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

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1. Introduction

The supersonic combustion RAM jet (SCRAM jet) engine is expected to be used in next-generation space planes and hypersonic airliners. To develop the engine, stabilized combustion in a supersonic flow field must be attained even though the residence time of flow is extremely short. A mixing process for breathed air and fuel injected into the supersonic flow field is therefore one of the most important design problems[1,2)]. Because the flow inside the SCRAM jet engine has high enthalpy, an experimental facility is required to produce the high-enthalpy flow field.

In this study, a detonation-driven shock tunnel was built to produce high-enthalpy flow, and a model SCRAM jet engine equipped with a backward-facing step was installed in the test section of the facility to visualize flow fields using a color schlieren technique and high-speed video camera. The fuel was injected perpendicular to a Mach 3 flow behind the backward-facing step. The height of the step, the injection distance and injection pressure were varied to investigate the effects of the step on air/fuel mixing characteristics. The results show that the recirculation region increases as the fuel injection pressure increases. For injection behind the backward-facing step, mixing efficiency is much higher than with a flat plate. Also, the injection position has a significant influence on the size of the recirculation region generated behind the backward-facing step. The schlieren photograph and pressure histories measured on the bottom wall of the SCRAM jet engine model show that the fuel was ignited behind the step.

2. Experimental

Figure 1 shows a schematic diagram of the experimental set-up. The detonation-driven shock tunnel, 50 mm in diameter and 15 m in total length, is constructed from an ignition tube, a detonation tube, a shock tube, a dump tube, an observation section and dump tank. A nozzle, installed at the end of the shock tube, is designed to produce a flow of Mach number three at the exit region of the nozzle. The shock tube is equipped with four pressure transducers (PCB Co., Ltd., Model 113A24, Response Time: 1μs) near the observation section to obtain the Mach number of the shock wave. The flow fields behind the backward-facing step are visualized using a color schlieren technique and a high-speed video camera (Vision Research, Inc., Phantom V7.0; 10^4 pps at 512×384 pixel, 1.6×10^5 FPS). A color filter is set at the focal point of the schlieren system. A schematic of the color schlieren optical system is also shown in Fig.1.

In the detonation tube, a gas mixture of oxygen and hydrogen (oxy-hydrogen) is detonated with an ignition tube consisting of four igniters and a subchamber. The burning

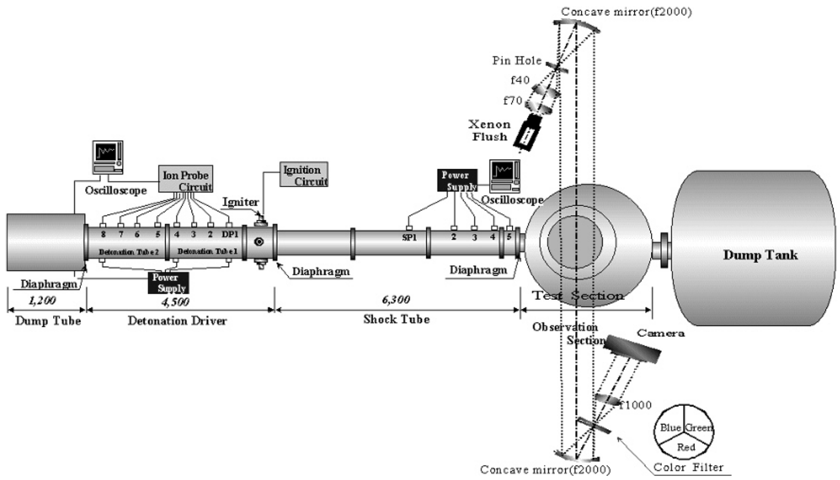

Figure 1: Experimental Set-up of detonation-driven shock tunnel.

gas is injected from the subchamber to the detonation tube through the 3 mm diameter straight nozzle where the oxy-hydrogen gas is instantaneously detonated. A diaphragm made of Mylar film (75 μm in thickness) is inserted between the detonation tube and shock tube. High-pressure and high-temperature gas behind the detonation wave is generated very quickly by the ignition to rupture the diaphragm and drive a shock wave of high Mach number into the shock tube.

Eight measuring stations are installed on the detonation tube and four stations are installed on the shock tube. Two piezoelectric pressure transducers (PCB Co. Ltd., Model 113A21) are mounted on the driven gas tube and four pressure transducers are mounted on the shock tube to measure the propagation velocity of the detonation wave and the shock wave, respectively. Ionization probes are also mounted on the detonation tube, diametrically opposed to the pressure transducers, to detect the arrival time of the detonation wave. The area between the two iron cores, measuring 1.4 mm in diameter (Gap: 1.0 mm, Length: 2.5 mm), is locally ionized. Output signals from the pressure transducers and ionization probes are stored by two oscilloscopes (Yokogawa Electric Co., DL1540, 200 MS/s) and processed by a personal computer.

3. Results and Discussion

In Fig.2 (a)$\sim$(d), schematic diagrams of the recirculation region (upper) and schlieren photographs of the flow field behind the backward-facing step (lower) are shown for the cases of D/h = 3.7, 5.0, 7.5, 15.0. The height of the step h is varied to investigate the effect of the step on mixing characteristics of the recirculation regions behind the step and upstream of the jet. In these cases, the distance of injection D is held constant at 30 mm, and the height of the step h is varied changed from 0 to 8 mm.

The recirculation region patterns for base injection indicate a shear layer between the oncoming boundary layer and the recirculating gases behind the step. In the case of small h, as shown in Fig.2(a), the flow behind the step reattaches to the bottom wall close to the end of the step, and the recirculation regions behind the step and upstream from the jet become separated. However, as the height of the step is increased as shown in Fig.2(b)

∼(d), an increase in the recirculation region may be confirmed. As a result, the size of recirculation region should strongly affect the ignition and combustion processes of the supersonic combustor. Thus, the recirculation region increases as the distance between the step and the injection increases. Therefore, for a large D/h, these two recirculation regions become separated.

Figure 3 is a schlieren photographs (left) and direct photographs (right), respectively, showing the flow field behind the SCRAM jet engine model as the height of the step h is varied from 2 to 8 mm. In the photograph, as the step height is increased, the recirculation region increases as indicated in Fig.2. In the case of $h = 2$ mm, hydrogen gas injected perpendicular to the flow is transported in the downstream direction only, and the recirculation region is not remarkably observed. However, hydrogen and air mixing is promoted by increasing the step height. Furthermore, in the case of higher step heights, hydrogen ignites near the injector as observed in Fig.3(d) and (e).

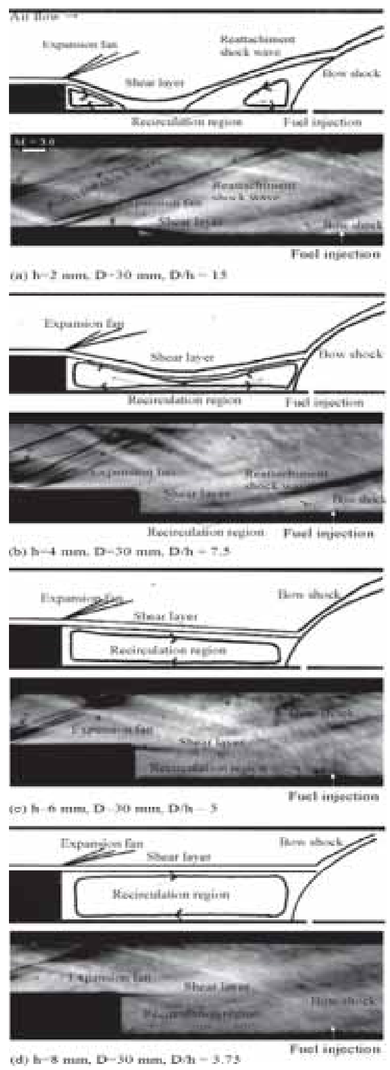

Figure 2: Schematic diagram of recirculation region patterns (upper) and schlieren photograph (lower). Injection: He, $p_i = 300$ kPa.

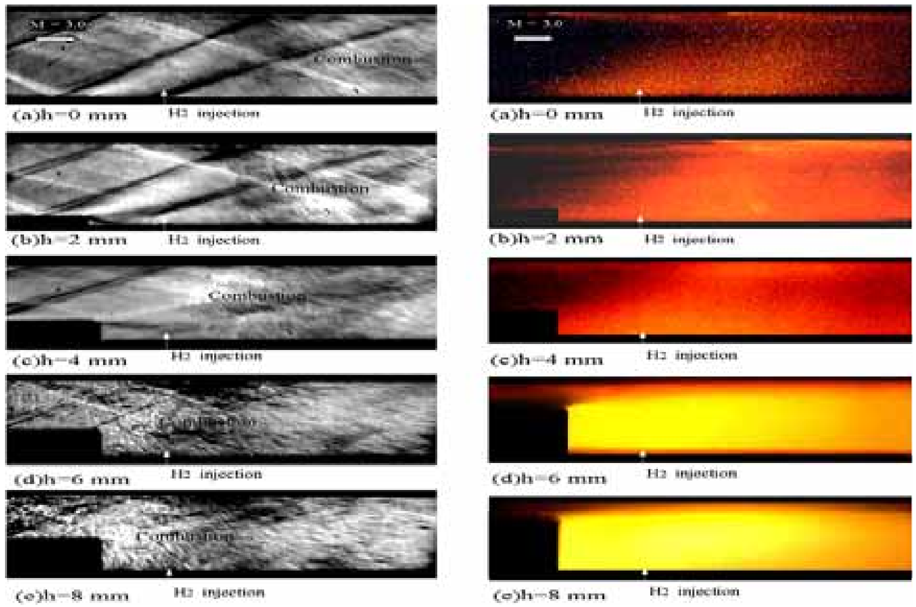

Figure 3: Schlieren photograph (left) and direct photograph (right) of region behind backward-facing step in combustor. Injection: H_2, $p_i = 300$ kPa.

4. Summary

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

The interaction of two separate recirculation regions were observed by varying the height of the step, the distance of the injector and the injection pressure. An increase in the recirculation region by an increase in step height is suggested, and this recirculation region is also increased by the penetration of fuel injection. Thus, in the case of injection behind a backward-facing step, the mixing efficiency is much higher than that of flat-plate injection. The recirculation region is increased by increasing the distance between the step and injector. However, when the injection is located too far from the step, the two recirculation regions become separated. When the injector is located less than $5h$, the two recirculation regions interact. Thus, the recirculation region between the step and the jet is influenced by the injection pressure, the height of the step and the distance of injection.

References

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