

Article

Study on the Explosion Characteristics and Pyrolysis Mechanism of Typical Wood Dust

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Abstract

This experiment investigated changes in the key parameters of explosion pressure peak ($P_{\max}$) and pressure rising rate peak $((dP/dt)_{\max})$ and flame propagation characteristics of wood dust explosion (pine, cypress and poplar dusts) under different wood dust diameters and concentrations using a 20 L spherical explosion apparatus. Combined with thermogravimetric analysis and Fourier transform infrared spectroscopy, the pyrolysis behavior of different wood dusts and the generation mechanism of gas-phase flammable products were elucidated. The results indicate that the type, wood dust diameter and concentration of dust had a great impact on the severity of explosion. As the dust diameter decreased, $P_{\max}$ and $(dP/dt)_{\max}$ both showed a trend of first increasing and then decreasing. Among them, the explosion pressure and K_{st} value of 300-mesh poplar wood were the highest, reaching 0.72 MPa and 11.6 MPa·m/s. The flame propagation characteristics were comprehensively influenced by dust morphology, volatile matter content and concentration. Among them, the peak height of flame propagation and its instantaneous velocity were obviously higher for poplar and pine wood dusts than those of cypress wood due to the high carbon and volatile matter contents. The overall quality loss rate of poplar dust in the thermogravimetric experiment was the highest, while its pyrolysis reaction rate was also the highest. The mass loss rate of 140-mesh poplar wood reached 90.5%, and the thermal decomposition reaction rate reached 19.48%/min. The large number of alkanes, aldehydes and ketones, as well as gases such as CO and CO₂ generated during the pyrolysis, provided the material basis for the chain reaction of a dust explosion. This study systematically elucidated the differences in explosion parameters, flame propagation behavior, and pyrolysis processes of different wood dust, thus providing theoretical support for their explosion risk assessment and safety protection.

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1. Introduction

The number of enterprises involved in dust processing and manufacturing is increasing with the continuous advancement of industrialization. Flammable dust is prone to escape and is suspended in the air during production. As the concentration reaches a certain range and forms a dust cloud, it is highly likely to cause dust explosion accidents, seriously threatening industrial production and life safety. Yuan et al. [1] collected and

analyzed more than 2000 dust explosion incidents that occurred globally between 1785 and 2012. They found that the food and wood processing industries are the most affected sectors, with wood dust accounting for approximately 17% of the total incidents; moreover, the frequency of accidents is closely related to the level of economic development. There are various types of dust explosions in industrial and commercial enterprises and they exhibit different explosion characteristics. Compared to gas explosions, a dust explosion has the characteristics of a long reaction time and large heat release, further resulting in greater losses. Mastering the characteristics of dust explosions can provide a theoretical basis for the prevention and control of dust explosion accidents.

Scholars have conducted corresponding research on the influencing factors of dust explosion characteristic parameters. Saeed et al. [2] investigated the effect of dust diameter on biomass dust minimum explosible concentration (MEC), and the results showed that the severity of dust explosions evidently increased as its diameter decreased. Guo et al. [3,4] found that the dust cloud minimum ignition temperature of dust clouds (MITC) of phthalic acid (PTA) presented an initial increase and then a decrease as the dust diameter decreased, while the MEC showed a gradually decreasing trend. Alba et al. [5] proposed that the ignition probability and explosion risk evidently increased as the dust diameter and the moisture content decreased. Chen et al. [6] tested the explosion characteristics of redwood dust through experiments, and the results showed that its minimum ignition energy first improved and then decreased with the increase in concentration, and increased with the enlargement of dust diameter. Pang et al. [7] pointed out that the flame propagation velocity showed a trend of first increasing and then decreasing as the concentration of sawdust increased. Meanwhile, the combustion time was obviously prolonged with the increase in dust diameter, and the flame propagation velocity was continuously decreased. Marková et al. [8] proposed that the temperature at which beech wood dust underwent the thermal decomposition was evidently reduced as the diameter reduced, and the risk of explosion also continued to increase. Yang et al. [9] found that the thermal decomposition of small diameter leaf red pigment dust was more complete and released more heat, which posed a higher risk of explosion. He et al. [10] pointed out that the lower explosive limit concentration and pressure peak of cork powder were all improved with the increase in initial pressure. Dong et al. [11] proposed that the flame brightness, velocity and temperature peaks all displayed a trend of first increasing and then decreasing with the improvement of wood dust concentration.

Currently, scholars have conducted a relatively systematic study on the explosion characteristics of typical flammable dust and obtained corresponding research results. Many studies have demonstrated that particle size distribution and concentration are critical parameters governing the explosibility of wood dust. Calle et al. [12] used a 20 L explosion sphere and found that finer particles produce higher maximum explosion pressures and rates of pressure rise; they also developed a kinetic and thermodynamic model to describe the pressure evolution during the explosion. Di Benedetto et al. [13] proposed a comprehensive mathematical model that incorporates internal/external heating, devolatilization, and volatile combustion, thereby quantifying the effect of particle diameter on the deflagration index. Lee et al. [14] conducted 20 L explosion tests on particleboard dust and introduced novel analytical approaches based on thermal decomposition rate and mass loss rate, showing that these two parameters correlate better with explosion behavior than dust concentration alone. Santamaria Herrera et al. [15] systematically characterized the particle size distribution, moisture content, and microstructure of various wood dusts, determining their minimum explosive concentration and ignition temperatures, they concluded that finer particles and lower moisture contents substantially increase the explosion hazard. Understanding the pyrolysis behavior of wood is fundamental to elucidating the generation mechanism of flammable volatiles during dust explosions.

Poletto et al. [16] performed thermogravimetric analyses on four Brazilian wood species and found that a higher content of extractives accelerates degradation, whereas higher cellulose crystallinity inhibits decomposition, suggesting that well-ordered cellulose regions hinder heat diffusion. Tapasvi et al. [17] conducted TGA experiments on Norwegian spruce and birch using nine different temperature programs; they established a kinetic model comprising three pseudo-components and validated its applicability to torrefaction conditions. Atreya et al. [18] focused on the influence of particle size and shape via both experiments and numerical simulations. Their results show that at high temperatures, small, slender particles pyrolyze faster, produce less char, and generate more volatiles findings that are directly relevant to explosion hazard assessment. Recent comprehensive reviews have deepened the understanding of wood dust explosions. Zhou et al. [19] provided a thorough overview of the causes, influencing factors, mechanisms, modeling approaches, and environmental and health impacts of wood dust explosions, identifying dust collection and conveying systems as the most critical equipment in terms of explosion vulnerability. Kien et al. [20] specifically examined dust generated from wood pellets a widely used biomass fuel by measuring key parameters. They introduced a two-dimensional risk matrix and classified wood-pellet dust as having a high explosion risk, comparable to that of polyethylene and aluminum powders, and emphasized the need for enhanced protective measures in biomass co-firing power plants.

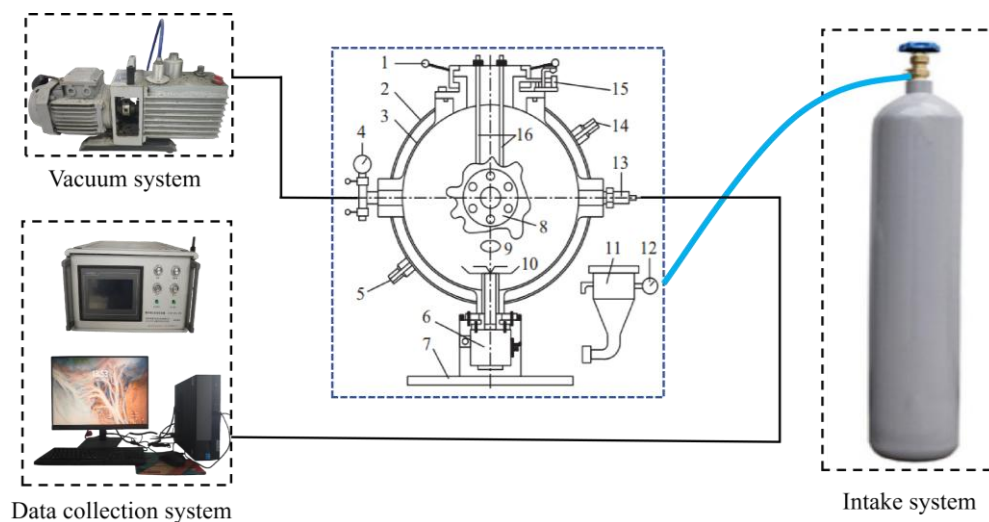
However, systematic research on the explosion characteristics of wood dust was still relatively insufficient, especially in terms of the influence factors such as dust type, diameter distribution and pyrolysis characteristics on its explosion behavior, which lacked in-depth analysis. Research indicates that there were significant differences in explosion intensity and behavior among different types and diameter of dust, which had important implications for the rational selection and the structure design of explosion protection equipment. Based on this, three typical types of wood dust (pine, cypress and poplar) as research objects were selected, and a combination of experimental research and theoretical analysis was adopted to systematically study the explosion characteristics of wood dust. The influences of concentration and diameter of three types of wood dusts on key parameters such as the explosion pressure peak ($P_{\max}$), pressure rise rate peak $(dp/dt)_{\max}$, and flame propagation characteristics were researched, further providing the scientific basis for the formulation of dust explosion prevention standards and the design of safety protection facilities in wood processing and related industries.

Compared with previous studies, this work systematically investigates the effects of wood type, particle size, and dust concentration on the explosion characteristics of wood dusts. In addition to conventional explosion parameters, the flame propagation behavior and instantaneous flame velocity of different wood dust clouds are further analyzed to reveal the dynamic combustion process. Moreover, the thermal decomposition characteristics and thermal stability of the three wood dusts are clarified, and the relationship between pyrolysis behavior, component differences, and explosion severity is discussed. Therefore, this study provides a more comprehensive understanding of the influence mechanism of wood dust explosion characteristics and offers a theoretical basis for dust explosion prevention in wood processing industries.

2. Experimental Apparatus and Materials

2.1. Experimental Apparatus

The experiment was conducted using 20 L spherical explosion testing system (ETD-20L-DG2, The industrial explosion protection research institute of Northeastern University, Shenyang, China), the system and its components are shown in Figure 1. The system consisted of a 20 L spherical vessel, a vacuum extraction system, an ignition system, an automatic gas distribution system, a data acquisition system, and a control system. The detailed information was annotated in Figure 1. Ignition energy: 2 kJ, dust dispersion pressure: 0.06 MPa, ignition delay time: 60 ms. Based on this device, the dust explosion parameters could be accurately measured. The flame propagation characteristic testing system consisted of a Hartmann tube device, a high-speed camera, and a data acquisition device (Phantom Camera Control, Software Revision: 2.8.761.0), as shown in Figure 2. The Hartmann tube device was composed of visual tube, the high-pressure output device, the ignition system, the air compressor and the controller, etc. (MIE-004-CA, Chilworth Technology Ltd., Southampton, Hampshire, UK). The Hartmann tube device had an inner diameter of 68 mm and a height of 300 mm, with a volume of approximately 1.2 L. To observe the characteristics of flame propagation, the top of pipeline was set as an opening. The bottom of the pipeline was a stainless-steel base, which was fixed to the base by a buckle. The ignition electrode (ignition energy: 5 kJ) was symmetrically set and located 110 mm away from the bottom of the pipeline. The high-speed camera (Phantom V7.3, Vision Research, Inc. Wayne, NJ, USA) was adopted to record the whole process of flame shape changes (acquisition frequency: 1000 Hz/s).



- 1.Sealing cap; 2.Outer layer of the jacket; 3.Inner layer of the jacket; 4.Vacuum gauge; 5.Inlet;
6.Quick-action valve; 7.Base; 8.Observation window; 9.Vacuum port; 10.Nozzle; 11. Storage bin;
12.Pressure gauge; 13.Pressure sensor; 14.Outlet; 15.Safety limit valve; 16.Ignition pole

Figure 1. 20 L spherical explosion testing system.

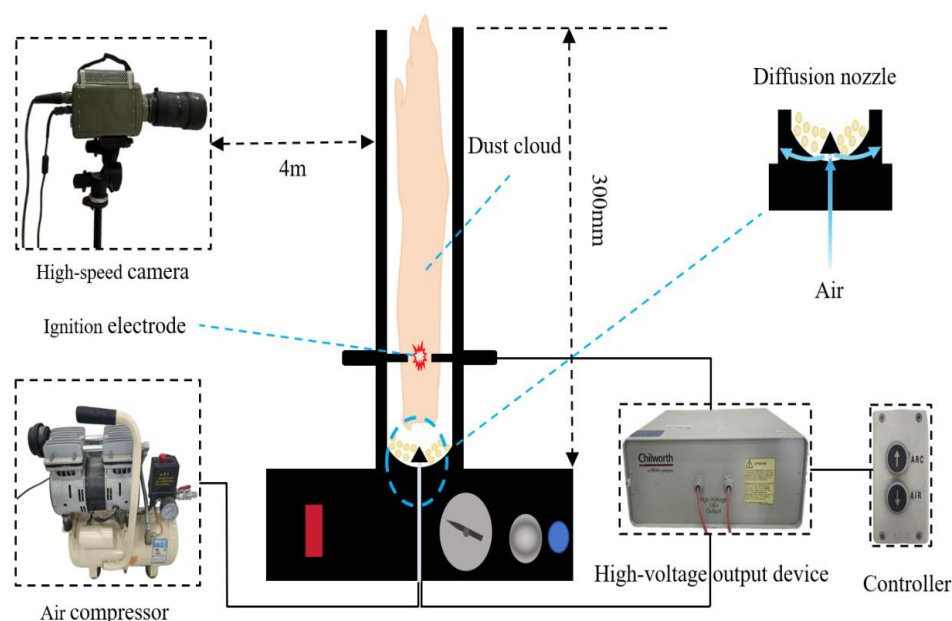


Figure 2. Flame propagation testing system. ¹ The blue solid arrow indicates the airflow direction; the blue dashed lines identify the corresponding components; the black solid lines represent the connection paths between the experimental devices; and the black dashed double-headed arrows indicate the relevant distances or dimensions. The dashed boxes distinguish the individual components of the experimental system.

2.2. Material Characterization

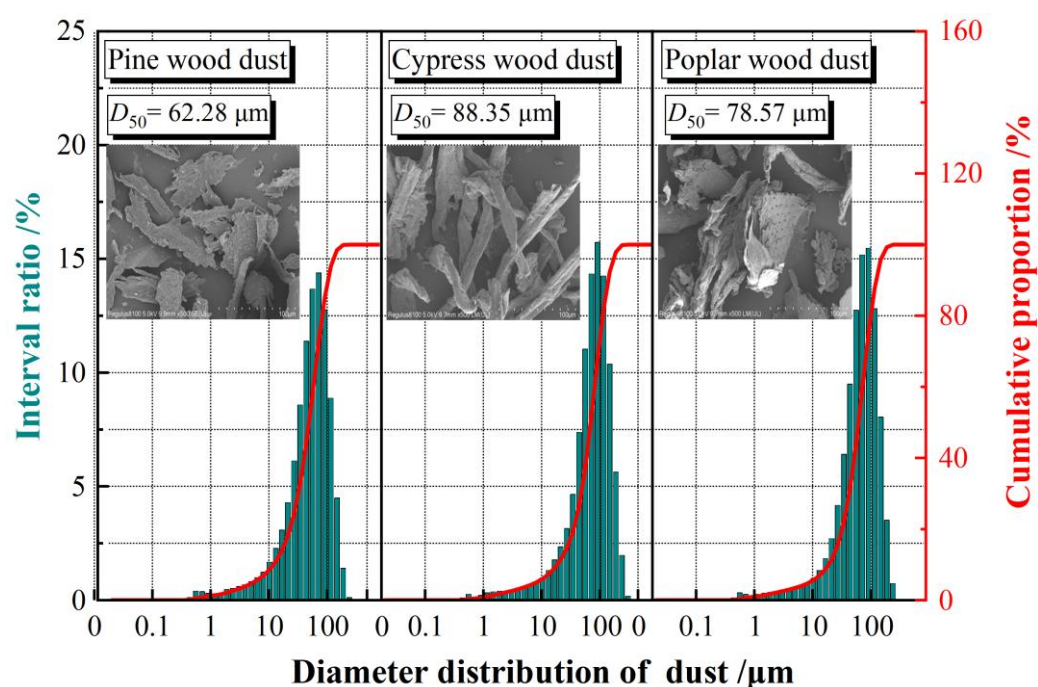
Three types of wood dust were used during the experiment (poplar dust, pine dust and cypress dust) and the elemental composition was shown in Table 1. Table 1 displays that there were significant differences in the elemental composition of three wood dusts. Pine and poplar wood dusts had higher carbon and volatile contents. Nevertheless, the poplar dust had the lowest ash and moisture contents, which was conducive to the rapid generation of flammable gas and release of heat. By comparison, the ash and fixed carbon contents of cypress dust were higher, which would have a certain inhibitory effect on the explosion reaction. Before the experiment, three types of wood dust were crushed and sieved to obtain dust diameter of 140 mesh number (m) ($80\ \mu\text{m}$ to $104\ \mu\text{m}$), 200 mesh ($50\ \mu\text{m}$ to $75\ \mu\text{m}$) and 300 mesh ($37.5\ \mu\text{m}$ to $50\ \mu\text{m}$), respectively. Meanwhile, the samples were vacuum-dried at $60\ ^\circ\text{C}$ for 20 h to remove moisture. The laser particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd., Malvern, UK) was used to test the diameter distribution of the samples. Detailed data were shown in Table 2. The sample was microscopically measured using a scanning electron microscope (Hitachi Regulus 8100, Hitachi High-Tech Corporation, Tokyo, Japan), as shown in Figure 3. It is clear that the pine wood dust was in the form of irregular sheet-like strips with a rough surface and the irregularly arranged elliptical small holes. The cypress dust was in the form of slender strips with a smooth surface and small fibers adhering. The interior was solid without pores, and the fibers were intertwined with each other. The poplar dust had an irregular sheet-like long strip structure with a rough surface and regularly arranged circular small holes.

Table 1. Composition of elements in pine, cypress and poplar dusts.

Experimental Sample	Element Composition/%				Industrial Analysis/%			
	C	H	O	N	Moisture	Ash Content	Volatile Matter	Fixed Carbon
Pine wood dust	47.13	6.16	44.50	0.04	6.72	1.67	79.17	12.44
Cypress wood dust	43.97	7.69	42.24	0.05	7.38	2.20	74.30	16.12
Poplar wood dust	52.72	6.13	40.65	0.04	5.75	0.76	78.95	14.54

Table 2. Dust diameter distribution of experimental samples.

Sample		D ₁₀ /μm	D ₅₀ /μm	D ₉₀ /μm
Pine wood dust	140 mesh	25.81	98.62	201.4
	200 mesh	15.35	62.28	130.6
	300 mesh	8.00	31.83	78.58
Cypress wood dust	140 mesh	33.93	125.3	243.9
	200 mesh	23.69	88.35	176.8
	300 mesh	10.85	40.09	106.0
Poplar wood dust	140 mesh	28.39	93.88	182.3
	200 mesh	24.09	78.57	156.2
	300 mesh	13.72	45.90	97.23

**Figure 3.** Particle size distribution and SEM images of pine wood dust, cypress wood dust, and poplar wood dust.

2.3. Thermogravimetric and Infrared Analysis Methods

The thermal decomposition behavior of the three wood dusts was investigated using a simultaneous thermal analyzer (TGA/DSC 3+, Mettler-Toledo GmbH, Greifensee, Switzerland). The heating range was from 50 °C to 800 °C under a nitrogen atmosphere with a gas flow rate of 20 mL/min and a heating rate of 20 °C/min. Fourier transform infrared spectrometer (Nicolet iS20 FTIR, Thermo Fisher Scientific, Madison, WI, USA) was used to detect the infrared absorption spectrum changes in the sample's transmittance with wavelength. The infrared spectra of three wood dusts were measured using the KBr pellet method, with wave numbers ranging from 4000 cm⁻¹ to 400 cm⁻¹. Each sample was tested four times, and the average value was taken.

3. Results and Discussion

3.1. Analysis of Dust Explosion Severity

3.1.1. Analysis of Dust Explosion Pressure

According to GB/T 16426-1996 "Determination Method for Maximum Explosion Pressure and Maximum Pressure Rise Rate of Dust Clouds", the influences of concentration and diameter on P_{max} and $(dp/dt)_{max}$ of three wood dust explosions were researched. Figure 4 shows the comparisons of pressure and its rising rate histories for three types of dust explosions ($m = 140$; $C = 1000 \text{ g/m}^3$). It is clear that the peaks of poplar dust explosion pressure and its rising rate histories were both the highest at the same concentration, followed by the pine and cypress woods. P_{max} was decreased from 0.63 MPa to 0.54 MPa, and $(dp/dt)_{max}$ was also decreased from 20.5 MPa/s to 9.3 MPa/s. This indicates that the poplar dust had the higher explosion reactivity. Based on Figure 5 and Table 3, it can be concluded that P_{max} of wood dust could be greatly affected by the type and diameter of the dust. Overall, P_{max} showed a characteristic of first increasing and then gradually decreasing as the dust concentration improved. At lower concentrations, an increase in dust concentration was beneficial for the release of volatile matter, thereby increasing the pressure. However, there was a relative lack of oxygen in the system and the heat shielding effect between particles was enhanced at a higher concentration, which limited the explosion reaction and led to a decrease in pressure. Therefore, the variation in P_{max} among different wood dusts was not solely governed by particle size but was also closely associated with the inherent physicochemical characteristics of the wood species. Under three different mesh numbers, P_{max} of corresponding poplar, pine and cypress dusts was decreased sequentially. This indicates that the type of wood had an evident impact on pressure. From the perspective of diameter, P_{max} of three types of wood dusts was all obviously increased as the mesh number was increased from 140 to 300. Among them, the pine wood dust was increased from 0.59 MPa to 0.67 MPa, the cypress wood dust was increased from 0.55 MPa to 0.71 MPa, and the poplar wood dust was also increased from 0.67 MPa to 0.72 MPa. This indicates that reducing diameter could greatly enhance the explosion strength of wood dust, mainly because smaller particles had a larger specific surface area and a shorter pyrolysis path, which was conducive to the rapid release of volatile flammable components and the full progress of gas–solid phase reactions.

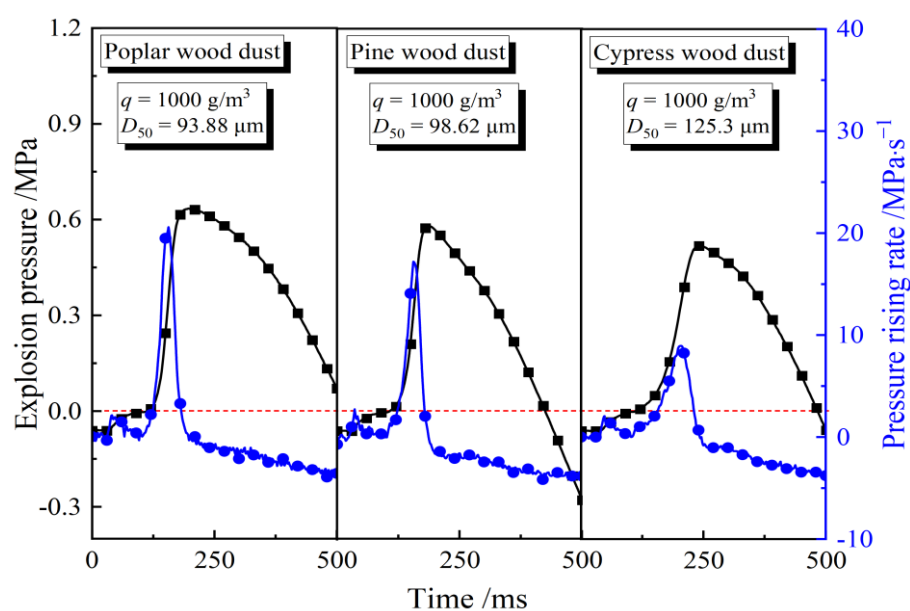


Figure 4. Comparison chart of explosion pressure and the rate of pressure increase for 140-mesh wood powder dust.

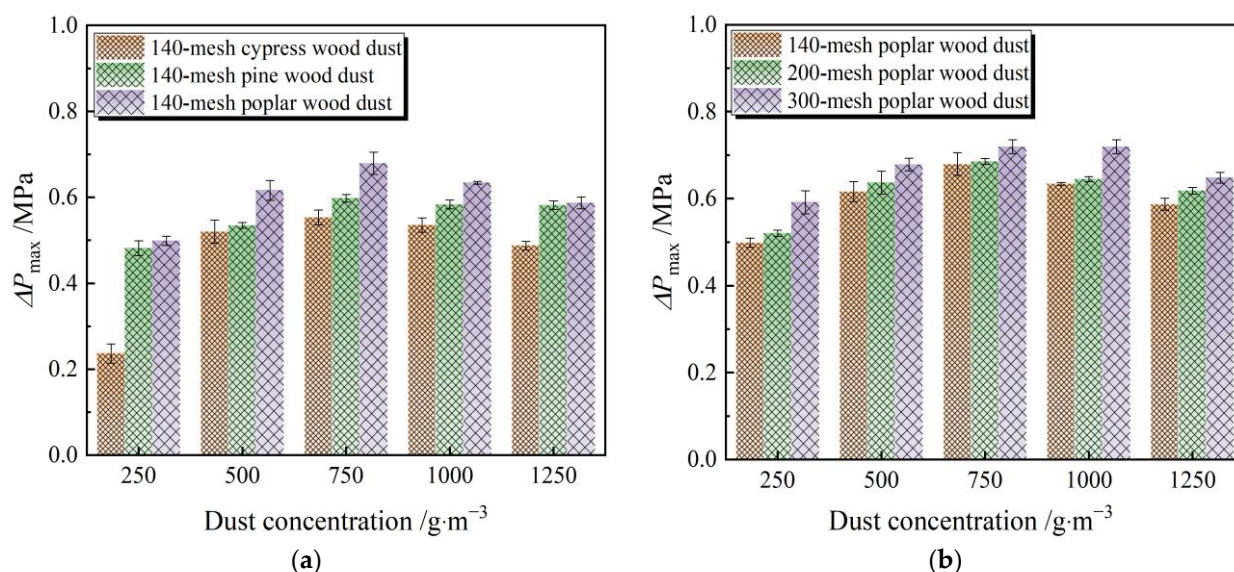


Figure 5. (a) The influence of concentration on the P_{max} of 140-mesh wood powder; (b) the influence of concentration on the P_{max} of different particle sizes of poplar wood.

Table 3. Explosion pressure peak and corresponding dust concentration.

Sample	P_{max}/MPa	Dust Concentration/ $\text{g}\cdot\text{m}^{-3}$
140-mesh pine wood dust	0.59	750
200-mesh pine wood dust	0.66	1000
300-mesh pine wood dust	0.67	1000
140-mesh cypress wood dust	0.55	750
200-mesh cypress wood dust	0.64	1000
300-mesh cypress wood dust	0.71	1250
140-mesh poplar wood dust	0.67	750
200-mesh poplar wood dust	0.68	750
300-mesh poplar wood dust	0.72	750

The concentration differences corresponding to the pressure peak of three types of wood dust explosions were related to their elemental composition. The poplar dust had the highest carbon content and lowest oxygen content, as well as the lowest content of inert components such as moisture and ash, further resulting in a higher proportion of effective combustible components and a stronger heat release rate per unit mass. Therefore, the poplar dust could reach its maximum explosion pressure at lower concentrations. The carbon and volatile matter contents of cypress dust were relatively low, while the moisture and ash contents were high, which slowed down the participation of flammable components in gas-phase explosion reactions. Therefore, a higher dust concentration was needed to compensate for the insufficient effective heat release. As the diameter decreased, the specific surface area of cypress dust was increased, and the volatilization and surface oxidation reactions were also enhanced, further increasing its optimal explosion concentration from 750 g/m^3 to 1250 g/m^3 . The pine wood dust had the highest volatile matter content, which was conducive to the release of flammable gas and propagation of flame in the early stage of explosion. Nevertheless, its carbon and inert component contents were between poplar and cypress, so its optimal concentration was increased from 750 g/m^3 under larger diameter conditions to 1000 g/m^3 under smaller diameter conditions. Overall, the dust with high carbon content, low moisture and ash content was more likely to reach the maximum reaction intensity at lower concentration; dust with weaker

volatile release ability and higher inert components required higher concentrations to achieve sufficient heat release.

3.1.2. Analysis of Pressure Rise Rate

The explosion pressure rising rate peak ($(dP/dt)_{max}$) and explosion index (K_{st}) were important parameters to evaluate the hazard of dust explosion. Figure 6 displays the effects of three wood dust concentrations on $(dP/dt)_{max}$ ($m = 140$). Under a condition of 140 mesh, the poplar dust exhibited the highest rising rate, followed by the pine wood, and the cypress wood had the lowest value. Meanwhile, $(dP/dt)_{max}$ of different wood dust showed an overall trend of first increasing and then decreasing with improving dust concentration. At a lower concentration, an increase in dust concentration could enhance the continuity of flame propagation and the rate of heat release, thereby increasing the explosion reaction rate. However, the reaction rate was limited due to the insufficient oxygen supply and particle heat shielding effect as the concentration was further increased, further leading to a decrease in increase extent of $(dP/dt)_{max}$. Figure 6 shows the effect of mesh number on $(dP/dt)_{max}$ at different poplar dust concentrations. According to Table 4, as the mesh number was increased from 140 to 300, $(dP/dt)_{max}$ and K_{st} of three wood dusts were all evidently improved. Among them, $(dP/dt)_{max}$ of pine wood dust was increased from 17.0 MPa/s to 30.4 MPa/s, the cypress wood was increased from 9.80 MPa/s to 21.6 MPa/s, and poplar wood was evidently increased from 20.5 MPa/s to 42.8 MPa/s. The corresponding K_{st} was also increased from 4.6 MPa·m/s, 2.7 MPa·m/s and 5.6 MPa·m/s to 8.3 MPa·m/s, 5.9 MPa·m/s and 11.6 MPa·m/s, respectively. This was mainly attributed to the increase in specific surface area after the decrease in dust diameter, which accelerated the precipitation of volatile matter and the rate of explosion reaction [21,22]. In addition, $(dP/dt)_{max}$ and K_{st} of poplar dust were evidently higher than those of pine and cypress wood, indicating that poplar dust has a stronger explosion reaction rate.

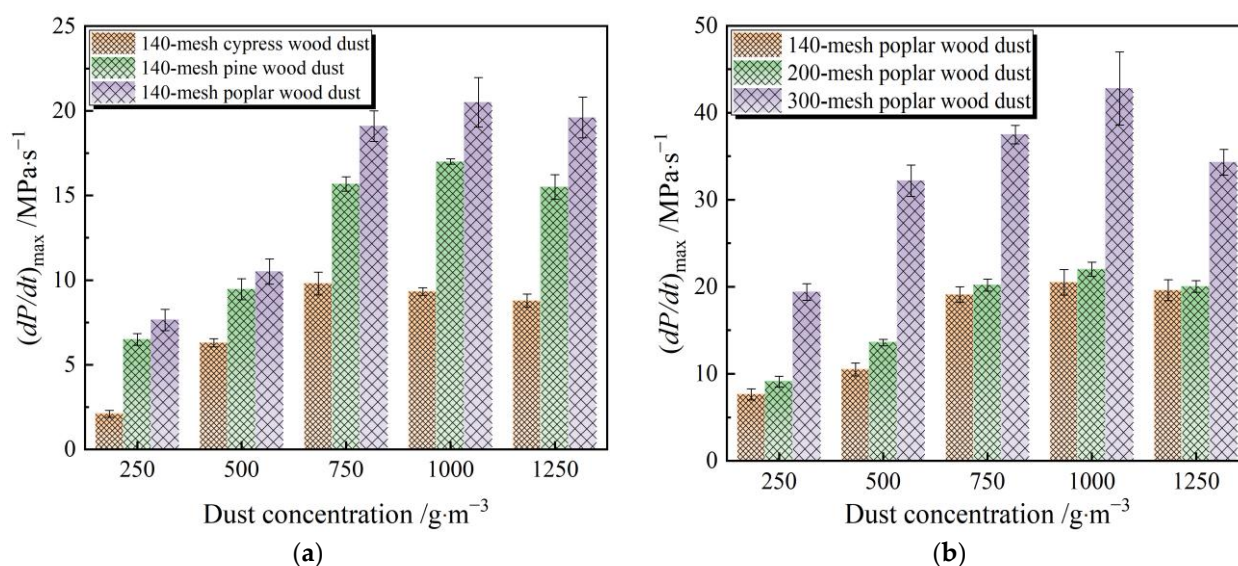


Figure 6. (a) The influence of concentration on the $(dP/dt)_{max}$ of 140-mesh wood powder; (b) the influence of concentration on the $(dP/dt)_{max}$ of different particle sizes of poplar wood.

Table 4. $(dP/dt)_{max}$ and K_{st} under different wood dust explosions.

Sample	$(dP/dt)_{max}/(\text{MPa/s})$	$K_{st}/(\text{MPa}\cdot\text{m/s})$
140-mesh pine wood dust	17.0	4.6
200-mesh pine wood dust	27.3	7.4
300-mesh pine wood dust	30.4	8.3

140-mesh cypress wood dust	9.80	2.7
200-mesh cypress wood dust	19.3	5.2
300-mesh cypress wood dust	21.6	5.9
140-mesh poplar wood dust	20.5	5.6
200-mesh poplar wood dust	22.0	5.9
300-mesh poplar wood dust	42.8	11.6

3.2. Analysis of Flame Characteristics

Mastering the flame propagation characteristics of dust explosion could be beneficial for effectively suppressing explosion accidents. During the experiment, the appearance of electric sparks was believed to have ignited wood dust ($t = 0$ ms). The instantaneous velocity was obtained by taking the derivative of the flame surface over time [23]. Figure 7 inserts the propagation process and velocity history changes in pine wood explosion flame ($P_{\text{spray}} = 0.6$ MPa, $Q = 1500$ g/m³ and $m = 200$). It is clear that the flame of pine wood presented a bright ellipsoidal structure, and its height continued to increase over time. Within the range of 120 to 240 ms, the flame height was evidently increased, and its propagation was relatively stable and developed rapidly during this stage. During the propagation process, the flame continuously expanded upward, and the reaction area continued to enlarge. At 360 ms, the peak height of the flame propagation was approximately 1.2 m. Unlike the monotonic increase in flame height, the instantaneous velocity showed a trend of first increasing and then decreasing over time. The instantaneous velocity of flame was increased rapidly in the initial stage of propagation, reaching its peak at 60 ms. Although there were some fluctuations afterwards, the overall trend showed a downward trend and remained at a lower level in the later stage. This was because the heat release rate of pine wood dust was fast, and the flame front was greatly affected by the expansion and pressure driving effects. Therefore, the spread velocity was relatively fast. As the reaction proceeded, the volatile content of pine wood was rapidly decreased, and the heat loss and propagation resistance inside the system were gradually increased, thus leading to a decrease in the instantaneous velocity.

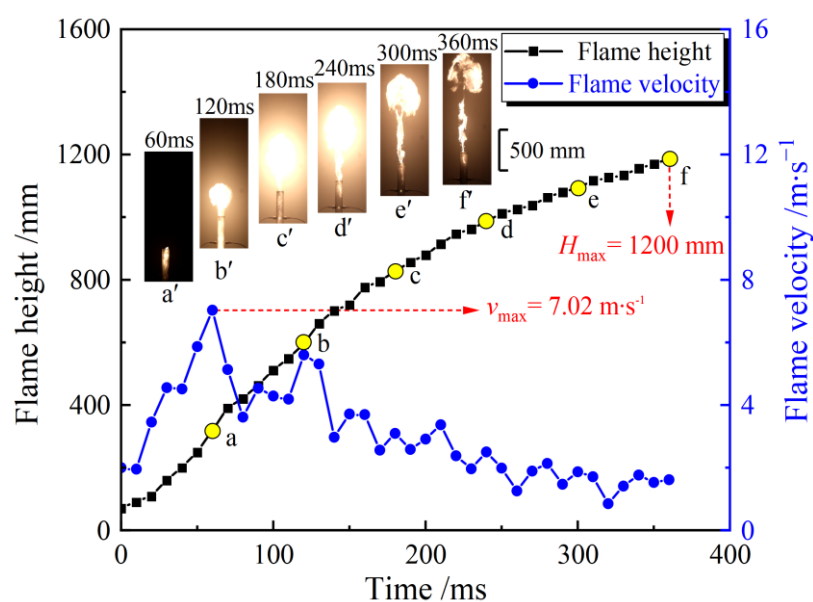


Figure 7. Parameters and image comparison analysis of flame propagation characteristics of 1500 g/m³ 200-mesh pine wood. ¹ Points a – f correspond to the flame-height data at 60, 120, 180, 240, 300, and 360 ms, respectively, and images a' – f' show the corresponding flame morphologies at these time instants.

Table 5 shows the changes in instantaneous velocity peaks and maximum propagation distances for three different dust concentrations and mesh numbers. As the dust diameter decreased, the velocity peak and maximum propagation distance of three dusts all showed an increasing trend, indicating that smaller dust diameter presented stronger flame propagation ability. This was mainly attributed to the increase in specific surface area of dust after the decrease in diameter, the increases in heating and volatilization precipitation rates, and the enhancement in reactions between dusts. The difference between dust types was closely related to their composition [24,25]. The pine wood dust had the highest volatile matter content with 79.17%, which was conducive to the rapid release of combustible volatile products in the early stage. Therefore, the flame propagation height and velocity were evidently increased with the decrease in dust diameter, and the maximum upward height and instantaneous velocity peak at 300 mesh reached 1213 mm and 17.47 m/s, respectively. The volatile matter content of cypress dust was the lowest, while the moisture and ash contents were the highest. The heat absorption of moisture evaporation and the inert dilution of ash weakened the processes of dust ignition and flame propagation. Therefore, the instantaneous velocity peak and maximum propagation distance were both at a relatively low level. The poplar dust had the lowest moisture and ash contents, and the inert heat absorption was also weaker, but its volatile matter content was high. Therefore, it still exhibited a high instantaneous velocity peak at a larger mesh number.

Table 5. Flame propagation height and velocity of nine types of dust specifications.

Sample	140-Mesh Pine Wood Dust	200-Mesh Pine Wood Dust	300-Mesh Pine Wood Dust	140-Mesh Cypress Wood Dust	200-Mesh Cypress Wood Dust	300-Mesh Cypress Wood Dust	140-Mesh Cypress Wood Dust	200-Mesh Cypress Wood Dust	300-Mesh Cypress Wood Dust
$H_{\max}$ (mm)	1070	1180	1213	968	979	991	1000	1038	1073
$v_{\max}$ (m/s)	10.89	16.53	17.47	5.28	7.92	8.91	12.63	14.35	15.81

3.3. Analysis of Thermal Decomposition Characteristic

Thermogravimetric analysis was a characterization of materials thermal stability under high temperature conditions, as shown in Figure 8. It is clear that the TG-DTG-DSC histories of the poplar, pine, and cypress dusts under air atmosphere all exhibited the typical thermal decomposition characteristics. The first stage of TG-DTG was a dehydration stage with minimal quality loss. The second stage was the main pyrolysis stage, where the quality rapidly decreased and the reaction rate reached a peak. Afterwards, the wood dust entered the slow carbonization and residual structure cracking stage. The third stage was the stable stage and did not present a significant weight loss change. The figure indicates that the initial pyrolysis temperatures of poplar, pine and cypress dusts were 211 °C, 216 °C, and 191 °C, respectively. The quality and thermal weight loss rates of poplar wood were especially the highest (90.5% and 19.48%/min), followed by the pine wood (77.9% and 17.23%/min), and the cypress wood was the lowest (75.5% and 14.56%/min). It was related to the composition of wood dust. The lower ash content in wood dust led to less residue after combustion, thus resulting in a higher pyrolysis weight loss rate. Due to the higher volatile matter content, the more gaseous products were released from the thermal decomposition of wood dust, thus leading to a more intense explosion reaction and a greater weight loss rate [26,27]. The higher moisture content resulted in the slower heat transfer rate. Among the three types of wood dust, the poplar dust had a higher volatile matter content and the lowest ash and moisture contents, thus resulting in the highest mass and thermal weight loss rates.

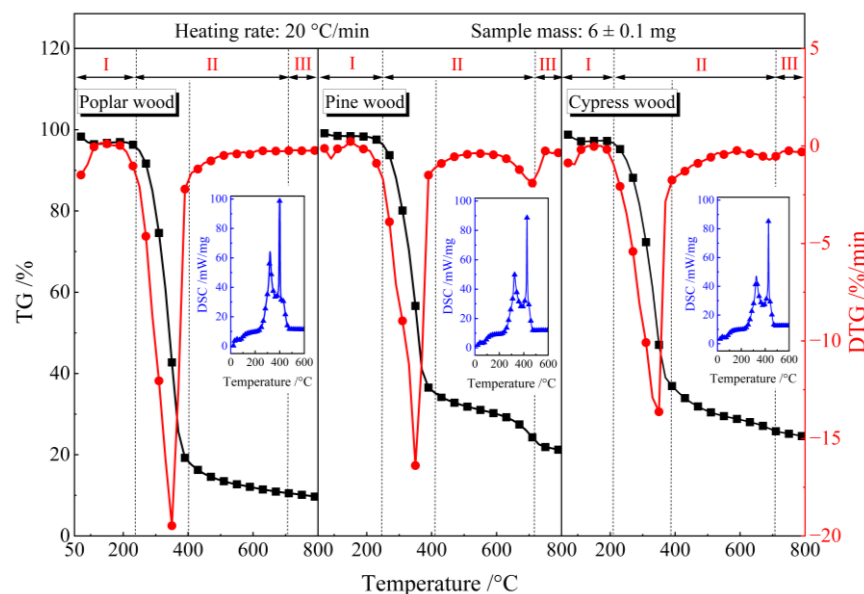


Figure 8. TG-DTG-DSC curves of 140-mesh wood dust.

¹ I, II, and III represent the dehydration stage, the main thermal decomposition stage, and the stable stage, respectively.

In addition, DSC histories of three wood dusts showed a significant exothermic effect. The exothermic peak of DSC corresponded to the same temperature as the weight loss peak of DTG, indicating that the weight loss at this stage was accompanied by a significant exothermic process [28–30]. Among them, the poplar dust exhibited the strongest thermal reactivity and the highest heat flux value (102.63 mW/mg). The thermal decomposition and heat flow rate of three wood dusts directly affected the severity of explosion. In addition, the combined effect of thermal weight loss rate and heat flow rate affected the intensity of wood dust explosion, which in turn affected its pyrolysis characteristics. The figure showed that the poplar dust had a higher quality loss rate and stronger exothermic peak, which made it exhibit the higher explosive reactivity and potential danger. The quality loss rate and heat release peak of cypress wood was the lowest, making its explosion reaction relatively weak. The quality loss rate and heat release peak of pine wood dust was between the two, making its explosion intensity moderate.

3.4. Analysis of Explosion Mechanism

Figure 9 shows the FTIR spectra of three wood dusts. As shown in the figure, three types of wood dusts all exhibited transmittance peaks at 3410 cm^{-1} , 2912 cm^{-1} , 1745 cm^{-1} , 1242 cm^{-1} , 1053 cm^{-1} and 613 cm^{-1} . Combined with Table 6, the absorption peak was O-H stretching vibration peak in cellulose, hemicellulose and lignin at 3410 cm^{-1} . The absorption peak at 2912 cm^{-1} was a symmetric stretching of C-H bond, which was a common absorption peak of cellulose and lignin [31]. The poplar and pine exhibited the significant absorption at 1745 cm^{-1} , which was C=O tensile vibration of -COOH in lignin. However, there was a red shift due to the conjugation of C=O with the benzene ring, and cypress wood showed obvious absorption at 1660 cm^{-1} . The absorption peak at 1597 cm^{-1} belonged to the stretching vibration of lignin benzene ring skeleton [32]. Due to the complex composition of wood dust, it formed a “fingerprint region” in the infrared spectrum range of 1600 cm^{-1} to 1100 cm^{-1} . The absorption peak at 1053 cm^{-1} was C-O stretching vibration [33]. The main components of three-wood dusts were cellulose, hemicellulose and lignin.

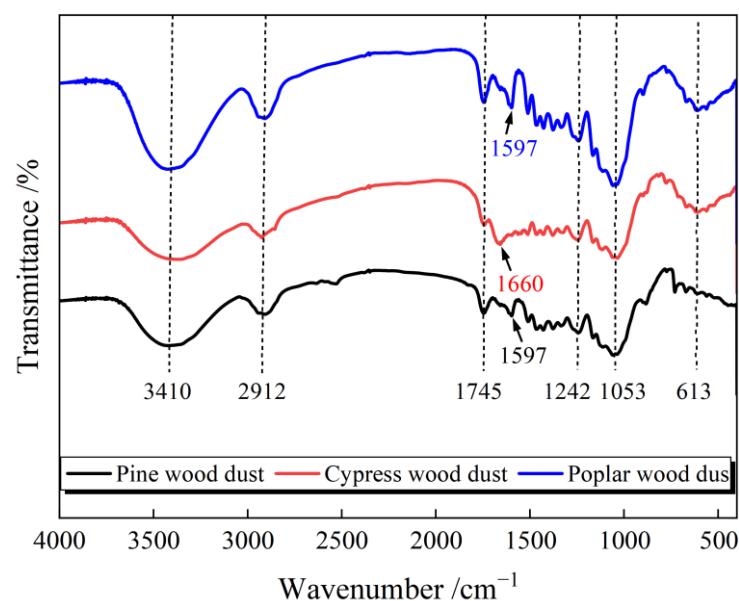


Figure 9. FTIR spectra of wood dust.

Table 6. Infrared spectral analysis of the combustion process.

Wavenumber Range/cm ⁻¹	Functional Group	Vibrational Mode	Product
4000~3500	O-H	Stretching vibration	H ₂ O
3000~2700	C-H	Stretching vibration	CH ₄
1900~1550	C=O	Stretching vibration	Aldehydes, ketones, acids
1900~1300	H-O-H	Bending vibration	H ₂ O
1475~1000	C-O, C-C, carbon-chain skeleton	Stretching vibration	Alkanes, alcohols, phenols, ethers
726~586	C=O	Bending vibration	CO ₂

Hemicellulose was a complex polysaccharide with a large number of side chains, weak intermolecular forces and the lowest thermal stability, and it could generate a large number of small molecule compounds (CO, CO₂, acetic acid, etc.). The cellulose is composed of glucose monomers connected by glycosidic bonds, with long and highly ordered molecular chains. It could be decomposed into various flammable compounds such as CO₂ and CO after heating. The lignin had the best thermal stability, which could decompose to produce organic compounds. The flammable gas and heat released by the pyrolysis of cellulose and hemicellulose could increase the reaction temperature and promote the pyrolysis of lignin, thereby enhancing the explosive reaction activity. Nevertheless, the lignin had the highest thermal stability and could reduce the pyrolysis rate of cellulose, thereby decreasing the explosive reaction activity [34]. The combustion and explosion characteristics of wood dust were influenced by the combined effects of cellulose, hemicellulose and lignin. According to reference reports, the poplar had the highest cellulose and the lowest lignin contents [35,36]. The lignin content of cypress wood was the highest among the three, while the hemicellulose content was the lowest [37]. The cellulose and lignin contents of pine wood was between that of poplar and cypress wood [38]. The combustion characteristics of wood dust could be comprehensively affected by the differences in the contents of cellulose, hemicellulose and lignin in three types of wood dusts.

The differences in explosion characteristics among the three wood dusts can be further interpreted from the perspective of pyrolysis behavior of their major macromolecular components. Previous studies have shown that cellulose, hemicellulose, and lignin exhibit

distinct pyrolysis kinetics, volatile evolution behaviors, and product distributions [39]. Cellulose and hemicellulose generally decompose more readily and release combustible volatile products during heating, which can promote the formation of a flammable gas–solid mixed atmosphere around dust particles. These volatile products participate rapidly in gas-phase combustion reactions, thereby enhancing flame propagation and increasing the maximum explosion pressure and the maximum rate of pressure rise [40]. In contrast, lignin usually decomposes over a wider temperature range and tends to produce more char and phenolic compounds, which may delay volatile release and weaken the instantaneous combustion intensity [41].

Therefore, the macroscopic explosion parameters are not determined only by particle size or total combustible content but are closely related to the pyrolysis kinetics and product distribution of cellulose, hemicellulose, and lignin. A higher content of easily pyrolyzed components can accelerate volatile release and improve the reactivity of the dust cloud, resulting in a higher pressure rise rate and greater explosion sensitivity [39,40]. Conversely, a higher proportion of components with slower decomposition and stronger char-forming tendency may weaken the rapid development of the flame front, leading to lower explosion intensity [41]. This explains why the differences in P_{max} , $(dP/dt)_{max}$, and flame propagation behavior among poplar, cypress, and pine dusts are intrinsically linked to their microscopic pyrolysis behavior and combustible product generation.

4. Conclusions

This article conducted in-depth research on the explosion characteristic parameters and corresponding pyrolysis characteristics of the pine, the cypress, and the poplar dusts through systematic experiments, and the influences of wood dusts type, its diameter and concentration on explosion pressure and explosion index were obtained. Conclusions were as follows:

Firstly, the explosion intensity of wood dust could be greatly affected by its type, diameter and concentration. At the same conditions, the explosion hazard of poplar dust was evidently higher in contrast to the pine and cypress dusts. As the dust diameter decreased, the severity of three wood dust explosions continued to increase, with the highest explosion intensity observed in 300 mesh poplar dust ($P_{max} = 0.72$ MPa; $(dP/dt)_{max} = 42.8$ MPa/s). The optimal dust concentration corresponding to the explosion pressure peak was evidently affected by dust diameter and type.

Second, there were significant differences in the flame propagation behavior of different wood dust, which were mainly related to the component content, the particle morphology and the pore structure. The pine and poplar wood dust had higher carbon and volatile content, and the corresponding peak height of flame and its instantaneous velocity were generally higher than those of cypress wood dust. The peak heights of the flame propagation for three wood dusts were 1213 mm for the pine wood, 991 mm for cypress wood and 1073 mm for poplar wood. The instantaneous velocity peaks were 17.47, 8.91, and 15.81 m/s, respectively. This indicates that the pine and poplar dust flames could spread rapidly. However, their flame propagation ability was relatively weak due to the high ash content and agglomeration effect of cypress dust.

Third, the thermal stabilities of three wood dusts were similar, and the pyrolysis process all exhibited three stages. The quality loss rate was closely related to the dust diameter. During the pyrolysis of cellulose, hemicellulose and lignin, the flammable small molecule gaseous such as CH_4 and aldehydes were produced through decomposition, which were key substances that promoted dust explosions. The differences in the pyrolysis reaction rate and product composition of wood dust were the key factors leading to differences in its explosion characteristics.

The results indicate that wood dust explosion protection should not only consider dust concentration and particle size, but also the intrinsic differences in wood species and their pyrolysis characteristics. For wood dusts with higher explosion pressure, faster pressure rise, stricter control measures should be adopted in practical production, including enhanced dust removal, reduction in fine dust accumulation, effective control of ignition sources, and reasonable design of explosion venting or suppression systems; real-time dust concentration monitoring and localized ventilation should be strengthened in cutting, sanding, polishing, and conveying processes.

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