SPARK IGNITION PROCESS IN A SCRAMJET COMBUSTOR EQUIPPED WITH MULTI-CAVITIES AT MACH 4 FLIGHT CONDITION

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Abstract

The spark ignition process in the scramjet combustor equipped with multi-cavities at Mach 4 flight condition fueled by hydrogen was observed by the high speed camera and Schlieren system, at the inflow conditions of Ma=1.92, T_0=846K, P_0＝0.7MPa. The spark generation, the flame spreading and shock structures in the combustor with different ignition setups were captured. The results revealed that spark generates near the igniter, and grows to form flame in the cavity. The initial flame spreads along the cavity shear layer and ignites the fuel distributed downstream very quickly. With the pressure downstream rises up, the pre-combustion shock and the flame go against the stream and finally the whole fuel jet flame is ignited and stabilized. The expand angle of the upper wall and the disturbance caused by the upstream cavity have an obvious effect on the fuel diffusion and convection into the cavity and further affect the ignition. Hydrogen fuel injected into the cavity directly could improve the ignition performance greatly at the experimental status.

1. Introduction

Scramjet engines are promising candidates for future air-breathing systems. A vital part of the effort to develop air-breathing propulsion systems capable of sustaining hypersonic flight in the atmosphere is the ability to understand the complex mixing, ignition and combustion process inside a scramjet combustor. The ignition process in supersonic flow is time depended and complex[1], since it is greatly influenced by many factors such as the local fuel equivalence ratio, flameholder configuration, fuel auto-ignition abilities and ignition energy. It was indicated that the one and two dimensional heat transfer almost had the same effect on flame spreading[1]. The current generation of hydrocarbon-fueled scramjet combustors typically requires a flame holding device in the fixed flow path to facilitate flame ignition and stable combustion, due to the relatively long ignition delay times of hydrocarbon fuels. A cavity with slanted aft wall is a usual preferred geometry to generate a flameholding region in supersonic flow. Accompanied by means of cavity flameholder scheme, transverse fuel injection is generally employed in the scramjet combustor.

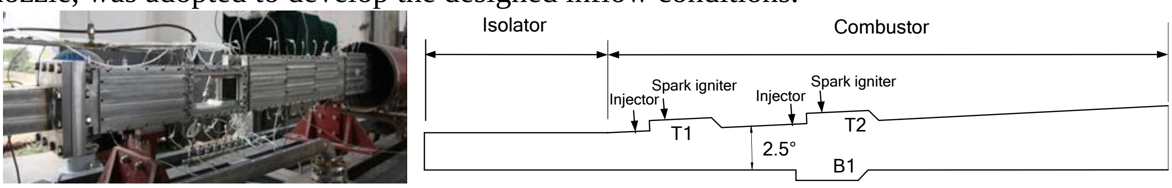
Considering the complexity of the ignition and mixing phenomena, the situation becomes more challenging during the engine start-up stage when the low chamber pressure and unsettled fuel-air mixing tend to blow out the flame, even when a cavity flameholder device is employed[2-4]. A major concern regarding stable ignition of the fuel-air mixture in a scramjet combustor is how a subsonic combustion environment can be established. One of the approaches is to impose an air throttle downstream of the combustor to modify the flow field in the engine. Recently Vigor Yang et al.[5, 6] summarized and performed numerical simulations to study the ignition transient and subsequent flame development under flow conditions with and without air throttling. Their results showed the air throttling decrease the flow velocity and increases in the temperature and pressure in the combustor section so as to improve the ignition characteristics and the flame stabilization process. Another common approach is to use additional hydrogen as a pilot energy to ignite the kerosene fuel in supersonic flow combustor. Ref [7] reported that the pilot hydrogen equivatence ratio could be reduced to be as low as 0.02 by using rear facing step and that the kerosene combustion efficiency was about 60% for the Mach 4.75 flight in a combustor cross section of 2.54cm X 2.54cm. Therefore, Ref[8] pointed out that an integrated fuel injector-flameholder using a simple cavity is a viable approach. For Mach 4 flight condition, if the combustor inlet size is large and the air mass rate is sufficiently large, it is difficult to build air-throttle of the engine to enhance the ignition. An injector-cavity setup with spark plug in the cavity bottom is a widely used integrated ignition/flameholding scheme.

Two main injection techniques can be used with cavity flame-holders: passive and direct. In case of passive injection, the fuel is injected upstream of the cavity, and it subsequently entrains into the cavity. In direct injection, the fuel injectors are present inside the cavity, and directly inject the fuel into the recirculation zone. Blowout limits, flame chemiluminescence, and non-reacting mixing patterns have been quantified in previous reports[9-11]. Sung et al.[12] investigated the ignition mechanism in a supersonic Hydrogen-air combustor. Mathur et al.[13] performed experiments using cavity after a ramp injector. The use of a cavity significantly improved the hydrocarbon combustion efficiency. Rasmussen et al.[14] performed experiments with cavity as a combined fuel injector/flameholder. Stable combustion was observed over a wide range of operating conditions. Micka et al.[15] used CH-PLIF to image the reaction zone in a dual mode scramjet combustor and demonstrated flame spreading procedure from cavity stabilized mode to fuel-jet-wake stabilized mode. Sun et al.[16] used OH-PLIF to study the flame structures and three-dimensional characteristics and revealed that the cavity shear layer plays an important role in flame spreading.

The present experiments have demonstrated that it is important to ensure the pilot hydrogen ignite firstly and the flame spread downstream efficiently to ignite the hydrocarbon fuel. In this experimental investigation, the ignition process of pilot hydrogen using cavity spark-igniter plug to establish stable combustion in the scramjet combustor is studied. Appropriate recommendations are made regarding spark location and the expanding effects of the upper wall. The present work investigates the detailed ignition transient and flame spreading in a reacting flow, and the influence of cavity-injection scheme.

2. Experimental Facility

A direct-connected test facility was used for the experiments which was composed of air heater, supersonic nozzle and scramjet combustor. The air heater combusted pure ethylalcohol and oxygen continuously to heat air from room temperature up to 846K and increase the total pressure of vitiated air up to 0.7Mpa. The total mass flow rate of vitiated air was 2.8Kg/s. The two dimensional converging-diverging M=1.92 nozzle section, configured with a rectangular nozzle, was adopted to develop the designed inflow conditions.



a) Direct-connected facility and installation b) Schematic of cavity, injector and spark plug setup

Figure 1 Schematic of test section and cavity installation scheme

Figure 1 shows the direct-connected facility and the test section. A constant 400mm long isolator is directly connected to the 54.5mm high and 75mm wide nozzle exit, followed by the 1000mm long test section where the top wall has a 2.5 degree expand angle of the combustor. There are three cavity installation in the test section, one in bottom side of the wall and the other two in the top side. For convenience, we denote the cavity depth as D, cavity length to depth ratio as L, the cavity aft wall angle as A, so the D15L7A45 is a cavity with depth of 15mm, length to depth ratio of 7, and aft wall angle of 45 degree; for all cavities the width are 75mm. Here for brevity we denote the cavity installed on top wall nearer to the isolator as ‘T1’, and the downstream cavity as ‘T2’. The cavity on the bottom wall is denoted as ‘B1’. In the present tests, only D15L7A45 is used and T1, T2 and B1 have the same configuration. Figure 1 (b) also shows the scheme of the fuel injection used for investigation on hydrogen ignition process. Gaseous hydrogen with room temperature is transversely injected into the combustor upstream of T1 or T2 cavity. The stagnation pressure for injection is fixed to 2.8Mpa. An injector with an orifice exit (diameter =2mm) is installed 32mm downstream of the isolator outlet. The distance from the injector centerline to the cavity front wall is 18mm. The forced spark ignition plug is used in T1 or T2. The pressures of combustor along the centerline of the top wall in the test section are measured by a strain-guage pressure transducer through pressure taps with the diameter of 0.5mm.

The flowfield is visualized by Schlieren image and high-speed-imaging camera, through the quartz window which is 190mm×100mm for photograph camera and 200mm in diameter for Schlieren observation. The Schlieren system utilizes the semiconductor continuous laser as light source. The wavelength of the laser is 532nm. To eliminate the influence of combustion radiation, a 532nm single pass filter is installed in front of the image recorder. Images are recorded by high-speed camera. Although the camera could reach the speed of 120,000fps when the image resolution is 128×64 pixels, only 4000fps is chosen in order to measure a larger area of 1024×512 pixels, with shutter time of 1/4000s. However, in the Schlieren system, the laser light is used and it is very bright for the test section and harmful for CCD camera, therefore the shutter time of 1/120000s is set for Schlieren imaging.

Due to the limitation of only one camera in our lab, each test is operated twice to acquire the results between flame photo and Schlieren image to make comparision. The repetitive ability of the experiment system has been validated by a large numbers of experiments, and it is confirmed that the difference is no more than 1ms. In the following discussion, the comparison between the Schlieren image and flame photo directly will be obtained by selecting two results of same moment in each experiment.

3. Experimental Results and Discussion

3.1 T2 cavity ignition with T2 upstream-injection

The injection scheme uses T2 injector upstream of the cavity and the igniter plug in the T2 cavity. The operation sequence of the system is presented here briefly. The operation starts with the delivery of heated-airflow through the entire engine. Once a steady flow is established, the T2 fuel injector is turned on. At the same time, the T2 spark igniter is activated. Ignition then occurs in the combustor, and the igniter is terminated after the flame is stabilized. The heat release and associated pressure rise in the combustor retains the condition required for sustaining combustion.

The camera is set 4000fps to measure a larger area of 1024×512 pixels, with shutter time of 1/4000s. Since the hydrogen flame is very weak and it is hard to identify the flame location in the original image, a brightness enhancing method is used to clear the image. Suppose that P_i is original picture, P' is enhanced picture and the P_0 is the background picture before the ignition, the enhanced method could be described as, $P_i' = 5.0 \times (P_i - P_0) + 0.5P_0$. Using this method, Figure 2 illustrates the spark generation and the flame propagation at anterior observation section during the ignition procedure, where t=0ms represents the time point of fuel injection starting.

As shown in Figure 2, the spark appears around the igniter which is near to the cavity front wall. The spark brightness is weak in the Figure 2 b)-c), while still could be identified in the circle windows ① and ②. The initial spark grows relatively slowly, however, it is seen that flame spreads very quickly (only 0.25ms) from Figure 2c) to Figure 2 d). Using cursory calculation, the flame speed could be as high as 400m/s. Considering the low static temperature and the total temperature condition in the main flow, it could not be the turbulent flame propagation. The reasonable explanation is that the spark penetrates the cavity shear layer and ignites the fuel remained in it, where the shear layer adjacent to the main flow has a high speed and advects the flame downstream very quickly. The main reason for the high flame spreading speed is the convection velocity. After the fuel downstream of the cavity is ignited, the flame gradually moves upstream due to the heat release procedure. At the same time, the flame spreads transversely and gradually ignites the injected fuel in the mainflow. During this period, the flame appears distortion which might be influenced by the shock incidence from the bottom cavity. At Figure 2 h), the flame gets a stabilizing state and the flame front extends to the injector location.

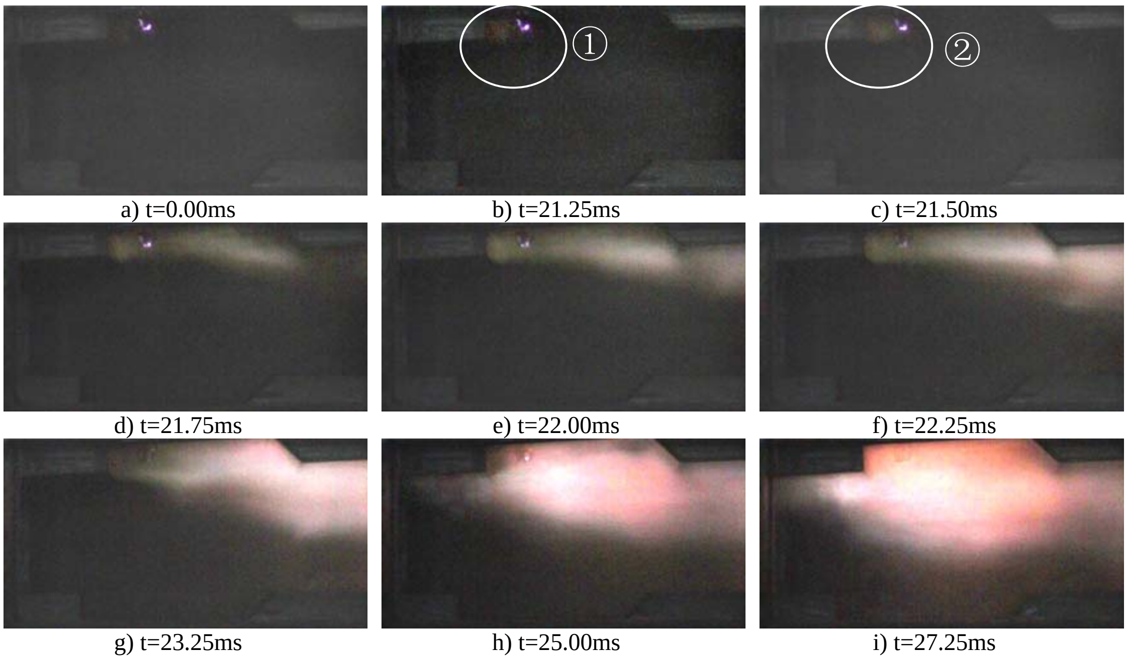
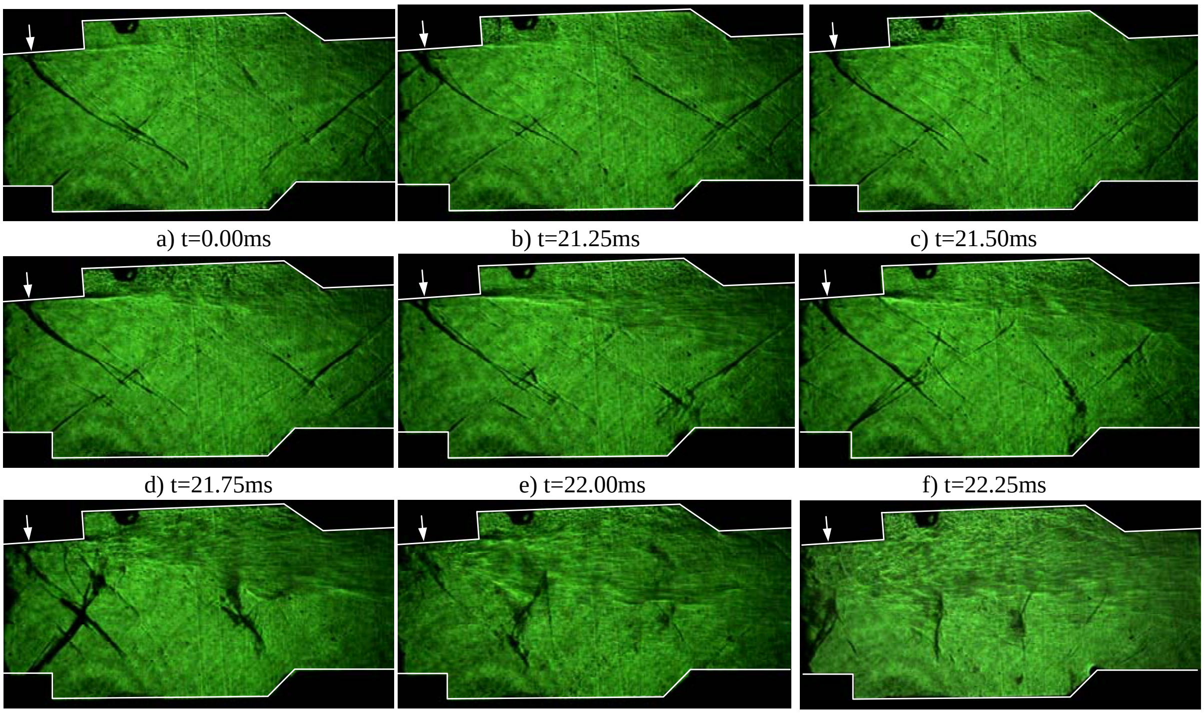


Figure 2 High-speed imaging of spark ignition process of hydrogen around the T2 cavity with T2 ignition

Figure 3 gives the schlieren images of the ignition procedure to compare to the high-speed-camera photos, where t=0ms represents the time point of fuel injection starting. In Figure 3, the flame region, the shock structures, the T2 cavity shear layer and heat release region can be clearly recognized. For the igniting process the flame was unsteady, so the shock train and flame bounds will change extremely. In Figure 3 b)-c), it is seen that initial spark is generated near the igniter, where the density field appears noisy and indicates chemical reaction processing in the cavity. It is interesting to see that at this time the T2 cavity shear layer is declined into the cavity, and the expanding waves are generated at the cavity front. The chemical reaction region propagates and extends around the igniter. In Figure 3c)-d), in the short period the flame diffuses to the whole internal cavity, the cavity shear layer and the downstream region, which compares well with the high-speed-imaging camera photos. Subsequently, the heat release downstream is intensified and the shock trains gradually move upstream and seem more intense, mainly because the resultant adverse pressure in the combustor increases. Meanwhile, the flow velocity and Mach number of the main flow decrease, and the frontal surface of the flame which is initially in the cavity shear layer, expands and spreads into the main flow. From the Figures, it is seen that the jet flame and the cavity are mainly in a subsonic region, the combustion results in a high-temperature and low-density state which decreases the Mach number under 1. In some region especially around the jet, shock-train penetration into the jet could be seen, however, it is mainly due to the three-dimensionality where the shock plane interacts with the jet beam.

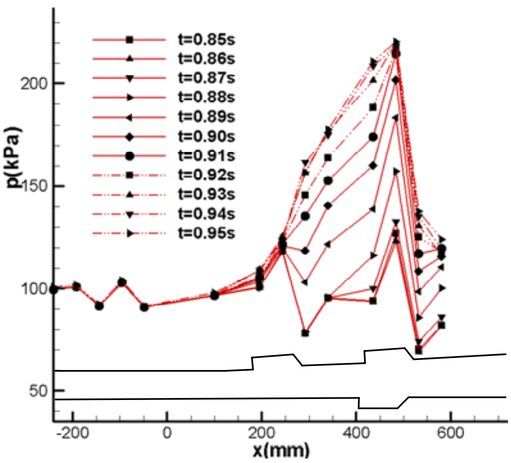


a) t=0.00ms b) t=21.25ms c) t=21.50ms

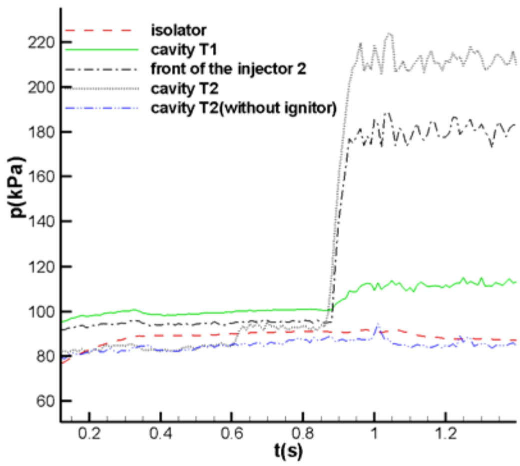
d) t=21.75ms e) t=22.00ms f) t=22.25ms

g) t=23.25ms h) t=25.00ms i) t=27.25ms

Figure 3 High-speed schlieren imaging of spark ignition process of hydrogen around the T2 cavity with T2 ignition



a) Wall pressure distribution along the upper wall



b) pressure in the T1, T2 cavity and the injector over time

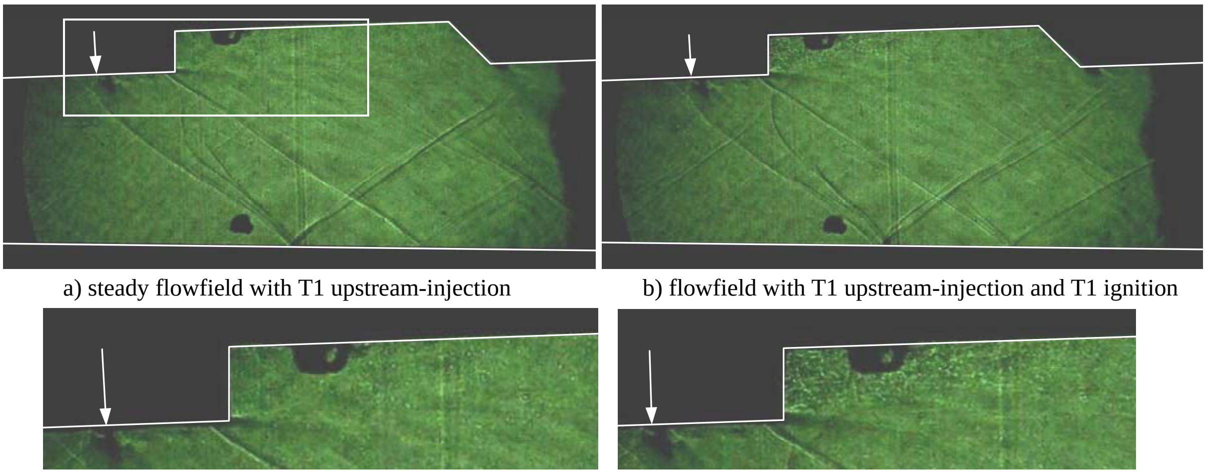
Figure 4 Pressure distribution and change over time in the combustor

Figure 4a) illustrated the wall pressure distribution at different time point in the experiment (t=0 represents the time point of air-heater starting-up), which almost reflects the ignition and the establishment of the steady combustion field. However, due to the long tube used in the facility to measure the pressure, the system has a significant time-delay to reflect pressure change. Therefore, the pressure change in Figure 4 only could be used to understand the ignition qualitatively. Due to the limitations of the pressure measurement (only 100 pressure samples obtained in one second, the time interval is larger than the ignition characteristic time), the detailed pressure change in ignition procedure cannot be acquired. Figure 4b) gives the wall pressure change over time in several locations, including T1 cavity, the T2 injector, T2 cavity. It is seen that the isolator state is steady. Moreover, in the non-reacting case, the pressure along the combustor decreases due to the expanded upper wall. Cavity T2 injection and ignition firstly drives the pressure in the T2 cavity increase. This is the effects of the shock wave induced by injection and the initial chemical reaction in the cavity T2. With the initial flame development, the cavity shear layer and the downstream fuel is ignited and the pressure in the cavity T2 gets a jump. After then the stable combustion is established and the pre-combustion shock trains get to the T1 location. From the figure, it is seen that at about t=60ms, cavity T2 pressure gets an 10kPa jump while in the non-reacting case the pressure does not change, which means that the pressure jump is not due to the injection, but the initial chemical reactions. This reflects the initial spark generation and the initial flame propagation.

3.2 T1 cavity ignition with T1 upstream-injection

This injection-ignition scheme uses T1 injector upstream of the cavity and the igniter plug in the T1 cavity. The operation starts until the steady flow is established, then the T1 injector is turned on. At the same time, the T1 spark igniter is activated. Under this condition, the experiment is repeated several times and no ignition procedure obtained.

Figure 5 gives the schlieren images in the operation. No flame region is observed in the procedure. It is seen that the T1 cavity shear layer declines to the main flow and a shock wave originates from the T1 cavity front. This is different from the T2 cavity case where expanding waves originates. It is obviously the flow patterns affect the fuel diffusion and convection into the cavity and the cavity shear layer, and ignition occurs in T1 cavity could not acquire enough energy to spread the initial flame and penetrate the cavity shear layer to ignite the fuel in the cavity shear layer and the region downstream of the cavity T1. In Figure 5 it is seen that at some time the igniter activates noisy density region (represents the initial flame) near the cavity shear layer, while the region does not extend further and the initial flame quenches immediately. From the analysis, it is concluded that the initial ignition energy in the cavity T1 is important for the successful ignition. To enhance the initial ignition energy, it is necessary to inject additional hydrogen into the T1 cavity directly to provide a powerful initial flame region.



a) steady flowfield with T1 upstream-injection   b) flowfield with T1 upstream-injection and T1 ignition

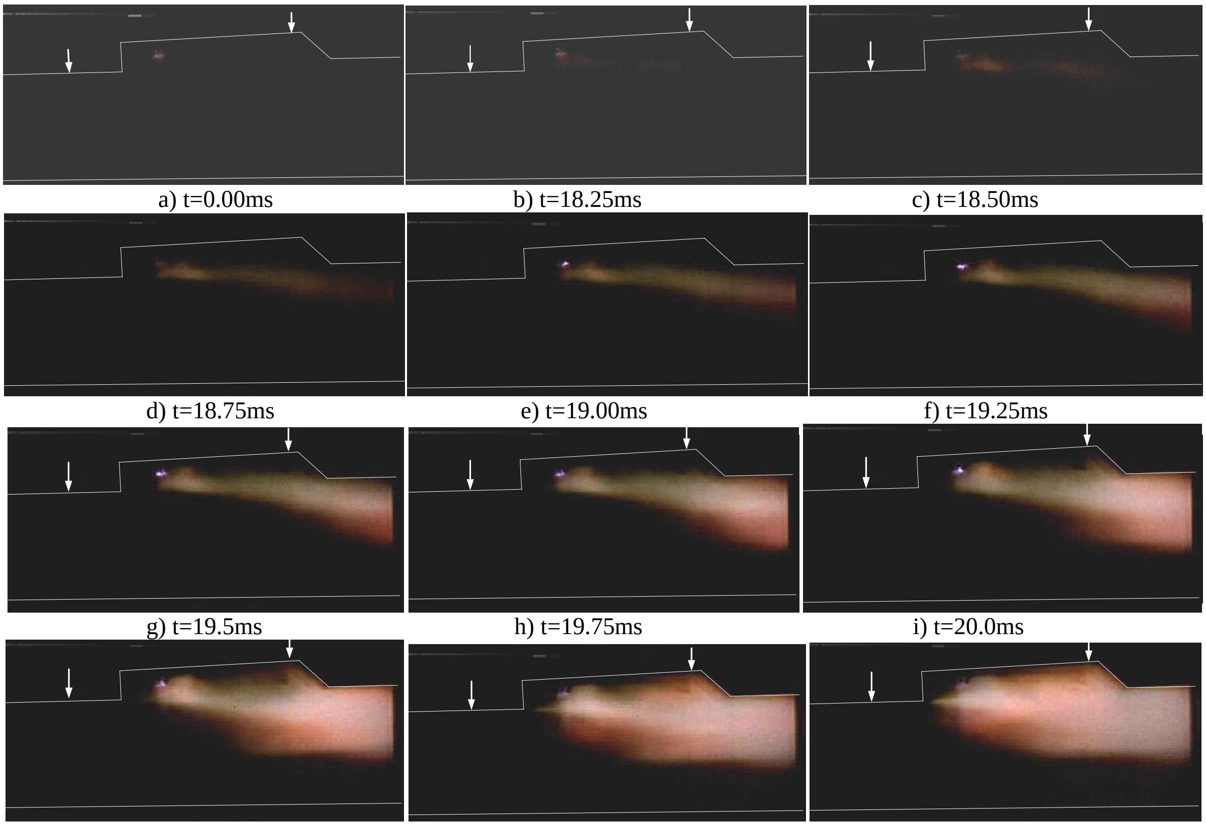
c) domain corresponding to the white window in a)   d) domain corresponding to the white window in a)

Figure 5 Schlieren imaging of spark ignition process of hydrogen around the T1 cavity using T1 injector upstream and T1 ignition

3.3 T1 cavity ignition with T1 upstream-injection and additional direct-injection

From the analysis in Section 3.2, besides T1 injector upstream of the cavity and the igniter plug in the T1 cavity are used, the additional direct-fuel injection from the T1 cavity bottom near to the cavity slanted aft wall is used. The injector has an orifice of 0.5mm diameter. The T1 injector and the additional direct-injector are turned on simultaneously. At the same time point, the T1 spark igniter is activated. Under this condition, the experiment is repeated several times and ignition procedure is obtained. The camera is set 4000fps to measure a larger area of 1024×512 pixels, with shutter time of 1/4000s. The hydrogen flame is weak and the same brightness enhancing method with Section 3.1 is used to clear the image. Figure 6 illustrates the spark generation and the flame propagation at anterior observation section during the ignition procedure using the enhance method, where t=0ms represents the time point of fuel injection starting.

As shown in Figure 6, the spark appears around the igniter and the initial spark grows very quickly (only 0.25ms) from Figure 6 b) to Figure 6 d). The flame penetrates the cavity shear layer and ignites the fuel in it. The flame spreading mechanism is like Section 3.1. The quick flame speed is due to the convection of main flow. The combustion of the fuel downstream of the cavity drives flame gradually move upstream due to the adverse pressure gradient, which intensifies the shock train, increases the static temperature of the main flow and decreases the velocity. The flame also spreads transversely and ignites the injected fuel in the mainflow. At Figure 6 k), the flame gets a stabilizing state and the flame front extends to the injector location.



a) t=0.00ms b) t=18.25ms c) t=18.50ms

d) t=18.75ms e) t=19.00ms f) t=19.25ms

g) t=19.5ms h) t=19.75ms i) t=20.0ms

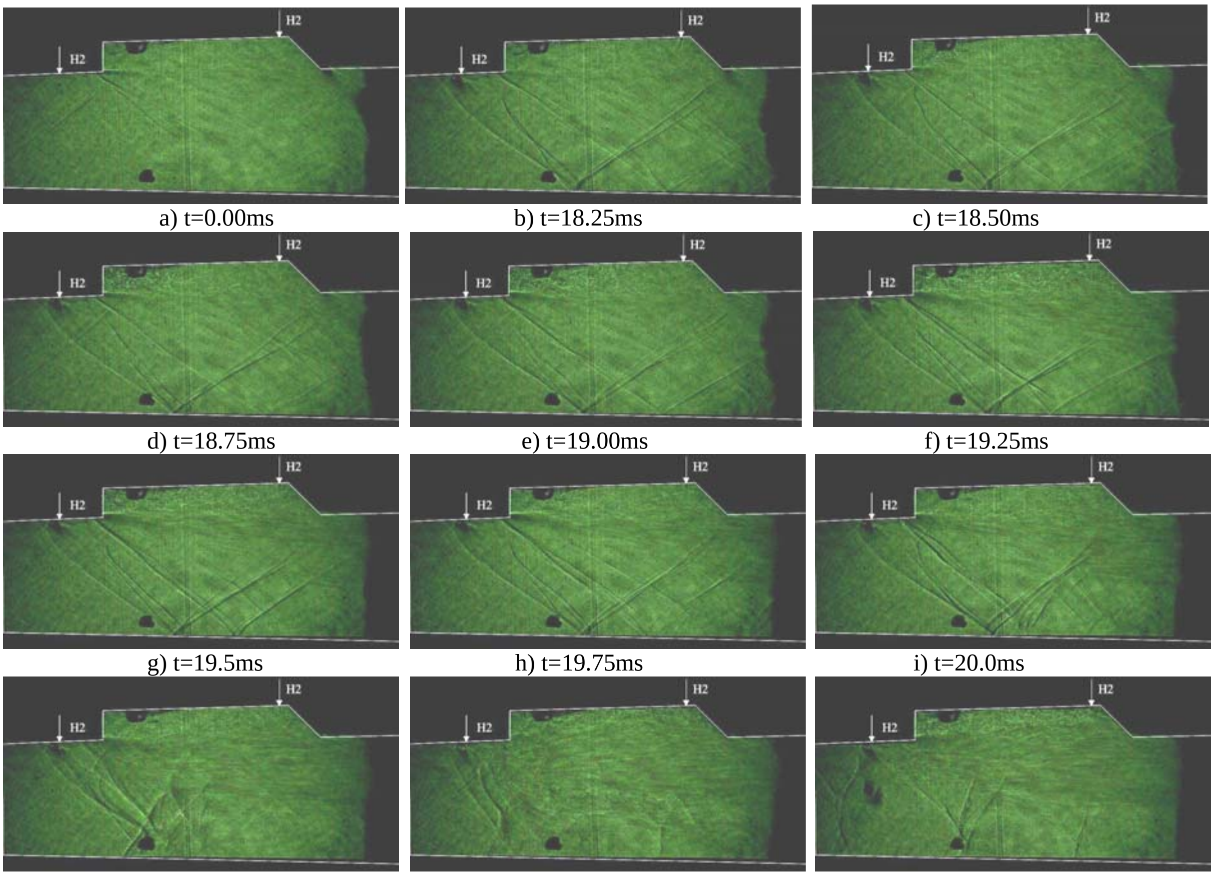
j) t=22ms k) t=23ms l) t=24.25ms

Figure 6 High-speed imaging of spark ignition process of hydrogen around the T1 cavity flame holder

j) t=22ms k) t=23ms l) t=24.25ms

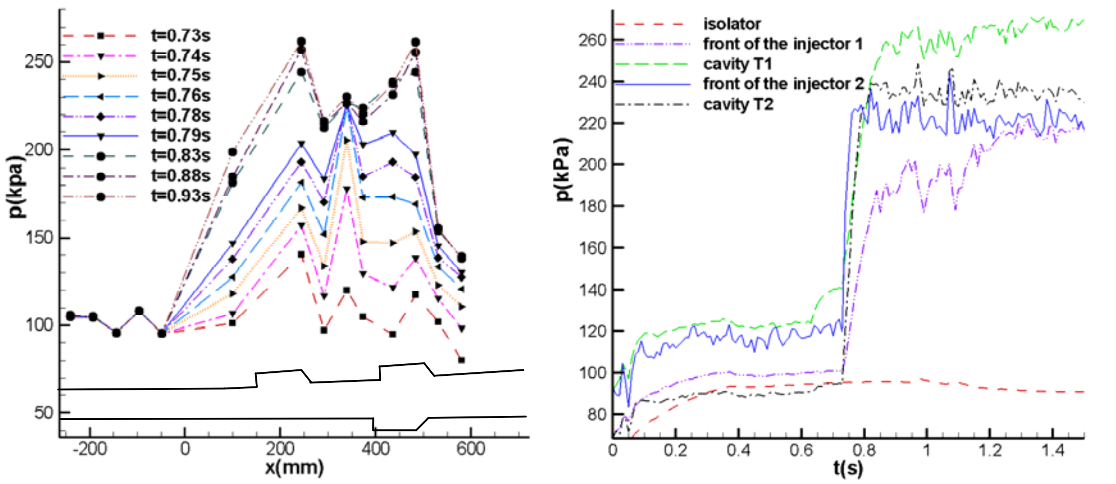
Figure 7 gives the schlieren images of the ignition procedure of the injection scheme, where t=0ms represents the time point of fuel injection starting. The igniting process is quite consistent with that in Section 3.1. In j) t=22ms k) t=23ms l) t=24.25ms

Figure 7 c)-e), it is seen that initial spark is generated near the igniter, where the density field appears noisy and indicates chemical reaction processing in the cavity. It is seen that the T1 cavity shear layer declines to the main flow and shock waves originates from the T1 cavity front. The phenomena is consistent with Section 3.2 and different from the T2 cavity case where expanding waves originate. In the short period the initial flame diffuses to the whole cavity, the cavity shear layer and the downstream region. Subsequently, the heat release downstream is intensified and the shock trains move upstream, due to the resultant increasing adverse pressure in the combustor. Meanwhile, the flow velocity of the main flow decreases, and the flame expands and spreads into the main flow. It is also seen that the jet flame and the cavity are mainly in a subsonic region. The whole procedure is quite similar with that shown in Section 3.1. Compared with the phenomena, it is concluded that to inject additional hydrogen into the T1 cavity directly could promote the initial energy in the spark, further result in a successful ignition.



a) t=0.00ms b) t=18.25ms c) t=18.50ms
d) t=18.75ms e) t=19.00ms f) t=19.25ms
g) t=19.5ms h) t=19.75ms i) t=20.0ms
j) t=22ms k) t=23ms l) t=24.25ms

Figure 7 High-speed schlieren imaging of spark ignition process of hydrogen around the T1 cavity flame holder



a) Wall pressure distribution along the upper wall b) pressure in the T1, T2 cavity and the injector over time

Figure 8 Pressure distribution and change over time in the combustor

Figure 8 a) illustrated the wall pressure distribution at different time point in the experiment, which reflects the ignition and the establishment of the steady combustion field. Figure 8 b) gives the wall pressure change over time in several locations, including T1 cavity, the T1 injector and the isolator. In Figure 8 t=0 represents the time point of air-heater starting-up. For the same reason analyzed in Section 3.1, the pressure change here only could be used to understand the ignition qualitatively. It is seen the isolator state is fairly steady. It is seen that at certain time before the pressure huge jump, cavity T1 pressure gets a 20kPa small jump and shortly after that, the pressure jumps to a steady combustion state, which indicates that the initial flame normal propagation. That is similar with Section 3.1, which reveals that direct-additional injection increases the high enough energy in the initial flame efficiently.

4. Summary

High-speed photography and Schlieren were used to research on ignition process in scramjet combustor at Mach 4 flight condition, which revealed the shock wave structure and flame spreading process. By comparing the dynamic flowfield of different injection scheme and cavity ignition, conclusions could be obtained as follows,

1) Spark generates near the igniter, and grows to form flame in the cavity.
2) The initial flame spreads along the cavity shear layer and ignites the fuel distributed downstream very quickly. With the pressure downstream rises up, the pre-combustion shock and the flame move against the stream and finally the whole fuel jet flame is ignited and stabilized.
3) The expand angle of the upper wall and the disturbance caused by the upstream cavity have an obvious effect on the fuel diffusion and convection into the cavity and further affect the ignition.
4) Hydrogen fuel injected into the cavity directly could improve the ignition performance greatly at the experimental status.

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