sampling of the gas through each hole.

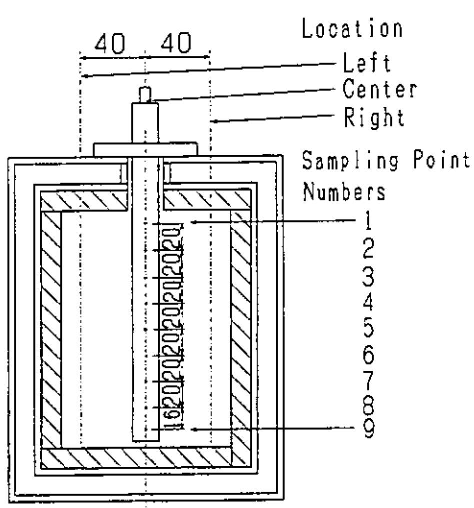

Figure 7 A schematic of sampling points at exit plane.

Test facility

Combustion air was pressurized by a compressor and was heated up to 750 K maximally by a heat exchanger, then was supplied to the test rig. In case of Mach 5 combustion test, a vitiation heater that was located 1500 mm upstream of the ram combustor was used to simulate such a high temperature. Though oxygen concentration of vitiated air was reduced by a vitiation, oxygen was not added to make a test procedure easy. Fuels used in this study were natural gas contained 98.5 % of methana for the ram burner and kerosene for the vitiate heater respectively.

Results and Discussion

Fuel Zoning Combustion Test

Figure 8 shows the combustion efficiency obtained by the premixing fuel nozzle and the zoning fuel nozzle with and without flow separator as a function of overall equivalence ratio. The equivalence ratio of the pilot fuel was kept constant, ϕ_p=0.085, for each case.
The result indicates that the premixing fual nozzle gave the combustion efficiency no more than 55 % at the design equivalence ratio of Mach 3, ϕ=0.3. The reasons of being poor combustion efficiency are not only the combustor inlet conditions such as low temperature and high velocity mentioned above, but also the low overall equivalence ratio. The equivalence ratio of 0.3 is much lower than that of ramjet engines that have been studied for the space plane.

To improve the low combustion efficiency a fuel zoning combustion concept was tried to apply in this ram combustor study. This concept was expected to achieve high combustion efficiency by making a locally stoichiometric mixture around the flameholder. Square plots show the test results obtained by the zoning fuel nozzle without the flow separator. Combustion efficiency was improved largely for all the equivalence ratios as compared with that of the premixing fuel nozzle and was

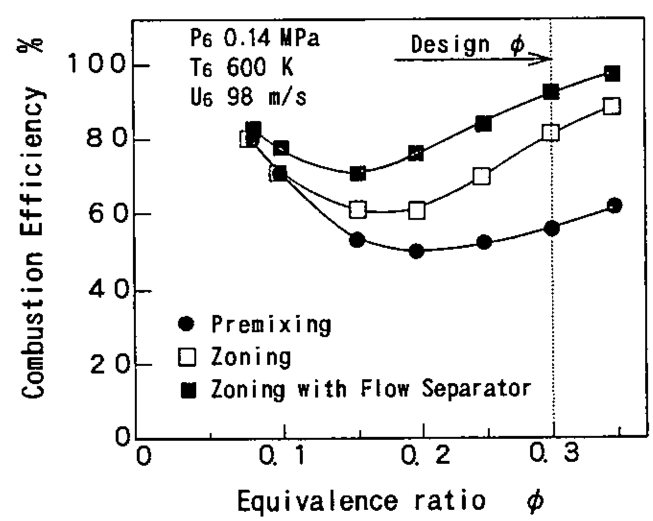

Figure 8 Effect of main fuel nozzle configrations on combustion efficiency

obtained about 80 % at the design equivalence ratio. Blackened square plots in the figure show the results of the zoning fuel nozzle with the flow separator. The flow separator was used to control an amount of air for mixing with fuel and was expected to enhance the zoning effect further. The result shows the highest efficiency more than 90 % at the equivalence ratio of 0.3. Consequently this fuel zoning combustion concept was found very effective for improving the low combustion efficiency at such a low overall equivalence ratio.

The fuel zoning combustion concept, however, had faults regarding flame stability and the pressure loss of the combustor. Figure 9 shows the stability loops for the premixing fuel nozzle and the zoning fuel nozzle. The lean blow out was the same with the two fuel nozzles, because it was occurred by an extinction of the pilot flame and it had nothing to do with main fuel. The equivalence ratios of lean blow out were very low for the wide range of inlet air velocity. The upper side of the stability loop means rich blow out that is primary interest and a continuous line of rich blow out was obtained by using the zoning fuel nozzle. Rich blow out of the premixing fuel nozzle could not be measured owing to limitation of the supplying pressure of main fuel. A dotted line in the figure shows maximum equivalence ratios that were tested and it indicates that the equivalence ratios of rich blow out were higher than those. Rich blow out by using the zoning fuel nozzle occurred at the lower equivalence ratio as compared with the premixing fuel nozzle over the entire range of the inlet air velocity as shown in the figure. The local equivalence ratio around the flameholder caused by the former nozzle was supposed to be much higher than those by the latter one if the overall equivalence ratio was the same. Therefore the pilot flame that was anchored in the wake of the flameholder was extinguished at a lower equivalence ratio to the zoning fuel nozzle. Fortunately, the equivalence ratio was about 0.4 at the inlet air velocity of 100 m/s, that is design velocity of Mach 3, and it exceeded the design equivalence ratio at Mach 3 condition, even though the zoning fuel nozzle was selected. Combustion oscillation was observed for both

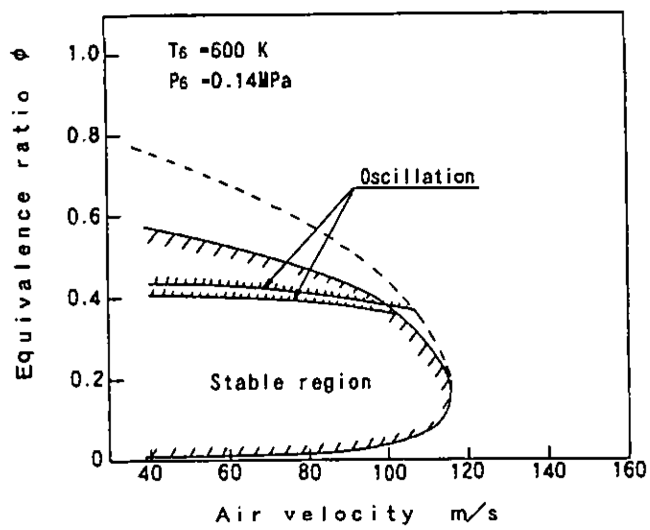

Figure 9 Effect of main fuel nozzle configrations on stability loops

the fuel nozzles and the equivalence ratios that the oscillation began to scream were shown in the figure. The results show that the oscillation occurred at almost the same the equivalence ratios over 0.4 for both the fuel nozzles.

An total pressure loss ratio is defined as

$$PLR = \frac{P_6 - P_7}{P_6} \times 100 \qquad (1)$$

The total pressure loss ratios measured by using the three nozzles, namely premixing fuel nozzle, zoning fuel nozzle with and without the flow separator, are shown in Figure 10 as a function of the equivalence ratio. The ratios at no-combustion condition were 3 % and 5 % for the premixing fuel nozzle and the zoning fuel nozzle with the flow separator respectively. This discordance was caused by a difference of the total blockage ratio between the two nozzles. The total pressure loss ratio was increased in proportion to an increase of the equivalence ratio and that of 8 % was obtained at the design equivalence ratio, ϕ=0.3, by the latter nozzle. It was certainly higher than the ratio obtained by the premixing fuel nozzle, however 8 % was met the requirement value.

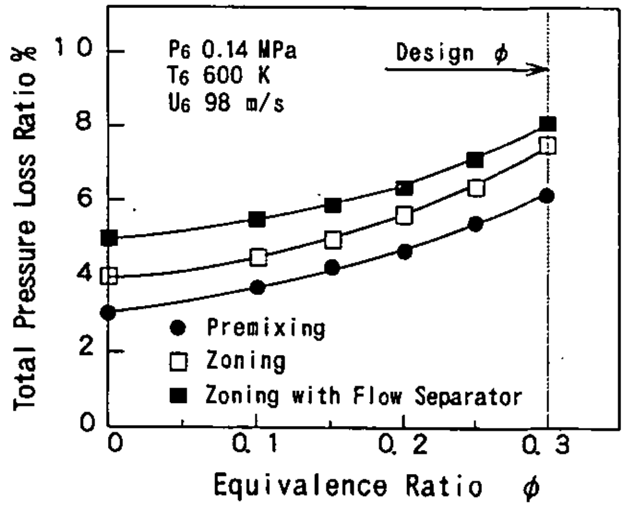

Figure 10 Effect of main fuel nozzle configuration on the total pressure loss ratio

Moreover emissions of nitrogen oxides are another prime interest from the environmental point of view. Figure 11 illustrates the emission index of nitrogen oxides obtained with the three fuel nozzles. As increasing the equivalence ratio, emission index of NOx decreased slightly first then it increased steeply for all the fuel nozzles. The zoning fuel nozzle gave the highest Nox emissions owing to achieving the highest combustion efficiency among the three fuel nozzles and the emission index of 1 g/kg fuel was measured at the design equivalence ratio of 0.3. However it is much lower than the NOx emissions of currently operated subsonic turbofan engines. The test result indicates that the level of NOx emissions is not significant at Mach 3 flight condition.

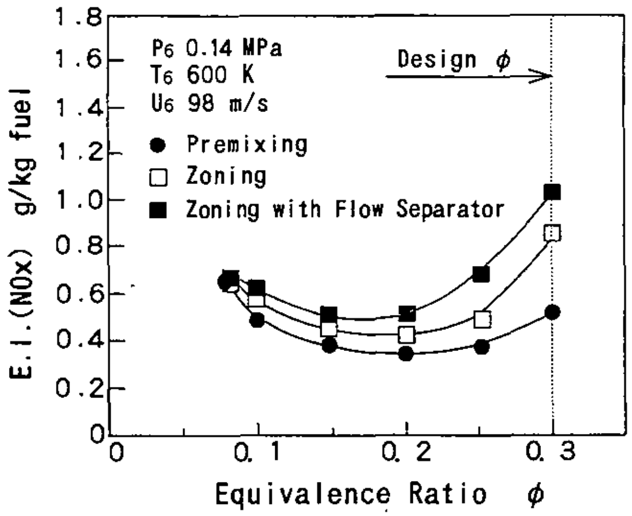

Figure 11 Effect of main fuel nozzle configuration on emissions of nitrogen oxides

Laboratory Scale Ram Combustor Test

Basic Performance at Mach 3

Combustion must be sustained stable over the entire range of operating conditions. Figure 12 shows the weak extinction of this combustor. Flame was stable for a wide range of inlet air velocity and the equivalence ratio of lean blow out was 0.013 at the design inlet air velocity of Mach 3, U_6=98 m/s. The rich extinction could not be measured for just the same reason as the fuel zoning combustion test. Ignition was accomplished reliably at low equivalence ratios over the wide range of inlet air velocity by injecting pilot fuel and minimum ignition equivalence ratios were very close to those of the lean blow out. Large pressure rises and instability at ignition were not observed. Hydrogen-Air torch ignitor system was used for ignition.

Pressure loss is one of the significant parameters for an engine performance and the total pressure loss ratio less than 8 % (no combustion condition) is required for the ram combustor of the combined cycle engine. The total pressure loss ratios of 3.5 % and 8 % were respectively measured at no combustion condition and at the design condition of Mach 3. Therefore the results met the requirement sufficiently and were almost the same as the total pressure loss ratios obtained with the sub-scale combustor.

The fuel zoning combustion technique, that was found to be very effective to achieve high combustion efficiency in the previous test, was applied to this laboratory scale ram combustor. Combustion efficiency is shown in Figure 13 as a function of the equivalence ratio, when the zoning fuel nozzle was used. The result of using the premixing fuel nozzle is also illustrated in the figure for comparison. The zoning fuel nozzle improved combustion efficiency and increased the value from 66 % that was obtained with the premixing fuel nozzle to more than 90 %. These results indicate that this application was successful but they also indicate that more efforts are needed to attain the same higher combustion efficiency as the currently used turbojet combustor.

The characteristic of NOx emissions of the laboratory scale ram combustor was similar to that of the sub-scale combustor and the NOx emission index of 1.7 g/kg fuel was obtained with the zoning fuel nozzle at the design condition of Mach 3.

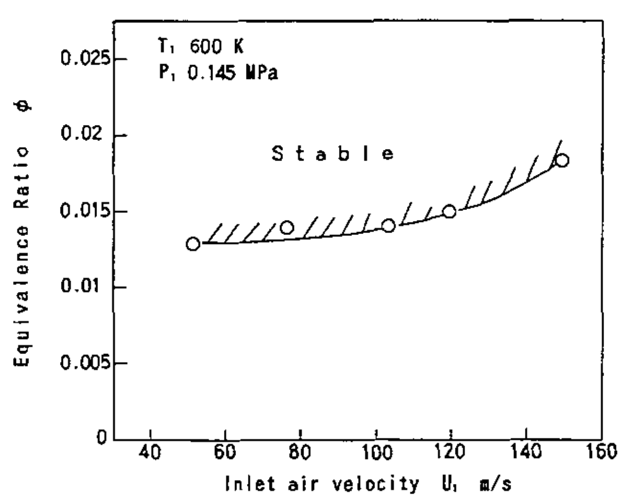

Figure 12 Weak extinction of the LSC at Mach 3 condition

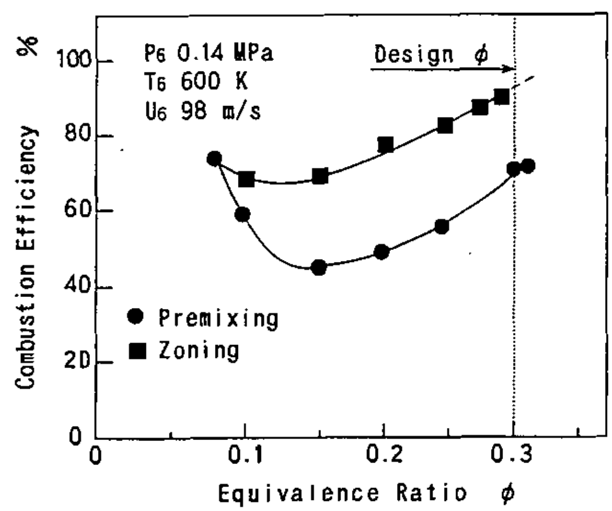

Figure 13 Combustion efficiency of the LSC at Mach 3 condition

Basic Performance at Mach 5

Combustor inlet conditions at Mach 5 are quite different from those at Mach 3 and they are: T_6=1263 K, P_6=0.4 MPa and U_6=40 m/s. It can be supposed from the conditions that the major problem on combustion is emissions of nitrogen oxides and that ignition, flame stability and pressure loss are not serious owing to its high inlet air temperature and low velocity. For the main purpose of reducing emissions of nitrogen oxides, the premixing fuel nozzle was chosen in this Mach 5 combustion test.

Ignition and flame stability performances were excellent and they were reported already by authers(1993). The total pressure loss ratios were very low and were measured less than 1 % owing to the low inlet air velocity at this condition.

Combustion efficiency at Mach 5, that is a cruising speed of the combined cycle engine, is also one of the concerns, because it influences directly not only the operating cost but also the environmental quality. A vitiation technique was used to simulate such a high temperature of Mach 5 and typical constituents of vitiated air are:

O_2	15.5 %	(Volume)
CO_2	4.0 %	(Volume)
CO	10.0 ppm	(Volume)
UHC	0 ppm	(Volume)
NOx	150 ppm	(Volume)

The vitiated air contained little carbon monoxide and unburned hydrocarbons, therefore it can be considered that these concentrations measured in the ram combustor were formed in the ram combustor itself. Figure 14 shows the local combustion efficiency distribution at the esit plane of the ram combustor. The test result indicates that the sphere, showing combustion efficiency more than 99.5 %, extended for the most part the exit plane. The result also indicates that much higher combustion efficiency will be expected to achieve in the practical combustor, because it will use fresh air.

The fuel zoning combustion concept can not be applied at such a high inlet temperature condition. It will increase flame temperature larger than premix combustion. An increase in flame temperature generates the CO emissions due to an increase of CO equilibrium concentration and it results in fall of combustion efficiency. Moreover it also generates the NOx emissions greatly.

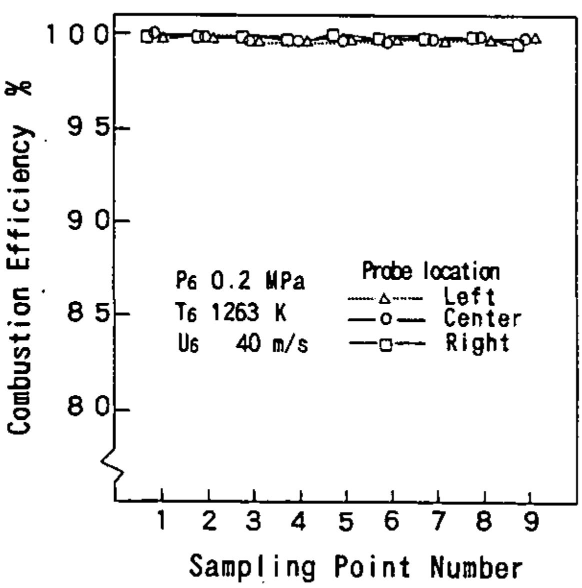

Figure 14 Combustion efficiency at exit plane of the LSC at Mach 5 condition

It is difficult to predict the emissions of nitrogen oxides quantitatively from the results. It is because that the vitiated air contained a large amount of nitrogen oxides already before it entered the ram combustor. However it is very important to know the emissions' level of the ram combustor even in a qualitative sense. Figure 15 shows the emission index of nitrogen oxides as a function of the equivalence ratio. The emission index was calculated by subtracting the NOx value of vitiated air from that of the exhaust gas measured at the combustor exit. An increase in equivalence ratio increased the emission index of nitrogen oxides largely and the index of 12.5 g/kg fuel for the climb equivalence ratio and the index of 11 g/kg fuel for the cruise equivalence ratio were obtained. These data were obtained at the inlet pressure of 0.2 MPa and with vitiated air. Therefore, it is supposed that the emission level of an actual combustor of the combined cycle engine will be extremely high.

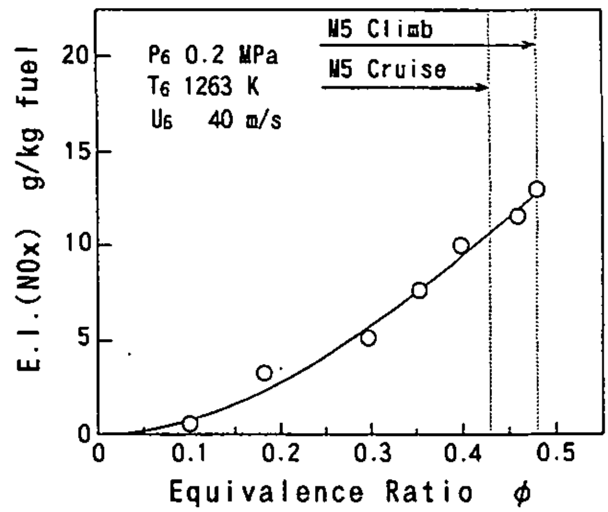

Figure 15 Emissions of nitrogen oxides of the LSC at Mach 5 condition

Figure 16 illustrates the NOx concentration distribution at the exit plane. Distribution figures were almost the same for each probe location and maximum concentrations were measured near the middle part of the ram combustor. The local equivalence ratios at the same exit plane were measured and are shown in Figure 17. The local equivalence ratio was calculated by subtracting the average equivalence ratio of the vitiation heater from the individual equivalence ratios at the ram combustor exit. Fuel rich zone was observed near the middle of sampling points for each horizontal location of the sampling probe. It is the place where showed the highest NOx concentration. The results indicate that making the local equivalence ratio even, namely improving the premixing quality, is needed to reduce the emissions of nitrogen oxides.

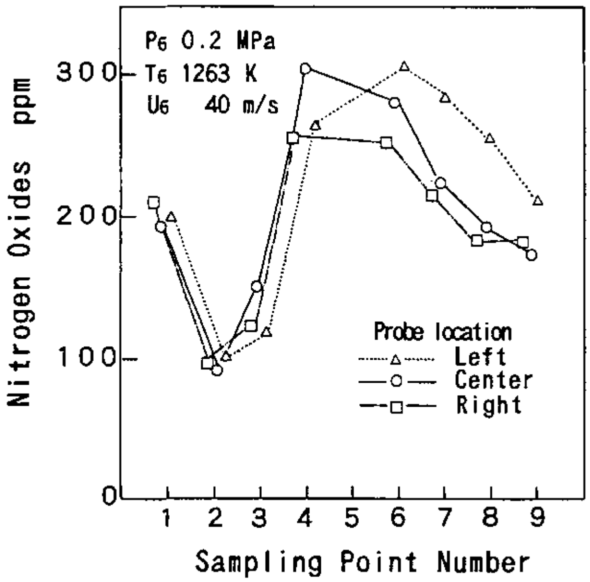

Figure 16 Emission distributions of nitrogen oxides at exit plane

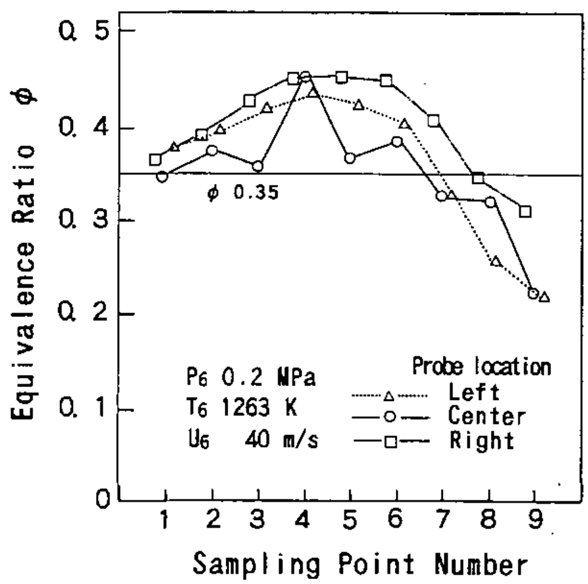

Figure 17 Equivalence ratio distributions at exit plane

Conclusions

The laboratory scale ram combustor (LSC) test program has been conducting to obtain the fundamental combustion characteristics of the ramjet engine combustor that operates from Mach 2.5 to 5 for the hypersonic transport.

Prior to the LSC test a fundamental combustion test on a fuel zoning combustion concept was investigated for the purpose of improving combustion efficiency at Mach 3 condition.

(1) Combustion efficiency was obtained more than 80 % by applying a fuel zoning combustion concept and it was found very effective for improving low combustion efficiency at Mach 3 condition.

(2) The faults regarding flame stability and pressure loss were made clear on the fuel zoning combustion concept but the degrees were not so serious.

A laboratory scale ram combustor was fabricated and combustion tests were carried out at the simulated condition of Mach 3 and 5.

(3) Combustion efficiency was successfully achieved 90 % at Mach 3 condition by applying the same concept as the fundamental combustion test. Combustion efficiency more than 99.5 % was measured for the most part of the combustor exit plane at Mach 5.

(4) NOx emission index of 11 g/kg fuel was obtained for the cruise equivalence ratio, therefore it is supposed that a large amount of NOx emissions will be generate at the an actual combustor. It is needed to improve a premixing quality for the reduction of the emissions of nitrogen oxides.

Acknowledgment

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