A Study of Combustion Mode Transition using a New Supersonic Mixer in Dual-Mode Scramjet Engine

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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. So, 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].

In the supersonic combustion, 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]. 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 diffusion of fuel [6]. Considering these factors, a new mixer, its name is vent mixer, is designed and manufactured in this work. A distinguishing feature of the vent mixer compared with other previous mixers is vent on the extended wall. Inflow through the vent may run into the recirculation region, which increases the circulation velocity and extends the recirculation region. And a lot of vortices can be developed due to the interaction between the inflow air and the wall or the parallel injected fuel.

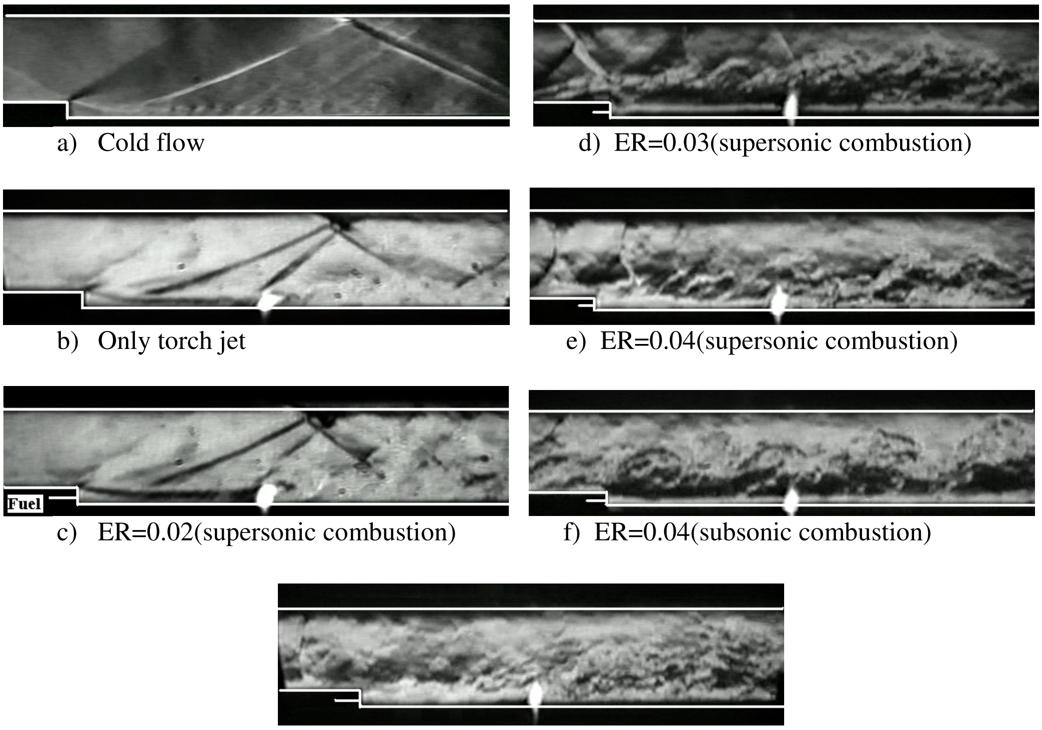
The present study was the first time that has been demonstrated the performance characteristics of the invented new mixer with the plasma torch igniter in the unheated inflow Mach 2 of the supersonic combustor models. Hydrogen was used as fuel and the wall pressure measurement and schlieren imaging method were taken to determine the combustion mode. And the new isolator design was conducted and was integrated with the supersonic combustor. The Billig's paper [1] was referred to define the terms in this paper.

$$S = \frac{2\sqrt{H\theta}}{(M_1^2 - 1)Re_\theta^{0.25}}\left[50\left(\frac{P_2}{P_1} - 1\right) + 170\left(\frac{P_2}{P_1} - 1\right)\right]$$

2 Combustion mode transition using Vent Mixer

Combustion mode with the SM

For the plasma jet injection, shock wave is developed ahead of the PJ torch in Fig. 1b. The large



a) Cold flow
d) ER=0.03(supersonic combustion)
b) Only torch jet
e) ER=0.04(supersonic combustion)
c) ER=0.02(supersonic combustion)
f) ER=0.04(subsonic combustion)
g) ER=0.06(subsonic combustion)

Fig. 1 Instantaneous schlieren images along ER with SM

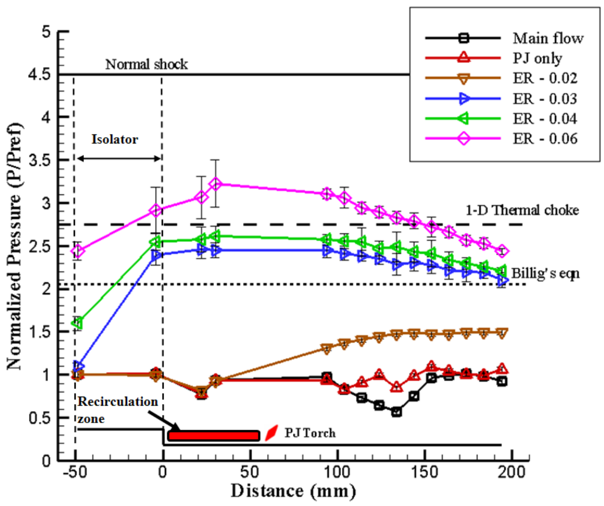
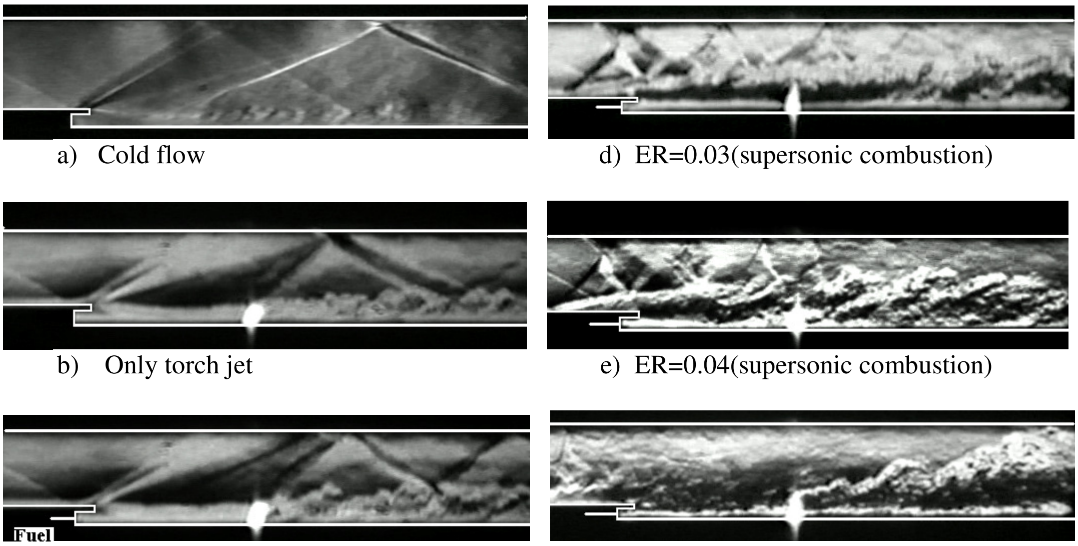


Fig. 2 Pressure distribution along streamwise direction with SM

separation bubble occurs on the upper wall in Fig. 1b, which is developed by colliding of oblique shock wave from the PJ torch. For ER=0.02, the upstream pressure difference is little between ER=0.02 and plasma torch jet condition, in Fig. 2. In Fig. 1c, the parallel fuel injection heightens 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. 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. 1c. 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 spread by high pressure due to heat release and the intensive combustion mode is attained. 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. 1d. While the onset of the shock train is oscillating in the isolator, the pressure is fluctuated in Fig. 2. Below ER=0.03, inflow Mach number at the combustor inlet is still supersonic flow in Fig. 1c, d, that means the "supersonic combustion". For ER=0.04, normalized pressure increases over the Billi's pressure ratio line and still distributes below the 1-D Rayleigh flow analysis in Fig. 2. 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. And then, the inflow to the combustor is frequently changed between subsonic and supersonic according the combustion back pressure in Fig. 1e, f. This can be called the "dual-mode" transition which depicts both dual-mode transition to subsonic due to the pressure increase associated with the combustion and dual-mode transition to supersonic because the heat release is alleviated in the combustor. For ER=0.06, normalized pressure 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. 1g. The combustor inflow is subsonic and the combustor is operating in the subsonic combustion mode.



a) Cold flow
d) ER=0.03(supersonic combustion)
b) Only torch jet
e) ER=0.04(supersonic combustion)
c) ER=0.02(supersonic combustion)
f) ER=0.04(subsonic combustion)

Fig. 3 Instantaneous schlieren images along ER with VSM

Combustion mode with VSM

The inclination of the PJ torch light in Fig. 3b is similar with that of the SM when plasma jet is injected case in Fig. 3c. This indicates that the recirculation region between the VSM and the PJ torch is developed because the vent, which works as air injector into the recirculation region, extends the recirculation region which meets the hot upstream flow of the plasma jet. For ER=0.02, pressure distribution ahead of the PJ torch increases a little in Fig. 4, which is associated with the combustion. The supersonic combustion is governed by the mixing rate. In the hot mixing region, air through the vent interacts with the injected fuel, which increases the mixing rate and induced the ignition in the mixing region. For ER=0.03, the combustion pressure affects the isolator, and this is still supersonic combustion mode because the peak pressure does not go over the 1-D thermal choke line in Fig. 4. The shock train does not reach the nozzle exit in Fig. 4, and the inflow to the combustor is supersonic because the oblique shock train exists in the combustor in Fig. 3d. For ER=0.04, inlet pressure ratio on the isolator exceeds over the designed Billig's pressure ratio and this is the dual-mode operation because the pressure distribution is still under the 1-D thermal choke condition. In Fig. 3e, f, the

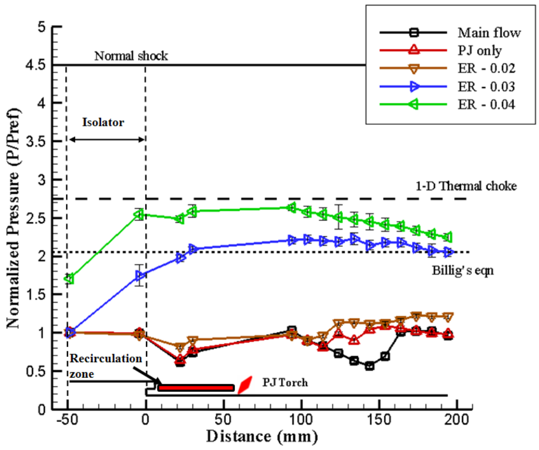


Fig. 4 Pressure distribution along streamwise direction with VSM

combustor mode is frequently changed between the supersonic combustion and the subsonic combustion. The transition of the combustion mode of the VSM is earlier than that of the SM for same ER. For dual-mode transition and subsonic combustion, the pressure error bar is large in the isolator and the around upstream flow of the combustor with the SM, in Fig. 2. The fluctuation of shock-train in the isolator has an effect to the combustor and this makes the combustor unstable in the DMSJ [3]. By the way, the pressure distribution of the VSM in Fig. 4 is different with that of the SM. Although there is fluctuation in the isolator, the error bar of the combustion pressure at the upstream region of the combustor 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

When integrated with 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 condition.

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