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Influence of Local Distribution of Polyethylene Dust Cloud on Flame Propagation

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The flame propagation characteristic of polyethylene dust cloud inside a semi-open tube is studied in virtue of high-speed photographing technology. The rules of the influence of initial distribution range of polyethylene dust cloud on flame speed and shape is focused on. Studies show that flame propagation range generally exceed the initial distribution range of dust cloud and is positively correlated to it. Flames within certain dust cloud distribution range can accelerate continuously; however, flames will decelerate after its initial acceleration when dust clouds are too centralized or decentralized. When dust mass is constant, the maximum flame speed and average flame speed generally increase and then decrease with the increasing initial distribution range. Initial distribution range affects flame shape evolution significantly, such as its influence on the flame width along the radial direction, flame brightness, front smoothness, fault, etc. The conclusions provide scientific basis for flame monitoring and safety control at the initial stage of accident.

1. Introduction

In the production process of polyethylene (PE) powder, flame sources, including spark and static electricity caused by friction and impact, and high-concentration dust cloud may exist in process and equipment, such as granulation, drying, pneumatic transfer and discharge equipment, and even the local areas of dedusting system. If these ignition sources and dust clouds are not scientifically controlled, it is easy to induce dust explosion accidents in local spaces.

The rule of flame propagation of PE dust cloud in tubes and containers serves as the theoretical basis for effective prevention and control of such dust explosion accidents. At present, reports about studies on flame propagation of PE dust explosion have not been available yet. With the help of small-size containers, Yuzuriha (2017), Gao (2012, 2013, 2014) and Zhang et al. (2016) studied the flame propagation of other chemical organic dusts, including Polymethyl methacrylate, long-chain monobasic alcohol and octadecanol, by checking and analyzing the influence of particle size distribution, thermal characteristics of particles and flow characteristics on flame propagation. Saeed et al. (2016) used a 1 m3 dust explosion vessel to study the effect of dust particle size on the burning rate of biomass dust. He found that the laminar burning velocity was very low for the most reactive mixture and depending on the biomass particle size. Yan et al. (2013) made experiments to study the secondary dust explosion in tube or container vent duct and its rule. Zhong and Deng (2000) realized the numerical simulation of transient flow field of coal dust explosion in long horizontal tubes in virtue of operator splitting method and FCT format. In order to improve the repeatability and accuracy of dust explosion tests in the 20-liters sphere, Murillo et al. (2016) used the CFD technique to study the dusting process in the vessel, and proposed the best ignition time. Ghaffari et al. (2016) used FLACS-DustEx to study sensitivity of dust explosion consequences in a roller mill, and the type of dust, ignition source location, ignition delay time and vent opening size were considered. As the existing characteristic parameters of dust explosion are not complete, Traoré (2009), Han and Lee (2014), and Benedetto et al. (2007, 2010) supplemented them relying on experimental and theoretical models. At the beginning of the accident, the flame will expand to the surrounding area along with the local distribution area of the dust cloud, resulting in more large-scale disasters. Therefore, the flame spread law of at the beginning of the accident is the key to the prevention and control of PE dust explosion. However, less attention has been paid to the flame expansion of the initial local dust cloud,

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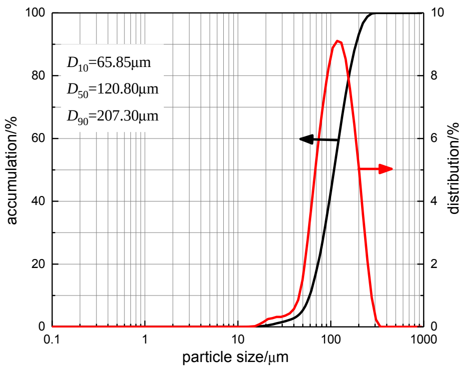
and the relationship between the development of the local dust cloud flame and the distribution state of dust clouds has not been grasped. In consideration of the above, the study tests the flame propagation of PE dust cloud in local areas in a semi-open tube with typical PE dust and high-speed photographing technology, and checks the influence of the initial distribution range of dust cloud on flame propagation, with the aim to provide scientific basis for the early prevention and control of PE dust explosion accidents.

2. Experimental

2.1 Experimental materials

A typical type of low-density-polyethylene industrial powder was selected as the study object. The particle size of the sample was analyzed by BT-9300LD laser particle size analyzer. Based on the analysis result, the accumulation and distribution diagram of particle shown in Figure 1 was obtained and the median particle diameter D50 of this dust was 120.80 μm. Besides, sample shape characteristics were analyzed with Quanta 400F scanning electron microscope, and the scanning electron micrograph (SEM) of particles magnified for 1,000 times shown in Figure 2 was obtained (Pang, 2019).



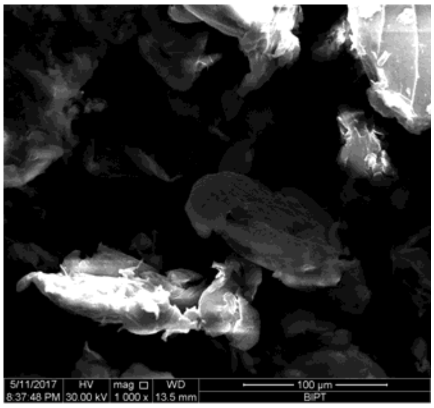


Figure 1: Particle size distribution of PE powder sample   *Figure 2: SEM images of PE powder sample*

2.2 Experimental installation and test methods

Experimental installation used for study is as shown in Figure 3 (Pang, 2019). Main body of this installation is a vertically placed quartz glass tube with a circular section of 0.068 m in diameter. With a total length of 1.2 m, this tube is opened and free of blockage at its upper end. Its bottom is closed and a dust diffuser is installed at this closed position. Connected with dust storage tank, this dust diffuser provides rising dynamic to dust with the help of compressed air and certain dust spray pressure, so as to form local dust cloud inside tube. A tube support is used to prevent glass tube from falling. A High-voltage discharge module is used to provide ignition energy. The horizontal position of the 2 ignition electrodes is 0.1 m from tube bottom, and the spacing between the two electrodes is 6 mm. Memrecam-GX-3 high-speed camera is used to take pictures of dust cloud formation and flame propagation process inside tube. This high-speed camera, characterized by highest shooting frame rate of 198,000 frames/s, maximum resolution of 1,024×1,024, and provided with trigger feature and 1-us electronic shutter, can start synchronously with ignition device.

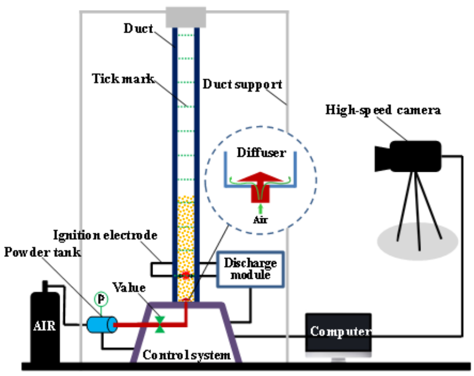


Figure 3: Experimental Installation diagram

The experiments was carried out under atmospheric pressure of 101 kPa, ambient temperature of 300 K. PE dusts was spread uniformly on the surface of dust diffuser at the experimental installation bottom, and then the dust spray system consisting of dust storage tank, compressor air cylinder, and diffuser was started to raise dust, forming dust cloud inside glass tube. In order to master the distribution status of dust cloud at the sparkling instant and flame propagation behavior, the picture-taking process was divided into the following two situations (Pang, 2019).

Taking pictures of dust cloud distribution: In order to observe the distribution of dust cloud at sparking instant, high-speed camera is set 1 m from experimental tube; the horizontal position of lens is set at the 1/4 height of tube. By taking sunlight as light source, the formation processes of dust cloud under different spray dust pressures are shot at 2000 frames/s to record the processes from dust spraying to dust rising.

Taking pictures of flame propagation process: High-speed camera was set 4 m from experimental tube; the horizontal position of lens was set the same as the middle position of tube. In dark conditions, high-speed camera was set at 2000 frames/s to take pictures, in order to observe flame propagation when ignition energy is 1 J. For the purpose of reading flame propagation distance better, a black narrow rubber hand was set on tube wall every 0.1 m horizontally as scales according to the self-illumination principle of flame. When flame propagated inside tube continuously, pictures of flame propagating to all scales were selected in sequence and time corresponding to these pictures was recorded. The value of 1.0 m divided by the difference between the arriving times of flame at adjacent two scales was taken as the transient flame speed corresponding to the central position of the two scales. When calculated with this method, the axial distribution of flame speed along tube can be obtained. As tube top fixing parts covered tube length of 0.07 m and ignition electrode is 0.1 m from tube bottom, the effective calculation range of flame speed inside tube was about 1 m.

3. Results and discussions

3.1 Analysis on the initial distribution state of cloud dust

High-speed camera is used to take pictures of dust cloud rising process. Sample mass tested in each group is 2 g. When dust spray pressure is 100 kPa, dust rising process is as shown in Figure 4 (Pang, 2019). Within 90 ms, the height of dust cloud increased gradually as time went by, demonstrating the whole dust rising process basically. When dust was sprayed for just 60 ms, dust cloud was about 0.23 m tall. Before 60 ms, dust rose quickly but it rose lower after 60 ms. On the whole, as dust samples were white and can be identified clearly, the concentration of dust clouds was high in middle and lower part and lower in the upper part.

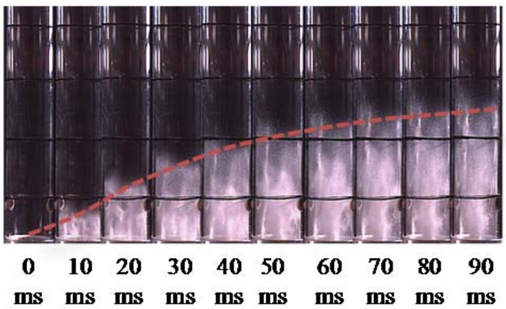


Figure 4: Typical formation process of dust cloud

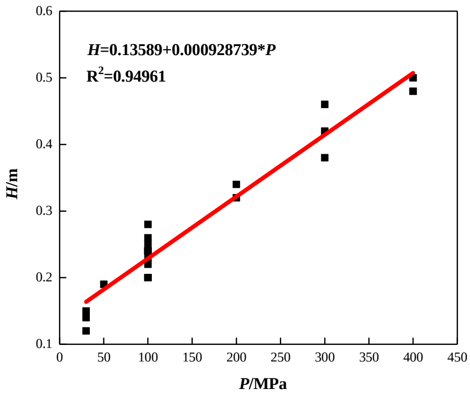


Figure 5: Dust cloud distribution range, H vs. spray pressure, P

To compare the influence of different distribution ranges of dust cloud on flame propagation characteristics, dust spray pressure was adjusted to change the initial distribution of dust cloud (changing the initial distribution range of dust cloud) and dust spray test was made repeatedly. It was then found from several tests that when powder spray pressure is constant, the difference between dust cloud raising processes is small. In order to facilitate the following explosion tests and comparative analysis, ignition delay was set 60 ms, which means dust is ignited after 60 ms to explode. Based on this, dust cloud distribution range, *H,* corresponding to different spray pressure at 60 ms and dust spray pressure, *P*, were fitted, which constitutes the linear rule shown in Figure 5.

3.2 Analysis on the influence of dust cloud distribution range on flame speed

Dust spray pressure of 30 MPa, 50 MPa, 100 MPa, 200 MPa and 300 MPa was selected for dust explosion test. Under each dust spray pressure, test was repeated for three times. The following speed data are the average value of the 3 repeated effective tests. Based on the quantitative relationship between dust cloud distribution range and spray pressure in Figure 5, it is inferred that the dust cloud distribution ranges corresponding to 5 dust spray pressures at 60 ms are 0.16 m, 0.18 m, 0.23 m, 0.32 m and 0.41 m, respectively.

Figure 6 shows the change of flame propagation distance along with time under different dust cloud distribution ranges. Obviously, flame propagation scope corresponding to five conditions exceeded the original distribution range, which was caused by the moving forward of unburned dust cloud in front of flame front pushed by explosion products and pressure wave. When the distribution range was 0.16 m, the longest flame propagation distance was about 0.2 m only; flame was not yet propagated to tube top. Within other four distribution ranges, flame was propagated to the whole tube. At the same time, flame front surface reached the tube opening the soonest when the distribution range was 0.32 m. However, when distribution range was 0.18 m, the corresponding flame front surface reached the tube opening the latest.

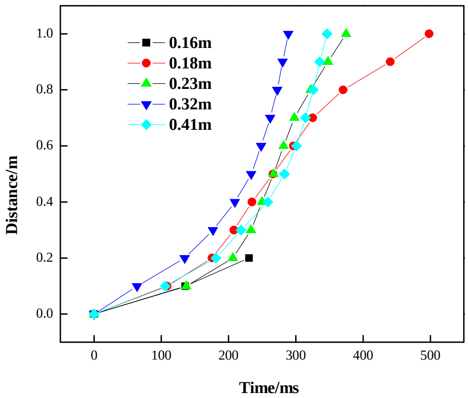


Figure 6: Flame propagation distance vs. time under different dust cloud distribution ranges

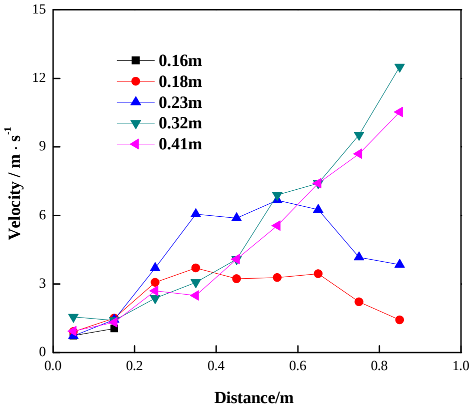


Figure 7: Flame speed vs. axial distance of tube under different dust cloud distribution ranges

Change of flame speed along with the axial distance of tube shown in Figure 7 can be obtained through conversion based on Figure 6. It can be thus seen that flames corresponding to 3 smaller dust cloud distribution ranges accelerated first and then decelerated. To be specific, the flame corresponding to 0.16 m distribution range died out when it accelerated to 1.05 m/s; the flame corresponding to 0.18 m distribution range reached its maximum speed 3.71 m/s at the 0.35 m radial distance of tube, fluctuated in the middle area of tube, and then decreased gradually at 0.65 m and afterwards; the flame corresponding to 0.23 m distribution range reached its maximum speed 6.67 m/s at the 0.55 m axial distance of tube and then decreased gradually. Flames corresponding to 0.32 m and 0.41 m distribution ranges accelerated continuously within the whole tube and their maximum speeds occurred around tube opening and were 12.50 m/s and 10.53 m/s, respectively.

Table1: Flame speed data under different dust cloud distribution ranges

Dust cloud distribution range/m	Average concentration of dust cloud/g•m^{-3}	Maximum flame speed/m•s^{-1}	Average flame speed /m•s^{-1}
0.16	3442	1.05	0.87
0.18	3059	3.71	2.01
0.23	2394	6.67	2.67
0.32	1721	12.50	3.46
0.41	1343	10.53	2.89

Table 1 shows the distribution of flame speeds corresponding to different dust cloud distribution ranges. Besides, the average flame speed within the whole tube can be calculated according to the time consumed by flame to reach the tube opening position, and the approximate average concentration within the initial distribution range of dust clouds can be obtained in the precondition of uniformly distributed dust clouds. Based on Table 1, when dust mass is constant, the maximum flame speed and average flame speed increased first and then decreased with the increasing dust cloud distribution range, and their maximum values occurred when dust cloud distribution range was 0.32 m (the average concentration is 1721 g/m^3). According to dust explosion principle, the expansion of dust cloud distribution range was equivalent to increasing the dispensability of dust particles, which is beneficial to the thorough contact between dust particles with O_2 and promotion of the complete combustion and accelerated flame transmission of dust particles. However, when dust cloud distribution range reached certain extent, the concentration of dust cloud was too low and the energy that was released continuously was not sufficient, which was not favorable for continuous flame acceleration. Similarly, when the distribution range was small and the concentration of dust cloud was high, the contact with O_2 was restricted and the adequate combustion and continuous flame acceleration were affected.

3.3 Analysis on the influence of dust cloud distribution range on flame shape evolution

Figure 8 shows the flame sequence diagrams corresponding to five dust cloud distribution ranges; they are the whole process from the explosion starting to the highest vertical position of flame. When dust cloud distribution range was 0.16 m, dust distribution was most centralized, flame was bright in the whole propagation process and flame front surface was always smooth; however, the total flame propagation distance was only 0.2 m as dust cloud scope was small and flame acceleration was stable. When dust cloud distribution range was 0.19 m, flame was bright in the first half propagation process but got dimmer in the second half. Besides, flame in tube section direction got narrower; flame accelerated obviously in the first half propagation process but decelerated gradually in the second half. When dust cloud distribution range was 0.23 m, flame was bright in the whole propagation process, and flame width in tube section direction was wider; flame acceleration was evident in the first half propagation process but decelerated obviously in the second half. When dust cloud distribution range was 0.32 m and 0.41 m, flame was bright in the whole propagation process. By contrast, acceleration of both flames was obvious in the first half propagation process, but the flame corresponding to 0.32 m dust cloud distribution range accelerated more significantly compared with the flame corresponding to 0.41 m distribution range. Besides, the latter encountered obvious fault in the later propagation stage due to too disperse distribution of dust cloud. Evolution of the above flame shape evolution process is consistent with the flame speed distribution characteristics shown in Figure 6.

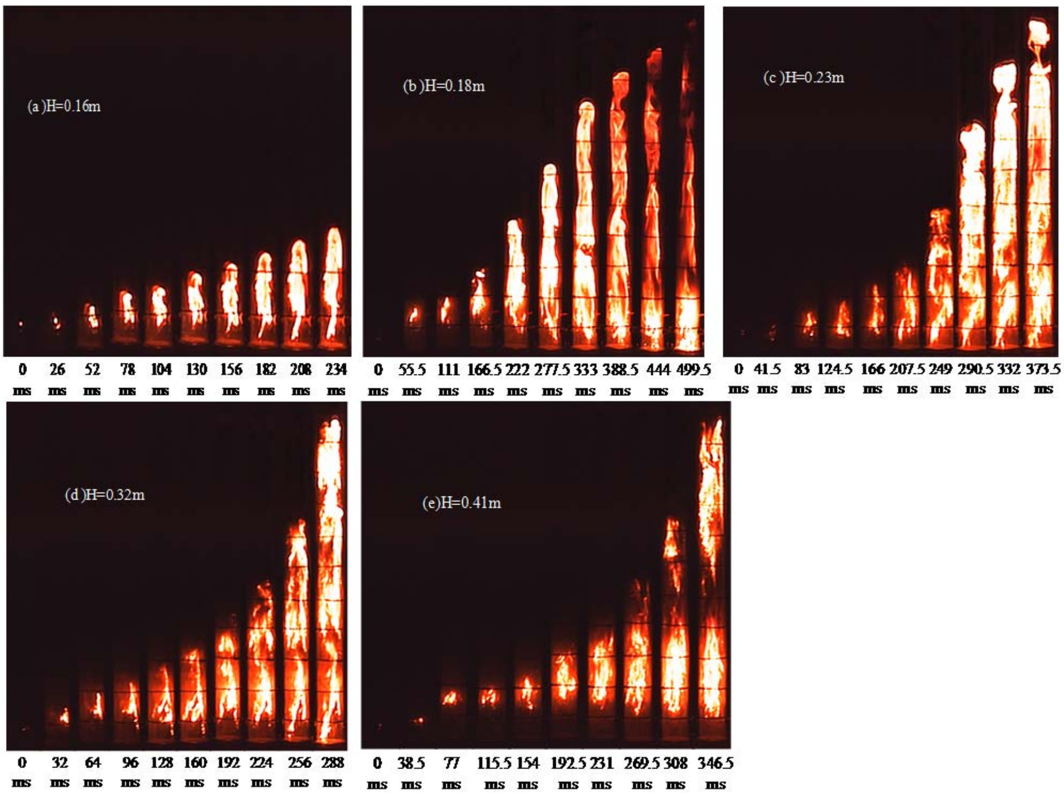


Figure 8: Flame sequence diagrams under different dust cloud distribution ranges

4. Conclusions

In order to provide scientific basis for the effective control of PE dust explosion in the initial stage of accident, tests were made to study the influence of different initial distribution ranges of dust clouds in semi-open tubes on flame propagation, reaching the following conclusions:

(1) Flame propagation scope generally exceeds the initial distribution range of dust cloud. The larger the initial distribution range, the larger the flame propagation scope.

(2) Dust cloud flames in certain distribution range can form continuous acceleration. When dust cloud is too centralized or dispersed, flame will accelerate first and then decelerate along the axial direction of tube.

(3) When dust mass is constant, the maximum flame speed and average flame speed of dust cloud increase first and then decrease along the increasing initial distribution range of dust cloud.

(4) The initial distribution of dust cloud can affect flame shape and its evolution process significantly, embodied in width along the radial direction, brightness, front smoothness, fault, etc.

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