
An Experimental Investigation on Combustion Characteristics of Hypermixer Injectors - Effects of the 'Swept' Applied to Hypermixer Injector Ramps -

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Abstract

Supersonic mixing and combustion enhancement is the key technology for success of the development of the scramjet engine. In this study, some types of hypermixer (ramp) injectors were investigated by the combustion test. Especially, we have focused on the effect of applying 'swept' to these injector ramps in this paper. According to the experimental result, there was little difference on the thrust performance due to the application of swept when streamwise vortices was strongly generated. When streamwise vortices were not introduced enough, swept type injectors were better thrust performance than unswept type.

Keywords: Hydrogen fueled scramjet; Supersonic combustion; Streamwise vortices; Hypermixer; Boundary layer sepration.

1. Introduction

For success of a scramjet engine, the development of fuel mixing enhancement technique and devices are important. The operational flight speed range of the scramjet engine is from about Mach 6 to 12 or higher, and in such a range, it is required to carry out rapid and efficient fuel/air mixing and combustion, because the residence time of fuel in the engine at supersonic speed is very short. Although the two-dimensional large-scale vortex

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structure plays an important role in the low-speed turbulent mixing, development of it in supersonic flow is inhibited because of the compressibility effect. Therefore, use of streamwise vortices is one of the promising ideas for enhancement of fuel/air mixing in supersonic flow because the three-dimensional structure grows up well rather than the two-dimensional structure in the flow with the compressibility effect [1,2,3]. In this study, two kinds of hypermixer injectors which strongly introduce streamwise vortices in the injector wake flow were investigated experimentally. One is strut type hypermixer and the other is hypermixer which was installed on the combustor wall. Furthermore, Northam et al. showed that the combustion efficiency was improved by giving a swept angle for the side wall of the conventional ramp injector [4,5]. Therefore, the effect of applying a swept angle to hypermixer injector ramps was investigated.

2. Experimental setup

2.1. Test facility and flow condition

The combustion tests were conducted using a direct connected combustion test facility at JAXA Kakuda Space Center. This facility uses a H₂/O₂ vitiation air heater to raise the flow enthalpy to a required level. Figure 1 shows the schematic of flow path of supersonic combustors used in the present investigation. As we can be seen in Fig. 1 (a) and (b), the geometry is different between the combustor which have the wall mounted ramp injector and the strut type injector. These combustor were directly connected to the vitiation air heater through a two dimensional supersonic nozzle and the combustor cross sections were two-dimensional rectangular. Major dimensions of the combustor are shown in Fig. 1. In this figure, the coordinates of the position of the fuel injection position is set as \( x = 0 \) mm and symbol 'H' and 'Hramp' indicates the height of the injector ramp.

![Fig. 1 The schematic of flow path of supersonic combustors](image)

In the combustion tests, the wall static pressure was measured along the scramjet combustor center line on the top wall side by using two sets of mechanical scanner. A scanning cycle took approximately 2.4 s to acquire the pressure distribution along the combustor, completely. Additionally, visualization of the flame was carried out by direct photography through a quartz window using a video camera. A quartz window was installed on the combustor side wall. On all test conditions, the combustion state was stable while wall pressures were measured, as long as they were monitored by the video camera. Nominal flow conditions in the combustion tests were adjusted to Mach
number 2.46, total pressure $P_0 = 993 \pm 27$ kPa, and total temperature $T_0 = 2243 \pm 56$ K. This flow condition corresponds to the Mach number 7.5 flight condition. O$_2$ concentration in the vitiation air including H$_2$O is controlled to be 21%. The fuel was gaseous hydrogen which at room temperature and was injected at the sonic speed through tubes of circular cross section. In the test of the strut injectors, the condition of total fuel equivalent ratio $\phi = 0.5$ and 0.9 were tested. In the test of the wall mounted injectors, two case of fuel injection were tested. In one case, fuel was injected from only bottom wall. In the other case, fuel was injected from both top and bottom walls. Experiments were conducted for the total equivalence ratio, $\phi = 0.20$ to 0.95.

2.2. Injector models

In this study, two kinds of injectors were investigated, i.e. strut type hypermixer and wall mounted type hypermixer. Strut type hypermixer tested in the present experiments is based on the design concept introduced by Sunami et al., which is called "Alternating Wedge Strut (AW-Strut)." Figure 2(a) and (b) show a schematic of the unswept type and swept type injector models used in the current work. In this study, AW-struts which have an trailing edge angle of wedge of 22 degrees and 36 degrees were tested. Detailed information of the design of these the injectors were described in reference number [6,7]. These injectors were installed on the center line of the combustor as shown in Fig. 1(a). Wall mounted type hypermixer were consisted of a two-dimensional compression ramp at upstream side, and a following generating streamwise vortices section. At this section, wedges were formed by extended compression ramp from the upstream side, and wedges and expansion ramps were arranged alternately in the span width direction. Moreover, the composition of alternating-ramp-wedge formed a cavity at under the compression wedge. Figure 3(a) and (b) show a schematic of the unswept type and swept type injector models used in the current work, respectively. Fuel was injected into the free shear layer through circular orifices locate at the trailing edge of wedges. These injectors which used in this study can introduce four pairs of large-scale counter-rotating streamwise vortices in a spanwise row configuration. These injectors were installed on the top and bottom walls of the supersonic combustor as shown in Fig. 1(b).

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![Fig. 2 The schematic of hypermixer injectors (strut type)](image)

![Fig. 3 The schematic of hypermixer injectors (wall mounted type)](image)
3. Result and discussion

3.1. Without combustion conditions

Fig. 4(a) and (b) show the wall pressure distribution along the combustor top wall for the strut type hypermixer injectors without combustion. As shown in Fig. 4, there is little difference in pressure distribution between hypermixer with swept ramps and non-swept ramps, which is the strut type and the wall mounted type respectively. Therefore, it seems that there is little effect that the application of swept shape to injector wedge of hypermixer on the total pressure losses.

Fig. 4 The wall pressure distribution without combustion

3.2. Result of combustion tests with strut type injectors

Fig. 5(a) and (b) show the wall pressure distribution along the combustor top wall for the strut type hypermixer injectors with combustion. In Fig. 5(a), hypermixer with swept ramps compared with non-swept ramps, which have a wedge ramp of an angle of 36 degree and 22 degree, at only about $\phi = 0.5$. The influence of the different in ramp angle on effects to apply swept shape to the ramp wedges of the hypermixer appear in Fig. 5(a). As shown here, in case of ramp angle of 22 degree, pressure rise due to combustion for the hypermixer with swept ramp is a larger compared to that with non-swept ramp. On the other hand, in case of ramp angle of 36 degree, the difference is hardly seen in both pressure rises due to combustion. The mixing efficiency and the circulation becomes larger in the larger ramp angle case wherein as shown by CFD simulation [8]. The result of this reference shows that mixing performance is better by increasing the ramp angle. In Fig. 5(b), hypermixer with swept ramps compared with non-swept ramps, which have a wedge ramp of an angle of 36 degree, at about $\phi = 0.5$ and 0.9. Differences in the pressure distribution between hypermixer with swept ramp and non-swept ramp is very small in both case of total fuel equivalent ratio. Considering these results, it is considered that effect on the fuel/air mixing and combustion to apply 'swept' shape to the ramp wedges of the hypermixer will not appear when streamwise vortices were introduced enough into wake flow of the injectors. These pressure rise data of each condition can be compared in Fig. 6 quantitatively. Figure 6 shows the relation between the thrust coefficient increment calculated from the integral pressure thrust and the total equivalent ratio. Here, the thrust coefficient increment, $\Delta C_T$ was evaluated as difference in values of the thrust coefficients between with and without combustion and $n_{sv}$ indicates the number of the streamwise vortex which was introduced in main flow by the wedge of hypermixer injector and into which the fuel jet was injected. From Fig. 6, that consideration is seen more definitely.
3.3. Result of combustion tests with wall mounted injectors

Figure 7(a) and (b) shows the wall pressure distributions in combustion conditions. In figure 7(a), the results of the case of fuel injection from only bottom wall (single-sided injection) were shown. The zig-zag formed wall pressure distributions indicate the shock reflections. Therefore, it is seemed that supersonic combustion was attained. In figure 7(b), the case of fuel injection from top and bottom wall (double-sided injection) is presented. The wall pressure distributions were show that there were pressure peaks in the constant area section. In the latter section of the constant area, wall pressure magnitudes were decreased due to the fuel heat release. Thus, it is considered that the behavior of flow and combustion is "subsonic likely." Direct photographs in the cases of single- and double-sided injection are shown in Fig. 8 (a) and (b), respectively. Figure 9 shows the relation between the thrust coefficient increment and the total equivalent ratio. In the case of single-sided injection, the flame does not covered the injector wedge. From these results, streamwise vortices are thought of as better generation in the injector wake. However, Fig. 9 shows that there is different between the combustion performance with swept and non-swept ramps at about $\phi/n_{eng} = 0.05$. This difference is caused by the flame attached to the wedge of injector. Flame was generated under the wedge of the injector, small boundary layer separation occurs at the expansion ramp of the injector. Then, the generation of streamwise vortices is weakened. As the result, it is considered that the mixing and combustion
performance to decline. In the case of double-sided injection, both thrust coefficient increments around $\phi/n_{eqv} = 0.025$ were similar. However, the thrust coefficient increment of hypermixer with non-swept ramp was saturated at total equivalent ratio above $\phi/n_{eqv} = 0.025$ on the other hand hypermixer with swept ramp achieved relatively better performance than non-swept ramp in such range. In all cases of double-sided injection, the injector wedges were covered by the flame. The reason is explained as follows. Once the injector wedges are covered by the separation bubble, the fuel/air mixing and combustion are controlled by the shear layer which was separated from the end of compression ramp on the injector. In such flow field, streamwise vortices could not be introduced as the design intent of these injectors. Consequently, mixing-controlled combustion in the separated shear layer may become dominant. Therefore, in the case of non-swept, the combustion performance reaches the ceiling at $\phi/n_{eqv} = 0.025$ when the effect of the artificial mixing enhancement on the flow field is lost. On the other hand, it is considered that swept ramp has the ability to disturb the shear layer and in such flow field, the turbulent mixing is more enhanced by swept ramp.

![Fig. 7 The wall pressure distribution with combustion (wall mounted type injector)](image)

![Fig. 8 Flame images at about $\phi/n_{eqv} = 0.2$ and 0.4 (wall mounted type injector)](image)
4. Conclusion

Effect to apply 'swept' shape to the ramp wedges of the hypermixer fuel injectors about the combustion performance on scramjet engine was investigated experimentally. Combustion tests were conducted in with a direct connect wind tunnel and the combustor which was installed the start injectors or the wall mounted injectors was connected. The following conclusions were obtained from the experimental results; When streamwise vortices were introduced enough into wake flow of the injectors by ramps of the hypermixer, there is no little difference between the wall pressure distribution from the combustor which had hypermixer with non-swept ramps and that with swept ramps. When streamwise vortices were not introduced well, hypermixer with swept ramps showed a higher thrust performance than that with non-swept ramps. Additionally, in the case of using the wall mounted hypermixers, the non-swept ramp injectors caused significant decrement of the combustion performance. Furthermore, performance decrements were remarkable in the high fuel equivalence ratio conditions. This reason was seemed that the fuel/air mixing and combustion are controlled by the shear layer separated from the injector, because of the injector wedges and expansion ramp were covered by with the separation bubble. In such a flow field, performance decrements were suppressed by using the swept ramp.

References