FLAME PROPAGATION DURING DUST EXPLOSIONS

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ABSTRACT
It is important to sufficiently understand the phenomena during dust explosions in order to take appropriate measures preventing accidental dust explosions. However, at present basic knowledge on flame propagation in combustible dust (dust flame propagation) is not enough. In this paper, the particular characteristics of the dust flame are pointed out, which are different from those of gas flames. Also the some recent experimental results on the dust flame are described.

The dust flame propagation has some special characteristics that the gas flame does not have. The important points are as follows;
1. The flame propagates in heterogeneous medium
   During dust flame propagation, the flame propagates in the region where combustible particles and vaporized gas and/or liquefied particles coexist. The region is heterogeneous medium, where solid, liquid and gas coexist. Therefore, complicated phenomena in such heterogeneous medium have to be considered to understand the dust flame propagation.
2. The movement of dust particles is different from that of gas
   The combustible dust particles are moving at the different velocity from gas flow, especially when the gas flow is accelerated. Near the combustion field, the gas flow is usually accelerated and the combustible particle can not follow the accelerating gas flow (velocity slip exists). It generates some special characteristics of the dust flames.

Our recent experimental studies show some interesting results concerning above mentioned features.
1. Studies on the flame propagation mechanism
   Flammable limit was examined in the experiments with Stearic acid particles changing the particle size distribution. It was found that the lower flammable limit strongly depends on the mass density of smaller particles (less than 60 μm on diameter). This result indicates that the smaller particles has important role on the flame propagation. Flame structure was also examined using ion probe and UV band observation system. It was found that the leading flame is maintained by the vaporization of the smaller particles.
2. Studies on the particle movement
   The effects on the velocity difference between the particle and gas was examined on the iron dust flame. The iron particles can not follow the surrounding gas movement, and then the number density of iron particle increases near the combustion zone. This behavior strongly affects the combustion phenomena of iron dust.

The particular characteristics of dust flame propagation were explained with the results of recent experimental studies.
Flame Propagation during Dust Explosions

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Background (1)
- Appropriate understanding of phenomena proceeded during dust explosion is necessary to take appropriate measures against the accidental dust explosions.
  - Prevention techniques
  - Mitigation techniques
  - Risk (consequence) analysis (appropriate consequence prediction; computer model et.al.)

Background (2)
- In most previous studies, practical characteristics of dust explosions are focused; such as,
  - Explosion concentration limits
  - Minimum ignition energy
  - Explosion pressure etc.
- Also the fundamental studies are needed for consistent measures.

Procedure of Dust Explosion

Flame Propagation

Characteristics of Dust flame

'Flame Propagation'
- Understanding of flame propagation during dust explosion is essential
- Dust flame has some particular aspects compared with gas flame
- The fundamental studies on dust flame are needed
### Difference between Dust and Gas explosions

<table>
<thead>
<tr>
<th></th>
<th>Gas explosion</th>
<th>Dust explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame type</td>
<td>Premixed</td>
<td>Non-Premixed</td>
</tr>
<tr>
<td></td>
<td>(homogeneous)</td>
<td>(heterogeneous)</td>
</tr>
<tr>
<td>Thickness</td>
<td>Thin</td>
<td>Thick</td>
</tr>
<tr>
<td>Supply speed of O&lt;sub&gt;2&lt;/sub&gt; and Fuel</td>
<td>Almost same</td>
<td>Often different</td>
</tr>
<tr>
<td></td>
<td>(selective diffusion)</td>
<td>(particle movement)</td>
</tr>
<tr>
<td>Influence of Radiation</td>
<td>Limited</td>
<td>Sometime strong</td>
</tr>
<tr>
<td>Flame front</td>
<td>Usually smooth</td>
<td>Not smooth originally</td>
</tr>
</tbody>
</table>

### Propagating Flame Structure

- Decane Spray
- Stearic Acid Dust
- Iron Dust

### Important points to be understood

- **Flame propagation mechanism**
  - Propagation limit $\Rightarrow$ Explosion limit
  - Propagation behavior $\Rightarrow$ Risk (consequence) analysis

- **Special aspects of Dust combustion**
  - Effect of particle movement
  - Effect of turbulence
  - etc.

### How the flame propagates?

- **Propagating Flame**
- **Diffusion Flame**

#### Relay Ignition Mechanism

- Ignition
- Flame development
- Heat transfer
- Sequential ignition
- Flame propagation

#### Premixed Flame

- Fuel $+\text{Oxidizer (O}_2\text{)}$ $\rightarrow$ Products $\text{O}_2 + \text{H}_2\text{O}$

#### Diffusion Flame

- Fuel
- Flame
- Oxidizer (O<sub>2</sub>)
- Products
Questions on the Relay Ignition Hypothesis (stearic acid flame)

- Why is the propagating speed (about a few tens cm/s) so fast?
- No flame of asymmetrical shape is observed.
- It is uncertain that the leading visible flame exactly corresponds to the leading combustion reaction zone.

More detailed study is needed.

Experimental Approaches

- Experiments for Organic Dust (resin)
  - Limit of flame propagation
  - Temperature Distribution
  - Measuring thermal structure
  - Ion Current Measurement
  - Observation by UV band
- Experiments for Metal Dust (Iron)
  - Temperature Distribution
  - Measuring thermal structure

Experimental setting

Combustible dust

Stearic acid
(melting point 343 K)
\(CH_3(CH_2)_{16}COOH\)

1-Octadecanol
(melting point 328 K)
\(CH_3(CH_2)_{16}CH_2OH\)

Particle size control

Quick cooling of liquid spray
Solid particles

Two fluids
Nozzle

at liquid state (heated)

Fuel

Pressure of feeding air \(p_a\), kPa

Pressure of feeding fuel \(p_f\), kPa

Flammable limit (Stearic acid)

Flammable

Non-flammable
Results (Limit of flame propagation)
- Flame propagation near lower flammable limit is only supported by the combustion of smaller particles.
- The leading combustion zone might be sustained by smaller particles, not by larger particle combustion (blue spot flame).
- The combustion character of dust cannot be indicated by averaged diameter such as SMD.

Estimation of the heat release rate \( \dot{Q} \)

\[
\rho \ C_p \ U \ \frac{dT}{dx} = \lambda \ \frac{d^2T}{dx^2} + \dot{Q}
\]

\( \rho \) represents the density
\( C_p \) the specific heat
\( U \) the flame propagation velocity
\( T \) the temperature
\( x \) the position
\( \lambda \) the thermal conductivity
Variation of the heat release rate (1-Octadecanol) about 2 mm ahead of visible flame

Results (Temperature Distribution)
- Heat release rate takes a maximum value at the position about 2 mm ahead of the visible leading flame edge
- Combustion reaction must already starts at the position about 2-3 mm ahead of the visible flame

Ion Current Measurement (Stearic acid) (detecting combustion reaction)

Structure of the dust flame (Stearic acid)

Results (Ion Current Measurement)
- Combustion reaction starts at the position a few mm ahead of the visible flame
- Thickness of the reaction zone (about ten mm) is thicker than that of gaseous hydrocarbon-air flame

UV band observation System
Function of band-pass filter

- **Chemical emission**
  - OH (281, 306 nm, UV)
  - CH (387, 432 nm, Blue)
  - CC (517 nm, Green)

- **Black body radiation**
  - Luminous flame

Band spectrum

To detect combustion reaction zone sensitively

Decreasing Luminous flame emission

Observation by UV band

- **Image intensifier + Band-pass filter**
- Detecting emission from combustion reaction

Sensitive detection of combustion reaction zone can be realized.

Observed propagating flames (UV band, Ordinary system)

- **Observation at UV band**
  - Observation by Ordinary system
  - White line indicates the leading edge of blue flame zone

- **Zone where blue spot flames exist**

Observed flame propagation (at UV band)

- **Almost continuous propagation**

Result (Observation by UV)

- The leading flame front is not discrete spot flames but continuous reaction zone ahead of spot flames
- The leading flame was observed to propagate continuously
Propagating Flame Structure

Decane Spray  Stearic Acid Dust  Iron Dust

Leading combustion zone; locates ahead of visible flame, is supported by smaller particles, propagates continuously

Smaller

Possible structure of the dust flame
(1-Octadecanol and Stearic acid)

Real leading combustion zone must exist at the position ahead of the visible leading combustion zone

It mainly consists of the burning of smaller particles

"relay ignition mechanism" can not be adopted

Possible structure of the dust flame
(1-Octadecanol and Stearic acid)

Leading combustion zone
(a kind of premixed flame)

Flame propagating direction

Experimental Approaches

- Experiments for Organic Dust (resin)
  - Limit of flame propagation
  - Changing particle size distribution
  - Temperature Distribution
  - Ion Current Measurement
  - Observation by UV band
- Experiments for Metal Dust (Iron)
  - Temperature Distribution
  - Measuring thermal structure

Structure of the flame propagating in Iron dust

Structure of iron particle cloud combustion zone

Scale


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Profile of the temperature across the combustion zone

Iron particle diameter distribution

Velocity and max. temp.

Max. Temp. and flame Velocity

Max. Temp. and flame Velocity

Result (Iron dust flame)

- Maximum measured temperature and propagating velocity are in linear relation
- Effect of radiative heat transfer ($\sim T^4$) is not dominant in this case

\[
S_{\text{net}} = \frac{\lambda_p (T_{\infty} - T_{\text{wall}})}{n} + 2 \cdot \eta = \sigma \cdot \frac{T^4 - T_{\text{wall}}}{\rho_v C_v (T_{\infty} - T_{\text{wall}})}
\]

Cassel, Liebman, and Mock, 1956

- Combustion reaction occurs only on the particle surface
- Thickness of combustion zone is about 5 mm
- Radiation is not the dominant heat transfer mechanism (propagating as a heat wave)
Propagating Flame Structure

- Surface combustion reaction (no gas phase reaction)
- Radiative heat transfer is not dominant (propagating as a heat wave)

Leading combustion zone; locates ahead of visible flame, is supported by smaller particles, propagates continuously

Decane Spray Stearic Acid Dust Iron Dust

Luminous zone

Larger Volatility Smaller Volatility

Premixed flame Diffusion flame? Surface combustion

Leading edge of combustion zone; locates ahead of visible flame, is supported by smaller particles, propagates continuously

Surface combustion reaction (no gas phase reaction)
Radiative heat transfer is not dominant (propagating as a heat wave)

Characteristics of Dust flame
Flame (Combustion zone)

Unburned
Burned

- Gas velocity $V_{gu}$
- Particle vel. $V_{pu}$
- $V_{gu}$ or $V_{pu}$?

similar as selective diffusion

Fuel Conc. $\neq$ Fuel Flux to reac. zone
Oxygen Conc. $\neq$ Oxygen Flux to reac. zone

Difficulty to define ‘Burning Velocity’ in dust flame

$$S_L = U_u = \frac{1}{\epsilon} U_b$$

$V_{gu}$ or $V_{pu}$?
$\epsilon$?
difficult to determine

Laser scattering observation on Iron dust flame

Iron particle trajectory

Laser light scattering

Distance from ignition point, cm

Time from ignition, ms

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Velocity slip between particle and gas

- Velocity slip must cause change of particle number density.

Change of particle number density

- The velocity difference causes the increase of particle number density just ahead of the combustion zone.

Flammability lean limit

<table>
<thead>
<tr>
<th>Fuel gas</th>
<th>Lean limit</th>
<th>Equivalence ratio</th>
<th>Lean limit</th>
<th>Equivalence ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.50</td>
<td>Adipic acid</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Ethane</td>
<td>0.52</td>
<td>Lactose</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.40</td>
<td>Poly-ethylene</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>0.49</td>
<td>Sulfur</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>0.46</td>
<td>Aluminum</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.49</td>
<td>Iron</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Results (Behavior of particles)

- Difference exists between particle velocity and gas velocity (velocity slip).
- The velocity difference causes the increase of particle number density just ahead of the combustion zone.

Flammability lean limit

- One of the reasons might be concentration increase by velocity slip.
Experimental setting to examine the stationary dust flame (work on progress)

Summary

The important aspects of dust explosion were presented to well understand dust flame propagation:
- Dust flame has some particular aspects compared with gas flame (heterogeneous combustion).
- Particle can easily move at the different velocity from gas flow. It causes some specific behaviors.

Future work

- Theoretical study and Modeling
- The effects to be examined
  - Scale
  - Stretch
  - Turbulence

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References