Investigation of an Unsteady Flame Propagating in a Curved Duct

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Abstract

Knowledge of behaviors of flame propagating in a curved duct is of great importance to prevent damage in practical industry. In this study, the premixed propane/air flame propagating through a square cross-section duct with a 90° bend was investigated. The high video camera and schlieren image technique were used to record the development of flame front structure. Ionization probes were applied to capture the characteristics of the flow field. Two cases of ignition positions were performed in the experiments. When ignition in the horizontal section, a tulip flame was formed and transition to turbulent flame occurred in the horizontal section. A blunt flame front was kept in the bend and the turbulence intensity was enhanced. However, when ignited in the vertical section, the keen-edged flame tip moved quickly along the lower wall of the bend. The flame kept laminar in the vertical section and bend. Only some weak turbulence was formed in the horizontal section. And the fluctuation of flame velocity was suggested mainly due to the variation of flame front surface area and turbulent combustion.

Keywords: ignition positions, premixed flame, curved duct, schlieren image, turbulent combustion

1. Introduction

Recent years, to promote the adjustment of industrial and energy structure of china, more and more petroleum gas and natural gas are transported and used to replace coal, such as the construction of the West-East Gas Pipe Project. Also it is well known that flammable gas explosions are potential hazards in industry engineering and daily life. Accident statistics of fires and explosions show that flammable gas causes more losses than other materials, which are involved in 90% of the total accidents [1]. Therefore, it is important to reveal the gas explosion mechanisms, and so that to predict and suppress these disasters with proper methods.

In order to achieve this target, it is necessary to investigate the flammable gas-air combustion process. Most studies of this type have been performed for straight duct. Dobashi [2] experimentally studied the effects on gas explosion behavior of gas flow turbulence, combustible gas concentration distribution and flame front instability. Bychkov [3] considered acceleration of premixed laminar flame in the early stages of burning in long tubes and develop the analytical theory to determine the growth rate, the total acceleration time and the increase of the flame surface area. Razus [4-6] made a series of experiments to evaluate the explosion characteristics of hydrocarbon-air mixtures in closed vessels. Gonzalez [7] simulated the last stage of the propagation of a premixed flame in a closed tube. The results showed that the flame front displaying a cellular structure was connected with the acoustic waves. Zhou [8] and Li [9] conducted experiments to study the tube diameter effect on deflagration flame and deflagration-to-detonation run-up distance of propane-oxygen mixtures.

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To explore the interaction between pressure wave and flame front, experiments in a small scale rectangular duct with methane- and propane-air mixture were carried out by Chen [8] and Sun [9] respectively. The authors discussed the interaction process and flame transition from laminar to turbulence.

However, practical ducts in industry usually consist of non-straight sections, such as T junctions, 90° bend or crosses. Thus, realizing the influence of these sections on flame propagation characteristics is also important for industrial safety and people lives. Preliminary studies on flame propagation in bends were conducted by some researchers. Sato [10] examined flame propagation in a small, open square duct including a 90° bend, both experimentally and numerically. It was revealed that the flame behavior around the bend is determined primarily by the nature of unburned gas flow toward the open end. Zhou [11] investigated a laminar flame in a closed rectangular duct with a 90° bend, and found a “flame shedding” phenomena and its cause of formation.

Although some important findings are revealed through these studies, the mechanism of flame propagation in curved duct is still ambiguous. In this paper, the flame structure and flame propagating behaviors are discussed based on the experimental results using schlieren image technique, high speed camera and ionization probes, in order to complete the data and well understand the flame propagation phenomena through the curved duct.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

Experiments were performed in a self-made small scale combustion duct. The experimental apparatus is composed of a mixture supplying part, a combustion duct, an ignition part, a data measurement setup, a controller part and a high speed schlieren image system. The combustion duct comprises a long straight horizontal section, a 90° bend and a short straight vertical section, with a square cross-section of 8cm × 8cm. The lengths of horizontal and vertical section are 50cm and 10cm, respectively. The 90° bend has an internal radius of 8cm and an external radius of 16cm. For observing and recording flame propagation process conveniently, side panels of the combustion chamber are made of K9 optical glass. All remaining structural parts are made of stainless steel. Two pairs of tungsten electrodes mounted at the horizontal section and vertical section are used to ignite the mixture, which locate 3cm apart from the endplate. A high voltage transformer of 25kV is used to produce an ignition spark. Three ionization probes are mounted on the lower surface and protruded 1.2 cm into the duct, two in the horizontal section and the other in the middle of the bend. The detailed structure of the curved duct is shown in Fig. 1.

![Fig. 1. Detailed structure of the curved combustion duct](image)

2.2. Experimental procedure

After 10 min of evacuation of the duct down to a pressure of 0.5kPa absolute, the mixed propane-air mixture was loaded in to the apparatus to a final pressure of 100kPa absolute. Ignition of the mixture is facilitated through the spark discharge. Then a flame propagates from the spark location towards the unburned reactants. The flame propagation process is recorded by the high speed video camera and schlieren image system.

The startup time of the ignition, high speed video camera and data recorder are set and controlled by a synchronization
controller.

The detailed experiment conditions are given as follows:

- Equivalence ratio of propane/air mixture: $\Phi = 0.8$;
- Ignition voltage: $25,000\text{V}$;
- Recording speed of the high speed camera: $2,000\text{ frames/second}$.

3. Results and discussion

3.1. Ignition in horizontal section

In this case, the premixed mixture was ignited by electrodes installed in horizontal section. The flame front propagated from left to right in the duct. When pressure in the chamber was up to a certain number, the membrane which was covered on the opening of vertical section would rupture. The whole process of premixed flame propagation in the curved duct was recorded by high speed schlieren system and ionization probes.

(1) Flame shape development

Combustion induces ample density changes in the medium through which it propagates. Therefore, density-sensitive visualization methods are an obvious choice for the optical recording of these phenomena [12]. Schlieren technique is applied in our research.

Fig. 2 is a series of high speed schlieren image photographs, depicting the flame propagation process and flame front structure. Flame was ignited at the axis of the left end of the duct. Then the premixed propane-air flame propagated towards the unburned mixture. At the beginning, flame expanded as a spherical front and generated an expanding source flow. However, as the flame came close to the walls, the flow in the radial direction was stopped, which made the flow in the axial direction stronger and induced flame acceleration. Then the flame front achieved a finger shape. The acceleration stopped when the flame skirt touched the wall. Then one outstanding phenomenon called “tulip flame” was observed. At $t=75\text{ms}$, the tulip flame formed completely.

After $t=95\text{ms}$, the flame front approached the bend. It dispersed in a wide region, unlike a thin flame front separated the burned and unburned mixtures before, and the tulip flame collapsed gradually. $120\text{ ms}$ after ignition, the flame front outline became a blur. Its branch at the lower side propagated much faster and exceeded that at the upper wall. With time going on, the branch at the lower wall was elongated while that at the upper wall almost died out. At $t=160\text{ms}$, the membrane broken and the combustion system discharged.
(2) Flame propagation velocity

Fig. 3 illustrates flame propagation velocity (the propagation velocity of the flame tip) versus time determined by examining the movement of the schlieren front. It is clearly that the flame did not move at a constant velocity. The flame accelerated in the horizontal inlet section as the mixture was ignited at a closed end. 44ms after ignition, flame front came into contact with the walls. Indeed, since the surface area of the radial part takes up the majority of the total surface area of the flame front, its disappearance would result in a significant reduction in expanding burned gas generation and heat release rate. Hence the acceleration was followed by a noticeable deceleration. At $t=78\text{ms}$, it got the minimum about 2m/s. When the flame front came around the bend about $t=110\text{ms}$, the flame tip moved rapidly, resulting in large flame surface area and also large flame velocity. However, by the closed end of the vertical section, the flame tip decelerated before venting. In a word, the fluctuation of flame propagation velocity was mainly due to the fluctuation of the total flame areas; usually larger flame areas could drive a faster flame propagation velocity.

(3) Ion current results

Fig. 4 shows the ion current profiles at three different measuring points when ignition in the horizontal section. From Fig. 4 (a), we can find that, 49.7ms after ignition, flame front reached the ionization probe and ion current began to increase. It increased quickly before 51ms and got the maximum value at 51ms. After that, it decreased to zero in 2ms. This profile was so smooth and it could be deduced that at this moment the flame was laminar combined with schlieren images. Fig. 4(b) and (c) show the ion current signals obtained at measuring point 2 and measuring point 3, which lagged behind point 1 about 45ms and 93ms respectively. Some small fluctuations appeared in both of the two profiles. About measuring point 2, the rise phase was similar with that of measuring point 1, but in the downward phase, great fluctuations turned up. From schlieren images, we can observe that the flame front was tore severely and flame thickness significantly increased. So after a rapid decline phase, the ion current decreased slowly. About measuring point 3, it is worth noting that the peak value fluctuated remarkably and greater fluctuations appeared compared to measuring point 2. Therefore, based on the ion measurements and schlieren photographs, a conclusion can be drawn that in the horizontal section, premixed flame transformed from laminar to turbulence, and the turbulent combustion strengthened in the bend.
3.2. Ignition in vertical section

In this case, the premixed mixture was ignited by electrodes installed in vertical section. The flame front propagated upward then leftward through the duct. The bend configuration would affect and influence the flame structure and the characteristics of the flow field.

(1) Flame shape development

As a comparison with the case of ignition in the horizontal section, Fig. 5 shows propagation process of the premixed flame which was ignited in the vertical section. It can be seen that, at the initial stage of flame development, the flame front was a convex spherical surface, like the former case. However, due to the shorter distance to the bend, flame front entered the configuration quickly ($t=28\text{ms}$). During close approach to the bend, a remarkable flame front deformation occurred. The symmetrical hemispherical structure disappeared, and the flame tip moved from the axial line toward the lower wall ($t=31\text{ms}$). Then the flame tip rounded the bend with greater velocity, while the local movement of flame front at the upper wall was small. Consequently, protraction of flame front along the lower wall increased with time. At $t=40\text{ms}$ a cusp was formed.

In the period between $t=50\text{ms}$ to $t=103\text{ms}$, the flame propagated in the horizontal section until venting and it presented a number of interesting features. After coming into this region, the flame front close to the lower side wall slowed down, while that close to the upper side wall accelerated. Then an arc shape came into being, instead of the cusp. Around $t=60\text{ms}$, an inversion was initiated in the flame front close to the lower wall, not in the centerline. Meanwhile, flame front thickened in this process and some small wrinkles appeared in the upper branch of the flame front, which should increase the flame surface area ($t=65\text{ms}$). After $t=70\text{ms}$, the thickness of the bifurcated flame front became different with each other. From the schlieren images it can be seen that the thickness of upper flame branch grew much bigger, which may be several times than that of lower flame branch ($t=85\text{ms}$). After then, the upper flame front became unstable and the turbulent flame region grew rapidly.
(2) Flame propagation velocity

Fig. 6 shows the relationship between flame propagation velocity and time. As shown in this figure, at the initial stage of flame development, the flame propagation velocity increased with time. After \( t = 28 \text{ ms} \), when the flame encountered the bend, flame structure and flame surface area changed, which induced fluctuation to flame propagation velocity. When \( t = 41 \text{ ms} \), the flame front was about to leave the bend and the flame velocity rose up to the maximum about 16m/s. During the period between \( t = 50 \text{ ms} \) to \( t = 103 \text{ ms} \), the flame passed in the horizontal section. As the flame surface area which was quenched at the upper side wall increased, the flame propagation velocity decreased gradually. Around \( t = 60 \text{ ms} \), a cusp appeared, and subsequently the turbulence in the flame front increased. The flame propagated slowly with oscillatory behavior and the flame velocity fluctuated periodically until venting.

(3) Ion current results

Fig. 7 shows the ion current profiles of propane/air premixed flame at three different measuring points when ignition in the vertical section. Flame front reached the probes at \( t = 35.2 \text{ ms}, 44 \text{ ms} \) and \( 76 \text{ ms} \) respectively. Relative to the case of ignition in the horizontal section, the three profiles were much smoother, only some small fluctuations were presented in the profile of measuring point 1, where a concave flame shape had been formed. Likewise, a conclusion we can make as follows: the premixed flame kept laminar in the vertical section and bend, and only weak turbulent combustion came into being in the flame front at the final stage when it propagated in the horizontal section.
4. Results and discussion

The unsteady propane-air premixed flame propagating in a curved duct was investigated experimentally. Two cases of ignition positions were considered in the research. High speed schlieren image system and ionization probes were used to record the flame front structure and propagation behavior. The following results were obtained:

For ignition in the horizontal section, a tulip shape flame was formed in the horizontal part 75ms after ignition, but it collapsed in the bend. Around the bend, the blunt flame front proceeded more quickly near the lower wall than that near the upper wall. In the process, the premixed flame transformed from laminar to turbulence in horizontal section and the turbulence intensity was strengthened in the bend. Simultaneously, high flame velocity occurred in the horizontal section. After a deceleration period, the flame propagation velocity increased for a while in the bend.

For ignition in the vertical section, as a shorter distance to the bend, the keen-edged flame tip moved much faster near the lower wall with an elongated flame front toward the axial direction. And an inversion in the flame front near the lower side wall happened around t=60ms. In this process, the premixed flame kept laminar in the vertical section and bend. Only some weak turbulence was formed at the final stage. High flame velocity occurred in the bend, and an oscillatory behavior was presented in the horizontal section.

It is suggested that the fluctuation of flame velocity is due primarily to the variation of total flame front surface area and turbulence intensity in the flame front.

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