Influence of rarefaction wave on premixed flame structure and propagation behavior*

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Accepted on September 1, 2006

Abstract To explore the influence of rarefaction wave on the structure and propagation behavior of the premixed propane/air flame in a rectangle combustion pipe, the techniques of high speed Schlieren photograph method, pressure measurement and so on are used to study the interaction processes between rarefaction wave and flame. Two cases of rarefaction wave-flame interaction were performed in the experiment. The experimental result shows that both the rarefaction waves can cause the flame transition from laminar to turbulent combustion quickly. The cowflow rarefaction wave decreases the flame speed, while the counterflow rarefaction wave leads the flame propagation speed to increasing on the whole, accompanied with sharp vibration.

Keywords: gas explosion, rarefaction wave, flame propagation, laminar flame, turbulent combustion.

Flammable gas fuel is one of the most important energy sources in industry and living. During the manufacture and use of gas fuel, fire and explosion accident often occurs and causes great loss and destruction[1,2]. Generally, in the case of gas explosion, the transition from laminar flame to turbulence usually takes place first and then accelerates the flame propagation speed, which increases the combustion surface area and heat release rate, and finally leads to serious explosion destruction due to the rapid overpressure rise[3,4]. Accordingly, the flame propagation and pressure rise are closely related to turbulent combustion occurrence. Then it is necessary to discern the micro-dynamic process and the intrinsic mechanism during the transition from laminar to turbulent, and further to suppress and prevent the combustion and explosion process.

The flame-flow interaction has been one of the most challenging areas in combustion science and technology field, which is closely related to the fundamental elements of the combustion process, such as the flame structure, flame propagation, flame instabilities and so on[5—8]. Many elements influence the gas combustion process, of which the pressure wave-flame interaction is one of the most typical reasons to induce turbulence combustion[9]. In most industry disasters, the pressure wave always increases the gas burning speed and the pressure-flame interaction induces the flame unstable and further elicits turbulence, even resulting in the transition from deflagration to detonation[10]. Accordingly, the pressure-flame interaction may change the whole combustion process and characteristic, which has attracted many researchers' attention. Markstain[11] firstly recorded the photos of flame instability induced by shock wave, describing the flame variation course when affected by incidence and reflection shock wave respectively. Kristoffersen et al.[12] experimented on premixed propane-air flame propagation in circular pipe, and the result showed the flame propagation depending strongly on acoustical wave disturbance through pipe, especially on the rarefaction wave action reflected from the vent end. The experiment on flame-shock wave interaction[13] showed that the shock wave can obviously accelerate the flame propagation speed, which was testified by Gamezo et al.[14]. But the instant interaction at the initial stage of flame propagation is rarely studied, especially on the microstructure variation during the interaction between rarefaction wave and flame[15,16].

As a whole, the pressure-flame interaction is complicated; especially the flame structure change induced by rarefaction wave needs further research. Therefore, in this work the premixed propane-air

* Supported by National Natural Science Foundation of China (Grant Nos. 50576093, 50536030)

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flame was observed as object, and the high speed video camera and Schlieren image technology were used to record the process of flame propagation and to investigate the interaction of rarefaction wave and premixed flame.

1 Experimental apparatus and procedures

The experimental system is schematically shown in Fig. 1, which is composed of a combustion chamber, an ignition system, a data recorder, a Schlieren image system, a high speed video camera and a synchronization controller. The Schlieren image system shown in Fig. 1 consists of a 25 W mercury vapor lamp, a knife edge and two concave mirrors. The combustion chamber is a square tube, of which the inner size is 80 mm × 80 mm × 550 mm. To observe flame propagation characteristic and flame structure evolution process conveniently, the sides of the chamber were made of high-intensity glass. The cross section of the combustion chamber is shown in Fig. 2. To investigate the rarefaction wave-flame interaction, the combustion chamber was divided into two parts, the chief combustion chamber and the adjunctive small room leftward, separated by a membrane. The chief combustion chamber was 500 mm long, and the adjunctive room was 50 mm long. On each part of the combustion the pipe was set up a high frequency-dynamic piezoelectricity transducer to detect the pressure variation of different regions in the duration of rarefaction wave-flame interaction. Two spark igniters were fixed at each end of the pipe, which can elicit flame propagation towards different directions to intervene in rarefaction wave. To ensure the safety during the experimental process, a pressure relief valve was fixed on the pipe.

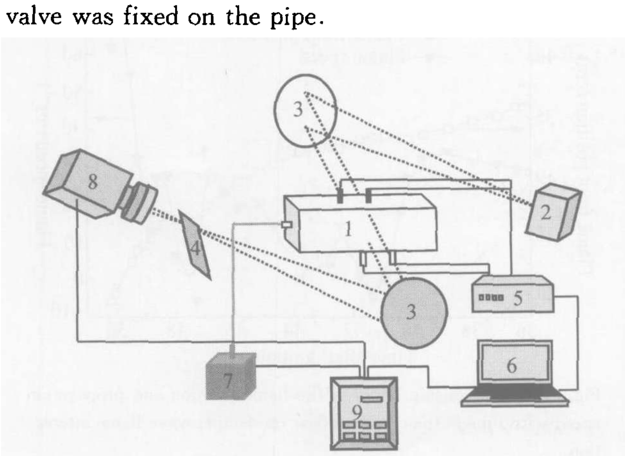

Fig. 1. Sketch of gas flame structure experiment system. 1. Combustion chamber; 2. mecurry vapor lamp; 3. concave mirror; 4. knife edge; 5. data recorder; 6. computer; 7. spark igniter; 8. high speed video camera; 9. synchronization controller.

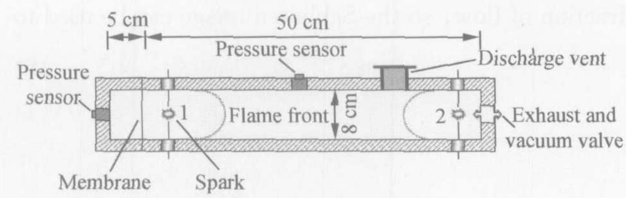

Fig. 2. Sketch of gas combustion experiment chamber.

After the experiment pipe was vacuumized, the chief combustion pipe was filled with 4.0% volume percent of propane/air mixture, and the adjunctive small room leftward filled with air of equivalent pressure equal to the atmospheric pressure.

In the test, the startup time of the high speed video camera (Photron, Fastcam Ultima APX), the high speed digital data recorder (HIOKI, 8826 Memory Hicorder) and the high voltage igniter was controlled by a synchronization controller. The detailed experimental conditions are given as following: ignition voltage 20000 V; discharge period 0.001 s; recording speed of high speed video camera 8000 fps; sampling rate of data recorder 100 kHz.

2 Results and discussion

Two cases of interaction between rarefaction wave and flame were performed in the experiment. When ignited by electrode 1, both the flame and rarefaction wave propagated rightward. When ignited by electrode 2, the rarefaction wave was elicited rightward, while the flame propagated leftward.

2.1 Interference action of coflow rarefaction wave on flame

In this case, the premixed mixture was ignited by electrode 1. The flame front propagated from left to right in the pipe. When membrane between the additional room and the chief combustion chamber ruptured, a rarefaction wave was induced to move rightward. When rarefaction wave caught up with the flame front, the interaction of rarefaction wave and flame was recorded by the high speed Schlieren system and pressure transducer.

2.1.1 Flame structure and propagation behavior based on Schlieren images results

It is well known that the flow field density change shows the direct influences of temperature, concentration and pressure on flame structure. The Schlieren image was obtained based on the light refraction of flow, so the Schlieren image can be used to reflect the inner flow structure characteristic.

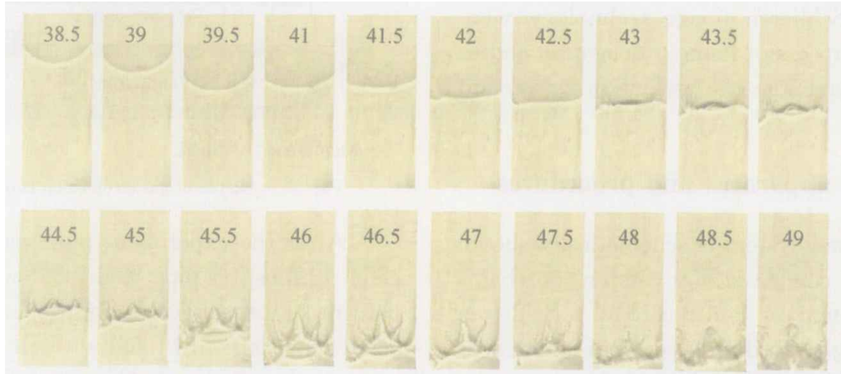

Fig. 3. High speed Schlieren images in the case of coflow rarefaction wave-flame interaction (Unit: ms).

Fig. 3 is a series of typical high speed Schlieren photographs, depicting the flame propagation process and flame front structure. As shown in Fig. 3, the convex flame front propagated towards the unburned gas in regular spherical wave shape and the flame was obviously laminar at the initial stages of flame development. Meanwhile, the burned and unburned gases were separated by a very thin flame front. When time $t = 41$ ms after ignition, the rarefaction wave induced by membrane rupture caught up with the flame front, and began to intervene in the flame structure. Hereafter, the flame configuration changed gradually and the curvature of spherical flame front began to decrease. At time $t = 42.5$ ms, the flame front became plane, indicating the flame front surface area reached the minimum. With the flame propagating, the flame front stretched and led to a thicker flame front. After time $t = 44.5$ ms, the regular flame front was torn up into dentiform shape, and many irregular wrinkles appeared, making for a greater flame front surface area. Here, the flame structure character indicated that obvious turbulence came into being. After time $t = 44.5$ ms, with further interaction of rarefaction wave and flame, bifurcation phenomena appearing on the flame front caused thicker flame front and greater turbulence intensity. It can be seen from Schlieren images that the turbulent flame propagated in a wide region, unlike the laminar flame in a very thin flame front. After time $t = 48$ ms, the flame front outline became blurry and the flame front propagated ahead with strong turbulence as a whole. The Schlieren images shown in Fig. 3 revealed the micro-process of flame configuration changing clearly, and also it can be seen that just the interference of rarefaction wave on flame induced the transition from laminar flame to turbulence immediately. Many experiments on the same test condition showed the similar results and phenomena as above.

Fig. 4 shows the relationship between flame front position and flame propagation speed with time. As shown in Fig. 4, at the initial stage, the laminar flame propagation speed increased with time going. After time $t = 40.5$ ms, the rarefaction wave overtook the flame and began to influence the flame behavior. Firstly, the flame speed decreased sharply from 33 to -4 m/s in no more than 2 ms. Subsequently, obvious speed oscillation appeared on the curve, due to the turbulence effect induced by rarefaction wave-flame interaction. Interference action of rarefaction wave on flame decreased the flame speed sharply at the initial stage while increasing the turbulence intensity quickly. With turbulence increasing, the flame speed was accelerated, simultaneously accompanied with fluctuations. When turbulence intensity became strong enough after time $t =$ 49 ms, the flame speed accelerated quickly again.

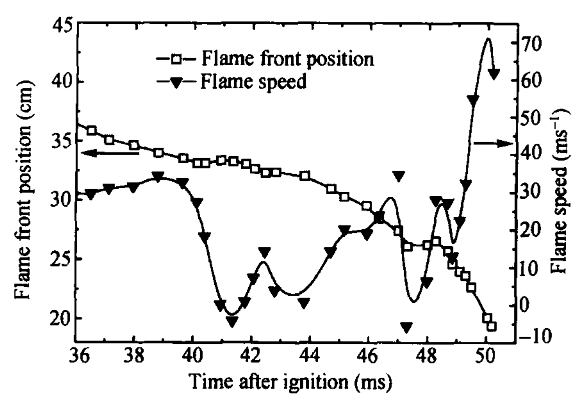

Fig. 4. Relationship between the flame position and propagation speed with time in the case of coflow rarefaction wave-flame interaction.

2.1.2 Analysis on pressure test results

Fig. 5(a) shows the pressure variation in addition room with time. It can be seen that the pressure value was nearly constant before time t = 41 ms. However, at about t = 41 ms, the pressure increased quickly from 16 to 32 kpa in 0.38 ms, accompanied with sharp pressure fluctuations. The pressure result indicates that, at time t = 41 ms, the membrane ruptures and a leftward compression wave was produced in the addition room. When t = 41.38 ms, the compression wave reaching the piezoelectricity transducer caused the pressure value to rise sharply. In addition, at the same time of membrane rupturing, a rarefaction wave was induced to move rightwards. As the rarefaction wave caught up with the flame front, the interaction between rarefaction wave and flame led to the transition from laminar to turbulence quickly.

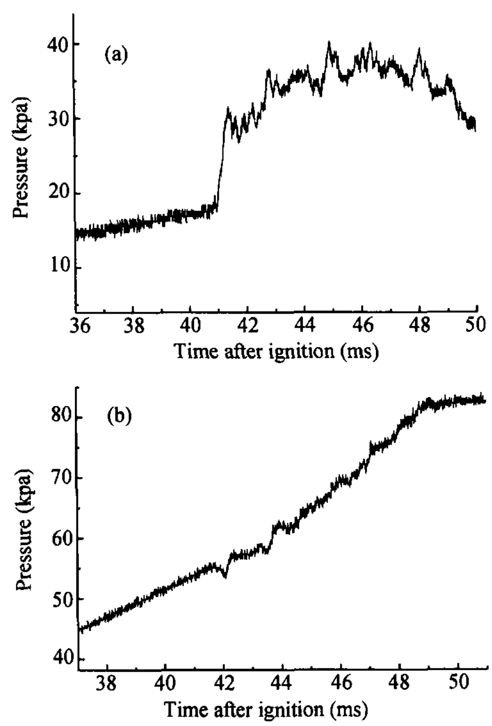

Fig. 5. Relationship between the pipe pressure variation with time in the case of coflow rarefaction wave-flame interaction. (a) Pressure in additional room; (b) pressure in chief combustion vessel.

Fig. 5(b) shows the curve of pressure variation in the chief combustion chamber with time. It can be seen that the pressure value in the combustion chamber increased with time, almost linearly with time going at the initial stages of flame development. At time t = 41.4 ms, obvious pressure fluctuations appeared on the curve, which indicates that rarefaction wave had already reached the pressure sensor in combustion chamber and began to influence the pressure in the chief combustion chamber. Combined with Schlieren images, the coflow rarefaction wave-flame interaction caused the transition from laminar flame to turbulence quickly, and led to obvious pressure fluctuations.

2.2 Interference of counterflow rarefaction wave on flame

In this case, the premixed mixture was ignited by electrode 2. After ignition, the flame front propagated leftwards, while the rarefaction wave moved rightward due to the membrane rupture. When rarefaction wave encountered flame front, they may overlap and intervene each other. The interaction would influence the flame front configuration and the characteristic of flow field.

2.2.1 Analysis on high speed Schlieren images

Fig. 6 shows the high speed Schlieren images of counterflow rarefaction wave influence on the flame structure. It can be seen that, at the initial stages of combustion, the laminar flame propagated ahead in smooth spherical wave. At time t = 50 ms, the flame front and the rarefaction wave encountered and overlapped, which caused the flame front to transform from convex spherical surface to plane shape (t = 50 ms) firstly, and then to concave front (after t = 51.5 ms). With the interaction of rarefaction wave and flame, the flame front was stretched to a greater flame surface area. When t = 52.5 ms, the flame front configuration became wedge-shaped, and some wrinkles began to appear in the flame front. Here, the whole flame front was turbulent, and the flame profile was clear, indicating that the flame was mid-small scale turbulent combustion. With the turbulence intensity increasing, the wedge-shaped flame front expanded quickly and reached the maximum at t = 53 ms. After then, the flame front grew narrow and the flame profile became blurry gradually. In the course of flame propagating, the V shape turbulent flame front once came into being from time t = 55 to 56.5 ms. Hereafter, the whole flame front became plane surface and propagated ahead with homogeneous and intensive turbulence combustion.

Fig. 7 shows the relations of flame front position and flame speed with time during the course of counterflow rarefaction wave-flame interaction. It is clear that laminar flame was not affected by rarefaction wave at the initial stages of the flame development, and the flame speed changed little. After the flame encountered rarefaction wave at $t=50$ ms, the flame speed rose up to more than 70 m/s quickly due to the interference of rarefaction wave. After then, there appeared sharp vibration on the speed curve. Comparing with the Schlieren images in Fig. 6, just the interaction between counterflow rarefaction wave and flame caused the flame speed to increase on the whole, simultaneously accompanied with great fluctuations, all which further led to the flame transition from laminar to turbulence.

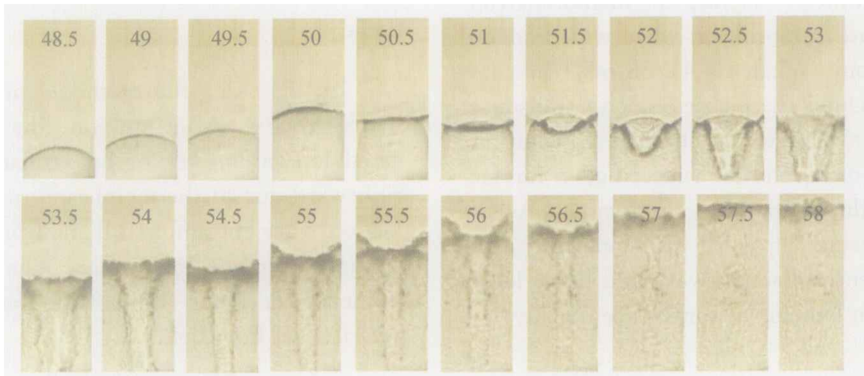

Fig. 6. High speed Schlieren images in the case of counterflow rarefaction wave-flame interaction (Unit: ms).

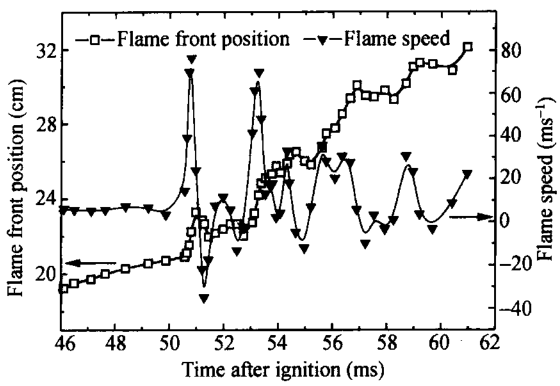

Fig. 7. Relationship between the flame front position and propagation speed with time in the case of counterflow rarefaction wave-flame interaction.

2.2.2 Analysis on pressure measuring results

The pressure variation with time is shown in Fig. 8. Curves (a) and (b) show the pressure value of additional room and chief combustion chamber respectively. At the initial stages, the pressure value of additional room kept constant. When the membrane broke at $t = 50$ ms, compression wave reached the bottom of the additional room, and caused the pressure signal to increase rapidly. After time $t = 50.3$ ms, the pressure value rose slowly with time, and obvious pressure fluctuations appeared on curve (a).

Before the membrane ruptured, curve (b) increased linearly with time on the whole. When the membrane broke, a rarefaction wave was induced to move rightwards in the chief combustion chamber. When flame front encountered rarefaction wave at $t=50.39$ ms, distinct pressure fluctuation signal occurred due to the interaction between flame and rarefaction wave. Coupled with the Schlieren images in Fig. 6, it can be seen that the pressure fluctuation promoted the flame front transformation, and finally led to the transition from laminar flame to turbulence.

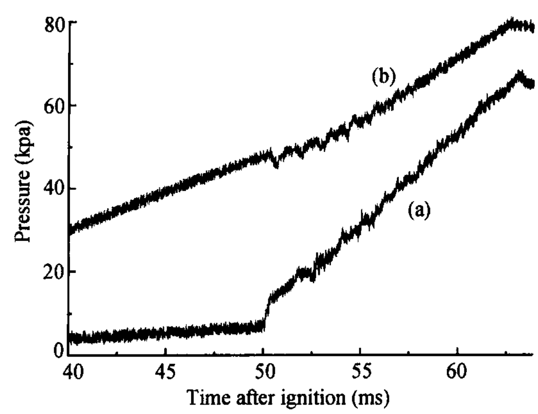

Fig. 8. Relationship between the pipe pressure variations with time in the case of counterflow rarefaction wave-flame interaction: (a) pressure in additional room; (b) pressure in chief combustion vessel.

3 Conclusions

In this paper, the interaction of premixed propane-air flame and rarefaction was studied. Two cases of rarefaction wave were induced to intervene in the flame. In the test, high speed Schlieren image and pressure measuring technology were used to record the flame front structure and flow field behavior. Based on the result and discussion, some conclusions can be drawn as follows:

(1) Rarefaction wave has a great influence on flame configuration and flame propagation behavior. When encountered with rarefaction wave, the flame is induced to quickly change from laminar to turbulence due to the rarefaction wave-flame interaction. During the course of flame propagation, the turbulence intensity is strengthened with time, and intensive turbulence comes into being in about 6 ms.

(2) The coflow and counterflow rarefaction wave can make different effect on flame configuration. In the case of coflow rarefaction wave-flame interaction, the interference of rarefaction wave causes the flame front transform to dentiform configuration firstly; here strong turbulence exists in only part of the flame front. With the flame propagation, intensive turbulence spreads to the whole flame front in the end. However, in the case of counterflow rarefaction wave-flame interaction, the wedge-shaped flame front structure is induced by the interference of counterflow rarefaction wave. Subsequently, the turbulence is intensified gradually throughout the whole flame front.

(3) The coflow rarefaction wave decelerates the flame speed on the whole, even once causes the flame to propagate reversely. After the turbulence became strong enough, the flame speed rises quickly again. However, counterflow rarefaction wave can speedup flame propagating on the whole, simultaneously accompanied with sharp fluctuations.

(4) During the course of flame structure change induced by rarefaction wave, obvious pressure fluctuation also comes into being, which further accelerates the laminar-turbulent transition.

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