Suppression of Pulverized Biomass Dust Explosion by NaHCO₃ and NH₄H₂PO₄

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ABSTRACT

A dust explosion may occur during the process of biomass fuel utilization, resulting from the existence of a high-concentration dust cloud. In this paper, the suppression capacities of NaHCO₃ and NH₄H₂PO₄ for pulverized biomass dust explosion were determined in an open-space dust explosion apparatus. Poplar sawdust and peanut shell dust with two particle size distributions were employed. Results showed that the amount of NaHCO₃ required to prevent the poplar sawdust explosion was lower in comparison with NH₄H₂PO₄. Flame morphology became irregular and discrete, as the suppressant concentration increased. By increasing the concentration of NaHCO₃ and NH₄H₂PO₄, the average flame velocity and flame temperature of pulverized biomass dust were significantly decreased. Detailed suppression mechanisms of NaHCO₃ and NH₄H₂PO₄ were further discussed by analysing the physical and chemical effects. Decomposition of suppressant particles could absorb the heat released from the flame front. Meanwhile, gaseous products altered flame chemistry by catalytic recombination of key flame radicals, which led to less heat release, a lower flame speed and a lower flame temperature.

KEYWORDS: Biomass, dust explosion, suppression, flame propagation, flame temperature.

INTRODUCTION

As an alternative to fossil fuels and a renewable energy source, biomass has received considerable attention [1]. For instance, poplar and peanut shell dust solid biomass fuels are the promising contenders for electricity and heat generation, and has a considerable reserves in China. A dust explosion may occur during the production, transport, and storage of biomass fuel, owing to the existence of a high-concentration dust cloud [2]. Dust explosions always lead to serious casualties and financial losses [3]. Hence, reducing the consequences of accidental biomass dust explosions is a crucial subject for safety management in industrial processes [4].

It is well known that phosphates, alkali metal salts and other materials all have a certain explosion suppression performance [5-8]. Na–containing and P–containing compounds are referred to as chemical suppressions [9, 10]. These suppressions show superior performance by virtue of its radical removal reactions [11-13]. Previous work [14-16] concluded that the mechanism of flame suppression by Na–containing and P–containing species is chemical and homogeneous. However, only few researchers have systematically studied the effect of NaHCO₃ and NH₄H₂PO₄ on biomass dust flame, especially the effect on the flame temperature and gas-phase chemical reactions. Even though NaHCO₃ and NH₄H₂PO₄ have demonstrated effectiveness in early studies, the suppression mechanisms of pulverized biomass flame by NaHCO₃ and NH₄H₂PO₄ have not been studied.
In this study, the suppression performance of poplar sawdust and peanut shell dust explosion by NaHCO₃ and NH₄H₂PO₄ is evaluated systematically. Detailed suppression mechanisms of NaHCO₃ and NH₄H₂PO₄ are further discussed.

**EXPERIMENTAL SETUP**

**Experimental apparatus**

The experimental apparatus similar with our previous study is shown schematically in Fig. 1 [17]. The experimental material was sprayed upward at a pressure of 0.45 MPa, the time of dispersion lasted 0.3 s. After injection, the moveable tube dropped down, then, the head of the thermocouple driven by a cylinder moved to the centre of the dust cloud. The spark duration was 0.02 s, which was set at a delay time of 0.5 s. Normal lens (Nikkor 50 mm f/1.2, Nikon) installed on a high-speed Photron SA4 video camera was used to record the flame propagation processes, and microscopic lens (AF Micro Nikkor 200 mm f/4D, Nikon) was used to record the flame microstructures, operated at 2000 frames per second. The thermocouple was composed of 13% Pt/Pt–Rh wires with a 25 μm diameter, whose measure range was 0–1900 °C. Note that the response time of fine wire thermocouple is on the order of microsecond. It is not suitable for temperature measurement during the combustion of the fuel with extremely high activity and very fast reaction rate, such as explosives and pure aluminum particles. To achieve reliable results, 5–6 replicate experiments were conducted, and the value of explosion parameters was averaged.

**Experimental materials**

Two types of biomass provided by Dalian Jiayuan New Energy Technology Development Co., Ltd. of China were chosen for the experiments. Biomass pellets were broken into smaller particles and sieved into two particle size distributions of 50–70 μm and 70–100 μm. NaHCO₃ powder was sifted into 50–100 μm using a sieve shaker. The diameter of NH₄H₂PO₄ was less than 14 μm. The NH₄H₂PO₄ content sample was larger than 90%. A scanning electron microscope (SEM) was used to observe the morphology of biomass and suppressant particles, as shown in Fig. 2. The ultimate analysis and the proximate analysis of the biomasses were given in Table 1.

![Fig. 1. Experiment apparatus.](image1)

![Fig. 2. SEM images of biomass and suppressant particles.](image2)

<table>
<thead>
<tr>
<th>Component</th>
<th>Ultimate analysis (wt%)</th>
<th>Proximate analysis (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbon</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Poplar sawdust</td>
<td>45.64</td>
<td>6.42</td>
</tr>
<tr>
<td>Peanut shell</td>
<td>34.32</td>
<td>4.84</td>
</tr>
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</table>
EXPERIMENTAL RESULTS

Flame morphology and microstructures

A series of dust explosion experiments using poplar sawdust and peanut shell dust with a mass density of 1000 g/m$^3$ are conducted using an open-space experiment apparatus. The biomass dust and suppressant powder are fully mixed prior to being dispersed and ignited.

Figure 3–4 shows a typical series of high-speed photomicrographs of the flame propagation in 50–70 μm biomass and 50–70 μm biomass / suppressant mixture dust cloud. Results for 70–100 μm biomass are similar, so they are not plotted. As shown in Fig. 3a and 4a, the flame front of biomass dust cloud is nearly regular in shape. As the particles burn, a yellow luminous flame forms behind the flame front, resulting from the formation of heated soot particles and the combustion of char. Compared with peanut shell dust, poplar sawdust has a stronger flame luminous intensity and a faster flame propagation velocity. Flame morphology and flame colour could change with the addition of suppressants. Fig. 3b and 4b show that with the addition of NaHCO$_3$, the flame colour changes to luminous yellow as sodium light. With the addition of NH$_4$H$_2$PO$_4$, the flame luminous intensity of biomass dust cloud becomes weak, and the flame colour changes to the dark yellow as ammonia burns (Fig. 3c and 4c). As shown in Fig. 3d and 4d, after adding 62.5 g/m$^3$ NaHCO$_3$, the flame morphology becomes irregular and discrete, and the flame cannot propagate to the edge of the
combustion space. By comparison, with addition of 62.5 g/m$^3$ NH$_4$H$_2$PO$_4$, the flame propagation of biomass dust cloud is still continuous, but has a considerably slower flame speed. After adding an appropriate amount of NH$_4$H$_2$PO$_4$, the flame morphology could become irregular and discrete, and the flame cannot propagate continuously. Therefore, NaHCO$_3$ is more effective than NH$_4$H$_2$PO$_4$ for flame suppression of pulverized biomass dust explosion.

By using high-speed photography with microscopic lens, the flame microstructures are revealed. As shown in Fig. 5a, the flame structure of poplar sawdust is smooth and continuous with a regular shape. The biomass combustion is dominated by the volatile combustion, since the characteristics of biomass are high volatile matter and low carbon content [18]. It can be inferred that poplar sawdust particles have been completely pyrolyzed in the preheat zone. Peanut shell particles forms a complicated structure, which consists of gas phase flame and numerous small yellow spots (Fig. 5b). The devolatilization of biomass generates char and volatiles. It can be extrapolated that small yellow spot flame is formed by the combustion of char. With addition of NaHCO$_3$, the gas phase flame and pyrolysis process of biomass are weakened (Fig. 5c and 5d). Bright envelope volatile flame around the biomass particles followed with char burnout is observed. As shown in Fig. 5e and 5f, gas phase flame without spot flames forms in the flame front. With the addition of NH$_4$H$_2$PO$_4$, the flame structure is smooth and continuous, but the flame luminous intensity becomes weak. Previous study [19] demonstrates that NH$_4$H$_2$PO$_4$ decomposes at 210°C with evolution of NH$_3$ (NH$_4$H$_2$PO$_4$ → H$_3$PO$_4$ + NH$_3$). It can be extrapolated that NH$_4$H$_2$PO$_4$ particles are pyrolyzed in the preheat zone, and that premixed NH$_3$/air flame are subsequently formed after the flame front passes through.

Flame propagation velocities

Figures 6–7 show the flame propagation velocity for poplar sawdust and peanut shell dust undoped and doped with NaHCO$_3$ and NH$_4$H$_2$PO$_4$. The flame propagation velocity can be determined by examining the movement of the flame front. The flame edges were recognized through a MATLAB program based on the Roberts operator, which was an image edge detection algorithm. It can be seen that the flame propagation velocity is not constant but pulsating. The flame–speed oscillation is attributed to the velocity slip between gases and particles near the flame front, which leads to the variations in local dust concentration and periodically flame-speed oscillations [20, 21].

As shown in Fig. 6, the average flame propagation velocities of 50–70 µm poplar sawdust and peanut shell dust are 1.02 m/s and 0.72 m/s, respectively. The overall burning rate of biomass dust is considerably high, resulting from the rapid release of volatiles and the high porosity of the char particles [1]. The average flame propagation velocity decreases as the concentration of suppressant increases. When the concentration of NaHCO$_3$ is 25 g/m$^3$ and 50 g/m$^3$, the average flame
propagation velocities of 50–70 μm poplar sawdust reduces by approximately 37% and 64%, respectively, the average flame propagation velocities of 50–70 μm peanut shell dust reduces by approximately 43% and 61%, respectively. When the concentration of NH₄H₂PO₄ is 50 g/m³ and 75 g/m³, the average flame propagation velocities of 50–70 μm poplar sawdust reduces by approximately 44% and 59%, respectively, the average flame propagation velocities of 50–70 μm peanut shell dust reduces by approximately 35% and 58%, respectively. In addition, with an increase of suppressant concentration, more heat is absorbed by the decomposition of suppressant powder. Burning rate of biomass particles also slows down gradually, resulting in the decrease of the amplitude in the velocity oscillation.

By comparing Fig. 6 and Fig. 7, it is apparent that the flame propagation velocities of 100–200 μm biomass dust clouds are slower. Gao et al. [17] reported that the average velocity of the flame propagation is a function of the particle size of biomass particles. Previous work has shown that the biomass combustion process consists of heating and drying; devolatilization producing char and volatiles, where the volatiles consist of tars and gases; and combustion of the volatiles and char [22]. Coarser biomass particles have the slow rates of drying, pyrolysis, volatile combustion, char formation, and char combustion. In addition, the highly volatile materials have a faster flame speed. When the concentration of suppressant is 50 g/m³, the average flame propagation velocity of 70–100 μm poplar sawdust reduces by about 54% for NaHCO₃ addition and decreases by about 37% for NH₄H₂PO₄ addition, the average flame propagation velocity of 70–100 μm peanut shell dust reduces by about 46% for NaHCO₃ addition and decreases by about 33% for NH₄H₂PO₄ addition. It appears that NaHCO₃ is more effective than NH₄H₂PO₄ for flame suppression of pulverized biomass dust explosion.

Figure 8 presents the average flame propagation velocities of doped flames as a function of suppressant concentration, the dash line representing the flame is discrete and the flame edge cannot be extracted. Results show that the average flame propagation velocity decreases with the increase

![Fig. 6. Flame front position and flame propagation velocity of 50–70 μm biomass/suppressant mixture.](image-url)
in the suppressant concentration. As shown in Fig. 10a, when the concentration of NaHCO₃ is 87.5 g/m³ and 100 g/m³, respectively, the flame of 50–70 μm poplar sawdust and peanut shell dust can be suppressed completely. The minimum suppression concentrations of NH₄H₂PO₄ for 50–70 μm poplar sawdust and peanut shell dust fire are 125 g/m³ and 150 g/m³. By comparison, the concentration of suppressant that required to suppress 70–100 μm biomass dust fire is lower. The minimum suppression concentrations of NaHCO₃ for 70–100 μm poplar sawdust and peanut shell dust fire are 75 g/m³ and 87.5 g/m³, respectively. The minimum suppression concentrations of NH₄H₂PO₄ for 70–100 μm poplar sawdust and peanut shell dust fire are 100 g/m³ and 125 g/m³. As it is apparent from the above results, the amount of NaHCO₃ that required to prevent the pulverized biomass dust explosion is lower than for NH₄H₂PO₄.

![Fig. 7. Flame front position and flame propagation velocity of 70–100 μm biomass/suppressant mixture.](image)

![Fig. 8. Average flame propagation velocity of (a) 50–70 μm biomass/suppressant mixture and (b) 70–100 μm biomass/suppressant mixture.](image)

### Flame temperatures

Flame temperatures of undoped and doped flames are shown in Fig. 9 and Fig. 10. It can be seen
that the flame temperature has an apparent increase when the flame touches the junction of the thermocouple. The flame temperature reaches the peak value rapidly, and then begins to decline due to the heat loss from the postreaction zone. The maximum flame temperature decreases significantly with the concentration of suppressant increases.

![Flame temperatures of 50–70 μm biomass/suppressant mixture.](image)

**Fig. 9.** Flame temperatures of 50–70 μm biomass/suppressant mixture.

![Flame temperatures of 70–100 μm biomass/suppressant mixture.](image)

**Fig. 10.** Flame temperatures of 70–100 μm biomass/suppressant mixture.
Part 4. Gas and Dust Explosions

Efficient decomposition of suppressant particles could absorb the heat released from biomass flame, which leads to a lower flame temperature. The characteristic times of devolatilization and combustion of biomass particles also become longer, and then the flame propagation velocities of biomass/suppressant mixture become lower. Thereby, the position at which the temperature begins to increase for biomass/suppressant mixture become farther to the origin of the coordinate system, and the rise rate of temperature of biomass/suppressant mixture is generally lower than that of pure biomass dust.

Experimental data show that poplar sawdust and peanut shell dust decompose at the temperature range of 150 – 500 °C [17]. By increasing the concentration of suppressants, flame temperature continues to decrease. As the flame temperature drops to approximately 300 °C, the biomass particles in the flame front cannot pyrolyzed completely, biomass dust flame cannot propagate continuously, so that biomass flame becomes discrete and the flame edge cannot be extracted. When flame temperature is lower than the ignition temperature, biomass dust flame cannot continue to propagate, and biomass dust explosion can be suppressed.

Fig. 11. Pyrolysis characteristic of biomass particles and biomass/suppressant mixture.
Analysis of flame suppression mechanism

The thermal effects

The flame inhibition is achieved through two major steps, including thermal effects (particle thermal decomposition) and gas–phase chemical interaction with the flame [10]. As shown in Fig. 11, the pyrolysis characteristics of biomass particles and biomass-suppressant mixture, thermal gravity analysis (TGA) and differential scanning calorimetry (DSC) were conducted with a heating rate of 10 K/min under an air atmosphere.

It can be seen that, the decomposition of NaHCO$_3$ and NH$_4$H$_2$PO$_4$ is a highly endothermic process. The maximum value of endothermic peak decreases significantly with addition of suppressant particles. It is indicated that the thermal stability of biomass particles can be enhanced by the addition of suppressant particles. Fig. 11a shows that the mass loss rate decreases as the amount of NaHCO$_3$ particles increases. However, the maximum mass loss rate increases with the addition of NH$_4$H$_2$PO$_4$ particles at the temperature range of 170–320 °C (Fig. 11b). As flammable gas, the main product of NH$_4$H$_2$PO$_4$ decomposition, NH$_3$ will be formed in the range of 170–300 °C. Therefore, the generation of NH$_3$ has an enhancement effect on biomass particles combustion. As a result, compared to NH$_4$H$_2$PO$_4$, NaHCO$_3$ has a more effective suppression capacity against the flame of biomass dust explosion.

Gas–phase chemical suppression mechanism

The heat of biomass combustion is generated during volatile and char burning. Since biomass features higher volatiles, about 70% of the heat of the biomass combustion is contributed to the volatile content of the biomass [18]. Hence, the biomass combustion process is dominated by the gas–phase volatile combustion. The gaseous products of biomass pyrolysis mainly consists of hydrocarbon, CO and CO$_2$. H atoms are significantly important in flame propagation, since the principal chain branching reaction in hydrocarbon flames is H + O$_2$ → OH + O. Na–containing species and P–containing species have long been known to be capable of flame suppression, which attribute to a gas–phase chemical interaction with the flame [7, 10]. As chemically active flame suppressant, gas–phase product decomposed by NaHCO$_3$ and NH$_4$H$_2$PO$_4$ acts catalytically on key flame radicals (H and O atom and OH radicals). Therefore, biomass flame suppression by NaHCO$_3$ and NH$_4$H$_2$PO$_4$ is likely to be achieved through a homogeneously gas–phase suppression mechanism.

Previous studies [10, 16] have proposed kinetic models of NaOH as the main gaseous agent. Na$_2$CO$_3$ generated by decomposition of NaHCO$_3$ decomposes further to Na$_2$O, and then Na$_2$O reacts with water vapor with formation of NaOH. Previous work [10, 15, 23] found that Na compounds promote catalytic recombination of radicals:

NaOH + H <=> Na + H$_2$O \hspace{2cm} (R1)
NaOH + OH <=> NaO + H$_2$O \hspace{2cm} (R2)
Na + OH + M <=> NaOH + M \hspace{2cm} (R3)

It can be seen that R1 and R3 form a catalytic cycle where the net effect is that H and OH recombine to form H$_2$O. Decomposition of NH$_4$H$_2$PO$_4$ was represented in the kinetic model by an overall chemical processes: NH$_4$H$_2$PO$_4$ → H$_3$PO$_4$ + NH$_3$. The thermal decomposition of H$_3$PO$_4$ was simplified on the basis of a single step approach: H$_3$PO$_4$ → HPO$_3$ (HOPO$_2$) + H$_2$O [24]. Many authors [7, 14, 25] proposed that small phosphorus compounds decomposed by NH$_4$H$_2$PO$_4$, such as H$_2$PO$_4$, HPO$_3$, HPO$_2$, and PO$_2$, also promote key radicals recombination:

PO$_2$ + H + M <=> HPO$_2$ + M \hspace{2cm} (R4)
Part 4. Gas and Dust Explosions

\[ \text{HPO}_2 + \text{OH} \leftrightarrow \text{H}_2\text{O} + \text{PO}_2 \]  \quad (R5)
\[ \text{PO}_2 + \text{OH} + M \leftrightarrow \text{HPO}_3 + M \]  \quad (R6)
\[ \text{HPO}_3 + H \leftrightarrow \text{H}_2\text{O} + \text{PO}_2 \]  \quad (R7)

R4 and R5, R6 and R7 form two main suppression cycles. As can be seen in both cycles, the P-containing species are acting catalytically to recombine H and OH to form H\(_2\)O. As a result, as gaseous agents, Na–containing and P–containing compounds are liberated and act as radical species scavenger reducing heat release, hence flame speed and a lower flame temperature.

**CONCLUSIONS**

Flame suppression of pulverized biomass dust explosion by NaHCO\(_3\) and NH\(_4\)H\(_2\)PO\(_4\) has been investigated experimentally. Poplar sawdust and peanut shell dust with two size distribution of 50–70 \(\mu\)m and 70–100 \(\mu\)m were selected as experimental sample. The conclusions obtained were as follows:

After adding suppressant, flame morphology and flame colour changed. With the concentration of suppressant increased, flame morphology became irregular and discrete. With addition of NaHCO\(_3\), bright envelope volatile flame around the biomass particles followed with char burnout was observed, the gas phase flame and pyrolysis process of biomass were weakened. With the addition of NH\(_4\)H\(_2\)PO\(_4\), the flame structure was smooth and continuous, but the flame luminous intensity became weak.

The concentration of NaHCO\(_3\) that required to suppress the aluminum dust explosion was lower in comparison with NH\(_4\)H\(_2\)PO\(_4\). The average flame propagation velocity and flame temperature significantly decreased with the concentration of suppressant increased.

Decomposition of NaHCO\(_3\) and NH\(_4\)H\(_2\)PO\(_4\) was a highly endothermic process. The thermal stability of biomass particles could be enhanced by the addition of suppressant particles. Na–containing and P–containing species were formed under high temperature inside the flame front, which could alter flame chemistry by catalytic recombination of key radicals and led to less heat release, a lower flame speed and a lower flame temperature.

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**REFERENCES:**


