Experimental study on flow field behind backward-facing step using detonation-driven shock tunnel

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Abstract

As a research to develop a SCRAM jet engine is actively conducted, a necessity to produce a high-enthalpy flow in a laboratory is increasing. In order to develop the SCRAM-jet engine, stabilized combustion in a supersonic flow-field should be attained, in which a duration time of flow is extremely short. Therefore, a mixing process of breathed air and fuel, which is injected into supersonic flow-fields is one of the most important problem. Since, the flow inside SCRAM jet engine has high-enthalpy, an experimental facility is required to produce such high-enthalpy flow-field. In this study, a detonation-driven shock tunnel was built and was used to produce high-enthalpy flow. Furthermore, SCRAM jet engine model equipped backward-facing step was installed at test section and flow-fields were visualized using color-schlieren technique and high speed video camera. The fuel was injected perpendicular to the flow of Mach number three behind backward-facing step. The height of the step, distance of injection and injection pressure were changed to investigate the effects of step on a mixing characteristic between air and fuel. The schlieren photograph and pressure histories show that the fuel was ignited behind the step.

Introduction

The supersonic combustion RAM jet (SCRAM jet) engine has attracted attentions because of its potential for use in next-generation for space plane, and hypersonic airliners. This engine is operated by mixing fuel and air in a supersonic flow field, and is required to undergo stable combustion. Recently, the research and development of supersonic combustion ramjet engine has promoted the study of combustion in supersonic flows. Mixture (self-ignition) of fuel/air supersonic combustion is one of the basic problems and it is to be resolved in order to develop of such engines.

Huber et al. (1979) investigated the correlations between the geometry and self-ignition conditions from a variety of published data as well as large number of experimental results. Also, Huber et al. (1979) developed simple experimental models for self-ignition regions with a first-order effect, which gave a baseline for estimation of self-ignition in simple geometry. In addition, McClinton (1979) conducted parametric studies of self-ignition characteristics transverse injection of hydrogen. Whitehurst et al. (1992) found that the ignition was likely occurred far downstream and combustion wave was propagated upstream with the speed of a detonation wave, but their experimental results showed that self-ignition might initiate further downstream, not adjacent to the flame-holder. Tomioka et al. (1995, 1998) studied the self-ignition for flight Mach number 6-8. Gardner et al. (2002) investigated the injection from portholes upstream of the combustion chamber and investigated a method to deliver fuel into a SCRAM jet, then combustion was observed in the combustion chamber using a shock tunnel. Itoh et al. (2002) studied the SCRAM jet engine model having a strut by using high-enthalpy shock tunnel, indicating drag coefficients by varying equivalence ratio. Since mixing properties between fuel and air is a key factor to develop a SCRAM jet engine, various types of engine model has to be tested by changing flow conditions, injection method and configurations promoting mixing. The major factors affecting self-ignition were found to be the static temperature, static pressure, fuel mixture and residence time. In addition, the flame-holder is necessary for the combustion region because the static temperature is too low and the residence time is too short in mainstream of the combustor. The flame-holder can provide where the static temperature is higher and residence time is longer.

In other to develop the combustion and self-ignition in a supersonic flow, it is necessary to investigated the conditions generation combustion such as fuel/air mixture process, static pressure, static temperature and residence time. The most suitable method to obtain stable combustion is to apply a turbulent mixing process between fuel and oxygen. Therefore, a useful structure to promote mixing and to hold flame is considered to use a backward-facing step. It is important for SCRAM jet engine studies to understand the turbulence characteristics of supersonic turbulent boundary layer behind a backward-facing step, because the backward-facing step flow has been considered as one of the candidate for SCRAM jet engine.

In this study, a detonation-driven shock tunnel was used to produce high-enthalpy flow and a performance of this facility was investigated in order to obtain a Tayloring condition. A SCRAM jet engine model having backward-facing step was installed at test section and flow-fields behind the step were visualized using color-schlieren technique and high-speed video camera. Furthermore, The height of backward-facing step, injection distance and injection pressure were changed to investigate the effects of step on mixing characteristics between air and fuel and on the combustion.

Experimental

Detonation-driven shock tunnel

Figure 1 shows a schematic diagram of experimental set-up. A detonation-driven shock tunnel (50 mm in diameter and 15 m in total length), generating high-enthalpy flow is constructed from an ignition tube, detonation tube, shock tube, dump tube, observation section and a dump tank. A nozzle is installed at the end of the shock tube, which is designed to obtain a flow of Mach number three at the exit of the nozzle. The shock tube equips four pressure transducers (PCB Co., Ltd., Model 113A24) near the observation section. The flow fields behind backward-facing step were visualized using a color-schlieren technique and high speed video camera (Phntom V7.0; 10,000pps at 512 x 384, 160,000 maximum). A color filter is set at the focal point of the optical system. A schematic of the color-schlieren optical system is also shown in fig. 1.

In a detonation tube mixture gas of oxygen and hydrogen (oxy-hydrogen) are detonated by using ignition tube, which equips four igniters with sub-chamber. A burned gas is injected from sub-chamber to detonation tube via straight nozzle of 3 mm diameter, then the oxy-hydrogen gas is instantaneously detonated. A diaphragm made of Mylar film (75 μm in thickness) is installed between detonation tube and shock tube. The high pressure and high temperature gas behind detonation wave is quickly produced by the ignition to rupture the diaphragm and to drive a shock wave of high Mach number into the shock tube.

SCRAM jet engine model

The experiments were carried out installing a SCRAM jet engine model into a test section as shown in fig.2. These experiments were conducted at flow Mach number three produced by using a raval nozzle 60 mm exit, 22.5 mm throat. The SCRAM jet engine model has a dimension of 210 mm in total length and 50 mm width. The leading portion of the model has sharp wedge, which prevent the supersonic flow-fields from disturbing. A backward-facing step was located 35 mm downstream distance from the leading edge and the height, h is changed from 0 to 8 mm.

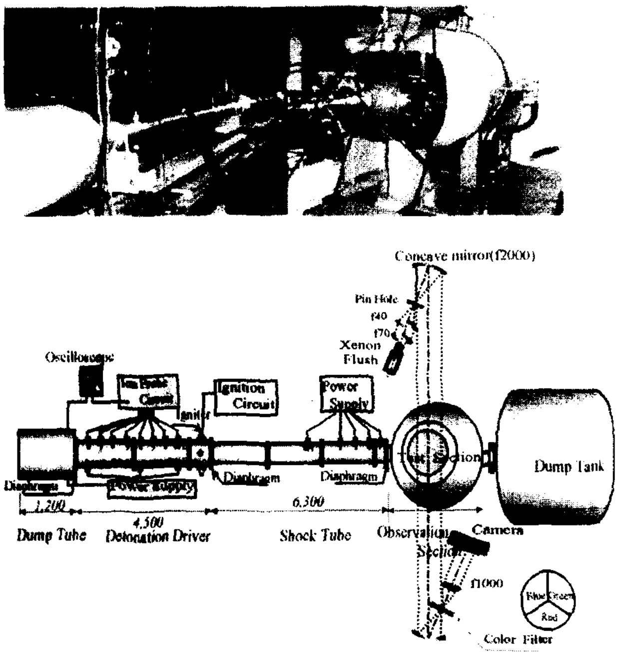


Fig.1 Schematic diagram of experimental apparatus

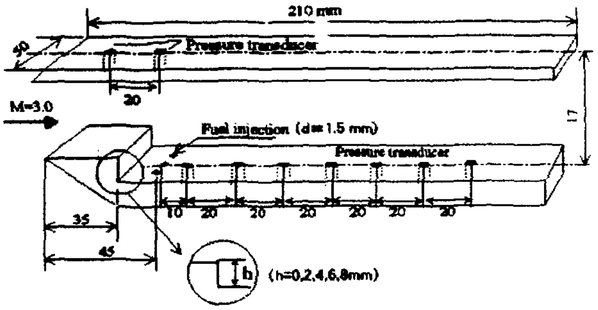


Fig.2 Detail of SCRAM jet engine model

Table 1 Experimental conditions of detonation-driven shock tunnel

Driver Gas	H_2, O_2
Equivalence Ratio, ϕ	1
Pressure of Driver Gas	300 ~ 440 kPa
Driven Gas	Air
Pressure of Driven Gas	4 ~ 31.3 kPa

Table 2 Freestream conditions

Test Gas	Air
Test time	3 ms
Static pressure	150 kPa
Injection Gas	H_2, He
Pressure of Injection Gas	50 ~ 300 kPa
Freestream Mach number	3

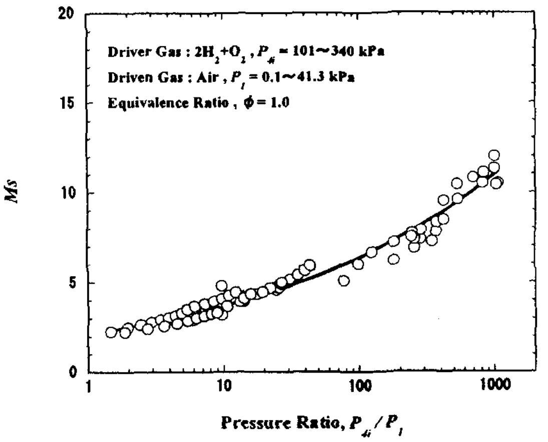


Figure.3 Relationship between Mach number of shock wave, M_s and initial pressure ratio, p_{4i}/p_1.

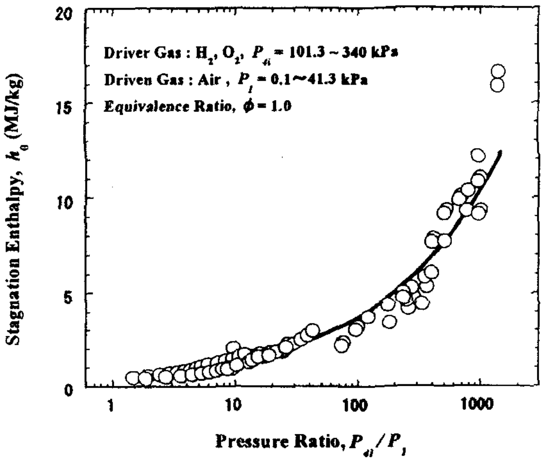


Figure.4 Relationship between stagnation enthalpy, h_0 and initial pressure ratio, p_{4i}/p_1.

A fuel injection hole of 1.5 mm diameter was made 45 mm apart from the leading edge. Pressure transducers (PCB Co., Ltd., Model 113A21, 113A24, Response Time: 1 μs) were mounted on the central line of combustor.

Experimental conditions

Table 1 indicates experimental conditions of the detonation-driven shock tunnel. The driver gas is stoichiometric oxygen and hydrogen (oxy-hydrogen) gas mixture and an initial pressure of driver gas is changed in a range from 300 to 440 kPa. The test gas filled in the shock tube and observation section is air and is change in a range from 4 to 31.3 kPa.

Table 2 indicates experimental conditions of the freestream. The velocity of the air at the exit of the nozzle is about three. In this injection conditions, hydrogen and helium gas are used as injection gas and is change in a range from 50 to 300 kPa.

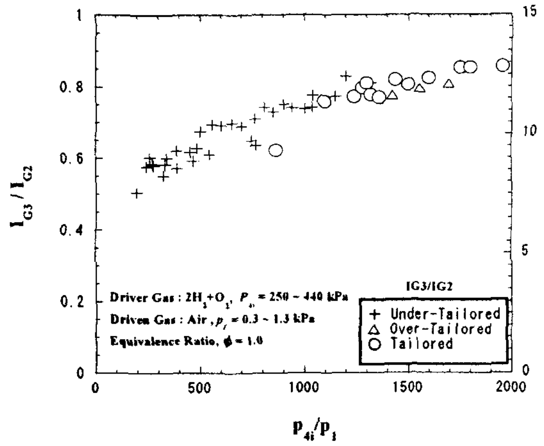


Figure.5 Relationship between acoustic impedance ratio, I_{G3}/I_{G2} and initial pressure ratio, p_{4i}/p_1.

Results and Discussion

Performance of detonation-driven shock tunnel

A detonation-driven shock tube is useful apparatus for producing high-enthalpy flow and it can be used to investigate a combustion flow inside SCRAM jet engine. This detonation-driven shock tube produces a shock wave of high propagation Mach number and high enthalpy using a particularly high-temperature gas behind reflected shock wave.

Figure 3 shows the relationship between Mach number of the shock wave, M_s and non-dimensional pressure of driver, p_{4i} to driven gas, p_1. The propagation Mach number of shock wave, M_s increases as the initial pressure ratio, p_{4i} / p_1 increases. The Mach number of the shock wave has obtained approximately 14 at the initial pressure ratio, $p_{4i} / p_1 = 1.3 \times 10^3$.

Figure 4 shows the relationship between stagnation enthalpy behind reflected shock wave h_0 and non-dimensional pressure, p_{4i} / p_1. The stagnation enthalpy, h_0 increases as the initial pressure ratio, p_{4i} / p_1 increases. The stagnation enthalpy of approximately 15 MJ/kg has obtained at the initial pressure ratio, $p_{4i} / p_1 = 10^3$. A stagnation enthalpy behind reflected shock wave was evaluated and experimental conditions producing high-enthalpy flow were clarified, which would be practical to investigate a combustion flow inside a SCRAM jet engine.

The detonation-driven shock tunnel used high-temperature and high-pressure gases produced by detonating oxy-hydrogen gas as a driver source of a shock wave. In general, a period of uniform flow generated by supersonic nozzle is very short, because the shock wave is followed by a contact discontinuities. Therefore, a Tayloring condition has to be indispensable for extending the test period, in which a reflected shock wave from a diaphragm interrupt the propagation of contact discontinuities.

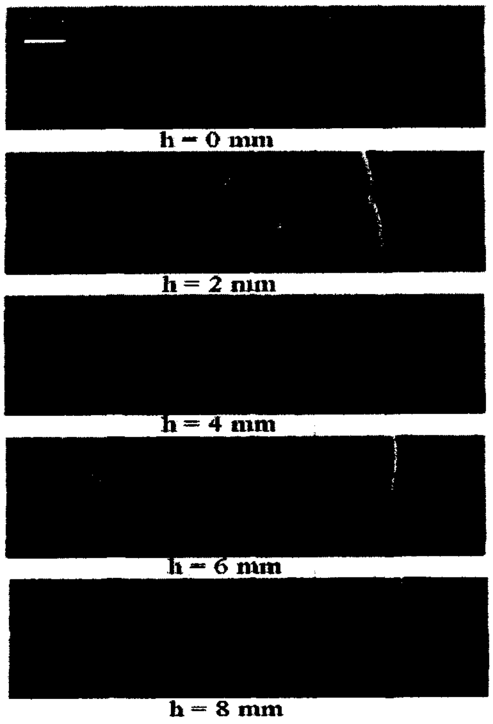


Fig.6 Color-schlieren photographs showing a flow-field behind backward-facing step

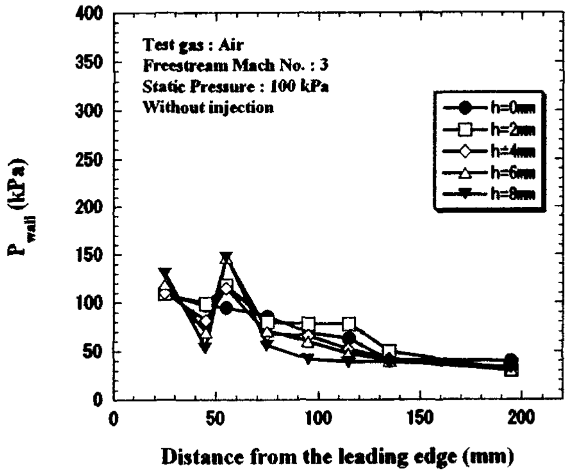


Fig.7 Pressure distribution on a bottom wall of combustor (without fuel injection)

Then, the pressure histories at the end of shock tube were measured to acquire the Tayloring condition.

Figure 5 shows the relationship between acoustic impedance, I_{G3} / I_{G2} and initial pressure ratio, p_{4i} / p_1. As a result, Tayloring condition is obtained for the experimental condition, where propagating Mach number of incident shock wave is about 12 and acoustic impedance across contact discontinuity is not largely changed. In this experimental condition, a reflected shock wave prevents the contact surface from propagating to terminate the test period.

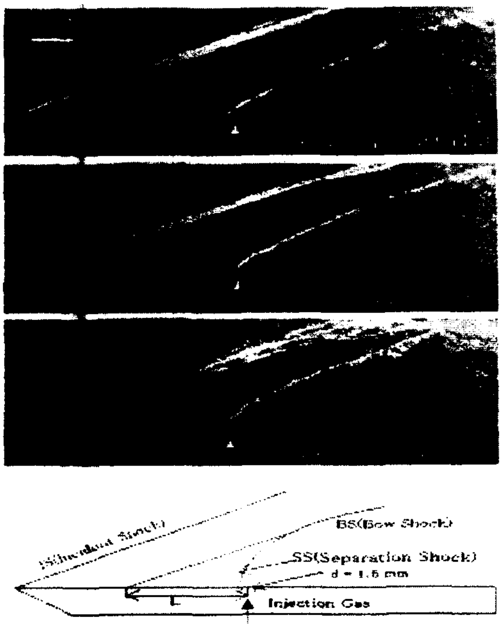


Fig.8 Color-schlieren photographs and the detailed picture of the flow-field in the nearby of a fuel injection in supersonic flow (He injection)

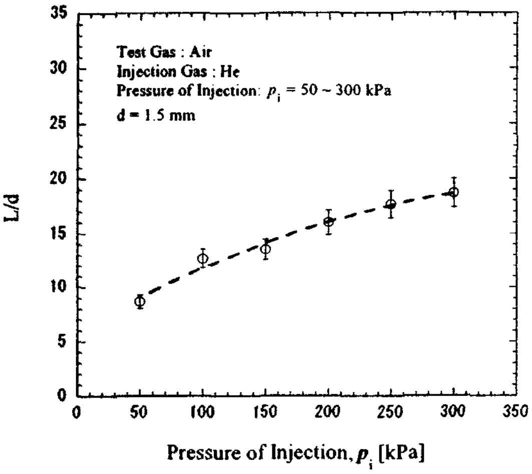


Fig.9 Relationship between penetration distance, *L/d* and Injection pressure, p_i

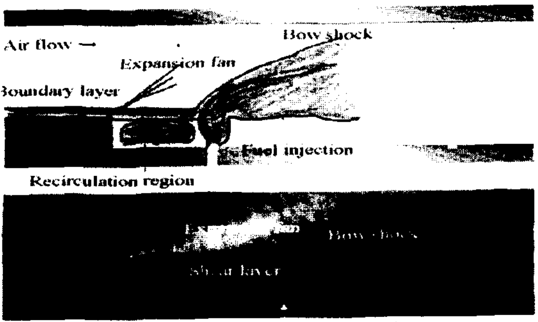
Flow-field without backward-facing step

Figure 6 shows color-schlieren photographs showing a flow-field behind backward-facing step by changing the height of the step *h* from 2 to 8 mm. It can be observed that a Prandtl-Mayer expansion fan, free shear layer, and recompression shock wave, emerging from downstream near the reattachment point. The free shear layer separates the recalculation region by increasing the height of the step.

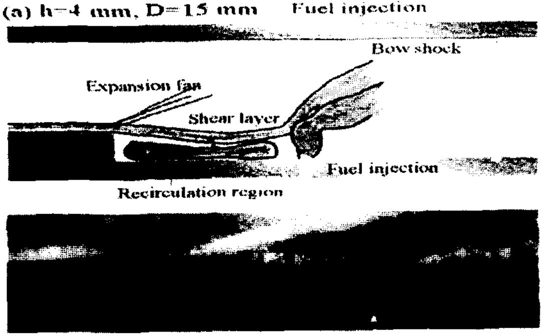
Figure 7 shows a static pressure distribution in a SCRAM jet engine model by changing the height of the step without injecting fuel. A horizontal axis is the distance from leading edge and vertical is static pressure. In this figure, pressure is gradually decreased toward downstream direction, while the pressure is fluctuated with increasing the height of the step. This is because expansion waves were generated at the corner of backward-facing step and reattachment shock wave was produced by the interaction of supersonic flow with a bottom wall behind backward-facing step.

Figure 8 is a schieren photographs showing the flow-field around a fuel injection in supersonic flow-field. This figure shows the supersonic flow-field from left to right with injecting helium gas from the bottom wall. The fuel injected behind step is a flow configuration, which is to enhance mixing between of air and fuel. The fuel injection is sonic at the injector and injection pressures are change in a range from 50 to 300 kPa. The obstruction caused by the jet generates a bow shock wave in the freestream. The bow shock wave and boundary layer generates a separation region of boundary layer upstream of the injector. The separation shock wave is produced and the small recirculation region is observed just ahead of the jet. Another recirculation region is also visualized downstream of the jet near the surface.

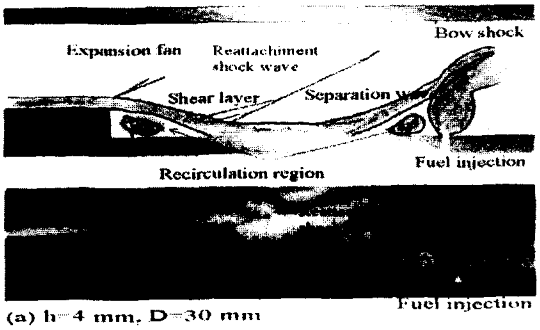
Figure 9 shows the relationship between diameter of injection hole d and non-dimensional penetration distance from the injector to the diameter of injection hole, L/d. called penetration distance. The penetration distance L/d increases as the injection pressure p_i increases. The recirculation region increases as the extent of fuel injection penetration increases.



(a) h=4 mm, D=15 mm



(b) h=4 mm, D=20 mm



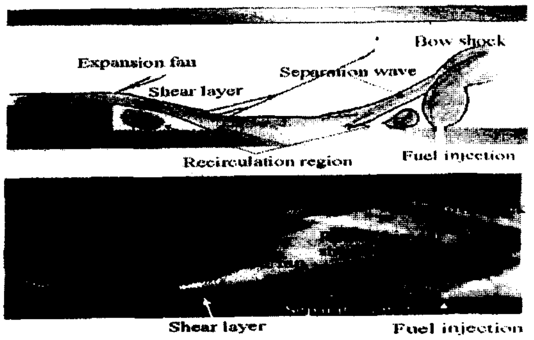
(a) h=4 mm, D=30 mm

Fig.10 Schematic diagram of Recirculation region patterns (upper) and schieren photograph (lower), Injection: He, p_i = 300 kPa

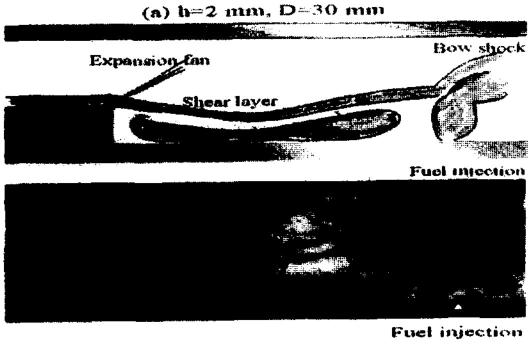
Flow-field using backward-facing step and *recirculation region pattern*

Figure 10 (a) ~ (c) show the results of the recirculation region patterns obtained from the flow-field behind backward-facing step visualized by schlieren photographs. The recirculation region patterns with base injection indicate the shear layer between the oncoming boundary layer and the recirculating gases behind the step. The distance of injection was changed to investigate the effects of step on mixing characteristics. The schlieren photograph shows the recompression shock wave and the reflected shock wave arising from the leading edge. It is visualized by that a Prandtl-Mayer expansion fan, free shear layer, recirculation region and reattachment shock wave. In this photographs, as increasing the height of the step, the interaction between the step recirculation region and jet upstream recirculation is increasing. The recirculation region increases by increasing the distance between step and injection hole. However, in fig. 10 (c) step recirculation and jet upstream recirculation are separated, the interaction between these recirculation region might be small. A reattachment was took place behind the step and ahead of the jet upstream recirculation region then it is not effective for the mixing. Therefore, injection distance is very effective for the mixing because of the interaction between the step recirculation region and jet upstream recirculation region.

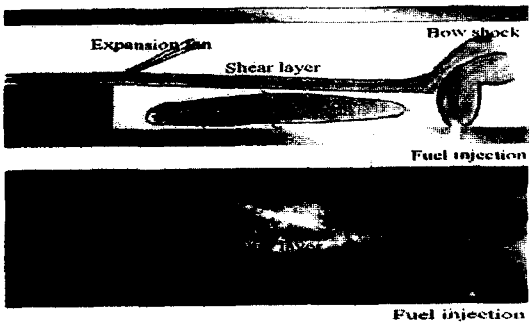
Figure 11 shows the recirculation region patterns with base injection, indicating the shear layer between the oncoming boundary layer and the recirculating gases behind the step. The height of step was changed to investigate the effects of step on mixing characteristics between step recirculation region and jet upstream recirculation region. In this case, as increasing the height of the step, it might be confirmed that recirculation region is increased. The size of the recirculation region could strongly affect the ignition and combustion processes of supersonic combustor, the size of recirculating region, which



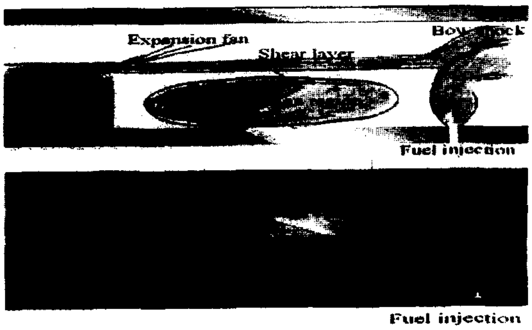
(a) h=2 mm, D=30 mm



(b) h=4 mm, D=30 mm



(c) h=6 mm, D=30 mm



(d) h=8 mm, D=30 mm

Fig.11 Schematic diagram of recirculation region patterns (upper) and schlieren photograph (lower), injection ; He, p_i = 300 kPa

might be typically determined from the height of step. Thus, the recirculation region increases with increasing the height of the step.

Figure 12 shows the relationship between interaction distance of recirculation region, *D* and height of the step, *h*. The interaction distance, *D* increases as the height of the step, *h* increases. As a result, the interaction distance, *D* has obtained *D*=5*h*. However, in case of the injection located in more than 5*h*, two recirculation regions are separated each other. It may be that the boundary layer reattached ahead of the jet upstream recirculation region.

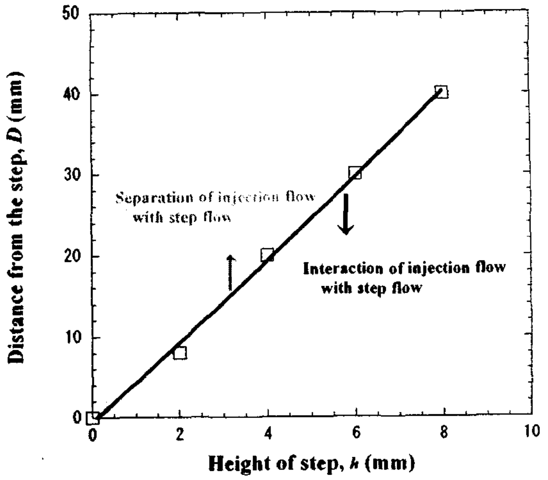
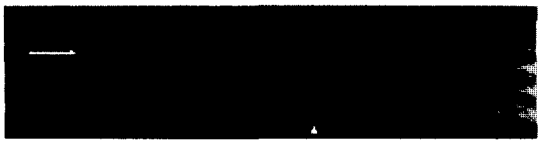


Fig.12 *Relationship between interaction distance of recirculation region and height of the step.*

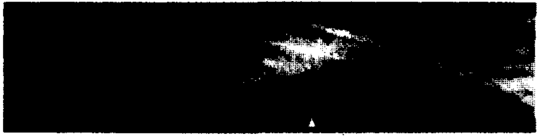
Effects of backward-facing step on combustion

Figure 13 is a schlieren photograph showing the flow-field behind backward-facing step. The helium gas is injected through the bottom wall and the heights of the step are change in a range from 0 to 8 mm. In case of *h*=2 mm, the recirculation region behind step has separated from an upstream recirculation region. The obstruction caused by the jet generates a bow shock in the freestream. A small recirculation region is created just ahead of the injection. The upstream separated region and its separation shock wave are expected to be small and the shock weak enough to that the ambient mixture is not ignited in this region. However, the recirculation region is increased with increasing the height of step height. The recirculation region behind backward-facing step and the jet upstream recirculation region which give part of the flow long residence time and serve as ignition sources and flamholders for the main flow.

Figure 14 and 15 are schlieren photographs and direct photographs respectively showing a flow-fields behind SCRAM jet engine model by changing the height of the step *h* from 2 to 8 mm. In this photograph, as increasing the height of the step, the recirculation region is increased. In a case of *h* = 2 mm, hydrogen gas injected perpendicular to the flow



(a)h=2 mm, D=10 mm He injection

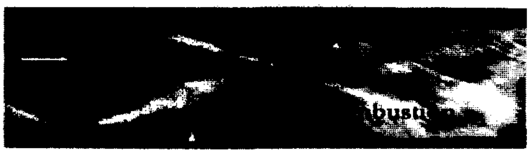


(b)h=4 mm, D=10 mm He injection

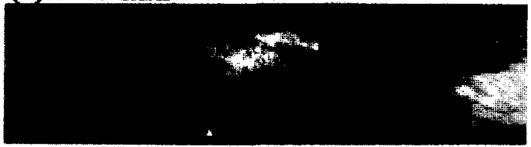
(c)h=6 mm, D=10 mm He injection

(d)h=8 mm, D=10 mm He injection

Fig.13 Schlieren photograph behind backward-facing step in combustor, injection; He, p_i = 300 kPa

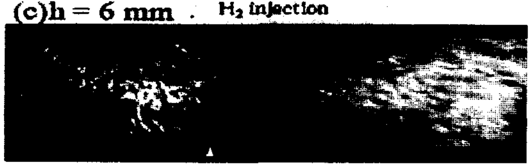


(a)h = 2 mm H_2 injection



(b)h = 4 mm H_2 injection

(c)h = 6 mm . H_2 injection

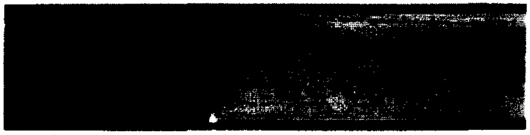


(d)h = 8 mm H_2 injection

Fig.14 Schlieren photograph behind backward-facing step in combustor, injection; H_2, p_i = 300 kPa

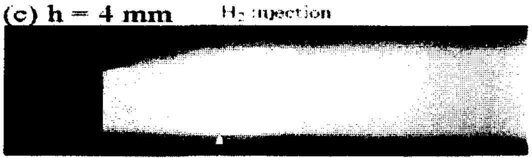
is just transported downstream direction and recirculation region is not remarkably observed. However, the mixing between hydrogen and air is promoted by increasing the height of the step. Furthermore, in the case using higher steps, hydrogen is ignited near the injector, observed in fig. 14, 15. In

(a) h = 0 mm H_2 injection



(b) h = 2 mm H_2 injection

(c) h = 4 mm H_2 injection



(d) h = 6 mm H_2 injection

(e) h = 8 mm H_2 injection

Fig.15 Direct photograph behind backward-facing step in combustor, injection; H_2, p_i = 300 kPa

the case of an injection behind a backward-facing step, the mixing efficiency is much higher than without step. As a result, the size of recirculation region could strongly affect the ignition and combustion processes of supersonic combustor.

Figure 16 shows the static pressure distribution in the combustor for this case without injection, with injection (helium injection) and combustion (hydrogen injection). A horizontal axis is the distance from leading edge and vertical is static pressure. In the case of without injection, the flow expands behind the step and the static pressure is decreased on the base region. The pressure recovers further downstream as the flow is compressed after reattachment on the bottom wall. On the other hand, the case of combustion, the pressure distribution is largely increased compared without injection. This is due to the heat release by combustion. The pressure increase observed in the combustion is attributed to heat release accompanying by the combustion. In the case with injection (hydrogen injection), fuel is trapped in the recirculation region, creating a region of hot gases and providing the main flameholding mechanism. The case of high step, most of the combustion occurred in the recirculation region.

The pressure for injection into hydrogen is consistently higher compared with heliem injection. The difference between these pressures is due to the

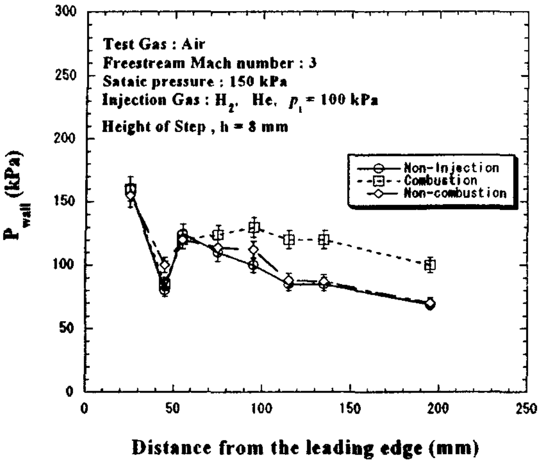


Fig.16 Pressure distribution on a bottom wall of combustor (without fuel injection, He injection, H_2 injection).

heat release arising from combustion. Figure 17 shows pressure histories in a combustion and clearly indicates a two-stage pressure increases caused by the propagation of shock wave and combustion.

Conclusions

Experiments were conducted to clarify the characteristics of detonation-driven shock tunnel and combustion behavior of SCRAM jet engine model. Conclusions are summarized as follows.

A performance of detonation-driven shock tunnel, generating a high-enthalpy flow is investigated and experimental conditions producing high-enthalpy flow were clarified, which would be practical to investigate a combustion flow inside a SCRAM jet engine and experimental condition occurring Tayloring is obtained for propagating Mach number of a shock wave $M_S \approx 12$.

A SCRAM jet engine model is installed at downstream position of supersonic nozzle and hydrogen gas is injected perpendicular to a supersonic flow behind backward-facing step. It is visualized using the color-schlieren technique that mixing between fuel and air is enhanced for increasing the height of the step. It is also visualized that hydrogen is burned behind backward-facing step. In the case of a higher step, the size of recirculation region becomes wider compared with lower step. It is considered that the backward-facing step is effective to improve the fuel mixture and ignition of the combustion in combustor.

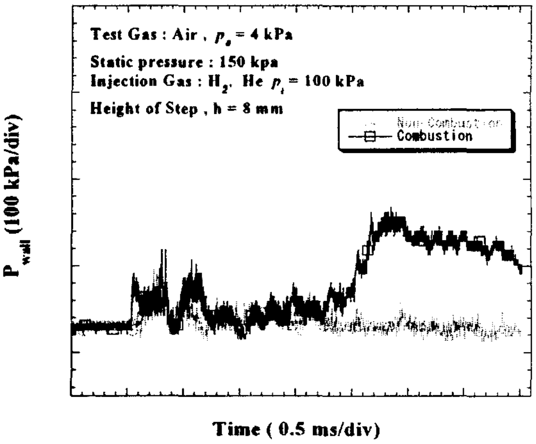


Fig.17 Pressure histories in a combustor (He injection, H_2 injection)

The recirculation regions increases as the extent of fuel injection penetration increases and the recirculation region increases with increasing the height of the step. Also, the strong combustion is observed in the recirculation region.

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