Flame propagation behavior of propane–air premixed combustion in a confined space with two perforated plates at different initial pressures

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Abstract
The aim of this paper is to analyze local autoignition induced by secondary flame acceleration. The secondary flame acceleration process and the local autoignition formation mechanism at the condition of the secondary flame acceleration propagation were investigated by utilizing an improved designed constant volume combustion bomb (CVCB) with two perforated plates. Primary flame and secondary flame propagation were recorded via high-speed schlieren photography. The results showed that there were three distinct stages in the process of flame propagation through two perforated plates, which were the primary jet flame stage, secondary jet flame stage, and flame-shock interaction stage. The morphologies of the flame were analyzed by high-speed Schlieren images, flame velocities, and pressure oscillation including primary jet propagation, secondary flame formation and acceleration, and location autoignition. Results show the effect of initial pressure on flame propagation, flame velocity, and pressure oscillation. Acceleration of secondary flame and local autoignition phenomenon was more precisely demonstrated as unburnt gases were compressed by flame waves (different velocities) with initial pressure increasing. Based on the morphology of flame, three different types of flame combustion modes were captured at different initial pressure involving turbulent flame, deflagration, and quasi-detonation. The present work might provide a new insight for combustion science in a confined space, such as autoignition due to compression effect of secondary jet flame and primary flame interaction. It also provides the theory guidance and research direction towards further studies on propane storage vessel deflagration.

KEYWORDS
deflagration, end-gas autoignition, local autoignition, pressure oscillation, quasi-detonation, secondary flame
1 | INTRODUCTION

As a high-grade vital alternative energy source, propane is becoming prevalent in many applications, such as industrial fuel, engine fuel, and so on. Due to its highly flammable and explosive characteristics, propane explosions in confined spaces occurred frequently owing to improper operation during production, transportation, application, and disposition process, resulting in serious equipment damage, environmental depletion as well as a human disaster. In gas explosions, vortices of different scales ahead of the flame front are produced by the unsteady coupling of the propagating flame and the flow field induced by the blockages along the flame path produces. Flame acceleration is induced by the interaction between flame and vortex. The unburnt gas is trapped and compressed by the moving flame front with different velocities, and its temperature as well as pressure increase significantly. Under suitable conditions, uncontrollable autoignition combustion may occur on end-gas, which may result in deflagration-to-detonation transition (DDT).

Accelerated flame might induce deflagration or detonation in confined spaces such as propane storage vessel explosions. Focusing on the flame acceleration mechanism, several studies have been conducted to investigate a series of combustion processes. There are two classical theories on the mechanism of flame acceleration including Shelkin mechanism and Bychkov’s theory. Shelkin attributed flame acceleration due to expansion of combustion gas, friction at the walls, and turbulence in a closed tube, thus the Shelkin mechanism was proposed. In closed space, expansion of burning gas promotes flame acceleration and pushes unburned gas flow. A nonuniform flame velocity distribution changes flame shape and increases flame area, which results in burning rate increases. The additional distortion of flame evolves into turbulence. Ever since research generally agreed that obstacles might create turbulence, which relied on the qualitative Shelkin mechanism. The other acceleration mechanism induced by obstacles was developed by Bychkov. Flame acceleration was induced by the delayed burning between the obstacles, and a powerful jet flow in the obstructed channel was produced. Wei extended Bychkov’s theory and discovered the jet flames when the flame front passed through a perforated plate. Jet flames integrated subsequently and generated turbulence. The self-acceleration process was discovered in the initial developing stage of turbulent flame. Law investigated the turbulent flame acceleration mechanism in a constant pressure container. Flame self-similar propagation was demonstrated by the normalized flame velocity as a function of transport property and length scale. Zhou discovered that small flames appeared and coalesced in the self-acceleration stage of the flame evolution process due to the expansion of the burned products, and then the secondary flame was formed on the basis of the primary flame. However, the formation and acceleration process of the secondary flame was not observed adequately in confined space.

Indeed, in the process of flame propagation, there are various combustion phenomena induced by flame instabilities, shock waves, and pressure waves. Autoignition is a typical destructive abnormal combustion phenomenon. There are extensive studies on autoignition but there has not been agreed on conclusion due to its inherent randomness and complicated physical mechanism. Plenty of particulars can be found in synthetic research on autoignition. Zel’dovich developed a theory of autoignition phenomenon in non-uniform reactive mixture. Bradley and Chen further investigated hot spot autoignition. The operational peninsula was proposed by the normalized temperature gradient method, which was used to analyze the autoignition phenomenon. Nagano and Qi investigated end-gas autoignition and pressure oscillation in a self-designed quasi one-dimensional closed experiment tube. Subsequence, Yu and Chen further investigated autoignition in one-dimensional simulation closed space, confirming pressure oscillations induced by autoignition. End-gas autoignition is produced by compressing unburned end-gas and increasing temperature and pressure. However, Wei discovered another end-gas autoignition induced by a combination of successive shock waves in a confined space. Wang and Pan investigated that local autoignition generated pressure pulse/wave. The unburned end-gas were compressed on the boundary walls to react rapidly. A detonation developed since local autoignition and pressure wave were coherently coupled. However, local autoignition is induced by the compression effect between the flame waves on the unburnt gas, which has not been investigated in detail. This local autoignition will be more precisely demonstrated since unburnt gas is compressed by flame waves (different velocities) in the present work.

This studied the flame propagation behavior of propane–air premixed combustion in an improved designed constant volume combustion bomb (CVCB) with two perforated plates at different initial pressures to clarify the formation mechanism of secondary flame acceleration and the local autoignition at the condition of the secondary flame acceleration propagation. The current work demonstrates the following new contributions: (1) The combustion phenomenon of secondary flame formation and enhancement induced by flame
acceleration; (2) the formation mechanism of local autoignition at the condition of the secondary flame acceleration propagation in confined space; (3) the effects of initial pressure on combustion modes involving turbulent flame, deflagration, and quasi-detonation; (4) the effects of flames interaction at different initial pressures on the pressure oscillations. This present work might provide a new insight for combustion science in a confined space, such as autoignition due to the compression effect of secondary jet flame and primary flame interaction. It also provides the theory guidance and research direction toward further studies on propane storage vessel deflagration.

2 | EXPERIMENTAL APPARATUS AND CONDITIONS

2.1 | Experimental apparatus

The details of the experimental apparatus are discussed in Yu et al., an improved CVCB device was used for the present experiments, and the schematic are shown in Figure 1. Two identical stainless steel perforated plates with a thickness of 3 mm are installed in the CVCB to simulate the actual perforated plates in the fuel storage vessel. As shown in Figure 1B, the structure of the perforated plate is identical to the section of CVCB, which evenly distributed 71 holes with a diameter of 5 mm and porosity of 12%. One perforated plate (Plate A) is located 22 mm from the left end wall. The other perforated plate (Plate B) is located 140 mm from right end wall. Two perforated plates divide the combustion chamber into three regions, which are part (I), part (II), and part (III). The orange shadow region in Figure 1A is taken as the optical region for the observation window with 160 mm in length and 80 mm in width. To record the pressure of the combustion bomb, the pressure transducer (100 kHz, Kistler 6113B) is arranged on the top of CVCB. The distance from the pressure transducer to Plate B is 10 mm (left). The tested pressure is high-pass filtered by 4 kHz. The pressure oscillation was employed to characterize the turbulent combustion intensity. The pressure is acquired by pressure data acquisition system with the uncertainty of 0.005 MPa.

2.2 | Experimental conditions

The detailed experimental conditions are shown in Table 1. The experiment in each group was repeated at least three times with different initial pressures, the difference between each test was kept within 5% to confirm the reproducibility. At the start of the experiment, the CVCB was heated up to a specified temperature of 343 K to prevent the residual gases from condensing droplets. Based on Dalton’s partial pressure law, the propane–air stoichiometric ratio was obtained. The propane–air mixture was charged into CVCB and premixed for 5 min to ensure uniform mixing. The spark plug (Bosch R6) is mounted on the left end wall to ignite mixtures. The mixtures are ignited by a spark plug with a duration of 0.7 ms. The experimental device was flushed with fresh air at least twice to avoid the effect of residual products in the last experiment.

2.3 | Definition of flame velocity

The flame velocity was obtained by the difference in flame front position between consecutive images. In the present experiments, 40,000 images per second were

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**FIGURE 1** Schematic of the experimental setup. (A) Constant volume combustion bomb (CVCB) and (B) perforated plate.
collected by the high-speed Schlieren photography system. And the consecutive image time interval is 0.025 ms. The uncertainty on flame front location is less than 0.18 mm. As a result, the flame velocity uncertainty is within 7.2 m/s.

3 | RESULTS AND DISCUSSION

3.1 | Evolution of flame propagation

To grasp the process of secondary flame acceleration and the formation mechanism of local autoignition at the condition of the secondary flame acceleration propagation, the relation between position and flame velocity at the initial pressure of 0.4 MPa is shown in Figure 2 and the schlieren images of flame propagation at the initial pressure of 0.4 MPa are shown in Figure 3. As shown in Figure 1, the position of flame just entering the orange shadow region at the X-axis direction represent the zero point, and the time also is 0 ms. The right end wall of the CVCB is located 160 mm. It is difficult to show some details to recognize original images, and the difference-highlighted images are obtained by a specific image-processing technique.

As shown in Figure 2, flame passed through Plate B, and flame propagation could be separated into three stages, including the primary jet flame stage, secondary jet flame stage, and flame-shock interaction stage.

① Primary jet flame stage.

As shown in Figure 3, in part (Ⅱ), at 0.15 ms flame propagation is clearly observed. At 0.45 ms a distinct boundary line (white-dotted line) can be observed. The formation mechanism of combustion phenomena was expounded in detail by the experiment of Zhou. The secondary flame front was generated on the surface of the primary flame due to the effect of the toroidal vortex when the flame passed through Plate A, and it appears as a similar laminar flame. Flame curled around the toroidal vortex. The vortex moved forward under the impetus of the flame, and the unburned mixture entrained in this process was consumed. During the propagation, the flame front was little disturbed by the interaction with the vortex and remains compact. With the expansion of the burned gas, the secondary flame front was developed on the basis of the primary flame. The primary flame consumed the unburned mixture involved in the vortex and burned slowly. The secondary flame front accelerated forward due to the increase of the burning surface and the expansion of the rear combustion products. At 0.525 ms primary flame and secondary flame are marked in detail. A prominent protrusion on the secondary flame surface is observed at the same time, and then becomes pointed due to the throttling effect. The flame front starts to accelerate. As shown in Figure 2 at the interval from 8.95 to 15.16 mm, the flame velocity curve is going up.

At 0.6 ms, the secondary flame in part (Ⅱ) just passes through Plate B, the primary jet flame is formed by shear effect of the perforated plate including flame velocity instantaneous increasing in part (Ⅲ). Turbulent flame is generated subsequently. According to Bychkov’s theory, KH/RT instability with shear effect played a vital role in increasing flame burning velocity. Along with primary jet flame keeping up propagation, the flame velocity increases initially until it reaches a maximum of 273.6 m/s. After that, the flame velocity decreases steeply due to the fluid dynamic mechanism.

② Secondary jet flame stage.

At the secondary jet flame stage, the secondary flame of part (Ⅲ) formation process, primary flame and the secondary flame of the part (Ⅲ) simultaneous acceleration in different modes, and local autoignition formation mechanism are expounded in detail in this section.

| Initial condition | Value |
|-------------------|-------|
| Initial temperature \( (T_0/K) \) | 343 ± 2 |
| Initial pressure \( (P_0/Mpa) \) | 0.1, 0.2, 0.3, 0.4, 0.5 |
| The equivalence ratio | 1.1 |
| Hole size/mm | 5 |
| Porosity/% | 12 |

![Figure 2](image_url) Relations between position and flame velocity at the initial pressures of 0.4 MPa.
As shown in Figure 3, at 0.95 ms, the primary flame in part (II) (before Plate B) starts to enter Plate B, throughs Plated B, jets, and accelerates due to the shear effect of the perforated plate. At the same time, the primary flame in part (III) (after Plate B) is pushed forward and accelerated due to the jet of primary flame in part (II). In part (III), small flames are generated subsequently at 0.975 ms on the primary flame surface of part (III). It is interpreted that the secondary jet flame is formed by shear effect of Plate B. Small flames continuously increase and fuse at 1.0 ms. At 1.1 ms small flames are fused completely, the secondary flame of part (III) is formalized. It can be explained by the acceleration mechanism, interior flames suddenly accelerate, and interior flames propagation is beyond the original flame front. Another interesting combustion phenomenon also is presented, during the secondary flame formation process, slight local autoignition combustion (marked by the white dotted rectangular line) occurs, and the area of local autoignition combustion keeps getting larger. It can be explained that at the interval from 96.8 to 115.43 mm, secondary flame velocity (red line) accelerates, meanwhile, the primary flame of part (III) velocity (black line) also increases, oscillates, and ripples up, as shown in Figure 3. However, the suddenly increased secondary flame velocity is beyond primary flame velocity, causing repetitive compression effects on the unburnt gas. The pressure and temperature increase. The unburnt gas is heated, which induced local autoignition. In terms of pressure, as shown in Figure 4, location $l$ appears as peak pressure, pressure oscillation (filtered pressure is 0.546 MPa) of location $l$ is caused by continuous compression between the flame waves, and
high-intensity combustion is induced, namely, local autoignition. The interesting phenomenon is explained that the comprehensive interaction of shear effect (KH/RT instability) and flame-pressure wave played an important role. This can also be used as a supplementary explanation, Wei20,21 did not explain the mechanism of small flame and secondary flame formation in the self-accelerating stage of flame propagation.

Besides, in Figure 3, at 1.125 ms, the area of autoignition combustion reaches the maximum. From 120.37 to 130.78 mm, the secondary flame of part (III) velocity accelerates. Secondary flame performs the self-acceleration process. It was similar to the acceleration mechanism of finger flame.45,46 And the multimechanisms could be found in Law and Akkerman’s works.17–19 Meanwhile, the primary flame of part (III) velocity decreases sharply. From 130.78 to 145.57 mm, both primary flame of part (II) and the secondary flame of part (III) velocities decline, forced by the shock wave.

3 Flame–shock interaction stage.

The flame propagation develops into the last stage, both two velocity curves in Figure 2 decrease sharply due to the confinement of the end-wall. The shock wave and reflect shock wave are induced due to the confinement of the end wall. Figure 5 shows the enhancement of the shock waves (discontinuity surfaces) at 1.25 ms (145.57 mm). At 1.35 ms, a reflected shock wave is generated since confinement of the end wall. The secondary flame of part (III) velocity decreases and even reverses as forced by the reflected shock wave in Figure 2. From 134.43 to 143.74 mm, the secondary flame of part (III) velocity decreases faster than the primary flame velocity of part (III). At 1.4 ms (143.74 mm), both merge and then propagate forwardly. Shock waves and reflected shock waves occur again from 144.66 to 151.96 mm. Similarly, the secondary flame front is pushed back propagation due to flame–shock interaction. The formation and enhancement of the shock waves and reflected shock waves were expounded in detail by the experiment of Zhou.38

Besides, Figure 6 shows the interaction between flame and end-wall at the end region of CVCB. At 1.9 ms a clear autoignition combustion phenomenon is captured at hole outlets of the Plate B (marked by a white dotted circular line). It can be explained that the temperature of compressed unburnt gas increases rapidly due to the sharp increase in compressive intensity and the thermal radiation of local autoignition during secondary flame propagation. At 2.125 ms end-gas autoignition is induced by the shock wave. Based on the confinement effect of the end-wall, the flame phenomenon becomes complex due to reflected waves and gas compression effects. The compressed unburnt gas is acted again and again by flame–shock. Its temperature, pressure, and density change dramatically. As a result, relatively high pressure and temperature-induced end-gas autoignition. At 2.225 ms, the end-gas autoignition propagates from the upper right to left with a velocity of about 254 m/s, as marked by the white dot line. Meanwhile, as shown in Figure 4, the peak pressure is 3.72 MPa with pressure oscillation up to 0.701 MPa thus developing deflagration (stochastic location and time) due to the stochastic nature of autoignition.47–49 RM instability47 is the main mechanism of autoignition combustion.

3.2 Effect of initial pressure on flame propagation and flame velocity

This section clearly shows the flame propagation modes and flame velocities evolutions at different initial pressures. Figure 7 shows the schlieren images of flame propagation at initial pressures of 0.1–0.5 MPa. Figure 8 shows flame velocities evolutions after passing through the Plate B at an initial pressure of 0.1–0.5 MPa. The different cases at different initial pressures indicate different flame propagation modes. Initial pressure has little effect on the flame velocity before Plate B in the observation area. Thus, the research on flame velocity after passing through Plate B is a focus. In Figure 8, the flame just passing through Plate B at the X direction axis represents the zero point. The right end wall of the CVCB is located at 140 mm.

Three kinds of combustion modes due to the flame–pressure/flame–shock wave interactions were discovered with the increasing initial pressure, which included turbulence flame, deflagration, and quasi-detonation in Figures 6 and 7.

When the secondary flame of part (II) approaches Plate B, the surface of the flame will appear prominent protrusion, and then becomes pointed due to the throttling effect at an initial pressure of 0.1–0.4 MPa. But at an initial pressure of 0.5 MPa, flame velocity increases, the secondary flame of part (II) approaches the

![Figure 5](image_url) Schlieren images of shock wave formation at an end region of constant volume combustion bomb.
Plate B, a small flatted flame is presented by the confinement of Plate B. As a result, the flame burns belatedly and decelerates. As shown in Figure 8, all flame propagations have undergone the primary jet flame stage and secondary jet flame stage at five kinds of different initial pressures. The maximum flame velocities increase with increasing initial pressure, that is, 208 m/s at 0.1 MPa, 225.45 m/s at 0.2 MPa, 245 m/s at 0.3 MPa, 273.6 m/s at 0.4 MPa, and 328 m/s at 0.5 MPa. Meanwhile, as shown in Figure 8F, flame velocity increases with the increasing initial pressure. In the interval about 68 to 100 mm secondary flame is formed, and flame velocities increase 66–109.6 m/s at 0.1 MPa, 94.78–144.4 m/s at 0.2 MPa, 129.2–182.4 m/s at 0.3 MPa, 131.6–212 m/s at 0.4 MPa and 131.2–240 m/s at 0.5 MPa. In Figure 7, a clear secondary flame can be observed after 1.625 ms (0.1 and 0.2 MPa), 1.2 ms (0.3 MPa), and 1.1 ms (0.4 and 0.5 MPa). During the formation of secondary flame, there is no local autoignition at an initial pressure of 0.1 MPa. At the initial pressure of 0.2–0.5 MPa, local autoignition with different intensities occurs due to the different compression effects caused by different flame jet velocities. The intensity of local autoignition increases with increasing initial pressure. Different combustion phenomena appear when flame propagates to the end of the combustion chamber. At initial pressure of 0.1 and 0.2 MPa, the present work has not observed the shock wave. The shock waves and reflected shock waves are generated at initial pressure of 0.3 MPa. Flame backward propagation in three intervals caused by reflected shock waves, and as shown in Figure 8C position of the flame front moves backward and then propagates forward, forming a circle shape. The high-intensity shock waves and reflected shock waves are observed at initial pressure of 0.4 and 0.5 MPa. There is also a backward flame propagation. Figures 5 and 7D show clearly the shock wave and the reflected shock, causing the position-flame velocity curve to become complex and irregular at this stage in Figures 8D,E.

Meanwhile, at the end of CVCB, combustion phenomena are also different. At initial pressure of 0.1,0.2, and 0.3 MPa, end combustion phenomena are turbulent flames. At initial pressure of 0.2 MPa, the unburned gas is compressed between flame waves due to secondary flame velocity being beyond primary flame velocity, inducing local autoignition in front of part (III). At initial pressure of 0.3 MPa, secondary flame velocity increases greately. In addition to greater intensity of local autoignition at the front end of part (III), autoignition occurs at the jet orifice of Plate B. A possible explanation for this might be that the primary flame of part (III) forms a high-speed jet flame at high initial pressure, resulting in strong compression effect and instantaneous increase of heat at the jet orifice. Under initial pressure of 0.4 and 0.5 MPa, the same local autoignition phenomenon also occurs at the jet orifice of Plate B and the end of the combustion chamber and becomes brighter. But at an initial pressure of 0.4 MPa, subsonic deflagration is induced by flame–shock interaction in the end-wall of the CVCB. Detailed explanations have been made in Section 3.1. It can be seen in Figure 7D, the end-gas autoignition marked by the white dot line propagated from the upper right to left with a velocity of about 485.2 m/s (approximate the local sound velocity of about 501 m/s) at 2.1 ms under initial pressures of 0.5 MPa, and velocity of end-gas subsonic deflagration exceeded that of initial pressure of 0.4 MPa (254 m/s). It should be noted that autoignition (marked by a red dotted circle) is brighter at the sidewall than end-gas autoignition at 1.6 ms before forming end-gas autoignition. The autoignition continues to propagate and becomes brighter and brighter. The peak pressure is 4.98 MPa and the filtered pressure is 1.16 MPa. Thus, a quasi-detonation or weak detonation develops since local autoignition in
front of part (Ⅲ) and pressure waves near the sidewall are coherently coupled. As shown in Figure 8F it can be seen that flame velocity is positively correlated to initial pressure from velocity curves. Figure 9 shows the relationship of the mean flame velocity in part (Ⅲ) on the initial pressure. It can be seen that the mean flame velocity increases with increasing initial pressure in the interval from 0.1 to 0.5 MPa.

3.3 | Effect of initial pressure on peak pressure and pressure oscillation

Figure 10 shows the time history of pressures and filtered pressures (high band of 4 kHz) under different initial pressures to understand the effect of initial pressure on peak pressure and pressure oscillation. Figure 11 shows pressures and filtered pressures contrastive analysis.
FIGURE 8  Flame velocity versus position under different initial pressures including (A) 0.1 MPa, (B) 0.2 MPa, (C) 0.3 MPa, (D) 0.4 MPa, (E) 0.5 MPa, and (F) contrast at different initial pressures.
under different initial pressures. As can be seen in Figures 10 and 11, at 0.5 ms pressure oscillations appear under different initial pressures. Zhou\textsuperscript{44} pointed out that compression waves were generated due to the acceleration of flame and confinement effect, even produced autoignition combustion, which led to higher pressure peaks and pressure oscillations. The intensity of combustion can be characterized by pressure oscillation. Peak pressures and amplitude of filtered pressures are analyzed by combustion phenomena in Figure 10.

The filtered pressure is relatively high to form a high-pressure oscillation at locations \(a\) and \(b\) (filtered pressure of 0.049 and 0.040 MPa) of Figure 8A, location \(c\) (filtered pressure of 0.110 MPa) of Figure 8B, location \(e\) (filtered pressure of 0.268 MPa) of Figure 8C, location \(k\) (filtered pressure of 0.546 MPa) of Figure 8D and location \(m\) (filtered pressure of 0.896 MPa) of Figure 8E. This phenomenon can be explained by the secondary flame of part (III) accelerating and forming a compression effect with the primary flame of part (II), resulting in a filtered pressure peak. The peak of filtered pressure increases with increasing initial pressure. This also supports the local autoignition phenomenon caused by pressure waves’ continuous compression between flames at different initial pressures. As shown in Figure 8A, compared with the other initial pressures, the pressure is relatively low and stable at an initial pressure of 0.1 MPa, no visible shock wave and disturbance are observed at the end of CVCB. The peak pressure is 0.63 MPa and the amplitude of maximum filtering pressure is 0.049 MPa at an initial pressure of 0.1 MPa. It is interesting that peak pressure and amplitude of maximum filtering pressure do not appear at the same time. The filtering pressure peak of location \(a\) and location \(b\) is the pressure oscillation caused by the compression effect between the two corrugated primary flames in part (II) after passing through Plate B and the primary flames in part (III). The peak pressure is caused by continuous compression between flames and the end wall when flame propagates to the end of the combustion chamber. The corresponding filtered pressure also appears a peak of pressure oscillation, but less than the pressure oscillation of locations \(a\) and \(b\). Thus, the intensity of compressive waves behind Plate B is greater than the end wall at an initial pressure of 0.1 MPa. In Figure 8B, at an initial pressure of 0.2 MPa, as with initial pressure of 0.1 MPa, pressure oscillation of location \(c\) is caused by compression waves of primary flame in part (II) which passes through Plate B. Peak pressure is 1.45 MPa, and is caused by compression waves of the flame-end wall. But the amplitude of maximum filtering pressure appears at location \(d\). The pressure oscillation can be contributed by slight local autoignition which is caused by the continuous compression of compression waves since the velocity of primary flame in part (II) after passing through Plate B is persistently accelerated. The maximum intensity combustion at position \(d\) occurs throughout the combustion process. In Figure 8C, at an initial pressure of 0.3 MPa, pressure oscillation of location \(f\) is caused by brighter local autoignition since continuous compression effects were formed between flame waves, and the maximum filtering pressure is 0.306 MPa. Pressure oscillation (filtering pressure of 0.214 MPa) of location \(g\) is caused by autoignition at the jet orifice of Plate B. Subsequently, a peak pressure of 2.27 MPa appears due to interaction between shock waves or reflect shock waves and the end wall. The corresponding filtering pressure is 0.275 MPa. In Figure 8D, at an initial pressure of 0.4 MPa, pressure oscillation (filtered pressure is 0.546 MPa) of location \(l\) is caused by brighter local autoignition since continuous compression between flame waves. Subsequently, peak pressure of 3.72 MPa and maximum filtered pressure of 0.701 MPa appear at the same time due to end-gas autoignition. In Figure 8E, at an initial pressure of 0.5 MPa, peak pressure of 4.98 MPa and maximum filtered pressure of 1.155 MPa appear at the same time due to brighter autoignition at the sidewall. Pressure oscillation (filtered pressure is 0.761 MPa) of location \(n\) is caused by end-gas autoignition. In Figures 9 and 6F, it can be seen that both peak pressure and the amplitude of maximum filtered pressure increase with increasing initial pressure. As a result, the peak pressures and the amplitude of maximum filtered pressure are also positively related to the flame velocity at an initial pressure of 0.1–0.5 MPa.
FIGURE 10  Time history of pressures and filtered pressures under different initial pressures including (A) 0.1 MPa, (B) 0.2 MPa, (C) 0.3 MPa, (D) 0.4 MPa, and (E) 0.5 MPa.
CONCLUSIONS

To analyze local autoignition induced by secondary flame acceleration, the propane–air mixture flame propagation behavior in an improved CVCB device equipped with two perforated plates was studied experimentally. Combustion phenomena were captured by high-speed schlieren photography including the secondary flame acceleration process, the local autoignition formation process at the condition of the secondary flame acceleration propagation, and end-gas autoignition with shock waves interaction. The effect of initial pressure on flame propagation, flame velocity, and pressure oscillation were analyzed in detail. The main conclusions are described as follows.

(1) There were three distinct stages in the process of flame propagation through two perforated plates, which are the primary jet flame stage, secondary jet flame stage, and flame–shock interaction stage. Primary flame acceleration was caused by shear effect and RT instability. Secondary flame formation and acceleration were caused by jet flame (primary flame in part (II) passes through Plated B) and RT instability. Primary flame in part (III) (after Plate B) is pushed forward and accelerated due to the jet of primary flame in part (II). In part (III), small flames are generated subsequently on the primary flame surface of part (III). Small flames continuously increase and fuse, thus secondary flame of part (III) is formalized. It can be explained interior flames suddenly accelerate, is beyond the original flame front. It should be noted that the compression effect between the primary flame and secondary flame of part (III) caused local autoignition as the second flame velocity is beyond the primary flame velocity. End-gas autoignition is caused by interaction between shock waves and the end wall and is then mainly induced by RM instability. They provided new scientific basics for propane combustion phenomena.

(2) The flame velocity including secondary flame velocity increased with the increasing initial pressure. The acceleration and formation of the secondary flame were observed adequately in confined space at a different initial pressure. Local autoignition phenomena were demonstrated since unburnt gas is compressed by flame waves (different velocities) during the acceleration and formation period of the secondary flame in part (III). Local autoignition is more precisely with increasing initial pressure. Subsequently, based on the morphology of flame, three different flame combustion modes are observed at different initial pressure involving turbulent flame, deflagration, and quasi-detonation.

(3) Pressure oscillation is obviously influenced by initial pressures. A higher initial pressure leads to faster flame propagation and stronger combustion intensity with pressure oscillations of higher amplitude. The peak of the filtered pressure due to the compression effect between flame waves increases with increasing of initial pressure. Both peak pressure and the amplitude of maximum filtered pressure increased with increasing initial pressure, and the peak pressures and the amplitude of maximum filtered pressure also were positively related to flame velocity at an initial pressure of 0.1–0.5 MPa.
This study represents a first step in the direction of investigating secondary flame acceleration and local autoignition formation mechanism. The experimental data produced will be used for validation of the simulation model of secondary flame acceleration in future work. Gas storage with two perforated plates is commonly used to transport gases such as propane, methane, natural gas, and so on. Improper operation results in serious disasters. The effect of different fuels and different initial conditions (including initial pressure, initial temperature, and equivalent ratio) on combustion phenomena under this acceleration condition and formation mechanism can be further investigated in detail. More combustion modes can be discovered to explain the mechanism of more serious explosion phenomena.

AUTHOR CONTRIBUTIONS
Yangyang Yu did experiments, conducted the analyses, and wrote the paper; Junhong Zhang contributed analysis tools; Jun Wang and Dan Wang revised the paper.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

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