Interaction between Combustion and Shock Wave in Supersonic Combustor

Lihong Chen, Fei Li, Tian Wan, Zhi Li, and Hongbin Gu

1 Introduction

Interaction between shock wave and combustion is very important for supersonic combustion. For scramjet, isolator is a key element to withstand the high pressure due to combustion and to avoid the unstart of the inlet. Therefore, the flow is very complex in isolator and combustor because of the interaction between combustion and shock wave. Usually, there are two modes of combustion in scramjet: supersonic mode and subsonic mode. Many researches have already shown how to achieve dual-mode scramjet to obtain better engine performance [1] [2] [3].

However, the mechanism of dual-mode combustion is still unclear. In this paper, experimental and numerical investigations were attempted for better understanding of the dual-mode combustion for scramjet applications.

2 Methodology

The experiments were performed in the direct-connected supersonic combustion test facility, of which the inlet vitiated air with high temperatures and high pressures was prepared by burning hydrogen and then supplying oxygen. Fig.1 was the schematic of the facility where the flow direction is from left to right, and Fig.1(a) is a side-view and Fig.1(b) is a topview. It consisted of heater, supersonic nozzle, isolator, combustor and exhaust. The Mach number of the main flow at the inlet of the isolator was Mach 1.8 and 2.5 respectively. The fuel was ethylene, and injected into the main flow upstream of the two cavities as indicated in the figure.

The optical windows were settled at four positions, corresponding to the entrance, the cavity 1, 2, and the exit. Three types of optical measurements: schlieren, TDLAS

Lihong Chen · Fei Li · Tian Wan · Zhi Li · Hongbin Gu
Key Laboratory of High Temperature Gas Dynamics
Institute of Mechanics, Chinese Academy of Sciences
No.15 Beisihuanxi Road, Beijing 100190, China

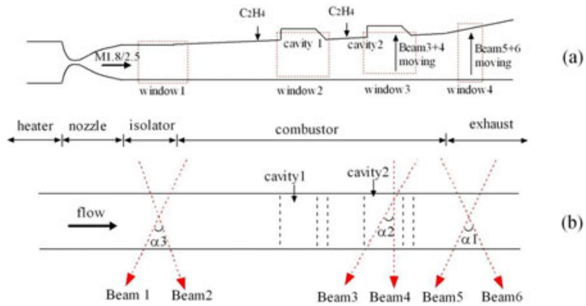

Fig. 1 Direct-connected SCRAMJET test facility.

[4] (Tunable Diode Laser Absorption Spectroscopy) and CH emission were applied in the experiment. The schlieren pictures and CH images were taken by a high-speed camera. As shown in Fig. 1, there are six beams of TDLAS used, to measure the static temperature, the velocity and the H_2O concentration of the combusted gas.

The static pressures along the central line were measured, which gives a pressure distribution along the combustor.

The full unsteady Navier-Stokes equation was solved by using data-parallel line relaxation [5]. Menter's k-ω with a compressibility correction for high Mach number flow was used for the simulation of the turbulence. The convective terms of the governing equations are calculated with a third-order upwind MUSCL-TVD scheme, and the diffusion terms are discretized with a second-order central scheme. The unsteady term is approximated with a second-order scheme, and dual time-step method was used. The reaction mechanism for ethylene is a 10 species, 8 step reduced mechanism [6].

3 Results and Analyses

Based on the experimental and numerical results, three modes of the interaction between combustion and shock wave can be observed. The first is the supersonic mode, which the main flow remains supersonic but the reaction zone is subsonic. The second is the subsonic mode, of which the flow downstream of the shock waves is fully subsonic. The third is the oscillation mode, i.e. the flow pattern changes between subsonic and supersonic with a frequency.

Fig.2 - 4 shown the typical results for the supersonic mode. Fig.2 shown the steady results. Fig.2(a) was the static pressure along the central line of the wall. The isolator was from $x = 0$ to $x = 400$ mm. In the region of $x < 400$ mm, the pressure distribution kept unchanged after combustion, but the pressure of $x > 400$ mm increases due to combustion. The static temperature profile at exit was shown in Fig.2(b), which was measured by TDLAS scanning. The position $H = 0$ denotes the wall with fuel injections and cavities. As shown in Fig.2(b), the temperature was not uniform and gives a peak of approximately 1400K at a location closer to the wall

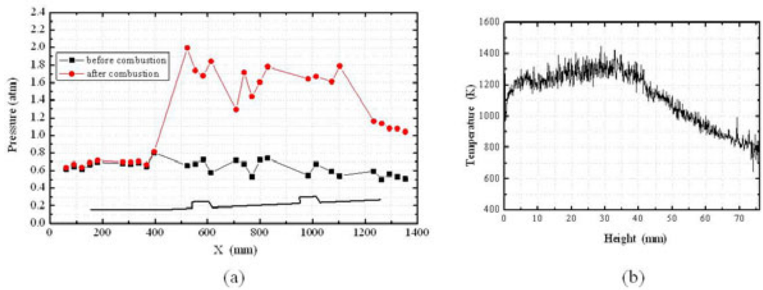

Fig. 2 Typical Profile for supersonic combustion mode; (a): Static pressure distribution along central line; (b): Static temperature at exit.

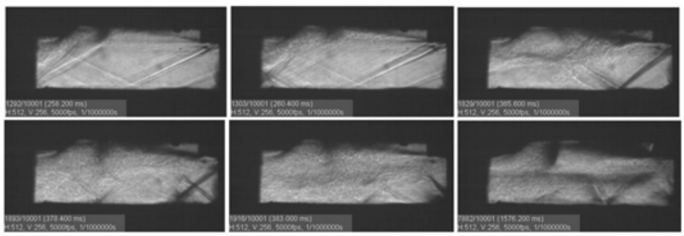

Fig. 3 Schlieren pictures at different moments (from optical window 2).

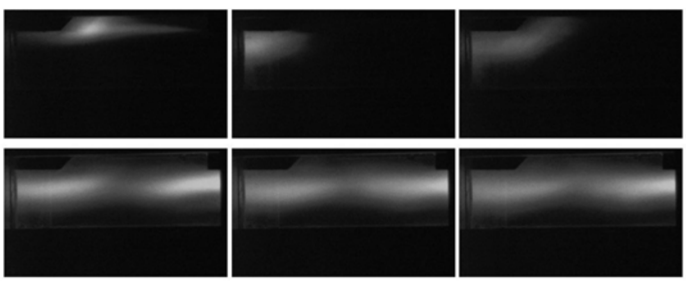

Fig. 4 CH (430nm) emission pictures at different moments (from optical window 2).

with cavities. It implies the combustion occurs only in the vicinity of the wall with fuel injection and cavity.

Fig.3 and Fig.4 demonstrates the establishment of the steady state as a function of time. Fig.3 was the schlieren pictures at different moments. The pictures were taken from optical window 2, as shown in Fig.1. The flow direction is from right to left. The cavity is on the top. The combustion started at the trailing edge of the cavity, as shown in image 1 of Fig.3. Then the main flow was compressed due to the pressure rise inside the cavity. The flow near the cavity then slowed down, which enhances the fuel/air mixing and reaction. The pressure inside the cavity increased further to push shock waves further upstream. Finally, the shock waves and the combustion approached a balance and a steady state was established. In this supersonic mode, the reaction occurs in a limited region near the cavity and the main flow remained supersonic. This flow change can also be shown in Fig.4 with the results of CH emission at different moments. Since CH is a very active radical, the intensity of the CH emission can be used to indicate the reaction zone. It is clearly shown in Fig.4 that the combustion started from the trailing edge of the cavity, and finally stabilized on the leading edge.

If the reaction is strong enough, the supersonic combustion would not be sustained. Fig.5-7 show the typical results for subsonic combustion mode.

Fig. 5 is the numerical schlieren images of the starting process. The flow direction is from left to right. The first image shows the original shocks generated by the fuel injection and cavity. Then the fuel ignited and caused the high temperature zone inside cavity. This zone expanded and compressed the main flow, causing the expansion wave at the leading edge of the cavity turns to a oblique shock. This shock propagated upstream due to the combustion, and finally, the oblique shock wave moved into the isolator and the downstream flow became subsonic.

Fig.6 is the related experimental schlieren pictures. In first image, there was only the bow shock induced by the fuel injection. After ignition, the pseudo-shock waves were generated. This shock train moved upstream as the combustion continues. Finally, the shock was moved further upstream and no shock wave can be observed in the window, which corresponds to the subsonic combustion mode.

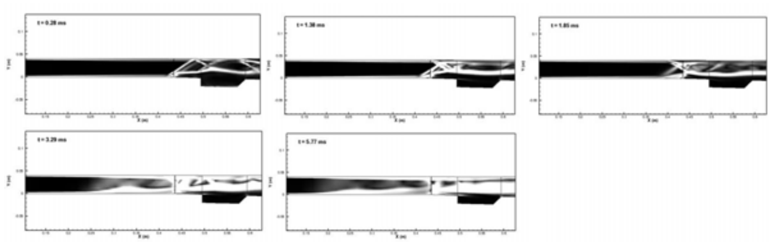

Fig. 5 Numerical schlieren pictures at different moments.

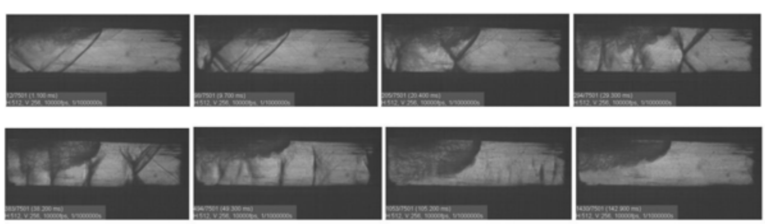

Fig. 6 Schlieren pictures at different moments (from optical window 1).

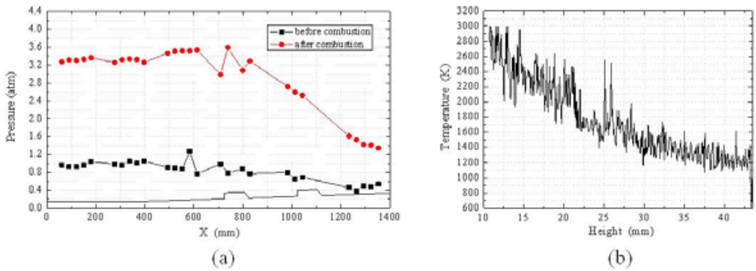

Fig. 7 Typical Profile for subsonic combustion mode; (a): Static pressure distribution along central line; (b): Static temperature at exit.

After the flow reaches a steady state, the pressure distribution of the subsonic mode is completly different from that of the supersonic mode. As shown in Fig.7(a), the pressure is very high in the isolator which indicates the existence of the shock waves. Fig.7(b) gives the static temperature at exit. Compared to the value without combustion, the temperature increases significantly, which indicates a high efficient reaction. Because it was subsonic mode, the static temperature was close to the total temperature, so the temperature was much higher than that of the supersonic mode as shown in Fig.2(b).

Between the above two stable combustion modes, there is an unsteady mode, so called the oscillation mode. In this case, because the combustion was not intensive enough to support the high pressure level, the shock train would oscillate upstream and downstream. The TDLAS results at optical window 1 are shown in Fig.8 and an oscillation at a frequency is obvious. The base line corresponds to the supersonic entrance, which has a lower static temperature, lower H_2O concentration, and higher velocity. In supersonic combustion mode, the reaction does not affect the upstream,

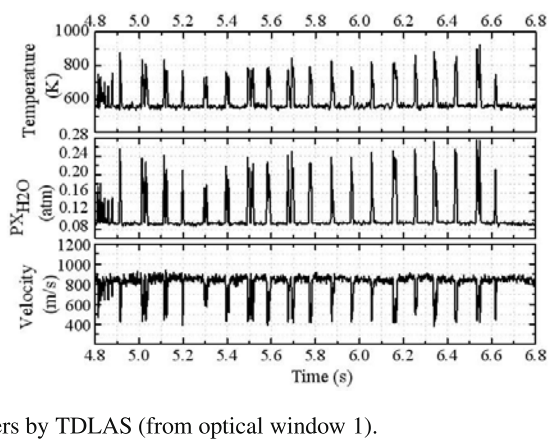

Fig. 8 Parameters by TDLAS (from optical window 1).

so the parameters remained the original supersonic entrance condition. The peaks in Fig.8 are related to the subsonic mode. Because of the movement of the shock, the temperature and H_2O concentration increased but the velocity decreased. Fig.8 also shows that the frequency of such an oscillation was almost a constant, which was about 10Hz.

4 Conclusion

In terms of the experimental and numerical investigations, the following conclusions can be drawn:

(1) The strength competition between combustion and compression is the major factor to determine different modes in scramjet.
(2) When the combustion is strong enough, the main flow is compressed, and the shock wave propagates upstream and generates a subsonic mode.
(3) When the reaction only occurred in a limited region, the flow may be divided into two parts: supersonic main flow with shock trains and subsonic reaction zone.
(4) When the combustion is not strong enough, the oscillation would happen. The flow mode would change between supersonic and subsonic.

The project is supported by the National Natural Science Foundation of China (11002148 and 10772188).

References

1. Eklund, D.R., Baurle, R.A., Gruber, M.R.: Numerical Study of a Scramjet Combustor Fueled by an Aerodynamic Ramp Injector in Dual-Mode Combusion. AIAA Paper 2001-0379
2. Choi, B., Goto, M., Mizushima, H., Masuya, G.: Effects of Heat Addiction and Duct Divergence on Pseudo-shock Waves, ISABE-2007-1235
3. Suguyama, H., Tsujiguchi, Y., Honma, T.: Structure and Oscillation Phenomena of Pseudo-Shock Waves in a Straight Square Duct at Mach 2 and 4, AIAA 2008-2646
4. Yu, X.L., Li, F., Chen, L.H., Chang, X.Y.: Spatial resolved temperature measurement based on absorption spectroscopy using a single tunable diode laser. Acta Mechanica Sinica 26, 147–149 (2010), Technical note
5. Wright, M.J., Bose, D., Candler, G.V.: A Data-Parallel Line Relaxation Method for the Navier-Stokes Equations. AIAA Journal 36(9), 1603–1609 (1998)
6. Mawid, M.A., Sekar, B.: Kinetic Modeling of Ethylene Oxidation in High Speed Reacting Flows. AIAA Paper 1997-3269