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Visualization of Vaporized Kerosene Combustion in a Supersonic Combustor Using Pulsed Schlieren System

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A pulsed schlieren system using a nanosecond-flashlamp has been developed to study the flow-field of supersonic combustion. A high speed camera was used to capture the instantaneous flow structures. The camera and the flash-lamp source were synchronized using a pulse generator. Due to the extremely high luminous density of the spark, the background illumination has been suppressed effectively with an exposure time of order of microsecond. The instantaneous schlieren images of injection and combustion of pilot hydrogen and vaporized kerosene in a Ma 2.5 combustor have been captured and analyzed.

Keywords: pulsed schlieren, supersonic combustion, Supercritical kerosene

I. Introduction

FLOW visualization is very important for understanding the process of supersonic combustion. Flow in a supersonic combustor is highly unsteady due to the turbulence and wave interactions. High speed capture system is required to visualize the instantaneous flow field. The background radiation from the combustion is very intensified, which should be eliminated to the great extent in order to obtain clear images. The high gas temperature in the combustor also brings difficulties in the protection of optical windows.

Schlieren photography has been widely employed to visualize the processes of fuel injection,[1-5] fuel-air mixing,[6-8] fuel ignition,[9,10] flame holding,[11-13] shock/boundary interaction,[14-17] etc. However, few literatures could be found for the visualization of the combustion process in a scramjet combustor. Kumasaka et al.[16] used schlieren system to record the ignition processes of hydrogen and methane. Only averaged flow-field structures had been obtained because relatively long exposure time was used, and the background illumination was not completely eliminated. Pan et al.[18, 19] studied the flow-field of kerosene combustion using a high speed schlieren system. A semiconductor continuous laser was used as light source, and a 532 nm single pass filter was installed before the image recorder to partially eliminate the combustion radiation. However, interference fringes appeared in the images due to the coherence of laser.

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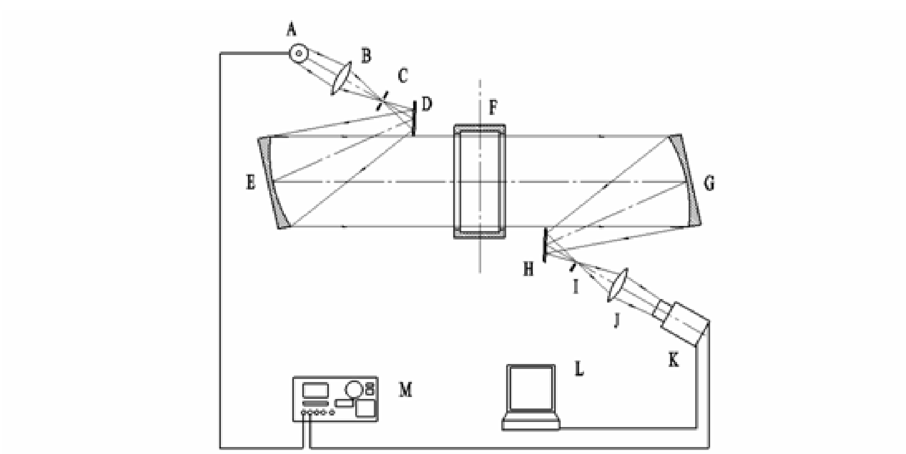
In this paper, a high speed pulsed schlieren system was developed. A nanosecond-flashlamp was used as light source. Compared to the high flash energy, the background radiation could be neglected if exposure time of microseconds was used. The flashlamp was synchronized with a high speed camera using a pulse generator. A short exposure time was chosen to freeze the instantaneous flow field. Using this schlieren system, the flow structures of injection and combustion of pilot hydrogen and supercritical kerosene were studied in a Ma 2.5 combustor.

II. Experimental Setup

A. Pulsed Schlieren System

A Z-type optical arrangement of the pulsed schlieren system is shown in Fig.1. Nanolite Nanosecond-flashlamp (KL-L) is used as the light source, which is controlled by Ministrobokin 20 high speed flash driver (High Speed Photo-System, Ltd.). It has a repetition rate up to 20 kHz and a flash duration less than 25 ns. Each pulse outputs a flash energy of 25 mJ. A high speed digital camera (PCO.1200hs) is used to capture the schlieren images. The camera has the shortest exposure time of 1 μs and the maxmium frame rate of 31250 fps. A 9514-type pulse generator (Quantum Composers, Inc.) is used to synchronize the flashlamp with the high speed camera.



A. spark flash lamp B. lens C. slit D. reflector1 E. parabolic mirror1 F. test section G. parabolic mirror2 H. reflector2 I. knife edge J. lens K. high speed digital camera L. computer M. pulse generator

Fig.1 The pulsed schlieren system optical arrangement

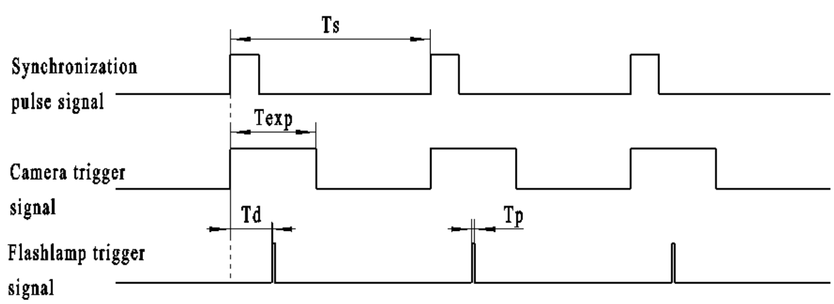


Fig.2 The control signal sequence of the pulsed schlieren system (T_s: Acquisition cycle time, T_{exp}: Exposure time, T_d: Delay time, T_p: Pulse duration of the flashlamp)

Figure 2 shows the control signal sequence of the pulsed schlieren system. At the beginning of each acquisition cycle, pulse generator sends one pulse to trigger the high speed camera, and after a delay T_d of 15 μs, sends another pulse to trigger the flashlamp. The camera's exposure time *Texp* is 30 μs. .

Figure 3 explains the method used to eliminate the background radiation from the combustion. The luminous density of the spark from the flashlamp is several order of the magnitude higher than the background combustion radiation, and thus, within a very short time of exposure, the integral effect of background radiation could be neglected.

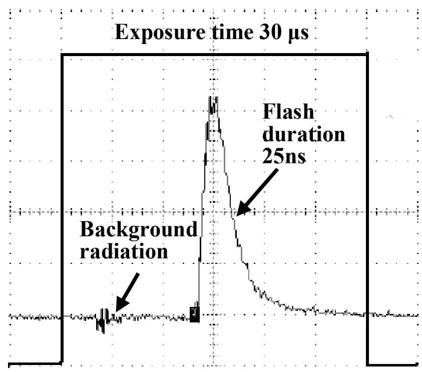


Fig.3 The theoretic diagram for eliminating the background radiation from the combustion

B. Test Facility

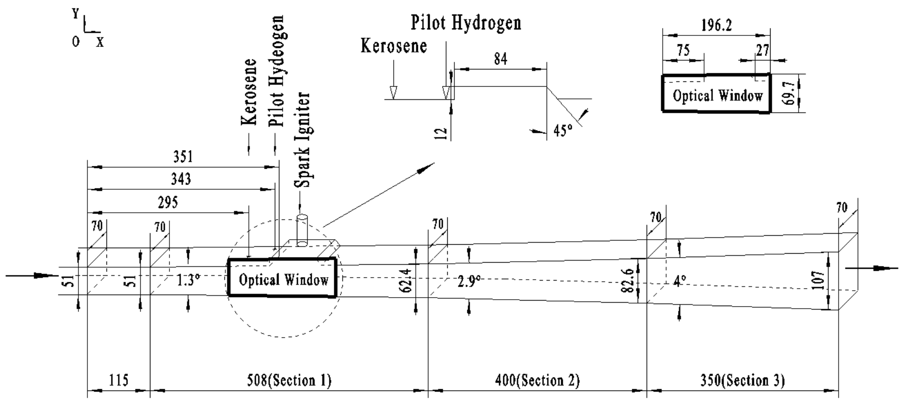


Fig.4 Schematic of supersonic model combustor (mm)

The flow visualization experiments were conducted in a Ma 2.5 direct-connect wind tunnel facility[20], which consists of a vitiated air supply system, a multi-purpose supersonic model combustor, a fuel delivery and heating system. The vitiated air heater, burning with hydrogen, oxygen, and air, was used to supply heated airflow. The air supply system was capable of supplying heated air at stagnation temperatures of 800-2100 K and stagnation pressures of 0.6-2.5 MPa. Supercritical kerosene at temperature 780 ± 20 K and pressure 4.0-6.0 MPa was prepared using a home-made two-staged kerosene heating and delivering system as described in ref. 21. The model combustor with a total length of 1373 mm is shown in Fig.4. It is composed of four sections, including one nearly constant-area section with a cross section of 51 mm in height and 70 mm in width and three divergent sections. The divergence angles of three divergent sections are 1.3°, 2.9° and 4°, respectively. An interchangeable integrated fuel injection/flameholder cavity module is installed on the one side of the combustor. The cavity has the depth of 12 mm , a 45°aft ramp angle, and an overall length to depth ratio of 7. There are one 4 mm diameter orifice designed for supercritical kerosene injection and two 2.5 mm diameter orifices for pilot hydrogen injection. Both supercritical kerosene and pilot hydrogen are transversely injected into the airflow upstream of cavity. For light access and observation, a pair of quartz windows is installed on both sides of the combustor near the location of cavity module. The geometry of the quartz window is as shown in Fig.4.

The stagnation pressure and temperature of the vitiated air were respectively measured by using a CYB-10S pressure transducer (accuracy ±0.1%, Beijing ZhongHangJiDian Technology Co. Ltd, China) and a Type-B thermocouple. The distribution of static pressure in the axial direction was determined by Motorola MPX2200 pressure transducers. Pressure measurement locations along the centerline of the test section are shown in Fig.5.

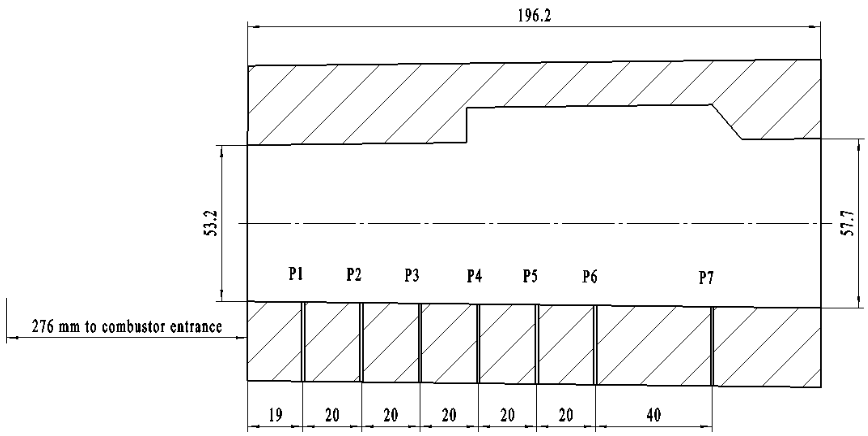


Fig.5 The field of view of schlieren and Pressure transducer positions (mm)

III. Results and Discussion

In order to avoid damaging the optical window, low air stagnation temperature of 1250 K was chosen in the experiments. The air stagnation pressure was kept at 10 atm. The temperature and pressure of supercritical kerosene were 764 K and 38 atm, respectively. The equivalence ratios of pilot hydrogen and supercritical kerosene were 0.08 and 0.384, respectively.

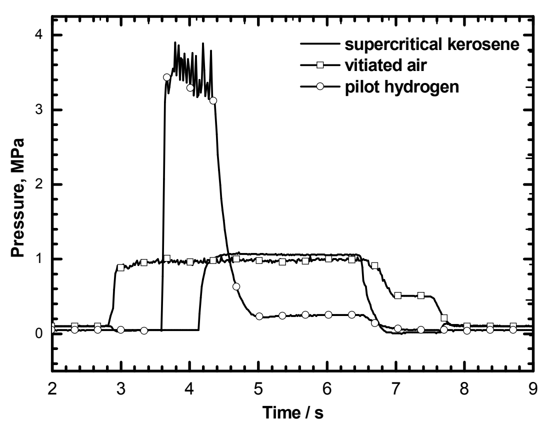
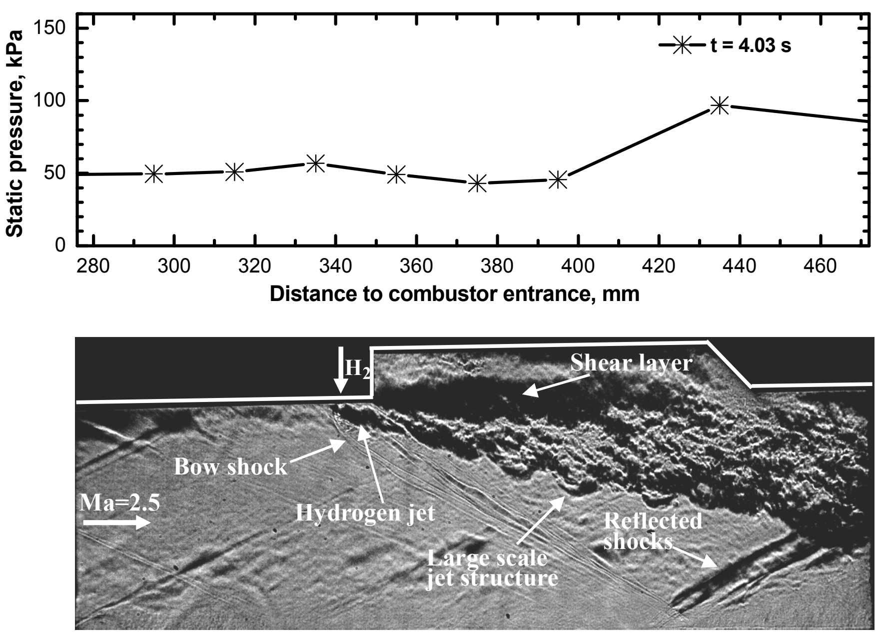


Fig.6 Stagnation pressure curves of pilot hydrogen, supercritical kerosene and vitiated air during the experiment

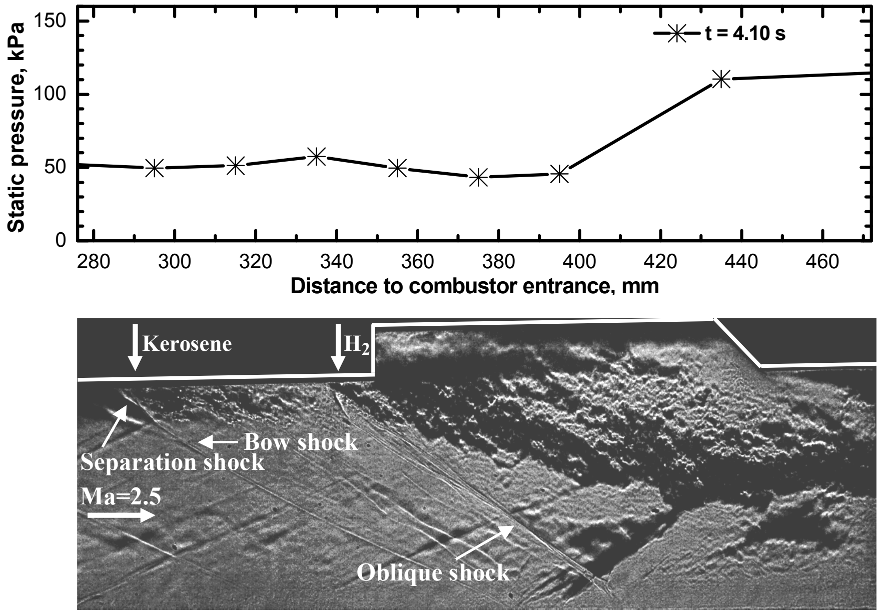
Figure 6 shows the stagnation pressure curves of pilot hydrogen, supercritical kerosene and vitiated air during the experiment. A steady Ma 2.5 airflow was established at approximately 3.0 s and lasted about 3.5 s. Pilot hydrogen was injected at about 3.5 s and shut off completely at 5.0 s. Supercritical kerosene was injected at 4.1 s and shut off at about 7.1 s.

Figure 7 shows the schlieren images at different stages of combustion. At the time of 4.03 s, the pilot hydrogen had been injected and ignited (Fig.7a). A bow shock developed ahead of the injector. It is reflected at the opposite of the combustor. Large scale vortex structures are visible at the edge of the hydrogen jet, which play an important role for mixing enhancement of fuel and air. The shear layer between the main flow and recirculation zone in the cavity can also be identified.

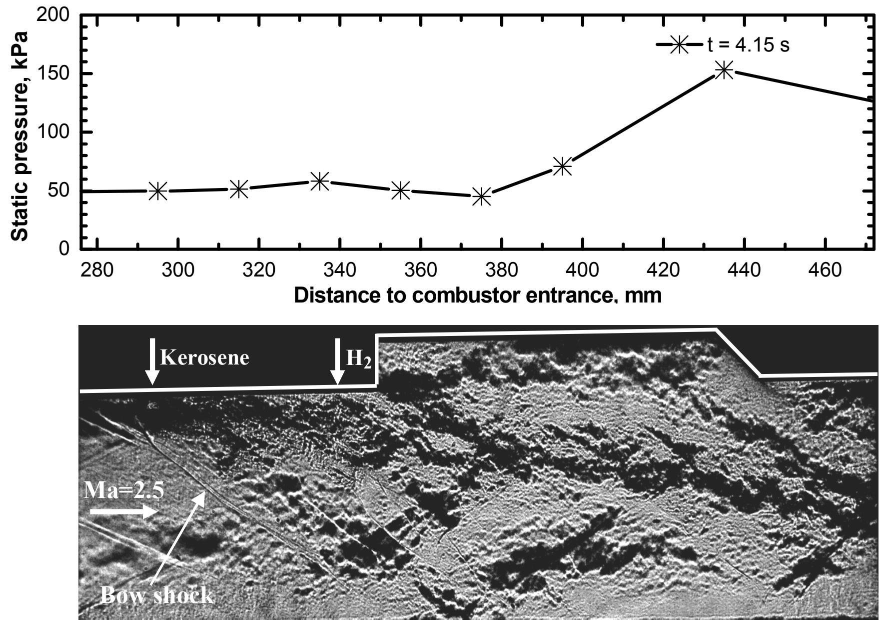
Supercritical kerosene was injected at 4.10 s, as shown in Fig.7b. A bow shock appeared ahead of the kerosene injector. The bow shock caused the upstream boundary layer separation and formed a separation shock. The supercritical kerosene was ignited by pilot hydrogen at the downstream. As the combustion processes, the combustor pressure increased, the strength of bow shock was enhanced and the angle of bow shock also increased, and the flow structure in combustion region was very complicated (Fig.7c). When compared with the fuel pressure in Fig.6, the amount of fuel injected into the combustor was few at 4.159s and static pressure rise was small. At the time of 4.42s, the kerosene flow rate and the combustion pressure reached the maximums. The bow shock was pushed out of the field of view. The kerosene penetration increased significantly due to decrease in flow speed (Fig.7d).



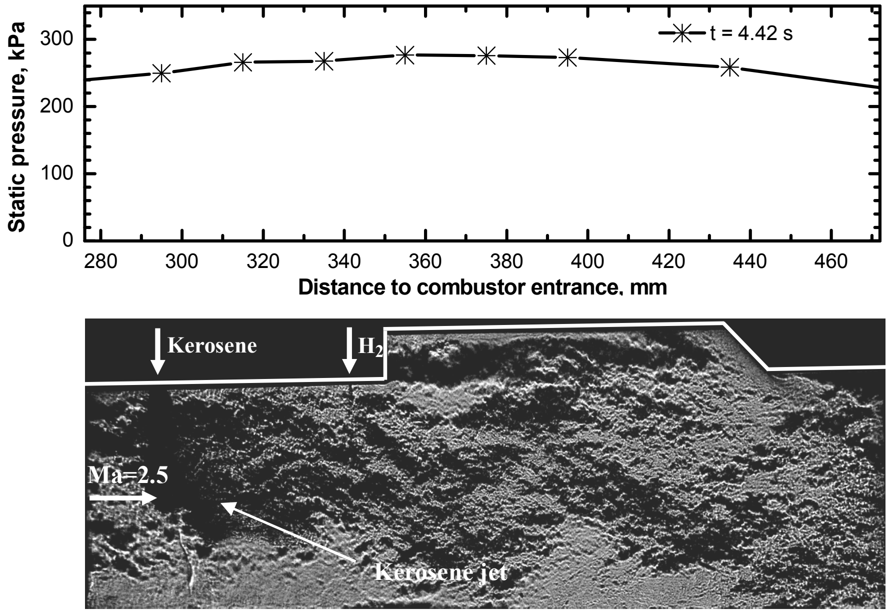
(a) t = 4.03 s



(b) t = 4.10 s



(c) t = 4.15 s

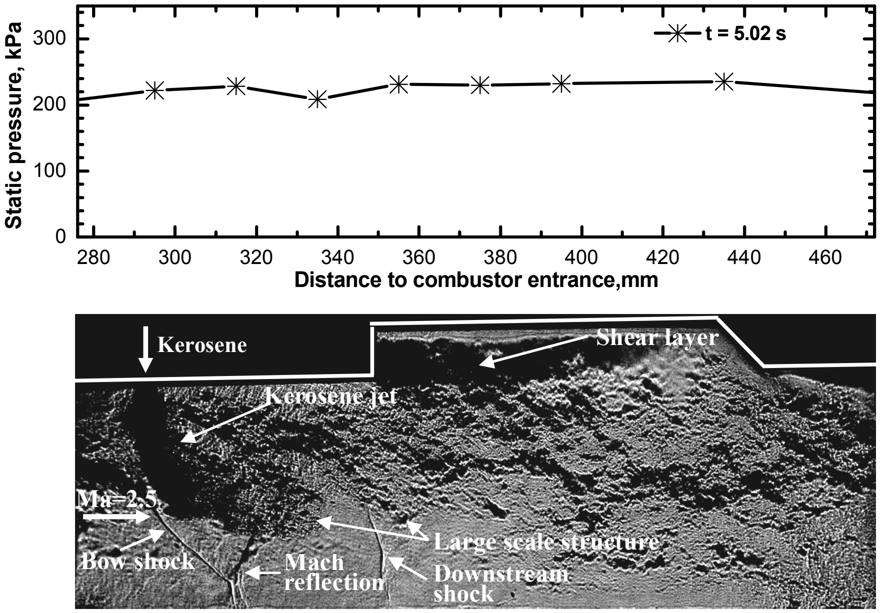


(d) t = 4.42 s

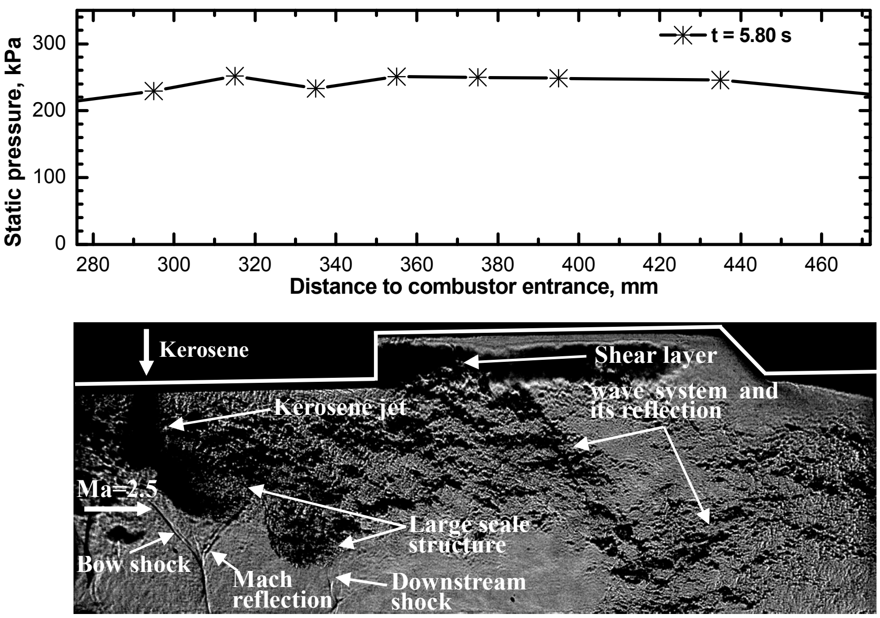
Fig.7 Schlieren images at different stages of combustion and the wall static pressure distributions along the top wall

Figure 8 displays the schlieren images at t = 5.02 s and 5.80 s, when only kerosene combustion occurred in the combustor. Compared to Fig.7d, with the pilot hydrogen shut off, the bow shock ahead of the kerosene injector came back. In order to match the high pressure in combustor, Mach reflection of the bow shock occurred at the opposite wall of the combustor. The flow after Mach reflection was also supersonic and some shock could still be observed downstream the reflection. The interaction of kerosene jet and crossflow generated large scale vortex structures. It is interesting to note that a wave system and its reflection can be identified inside the jet-shear layer (Fig.8b), which indicates that the flow in this region is supersonic. In contrary, no such wave system exists in Fig.8a, although the experimental conditions were similar in both cases. It can be inferred that the flow in this jet-shear layer was unsteady and its Mach number was very close to 1.0.

The wall static pressure distributions at 5.02 s and 5.80 s are similar as shown in Fig.8. The pressures increased from 295 mm and 315 mm due to bow shock and its Mach reflection. The pressures decreased from 315 mm to 335 mm, which indicates that some expansion existed downstream the Mach reflection. The pressure rises between 335 mm and 355 mm were due to the downstream shock as shown in the schlieren images.



(a) t = 5.02 s



(b) t = 5.80 s

Fig.8 Schlieren images at t = 5.02 s and 5.80 s and the wall static pressure distributions along the top wall

IV. Conclusion

A high speed pulsed schlieren system was developed. A nanosecond-flashlamp was used as light source. Compared to the high flash energy, the background radiation could be neglected if exposure time of microseconds was used. The flashlamp was synchronized with a high speed camera using a pulse generator. A short exposure time was chosen to freeze the instantaneous flow field.

Using the pulsed schlieren system, combustion of pilot hydrogen and vaporized kerosene were visualized in a Ma 2.5 model combustor. High quality schlieren images of the flow-field and their evolution were obtained. Bow shock wave and its reflection of fuel jet, downstream shock wave, large scale jet-shear layer structures and shear layer between main flow and cavity flow have been identified clearly. Existence of supersonic combustion was confirmed for vaporized kerosene equivalence ratio of 0.384 by schlieren visualization in this Ma 2.5 combustor.

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References

[1] Aguilera, C., Peng, B., and Yu, K. H., "Fin-Guided Liquid-Feul injection ito March 2.1 Airflow," *AIAA 2011-5763*, 2011.

[2] Kim, C. H., and Jeung, I. S., "Effect of Fuel Injection Locations with Hyper Mixer in Supersonic Combustion," *AIAA 2011-5830*, 2011.

[3] Schranmm, J. M., Karl, S. and, Hnnemann. K., "Ground Testing of the HyShot II Scramjet Configuration in HEG," *AIAA 2008-2547*, 2008.

[4] Fan, X. J., Yu, G., Li, J. G., and Zhang, X. Y., "Investigation of Vaporized Kerosene Injection and Combustion in a Supersonic Model Combustion," *Journal of Propulsion and Power*, Vol.22, No.1, 2006, pp. 104-110.

[5] Lavante, E. V., Zeitz, D., and Kallenberg, M., "Numerical Simulation of Supersonic Airflow with Transverse Hydrogen Injection," *Journal of Propulsion and Power*, Vol.17, No.6, 2001, pp. 1319-1326.

[6] Kondo, A., Sakaue, S., and Arai, T., "Fluctuation of Mass Flux and Concentration on Supersonic Mixing using Streamwise Vortices," *AIAA 2008-2535*, 2008.

[7] Kim, C. H., Jeong, E., Kim, J. W., and Jeung, I. S., "Mixing and Penetration Studies of Transverse Jet into a Supersonic Crossflow," *AIAA 2007-5420*, 2007.

[8] Bonanos, A. M., Jeffrey, M., and Dimotakis, P. E., "Molecular Mixing and Flowfield Measurements in an Expansion-Ramp Combustion: Supersonic Flow," *AIAA 2007-5417*, 2007.

[9] Tomoaki, K., Atsushi, M., Kenichi, T., and Goro, M, "Ignition Characteristics of Methane and Hydrogen Using a Plasma Torch in Supersonic Flow," *Journal of Propulsion and Power*, Vol. 19, No.5, 2003, pp. 853-858.

[10] Koichi, M., Aya, N, Kenichi, T., and Goro, M, "Ignition Characteristics of Hydrocarbon Fuels by Plasma Torch in Supersonic Flow," *AIAA 2003-6939*, 2003.

[11] Song, J., Jung, C, Hwang, J., and Yoon, Y. "An Experimental Study on the Flame Dynamics with V-Gutter Typer Flameholder in the Model Combustor" *AIAA 2011-6126*, 2011.

[12] Leonov, S., and Yaeantsev, D., "Eeperiments on Electrically Controlled Flameholding on a Plane Wall in Supersonic Airflow," *Journal of Propulsion and Power*, Vol. 25, No.2, 2009, pp. 289-294.

[13] Rasmussen, C. C., and Driscoll, J. F., "Characteristics of Cavity-Stabilized Flames in a Supersonic Flow," *Journal of Propulsion and Power*, Vol. 21, No.4, 2005, pp. 765-768.

[14] Estruch, D., Lawson, N. J., MacManus, D. G., Garry, K. P., and Stolley, J. L. "Measurement of Shock Wave Unsteadiness using a High-Speed Schlieren System and Digital Image Processing," *Review of Scentific Instruments*, Vol. 79, 126108, 2008.

[15] Sugiyama, H., Tsujiguchi, Y., and Honma, T., "Structure and Oscillation Phenomena of Pseudo-Shock Wave in a Straight Square Duct at Mach2 and 4," *AIAA 2008-2646*, 2008.

[16] Tsuyoshi, K., Noritaka, I., Goro, M., and Kenichi, T, "Influence of Combustion on Behavior of Pesudo-Shock Wave," *AIAA Paper 2003-6912,* 2003.
[17] Ferry F, J. Schrijer., Fulvio, S., and Bas W, Van Oudheusden. "Experiments on Hypersonic Boundary Layer Separation and Reattachment on a Blunted Cone-Flare using Quantitative InfraRed Thermography,". *AIAA Paper 2003-6967,* 2003.
[18] Pan, Y., Tan, J. G., Liang, J. H., Liu, W. D., and Wang, Z. G., "Experimental Investigation of Combustion Mechanisms of Kerosene-Fueled Scramjet Engines with Double-Cavity Flameholders," *Acta Mech. Sin*, Vol. 27, No. 6, 2011, pp 891-897.
[19] Pan, Y., Lei, J., Tan, J. G., Liang, J. H., and Wang, Z. G., "Experimental Investigation on the Combustion Oscillation in a Model Scramjet Engine," *ISABE 2011-1528,* 2011.
[20] Fan, X. J., Zhong, F. Q., Yu, G., Li, J. G., and Sung, C. J., "Catalytic Cracking and Heat Sink Capacity of Aviation Kerosene under Supercritical Conditions," *Journal of Propulsion and Power,* Vol. 25, No. 6, 2009, pp.1226-1232.
[21] Fan, X. J., and Yu, G., "Experiments on Supersonic Combustion of Supersonic Kerosene," *Journal of Propulsion Technology*, Vol. 27, No. 1, 2006, pp. 79-82.