Effect of a Perforated Polyethylene Material on Propane–Air Explosion in a Confined Space
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ABSTRACT: In this study, the effect of polyethylene barriers with different blockage ratios on the explosion behavior of a propane–air premixed gas in a confined space is investigated. The maximum explosion pressure ($P_{\text{max}}$), the deflagration index ($K_G$), and the flame propagation process of the propane–air premixed gas with different barrier thicknesses are examined by using a horizontal closed tube with a length of 0.5 m and a diameter of 0.1 m and a high-speed camera. The atmospheric pressure and temperature of the premixed gas were 101.3 kPa and 18 °C, respectively. Based on the Canny operator, the position of the flame front at different times and the shape of the barriers before and after the explosion are determined, and the propagation speed of the premixed flame and the deformation rate of the barriers are obtained. The results indicate that the barriers change the flow field structure of the unburned gas and increase the folding degree of the flame front. With the increase in the blockage ratio, the explosion of a premixed system becomes more rapid and violent. Under the action of Rayleigh–Taylor instability, the variation in the flame propagation speed induces a change in the tube pressure. In addition, the deformation of a barrier causes a change in the maximum explosion pressure. The greater the deformation ratio of the barrier after the explosion, the larger the maximum explosion pressure.

1. INTRODUCTION
Propane is a widely used energy source and is an important constituent of liquefied petroleum gas. It is commonly used in welding, electric systems, and industrial fuels.1 However, due to improper production, transportation, and utilization processes, propane is prone to leakage and explosion accidents.2 Meanwhile, the uneven walls of the equipment used in the production and transportation processes can be regarded as barriers that affect the propagation of explosive flame. It has been reported that the presence of barriers can promote the acceleration of explosive flame and aggravate the rise of explosive overpressure.1–6 Therefore, a clear understanding of the interaction of barriers with explosive flame is needed.

Over the recent years, the explosive characteristics of combustible gas with barriers have been extensively studied experimentally.7,8 These studies focused on the shape,7–15 blockage ratio,16–19 location,20–23 number,24–26 spacing,27,28 and fuel concentration.29–33 Further, experiments have been conducted to obtain the explosive pressure parameters and flame transmission characteristics. The results indicated that the number of barriers can increase the flame propagation speed and peak pressure, but the peak pressure is not entirely determined by the number of barriers. In addition, the dynamic characteristics of combustible gas explosion flame34,35 and the effect of porous barriers on combustible gas explosion have been analyzed using a high-speed camera system.36 It has been reported that the obstacle-induced turbulence can continuously accelerate the flame during the flame propagation process. The shear flow formed on the surface of barriers and the flame instability caused by it determine the magnitude of turbulence. The influence of barriers on the explosive properties, flame propagation speed, and peak pressure of mixed gas has also been examined experimentally.37 These studies revealed that the flame propagation speed and peak pressure of mixed gas are higher than that of a single combustible gas. The above reports have provided effective data support for preventing combustible gas explosion and evaluating explosion risks.

The experimental research primarily focuses more on the macroscopic propagation process of explosive flame. Furthermore, due to the limitations of technology, cost, and safety, it is difficult to obtain the detailed flame structure and flow field characteristics through experiments. Numerical simulation
is an effective and widely used technology to resolve these issues. It combines computational fluid dynamics and chemical methods to study the flow field parameters in the combustion process.\textsuperscript{38}

There are three numerical simulation approaches to solve the transient Navier−Stokes equation: direct numerical solution, Reynolds averaged Navier−Stokes simulation, and large eddy simulation (LES). Chen et al.\textsuperscript{39} used the LES to study the flame acceleration and vortex generation mechanism under different blockage ratios. Coates et al.\textsuperscript{40} analyzed the effect of barrier shape on the explosion to detonation transition in a hydrogen−air mixture by using a two-dimensional model. The results indicated that the vortex and air pressure waves existing in the unburned gas were the main factors that caused the flame to spread during the combustion process. Rubtsov et al.\textsuperscript{41} believed that the instability and turbulence of flame could lead to the acceleration of combustion under the presence of barriers. Moreover, several researchers have simulated the dynamic characteristics of flame propagation under the presence of barriers.\textsuperscript{42−44}

All the above studies focused on the effect of rigid barriers on the explosive flame and overpressure, and subtle changes in the barriers did not affect the flame propagation and overpressure. However, when the Young’s modulus of the barrier is low, the deformation of a barrier can affect the flame and overpressure, especially the flame acceleration and overpressure increase rate.

A clear understanding of the propagation mechanism of propane explosion flame and pressure is vital for the effective prevention of propane explosion in underground pipelines with flexible barriers. To this end, in this work, we have investigated the effect of flexible barriers represented by a polyethylene film on the flame propagation behavior and overpressure during the explosion of propane−air premixed gas. Experiments have been conducted using small-sized tubes, setting obstacles with different blockage ratios (number of holes) in the center of the tube, and recording the internal flame and pressure changes in the tube through high-speed cameras and pressure sensors. The effects of deformation and rupture of the barriers on flame morphology, flame propagation speed, degree of flame folding, combustion time, and overpressure are analyzed. The results indicate that the maximum explosion pressure, the time to reach the maximum explosion pressure, and the deflagration index change monotonically with the decrease of blockage ratio. However, the variation trend of each parameter is opposite to that of rigid barriers. The results can serve as a useful reference for the design optimization of underground propane pipelines and development of explosion suppression measures.

2. EXPERIMENTAL SECTION

2.1. Experimental System and Methods. A schematic of the experimental system used to determine the effect of a single barrier on the propane−air explosion is shown in Figure 1. The system consists of an explosive reaction tube, a pressure data acquisition system, a high-speed camera, a gas configuration system, a remote ignition system, and a synchronous control system. The explosive tube is made of a poly(methyl methacrylate) material. It has a total length of 500 mm, an inner diameter of 110 mm, and an outer diameter of 100 mm and can withstand an internal pressure of 0.4 MPa. The tube is filled with propane/air mixed gas before ignition. The right end of the tube is sealed with a 5 mm-thick TP304 stainless steel pipe. The spark plug, the JC-80XB pressure gauge, and the gas inlet are mounted on the plate. It may be noted that the spark plug is located at the center of the plate. The pressure data acquisition system is composed of a high-frequency pressure sensor (sampling frequency: 10 kHz, range: 0−2.0 MPa, and error: ±0.5% F.S.) and a Smaq data acquisition card (USB-3110, sampling rate: 125 kSa/s). A high-speed camera (NPX-GS6500UM; it has a maximum frame rate of 2000 fps, 640 × 640 pixels, and an exposure time of 0.5 ms) is used to record the flame propagation process. The gas configuration system consists of a pressure gauge (JC-80XB), a 10 L collection cylinder (containing 99.95% pure propane), and a mass flow controller (Alicat MCS, precision: 0.01 L/min). The remote ignition system includes a DC power supply (5 V, 10 A), a spark plug, a signal transmitter, a signal receiver, and a timer. When the signal receiver receives the ignition signal, the power supply of the ignition system is switched on, and the spark plug emits an electric spark with an energy of 800 mJ and a diameter of 4 mm. At the same time,
the timer starts counting down to 1 s. When the timer counts down, the power to the ignition system is disconnected and the spark plug no longer discharges. The synchronous control system consists of an FS-N18N photoelectric sensor. Once the mixture gas is ignited, the synchronous control system triggers the pressure sensor and the high-speed camera. For safety, a discharge vent is set at the duct’s rear. The outlet end of the tube is sealed with a polyethylene film, which can withstand a maximum impact force of 0.0375 MPa. When the mixture gas is injected, the tube is sealed by a polyethylene film with a thickness of 0.075 mm and a maximum pressure of 0.0375 MPa.

The oxygen concentration, atmospheric pressure, and temperature of the experimental environment were determined by an oxygen concentration detector, a pressure gauge, and a thermometer, respectively. The volume fraction of propane upon a complete reaction with the tube air was calculated based on the corresponding chemical reaction equation. Using Dalton’s law of partial pressure, the partial pressure of propane gas in the premixed gas was calculated. First, a negative pressure pump was used to extract a certain proportion of air from the closed tube. The pumping of air was stopped when the gauge indicator value was the same as the partial pressure of propane in the premixed gas. Then, the negative pressure pump was turned off, and the quality flow controller was opened to fill the propane gas into the explosion tube. When the registration of pressure gauges for pressure measurement was 0, the quality flow controller was turned off. The circulating pump was opened for 4 min to ensure the uniformity of the premixed gas. The gas in the tube was placed for 10 min to ensure that the turbulence in the tube did not affect the experimental results. Before ignition, the volume fraction of propane gas in the tube was measured using a concentration detector. If the measured volume fraction was 4% (±0.1%), the experiment could be carried out. Otherwise, the circulation system was restarted until the measured values met the experimental requirements. Every experiment was repeated three times to test the repeatability, and the standard deviation was represented by error bars.

2.2. Experimental Materials and Data Specification. The experimental gas was provided by Ping An Gas Co., Ltd. Polyethylene barriers with different blockage ratios have been employed, as shown in Figure 2, where the diameter of each small hole is 20 mm. The various parameters of the experimental environment are shown in Table 1. The volume fraction of propane required for the experiment as calculated from the oxygen concentration in Table 1 is approximately 4.0%.

2.3. Flame Image Processing Method. The flame images at different moments were processed using MATLAB combined with the Canny edge detection algorithm. The flame propagation speed was calculated based on the location of white pixels on the flame edge.

2.3.1. Calculation of the Flame Front Position. First, a cyclic function was used to convert flame images into gray scale and perform binarization treatment. The flame edge was obtained to determine the boundary of the flame area. The triangular function was used to calculate the distance between the white pixels on the flame edge and the ignition source plane. Comparing the results, the maximum distance corresponds to the flame front tip position, as shown in Figure 3.

\[ v_f = \frac{x_{n+1} - x_n}{\Delta t} \]  

where \( v_f \) is the blast flame propagation speed, m/s; \( x_{n+1} \) is the position of flame front in the tube at the current moment, m; \( x_n \) is the position of flame front in the tube at the previous moment, m; and \( \Delta t \) is the difference between the current and previous moments, s.

2.3.2. Calculation of the Flame Propagation Speed. The maximum flame propagation speed at different times in the pipeline is calculated as follows:

\[ \varphi = \frac{S_{BR}}{S_A} \]  

where \( S_{BR} \) is the barrier area and \( S_A \) is the cross-sectional area of the explosive tube.
3. RESULTS AND DISCUSSION

3.1. Effect of Barriers on the Propane Explosive Flame. 3.1.1. Flame Structure and Trajectory Evolution. The structure and morphology of the flame are important parameters to characterize the flame behavior and instability. As shown in Figure 4, the flame structural changes are similar across all the experiments before the flame crosses the barrier. The explosive flame is constrained by the tube and transforms from spherical to hemispherical to finger shape. The initial phase of the flame begins to undergo a spherical expansion around the electric spark on the electrode, and then the flame is constrained by the flange in the horizontal direction to form a hemispherical flame. During the flame propagation to the inner wall of the tube, a small gap exists between the flame edge and the inner wall of the pipe, namely, the flame skirt. When the vertical flame spreads to the inner wall of the pipe, constrained by the wall, the flame completely travels along the horizontal direction. Meanwhile, the flame front stably propagates to the midpoint of the pipe in the shape of a fingertip.

In condition 4 (without barriers), when the flame reaches the center of the tube, the polyethylene film at the outlet end of the tube breaks, and the pressure inside the tube is released, resulting in a large displacement when the flame front enters tube2 from tube1, and the flame front radian is significantly reduced. During the pressure relief process, the oxygen content in the tube decreases continuously, so the displacement of the explosion flame at $t = 35.5-36.0$ ms decreases. When $t = 36.5-38.5$ ms, the displacement of the central flame gradually decreases, the shape of the flame changes from “finger” to “funnel”, and a spiral flame curling to both sides appears at the root of the “funnel”.

When barriers are added to the tube, the structure and morphology of the flame change significantly. When the flame passes through the barrier, the airflow field in front of the flame is compressed. Therefore, the flame front gradually becomes sharp and flows to the opening of the barrier. At this time, the flame surface is still smooth, indicating that the flame is still burning in a laminar flow, and the combustion form is not affected by the barriers. When the airflow passes through the barrier, a shear flow is formed in front of the barrier. Therefore, when the flame passes through the barrier, the shear flow acts around the flame, causing Kelvin–Helmholtz instability. At the same time, the turbulent shear layer forms a circulation region, which causes a random flow of propane–air premixed gas in front of the flame, resulting in turbulence.

As the blockage ratio of barriers decreases, the flame front presents a more significant change in the structure. Due to the turbulence effect and eddy current around the barrier, the folding degree of the flame front is substantially enhanced. In the second section of the tube, many irregular flame shapes appear, which in turn affect the turbulence in front of the flame, and the subsequent comprehensive mechanism further affects the flame propagation and pressure. This is because the turbulence increases the local combustion velocity by increasing the flame front area as well as the transmission of local mass and energy. The larger the combustion rate, the higher the flow rate of unburned gas. This “turbulent” feedback mechanism may cause further flame acceleration.

When the blockage ratio of the barrier is 96%, near the barrier, the flame propagation becomes more obviously restricted by the barrier. It can be seen in Figure 4 that the
tip of the flame is gradually stretched and extended, and an
annular unburned area is formed near the barrier in the tube1. When the flame completely passes through the barrier, due to the strong turbulence around the barrier, the flame front continues to shrink, forming an annular unburned area in tube2, which is gradually consumed and is finally completely submerged by the flame (Figure 5a). Because the turbulence intensity is further intensified, the flame quenching phenomenon occurs during the combustion process, causing a reduction in the effective energy release rate. When the thickness of the barrier increases, the quenching phenomenon of the flame becomes more obvious. In addition, the heat loss in tube2 cannot be enhanced. Therefore, during the forward flame propagation process, propane gas is not fully burned, resulting in secondary combustion of propane gas in the tube when polyethylene at the outlet end of the tube is broken. During the secondary combustion process, the flame moves from the second section of the pipe to the first section. Here, the return of the flame is attributed to the pressure wave induced by the flame and the reflected wave generated at the end of the tube, which drives the gas in the unburned zone to diffuse to the combustion zone, resulting in the reversal of flame front. To some extent, this process is similar to the Rayleigh–Taylor instability mechanism.

When the blockage ratio of the barrier is 88%, the annular unburned area near the barrier in the first section of the tube gradually decreases before the flame front passes through the barrier. After the flame front passes through the barrier, the barrier divides the flame into three cylindrical flames. There is a large unburned area between the flames, and a certain angle exists between the flames. According to the deformation mechanism of the barrier in Figure 5b, during the explosion process, the pressure of tube1 causes the expansion of the barrier toward the outlet of the tube, resulting in the transformation of the plane barrier into a curved barrier. Therefore, an inclination angle is generated between the flame when it passes through the barrier. When the flame enters the second section of the tube, the flame is accelerated to a certain extent. When the flame propagates to the center of the second section of the tube, the flame located on the center line of the tube diffuses to both sides under the influence of the vortex between the flames. With the increase in the barrier thickness, the flame diffusion position gradually moves to the outlet direction.

When the blockage ratio of the barrier is 80%, the flame is divided into five cylindrical flames after passing through the barrier. The flame propagation speed at the tube axis is greater than that near the tube wall. As the thickness of the barrier increases, this phenomenon becomes more obvious. When the barrier is a single-layer barrier, Kelvin–Helmholtz instability can be clearly observed on the flame front at \( t = 35.5 \text{ ms} \). When the thickness of the barrier increases, the Kelvin–Helmholtz instability on the flame surface becomes increasingly blurred.

### 3.1.2. Flame Propagation Speed

The flame image in Figure 4 suggests that the flame front exhibits frequent changes during the propagation process in the tube. Therefore, Figure 6 only describes the flame propagation speed from the electrode to the pipe outlet. In the experiment with barrier, the flame propagation speed slowly increases before crossing the barriers, while it suddenly increases after crossing the barriers.

Before the flame approaches the barrier, the increase in the flame propagation speed mainly depends on the expansion of combustion products. In the explosion process, the increment of combustible gas volume is expressed as follows

\[
\frac{dV}{dt} = \sigma_A S L
\]
where $V_t$ is the volume of propane; $t$ is the time; $\sigma$ is the coefficient of expansion, $\sigma = \rho_u/\rho_0$; $\rho_u$ is the density of unburned gas; $\rho_0$ is the density of ignited gas; and $A$ is the total surface area of flame. $S_o$ is the laminar flame speed of premixed gas, which can be calculated as follows$^{5,37}$

$$
S_L = S_0 \left( \frac{T_u}{T_0} \right)^a \left( \frac{P_u}{P_0} \right)^b
$$

(4)

where $T_u$ and $P_u$ are the pressure and density of unburned gas; $T_0$ and $P_0$ are the temperature and pressure of the premixed gas before combustion; $S_0$ is the initial laminar flame speed of premixed gas, $S_0 = C_1 + C_2(\phi - C_3)^2$, where $C_1$, $C_2$, and $C_3$ are the specific constants for the fuel; $\phi$ is the equivalence ratio of the fuel; and $a = 2.18 - 0.8(\phi - 1)$ and $b = -0.16 + 0.22(\phi - 1)$.

In addition, during the subsequent propagation process, when the blockage ratio of the barrier is 96%, the maximum propagation speed of the flame decreases with the increase in the barrier thickness. When the blockage ratio of the barrier is 88%, the maximum propagation speed of the flame decreases and then increases with the increase in the barrier thickness. This speed continues to increase as the flame propagates forward. Near 0.4 m of the tube, the flame propagation speed reaches the maximum values of 200.31, 84.51, and 71.9 2m/s, which is 58.02, −33.33, and −43.26% higher than the value without the barrier (126.76 m/s).

In the experiment with barriers, the flame propagation speed increases after crossing the barrier. This is because the turbulence effect around the barrier increases the flame front area as well as the local mass and energy transmission, thereby increasing the local combustion rate. Therefore, the flame propagation speed is significantly enhanced. Higher combustion rate leads to a higher flow rate of unburned gas, and this “turbulent” feedback mechanism may lead to further acceleration of the flame.

However, as the flame continues to propagate forward, the large-area interaction between the flame front and the inner wall of the pipe leads to a large amount of energy loss (heat and momentum). Large-scale turbulence cannot be maintained for a long time, and the flame propagation speed decreases.

In condition 1, when the thickness of the barrier is 0.15 and 0.225 mm, the flame propagation speed significantly decreases at 0.36 and 0.45 m of the tube, respectively. This is because the flame is quenched at these two positions. In a short time, the propane–air premixed gas in the second section of the tube cannot react continuously, and the flame cannot propagate to the outlet of the tube. This phenomenon can be observed in Figure 4.

3.2. Dynamic Effect of the Barrier on the Propane Explosion Pressure. For explosive tubes of different shapes and volumes, $P_{\text{max}}$ and $(\text{d}P/\text{d}t)_{\text{max}}$ can be discretized, as shown in Figure 7. The correlation between these two parameters and the shape and volume of the explosive tube is irregular. This is because the aspect ratio and the specific surface area of the cylindrical vessel can also affect both the parameters. At a certain volume, the $P_{\text{max}}$ and $(\text{d}P/\text{d}t)_{\text{max}}$ values decrease with the increase in the aspect ratio and specific surface area.

3.2.1. Maximum Explosion Pressure. According to Figure 4, the sensor in this experiment is arranged at the outlet of the pipeline. Therefore, the measured pressure is examined as the explosion venting pressure. Figure 8a shows the maximum explosion pressure measured by the pressure sensor under various experimental conditions. When the blockage ratio of the barrier is 96%, the $P_{\text{max}}$ values decrease with the increase in the barrier thickness. When the barrier thickness increases from 0.150 to 0.225 mm, the increase of $P_{\text{max}}$ is only 3.82%, indicating that the barrier has a minor effect on the maximum explosion pressure under this blockage ratio. When the blockage ratio of the barrier is 88 and 80%, the $P_{\text{max}}$ values decreases with the increase in the barrier thickness. The $P_{\text{max}}$ value in the experiment with a barrier is higher than that in the experiment without a barrier. After adding the barrier, the value of $P_{\text{max}}$ increases by approximately 4.47–185.05%. Therefore, the presence of a polyethylene barrier increases the risk of propane gas explosion in the tube.

The $P_{\text{max}}$ value decreases with the increase in the thickness of the polyethylene barrier because the barrier can easily accumulate the explosion pressure in the tube. After the pressure generated by explosion passes through the barrier, it transits from a relatively concentrated state to a dispersed state. With the increase in the barrier thickness, the ability of the barrier to accumulate pressure increases, causing a continuous increase in the pressure accumulated in the first section of the tube when the film at the tail end of the tube breaks.

According to the blockage ratio change and the similarity of position relationship among the electrode, barrier, and sensor, the experimental results in ref 37 are selected to compare with our experimental results. By comparing the variation trend of $P_{\text{max}}$, it can be found that when the thickness of the barrier remains the same, the change in the $P_{\text{max}}$ value is related to the blockage ratio. When the blockage ratio decreases, the value of $P_{\text{max}}$ generally increases during the premixed gas explosion. In addition, this variation law does not change with the variation in the thickness and toughness of the barrier.

In the barrier placement experiment, there is no difference between the measured maximum explosion pressures if uncertainty is taken into account.

3.2.2. Time to Reach the Maximum Explosion Pressure. Figure 9a shows the relationship between the blockage ratio and the barrier thickness and the time $t_{\text{max}}$ when the maximum explosion pressure is reached. Under the same barrier thickness, the variation trend of $t_{\text{max}}$ with the blockage ratio remains the same. As the blockage ratio decreases, the value of $t_{\text{max}}$ decreases. Under the same blockage ratio, $t_{\text{max}}$ varies with
the thickness of the barrier. When the blockage ratio of barrier is 88%, the value of $t_{\text{max}}$ first increases and then decreases with the increase in the barrier thickness. When the blockage ratio is 80%, the value of $t_{\text{max}}$ decreases with the increase in the barrier thickness. Compared to all the experiments with a barrier, it can be found that with the decrease in the barrier blockage ratio, the variation trend of $t_{\text{max}}$ changes from monotonically increasing to monotonically decreasing.

Compared with the barrier-free experiment, the addition of a polyethylene barrier in the tube changes the value of $t_{\text{max}}$. When the blockage ratio of the barrier is high and the thickness is large, the value of $t_{\text{max}}$ increases. When the blockage ratio of the barrier is high and the thickness is large, the value of $t_{\text{max}}$ increases.

Figure 8. Maximum explosion pressure in different experiments.

Figure 9. Time to reach the maximum explosion pressure in different experiments.
the barrier is small and the thickness is large, the value of $t_{\text{max}}$ decreases. Therefore, it can be concluded that the sudden addition of the polyethylene barrier in the tube can increase the severity of propane–air explosion in the tube, making emergency rescue difficult after explosion accident.

Figure 9b shows the impact of blockage ratio on $t_{\text{max}}$ under the same barrier thickness. Under the same barrier thickness, the variation trend of $t_{\text{max}}$ is opposite to that reported in ref 37. This indicates that the barriers with low blockage ratio have a greater turbulence generation effect when they are made of flexible and easily breakable materials. This effect speeds up the combustion rate of premixed gas in the container and reduces the $t_{\text{max}}$ value.

As shown in Figure 9a, when the thickness of the barrier increases, the uncertainty of the result does not affect the variation trend of $t_{\text{max}}$.

3.2.3. Deflagration Index. $K_G$ is one of the vital indicators to evaluate the severity of explosion, and it plays a key role in the design of industrial protective gear and study of explosion suppression measures. It is expressed as follows

$$K_G = \left( \frac{dP}{dt} \right)_{\text{max}} \cdot V^{1/3}$$

(5)

where $K_G$ is the deflagration index, $(dP/dt)_{\text{max}}$ is the maximum value of pressure change rate, and $V$ is the volume of the explosion tube.

In refs 1–34, the shape and volume of containers used in the experiment are different, so it is not reasonable to choose $V^{1/3}$ for representing the characteristic length of explosive containers. For tubular explosive vessels, the distance $L$ between the ignition source and the tube outlet can be used to represent the characteristic length. Therefore, eq 5 is modified as follows

$$K_G = \left( \frac{dP}{dt} \right)_{\text{max}} \cdot L$$

(6)

Figure 10a shows that when the blockage ratio of the barrier is constant, the $K_G$ value decreases with the increase in the barrier thickness. When the blocking ratio of the barrier is 96%, the $K_G$ value first increases and then decreases. Compared with the barrier-free experiment, the addition of a polyethylene barrier in the tube increases the value of $K_G$. When the blockage ratio of the polyethylene barrier is 80–90% and the thickness is 0.075–0.225 mm, the value of $K_G$ increases by approximately 69.01–542.96%.

Under the condition of the same equivalence ratio of premixed gas in the tube, $K_G$ is not a constant value, and it varies under different experimental conditions. It is related to the volume of the explosive vessel and the ignition energy.

As shown in Figure 10b, under the same barrier thickness, the value of $K_G$ increases with the decrease in the blocking probability. In particular, when the blockage ratios are 80 and 88%, the $K_G$ value is greater than 30 MPa m/s, which is the most dangerous level. When the barrier thickness is 0.075 mm, the change in $K_G$ becomes more obvious. Comparing the results of ref 37, it can be found that the variation trend of $K_G$ is opposite. When the blockage ratio increases, the turbulence generation effect increases. In this experiment, a flexible barrier with a small Young’s modulus was used. When the shock wave and combustion heat cause the breakage of the barrier, the turbulence instability in the tube is intensified and the combustion rate of the mixed gas is accelerated. When the blockage ratio is reduced, the barrier is more likely to break. Therefore, the value of $K_G$ decreases with the increase in the blockage ratio.

When the barrier thickness is 0.075 and 0.225 mm, the uncertainty of the result does not affect the variation trend of
relationship between the propane explosion pressure and flame propagation speed. When the blockage ratio of the barrier is 96% and the thickness is 0.150 and 0.225 mm, the pressure variation trend during the explosion is different from that in other experiments. Therefore, taking the experimental results under the above two conditions as an example, the influence of barriers on the relationship between explosion pressure and flame is studied.

When the flame propagates in the first section of the tube, the flame propagation speed reaches 11.55 and 7.14 m/s, the explosion pressure is 0.06366 and 0.06132 MPa, and the pressure gradually approaches the maximum value. When the flame crosses the barrier and enters the second section of the tube, the flame propagation speed is obviously enhanced. At the same time, the explosion pressure increases to 0.07268 and 0.07546 MPa. At this time, when the barrier thickness is 0.150 mm, the flame propagation speed reaches the maximum, while when the barrier thickness is 0.255 mm, the flame propagation speed continues to increase. At 0.061–0.080 and 0.077–0.085 s, the flame propagation speed and the explosion pressure decrease with time. When the propane in the tube exhibits secondary combustion and explosion, the flame propagation speed increases, and the explosion pressure fluctuates slightly. At this time, in the experiment with a barrier thickness of 0.255 mm, the flame propagation speed reaches the maximum value.

During the propagation of the flame along the axis of the explosion tube, the area of the flame front gradually increases, resulting in an increase in the combustion speed of the premixed gas. Therefore, the flame propagation speed and explosion pressure change synchronously.

3.3. Change of the Barrier Form. The edge detection algorithm is used to binarize the barriers before and after the explosion. An image processing tool is used to color the binary images, and the result is shown in Figure 11. The number of pixels in a single image are 1280 × 1280, and the sum of pixels is 163,8400. The statistical results for the white pixels in all the images of Figure 12 are shown in Table 2. Figure 12 shows that due to the dual effects of explosion pressure and high temperature, the barriers have different degrees of plastic deformation after the explosion of propane–air premixed gas in the tube. Under the same blockage ratio, the plastic deformation rate of the plate decreases with the increase in the barrier thickness. When the thickness remains constant, the plastic deformation rate of the barrier decreases with the decrease in the blocking ratio. This is because when the blockage ratio of the barrier remains the same, the resistance of the barrier to the explosion shock wave and high temperature depends on the intrinsic properties of the barriers. When the thickness of the barrier increases, it has a strong resistance to shock waves and high temperature, so the probability of deformation in the barrier decreases. When the thickness of the barrier remains the same and the blockage ratio decreases, the ability of barriers to accumulate pressure decreases, and the destructive effect of explosion pressure on the barrier thickness is reduced. Therefore, the lower the blockage ratio, the smaller the shape variable.

Combined with Figure 8, it can be found that after the explosion, the deformation rate of the obstacle changes synchronously with the value of \( P_{\text{max}} \) in the relevant experiment. When the deformation rate of the barrier increases under a constant blockage ratio, the value of \( P_{\text{max}} \) increases.

4. CONCLUSIONS

The effect of polyethylene barriers with different blockage ratios on the explosion behavior of premixed propane–air gas in a confined space was examined. The results suggested that a polyethylene barrier with holes had a significant effect on the explosion. The flame propagation speed and flame structure were more unstable in the tube with a polyethylene barrier than that in the tube without a polyethylene barrier. In addition, in the tube with a polyethylene barrier, the flame propagation velocity did not exhibit a monotonic change, but a fluctuating increasing or decreasing trend. The maximum explosion pressure, time to reach the maximum explosion pressure, and deflagration index of the tube with barrier were
different from those without a barrier. The main findings of the study are summarized as follows:

1) Before the flame crosses the barrier, the flame propagation speed under different experimental conditions was similar. After the flame passes through the polyethylene barrier, it was crimped due to turbulence, and the degree of folding of the flame front increased. In addition, in the second section of the tube, the flame shape was very irregular, such as trident and canyon shape.

2) The polyethylene barriers with high blockage ratio decreased the maximum flame propagation speed to a strong extent. When the blockage ratio of the barrier was 96%, the accumulation of explosion pressure by the barrier reduced the maximum flame propagation speed. As the thickness of the barrier increased, this "pressure" feedback mechanism further reduced the maximum flame propagation speed.

3) Rayleigh–Taylor instability was found to be the main cause of turbulent change in the barrier tube. Turbulence increased the local combustion rate by increasing the flame front area as well as local mass and energy transfer. A higher combustion rate accelerated the flame and increased the explosion pressure in the tube. In this work, the decrease in the blockage ratio and barrier thickness determined the increase in the explosion risks.

4) In general, the polyethylene barriers increased the values of $P_{\text{max}}$ and $K_{\text{cpr}}$ and the value of $t_{\text{max}}$ was reduced. This was attributed to the combination of several factors. First, the turbulence near the barrier increased the degree of folding in the flame front. Then, the synergy of flame and pressure caused the pressure wave reflection, superposition, and hedging.

5) The pressure and high temperature produced by the explosion caused the plastic deformation of the polyethylene barrier. After the explosion, the deformation rate of the barrier changed synchronously with $P_{\text{max}}$ in the relevant experiment.

### Table 2. Barrier Parameters before and after the Experiment

| condition       | white pixels (px) | deformation rate (%) |
|-----------------|-------------------|----------------------|
| condition 1     | pre-experiment    | 17,905               | 0                    |
|                 | post-experiment   | 38,087               | 112.7                |
|                 | 0.075 mm          | 21,758               | 21.5                 |
|                 | 0.150 mm          | 18,078               | 1.0                  |
|                 | 0.225 mm          | 55,190               | 0                    |
| condition 2     | pre-experiment    | 74,503               | 35.0                 |
|                 | post-experiment   | 59,138               | 7.2                  |
|                 | 0.075 mm          | 56,189               | 1.8                  |
|                 | 0.150 mm          | 85,382               | 0                    |
| condition 3     | pre-experiment    | 106,386              | 24.6                 |
|                 | post-experiment   | 87,337               | 2.3                  |

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