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Effects of particle thermal characteristics on flame structures during dust explosions of three long-chain monobasic alcohols in an open-space chamber

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HIGHLIGHTS

- Flame front was smooth and continuous in methanol, propanol mist combustion.
- Discrete blue spot flames appeared ahead of luminous flames in other particles.
- A dark zone appeared between the flame and particles.
- The propagation velocity of the combustion zone was not constant.
- Radiative heat transfer played an important role in the flame propagation.

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ABSTRACT

To reveal clearly the effects of particle thermal characteristics on flame structures during organic dust explosions, the flame structures in the dust clouds and liquid mist observed during the combustion of several long-chain monobasic alcohols in an open space chamber were recorded using an approach combining high-speed photography and a band-pass filter. From direct-light-emission photographs and CH-emission photographs, it was demonstrated experimentally that the structures of propagating flames changed as the thermal characteristics of the dust clouds and liquid mist varied. For methanol and propanol mist combustion, the flame structures were similar to the premixed gas explosion; in contrast, from hexanol mist combustion to eicosanol dust combustion, the flame formed a complicated structure that exhibited heterogeneous combustion characteristics. The estimated results of the combustion reaction's final state show that all of the materials should react in the gas phase and that the comparative relationship between the characteristic time for the heating and devolatilisation of dust particles and the characteristic time for the gas-phase combustion of the premixed volatiles is a critical condition for the flame structure transition from homogeneous combustion to heterogeneous combustion in different materials.

1. Introduction

A dust explosion generally occurs when the air in a factory or other confined space is full of dust particles that somehow come into contact with a flame or spark, generally causing an explosive effect that can be sufficiently powerful to cause buildings to burst apart and easily injure or kill people [1]. To take appropriate measures against such dust explosion accidents, it is necessary to understand the flame propagation mechanisms in this phenomenon. Some recent research has focused on the flame propagation process during dust explosions [2–8]; however, basic flame propagation mechanisms of such heterogeneous mixtures are not yet well-understood due to the major problem facing dust-explosion research that is the complexity of the particle cloud of the combustion processes. In organic dust explosions, particles undergo combustion processes, such as particle heating, vaporisation, mixing with oxidiser, ignition, burning, and flame extinction, which are governed by many factors.

In all of the influencing factors, the physical and chemical properties of the particles, especially the thermal characteristics, are essential. In dust explosions there are two aspects to consider, namely, the thermodynamics of the explosion, and the kinetics. The thermodynamic aspect is concerned with the amount of heat that is liberated during the explosion, while the kinetic aspect is concerned with the rate at which the heat is liberated. Both the

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thermodynamic and kinetic aspects are related to the particle thermal characteristics. Hence, the particle thermal characteristics could determine two different flame types. The first type is controlled by premixed gas combustion, where a homogeneous chemical reaction takes place. In the second type, the rate of gasification, pyrolysis, or devolatilisation is the controlling process, and the chemical reaction takes place mainly in a heterogeneous phase [9]. Unfortunately, to date no studies have been conducted on the effect of material thermal characteristics on flame propagation mechanism.

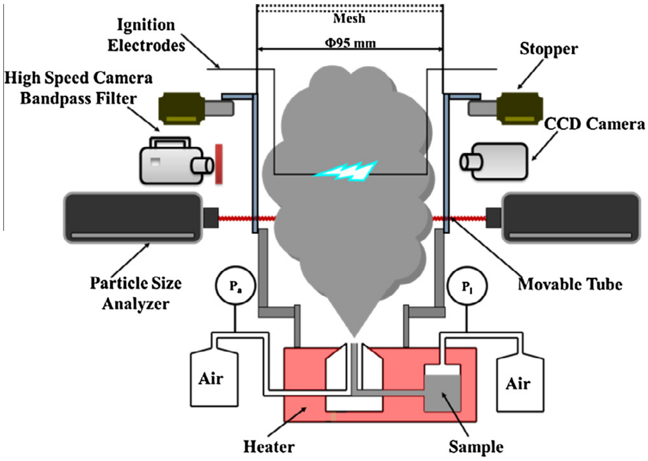

Fig. 1. Experimental apparatus.

In this paper, several long-chain monobasic alcohols, similar in physical–chemical properties, were chosen for experiments using a high-speed camera and a UV-band filter observation system in an open-space chamber to examine the effects of particle thermal characteristics on the flame propagation mechanism during organic dust explosions.

2. Experiments

2.1. Experimental apparatus

In our previous study [10], the flame propagation behaviour during the dust explosions of three long-chain monobasic alcohols in a half-closed chamber were recorded by a high-speed video camera. After a spark from electrodes ignited the dust, the flame began to propagate through the chamber. However, there was almost no flame during the initial several milliseconds. Because of the weak blue spots of flame and limited sensitivity of the high-speed camera, the true flame front, which is necessary to clarify the flame propagation mechanism, was not captured during the flame propagation process. In this study, using a higher-sensitivity high-speed camera and an open combustion chamber, the flame can propagate in an open field without any influence of the chamber wall, and observation can be made directly.

The open-space experimental set-up used in this study is shown in Fig. 1. This set-up consisted of an air–fuel sprayer with a nozzle measuring 0.5 mm in diameter, and a set of cylindrical ducts. The solid experimental materials in the fuel tank were heated to a temperature higher than their melting points, at which point they became liquid. The materials were subsequently sprayed upward into the duct with surrounding air using a two-phase nozzle. The liquid

Table 1
Thermal characteristics of the three long-chain solid monobasic alcohols.

Name	Hexadecanol	Octadecanol	Eicosanol
Formula	$CH_3(CH_2)_{14}CH_2OH$	$CH_3(CH_2)_{16}CH_2OH$	$CH_3(CH_2)_{18}CH_2OH$
Molecular weight (kg/kmol)	242.44	270.50	298.55
Density (g/cm^3)	0.811	0.8124	0.841
Melting point (K)	322.3	332.8	338.5
Boiling point (K)	593	618	642
Enthalpy of vaporisation[a] (kJ/mol)	107.8	115.9	124.9
Enthalpy of fusion[a] (kJ/mol)	58.4	69.6	78.4
Activation energy[b] (kJ/mol)	84.60	87.65	89.85
Standard enthalpy of combustion[c] (kJ/mol)	−10,510	−11,820	−13,130
Constant pressure heat capacity of solid[c] (J/mol × K)	441.24	486.75	537.75
Constant pressure heat capacity of liquid[c] (J/mol × K)	566.5	630.3	694.1
Thermal conductivity[d] (W/m K)	0.0849	0.07727	0.08418
Thermal diffusivity[d] (mm^2/s)	0.2000	0.2303	0.1348
Specific heat[d] (mJ/mm^3 K)	0.4248	0.3358	0.6246

[a] Heat of evaporation and fusion are obtained from Ref. [12].
[b] Activation energy is calculated through TG experimental results.
[c] Constant pressure heat capacity of solid, liquid and standard enthalpy of combustion are obtained from Nist Chemistry WebBook [13].
[d] Thermal conductivity, thermal diffusivity and specific heat were measured by Hot Disk TPS2500s Thermal Properties Analyser.

Table 2
Thermal characteristics of the four liquid monobasic alcohols.

Name	Methanol	Propanol	Hexanol	Octanol
Formula	CH_3OH	$CH_3(CH_2)_2OH$	$CH_3(CH_2)_5OH$	$CH_3(CH_2)_7OH$
Molecular weight (kg/kmol)	32.0419	60.095	102.1748	130.2279
Density (g/cm^3)	0.7918	0.8034	0.8136	0.824
Melting point (K)	161.85	184.39	218.2	240.74
Boiling point (K)	314.46	360.22	428.86	474.62
Enthalpy of vaporisation[a] (kJ/mol)	37.83	47.50	60.61	70.98
Constant pressure heat capacity of liquid[b] (J/mol × K)	80.35	144.44	243.20	304.0

[a] Enthalpy of vaporisation is obtained from Ref. [12].
[b] Constant pressure heat capacity of liquid is obtained from Nist Chemistry WebBook [13].