EFFECT OF VENT MIXER TO MIXING CHARACTERISTICS IN SUPERSONIC FLOW

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Abstract

A Mach 2 hydrogen – air supersonic combustor model with no diffuser was designed and operated in atmospheric inflow condition. A new supersonic mixer, which was vent slot mixer (VSM), was developed and fabricated to use as the device of the fuel-air mixing. At low enthalpy inflow condition, a plasma jet torch was used as the igniter and the flame-holder. An isolator was located between the nozzle and the combustor. In supersonic combustion, the VSM had an effect to increase the mixing efficiency compared with the step mixer. While the combustion pressure was increased, the combustion mode was changed from unstable supersonic combustion to dual-mode transition. When the unstable flow of shock train affected the combustor inlet, the VSM was showed that the combustion stability was slightly sustained when compared with the case of the step mixer.

Nomenclature

d = diameter of fuel injector
d_J = diameter of plasma injector
ER = global equivalence ratio
h = height of the mixer
h_{th} = thermal efficiency
H = isolator duct height
M = Mach number
m = mass flow
n = number of samples
P = pressure
P_{IN} = input power of Plasma torch
P^* = pressure at thermal choke
T = temperature
Re = Reynolds number
S = isolator length
U = velocity
X = stream-wise direction
γ = ratio of specific heat
σ = standard deviation
Θ = momentum thickness

Subscripts

A = air
a = flight altitude condition
F = fuel
ref = isolator inlet condition at cold-flow
0 = stagnation condition
1 = isolator entrance condition
2 = combustor entrance condition

1. Introduction

The supersonic combustion ramjet (scramjet) engine is expected to be one of the propulsion systems for hypersonic air-breathing vehicle and space plane. However, it is difficult to obtain a high speed for scramjet engine without any acceleration auxiliary engine. For this reason, dual-mode scramjet (DMSJ) is practically promising candidate for these vehicles because they have an advantage of operating on both ramjet and scramjet modes [1, 2]. A schematic of a DMSJ illustrating its main components is displayed in Fig. 1. In the DMSJ, there is transition from subsonic to supersonic combustion by the heat

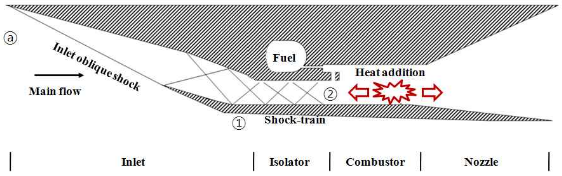

Fig. 2 Schematic of a dual-mode scramjet engine.

release from the combustor. During this mode transition, the pre-combustion shock train is generated and increases the inlet exit pressure in the combustor. At $M_0 > 8$, the heat release is not sufficient to choke in the combustor, shock train disappears and dual-mode transition to supersonic combustion occurs [1]. However, the shock train can reach its maximum length during dual-mode transition to the subsonic combustion associated with the high back pressure in the combustor. Unstart condition in the inlet occurs if the shock train reaches the inlet [3]. Therefore, an isolator is placed between the inlet and the combustor to prevent undesirable combustor-inlet interaction in the DMSJ. The previous literatures [4, 5] about the isolator indicated that shock-inlet interaction does not occur during dual-mode transition to subsonic combustion, and the shock train did not reach the facility nozzle in the subsonic combustion. Clearly, the isolator is necessary to prevent the inlet-combustor interaction and to work well for DMSJ operation. The isolator length is typically designed using Billig [1] empirical expression which has pressure ratio (P_2/P_1) between inlet (P_1) and outlet (P_2) pressure in the isolator. In previous experiments [4, 5], the estimated pressure ratio (P_2/P_1) was about 4.5, that is pressure ratio of normal shock at Mach 2. For this study, the different pressure ratio (P_2/P_1 = 2.05) for the Billig's empirical expression was used to confirm the difference of the previous results when the pressure ratio of the isolator was designed under that of one dimensional Rayleigh thermal condition (P_2/P_1 = 2.75) and the normal shock condition because the paper about this case has not been published yet.

In the supersonic combustion, the inflow velocity in the combustor is several thousand meters per second which reduces the fuel residence time in the supersonic flow. Fuel-air mixing, flame holding, pressure losses, and

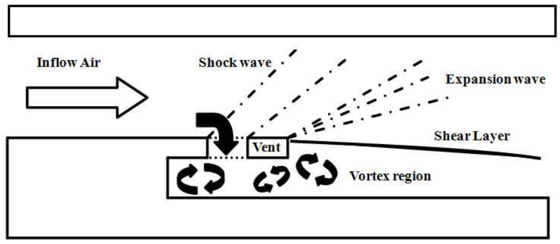

Fig. 2 Schematic of a vent mixer.

thermal loading must all be considered for the successful design of a scramjet engine [3].

The key to scramjet combustion is the proper design of the fuel injector, which must reconcile in the opposing goals of low pressure loss, intense mixing, and high flame stability. Several devices for fuel injection into supersonic crossflow were studied to enhance mixing and reduce pressure losses in the supersonic combustor [3]. These included transverse injection, ramps, lobe mixers, tabs, steps, cavities, chevron, and strut-based injector, etc. Although each design was different, common desirable characteristics was the aerodynamic efficiency of the fuel injection system. For scramjet application, methods utilized to increase mixing efficiency of fuel with oxidizer must first be capable of rapid mixing both supersonic streams on a macro-scale and then generating small-scale turbulence to increase the diffusion of fuel [6].

For practical fuel-air mixer on scramjet operability, both macro-scale and micro-scale mixing with low pressure loss are needed in the supersonic flow. Considering these factors, a new mixer which is named as vent mixer is developed and designed in Fig. 2. A distinguishing feature of the vent mixer compared with other previous mixers is vent on the extended wall. Inflow air through the vent may run into the recirculation region, which increases the circulation velocity and extends the recirculation region. Furthermore, a lot of vortices can be developed due to the interaction between the inflow air and the wall, or the parallel injected fuel.

The present study was the first time that has been demonstrated the performance characteristics of the invented new mixer with the plasma torch igniter in the unheated inflow

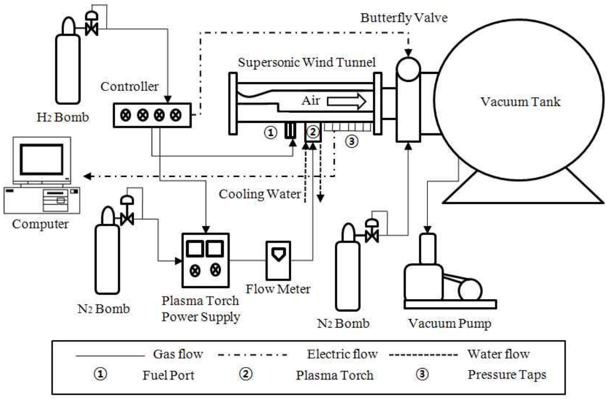

Fig. 3 Schematic of experimental facility system.

Mach 2 of the supersonic combustor model. Hydrogen gas was used as fuel and the wall pressure measurement and schlieren imaging method were taken to determine the combustion mode. The Billig's paper [1] was referred to define the terms in this paper.

2. Experimental Apparatus

Supersonic wind tunnel

The experimental apparatus is shown in Fig. 3. An intermittent suction-type supersonic wind tunnel was used. The unheated atmospheric air was inhaled to a vacuum tank through a two-dimensional half contoured nozzle. Upper wall was one block from the supersonic nozzle to the flat plate. Bottom wall was a flat plate and the mixer models were attached before the throat of the nozzle to reduce the shock development. The vacuum tank had a volume of 8 m^3 and was evacuated to about 5 kPa before each run.

Hydrogen gas was injected parallel to the main flow from the wall of supersonic mixer. The combustor duct dimensions are 30 mm x 36.7 mm with no divergence. The duration of each run and the data recording time was about 20 s and 4 s, respectively.

Isolator

Isolator was typically designed using Billig's empirical expressions [1]. The length of the isolator was designed to get a designed pressure ratio between the isolator inlet and exit. This expression was relation between the shock-train length, *S*, to the isolator pressure ratio P_2/P_1, according to Billig's equation. For a sudden change surface contour, such as a step between

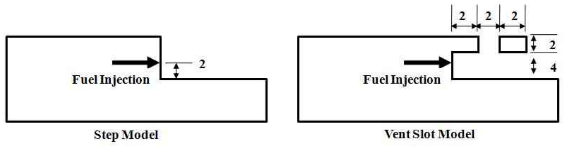

Fig. 4 Schematic of a SM and a VSM.

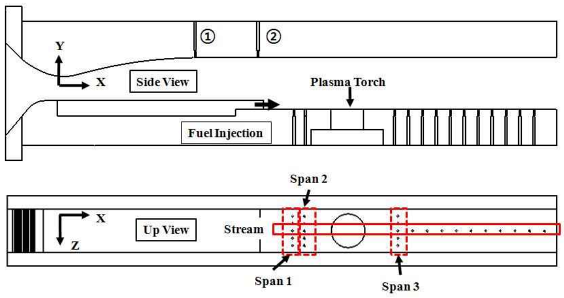

Fig. 5 Schematic of supersonic combustor.

the isolator and the combustor, no ambiguity arises [1]. Therefore, this expression can be applicable to the supersonic combustor with the SM and the VSM in this study. Based on this equation, the isolator was designed in this experiment. Its aspect ratio of the isolator width and height was 1 : 1.02. Although the maximum pressure ratio generally measured for the dual-mode scramjet without an isolator was about 4.5 [4, 5], designed pressure ratio of isolator in this experiment was 2.05 to reduce the length and the weight of the test section within unheated air flow condition.

The addition of heat from combustion into a supersonic flow decreases Mach number to sonic condition, which induces a thermal choke that inflow of the combustor becomes subsonic condition. To get the expected pressure ratio required for a thermal choke in the isolator and combustor, a one-dimensional Rayleigh flow analysis was carried out assuming a calorically perfect gas (ratio of specific heat is 1.4) [7].

$$\frac{P^*}{P_1} = \frac{1+\gamma M_1^2}{1+\gamma}$$

Supersonic mixer

A new supersonic mixer was developed and was tested in this experiment, which was named as the vent mixer because a vent has a significant effect on the mixing and the combustion. Inflow through the vent interacts with the fuel flow in the recirculation region, which increases the mixing efficiency and combustion efficiency. The characteristic shape of the vent mixer was indicated in Figs. 2 and 4. The wall of thickness 2 mm was elongated from the step wall, and the slot of width 2 mm was perforated on the center of the wall. The step mixer, whose height was 6 mm, was used as the basic mixer to compare with the vent mixer. In this paper, the step mixer and the vent slot mixer, as a matter of convenience, were named as 'SM' and 'VSM', respectively.

Data acquisition

The windows of the test section were made of Pyrex glass for schlieren visualization using a stroboscope lamp of 180 ns pulse time. The image was monitored by a video camera with schlieren image method.

The wall static pressures (low-frequency measurement) on the upper wall and the bottom wall of the test section were measured by the strain-gauge type pressure transducer attached in a mechanical pressure scanner at a tap-scanning frequency of 1 kHz in Fig. 5. The strain-gauge type pressure transducers (PDCR23D – 200 psi : SCANIVALVE Inc and PAB-A200KP : KYOWA Inc) were used for measurements of the wall pressures and the injectant total pressure in the test section. The signal from each transducer was amplified by a d.c. amplifier (AS2102: NEC Inc) and digitized by a 14-bit A/D converter, and recorded by a data recorder (NR2000: Keyence Inc). The accuracy of the pressure measurement system was estimated as ±1% for the measurements of the injectant total pressure and ±2% for the wall pressures, respectively. The 95% confidence large sample uncertainty analysis of the measured pressure data was carried out with data reduction. And standard deviation was then calculated to quantify the fluctuations in pressure [8].

$$(\text{Total error})^2 = (2\sigma/\sqrt{n})^2 + (2\%\ \text{experimental uncertainty})^2$$

a) Image of SM

b) Image of VSM

Fig. 6 Schlieren image of supersonic mixers.

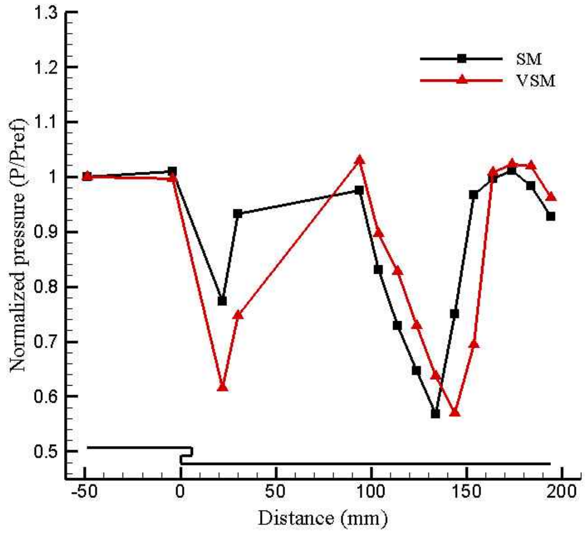

Fig. 7 Pressure comparisons between the SM and the VSM.

3 Result and Discussion

Non-reacting condition

The difference of the flowfield between the SM and the VSM is clearly visible in Fig. 6. Upstream boundary layer separated at the SM. The separated shear layer curves sharply downward in the reattachment zone and impinges on the bottom wall. For the VSM, the recirculation region is extended and the inclination of the shear layer is gentle, which reduces the pressure loss in the combustor. Inflow air through the vent into the recirculation region makes a disturbance, which increases the mixing efficiency and extends the recirculation region. Although the shock wave is generated from the vent in Fig. 6b, reflected shock wave form the bottom wall is barely observed because its strength is weak through the expansion wave. Vortex is generated from the recompression region. The vortex structure of the VSM is distributed largely and widely compared with that of the SM. For this reason, the VSM renders the large subsonic recirculation region which is highly turbulent flow because the air through the vent impinges the wall, which makes a lot of vortices in the recirculation region. Finally, these vortices in the subsonic region increase the fuel-air mixing in the supersonic combustor.

The pressure loss from the mixer is an important factor to design the supersonic combustor. The pressure distribution of both models is indicated in Fig. 7. Behind the SM, the large pressure drop generally occurs due to the rapid expansion and the pressure recovery is fast in the small recirculation region. In Fig. 6a, the recirculation region is developed about 3*h* from the SM where a pressure tap is placed. So the pressure drop of the SM is not high compared with that of the VSM. While the pressure rise of the SM is very steep, that of the VSM increases gradually which reduces the total pressure loss. After recirculation region is passed, the pressure distribution of two models is similar according to the shock and expansion wave structure.

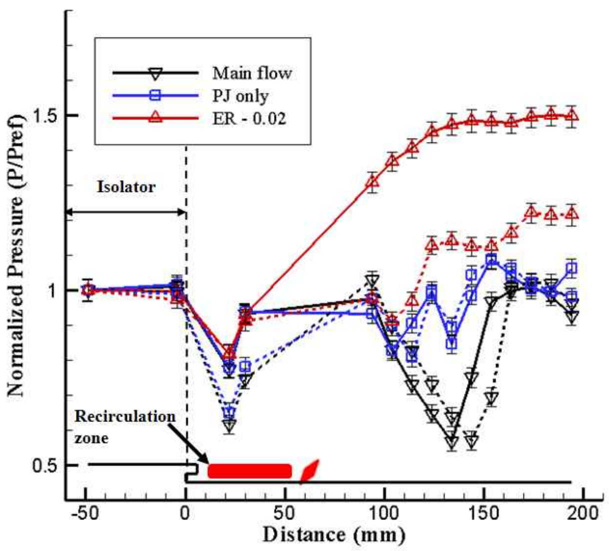

Fig. 8 Pressure distribution along streamwise direction; solid line - SM, dot line - VSM.

Reacting condition

Figure 8 shows the pressure distribution along stream wise direction with the SM and the VSM. All pressure is normalized by the nozzle exit pressure, p_{ref}.

When the plasma jet is injected, upstream pressure rise is little but pressure increases from the downstream of the plasma jet for both the SM and the VSM in Fig. 8. Furthermore, the plasma jet does not nearly affect the increase of the pressure in the recirculation region of the mixers. For ER = 0.02, clear difference of two mixer models is observed. The pressure of the SM highly increases at downstream flow. Injected fuel is mixed with air through the plasma jet because the ignition and the combustion in the supersonic flow are governed by the mixing efficiency [11]. The pressure difference ahead of the PJ is very low between the plasma jet and ER = 0.02, that means there is no ignition in the recirculation region. However, the pressure of the VSM rises in the recirculation region. Therefore, two things can be aware of that the recirculation is hot to ignite the mixed gas and the fuel-air mixing is well by the vent. The pressure difference of the front and rear of the plasma jet is also low because non-exhausted gas is ignited by the plasma jet and downstream combustion pressure gradually increases in the combustor.

The VSM showed that it enhanced the mixing efficiency and sustained the stable combustion. In this work, however, the combustion efficiency of two model mixers cannot be indicated only with pressure data and schlieren images.

Combustion mode transition

The one-dimensional Rayleigh flow with heat addition was calculated to indicate the expected pressure ratio, which was 2.75, required for thermal choke [7]. For previous literature such as Le et al [4, 5], the isolator length is designed using Billig' empirical equation based on the pressure ratio of normal shock (P_2/P_1 = 4.5) at Mach 2 flow. The leading of the shock-train is generated from some region within the isolator until reaching the un-start condition. In this study, the pressure ratio (P_2/P_1 = 2.05) is designed under the pressure ratio of the normal

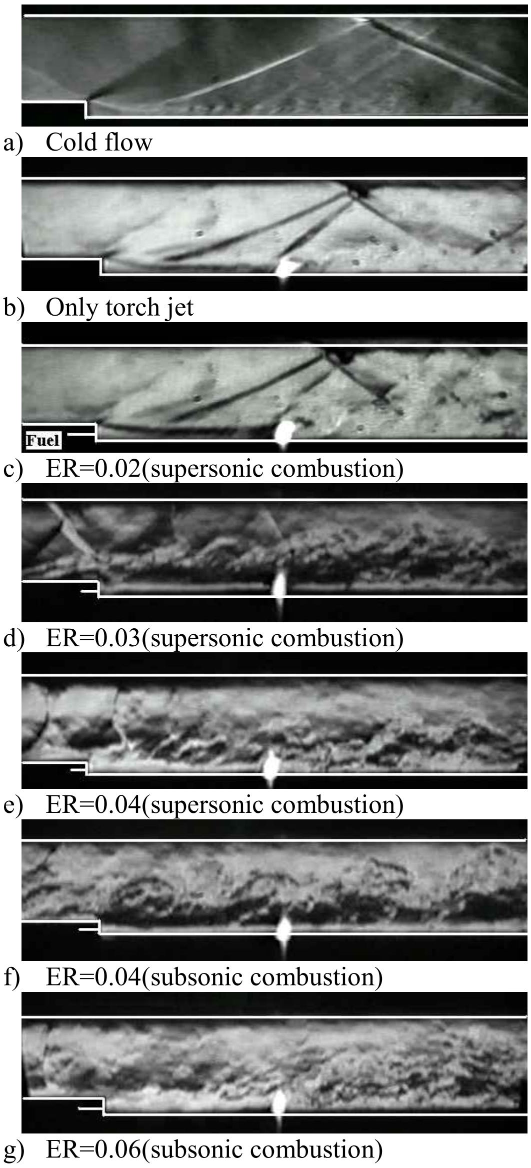

Fig. 9 Schlieren images along ER with the SM.

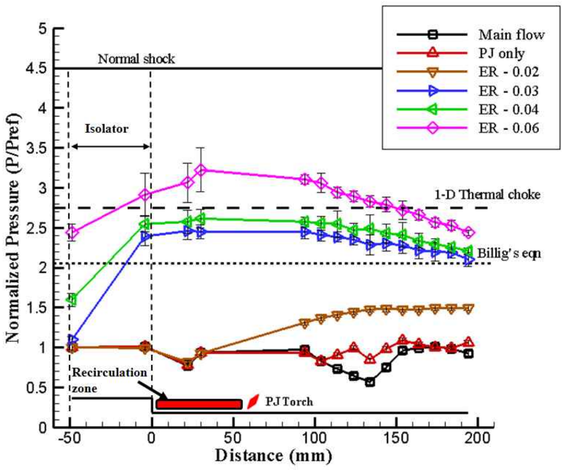

Fig. 10 Pressure distribution along streamwise direction with the SM.

shock condition to reduce the length and the weight of the supersonic combustor model.

It is somewhat difficult to confirm the combustion mode only based on the pressure distributions because the estimated pressure ratio of the isolator is under the thermal choke condition and this kind of experiment was not reported yet. With the pressure distributions, instantaneous schlieren images were used to show the flowfield characteristics of each combustion mode in the supersonic combustor. In this paper, the combustion modes were determined according to the inflow condition at the combustor entrance [1]. For example, if the inflow to the combustor is subsonic (or supersonic), the combustor is operating in the subsonic (or supersonic) combustion mode.

Combustion mode with the SM

For the plasma jet injection, a shock wave is developed ahead of the PJ torch in Fig. 9b. The large separation bubble occurs on the upper wall in Fig. 9b, which is developed by colliding of oblique shock wave from the PJ torch. For ER = 0.02, the pressure difference is increased between ER = 0.02 and plasma torch jet condition, in Fig. 10. In Fig. 9c, the parallel fuel injection increases the shear layer thickness of the recirculation region behind the SM, which makes the hot recirculation region because the hot gas from the upstream region of the PJ torch can be supplied into the recirculation region of the SM. However, mixed gas is ignited through the PJ torch. Combustion only occurs behind the PJ torch because the kink bow shock ahead of the PJ torch still stands in Fig. 9c and the upstream pressure does not increase in Fig. 10. Weak oblique shock train is developed between the combustion region on the bottom wall and the separated boundary layer on the upper wall. For ER = 0.03, the combustion region is extended by high pressure due to heat release. The boundary layer in the isolator is separated and the plasma jet is directly injected into the combustion region with straight PJ light in Fig. 9d. Although the shock train is developed in the isolator, the inflow to the combustor is still supersonic flow in Figs. 9d and 9e.

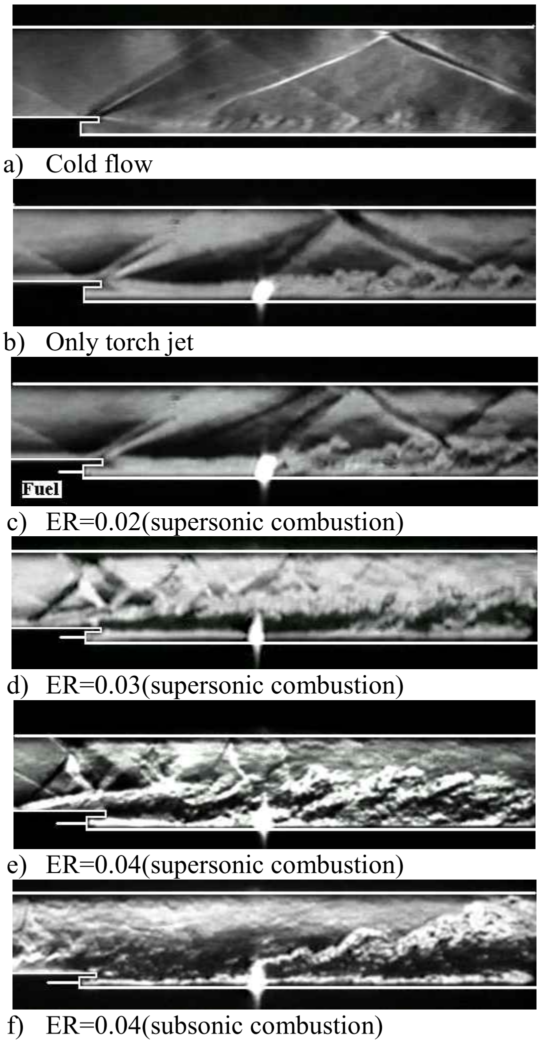

Fig. 11 Schlieren images along ER with the VSM

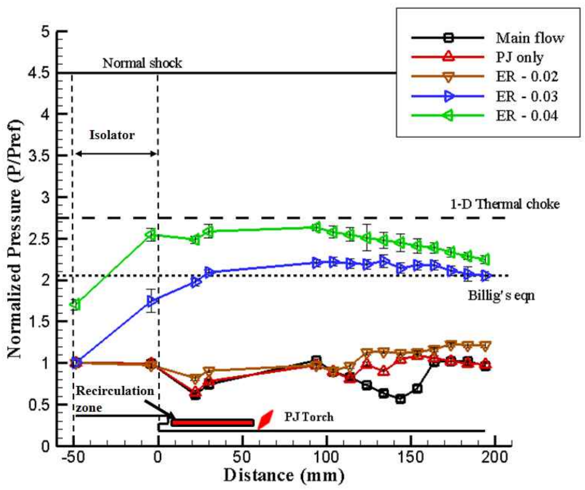

Fig. 12 Pressure distribution along streamwise direction with the VSM

The combustion pressure of the recirculation region, however, is unstable because the instability of the inflow characteristic to the combustor has a bad effect on the combustion stability.

Below ER = 0.03, if the shock-train does not reach the inlet of the isolator, inflow Mach number at the combustor inlet is still supersonic flow in Figs. 9c and 9d, which is “supersonic combustion.” For ER = 0.04, inlet pressure ratio of the isolator increases over one and the pressure ratio within the isolator still distributes below the 1-D Rayleigh flow analysis in Fig. 10. This means that thermal choke does not occur in the combustor. However, the pressure distributions exist around the 1-D thermal choke condition and the flow condition reaches critical point to maintain the supersonic inflow to the combustor. Then the inflow to the combustor is frequently changed between subsonic and supersonic according the combustion back pressure in Figs. 9e and 9f. This can be called the “dual-mode” transition, which depicts both the dual-mode to subsonic and the dual-mode to supersonic, which is associated with the combustion pressure. For ER = 0.06, pressure distribution of the isolator exceeds the 1-D thermal choke condition, which indicates that thermal choke occurs in the combustor. The inflow to the combustor is subsonic and oblique shock is not visible in Fig. 9g. The combustor inflow is subsonic and the combustor is operating as the subsonic combustion mode (unstart condition).

Combustion mode with VSM

The inclination of PJ torch light is similar with that of the fuel injected case, comparing in Figs. 11b and 11c. This indicates that the recirculation region between the VSM and the PJ torch is connected because inflow air through the vent extends the recirculation region to the hot upstream flow of the plasma jet. For ER = 0.02, pressure distribution ahead of the PJ torch increases a little in Fig. 12, which is associated with the combustion. In the hot mixing region, the air through the vent interacts with the injected fuel, which increases the mixing rate and induced the ignition in the mixing region because the supersonic combustion is governed by the mixing rate [11].

For ER = 0.03, the combustion pressure affects the isolator, but it is still supersonic combustion mode because the shock train does not affect the isolator inlet flow in Fig. 12 and shock train is occurring in the combustor in Fig. 11d. In the upstream combustor, the combustion pressure is a little stable, although the inflow pressure to the combustor is unstable in Fig. 12.

For ER = 0.04, the pressure ratio is similar with that of the SM in Fig. 10. In this case, the performance of the mixer is of no significance. In Figs. 11e and 11f, the combustor mode is frequently changed between the supersonic combustion and the subsonic combustion according to the combustion pressure. For the dual-mode transition and the subsonic combustion, the pressure error bar is large in the isolator and the upstream flow of the combustor with the SM in Fig. 10. With the SM, this kind of the instability directly affects the combustion stability in Fig. 10. However, the pressure fluctuation behind the VSM in Fig. 12 is different with that of the SM. Although there is fluctuation in the isolator, the error bar of the combustion pressure behind the VSM is similar with other cases, such as no-injection and supersonic combustion. Therefore, the combustion of the VSM can be considered to be stable during the dual-mode transition.

4 Conclusion

Supersonic combustion experiments were conducted in a low-enthalpy inflow condition with the PJ torch which acted as the igniter and the flame holder. Furthermore, a new supersonic mixer, the vent mixer, was developed and used to study its mixing efficiency compared with a step mixer. Hydrogen gas was used as a fuel and injected parallel to the downward wall. The isolator was designed using the pressure ratio, P_2/P_1 = 2.05, which was lower than that of the 1-D thermal choke condition and the typical design pressure ratio.

For ER = 0.02, combustion with the VSM occurred form the recirculation region but ignition of the SM happened behind the PJ torch. For ER = 0.03, combustion pressure developed the shock train in the isolator. For ER = 0.04, dual-mode operation progressed, which showed the continuous transition between the supersonic combustion and the subsonic combustion, and the isolator still operated until the 1-D thermal choke condition.

For the combination of the vent mixer and the plasma torch igniter, low enthalpy air and the fuel was forced to ignite with high combustion performance, and the isolator, whose length was shorter than that of previous experimental studies [4, 5], was operated well within the limit of the 1-D thermal choke limit.

This study suggests the possibility to approach the optimal hypersonic vehicle because the mixer with high mixing efficiency can sustain the supersonic combustion by using the igniter during the low flight Mach range. It is possible to reduce the length of the isolator in the supersonic combustion. To analyze the performance of the vent mixer in detail, the additional experiments and computational analyses were scheduled and would be conducted in near future.

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