Experimental investigations of detonation initiation by hot jets in supersonic premixed flows*

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A new method to initiate and sustain the detonation in supersonic flow is investigated. The reaction activity of coming flow may influence the result of detonation initiation. When a hot jet initiates a detonation wave successfully, there may exist two types of detonations. If the detonation velocity is greater than the velocity of coming flow, there will be a normal detonation here. Because of the influence of boundary layer separation, the upstream detonation velocity is much greater than the Chapman–Jouguet (CJ) detonation velocity. On the other hand, if the detonation velocity is less than the velocity of coming flow, an oblique detonation wave (ODW) will form. The ODW needs a continuous hot jet to sustain itself. If the jet pressure is lower than a certain value, the ODW will decouple. In contrast, the normal detonation wave can sustain itself without the hot jet.

Keywords: hot jet, detonation, supersonic flow

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1. Introduction

Detonation is a combustion type with supersonic speed and fast heat release. It can sustain itself by chemical energy release or other energy such as laser.[1] Because of its high thermal cycle efficiency, it is desirable for adoption in propulsion systems. Many kinds of detonation wave engines have been studied for many years, such as the pulse detonation engine (PDE),[2,3] the continuously rotating detonation engine (CRDE),[4,5] the supersonic pulsed detonation ramjet engine (SPDRE),[6] the oblique detonation wave engine (ODWE), and so on. The ODWE is suitable for hypersonic aerocraft. Ordinarily, a hypersonic projectile or a wedge is used to initiate and sustain an ODW in laboratory studies. The ratio of projectile curvature radius to cell size, the projectile speed and the condition of the premixed gas may determine whether or not a detonation wave or a shock induced combustion will form.[7−13] An expanding tube[14,15] is adopted to study the ODW initiated by a wedge with Schlieren and OH-PLIF systems at the same time. Many other researchers[16−19] have paid their attention to the structure and stability of the ODW using numerical methods. According to these studies, the ODW is found though a wedge to have some advantages such as simple structure and easy analysis in theory, but it brings many disadvantages as well. Great hydrodynamic drag, cooling troubles, and difficulties in controlling detonation state may all arise from it. Hence another detonation initiation and stabilization scheme of using a jet to replace the wedge is considered. It is easy to control, and it does not need cooling. This method is usually adopted in low speed flow. It is found that d/λ is a key factor which can determine whether or not a detonation forms, where d is the jet diameter and λ is the detonation cellar size.[20] Many other people[21,22] have also investigated the properties of detonation initiation by hot jets in static or low speed gas. Only Ishii *et al.*[23] studied the detonation initiation by a hot jet in a flow whose mach number is about 1.0. Their results showed that a hot jet can initiate a detonation wave in a supersonic flow.

In this paper, a new scheme is designed to initiate and stabilize the detonation wave. In addition, the results of some experimental studies are also given in this paper.

2. Model and method

The whole experiment structure of detonation initiation and stabilization is shown below in Fig. 1.

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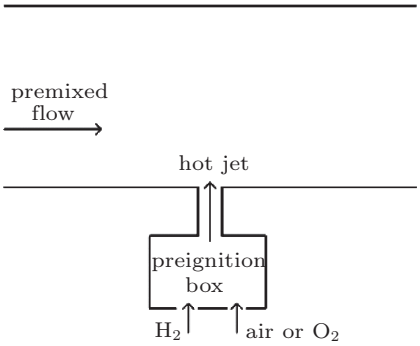


Fig. 1. Detonation initiation and stabilization by a hot jet.

A preignition box is set at the combustion chamber wall. Fuel is H_2 and an oxidizer such as air is obtained from atmosphere or O_2 will burn in it. Then a hot gas is jetted into the combustion chamber. If the state of the hot jet satisfies the detonation initiation condition of coming flow, a detonation wave will form. Additionally, if the hot jet continues, the detonation will sustain itself. Ordinarily, the hot jet diameter is small and consumes a small quantity of fuel.

In theory, if the coming flow velocity v_f is higher than its CJ (Chapman–Jouguet) detonation velocity D, an ODW detonation will form. Because the hot jet turns parallel to the coming flow very quickly, a CJ ODW will form in a short distance. On the other hand if $v_\mathrm{f} < D$, normal detonation will form, and propagate upstream.

The experiment setup shown in Fig. 2 is used to study the detonation initiation and development by hot jets in supersonic flow. The design of this experiment scheme is detailed in Ref. [24]. The coming flow produced by air heater is at pressure 54 kPa, temperature 805 K, and Mach number 3.0. The equivalence ratio δ is alterable. δ is defined as

$$\delta = \dot{m}_\mathrm{hr}/\dot{m}_\mathrm{hp}, \tag{1}$$

where $\dot{m}_\mathrm{hr}$ is the H_2 mass flux in coming flow and $\dot{m}_\mathrm{hp}$ is the idealized H_2 mass flux which can completely react with O_2 of the coming flow.

A jet tube will provide a hot jet by burning H_2 and O_2. The exit diameter of the jet tube is 4 mm.

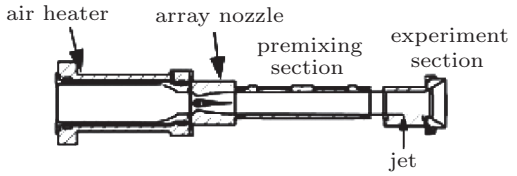


Fig. 2. Experimental setup.

A shadowgraph system is used to image the processes of detonation initiation and development. The system includes a high speed video camera which can record 10^5 frames per second with $1/2.73\times10^6$ s exposure time, a laser lamp and a series of mirrors.

3. Results and discussion

Firstly, the characteristics of the jet tube are studied to match the whole experimental setup. The molar ratio of H_2:O_2 is 1.76. Its operation time order is shown in Fig. 3.

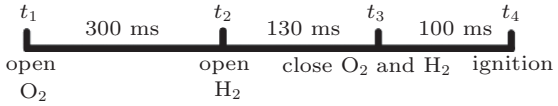


Fig. 3. Operation time order of the jet tube.

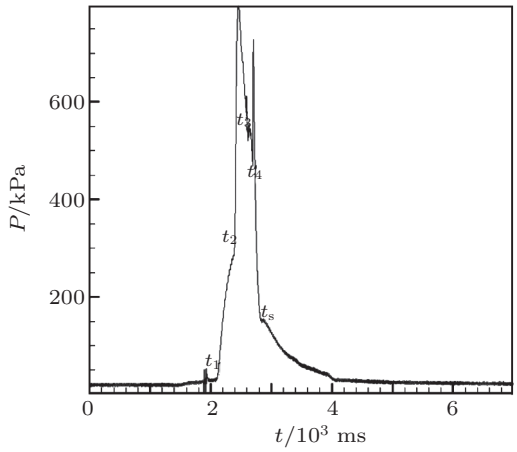


Fig. 4. Pressure development in the jet tube.

The pressure development process in the jet tube is shown in Fig. 4. After opening the H_2 valve, pressure rises sharply. Then it falls and approaches a balanced state. When H_2 and O_2 valves are shut down at t_3, the pressure decreases continuously. In Fig. 4, the time interval is 198 ms between t_2 and t_3, which is larger than that in Fig. 3. The reason lies in that the valve response delay will change the time interval. At t_4, the premixed gas ignites and pressure rises abruptly. After reaching climax, it falls very quickly until t_s because reaction products are jetted into the combustion chamber. After t_s, the pressure changes slowly. This is because with the pressure of the tube falling, the Mach number of the jet becomes smaller than 1.0. The back pressure in the combustion chamber will influence the jet tube in a subsonic state, and

then mass flow of the hot jet decreases. The operation characteristic time is defined as $t_j = t_s - t_4$, which refers to the hot jet operation time in a sonic state.

The detonation initiation process of $\delta = 0.29$ is shown in Fig. 5. The CJ detonation velocity in this condition is 1395 m/s, which is smaller than that of the coming flow. Hence an ODW may form in theory. The CJ ODW angle θ_{CJ} is 52° which is calculated by using Chemkin 4.1 software. At the beginning, H_2/O_2 premixed gas at low pressure is jetted into the coming flow, which induces a bow shock wave. When premixed gas ignites at t_4, a high pressure hot jet is jetted into the combustion chamber. Then a hemisphere shock wave forms. Because the pressure and temperature are enhanced sharply by the upstream shock, an overdriven bow detonation wave forms here. However, the downstream shock becomes weaker and weaker, for it expands all the time but no jet sustains it. So on the whole shock surface, only the upriver local part will form a detonation wave. With shock expanding, the detonation part raises the angle of other parts and results in the formation of detonation. Near the wall there is an oblique shock in front of the jet. The reason for the appearance of this shock is that the jet may lead to boundary layer separation. Additionally, the detonation near the boundary layer may also induce boundary layer separation, but the mechanism has been unknown until now.

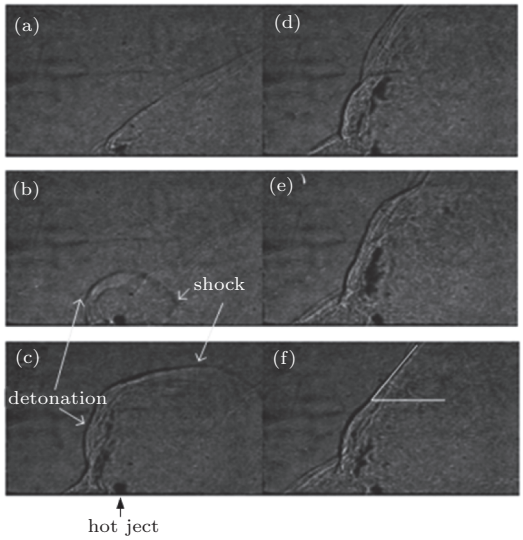


Fig. 5. Detonation initiation when $\delta = 0.29$.

In Fig. 5(f), the shock wave rises completely and transforms into a detonation wave. Detonation angle θ is nearly 90° in the area near the lower wall and diminishes away from the lower wall, but remains constant far from the jet. This fixed angle is 50.9°, which approximates to the CJ ODW angle of 52°. That means an overdriven detonation will transform into a CJ ODW as the influence of jet becomes weaker and weaker. Thus the structure of the whole ODW is shown in Fig. 6.

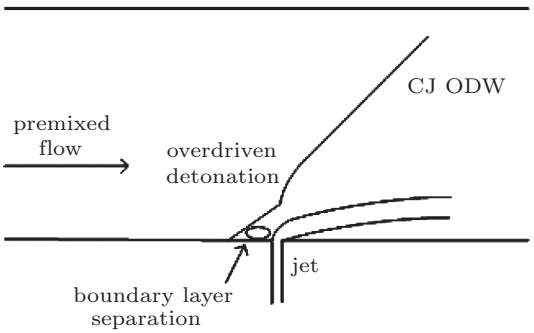


Fig. 6. Structure of an ODW initiated by a jet.

The developing process of detonation is shown in Fig. 7. The ODW hits the top surface of chamber and reflects from it. This reflected shock raises the pressure near the wall, induces the boundary layer to separate and then propagates vertically. The detonation behind it is in an overdriven state. So the detonation velocity is faster than the CJ velocity. For this reason and the influence of the boundary layer, the detonation will turn into a normal detonation and propagate upstream. Therefore though the coming flow velocity is faster than the CJ detonation velocity, the detonation may propagate upstream due to the influence of boundary layer separation. So an overdriven normal detonation will form in the core flow area. On the side, the boundary layer separation is larger in Fig. 7(d) than that in Fig. 5(f), which means that a stronger overdriven detonation will lead to the serious separation of the boundary layer. Because the camera recording speed is too fast with a small visual field, the up wall of the chamber cannot be observed.

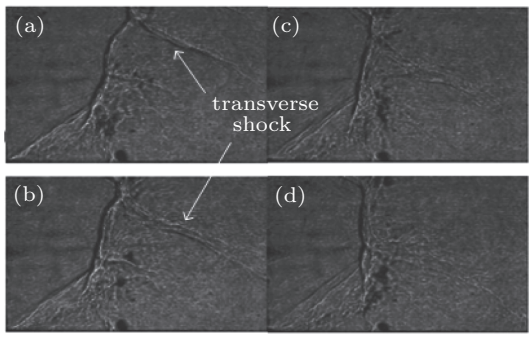


Fig. 7. Detonation developing process recorded with a camera at a speed of 10^5 ft/s.

To observe the whole combustion chamber, we reduce the camera record speed to 3×10^4 ft/s with the exposure time remaining the same. The detonation developing process is shown in Fig. 8. It is clearly shown that the boundary layer separation takes place when the ODW reflects from the up wall. This boundary layer separation induces a transverse shock rising in front of it. The ODW transforms into a normal detonation wave finally. The structure of normal detonation is shown in Fig. 9.

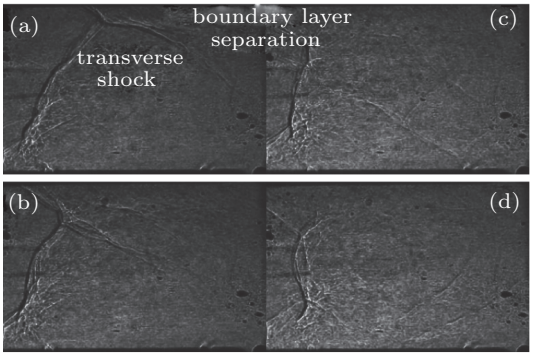


Fig. 8. Detonation developing process recorded with a camera at a speed of 3×10^4 ft/s.

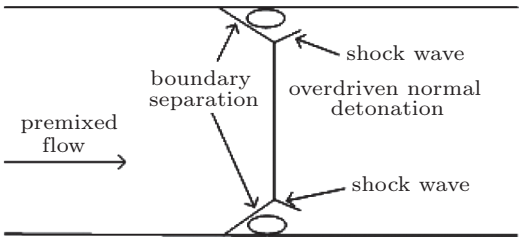


Fig. 9. Structure of normal detonation.

Reducing the equivalence ratio to 0.25 changes the reaction activity of coming flow with the hot jet condition remaining the same. The detonation initiation process as shown in Fig. 10 is similar to that for $\delta = 0.29$, but the rising speed of the shock wave surface decreases. According to Figs. 5(b) and 5(c), the speed of the top shock surface is 1460 m/s. On the side, this speed is 930 m/s, as can be calculated from Figs. 10(b) and 10(c). This means that the reaction activity can have an influence on the rising speed of the shock wave surface, but little on the detonation initiation process.

The detonation developing process after initiation is very different from that for the condition of $\delta = 0.29$. The detonation will not transform into a normal overdriven detonation, but exists as an ODW. The CJ detonation velocity at $\delta = 0.25$ is 1333.6 m/s. Though the boundary layer separation will also increase the detonation velocity upstream, this detonation velocity is still smaller than that of the coming flow. A hot jet initiates a detonation wave and induces a hydrodynamic wedge at the same time. If this hot jet pressure is large enough to hold the hydrodynamic wedge curvature radius greater than a certain value, an ODW will stabilize in the combustion chamber as shown in Fig. 11(a). On the other hand, if the hydrodynamic wedge curvature radius is smaller than this certain value, the ODW will decouple and evolve into an oblique shock wave inducing combustion as shown in Fig. 11(b). Additionally, the boundary layer separation is less obvious at lower and upper walls than that in the case of an ODW, as shown in Fig. 11(a). This indicates that the boundary layer separation is caused by the ODW and the hot jet together.

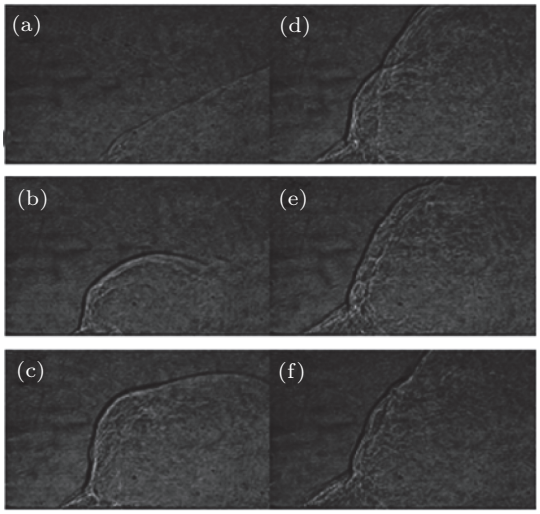


Fig. 10. Detonation initiation when $\delta = 0.25$.

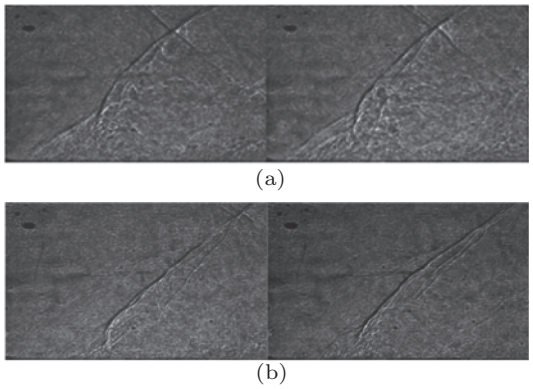


Fig. 11. (a) Stable ODW and (b) ODW decoupling at δ=0.25.

If the equivalence ratio decreases continuously to 0.19, the hot jet cannot initiate a detonation wave as

shown in Fig. 12. There is only a bow shock wave arising from the jet. This indicates that the reaction activity may affect whether or not a detonation wave will be initiated. The coming flow with low reaction activity will need higher energy hot jets to initiate detonation waves.

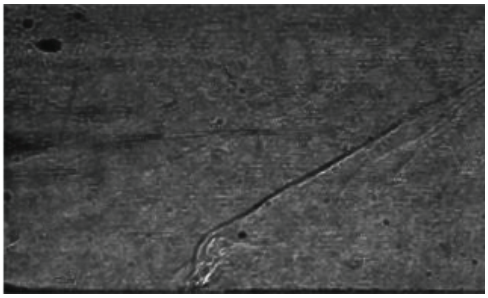


Fig. 12. Failing detonation initiation at $\delta = 0.19$.

4. Conclusions

A hot jet can initiate and hold a detonation wave in a supersonic premixed flow. The detonation velocity is faster than CJ detonation velocity due to the influence of boundary layer separation. If the detonation velocity is greater than the velocity of the coming flow, a normal overdriven detonation forms in the core area of the coming flow and propagates upstream. The detonation can sustain itself without hot jets after it has been initiated. But if the detonation velocity is slower than the velocity of the coming flow, an ODW forms and stabilizes with the jet. When the hot jet pressure is lower than a certain value, the hydrodynamic wedge curvature radius will be too small to sustain the ODW. Shock inducing combustion may occur and goes out finally. Otherwise, the equivalence ratio of coming flow will affect whether or not the detonation initiation will be successful. If it is too low, a hot jet will not be able to initiate a detonation wave.

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