

論文の内容の要旨

論文題目 Effects of particle characteristics on flame propagation mechanism
in dust explosions
(粉体特性が粉じん爆発時の火炎伝ば機構に及ぼす影響)

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1. Introduction

To take appropriate measures preventing accidental dust explosions, it is necessary to sufficiently understand the flame propagation mechanisms in dust explosions. Numerous factors govern the initiation and subsequent propagation of the dust flames [1]. In all of the influencing factors, the particle characteristics including the thermal properties and size distributions are essential. The present study is concerned with achieving a better understanding of the effects of particle characteristics on flame propagation mechanism in dust explosions by experiments.

2. Experimental

In the experiments, hexadecanol, octadecanol and eicosanol, which are solid at room temperature and similar in physical-chemical properties, were chosen for experiments to examine the effects of particle characteristics on flame propagation behaviors and to observe the changes of the flame front structures during dust explosions.

3. Experimental results

3.1 Flame propagation behaviors

Figure 1 shows the flame propagation processes through the three alcohols dust clouds in a vertical chamber. After ignition, the flame began to propagate through the chamber. For hexadecanol, octadecanol and eicosanol, the flame can almost not be seen until 12.5 ms, 15.5 ms and 33 ms. In the upward propagation process, the flame propagated quickly and emitted strong yellow light, and the luminous zone increased during its propagation. It was observed that the flame propagated more quickly and emitted more light in the higher volatile dust cloud. That was because less time was needed for pyrolysis to combustible small molecules gases for smaller higher volatile particles. After that the larger particles began to participate in the combustion reaction and the pyrolysis was going on after the flame front passed through, and the pyrolyzed gases participated in the combustion reaction continuously, causing the combustion reaction last a longer time.

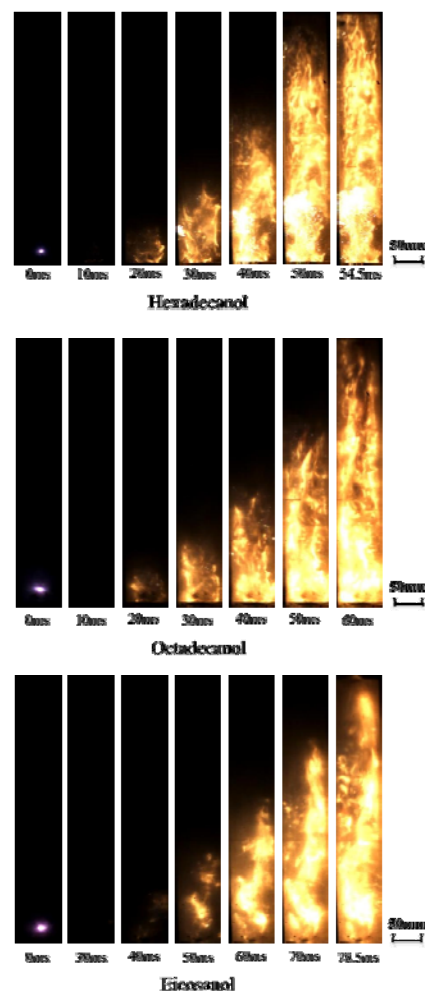


Fig.1. High-speed direct photographs of flame propagation.

Figure 2 shows the dust flame microstructures of the three long-chain monobasic alcohols, which includes the revised temperature curve and ion current curve. t_1 is the onset time of the temperature, t_2 is the onset time of the ion current. During the period of t_1 to t_2 , the temperature increased but there was no chemical reaction. So the temperature increase was mainly caused by the heat conduction and radiation from the chemical reaction zone. This zone is the preheated zone, for hexadecanol, octadecanol and eicosanol, the thicknesses of the preheated zone were about 15.0 mm, 20.3 mm and 27.5 mm, respectively. In the preheated zone, the smaller particles were pyrolyzed to some much smaller intermediates. From t_2 , the pyrolyzed much smaller intermediates began to participate in the combustion reaction and maintained the flame propagation process.

Generally, a combustion zone propagates in a combustible medium as a heat wave. Therefore, the heat transfer type from the reacting combustion zone to the unburned region ahead of it governs the propagation velocity. In dust explosions, conductive and radiative heat transfer governs the flame propagation process. Which heat transfer type is dominant in dust explosions depends on the conditions. The measured relationship between the flame propagation velocity and temperature shown in Fig. 3 indicated that the role of conductive heat transfer was more significant than that of radiative heat transfer at current conditions.

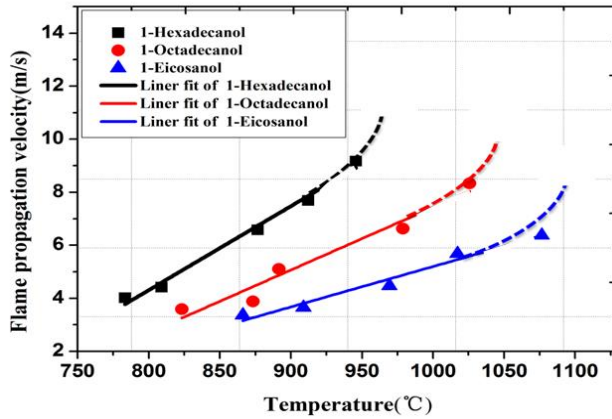


Fig.3. Relationship between the maximum temperature and the propagation velocity of the combustion zone.

3.2 Flame front structures

To observe the true leading edge of the reaction zone, the propagating flames were recorded by a special high-speed-video system at band-pass observation and an ordinary observation system in an open-space chamber, as shown in Fig. 4. For methanol and propanol mist combustion, the flame fronts were smooth in shape and blue flames

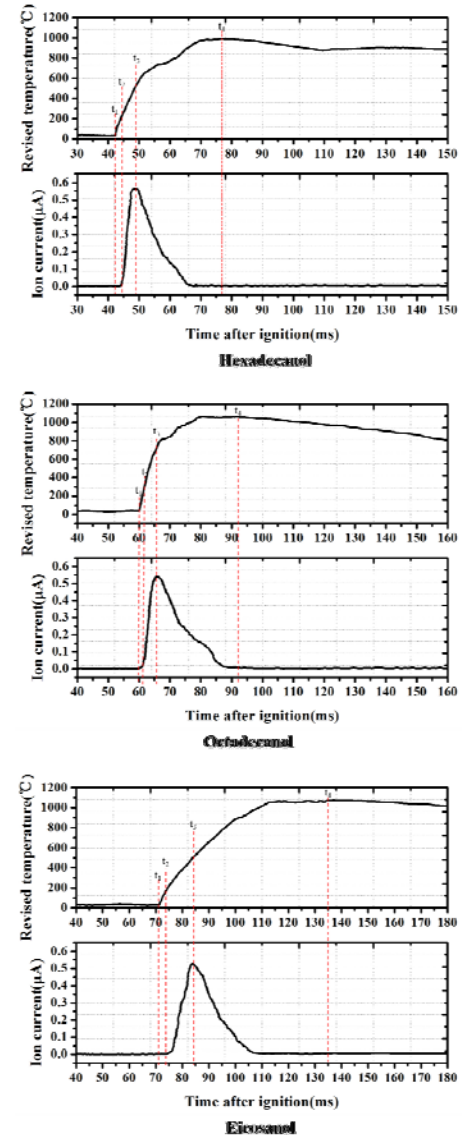


Fig.2. Dust flame microstructures of the three materials.

appeared in the flame fronts. It can be inferred that all of the droplets were pyrolysed or evaporated before the flame front passed through. The combustion regions seemed connected and continuous in structure, similar to an ordinary gas flame that propagates in homogeneous combustible gases, and the regions retained their surface as they propagated, though propagating velocities differed at each point. In contrast, the flame propagating through other droplets and particles formed a complicated structure. The flame zones consisted of blue spots flame at the leading zone and luminous flames behind them. The flame zones seemed to be discrete. The blue spots would represent burning of larger particles or gaseous lumps of materials that resulted from their evaporation. The thickness of the blue spot zone and number of blue spots increased with decreased volatility of the materials. As the particles burned, a small luminous flame appeared that resembled a yellow dot. This phenomenon can be explained as follows: around the particles, local high-concentration regions of fuel existed; when those particles burn without sufficient oxygen, soot particles were formed, and these particles emitted yellow flame. These small luminous flames grew under buoyancy and combined with each other, and in the end formed a whole luminous zone in an irregular shape. This luminous zone was composed of heated soot particles that were created by the decomposition of gasified fuel ejected from particle surface. Because the particles were scattered, the gasified fuel concentration was not uniform. This must be the reason for the irregular shape of the luminous zone. Furthermore, from the magnified CH emission images, it was found that the leading isolated spot flames were supported by the vaporised gas from smaller particles, which could be vaporising quickly. However, the number of the small particles per unit volume was sufficiently small such that whole flames kept their discrete structures instead of being united and forming continuous surfaces. Hence, the flames propagate continuously on a locally scale, unlike the relay ignition mechanism.

4. Flame propagation mechanisms

Dust clouds with different volatility and particle size distributions would form different flame structures. The homogenous combustion, whose flame front formed was smooth in shape, was controlled by the kinetics-controlled regime; while the heterogeneous combustion, whose flame front had a complicated structure, was controlled by the devolatilization-controlled regime. The flame structures and propagation mechanisms are shown in Fig.5. The flame propagation mechanism was found to transit from the kinetics-controlled regime to the

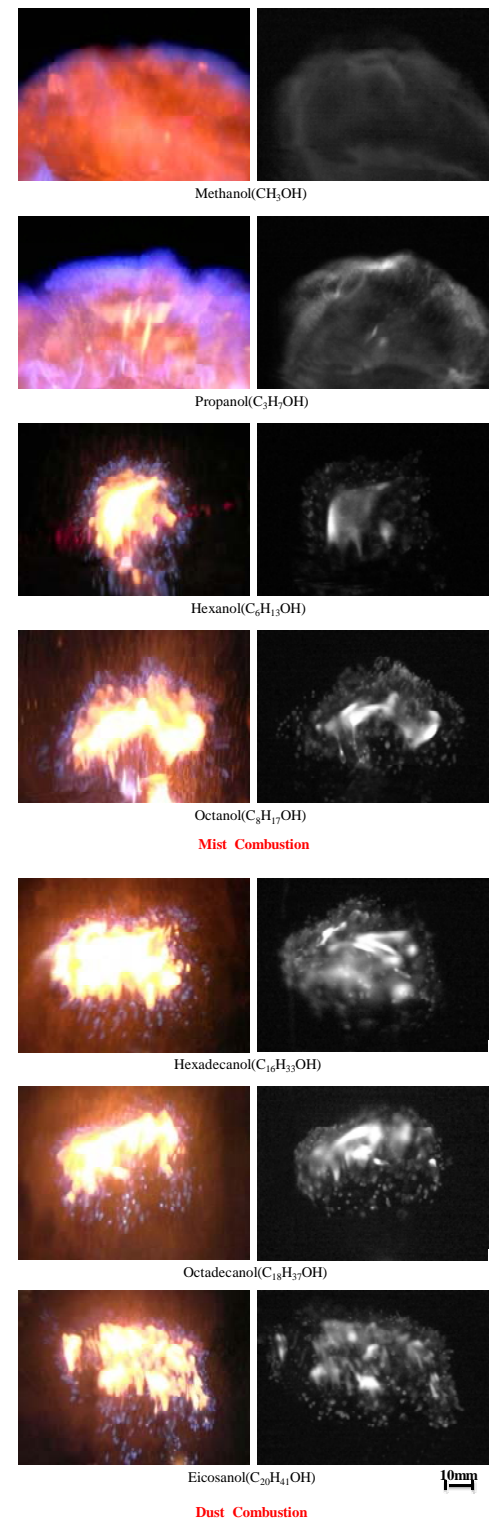


Fig. 4. Flame images by two observation methods.

devolatilization-controlled regime when decreasing the volatility of the materials or increasing the size of the particles. Damköhler number was defined to reflect this flame propagation mechanism transition, which was expressed by:

$$Da = \frac{C_3^3 \rho_d D_{32}^2 (T_i - T_u) V_f^2 T_u^2}{8 C_1 (\lambda / c_p)_g \phi \ln(1 + B) (\lambda / C \rho) (T_f - T_i) T_i^2} \quad (1)$$

Where B_s , the Spalding number, is the mass transfer number, which is a function of boiling point, gas temperature, surface temperature, heat of combustion, and the other parameters [2]. It is found that when Damköhler number was less than 1, homogeneous combustion controlled the flame propagation process; on the contrary, when Damköhler number was larger than 1, heterogeneous combustion controlled the flame propagation process.

5. Conclusions

(1) The following results were drawn. Flame propagation behaviors depended on the particle characteristics strongly; dust flame surfaces were completely covered by cellular structures; the propagation velocity of the combustion zone was not constant and flames accelerated in the flame propagation process. In high volatile dust clouds, flame propagated more quickly, maximum flame temperature was lower and ion current was higher. Conductive heat transfer and radiative heat transfer played an important role in the flame propagation process.

(2) Two obviously different flame propagation regimes appeared in dust clouds of different materials or dust clouds with different particle size distributions. For the kinetics-controlled regime, the flame front was smooth in shape, and blue flame appeared in the flame front. In contrast, for the devolatilization-controlled regime, the flame formed a complicated structure. The flame zone consisted of blue spots of flame at the leading zone and luminous flames behind them. Flame firstly propagated towards the small particles nearby. When the smaller particles were completely pyrolyzed, the local pre-mixing flame would continue to heat the larger particles, establishing the local diffusion flame.

(3) Damköhler number, which can be evaluated by the particle characteristics, was introduced to reflect this flame propagation mechanism transition. It was found that the kinetics-controlled regime and devolatilization-controlled regime can be categorized by whether Damköhler number was less than 1 or larger than 1.

References

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- [2] Ballal D. R. (1983). Flame propagation through dust clouds of carbon, coal, aluminium and magnesium in an environment of zero gravity. *Proceedings of the royal society a mathematical physical and engineering sciences*, 385(1788), 21-51.

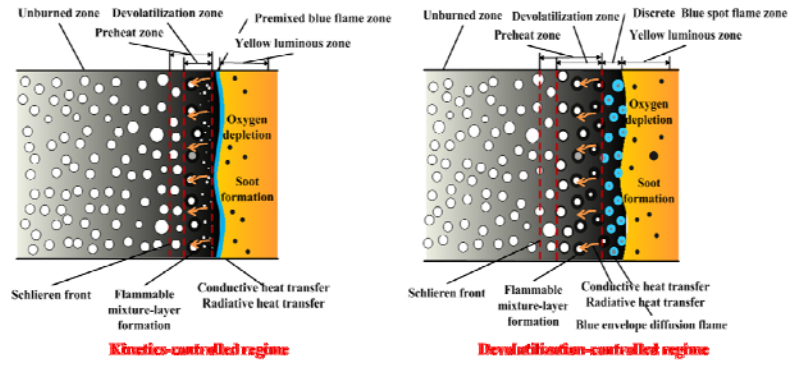


Fig. 5. Schematics of flame propagation regimes in dust explosions.