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Flame Propagation Characteristics of Hybrid Explosion of Ethylene and Polyethylene Mixture under Pressure Accumulation

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Abstract: In order to study the flame propagation characteristics of a ethylene/polyethylene hybrid explosion under pressure accumulation, a visual pressure-bearing gas/power hybrid-explosion experimental platform was built. The flame propagation characteristics of polyethylene and ethylene/polyethylene hybrid explosions in the closed vessel were analyzed. The results show that the flame brightness, flame front continuity and average flame propagation velocity of polyethylene dust explosion in the closed vessel increased first and then decreased when the polyethylene dust concentration increased. The curve of the flame propagation velocity with time had obvious pulsation characteristics. Adding 1% and 3% ethylene to different concentrations of polyethylene dust significantly improved its explosion flame brightness, flame front continuity and average flame propagation velocity. Moreover, it also improved the fluctuation amplitude of the explosion flame propagation velocity with time curve. The explosion flame of the polyethylene dust and ethylene/polyethylene hybrid mixture included four zones during the propagation process, which were denoted as the unburned zone, preheated zone, premixed flame zone and dust flame zone. The addition of ethylene to polyethylene dust can significantly increase its thickness of premixed flame zone and preheated zone, and the thickness increased when the ethylene concentration increased.

Keywords: polyethylene; ethylene; mixed explosion; explosion flame propagation characteristics; pressure accumulation

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1. Introduction

Polyethylene is a thermoplastic resin obtained by the polymerization of ethylene. It is widely used in industries such as agriculture and in daily life [1–3]. In the production process of polyethylene covering pneumatic conveying pipelines to silos and other places, there often exist certain explosion risks of the creation of a hybrid mixture of ethylene and polyethylene dust [4]. This has been proved by some accidental occurrences. For example, in 2002, the explosion of polyethylene production unit in Liaoyang Petrochemical Branch resulted in 8 deaths and 19 injuries. This explosion was due to the leakage of ethylene gas from the material tube, which was then sucked into the boiling dryer. This ethylene/polyethylene mixture was ignited by the electrostatic sparks [5]. In 2013, the welding sparks ignited ethylene/polyethylene mixture of storage silos of Korean Dalim Industrial Co., Ltd., resulting in many casualties [6]. Various studies have shown that the explosion hazard and harmfulness of the hybrid mixture are obviously greater than that of the single-phase dust [7–14]. Therefore, it is very important to understand the explosiveness of ethylene and polyethylene mixture in the safety review of the polyethylene production process.

Studies on the variations in explosion pressure, explosion index, minimum explosion concentration (MEC) and minimum ignition energy (MIE) of the ethylene/polyethylene mixtures have been systematically carried out in the literature. The results show that ethylene can significantly improve the explosion pressure and explosion index of polyethylene dust, and reduce the minimum ignition energy and minimum explosion concentration of polyethylene dust [15–18]. These studies clarified the variations in the explosion characteristic parameters of ethylene/polyethylene, and laid a solid foundation for the risk assessment. The variations in these parameters reflect the macroscopic explosion characteristics of the hybrid mixtures of ethylene and polyethylene, but they cannot fully disclose the explosion mechanism(s) of the ethylene/polyethylene mixtures. However, flame propagation characteristics are an important basis for analyzing the evolution mechanism of the medium explosion. Therefore, studying the explosion flame propagation characteristics of ethylene/polyethylene mixtures is necessary.

Several researchers have studied the flame propagation characteristics of polyethylene dust explosions. For instance, the effects of dust concentration [19–21], particle size [19,20] and inert medium [22–24] on the flame morphology, front structure and explosion flame propagation velocity of polyethylene dust have been studied. However, the existence of ethylene affects the pyrolysis, volatilization and other dynamic characteristics of polyethylene dust particles to a certain extent, thereby increasing the complexity of the polyethylene dust explosion process. Therefore, the above research works cannot fully reflect the explosion mechanism and flame propagation characteristics of ethylene/polyethylene mixtures. Although Gan et al. [15,25] have carried out studies about the flame propagation characteristics of hybrid explosions, the device used in their research was a semi-closed pipeline. At present, the model which can reveal the flame propagation mechanism of ethylene/polyethylene hybrid explosions under pressure accumulation has not been proposed. However, a considerable number of explosion accidents occur in closed-space environments in real-life production processes [26], indicating that the explosion process is usually a coupled process of pressure and flame propagation. However, the existing research works have not paid enough attention to the explosion flame propagation characteristics under pressure accumulation, which makes it impossible to accurately and comprehensively describe the flame propagation mechanism(s) in the real explosion process. Various studies have shown that explosion pressure significantly affects the flame propagation behavior, such as flame thickness and propagation velocity, thereby affecting the flame propagation mechanism(s) [27–30]. In addition, due to the confinement of the closed space wall, the product of the high temperature and high pressure produced by the explosion process cannot be released in time. The superposition and reflection of the shock wave on the wall cause the damage to the structure and the casualties to be more severe than the case in an open or semi-closed space. Therefore, further study on the explosion mechanism and flame propagation characteristics of ethylene/polyethylene hybrid explosion under the condition of pressure accumulation in the closed space is of great significance to improving the theoretical aspects of the polyethylene explosion disaster prevention.

Considering the above-mentioned problems, a visual and pressure-bearing experimental device for determining the explosion flame propagation characteristics of a hybrid mixture was designed. By adjusting the concentration ratio of ethylene/polyethylene, the variations associated with flame morphology, flame brightness and flame propagation velocity of the ethylene/polyethylene mixture in a closed vessel were studied; and then the flame propagation mechanism(s) of an ethylene/polyethylene hybrid explosion in the closed vessel was analyzed. The research results can provide a theoretical reference for the safety of the polyethylene industry.

2. Experiments

2.1. Experimental Apparatus

The schematic diagram of the experimental device is shown in Figure 1. The apparatus was mainly composed of an explosion vessel, a powder injection system, an ignition system, a high-speed photography system and time control system.

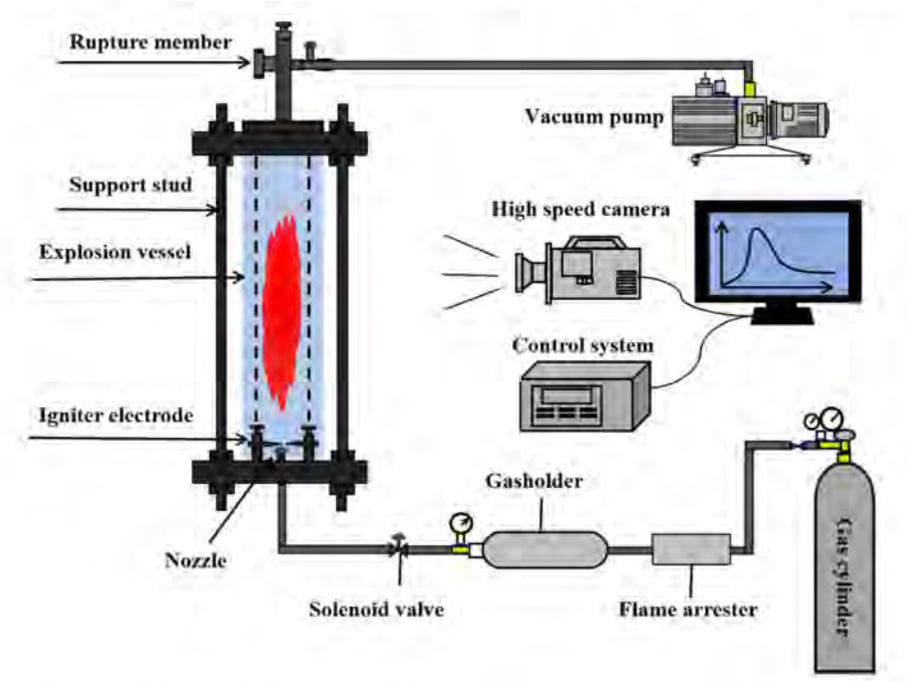

Figure 1. Schematic diagram of the explosion experimental apparatus.

Since the explosion vessel needs to meet the pressure-bearing and visual requirements at the same time, a vertical cylindrical quartz glass pipe was used as the explosion vessel. The upper and lower ends were sealed with metal flanges. The total volume was about 1 L, and the maximum allowable pressure was 1.5 MPa. The powder injection system was mainly composed of a mushroom nozzle, a solenoid valve, a high-pressure gas storage tank and a flame arrester. The ignition system adopted the HY-12A pulse igniter. The images of dynamic flame propagation in the experiment were captured by a FASTCAM SA4 high speed camera at 1000 frames per second. The time control system controlled the open/close position of the solenoid valve, and also controlled the electrode ignition and high-speed photography triggering device on an orderly basis. By systematically adjusting the powder injection pressure and ignition delay time, combined with the distribution of dust in the vessel under non-ignition conditions, the ignition delay time and optimal powder injection pressure of the experimental platform were determined, which were 100 ms and 0.15 MPa, respectively. In order to ensure the reliability of the experimental data, each experimental condition was repeated three times.

2.2. Experiment Materials

According to the literature, about 63% of polyethylene dust explosion accidents were caused by low density polyethylene [31]. Therefore, low-density polyethylene was selected for use in this study, and provided by Jiangsu Haosheng Plastics Co, Ltd. (Suqian, China). The particle size distribution and structure are displayed in Figure 2. The overall structure was chip-like, and the surface was rough. The median particle size (d50) was 19.2 μm. It was dried at a constant temperature for 4 h before the experiment. Ethylene used in this study was provided by Henan Yingzhong Chemical Products Co., Ltd. (Zhengzhou, China). with a purity of 99.99%.

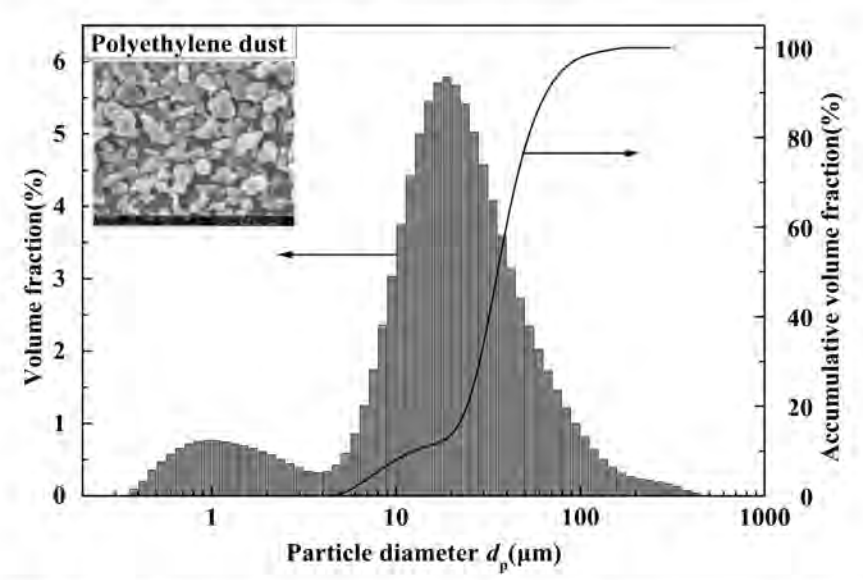

Figure 2. Particle size distribution and electron microscopy of the polyethylene dust.

3. Results and Discussion

3.1. Flame Propagation Characteristics of Polyethylene Dust Explosion

For comparison, the flame propagation characteristics of a polyethylene dust explosion in a closed vessel were first studied. Figure 3 shows the flame structure variation with time for the polyethylene dust explosion. When the polyethylene concentration was 200 g/m^3, the flame brightness in the vessel was low, the flame structure was mainly spatial discrete bundles and the flame front was sharp or serrated. With the increase in polyethylene concentration to 400 g/m^3, the brightness of explosion flame became significantly improved, the structure tended to be full and the continuity of flame front was enhanced. However, when the polyethylene dust concentration increased to 600 g/m^3, the flame brightness failed to further improve, the flame structure plumped up and the flame front continuity was also decreased. When polyethylene dust concentration further increased to 800 g/m^3; explosion flame brightness and structural plumpness were further weakened; and the flame front was sharper and more discrete. Especially in the late propagation stage, the bundle flame structure was more obvious.

The distance between the flame front and the bottom of the pipeline was measured by the measurement tool in Adobe Photoshop CS6. The time interval of adjacent pictures is 1 ms. Since the time interval between adjacent images is small, the average velocity within in a short time can be approximately regarded as the instantaneous velocity of flame propagation at the corresponding time. Based on the flame front position and the corresponding time, the time-varying curve of the explosion flame propagation velocity of polyethylene dust with different concentrations in a closed vessel was calculated. Combined with the length of the pipeline (L) and the time of the flame front propagating from the ignition electrode to the top of the pipeline (t), the average propagation velocity (vA) of the explosion flame of polyethylene dust with different concentrations in the vessel was calculated. The results are shown in Figure 4.

Figure 4 shows that the flame propagation velocity curves for four different concentrations of polyethylene dust explosion in a closed pipe have obvious pulsation characteristics. The fluctuation range of the curve for flame propagation velocity with time was large in the early stage of the explosion, and flame propagation velocity was stable with low speed in the later stages. The fluctuation of explosion flame propagation velocity is related to the motion characteristics of polyethylene dust particles in the vessel. The dust particles in the closed pipe were affected by viscous force, thermophoresis force and gravity, and the resultant force of these forces determines the motion state of the particles. At the beginning of the explosion, the polyethylene particles mainly settled down under the action of gravity at a place far from the flame surface. It was less affected by flame thermal expansion. When the unburned polyethylene particles slowly approached the flame front, due to the effect of flame thermal expansion gas, the downward velocity of the particles decreased slowly, and the velocity decreased to zero at some point above the flame front [32], forming a local high concentration area [33]. When the particles were further close to the flame, the motion direction of the particles and the flame propagation direction were the same. The relative motion of the particles caused the change in the particle concentration in flame front. When the flame front contacted with more unburned dust, the combustion reaction was more intense and the flame propagation speed was faster. When the flame front position propagated to the low concentration range, the combustion reaction was weaker, and the flame propagation velocity was slower. This situation caused great fluctuation in the early stage in the flame propagation velocity. In the middle and later stages of the explosion, most particles entered the combustion area of the flame, and the concentration of particles in unit volume rapidly decreased. Therefore, the flame front propagated in a stable manner at low speed. In addition, in a closed space, the pressure wave generated by the explosion could not diffuse in time. These pressure waves bounced back at the top of the vessel and the surrounding wall cross-coupled with subsequent pressure waves. As a result, the medium in the container fluctuated during the flow process, which was also one of the reasons for the fluctuation of flame propagation velocity.

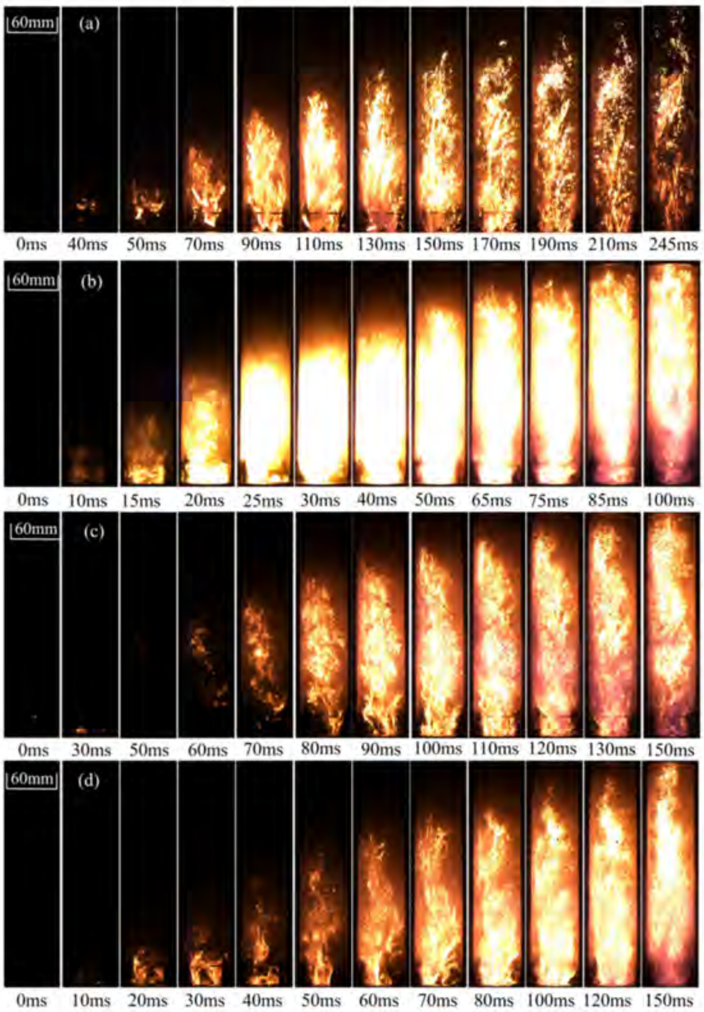

Figure 3. Flame structure of polyethylene dust with different concentrations: (**a**) 200 g/m^3; (**b**) 400 g/m^3; (**c**) 600 g/m^3; (**d**) 800 g/m^3.

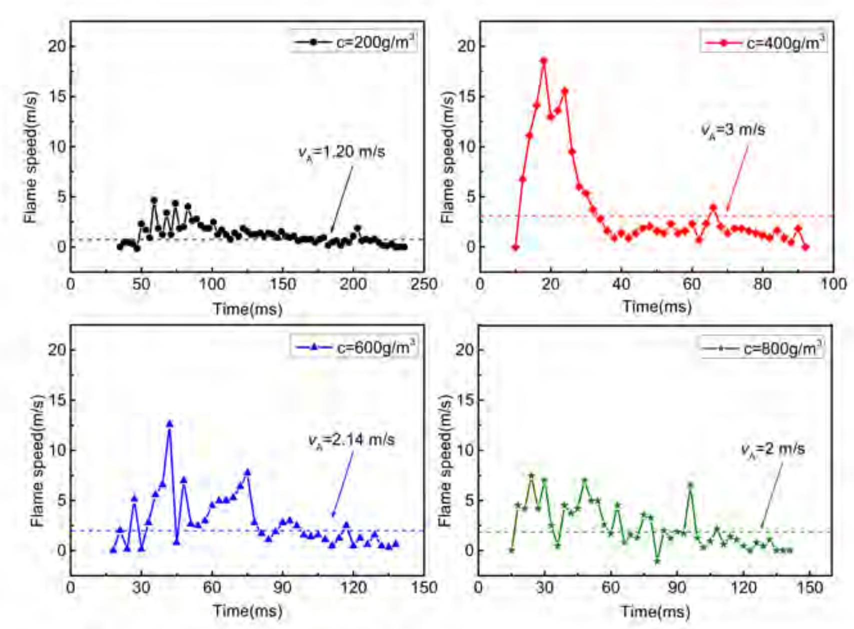

Figure 4. Time-dependent curves of flame propagation velocity of polyethylene with different concentrations.

It can also be found in Figure 4 that the average flame propagation velocities (vA) of polyethylene dust explosion in the vessel at four different concentrations were 1.20, 3.00, 2.14 and 2.00 m/s, respectively. The average flame propagation velocity first increased and then decreased with the increase in polyethylene dust concentration, and reached the maximum at 400 g/m^3.

Comprehensively, 400 g/m^3 was the optimal explosion concentration at four different concentrations of polyethylene dust. Under this concentration condition, the flame brightness, structural plumpness and flame front continuity of polyethylene dust explosion reached the optimal, and the average flame speed reached the maximum. This was because the flame brightness, structural plumpness, flame front continuity and propagation speed of dust explosion in the closed container were mainly affected by the amount of dust. When the polyethylene dust concentration was lower than 400 g/m^3, the dust explosion process belonged to the lean fuel combustion process. The greater the dust concentration, the smaller the distance between the particles, and the more intense the burning intensity. This also means that the flame becomes brighter, the flame front is more continuous and the flame spreads faster. When the polyethylene dust concentration was greater than 400 g/m^3, the dust explosion process changed from lean fuel combustion to rich fuel combustion, and the combustion intensity began to be controlled by the oxygen content in the container. The greater the dust concentration, the more incomplete the combustion reaction and the smaller the heat release. Moreover, the redundant dust particles absorbed the heat released from the combustion reaction, which reduced the flame brightness, weakened the continuity and reduced the flame propagation velocity.

3.2. Flame Propagation Characteristics of Ethylene/Polyethylene Hybrid Explosion

Some ethylene gas inevitably exists in the production and manufacturing process of polyethylene, but the concentration is often low. Therefore, this study takes the lower explosion limit of ethylene (i.e., 2.7%) as the reference, and selects two levels of low concentration ethylene (i.e., 1% and 3%) to explore its effect on the flame propagation characteristics of polyethylene dust explosion.

3.2.1. Variations in Flame Structure

Figure 5 shows the variation in flame structure with time for 200 g/m^3 polyethylene dust under different ethylene concentrations. As shown in Figure 5, the flame brightness was significantly improved and the continuity of flame structure was enhanced after adding 1% ethylene. The spatial discrete bundle structure disappeared, and the flame structure became more continuous. Further increasing the ethylene concentration to 3% resulted in greater brightness flame and fuller structure in the propagation process. The flame front, which was smooth and continuous, was similar to the gas explosion flame.

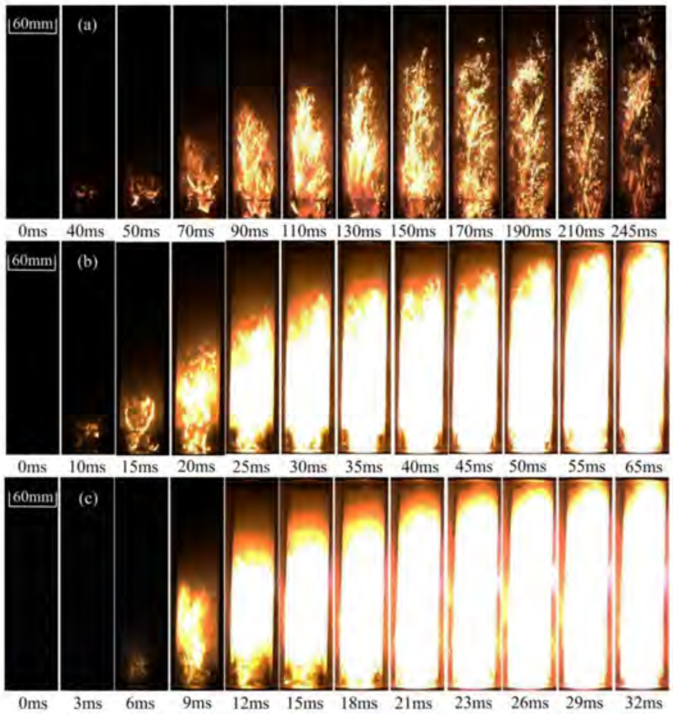

Figure 5. The variation in flame structure with time for 200 g/m^3 polyethylene dust under different ethylene concentrations: (**a**) 200 g/m^3; (**b**) 1%C_2H_4 + 200 g/m^3; (**c**) 3% C_2H_4 + 200 g/m^3.

Figure 6 shows the variation in flame structure with time for 400 g/m^3 polyethylene dust under different ethylene concentrations. In Figure 6, the addition of 1% ethylene still improved the flame brightness and flame structure continuity for 400 g/m^3 polyethylene dust. When ethylene concentration increased to 3%, flame brightness and flame structure continuity were further improved.

According to Figures 7 and 8, the 1% ethylene still improved the flame brightness and structure continuity of the polyethylene dust explosion at increased concentrations of polyethylene dust (i.e., 600 and 800 g/m^3). When ethylene concentration increased to 3%, flame brightness and structure continuity were further improved.

It can be concluded that 1% and 3% ethylene improved the flame brightness and flame structure of the explosions with four different concentrations of polyethylene dust, and 3% ethylene causes a greater enhancement than 1% ethylene. This is because combustible gas, ethylene, mixed with air at molecular level, improved the continuity of the polyethylene dust flame front to a certain extent, thereby improving the fullness of the flame structure and the continuity of the flame front. In addition, ethylene is a highly reactive combustible gas [17,34], whose combustion rate and intensity are much greater than those of polyethylene dust. In the process of ethylene/polyethylene hybrid explosion, ethylene first reacts with oxygen in the air to release heat. When the concentration of polyethylene dust was lower than the optimal explosion concentration (200 g/m^3), the explosion process of polyethylene in the closed vessel was a lean fuel combustion process. The addition of ethylene increased the volume of fuel. Moreover, the heat released by the first combustion of ethylene promoted the decomposition of polyethylene, thereby enhancing the combustion intensity and flame brightness. When the polyethylene dust concentration was equal to or greater than the optimal explosion concentration (400, 600, or 800 g/m^3), the addition of ethylene improved the combustion intensity of the hybrid system. It also aggravated the incomplete combustion of polyethylene dust, caused some polyethylene particles being unable to participate in the explosion reaction and reduced the combustion intensity. However, the combustion intensity and combustion velocity of ethylene were much larger than those of polyethylene. Therefore, the promotion effect was greater than the reduction effect within a certain ethylene concentration range. The greater the ethylene concentration, the more obvious the promotion effect.

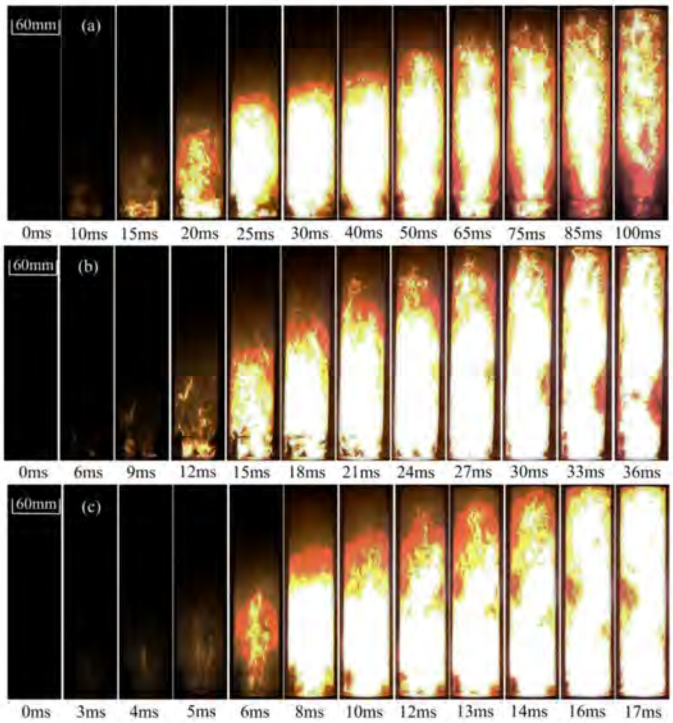

Figure 6. The variation in flame structure with time for 400 g/m^3 polyethylene dust under different ethylene concentrations: (**a**) 400 g/m^3; (**b**) 1%C_2H_4 + 400 g/m^3; (**c**) 3% C_2H_4 + 400 g/m^3.

3.2.2. Variation in Flame Propagation Velocity

In Figure 9, the flame propagation velocity showed pulsation characteristics with increased pulsation amplitude after adding 1% ethylene. Additionally, the average flame propagation velocity increased from 1.20 to 4.62 m/s. With the increase in ethylene concentration to 3%, the fluctuation amplitude of the curve further increased, and the average flame propagation velocity further increased to 9.09 m/s.

In Figure 10, adding 1% and 3% ethylene improved the fluctuation amplitude of the curve when the concentration of polyethylene dust was increased to 400 g/m^3, and the fluctuation amplitude increased when ethylene concentration increased. The average flame propagation velocity was also improved from 3.00 to 8.33 m/s or 11.11 m/s, respectively.

As shown in Figures 11 and 12, adding 1% and 3% ethylene improved the fluctuation amplitude of the curve with a further increase in polyethylene concentration to 600 or 800 g/m^3, and the fluctuation amplitude improved by the increase in ethylene concentration. The average flame propagation velocity was also improved by the increase in ethylene concentration. When the polyethylene concentration was 600 g/m^3, the average flame propagation velocity was improved from 2.14 to 11.11 or 23.08 m/s, respectively, after adding 1% or 3% of ethylene. After adding 1% or 3% ethylene, the average flame propagation velocity was improved from 2.00 to 14.29 or 17.65 m/s, respectively, at a polyethylene concentration of 800 g/m^3.

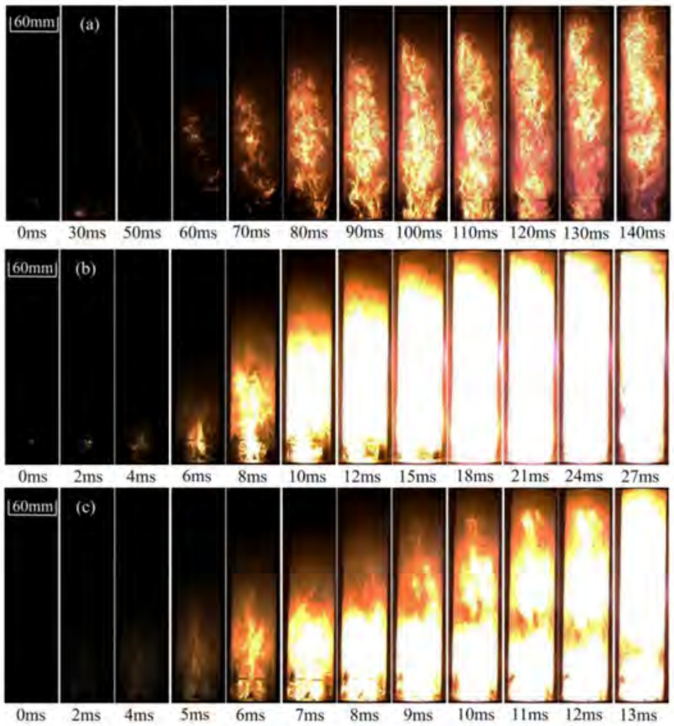

Figure 7. The variation in flame structure with time for 600 g/m^3 polyethylene dust under different ethylene concentrations: (**a**) 600 g/m^3; (**b**) 1%C_2H_4 + 600 g/m^3; (**c**) 3% C_2H_4 + 600 g/m^3.

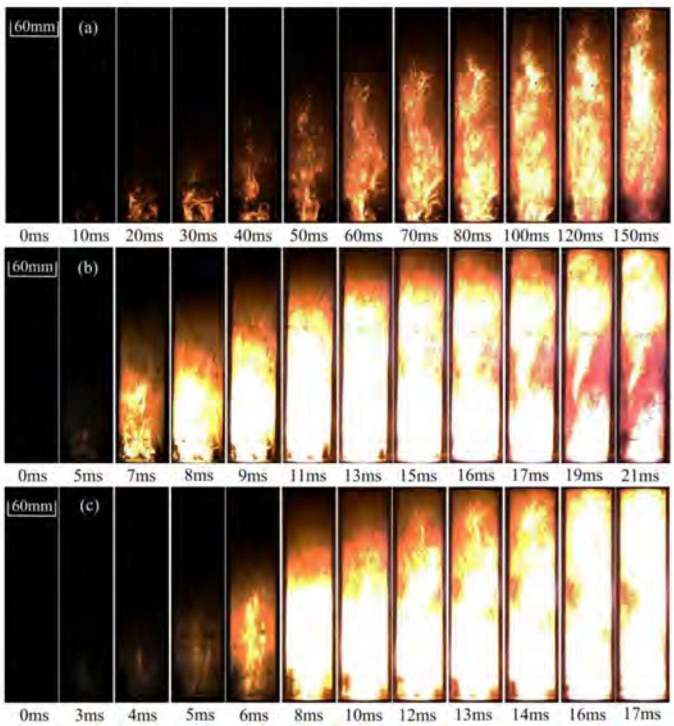

Figure 8. The variation in flame structure with time for 800 g/m^3 polyethylene dust under different ethylene concentrations: (**a**) 800 g/m^3; (**b**) 1%C_2H_4 + 800 g/m^3; (**c**) 3% C_2H_4 + 800 g/m^3.

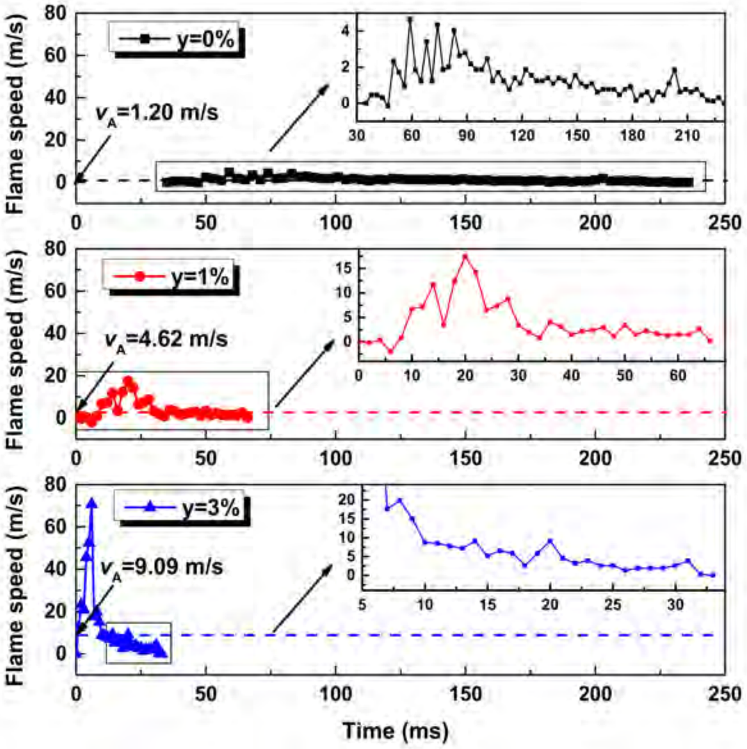

Figure 9. Variation in flame propagation velocity with time for 200 g/m^3 polyethylene dust under different ethylene concentrations.

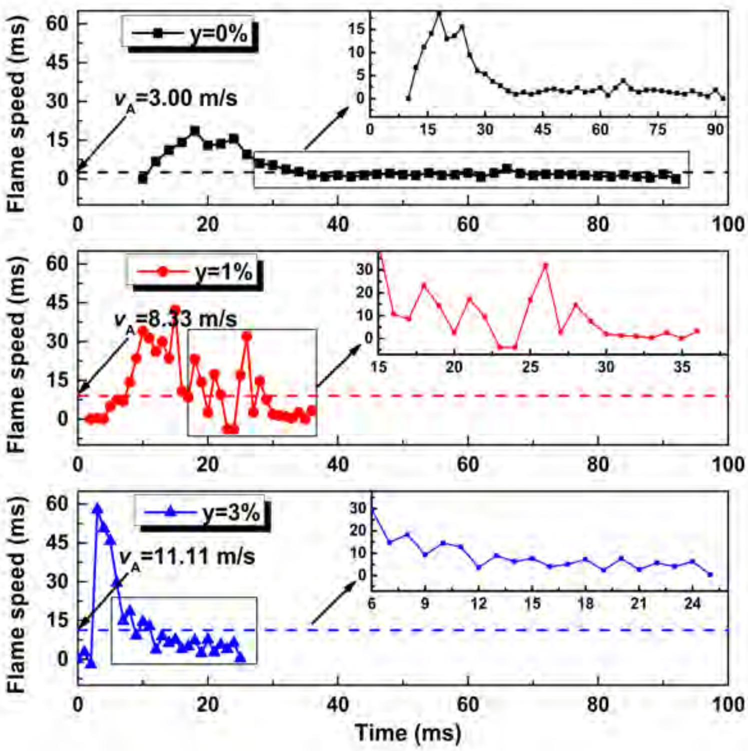

Figure 10. Variation in flame propagation velocity with time for 400 g/m^3 polyethylene dust under different ethylene concentrations.

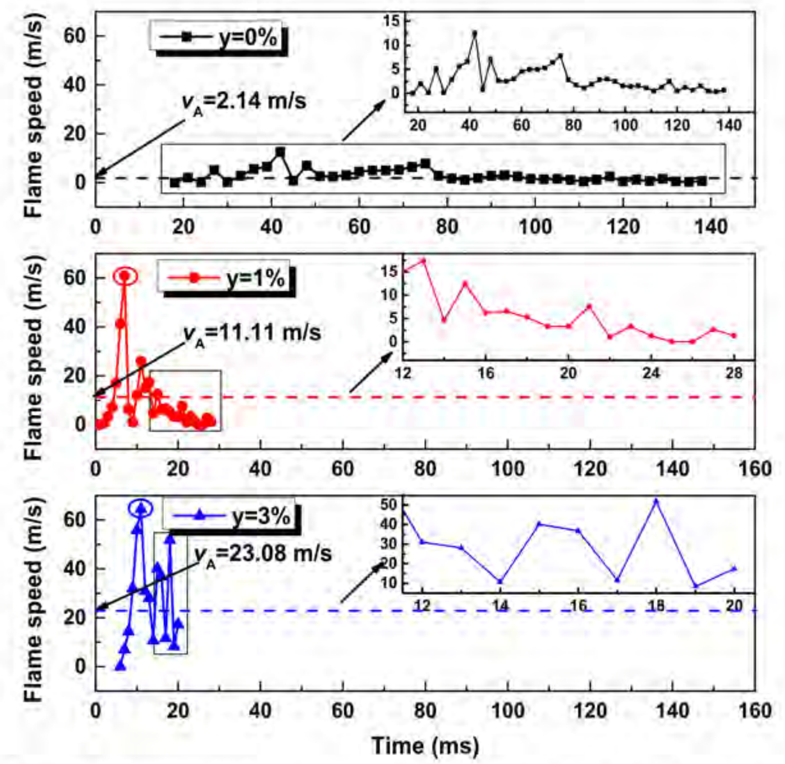

Figure 11. Variation in flame propagation velocity with time for 600 g/m^3 polyethylene dust under different ethylene concentrations.

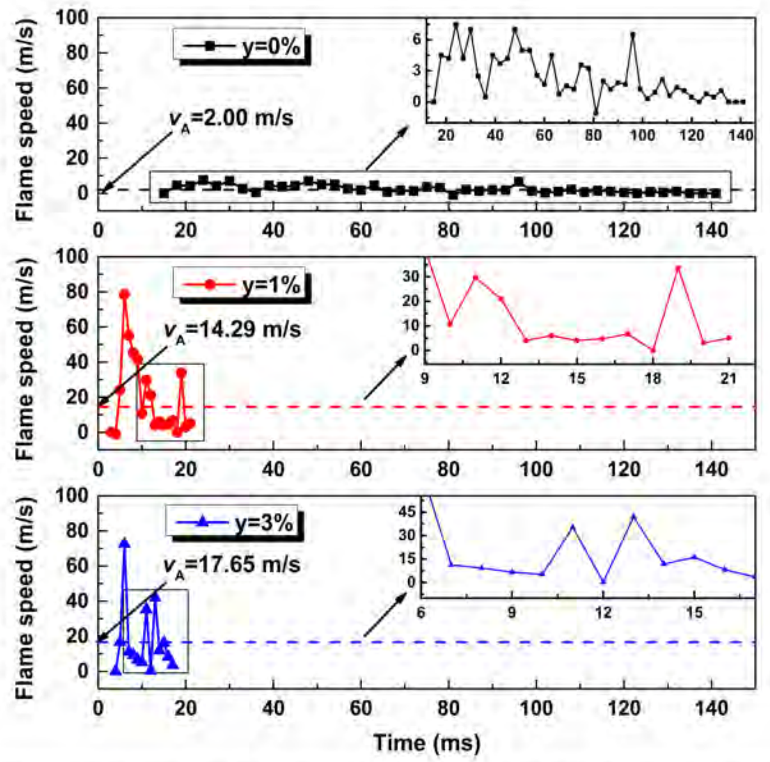

Figure 12. Variation in flame propagation velocity with time for 800 g/m^3 polyethylene dust under different ethylene concentrations.

Under the same ethylene gas concentration, with the average flame propagation velocity of 400 g/m^3, the polyethylene dust/ethylene mixture was less than 600 or 800 g/m^3

of the polyethylene dust/ethylene mixture. The average flame propagation velocity is related to the number of polyethylene particles participating in the reaction, the oxygen content, the ethylene gas concentration and the surface contact areas of polyethylene and oxygen on the combustion flame front. When the concentration of polyethylene dust in the mixed system was greater than its optimal explosion concentration, the number of polyethylene dust particles actually participating in the reaction decreased under the condition of rich combustion. However, during the explosion process, the flame front can contact more unburned polyethylene dust particles, increasing the total contact area between the polyethylene dust and the air. On the other hand, 400 g/m^3, as the optimal explosion concentration of polyethylene dust, played a strong leading role in the mixed system, resulting in ethylene gas having a lesser effect on the average flame propagation speed of the mixed system.

For four different concentrations of polyethylene dust, 1% and 3% ethylene improved the pulse amplitude of the curve and average flame propagation velocity, and the lifting effect of 3% ethylene was greater than that of 1% ethylene. This is because polyethylene dust explosion needed to undergo a series of processes, such as heat absorption, decomposition, mixing with air and ignition, which was a typical heterogeneous combustion process. After the addition of ethylene, on the one hand, the heat released by the first combustion of ethylene accelerated the pyrolysis of polyethylene. On the other hand, the presence of ethylene shortened the time from pyrolysis to combustion of polyethylene dust, especially at the 3% ethylene level, which was directly combusted. Therefore, the addition of ethylene changed the polyethylene explosion process from heterogeneous combustion to homogeneous combustion to a certain extent [35], which led to an increase in the fluctuation amplitude of the curve of polyethylene explosion flame propagation velocity with time and the average flame propagation velocity.

3.3. Flame Propagation Mechanism of Ethylene/Polyethylene Hybrid Explosion

In summary, ethylene has significant influences on the explosion flame propagation characteristics of polyethylene dust. Combined with the flame propagation behaviors of ethylene/polyethylene hybrid explosion and the kinetics process of polyethylene dust explosion, a simple physical model of the explosion mechanism of ethylene/polyethylene under the condition of pressure accumulation in a confined space was established based on the flame microstructure of 400 g/m^3 polyethylene dust with different ethylene concentrations. As shown in Figure 13, the explosion flames of the polyethylene dust and ethylene/polyethylene hybrid system included four zones during the propagation process, which were denoted as the unburned zone, preheated zone, premixed flame zone and dust flame zone. For pure polyethylene dust explosion, the premixed flame zone was dominated by the homogeneous combustion formed by pyrolysis gas of small particles of polyethylene, and the dust flame zone was dominated by the heterogeneous combustion of large particles of polyethylene dust. Due to the limitation of the amount of small particles of polyethylene dust and the pyrolysis rate, it was difficult to form a wide range of combustible premixed gas in the premixed flame zone, so the thickness of the premixed flame zone of pure polyethylene dust was relatively small. When 1% ethylene was added, the thicknesses of the premixed flame zone and preheated zone both increased significantly, and the thicknesses of the premixed flame zone and preheated zone increased further as the concentration of ethylene increased to 3%. It was due to that the addition of ethylene increased the pyrolysis rate of polyethylene dust and the combustible gas concentration in the premixed flame zone to some extent. As a result, the range of the flammable gas that can be burned increased, and then the thickness of premixed flame zone increased. At the same time, ethylene gas with high reactivity improved the combustion intensity of premixed flame zone, increased the temperature of combustion zone and then improved the thickness of preheated zone.

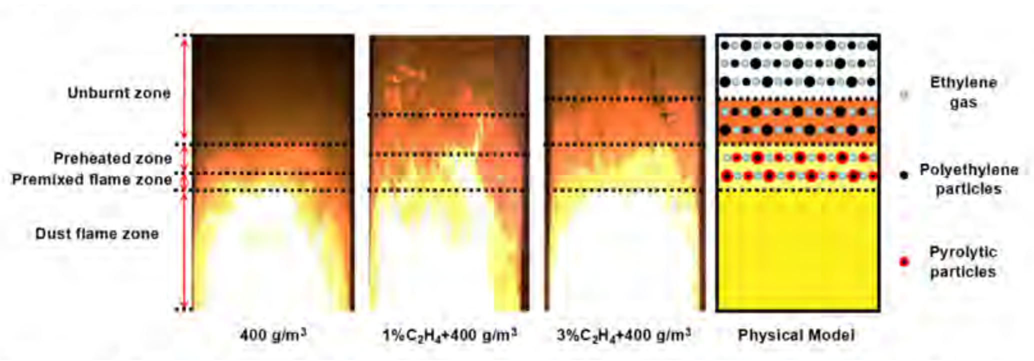

Figure 13. Physical model of the explosion mechanism of ethylene and polyethylene dust.

4. Conclusions

A visual and pressure-bearing experimental device for studying the explosion flame propagation characteristics of a gas/powder two-phase mixture was designed and manufactured. The explosion flame propagation characteristics and the mechanism(s) of ethylene/polyethylene mixture accumulation under pressure were studied, and the following conclusions were obtained:

1. The flame brightness, flame structure continuity and average flame propagation velocity of polyethylene dust explosion increased first and then decreased with the increase in polyethylene dust concentration, and reached its maximum at 400 g/m^3. The flame propagation velocity curves with time all had obvious fluctuation characteristics. The fluctuation range of flame propagation velocity with time was large in the early stage of explosion, and the flame propagation velocity was stable at low speed in the later stage.
2. The flame brightness, flame front continuity and average flame propagation velocity of polyethylene dust explosion increase with the addition of ethylene, and increase further as the ethylene concentration increases from 1% to 3%. The flame propagation velocity with time for the ethylene/polyethylene hybrid explosion also presented the characteristics of pulsation, and the pulse amplitude was improved by the increase in ethylene concentration.
3. The explosion flame of polyethylene dust and ethylene/polyethylene hybrid mixture both included four zones during the propagation process, which were denoted as the unburned zone, preheated zone, premixed flame zone and dust flame zone. For pure polyethylene dust explosion, the thicknesses of the premixed flame zone and preheated zone were relatively small. After adding ethylene, the thicknesses of the premixed flame zone and preheated zone increased significantly, and the thickness was improved by the increase in ethylene concentration.

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