

Chapter 2

Experiments of Premixed Hydrogen–Air Flame Propagation in Ducts

2.1 Introduction

Experimental study is essential for revealing new phenomena of flame propagation and developing new theory and numerical models [1]. For flame propagation in tubes, most of the previous studies primarily focused on flame acceleration and DDT [2–5] while fewer studies on detailed flame structure and shape changes [6]. The usual combustible gases used were hydrocarbons such as methane, propane, and ethylene [7–11]. Although hydrogen–air flames may differ from those of hydrocarbons [12], the study of premixed hydrogen–air flame propagation in tubes is not enough. With emerging hydrogen economy, large-scale experiments of hydrogen–air explosions in open spaces and tunnels were carried out [12–18], aiming to provide data for safety evaluation and validation of numerical models. In these works, primary attention was paid to explosion dynamics parameters, namely overpressure, pressure rise rate, flame speed, and the influence of obstacles arranged beforehand. The information on detailed premixed hydrogen–air flame shape changes, characteristics, and dynamics included in this work could also be used to assess the accuracy and robustness of the theoretical and numerical models/assumptions.

In this experimental study, to further reveal premixed hydrogen–air flame behaviors, characteristics, and mechanisms, and to elucidate the effects of equivalence ratio, opening area, and gravity on flame dynamics, an experimental system of premixed flame propagation is constructed and a series of experiments are conducted.

2.2 Experimental Setup and Methods

The experimental setup is shown in Fig. 2.1. It consists of a constant volume combustion vessel, a high-speed schlieren cinematography system, a pressure recording system, a gas mixing system, a high-voltage ignition system, and a synchronization controller.

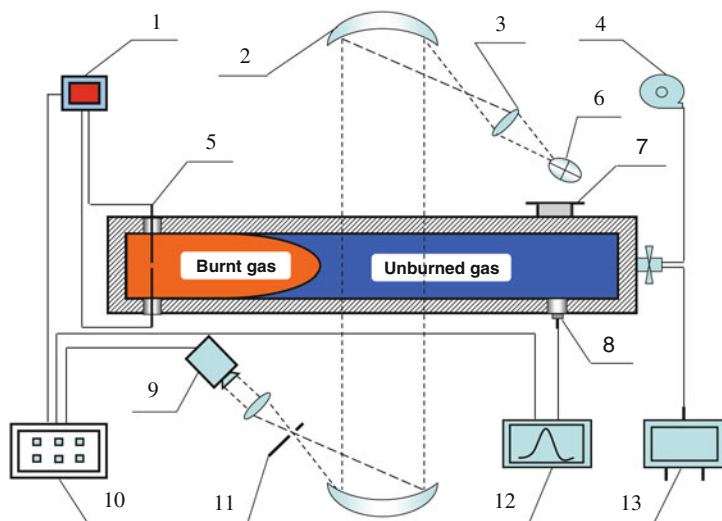


Fig. 2.1 Sketch of experimental apparatus: (1) spark igniter, (2) schlieren mirror, (3) focusing lens, (4) vacuum pump, (5) ignition electrode, (6) point light source, (7) discharge vent, (8) pressure transducer, (9) high-speed video camera, (10) synchronization controller, (11) knife edge, (12) data recorder, (13) gas mixing device

2.2.1 Combustion Tube

The combustion vessel is a rectangular duct 82 mm square by 530 mm long. Parallel side walls are important for schlieren photography and there is little qualitative difference between tulip formation in square cross-section and circular cross-section tubes [11]. The duct is placed horizontally in the center of the schlieren optical path. The two side panels of the duct are made of quartz glass with a thickness of 1.6 cm to provide optical access, while the upper and lower walls are made of TP304 stainless steel with a thickness of 1.5 cm. An ignition electrode is placed at the duct axis at a distance of 5.5 cm from the left-end wall. A mounting hole is located at the bottom of the duct for installation of pressure transducer, at a distance of 7.5 cm from the right-end wall. Two valves are set in the right-end wall for gas filling and tube vacuuming. A discharge vent, which is initially closed, is setup close to the right end of the duct for safety. The vent is a circle with a diameter of 4.0 cm and its center is located at a distance of 7.5 cm from the right-end wall.

2.2.2 Gas Mixture Preparation and Filling System

The gas mixture preparation and filling system is schematically shown in Fig. 2.2. The mixture is a combination of pure hydrogen and dry air. The hydrogen

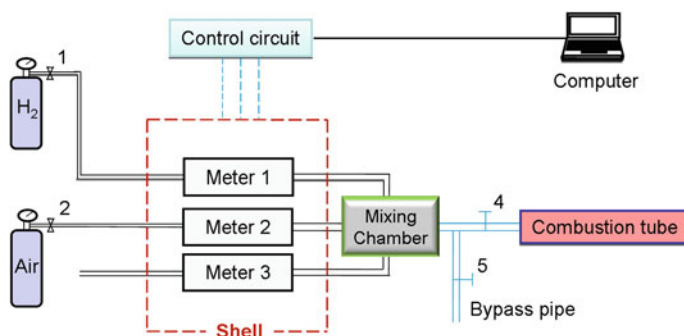


Fig. 2.2 Schematic of hydrogen–air mixture preparation and filling system

concentration is controlled using high-precision mass flow meters 1 and 2 in the experiments. Note that mass flow meter 3 is designed for future experiments on effect of addition of inhibitor gases on flame dynamics.

Before mixture preparation, the system should run at least 20 min to warm up itself. When preparing the mixture, first set the hydrogen concentration and mass flow rate in the computer, then open valves 1, 2, and 4 and close valve 3. The pressure gauges of hydrogen and air gas cylinders 1 and 2 should be kept around 2.5 atm during the gas preparation process. Hydrogen and air are mixed in the premixing chamber. The system needs approximately 1 min to stabilize the hydrogen concentration, and the equivalence ratio of the prepared mixture within the first 1 min may differ from the target ratio. Thus the mixture at the first 1 min should be discharged into open air through valve 4 of the bypass pipe. After that, close valve 4 and open valve 3. The premixed hydrogen–air mixture enters into the combustion tube. When the pressure inside the tube reaches 1 atm, stop filling. When a set of tests are finished, valves 1 and 2 need to be closed to prevent gas leak. If the tube is filled with mixture by purging, the purging time is 3–5 min for fuel-lean mixture and 5–10 min for fuel-rich mixture.

2.2.3 High-Voltage Ignition System

In laboratory and industry, there are various ignition techniques, e.g., chemical ignition, high-voltage electrode, spark, compression, and laser. Chemical ignition source such as priming can be very strong, and it is usually used for engineering blasting or detonation initiation. Most of the explosion accidents in industries are due to weak ignition source. In order to mimic general explosion process in industries, a weak ignition technique, i.e., capacitor discharging, is adopted. A home-designed high-voltage pulse generator Model 2002-1 is applied to charge the capacitor by normal alternating current. When discharging, the voltage is increased by a ratio of 50:1. A transient high voltage is imposed to the electrodes which subsequently create spark for ignition.

The spark energy released by the high-voltage electrodes depends on the stored energy in the capacitor [19]:

$$E = \frac{1}{2}CU^2, \quad (2.1)$$

where E is the stored energy in the capacitor (J), $C = 200.0 \mu\text{F}$ is the capacitance, and $U = 300.0 \text{ V}$ is the charging voltage. The stored energy calculated by Eq. (2.1) is 9.0 J. The ignition system is triggered by the synchronization device.

2.2.4 High-Speed Photography System

The high-speed photo camera employed in the experiment is the Fastcam Ultima APX model produced by Photron company. A high-photosensitivity CMOS sensor with one million pixels is used in the camera. CMOS sensor is an advanced type of sensor with good performance of anti-disturbance. An electronic shutter of $4 \mu\text{s}$ ensures the fidelity and accuracy of images. It is very important for capturing a high-speed transient flame. The camera is composed of high-speed processor, CCD, and LCD, as shown in Fig. 2.3. The maximum speed of the camera is 120,000 fps. The speed can be 2,000 fps with a 1024×1024 resolution. Reducing the resolution increases the speed. In the present experiments, the operating speed is chosen to be 10,000–15,000 fps depending on the actual flame speed since hydrogen–air flames generally propagate very fast.

Fig. 2.3 Photograph of high-speed photo camera



2.2.5 Schlieren Optics System

A flame is a strong discontinuity of density, so that there is a large density gradient of flow across the flame front. Because the refractive index of gas is proportional to density, when a light passes through a density discontinuity its position, direction, and path can be deviated. Thus the flame front (density discontinuity) can be captured using optical measurements without disturbing the internal flow field. Schlieren, shadowgraph, and interferometric techniques are three common optical methods for recording changes of flow features [20]. Shadowgraph measures the second derivative of density, namely the displacement of light beam. Schlieren technique records the derivative of density, i.e., the deflection angle of light. Both schlieren and shadowgraph techniques give the variation of density gradient of flow field. Interferometry records the phase difference of light and can be used for quantitative measurement of flow field. In this work, the schlieren technique along with the high-speed camera is used to record the dynamics of flame front propagation.

Schlieren photography has been widely used for many years in science and industry of fluid flow, combustion, boundary layer, gas convection, and wind tunnel. It was proposed by Toepler in 1884 and was applied in the detection of refractive index of optical glass [21]. Schlieren is also commonly used in the visualization of flow field during transient flame propagation [22]. In a schlieren system, the image from the light source is cut by a knife edge, so that the disturbance of lights caused by features of flow field can be described by a light intensity distribution on a plane [23].

The Schlieren system in the present experiment is arranged in a standard Z-configuration with the combustion tube placed in the center of the optical path, as show in Fig. 2.4. The light source is an iodine lamp with a 2.0 mm aperture. The aperture is used to create a point light source. The light rays from the source become parallel light rays after reflected by mirrors M_1 and M_2 . After reflected from

Fig. 2.4 Diagram of optical path of the high-speed schlieren system

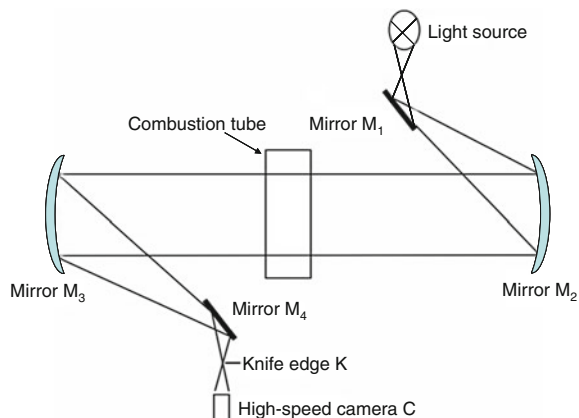




Fig. 2.5 Light source (*upper right*), reflection mirror (*left*), and knife edge (*bottom right*) of the schlieren optics system

M_3 and M_4 , the light rays enter into the camera C. The major components of the schlieren system are shown in Fig. 2.5.

2.2.6 Pressure Transducer

The pressure transient inside the duct is measured using a PCB Piezotronics model 112B10 quartz transducer. This transducer is usually used in internal combustion engines. Its main parameters are as follows: (1) response frequency ≥ 200 kHz, (2) measuring range ≤ 2.0 MPa, and (3) maximum flash temperature 2482 °C.

2.2.7 Data Acquisition Device

The data acquirer in the experiments is a HIOKI data recorder, model 8826, produced by HIOKI company, as shown in Fig. 2.6. The recorder provides various types of input unit and has 32 channels. The sampling rate of each channel is 1 MS/s.

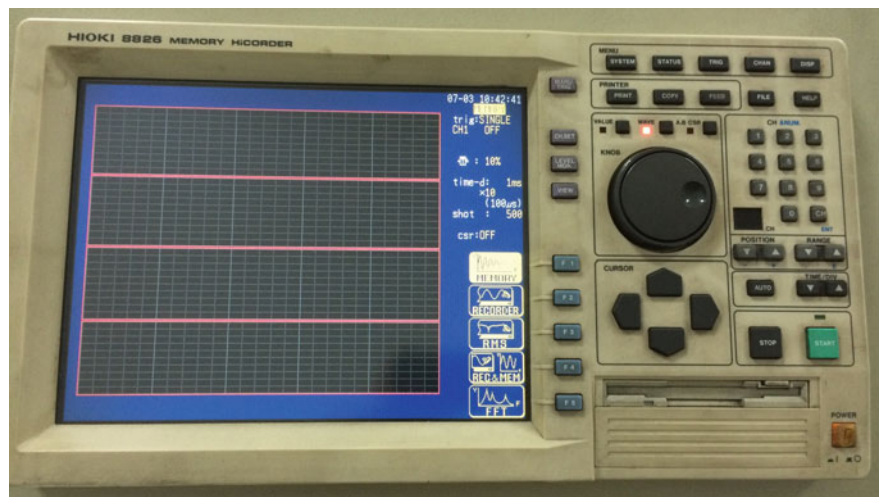


Fig. 2.6 Picture of HIOKI data recorder, model 8826

2.2.8 Synchronization System

The spark igniter, pressure recorder, and high-speed video camera are triggered by the synchronization system in the experiment. The synchronization controller is an OMRON SK20 controller which is a programmable logic controller (PLC). The controller comprises a control panel and a CPU. The commands are programmed into the control panel and stored in the CPU. The triggering time of every terminal is controlled by the CPU. The working principle is shown in Fig. 2.7.

In general, each terminal needs an independent power source with unique voltage, such that each terminal has its own power supply. The direct current (DC) voltages of the high-voltage ignition system and the synchronization controller are 5 and 24 V, respectively. And the DC voltages of both the high-speed camera and data recorder are the same, 3.3 V.

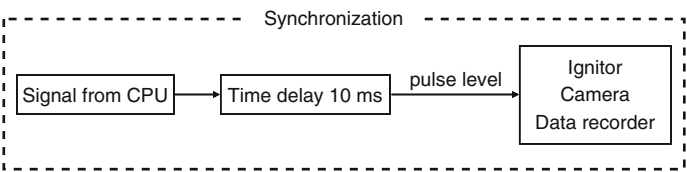


Fig. 2.7 Schematic drawing of working principle of the synchronization system

2.3 Experiment Procedure and Initial Conditions

2.3.1 Methodology

(1) High-speed schlieren photography

The variations in flame structure, shape, and position as a function of time is recorded using the high-speed schlieren system. The flame instabilities that develop during flame propagation can be subsequently analyzed.

(2) Pressure measurement

The pressure dynamics inside ducts is measured using the pressure transducer described above. The pressure data together with the high-speed schlieren records are used to examine the relationships between flame evolution and pressure rise. Then the interactions between flame front and pressure waves can be studied. The effects of various parameters, such as equivalence ratio, gravity, and opening ratio, on the flame propagation can be scrutinized as well.

2.3.2 Procedure

- (1) Setup and test the experimental system, as shown in Fig. 2.1, to ensure that all the units of the system are in good state. The vacuum of the combustion duct needs to be tested as well before experiment when conducting experiments in a closed duct.
- (2) Warm up the gas mixing device for 20 min and then fill the duct with hydrogen–air mixture using the gas mixing device.
- (3) A short time delay of about 30 s is incorporated into the filling sequence before ignition, in order to allow the gas mixture to become substantially quiescent. This is important to ensure the reproducibility of experiments.
- (4) Start the high-voltage ignitor and set the electric voltage to 300 V. And then start the data collector, synchronization controller, and high-speed camera. After that, start the synchronization system to perform a test.
- (5) Store the data recorded by the high-speed schlieren system and pressure transducer. Then repeat the experiment.

2.3.3 Initial Parameters

- (1) Various compositions of hydrogen–air mixture are used in the experiments. The concentration of hydrogen–air mixture used in the experiments ranges from 5 to 75 % in steps of 5 %. In addition, the stoichiometric hydrogen–air mixture is also used. Therefore, 17 different hydrogen–air mixtures are

employed in the experiments. Each test is repeated three to five times to ensure the reproducibility of the experiments.

- (2) The initial pressure and temperature in the duct are 101,325 Pa and 298 K, respectively.
- (3) The mixture is at rest before ignition.
- (4) The vent should be opened immediately before ignition when performing an experiment in a half-open duct. When conducting an experiment in a closed duct, the vent should be closed during the flame propagation. The vent is opened when the pressure inside the duct exceeds the pressure threshold of the vent.

2.4 Experimental Results and Discussion

Although there have been many experimental, numerical, and theoretical studies on premixed flame propagation in tubes, the flame dynamics has not been sufficiently understood [24–26]. Hydrogen–air flame can be different from that of common hydrocarbon–air flames because of the unique properties of hydrogen, especially the wide flammability limits (equivalence ratio $0.1 \leq \Phi \leq 7.14$, i.e., hydrogen concentration 4.0–75.0 % by volume) and large laminar burning velocity (the maximum can be approximately 3.0 m/s) [27]. In the present work, a series of experiments with a wide range of equivalence ratio are conducted in order to further reveal the behaviors and characteristics of hydrogen–air flames propagating in ducts. The dependence of flame propagation on equivalence ratio, laminar burning velocity, and expansion ratio are examined. The effects of gravity and opening ratio on flame evolution are also discussed. The equivalence ratio is conventionally defined as the ratio of the actual hydrogen–air ratio to the stoichiometric hydrogen–air ratio:

$$\Phi = \frac{n_{\text{fuel}}/n_{\text{air}}}{(n_{\text{fuel}}/n_{\text{air}})_{\text{st}}}, \quad (2.2)$$

where n_{fuel} and n_{air} are the mole number of hydrogen and air, respectively. The subscript st denotes stoichiometric.

2.4.1 Hydrogen–Air Flame Propagation in Half-Open Tubes

Under adiabatic conditions a premixed flame can keep a planar front during propagation in a sufficiently narrow channel, whereas in a channel with a width significantly larger than flame thickness it is impossible for a premixed flame to maintain a plane front due to the intrinsic Darrieus–Landau (DL), diffusive-thermal, and

Rayleigh–Taylor (RT) instabilities, etc. [24, 25]. According to Gonzalez et al. [28], the DL instability is always present during the flame formation. On the other hand, Bychkov and Liberman [25] suggested that in order to observe a strongly curved tulip flame as a result of the DL instability in a closed tube, one has to consider tubes of lengths of $200 \delta_L$ and longer. The ducts length in the present work is 530 mm, and the laminar flame thickness of premixed hydrogen–air mixtures is less than 1 mm [29]. So the length scale of the ducts (with length $> 530 L_f$) in the experiment is large enough to support the DL instability. The diffusive-thermal instabilities play a key role when differential diffusion remains significant in premixed flames of lean hydrogen–air mixtures characterized by a Lewis number less than unity [24]. The RT instability develops at an interface between a heavy and a light matter, when the heavy matter is supported by the light one in a gravitational field [25, 30].

A well-known example of premixed flame propagation in a tube has been suggested and investigated by Clanet and Searby [31] in 1996. Four stages of flame dynamics were proposed and demonstrated [31, 32]: (1) hemispherical expansion flame unaffected by the side walls; (2) finger-shaped flame; (3) elongated flame with the skirt touching the sidewalls; and (4) tulip flame. In the present work, the premixed hydrogen–air flames propagating in the half-open duct exhibit more important information on the premixed flame behaviors and characteristics.

Figure 2.8 shows a series of representative high-speed schlieren images of premixed hydrogen–air flame shape during propagation in the half-open duct at

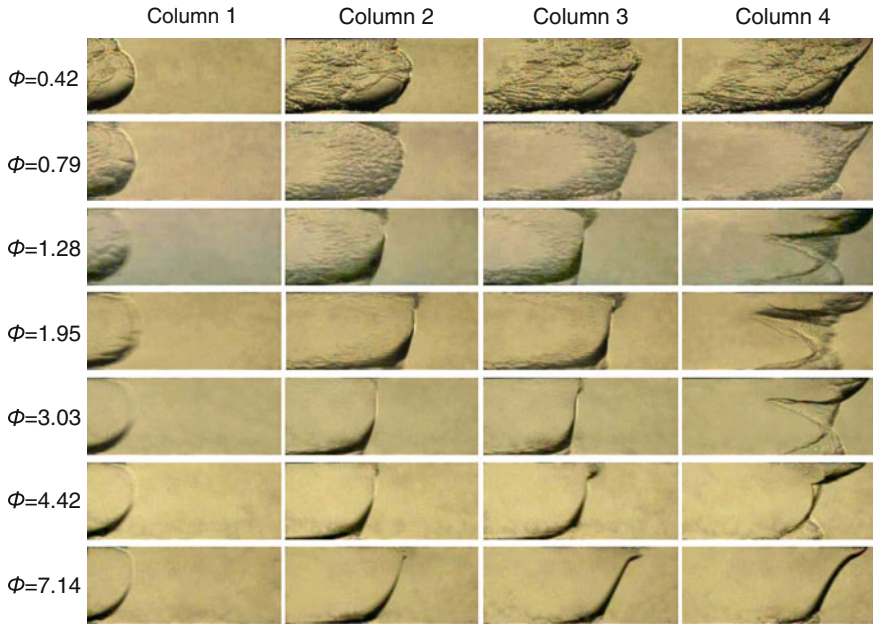


Fig. 2.8 High-speed schlieren images of premixed hydrogen–air flame shape changes during propagation in a half-open duct at various equivalence ratios

various equivalence ratios. The first column indicates the finger-shaped flame front. The second column displays the flame shape with the small parts near the side walls traveling faster than the central region of the flame before the flame front becomes a quasi-plane, as shown in the third column. The fourth column shows the flame shape (tulip flame for some cases) after the formation of quasi-plane flame. Classical tulip flame is observed only at equivalence ratios in the range of $1.17 \leq \Phi \leq 4.05$ in the experiments. The experimental results indicate that at equivalence ratios $0.10 < \Phi < 1.17$ and $4.05 < \Phi \leq 7.14$ the tulip flame could not form, and only the first three stages distinguished by Clanet and Searby can be identified. However, even though no tulip flame forms, a quasi-flatten flame front (actually not exactly plane) will always appear, as shown in Fig. 2.8, except the flame at equivalence ratios very close to the lean flammability limit ($\Phi < 0.36$). In fact, at this low equivalence ratio, the flame advances at a relatively low speed along the upper wall as a result of buoyancy.

In the experiments, an exact plane flame shape is not formed but a quasi-plane flame front is produced at equivalence ratios in the range of $0.36 \leq \Phi \leq 7.14$, as shown in the third column in Fig. 2.8. The quasi-plane flame is an inclined front with the upper and lower small leading tips advancing faster than the central region, forming almost a “I” shape front when $0.67 \leq \Phi \leq 7.14$. The obliquity becomes larger as equivalence ratio gets closer to lean or rich flammability limit. In addition, the upper and/or lower parts of the front have already traveled with a higher speed than the central region just before the formation of the quasi-plane front, as shown in the third column in Fig. 2.8. This phenomenon may be explained by the “squish flow” suggested and discussed by Dunn-Rankin et al. [33] and Gonzalez et al. [28]. “Squish flow” is an accelerated flow which is generated in the unburned region wedged by the flame front and the side walls just ahead of the flame front. The “squish flow” during premixed hydrogen–air flame propagation is more pronounced due to high diffusivity and high laminar burning velocity of hydrogen. “Squish flow” can drive the flame to propagate faster near the walls than in the central region; however, it is not the essential cause that initiates the tulip formation. When equivalence ratio in the range of $0.67 \leq \Phi < 1.17$ and $\Phi > 4.05$, though the squish flow is active, no tulip flame is observed as shown in Fig. 2.8. The “squish flow” is weaker near the lower wall than the upper wall due to the buoyancy. It is also found that with the decreasing of equivalence ratio, the wrinkles become more pronounced. Under the experimental conditions in this work, molecular diffusion acts to stabilize the short wavelength disturbances, and a smooth flame front results for rich hydrogen–air mixtures, whereas the diffusive-thermal instability obviously wrinkles the flame surface in lean hydrogen–air flames.

2.4.2 Hydrogen–Air Flame Propagation in Closed Tubes

Figure 2.9 shows a series of representative high-speed schlieren images of premixed hydrogen–air flame shape changes during propagation at various equivalence ratios

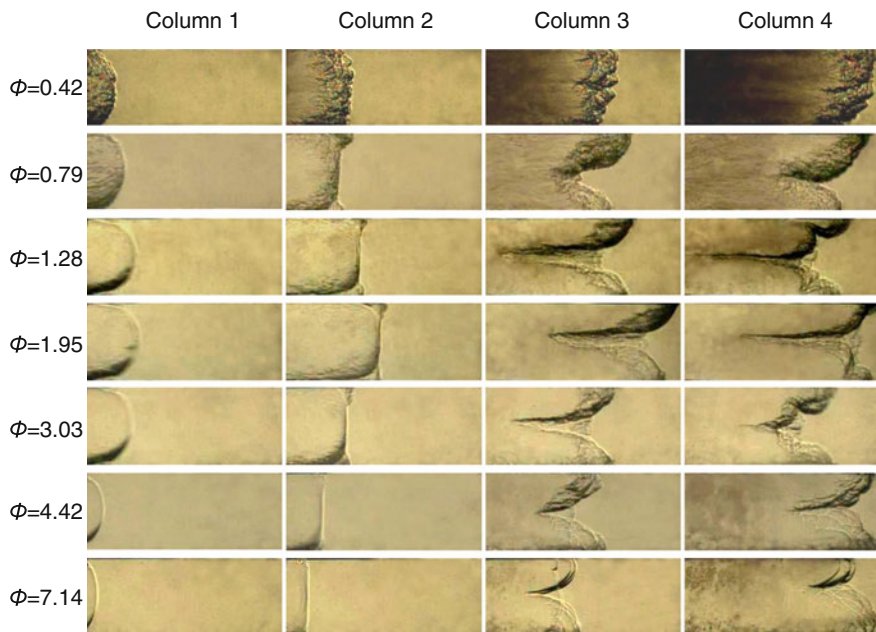


Fig. 2.9 High-speed schlieren images of flame premixed hydrogen–air shape changes during propagation in a closed duct at various equivalence ratios

in closed duct. The first column indicates the ordinary finger-shaped flame front before the flame front transforms significantly into a quasi-plane/plane front, as shown in the second column. The third column designates the complete tulip flame except $\Phi = 0.42$. The fourth column represents the development of tulip flame after its full formation except $\Phi = 0.42$, and the obvious distortion of tulip flame appears at some equivalence ratios. The flame shape shows no distinct change after plane flame formation at $\Phi = 0.42$.

In the experiment, an important finding is that when $\Phi < 0.49$, tulip flame would not be initiated anymore, and when $0.49 \leq \Phi < 0.84$ and $4.22 < \Phi \leq 7.14$, a classical tulip flame, which has been widely described and studied [11, 28, 31, 32, 34], will be produced without apparent distortion. Another outstanding finding in the premixed hydrogen–air propagation is that significant distortion, with the two tulip lips bent/dented obviously from its center to duct sidewalls, will happen to tulip flame after its complete formation when Φ ranges from 0.84 to 4.22, for example $\Phi = 1.28, 1.95$, and 3.03, as shown in Fig. 2.9. Moreover, a normal tulip flame is observed to be reproduced after distortion at $0.84 \leq \Phi \leq 1.12$ and $2.58 \leq \Phi \leq 4.22$. The development of tulip flame after its distortion was not captured at other equivalence ratios as they are out of the measuring range of the schlieren system. The behaviors and dynamics of distorted tulip flame will be discussed in detail in the next two subsections.

In addition, when $0.52 < \Phi < 5.82$, an exact plane flame could never be formed instead the flame displays a quasi-plane front with the leading edges very close to the side walls of the flame front propagating faster than the central region, e.g., at $\Phi = 1.28, 1.95, 3.03$, and 4.22 , as shown in the second column in Fig. 2.9. This may also be due to the “squish flow,” which has been interpreted in the last section. It should be noted that a plane flame is formed at other equivalence ratios except extremely low equivalence ratios ($\Phi < 0.36$) because the relatively low laminar burning velocity may reduce the effects of the “squish flow.” This proves again that the “squish flow” is not important for tulip formation. And the plane flame front will be wrinkled in very lean hydrogen–air flames due to combustion instabilities, e.g., when $\Phi = 0.42$ as shown in Fig. 2.9.

Experiments in this work also indicate that the flame front instability in closed duct shows the same tendency as that in half-open duct described in the last section, as shown in Fig. 2.9. However, more intense flame disturbance is induced in closed duct due to the higher pressure, and even at extremely high equivalence ratios the wrinkles appear after flame inversion. This can be explained by the fact that as the pressure increases during the propagation in closed duct the flame front becomes thinner, and consequently the hydrodynamic instability is enhanced [24, 35].

2.4.3 Behaviors and Characteristics of Distorted Tulip Flames

The experimental results indicate that more intense tulip flame distortion is generated when equivalence ratio is in the range of $1.12 \leq \Phi \leq 2.58$ than in other cases; meanwhile, the position of the distortion gets closer to the right end of duct, for example $\Phi = 1.28$ and 1.95 , as shown in Fig. 2.9. In order to investigate the behaviors and dynamics of the flame with tulip distortion (distorted tulip flame), the premixed hydrogen–air flame propagation accompanied by full tulip distortion development at $\Phi = 3.03$ is taken as the typical case. Figure 2.10 illustrates the typical evolution of premixed hydrogen–air flame with tulip formation and twice distortions at $\Phi = 3.03$ (Fig. 2.10a), as well as schematic classical tulip flame formation (Fig. 2.10b) and schematic premixed hydrogen–air flame shape changes with tulip flame distortion (Fig. 2.10c). In this case, a normal tulip flame is produced once more after its first distortion and then a second distortion is produced again. The flame shapes undergoes more complex changes than classical tulip flame, as shown in Fig. 2.10. The schlieren images show that the tulip is initiated just after the flame burns out at the side walls and then a complete tulip flame is formed. As the flame moves on, two distortions will be produced one after another.

Figure 2.11 shows the relationship between normalized pressure and flame front speed in the propagation direction versus reduced time at $\Phi = 3.03$. The time scale is reduced by W/S_{Lo} , where W is the width of the duct cross-section and S_{Lo} is the laminar burning velocity. W/S_{Lo} is twice of the time scale for the flame to reach the

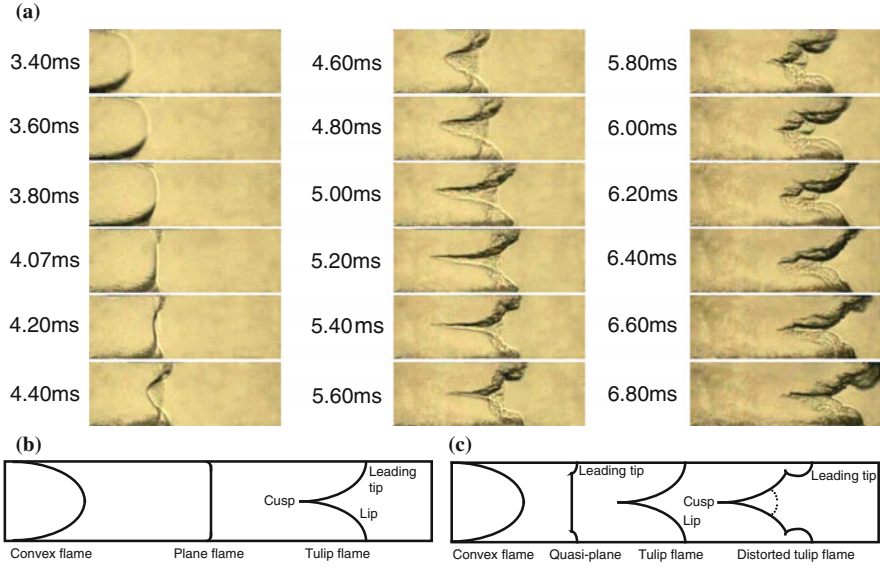
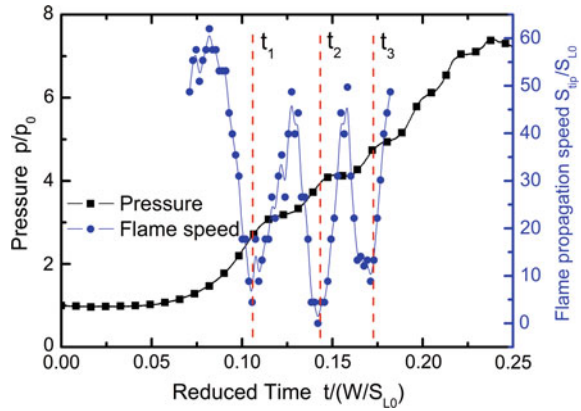


Fig. 2.10 **a** High-speed schlieren images of premixed hydrogen–air flame at $\Phi = 3.03$. **b** Schematic figure showing classical tulip flame formation. **c** Schematic figure showing distorted tulip flame during premixed hydrogen–air flame propagation

Fig. 2.11 Relationship between normalized pressure and speed of flame front versus reduced time at $\Phi = 3.03$. $P_0 = 101,325$ Pa. $t_1 = 0.106$ (3.87 ms), $t_2 = 0.142$ (5.20 ms), $t_3 = 0.173$ (6.33 ms)



duct side wall. The pressure is reduced by P_0 , $P_0 = 101,325$ Pa. The flame front speed is reduced by laminar burning velocities S_{L0} . Before inversion, the flame speed is determined by the front speed at the symmetry axis, while the speed of the leading tip close to the upper wall is taken as the front speed after inversion. Generally, before tulip formation the flame front accelerates quite fast for a short time with the flame surface area growing exponentially then decelerates sharply due to the loss of flame surface area [31, 32].

The flame front speed reaches its minimal speed close to zero at $\tau = 0.106$ (3.87 ms) just before the flame is flattened at $\tau = 0.111$ (4.07 ms), as shown in Fig. 2.10a and Fig. 2.11. The first inflection in the pressure trace, which appears at about $\tau = 0.113$ (4.13 ms), correlates very closely with the tulip flame initiation. And then the flame speed increases quickly once more. Just before the first tulip distortion the flame front decelerates fast again. The tulip flame starts to distort at approximately $\tau = 0.137$ (5.00 ms), immediately the flame speed approaches its minimum value of zero at about $\tau = 0.142$ (5.20 ms). And the second inflection of the pressure trace happens just after the first tulip distortion. Thereafter, the flame accelerates with a salient distorted tulip shape. The distorted tulip flame transforms into a normal tulip flame once more about $\tau = 0.169$ (6.20 ms) and last for a quite short time with a much shorter tulip cusp. Another distortion recurs approximately at $\tau = 0.175$ (6.40 ms) near the end of combustion, but with the lips dented more slightly than the first distortion. The flame front speed decreases to a minimum for the third time at $\tau = 0.173$ (6.33 ms), when the pressure trace just begins its third inflection.

On the basis of above analysis, three significant flame shape deformations (one tulip flame, two tulip distortions) were observed as shown in Fig. 2.10. And it can be concluded that the periodic vibrations in the pressure signal correspond to the flame front speed oscillations with 90° phase shift, as shown in Fig. 2.11. When the flame deformation appears accompanied by the flame speed deceleration, the pressure rise comes down due to the loss both of flame surface area and heat of combustion. The flame sharp deceleration is a manifestation of the flame-induced reversal flow analyzed early by Gonzalez et al. [28], and when the flame speed gets close to zero (even equal to zero) it indicates that the absolute velocity value of reversal flow around flame front becomes very close to the laminar burning velocity in propagation direction of flame leading tip. Therefore, the onset of flame deformations coincides with the deceleration both of pressure rise and flame speed.

2.4.4 Comparisons of Distorted Tulip Flame to Classical Tulip Flame

The distortions of tulip flame should be distinguished from the classical tulip disappearance discussed by Starke and Roth [36] and Gonzalez et al. [28], who concluded the propagation of its lateral lips one toward the other finally causes the tulip collapse in tubes of larger aspect ratio. However, in the present study, the tulip flame has a propensity to disappear in this way without apparent tulip distortion, showing classical tulip flame features as schematically shown in Fig. 2.10b, at equivalence ratio in the range of $0.49 \leq \Phi < 0.84$ and $4.22 < \Phi \leq 7.14$. In order to distinguish the tulip distortion from the typical tulip collapse after its full formation, the development of the tulip flame without notable distortion after its full formation is also investigated here for comparison. Figures 2.12 and 2.13 show high-speed

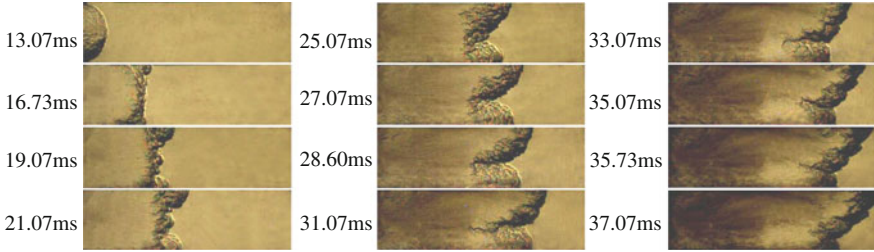


Fig. 2.12 High-speed images of premixed hydrogen–air flame shape changes at $\Phi = 0.59$, representing classical tulip flame in low equivalence ratio range of $0.49 \leq \Phi < 0.84$

schlieren images of the tulip flame initiation, development, and disappearance at $\Phi = 0.59$ and 7.14, representing the classical tulip flame in low equivalence ratio range of $0.49 \leq \Phi < 0.84$ and high equivalence ratio range of $4.22 < \Phi \leq 7.14$, respectively.

It can be seen from Fig. 2.12 that at $\Phi = 0.59$ the tulip flame disappears gradually after its full formation with the upper lateral lip moving at a higher propagation speed toward the lower one, while at $\Phi = 7.14$ the lower lip moves at a higher speed toward the upper one gradually after the complete formation of the tulip flame, and finally the tulip flame vanishes, as shown in Fig. 2.13. The disappearance of tulip flame in this work is consistent with the result obtained by Starke and Roth [8]. From Figs. 2.12 and 2.13, it is known that during the whole process of initiation, development, and disappearance of the classical tulip flame, the tulip distortion does not occur except flame wrinkles which result from various hydrodynamic and combustion instabilities.

The pressure dynamics and flame propagation speed during the flame propagation without noticeable tulip distortion are also examined to further reveal the different characteristics between the distorted tulip flame and the classical tulip flame. Note that the flame propagation speed is defined throughout this thesis is the displacement speed of flame front in the laboratory frame of reference. Figures 2.14a, b illustrate the reduced pressure and reduced flame front speed during the flame propagation of classical tulip flame versus the reduced time at

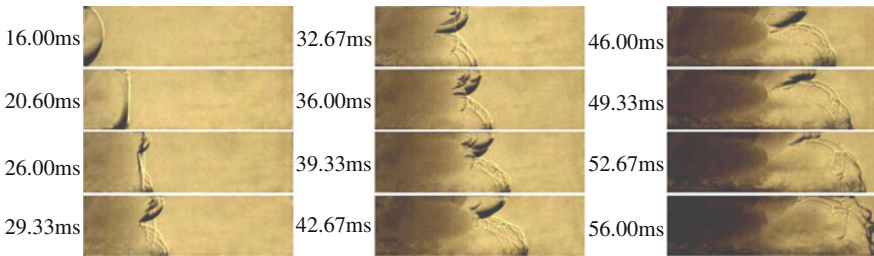
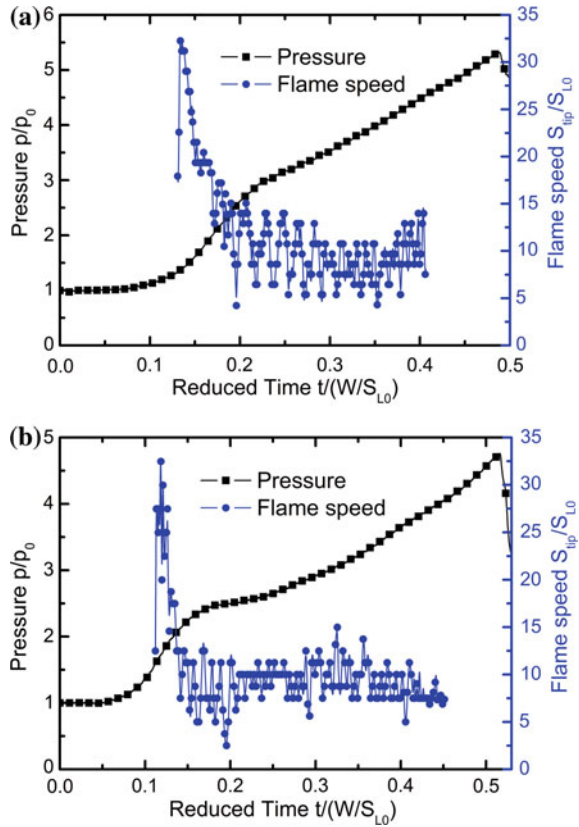


Fig. 2.13 High-speed images of premixed hydrogen–air flame shape changes at $\Phi = 7.14$, representing classical tulip flame in high equivalence ratio range of $4.22 < \Phi \leq 7.14$

Fig. 2.14 Pressure rise and flame front speed during classical tulip flame propagation at $\Phi = 0.59$ (a) and $\Phi = 7.14$ (b)



$\Phi = 0.59$ and $\Phi = 7.14$, respectively. Both the pressure traces at the two equivalence ratios show no apparent vibration before the vent was opened. In fact, it is found that no obvious vibration, except an inflection around the tulip initiation time, will happen to the pressure trace at equivalence ratio in the range of $0.49 \leq \Phi < 0.84$ and $4.22 < \Phi \leq 7.14$. The pressure rise of classical tulip flame during propagation is similar to that obtained by Dunn-Rankin and Sawyer [11]. The flame front speed at $\Phi = 0.59$ and $\Phi = 7.14$ also shows different features from that of the distorted tulip flame. Although the flame speed fluctuates during tulip flame propagation, as shown in Figs. 2.14a, b, the fluctuation amplitude is much smaller than that of distorted tulip flame. And the flame speed fluctuation of classical tulip flame is caused by the vibrations of the flow velocity [8]. These phenomena indicate that classical tulip flame propagates without sudden shape change and abrupt loss of the flame surface area. It also implies that the classical tulip flame behaves in a more stable manner than distorted tulip flame.

Based on the above analysis, the dynamics of distorted tulip flame shows different characteristics from the classical tulip flame. The distorted tulip flame undergoes more complex shape changes than classical tulip flame. The pressure rise

vibration, correlating very closely with flame deformation, acceleration and deceleration, is a manifestation of more unstable combustion of distorted tulip flame. The relatively smooth pressure rise of classical tulip flame results from more stable combustion.

The “distorted tulip” flame shows more shape changes and behaves in a more unstable manner than the classical tulip flame. Furthermore, it is worth noting that the “distorted tulip” flame is also distinct from the traditional “multi-tulip-shaped” flame [28, 37]. This can be explained by the fact that these “multi-tulip-shaped” flames are initiated by several ignition sources while in the present experiment only one-point ignition source is used. In the case of traditional “multi-tulip-shaped” flames, multiple similar tulip flames propagate at the same time with parallel cusps. However, the cusps of the “distorted tulip” flame are never parallel to each other and the secondary cusps are always smaller than the original one. In addition, Petchenko et al. [38, 39] studied premixed flame propagation from an open end to a closed one in a tube using direct numerical simulation (DNS) and found violent folding and distortion of the flame front due to flame-acoustic interaction. Nevertheless, the flame distortion is different from that in the present work. First, the vessel used in the simulations in [38, 39] is a half-open tube and the flame propagates from the open end to the closed one. Second, the tube width and length considered in the simulations [38, 39] are much smaller than those of the square duct in the present study and any other realistic tube due to the limitation of the length scales for DNS. The inevitably limited computational domain makes the direct comparison of the numerical results to the experiments difficult as indicated in the papers [38, 39]. Finally, the flame distortion can also be distinguished following the shape of the distortion itself.

The flame distortions in [38, 39] appear with two hooked cusps concaved from the sidewall to the center of the duct and a blob of burnt gas pushed into the unburned mixture, which is apparently different from the distortions in the present study. Akkerman et al. [40] investigated flame-flow interaction and generation of vorticity in laminar flame propagation in a closed chamber and found an additional small cusp appearing on the lower lip of a slightly curved flame. The slight distortion in [40] originally occurs near the center of the lip and subsequently corrugates the flame front. Still, this corrugation differs from the present flame distortion since the distortion in the present work is originally initiated close to the flame leading tip and moves toward the primary cusp, and finally develops into a very pronounced secondary cusp in the proximity of the center of the primary tulip lip with the secondary cusp comparable to the primary one (Fig. 2.9). Besides, the ignition source was located at the center of one of the sidewalls in [40].

2.4.5 *Effects of Gravity*

Gravity can have significant influence on flame stability. The instability is known as gravity instability [24, 25, 41–43]. The upper lip propagates obviously faster than

the lower one at low equivalence ratios whereas the later travels at higher speeds than the former due to the buoyancy. As shown in Figs. 2.12 and 2.13, the effects of the gravity become pronounced after tulip inversion. The asymmetrical shape of flame is mainly caused by body force [44]. For the premixed flame propagating in a duct, the body force primarily comes from gravity. The gravity influences the flame front in the following two aspects [45]: (1) the streamlines of unburned mixture close to flame front are deflected by the expanding burnt matter due to the effects of gravity and (2) when the flame is wrinkled, the flame instability can be enhanced or depressed by gravity. This leads to change in burning velocity.

According to Pelce [41], the Froude number and the propagation direction of the flame front may influence the flame shape and flame propagation velocity. The Froude number is defined as

$$Fr = \frac{gW}{S_L^2}, \quad (2.3)$$

where g is the acceleration of gravity. As in the reference [41], upward propagation is represented conventionally by a negative Froude number and downward propagation by a positive Froude number. Therefore, for the tulip flame the upper lip propagates downward with a positive Froude number and the lower one propagates upward with a negative Froude number in the vertical direction, as shown in Fig. 2.15.

For the lean hydrogen–air mixture characterized by a Lewis number less than unity, the diffusive-thermal effects will play an important role in the flame propagation [24]. In that case, the flame thickness will increase and hence stabilize the flame front for upward propagating flame ($Fr < 0$) [24, 27, 41] due to gravity. For sufficiently rich hydrogen–air mixture characterized by a Lewis number larger than unity, when a flame propagates upward ($Fr < 0$), the DL instability is amplified by the RT instability and the flame velocity increases as a result. In the opposite case of a downward propagating flame ($Fr > 0$), the gravity plays a stabilizing role. The joint effect of the stabilizing gravity and thermal conduction leads to suppression of the flame instability [25, 41]. Based on the above analysis, it can be concluded that

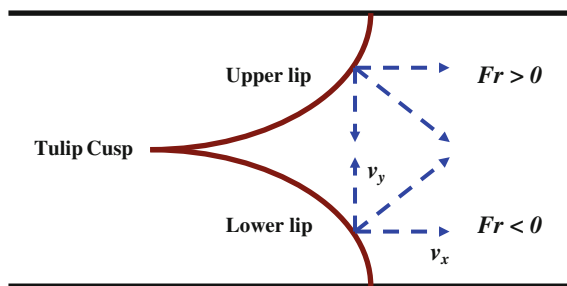


Fig. 2.15 Relationship between Froude number and the propagation of Tulip upper and lower lips

the discrepancies of the propagation speed between the upper lip and the lower one, as shown in Figs. 2.12 and 2.13, are due to the interactions between the flame instabilities and the gravity.

2.4.6 Effects of Equivalence Ratio

According to Clanet and Searby [31], the only relevant parameters influencing the tulip flame formation are the duct cross-section width W , the laminar burning velocity S_L and the nondimensional gas expansion coefficient E as long as flame thickness is small compared to the duct dimensions. The expansion coefficient E is defined as the ratio of the density of unburned mixture to that of the burnt matter. The laminar burning velocity and gas expansion coefficient are directly related to the equivalence ratio Φ . From successful experiment, Dunn-Rankin and Sawyer [11] thought that the formation of a tulip flame is relatively insensitive to equivalence ratio.

Based on the above analysis, the formations of quasi-plane/plane front, tulip flame, and distorted tulip flame depend on the equivalence ratio distinctly both in half-open and closed ducts. And the equivalence ratio range, in which tulip flame can form, is much wider in closed duct ($0.49 \leq \Phi \leq 7.14$) than that in half-open duct ($1.17 \leq \Phi \leq 4.05$). One reason investigated for this circumstance is that the laminar burning velocity increases very quickly due to the increase of the temperature of unburned mixture in the closed duct. Flames propagating in open duct consume fuel in a nearly isobaric regime, since expansion of burning gas in the combustion process may be balanced by the flow of the mixture away from the flame front. However, expansion of burning matter causes adiabatic compression of the fresh fuel ahead of the flame front in closed duct. And the compression of the fuel is accompanied by significant pressure and temperature build up in comparison with the initial values [25]. The dependence of the laminar burning velocity on pressure and temperature is usually expressed as a polynomial function [46]:

$$\frac{S_L}{S_{L0}} = \left(\frac{T}{T_0}\right)^m \cdot \left(\frac{p}{p_0}\right)^n, \quad (2.4)$$

where S_L is the laminar burning velocity at temperature T and pressure p , S_{L0} is the laminar burning velocity at initial temperature T_0 and p_0 , m and n are temperature and baric indexes independence of the burning velocity. The flame propagation time in the experiment is rather short and the combustion process can be assumed as adiabatic. According to adiabatic compression law:

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{(\gamma-1)/\gamma}, \quad (2.5)$$

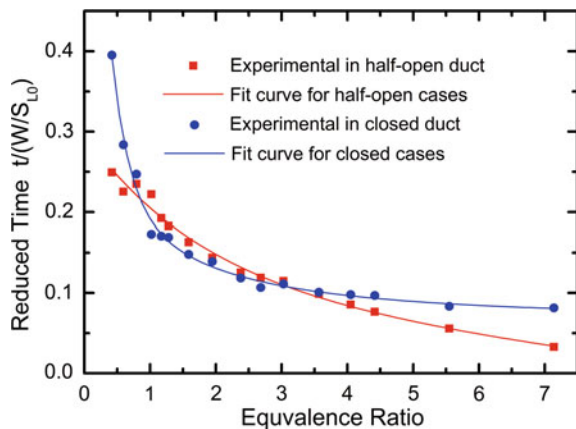
where $\gamma = c_p/c_v$, is the specific heat ratio, c_p and c_v are specific heats at constant pressure and constant volume correspondingly. During the adiabatic compression of the unburned matter, pressure and temperature change simultaneously. Therefore, the laminar burning velocity can be defined as a function of pressure only [47]:

$$S_L = S_{L0} \left(\frac{p}{p_0} \right)^\varepsilon, \quad (2.6)$$

where $\varepsilon = m_0 + n_0 - m_0/\gamma$, is the overall thermokinetic index. Values of m , n , and ε can be recommended according to [48]. From Eqs. (2.5) and (2.6), it is known that the laminar burning velocity increases fast due to the adiabatic compression. Therefore, it could be concluded that the adiabatic compression of unburned mixture may plays an important role in causing the wider equivalence ratio range for tulip flame formation in the closed duct.

The time of quasi-plane/plane flame front formation is a critical time, characterizing the significant flame shape change. And this critical time is the flame front inversion time for tulip flame (tulip initiation time). Both the quasi-plane and plane flames are referred to as plane flame here for convenience. The formation time of plane flame versus equivalence ratio in half-open and closed duct is shown in Fig. 2.16. The formation time is reduced by W/S_{L0} . Both in half-open and closed ducts, the formation time as a whole decreases exponentially as the equivalence ratio increases, but the decrease rate is more uniform in half-open duct. The formation time decrease might be a result of the combined action of laminar burning velocity, expansion efficient, and flame instabilities. The time decreases faster in closed duct than that in half-open duct with a larger absolute value of slope when $\Phi < 1.59$, while the opposite is true when $\Phi > 1.59$. The time decreases very slightly with slope close to zero when $\Phi > 2.37$ in closed duct. It also found that between $\Phi = 1.17$ and 4.05, the plane flame formation time in half-open duct is almost the same as that in closed duct within experimental error. And this

Fig. 2.16 Formation time of plane flame versus equivalence ratio in half-open and closed ducts



equivalence ratio range is just consistent with the tulip formation equivalence ratio range in half-open duct. Therefore, it would be reasonable to conclude that the tulip initiation time in half-open duct is equal to that in closed duct at the same equivalence ratio.

Figure 2.17 shows the relationship between tulip initiation time and first tulip distortion initiation time in closed duct. The time scale is also reduced by W/S_{L0} . The first tulip distortion initiation time and the tulip initiation time nearly share the same tendency versus the equivalence ratio in the distortion range of $0.84 \leq \Phi \leq 4.22$. The inversion time decreases gradually accompanied by slight fluctuation as the equivalence ratio increases. So does the tulip distortion initiation time, except in the range of $0.84 \leq \Phi \leq 1.02$. The discrepancy might be due to the rich shift of the peaking of hydrogen laminar burning velocity.

Figure 2.18 shows the relationship between expansion coefficient and the reduced distances from plane flame and its leading tip to the ignition point in half-open and closed ducts versus equivalence ratio. The distance is reduced by $E \cdot W$. So does that in Fig. 2.19, which will be shown later. The hydrogen adiabatic

Fig. 2.17 Relationship between the initiation time of tulip flame and the first tulip distortion. The equivalence ratio ranges from 1.02 to 3.57 in closed duct

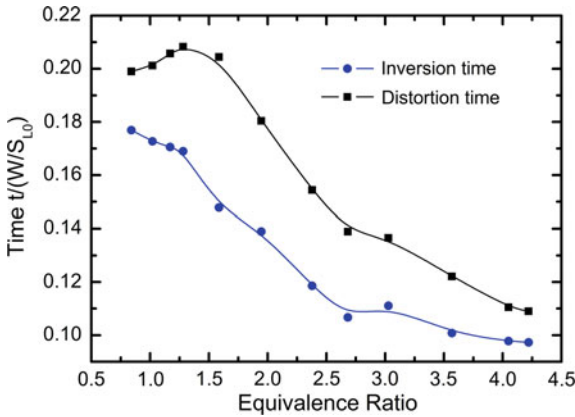


Fig. 2.18 Relationship between expansion coefficient and distances from the plane flame and its leading tip to the ignition point in half-open and closed ducts

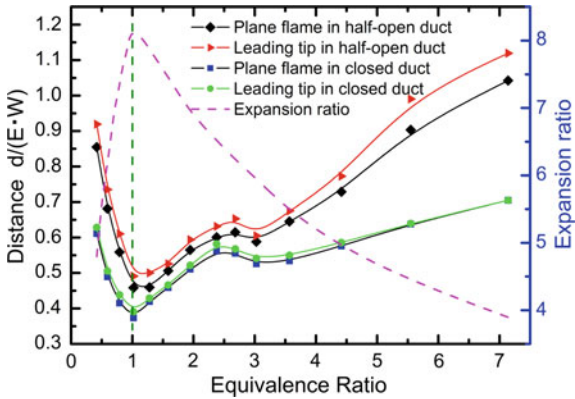
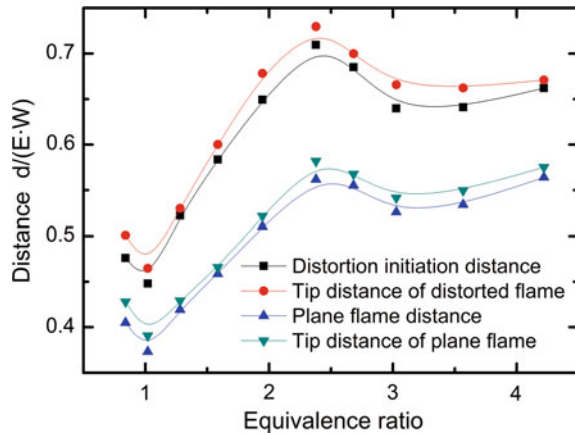


Fig. 2.19 Distances from the first distortion initiation position and its leading tip to the ignition point in closed duct compared with those of the corresponding plane flame and leading tip



flame temperature can be obtained from an overall energy balance [24, 27], and the expansion coefficient is determined by the ratio of temperature of burnt matter and the temperature of the unburned gas [25, 32]. The position of the plane flame center is taken as the plane position when the plane is a sloping front. The dimensionless distances vary significantly as equivalence ratio increases in half-open duct with a similar trend to those in closed duct. At the beginning, the distances decrease sharply and reach to the minimum value in the vicinity of $\Phi = 1.0$ which is just the location of the maximum of both the hydrogen adiabatic flame temperature and expansion coefficient in air. Indeed, the distance displays an opposite tendency on the whole with the expansion coefficient. Therefore, it is rational to conclude that the formation position of plane flame/initiation position of tulip flame shows an approximately negative correlation with the expansion coefficient versus equivalence ratio, as shown in Fig. 2.18.

Figure 2.19 presents the reduced distances from the first distortion initiation position and its leading tip to the ignition point in closed duct in comparison with those of the corresponding plane flame and leading tip. Both the distances of distortion initiation position and the leading tip of distorted flame keep the same trend with the later located above the former a little with fluctuations. Actually, the first distortion is always initiated near the center of the tulip lips, as shown in Figs. 2.9 and 2.10. The distances of the first distortion/its leading tip also show the same tendency versus equivalence ratio as those of the corresponding plane flame/its leading tip with the former located above the later obviously.

It also can be seen that in half-open duct, the plane flame appears always with leading tips located in front of flame front near the duct side walls, taking the shape of quasi-plane. In closed duct, the distance between the central plane region and the leading tip is less than that in half-open duct, and decreases apparently when $\Phi \geq 5.82$, forming an plane flame subsequently.

2.4.7 Effects of Opening Ratio

In order to examine the influence of opening condition on the flame propagation, an opening ratio σ is defined here as the ratio of open area to the area of the original vent (actual open area/maximum area of vent). Table 2.1 gives the opening ratios and the corresponding diameters of the opening vent at different opening conditions.

Figure 2.20 presents a sequence of high-speed schlieren images of premixed flame propagation for hydrogen–air mixture at opening ratios $\sigma = 0.2$ (a), 0.4 (b), 0.6 (c), 0.8 (d) and 1.0 (e), illustrating typical flame shape changes. Basically, a premixed flame can maintain a plane front in a sufficiently narrow channel under adiabatic conditions, whereas it is impossible for a premixed flame to keep a planar front in a tube with larger width such as that in the present study. A well-known example of premixed flame development in a half-open tube was suggested by Clanet and Searby [31], who proposed four stages of the tulip flame propagation. The experiments for hydrogen–air mixture in the present work show more curious characteristics of premixed flame propagation. The flame evolves differently as the opening ratio increases, as shown in Fig. 2.20. The experimental results show that a noticeable distorted tulip flame is generated after the full formation of a classical tulip flame when the opening ratio is small, namely $\sigma \leq 0.4$. The formation and characteristic features of a distorted tulip flame in the partially open duct (at low opening ratios) are found to be similar to those in a closed duct. Here, take the flame propagation at $\sigma = 0.2$ as a representative example of distorted tulip propagation. After flame inversion at about $t = 6.2$ ms, as shown in Fig. 2.20a, a well-pronounced tulip flame is formed with a slender cusp. The distortions of the tulip flame are initiated close to the tips of the primary tulip tongues. The distortions move backward along the primary tulip tongues and a distorted tulip shape is subsequently created (e.g. flame shape at $t = 7.867$ ms). As the distortions approach the center of the primary tulip tongues, the distorted tulip flame develops into a triple tulip flame (e.g., flame shape at $t = 8.2$ ms). In the meantime, the distortions or secondary cusps appear comparable to the primary one. The distorted tulip flame tends to disappear near the end of the combustion as the primary cusp and the secondary ones propagate to each other, as shown in Fig. 2.20.

When the opening ratio ranges from 0.5 to 1.0, no obvious distorted tulip shape can be observed in the present experiment. As demonstrated above, the interaction between flame front and the combustion generated flow and pressure wave reflected from the right end is responsible for the formation of distorted tulip flame. When the opening ratio is small, the pressure wave can interplay with the flame front and

Table 2.1 Opening ratios and the corresponding diameters of the opening vent at different opening conditions

Opening ratio σ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Diameter (mm)	12.6	17.9	21.9	25.3	28.3	31.0	33.5	35.8	37.9	40.0

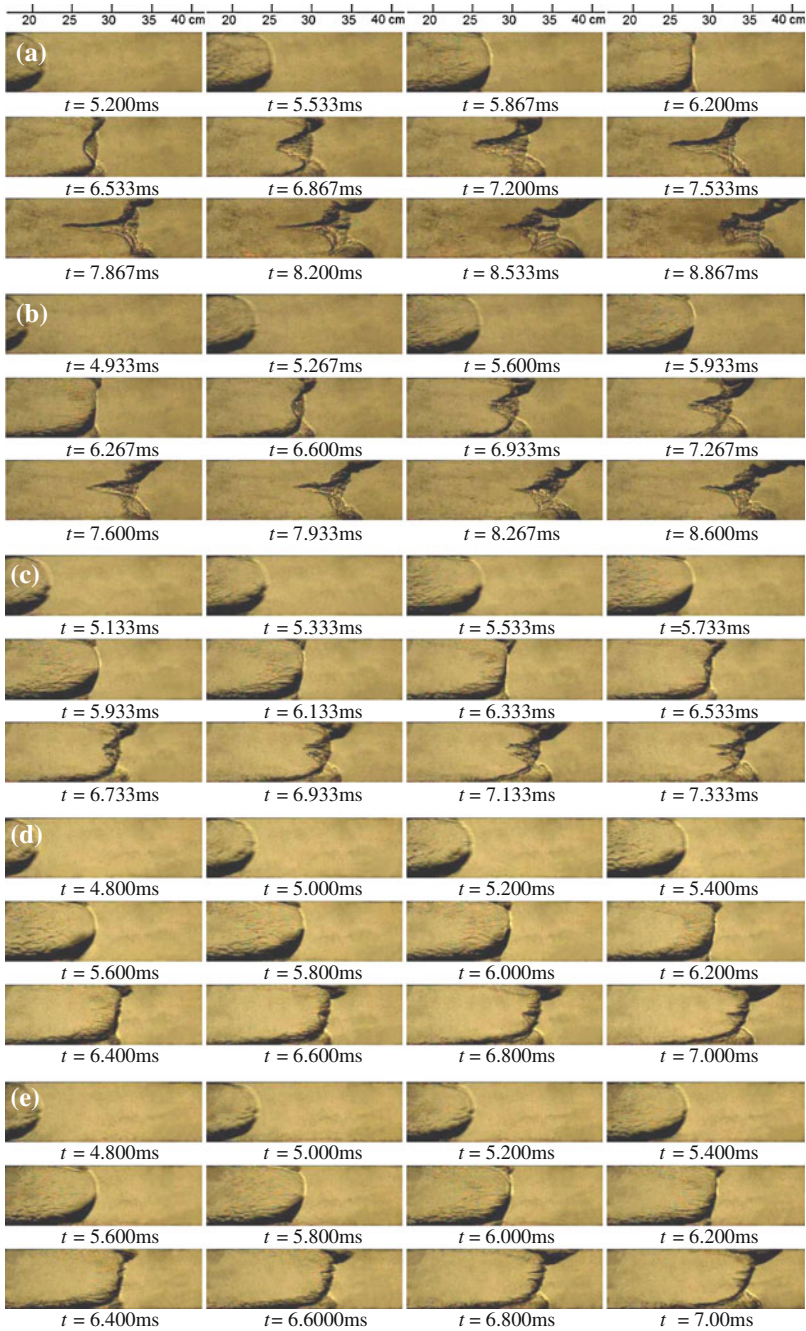


Fig. 2.20 Schlieren images of premixed hydrogen–air flame propagation at opening ratios $\sigma = 0.2$ (a), 0.4 (b), 0.6 (c), 0.8 (d), and 1.0 (e)

thus drive the flame to display a distorted shape. However, when the opening ratio is large, the effect of the pressure wave may be balanced by the strong flow of the unburned mixture away from the flame front. A tulip flame is produced for all the opening ratios. The larger is the opening ratio, the less pronounced is the tulip flame, as shown in Fig. 2.20. Particularly, when the opening ratio is close to 1.0, the planar front remains in the center of the duct until the end of the propagation process and no remarkable tulip cusp can be formed. On the other hand, with the increase of opening ratio the flame acceleration along the sidewalls becomes stronger. This flame acceleration is caused by the “squish flow,” as discussed in Sect. 2.4.1. A squish flow is actually an accelerated flow induced in the unburned region wedged by the flame front and the lateral walls just ahead of the flame. The squish flow can drive the flame near the sidewalls to travel faster than in the central region. The squish flow during premixed hydrogen–air flame propagation is more intensive with the increase of opening ratio since smaller confinement could result in higher flow velocity in the fresh mixture.

Based on the above analysis, it can be concluded that the flame behaves differently with different opening ratio and the flame experiences more drastic flame shape changes as the opening ratio decreases. For this reason, the opening ratio of the vent orifice near the right-end wall of the duct (opposite to the ignition end wall) is an important parameter that affects the flame dynamics.

In the early stages, i.e., the spherical stage and the early phase of the finger stage, the flame in a closed duct propagates nearly at the same speed as those in a half-open tube and exhibits very similar features since the pressure build up in the duct at the early stage can be neglected. The flame propagation (displacement) speed would be smaller in the later stages in a closed duct because additional deceleration is caused by the inability of the gases to expand freely and flow toward the closed end. From this point of view, it could be expected that the flame in the current study travels at the same speed in the early stages for all the opening ratios whereas the flame propagation speed will increase with the increase of opening ratio in the later stages. The main attention of this study is given to the later stages of flame propagation.

Figures 2.21 and 2.22 show the location and propagation speed (displacement speed) of the flame leading tip with time under various opening conditions, respectively, where location is defined as the distance from the ignition point. Before flame inversion, the flame tip along the duct axis is treated as the flame leading tip while the flame tip near the upper sidewall is taken as the leading tip after inversion in this work. Here $H = 4.1$ cm, $S_{LO} = 2.1$ m/s. The increase of opening ratio leads to larger distance at the same time instant, as shown in Fig. 2.21, which indicates that the flame propagation speed increases at the later flame stage with the increase of opening ratio. And the discrepancy becomes more significant with time. Meanwhile, the difference of the flame movement speeds between two adjacent opening ratios approximately becomes smaller as the opening ratio increases.

Oscillations occur in the trajectories of the propagation speed of flame leading tip with location for all the opening conditions, especially for $\sigma \leq 0.5$, as shown in Fig. 2.22. Thermal expansion of combustion products produces movement in the

Fig. 2.21 Location of flame leading tip as a function of time at various opening ratios

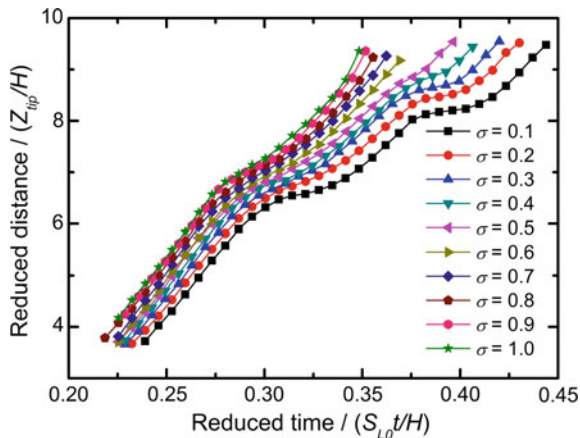
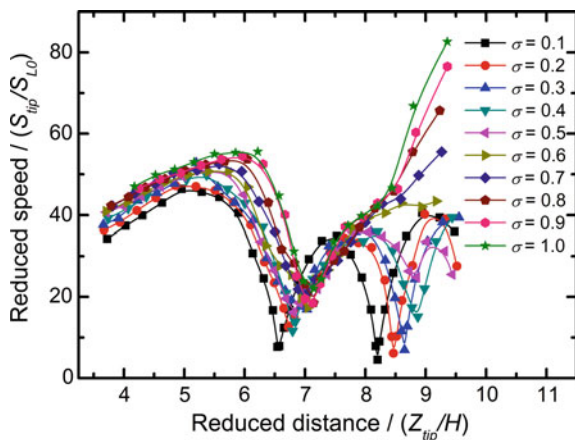


Fig. 2.22 Propagation speed (displacement speed) of flame leading tip with location under different opening conditions



unburned mixture and the confinement of the duct leads the flame to accelerate quickly. The flame acceleration terminates as the flame skirts reaches the sidewalls of the duct. As the opening ratio increases the flame accelerates more rapidly, as shown in Fig. 2.22. Note that since the surface area of the flame front near the left-end wall is much smaller in comparison with the lateral sides (skirt) of the flame and the flame approaches the left-end wall at a much lower speed, the contact of the flame with the left-end wall would further the flame deceleration, but to a lesser extent. The first flame deceleration stops with flame surface area reduced to a minimum value as the flame front is flattened out. The formation of tulip flame results in another increase of the flame surface area, and consequently the flame accelerates again. When the opening ratio is small, i.e., $\sigma \leq 0.5$, the flame accelerates over a few centimeters and then assumes a second flame deceleration, as shown in Fig. 2.22. The second deceleration is in close connection with the pressure wave generated by the first contact of the flame with sidewalls, which will be shown

later (Chap. 5). The flame keeps accelerating fast when $\sigma > 0.5$, especially near the orifice. This confirms again that the interaction of flame with pressure wave is pretty weak when $\sigma > 0.094$. Note that although the flame at $\sigma = 0.5$ experiences a second deceleration, it could be too weak to create a remarkably distorted tulip shape.

Figure 2.23 gives the pressure dynamics inside the duct obtained from the pressure transducer at different opening ratios ($P_0 = 101,325$ Pa). The pressure at all the opening ratios grow exponentially with the exponential increase of flame surface area at the finger stage. The pressure growth rate drops due to the reduction of combustion products arising from the sudden reduction of flame surface area after the flame skirt touches the sidewalls. This initiates a pressure wave (acoustic wave) which then travels forth and back in the duct. The pressure grows fast again with the generation of the tulip shape. The subsequent oscillations of the pressure dynamics result from the interaction of the flame front with the pressure wave. It is also shown in Fig. 2.23 that increase of the opening ratio leads to a lower pressure growth rate and consequently a smaller peak pressure. The differences of pressure dynamics between the cases at opening ratios close to 1.0 is quite small during the entire combustion process but much larger at opening ratios near 0.1, especially at the later phase of the combustion. Furthermore, the lower is the opening ratio, the larger is the amplitude of pressure oscillations. This implies that the coupling of flame front with pressure wave becomes stronger with decrease of the opening ratio.

As analyzed above, the flame dynamics in the partially open duct is in close connection with the opening ratio at the later stage. The formation of the distorted tulip flame depends on the opening ratio. Figure 2.24 shows the time τ_{wall} at which the flame touches the lateral walls of the duct under various opening conditions. The time τ_{wall} increases gradually as the opening ratio increases. Nevertheless, the increase rate decreases when the opening ratio approaches 1.0. Following the theory by Bychkov et al. [32], the characteristic time t_{wall} when the flame touches the sidewalls can be calculated as:

Fig. 2.23 Pressure dynamics under various opening conditions

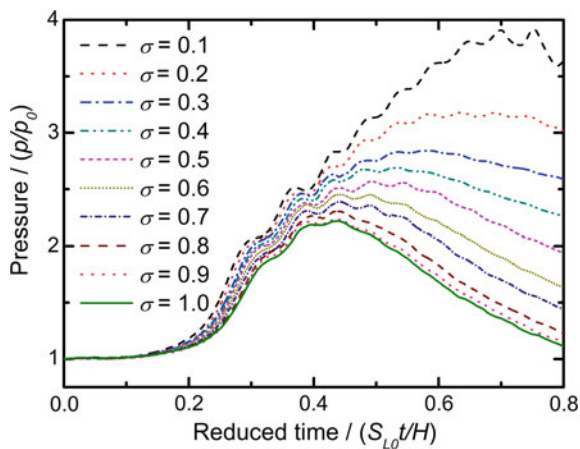
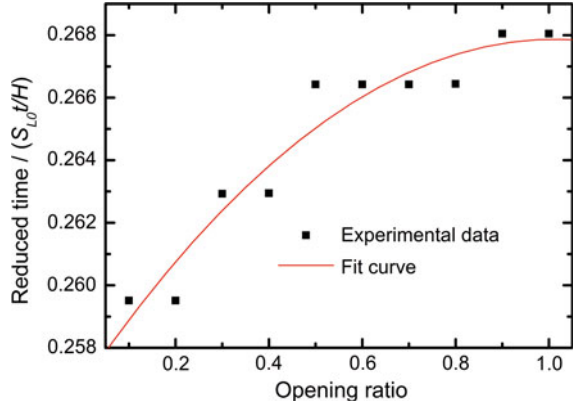


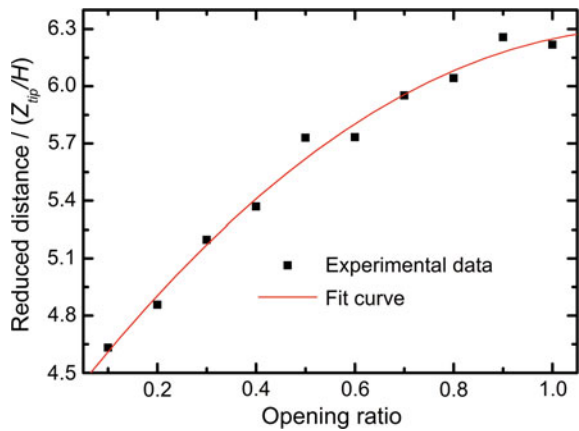
Fig. 2.24 Time when the flame reaches the sidewalls of the duct at various opening ratio



$$t_{\text{wall}} = 1/(2\alpha) \cdot H/S_L \cdot \ln[(E + \alpha)/(E - \alpha)], \quad (2.7)$$

where $\alpha = \sqrt{E \cdot (E - 1)}$, $E = 7.22$ is the expansion ratio and S_L is the laminar burning velocity at temperature T and pressure P . When the opening ratio is small, the precompression of the unburned fuel caused by the thermal expansion of the burning matter can be significant. The compression of the fresh mixture is accompanied by considerable pressure and temperature build up compared to the initial values. According to Eq. (2.7), the increase of laminar burning velocity S_L leads to decrease of the time t_{wall} when the flame reaches the sidewalls. Therefore, the dimensionless time τ_{wall} decreases with the decrease of opening ratio since larger confinement results in higher pressure build up (as shown in Fig. 2.23). Figure 2.25 shows the location of the flame leading tip with opening ratio at the time when the flame skirt touches the sidewalls of the duct. The location increases with the increase of opening ratio. This can be explained by the fact that the speed of flame leading tip increases with the opening ratio, as shown in Figs. 2.21 and 2.22.

Fig. 2.25 Flame leading tip location as the flame touches the lateral walls at different opening conditions



Nevertheless, the increase rate reduces with the increase of opening ratio, as shown in Fig. 2.25.

Figure 2.26 presents the time when the flame front deforms into a planar shape (i.e., flame inversion time) with opening ratio. The flame inversion time increases with the increase of the opening ratio. Following the analytical theory by Bychkov et al. [32], the flame inversion time t_{inv} can be expressed by:

$$t_{\text{inv}} = \delta \sigma^{-1} H / S_L, \quad (2.8)$$

where δ is a model constant comparable to unity. It is clearly shown in Eq. (2.8) that the flame inversion time is inversely proportional to the laminar burning velocity. As remarked above, the decrease of the opening ratio results in an increase of the pressure in the unburned mixture and consequently an increase of the laminar burning velocity (see Eq. (2.5)).

Figure 2.27 shows the location of the planar flame and its leading tip at different opening ratios. Though the flame front at the inversion time is conventionally referred to as plane flame, it is actually not an exact planar shape in the present study because the flame near the sidewalls leads the flame propagation, as shown in Fig. 2.20. In addition, the plane flame is apparently inclined after inversion at high opening ratios. The location of the plane flame is defined here as the location of the flame front at the duct axis while the leading tip is the flame tip close to the upper sidewall. The location of the plane flame undergoes an exponential increase until σ reaches to 0.8. The location of the plane flame increases very slowly when $\sigma > 0.8$. The location of the leading tip of the plane flame shows a quite similar trend, but at a higher increase rate. The discrepancy between the locations of the plane flame and its leading tip grows larger as the opening ratio increases. This is thought to be due to two reasons. First, a more inclined plane flame forms as the opening ratio increases, as shown in Fig. 2.20. Second, the flame front near the sidewalls travels faster with the increase of opening ratio due to the enhanced squish flow by the higher flame propagation speed (see Fig. 2.22). As aforementioned, when the

Fig. 2.26 Flame inversion time as a function of opening ratio

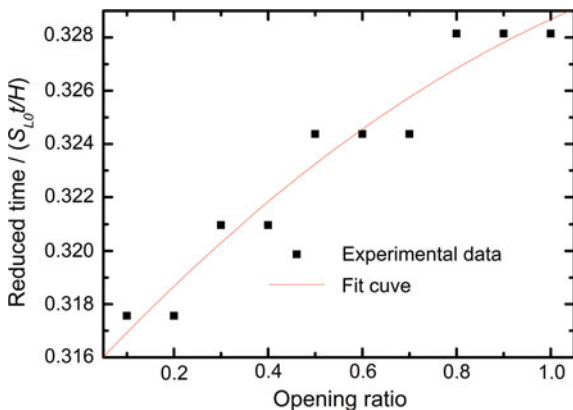
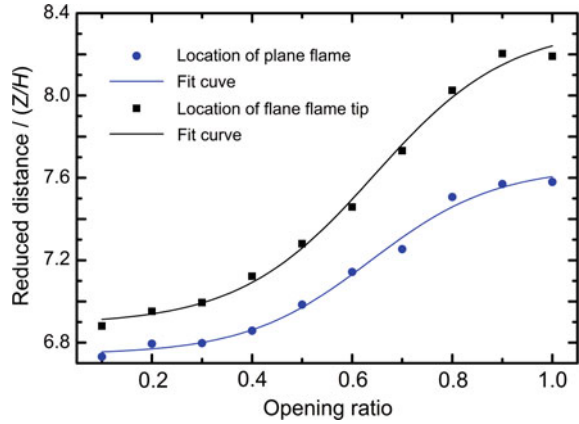


Fig. 2.27 Location of plane flame and its leading tip with opening ratio



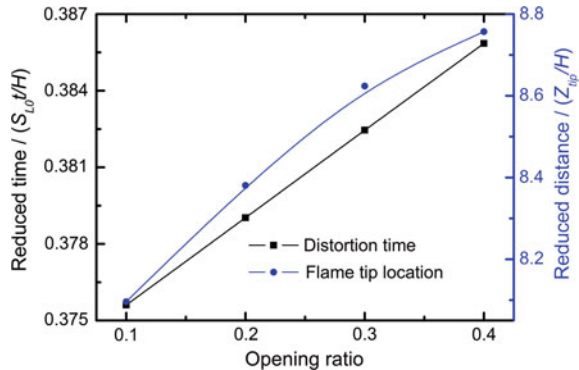
opening ratio approaches 1.0 the impact of the opening ratio is not significant any more.

Figure 2.28 shows the onset time of the distorted tulip flame and the location of its leading tip. The initiation time of the tulip distortion increases as the opening ratio increases in the range of $\sigma \leq 0.4$. The formation of a distorted tulip flame has a close connection with the pressure wave and a tulip distortion is created immediately after the pressure wave passes the flame front from the unburned side (will be shown in Chaps. 4 and 5). The compression of the unburned mixture leads to an increase of the temperature. The sound speed c_s is increased as a result as follows:

$$c_s = \sqrt{\gamma R_g T}, \quad (2.9)$$

where R_g is the gas constant of the mixture. Therefore, the time required for the formation of tulip distortion reduces with the increase of the sound speed. The location of the flame leading tip at the onset time of tulip distortion increases almost linearly with the increase of opening ratio due to the increase of the propagation speed of the flame leading tip.

Fig. 2.28 Initiation time of tulip flame distortion and the corresponding flame leading tip location



In summary, the opening ratio has a significant influence on the combustion dynamics, including the flame behaviors and pressure dynamics. Smaller opening ratio leads to more drastic flame shape changes. When the opening ratio is in the range of $\sigma \leq 0.4$, a noticeably distorted tulip flame can be produced after the full formation of a classical tulip flame. When $\sigma > 0.4$, no remarkable tulip distortion can be observed. The propagation speed of flame leading tip increases with the increase of the opening ratio. The flame leading tip undergoes a second strong deceleration with $\sigma \leq 0.5$. The flame shape and propagation speed of the flame leading tip are in close connection with the pressure wave, especially for combustion processes at the low opening ratio. Both the growth rate and oscillation amplitude of the pressure inside the duct increase as the opening ratio decreases. The flame tip locations with the initiation of tulip and distorted tulip flames increase with the increase of the opening ratio. The effect of the opening ratio on the flame and pressure dynamics becomes weak when it is close to 1.0.

2.5 Summary

- (1) Premixed hydrogen–air flames propagating in a duct exhibit consistent deformations with other typical gas fuels, forming classical tulip flames, only in special equivalence ratio ranges, $1.17 \leq \Phi \leq 4.05$ in the half-open duct, and $0.49 \leq \Phi < 0.84$ and $4.22 < \Phi \leq 7.14$ in the closed duct, respectively.
- (2) It is found that outstanding tulip distortions are generated after full tulip formation in the equivalence ratio range of $0.84 \leq \Phi \leq 4.22$ in closed duct. This curious flame phenomenon is referred to as distorted tulip flame. In some cases, the classical tulip flame is observed to be produced again after the first distortion and then a second distortion will appear subsequently. The onset of flame deformations coincides with the deceleration both of pressure rise and flame front speed. The behaviors of distorted tulip flame are distinguished from those of classical tulip flame in detail. The classical tulip flame develops, and then disappears gradually without distortion after its full formation. The dynamics of distorted tulip flame is different from that of classical tulip flame. The distorted tulip flame undergoes more complex shape changes and more unstable combustion process than the classical tulip flame.
- (3) The initiation of flame shape changes, including the formation of quasi-plane/plane flame, tulip flame, and tulip distortion, greatly depend on the mixture composition. The equivalence ratio range that can form tulip flame is much wider in the closed duct ($0.49 \leq \Phi \leq 7.14$) than that in the half-open duct ($1.17 \leq \Phi \leq 4.05$). The dimensionless time of formation quasi-plane/plane flame and initiation of tulip flame as a whole exponentially decreases as the equivalence ratio increases both in the half-open and closed ducts. And the tulip flame formation time in half-open duct is nearly equal to that in closed duct at the same equivalence ratio. The dimensionless distances from quasi-plane/plane flame to ignition point vary significantly as

equivalence ratio increases in half-open duct with the same trend as those in closed duct. The formation position of the quasi-plane/plane shows an approximately negative correlation with the expansion coefficient. The distances of the first tulip distortion/its leading tip also show the same tendency versus equivalence ratio as those of plane flame/its leading tip.

- (4) The “squish flow” is active and can cause local deformations of flame shape near the duct walls. However, it may be unimportant for tulip flame formation. The gravity has a noticeable influence on the tulip flame and can make the tulip flame collapse in different way between low and high equivalence ratios, but may not lead to substantial flame shape change.
- (5) Both gravity and opening ratio have significant influence on the flame dynamics. The upper lip propagates obviously faster than the lower one at low equivalence ratios whereas the later travels at higher speeds than the former due to the buoyancy. Smaller opening ratio leads to more drastic flame shape changes. When the opening ratio is in the range of $\sigma \leq 0.4$, a noticeably distorted tulip flame can be produced after the full formation of a classical tulip flame. The propagation speed of flame leading tip increases with the increase of the opening ratio. The flame leading tip undergoes a second strong deceleration with $\sigma \leq 0.5$. Both the growth rate and oscillation amplitude of the pressure inside the duct increase as the opening ratio decreases. The flame tip locations with the initiation of tulip and distorted tulip flames increase with the increase of the opening ratio.

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