Experimental study on a performance of detonation-driven shock tunnel and flow-fields behind backward-facing step

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Abstract As is well known, a Scramjet-engine has very short period in a supersonic flow residence time. Therefore, fuel injected into a supersonic flow has to mix with the air quickly in order to obtain stable combustion. In order to investigate a flow-fields of supersonic combustion region, high-enthalpy shock tunnel is considered as useful facilities. In this study, detonation-driven shock tunnel is used to produce high-enthalpy flow and firstly the performance of this facility was investigated obtaining a Tayloring condition. Secondly, Scramjet-engine model was installed at test section and flow-field behind backward-facing step was visualized using color-schlieren technique.

Key Words: Scramjet-engine, Shock tunnel, Backward-facing step, Supersonic combustion

1. Introduction

The supersonic combustion RAM (SCRAM) jet engine has attracted attention 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 [(1)]. Therefore, mixing process between fuel and air is significant issues and this report is concerned with the mixing of fuel with air, and supersonic combustion flow-fields behind backward-facing step.

Injection from portholes upstream of the combustion chamber was investigated as a method of delivering fuel into a scramjet and combustion was observed in the combustion chamber using a shock tunnel [(1)]. Scramjet-engine model having a strut was investigated using high-enthalpy shock tunnel, indicating drag coefficients by varying equivalence ratio [(2)]. Since mixing properties between fuel and air is a key factor to develop a Scramjet-engine, various types of engine model has to be tested by changing flow conditions, injection method and configurations promoting mixing.

In this study, a detonation-driven shock tunnel was used to produce high-enthalpy flow and firstly the performance of this facility was investigated in order to obtain a Tayloring condition. Furthermore, Scramjet-engine model was installed at test section and flow-fields behind backward-facing step were visualized using color-schlieren technique. The height of backward-facing step was changed to investigate the effects of step on mixing characteristics between air and fuel. The fuel was injected perpendicular to the flow of Mach number three behind step. The schlieren photograph and pressure histories show that the fuel was ignited behind step.

2. Experimental

2.1 Experimental set-up

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 chamber, detonation tube, shock tube, dump tube, observation section and a dump tank. The experiments were carried out installing a Scramjet-engine model into a test section as shown in fig.2. These experiments were conducted at flow Mach number of about three. The Scramjet-engine model has a dimension of 210 mm in total length and 50 mm width. The leading edge of the model has sharp wedge, which prevent the supersonic flow-fields from disturbing. A backward-facing step was located 35 mm downstream position from the leading edge and the height of it *h* is changed from 0 to 8 mm. 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 s) were mounted on the central line of supersonic nozzle as shown in fig.2.

2.2 Experimental conditions

Table 1 indicates experimental conditions. The driver gas is stoichiometric oxygen and hydrogen (oxy-hydrogen) gas mixture and an initial pressure of driver gas is changed in a range $300 \leq p_{4i} \leq 440$ kPa, then the propagation Mach number of incident shock wave is changed as $5 \leq Ms \leq 12$.

3. Results and Discussion

3.1 Performance of detonation-driven shock tunnel

The detonation-driven shock tunnel was used in order to produce high-enthalpy flow fields. In this apparatus, high-temperature and high-pressure gases produced by detonating oxy-hydrogen gas are used as a driver source of a shock wave. In general, a period of uniform flow generated by supersonic nozzle is quite 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. In experiments, pressure histories at the end of shock tube were obtained to acquire the Tayloring condition. Figure 3 shows the results of stagnation pressure histories behind reflected shock wave. Figure 3(a) to (c) show the results for stoichiometric gas mixture, varying the initial pressure ratio between driver gas and driven gas. In fig.3(a), the pressure risen by an incident shock wave is gradually decreased and this might be an under-Taylored condition, in which a expansion wave is reflecting from contact surface. In fig.3(b), secondary shock wave is observed, then this shows over-Taylored conditions. While, in fig.3(c), the pressure maintains almost constant value approximately for 3 ms. Therefore, Tayloring condition is obtained for this experimental conditions, where propagating Mach number of incident shock wave is about 12. In this experimental condition, a reflected shock wave prevent the contact surface from propagating to terminate the test period.

3.2 Flow-fields behind backward-facing step

Figure 4 shows a static pressure distribution in a Scramjet-engine model by changing the height of the step without injecting fuel. A horizontal axis is the distance from leading edge and vertical one 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 behind backward-facing step and reattachment shock wave was produced by the interaction of supersonic flow with a bottom wall behind backward-facing step.

Figure 5 shows the static pressure distribution by injecting hydrogen from bottom wall of combustion channel perpendicular to the supersonic flow. The hydrogen is injected with a pressure of p_{inj} = 100 kPa. The pressure distribution is largely increased compared with fig.4, indicating that the fuel was ignited behind a step.

Figure 6 is color-schlieren photograph showing a flow-fields behind Scramjet-engine model by changing the height of the step h = 2 mm to 8 mm. In this photograph, as increasing the height of the step, it might be confirmed that mixing region is increased. In a case of h = 2 mm, hydrogen gas injected perpendicular to the flow is just transported downstream direction and mixing region is not remarkably observed. However, the mixing between hydrogen and air is promoted by increasing the height of the step. In a case of h = 8 mm, Prandtl-Meyer expansion fan is observed behind step and the flow direction undergoes a change to a bottom wall of combustion channel. Then, this flow might play a role on the mixing between hydrogen and air. In case using higher steps, hydrogen is ignited behind step and this might give rise to pressure enhancement, observed in fig.5.

4. Conclusions

(1) A performance of detonation-driven shock tunnel, generating a high-enthalpy flow is investigated and experimental condition occurring Tayloring is obtained for propagating Mach number of a shock wave $M_s \simeq 12$.

(2) A Scramjet-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.

References

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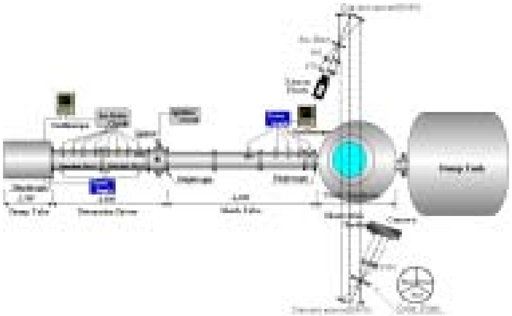


Fig.1 Schematic diagram of experimental set-up.

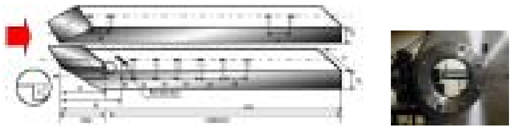
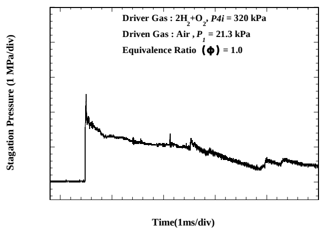


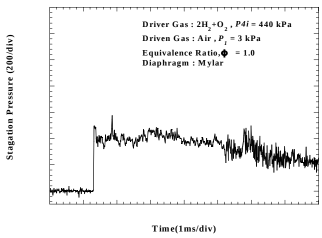
Fig.2 Scramjet-engine model having backward-facing step.

Table 1 Experimental conditions.

Driver Gas	H2 , O2
Pressure of driver Gas	300 ~ 440 kPa
Test Gas	Air
Equivalence Ratio, ϕ	1.0
Mach number	5 ~ 12



(a)



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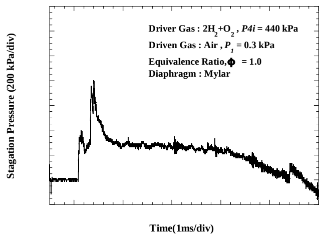


(c)

Fig.3 Pressure histories behind reflected shock wave, measured at stagnation point.

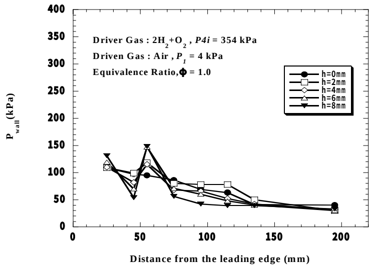


Fig.4 Pressure distribution on a bottom wall of combustor (without fuel injection).

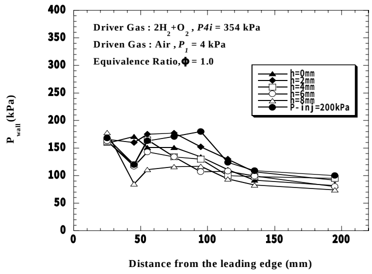
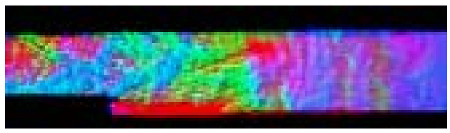
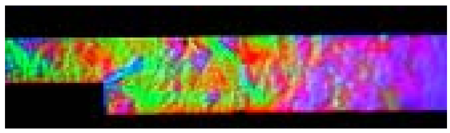


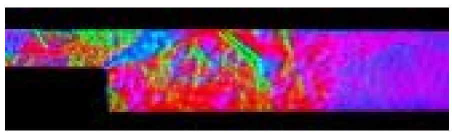
Fig.5 Pressure distribution on a bottom wall of combustor (with fuel injection, p_{inj} = 100 kPa).



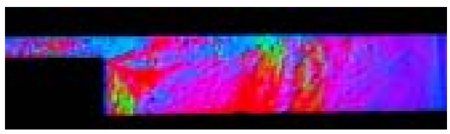
h=2 mm



h=4 mm



h=6 mm



h =8 mm

Fig.6 Color-schlieren photographs showing a flow-field behind backward-facing step (with fuel injection, p_{inj} = 100 kPa).