Comparative Studies on the Explosion Severity of Different Wood Dusts from Fiberboard Production

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Wood dust samples with different particle sizes were used to investigate the explosion characteristics of wood dust. The dust samples came from *Populus alba* L., *Pinus massoniana* Lamb., and *Cinnamonum camphora* (L.) Pres., species that are commonly utilized in medium density fiberboard production in China. The thermogravimetric characteristics, element composition, and morphology of dust samples were analyzed to help explain the explosion phenomena in a 20 L sphere. The analysis showed that both the maximum explosion pressure and explosion index of wood dust presented a decreasing trend with increasing particle size, and the maximum explosion pressure values were in the range of 7 to 9 bar, regardless of species. For both explosion pressure and explosion index values, the wood dust with similar particle sizes were different, which are ranked as *Populus alba* > *Cinnamonum camphora* > *Pinus massoniana*. In addition, for the explosion pressure of wood dust with similar particle size, the dust concentration had threshold values. Additionally, the particle size and dust concentration had a synergistic effect on the explosion pressure and explosion index. Wood dust with a smaller particle size is more likely to explode at the threshold of concentration.

Keywords: Wood dust; Particle size; Dust concentration; Maximum explosion pressure; Explosion index

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INTRODUCTION

With the development of modern industry and the extensive application of powder technology, a growing number of industries are becoming involved in the production, processing, transportation, and storage of flammable powder. In recent years, the types and amounts of flammable powder have increased greatly, resulting in a significant increase in equipment abrasion, dust explosion casualties, and serious environmental pollution (Abbasi and Abbasi 2007; Yan and Yu 2012; Yuan *et al.* 2015). As a typical type of flammable powder, biomass dust, especially wood dust, also possesses serious explosive potential (Huescar Medina *et al.* 2013; Calvo Olivares and Rivera 2014). Dust burning is likely to occur in almost all sections involving wood dust processing, transportation, and storage, and such incidents do harm to the human body, equipment, and the environment (Hedlund *et al.* 2014; Krentowski 2015). In the fabrication board production, wood grinding, sawing, milling, planing, carving, and other processing processes will produce shavings, sawdust, sanded wood powder, *etc*. When the wood dust is suspended in the air or scattered on the hot surface of the equipment, the dust is accumulated. If there is a suitable ignition source in the surrounding environment, the wood dust will be ignited, releasing heat and causing an explosion accident. Yuan *et al.* (2015) examined and analyzed more than 2000 dust explosion accidents that occurred worldwide between 1785 and 2012, and found that 17% of the incidents were caused by wood dust. Wood dust is an important type of combustible dust that accounts for 46% and 27% of all explosion accidents in the US and China, respectively. On January 31, 2015, a wood dust explosion occurred in Jinhe Xingan Wood-based Panel Co. Ltd., Genhe, Inner Mongolia in China killing six, injuring three, and badly damaging the factory building (State Administration of Work Safety of China 2015). According to a preliminary investigation, the accident was caused by an initial wood dust bin explosion in the sanding and dust collecting system, which led to a secondary wood dust explosion in the workshop, triggering a fire in the workshop and storehouse.

Increasing attention has been paid to research on combustible dust explosions in the United States, Britain, France, Germany, Japan, Norway, and other developed countries (Nagy and Verakis 1983; Eckhoff 2005, 2009; Amyotte and Eckhoff 2010). They studied the causes and consequences of dust explosions, mechanisms of dust explosions, physical and chemical experimental methods related to dust cloud generation and combustion, explosion test parameters, and safety improvement procedures to reduce the probability and damage of dust explosions in industry.

The maximum explosion pressure (P_{max}), the maximum rate of explosion pressure rise $(dp/dt)_{max}$, and the explosion index (K_{st}) derived from $(dp/dt)_{max}$ are safety characteristic factors usually used for hazard identification in various industries, suggesting safety improvement procedures, and designing safety measures for the mitigation of destructive effects of dust explosions (BSEN 14034-1(2004) and BS EN 14034-2 (2006)).

Cashdollar (2000) believed that the particle size, shape, and specific surface area of dust were closely related to its explosion characteristics. Amyotte *et al.* (2012) conducted a comparative study on the effects of dust particle size and shape on the maximum explosion pressure as well as the rise in the maximum rate of explosion pressure of wood fibers and polyethylene dust. They deemed that fibrillar particles such as wood dust were more likely to explode because they would remain suspended in air for a long time, increasing their ignition probability. Calle *et al.* (2005) also studied the explosion characteristics of wood dust with different particle size in a 20 L sphere, and confirmed that explosion violence decreases with increasing particle size. The researchers then developed a model based on balances of chemical reactions, kinetics, and thermodynamics during the explosion.

Most studies on dust explosions have focused on coal, metal, and food dust. To date, the reports about wood dust explosion characteristics are still in a fragmentary stage, including the description of the individual explosion characteristics of wood dust, describing common physical laws of various dust types such as explosion incentives, explosive conditions, as well as explosion and explosion factors (Hedlund *et al.* 2014; Krentowski 2015). Minimal attention has been paid to the combustion and explosion dynamics in wood explosions (Calle *et al.* 2005; Huescar Medina *et al.* 2015), mainly because of the considerable variation in wood particle size and morphology, as well as the low density and large specific surface area of wood dust.

The 1990s saw a rapid development of fiber board production as an effective way to comprehensively utilize wood resources in China. However, it is unavoidably accompanied by a lot of dangerous wood dust explosions. In fiberboard production, the equipment that is prone to dust explosion includes the wood fiber drying system, dry wood fiber or sanding dust silos, dry wood fiber conveying systems, mat forming units, mat or panel cutting units, wood dust collecting systems, as well as the grinding and sanding systems. Combustible dust clouds can be easily formed in the above units and thus could be ignited by heat, fire, or spark. Therefore, more attention should be paid to these units in production. The measurement of P_{max} and $(dp/dt)_{max}$ are the basis for designing, constructing, and monitoring critical equipment and protective systems. In this research, wood dust was obtained from *Populus alba* L., *Pinus massoniana* Lamb. and *Cinnamonum camphora* (L.) Pres., which are commonly utilized for fiberboard production in China. The influences of particle size and concentration on the wood dust explosive power were investigated.

EXPERIMENTAL

Preparation of Wood Dust Samples

Wood dust samples from three species of trees, *Populus alba* L., *Pinus massoniana* Lamb., and *Cinnamonum camphora* (L.) Pres., commonly utilized in medium density fiberboard production in China, were used to investigate the explosion characteristics of wood dust. All dust samples were generated by sawing, chopping, and grinding from solid wood supported by Dare Artificial Board Group Co., Ltd., Jiangsu province. Four groups of wood dust samples with different particle size (250 to 500 µm, 125 to 250 µm, 63 to 125 µm, and 0 to 63 µm) for each species were obtained by sieving (Analysette 3 Spartan, Fritsch, Idar-Oberstein, Germany) and particle size analyzing (Mastersizer2000, Malvern Analytical, Malvern, UK).

Experimental Methods

Morphological, thermogravimetric, and elemental characteristics of wood dust from three different species were investigated using a polarizing microscope (Olympus BX51, Tokyo, Japan), a synchronous thermal analyzer (Netzsch STA 449C, Bavaria, Germany), and an elemental analyzer (2400 II, PE, Waltham, MA, USA), respectively. In the thermogravimetric analysis, dust was heated from room temperature to 750 °C using a heating ramp of 20 °C/min in an N_2 environment (20 mL/min). The content of carbon, hydrogen, nitrogen, and sulfur element were determined in an O_2 environment.

Investigation of the maximum explosion pressure (P_{max}) and the maximum rate of explosion pressure rise ($(dp/dt)_{max}$) were carried out with a Siwek 20 L apparatus (Kuhuer, as shown in Fig. 1) in accordance with the standardized test procedures BS EN 14034-1 (2004) and BS EN 14034-2 (2006). This apparatus is comprised of a water-cooled explosion vessel with a volume of 20 dm^3, an ignition source composed of two chemical igniters each with 5 kJ of energy, a control unit sequencing, and a pressure measuring system including at least two pressure sensors and one piece of recording equipment (KSEP 310 and KSEP 332, Kühner, Zurich, Switzerland).

Before starting the test procedure, the moisture content of all dust samples was conditioned to less than 5% using an oven (BPG-9050AH, HASUC, Shanghai, China) and the temperature inside the vessel was 20 °C. For testing, the required amount of dust was placed in the dust container. After being vacuumed to a vacuum of 0.6 bar, the container was pressurized to an over-pressure of 20 bar. The dust sample was dispersed into the sphere from the dust container via the fast-acting valve and a rebound nozzle. The time lag of the outlet-valve (t_d) was outside the acceptable range of 30 to 50 ms. The delay between the initiation of the dust dispersion and activation of the ignition source (ignition delay t_v) was 60 ms. The pressure was recorded as a function of time. From the pressure/time curve, the explosion pressure (p_{ex}) was determined by taking the arithmetic mean of the values measured by the pressure sensors. The testing procedure was started from a concentration of 250 g/m^3, and the concentration was increased by steps of 250 g/m^3, which is shown as 250 g/m^3, 500 g/m^3, 750 g/m^3, 1000 g/m^3, 1250 g/m^3, and 1500 g/m^3 for each kind of wood dust with different particle size. Then researchers determined the explosion pressure (p_{ex}) under each concentration and found a maximum value P_{max}.

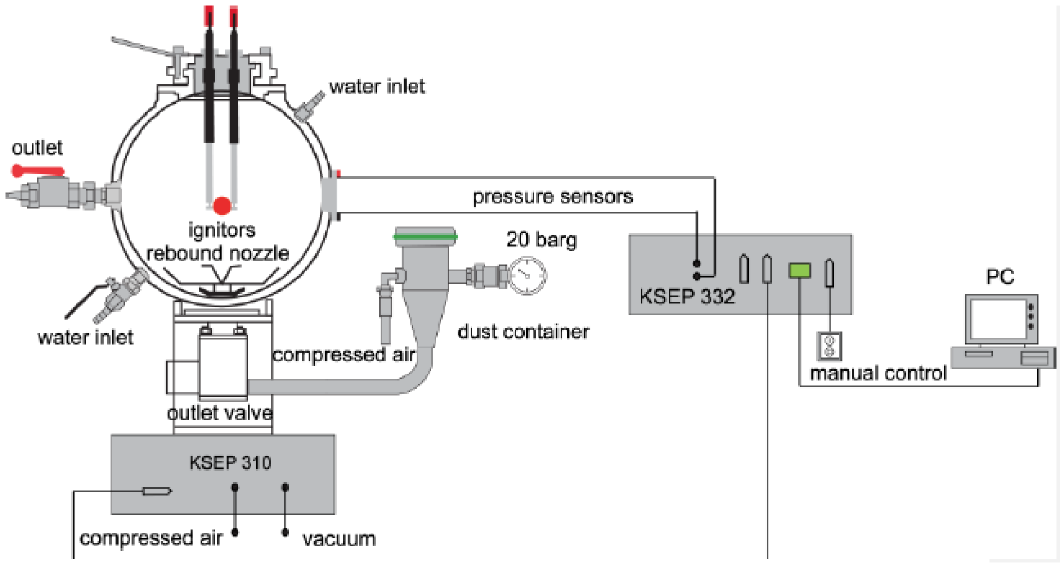


Fig. 1. 20 dm^3 sphere explosion testing system

RESULTS AND DISCUSSION

Particle Size and Surface Morphology of Dust

Tables 1 through 3 show the D_{10}, D_{50}, D_{90} and specific surface area for each fraction of wood dust samples. For all dust samples, the values of D_{10}, D_{50}, and D_{90} gradually increased with increasing particle size, yet the values of specific surface area presented an opposite trend. Generally speaking, the median diameter of dust (D_{50}) should be smaller than the corresponding upper bound value of the particle size, as shown by the particle size of 0 to 63 µm, 63 to 125 µm, 125 to 250 µm, and 250 to 500 µm. *P. massoniana* dust had median diameters of 34 µm, 57 µm, 120 µm, and 219 µm, respectively, and *P. massoniana* dust showed a median diameter of 30 µm, 66 µm, 162 µm, and 303 µm. However, for *P. alba* dust, the median diameters were 38 µm, 89 µm, 180 µm, and 566 µm, respectively. Herein a median diameter of 566 µm was larger than the corresponding upper bound value of the particle size, 250 to 500 µm. This phenomenon can be explained from the morphology of wood dust samples, as shown in Figs. 2 through 4. Dust from *P. alba* had a higher length to diameter ratio, and the long needle shapes can pass through the lengthwise portion of the sieve. In addition, in the same particle size, the D_{10}, D_{50}, and D_{90} values of *P. alba* dust were greater than those of *P. massoniana* and *C. camphora* dust. This is mainly attributed to *P. alba* dust's slender fiber-like and irregular shape, rough surface, various particle sizes, and uneven dispersion (Lee *et al*. 2016).

Table 1. D_{10}, D_{50}, D_{90} and Surface Area for Each Fraction of *Populus alba* Dust

Size fraction	0-63 µm	63-125 µm	125-250 µm	250-500 µm
Particle size D_{10}(µm)	12.91	30.25	56.84	164.62
Particle size D_{50}(µm)	38.06	89.44	180.78	565.78
Particle size D_{90}(µm)	94.91	204.33	418.62	1402.98
Surface area (m^2/g)	0.27	0.11	0.06	0.02

Table 2. D_{10}, D_{50}, D_{90} and Surface Area for Each Fraction of *Pinus massoniana* Dust

Size fraction	0-63 µm	63-125 µm	125-250 µm	250-500 µm
Particle size D_{10}(µm)	12.77	18.12	29.78	66.67
Particle size D_{50}(µm)	34.16	57.21	120.09	219.04
Particle size D_{90}(µm)	77.90	154.14	279.06	459.90
Surface area (m^2/g)	0.28	0.18	0.10	0.05

Table 3. D_{10}, D_{50}, D_{90} and Surface Area for Each Fraction of *Cinnamonum campora* Dust

Size fraction	0-63 µm	63-125 µm	125-250 µm	250-500 µm
Particle size D_{10}(µm)	10.29	17.76	52.25	138.30
Particle size D_{50}(µm)	29.76	66.50	161.86	303.23
Particle size D_{90}(µm)	66.78	157.51	313.18	568.19
Surface area (m^2/g)	0.35	0.19	0.07	0.04

Besides, the dust of *P. massoniana* and *C. camphora* had similar shapes, being oval and slender, and the dust of *P. alba* and *P. massoniana* had a relatively uniform and normal particle size. All the samples had particles of 1000 µm, not only *P. massoniana* and *C. camphora*, and even *P. alba* reached the 1500 µm size. National Fire Protection Association (NFPA) Standard 68 defines combustible dust as particles less than 420 µm in diameter and believes that these particles have a potential to cause a fire or explosion when dispersed and ignited in the air. In this paper, wood dust from three species is considered to be combustible dust because the particles less than 420 µm in diameter account for about 50% of all dust samples for each species.

Elemental and Thermogravimetric Analysis of Wood Dust

Table 4 shows the carbon, hydrogen, nitrogen, and sulfur content in the dust of *C. camphora, P. alba,* and *P. massoniana*. The H/C ratio of *P. alba, P. massoniana,* and *C. camphora* was 9.7%, 8.4%, and 9.1%, respectively. Compared with poplar and pine trees (Liao *et al*. 2004), the chosen wood dust samples in this paper had a lower hydrogen and nitrogen content, and a higher nitrogen and sulfur content.

Figure 5 shows the TG and DTG curves for the wood dust samples. In general, the pyrolysis process of wood dust is divided into three main stages: water loss drying, devolatilization, and carbonization (Xu *et al*. 2010). For all dust samples, the water was dehydrated at 30 °C to 100 °C, and most cellulose and hemicellulose were decomposed at 220 °C to 400 °C (Yan 1997; Yang *et al*. 2000).

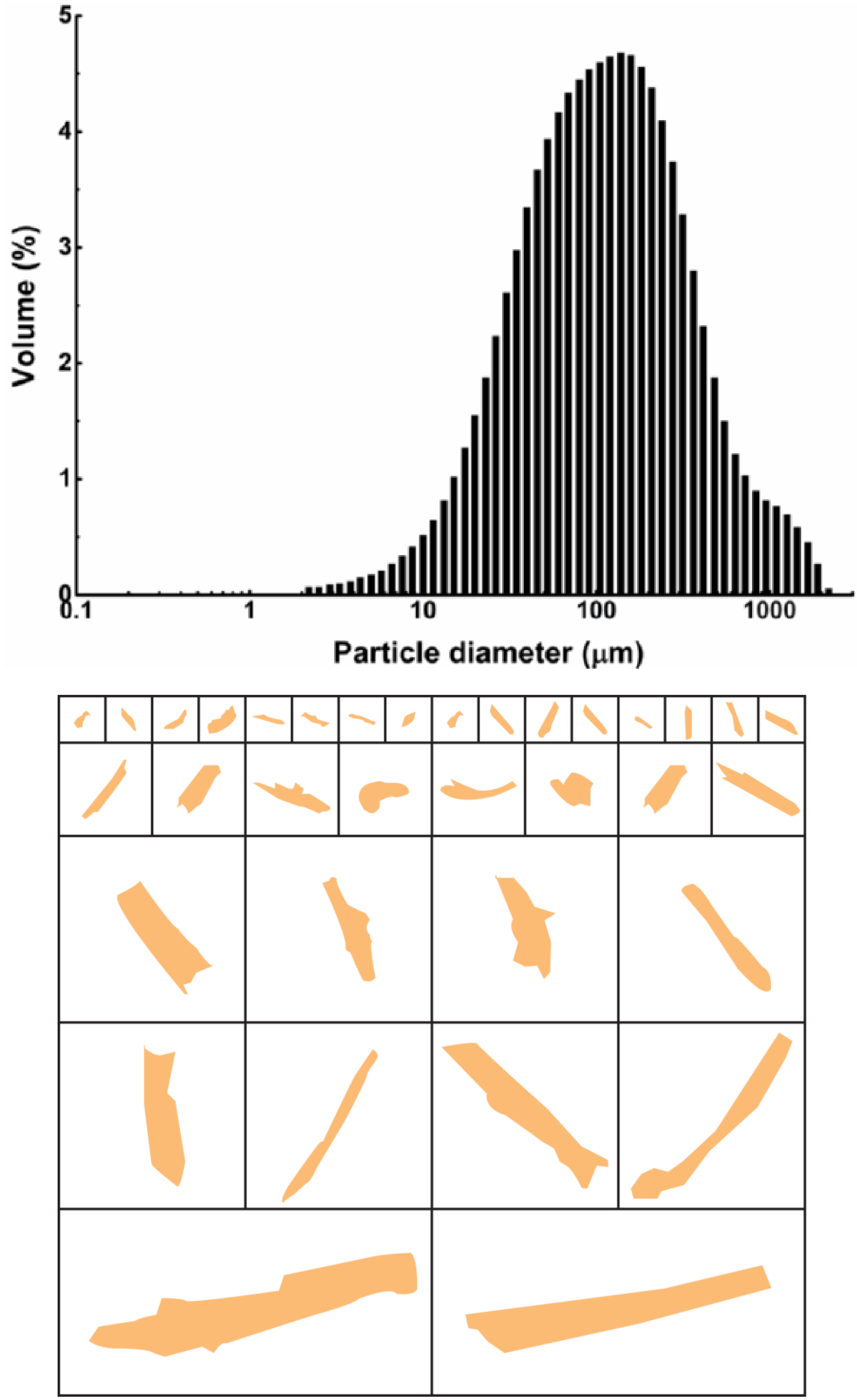


Fig. 2. Particle shape and particle size of unsieved *Populus alba* dust

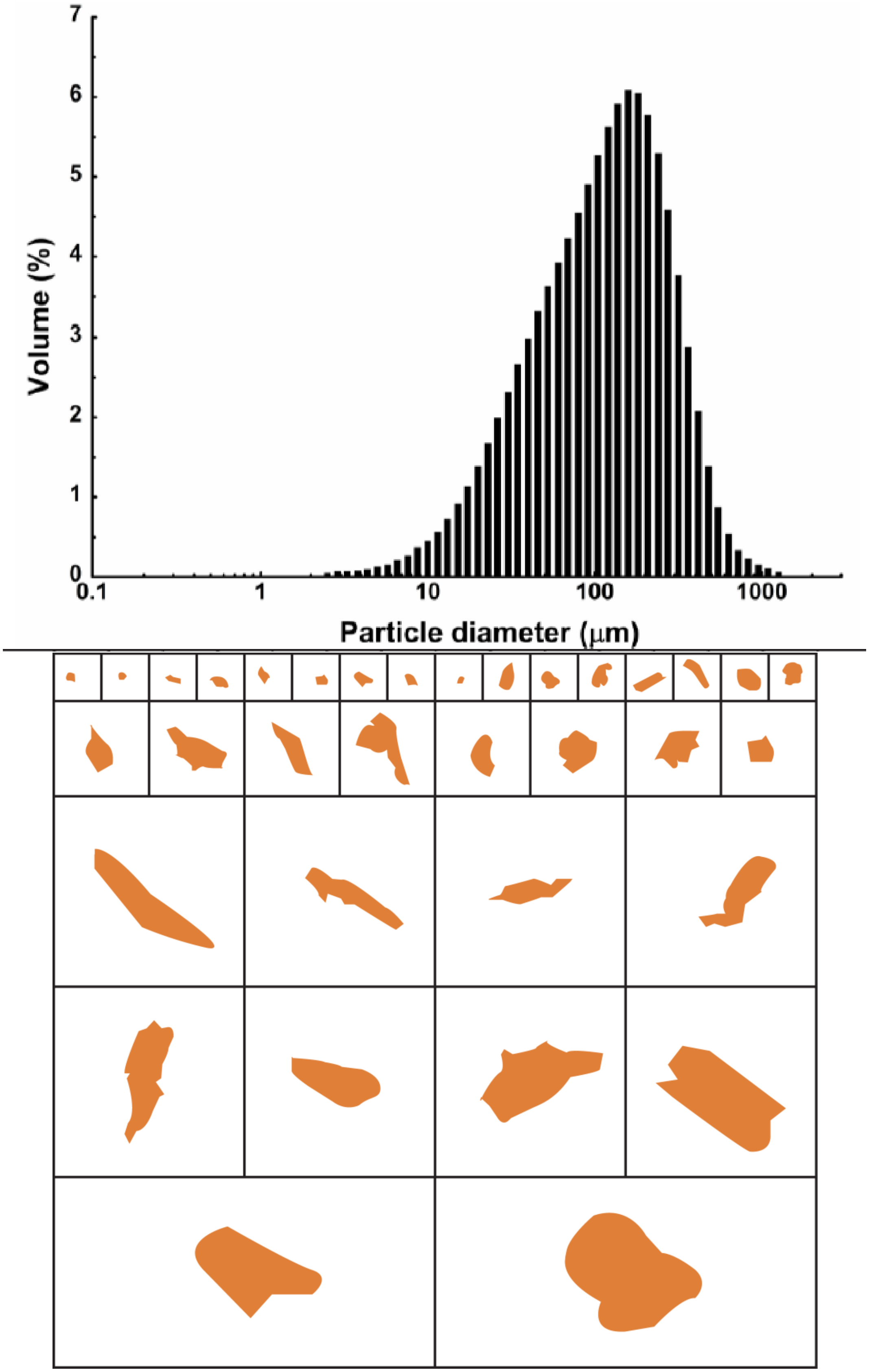


Fig. 3. Particle shapes and particle size of unsieved *Pinus massoniana* dust

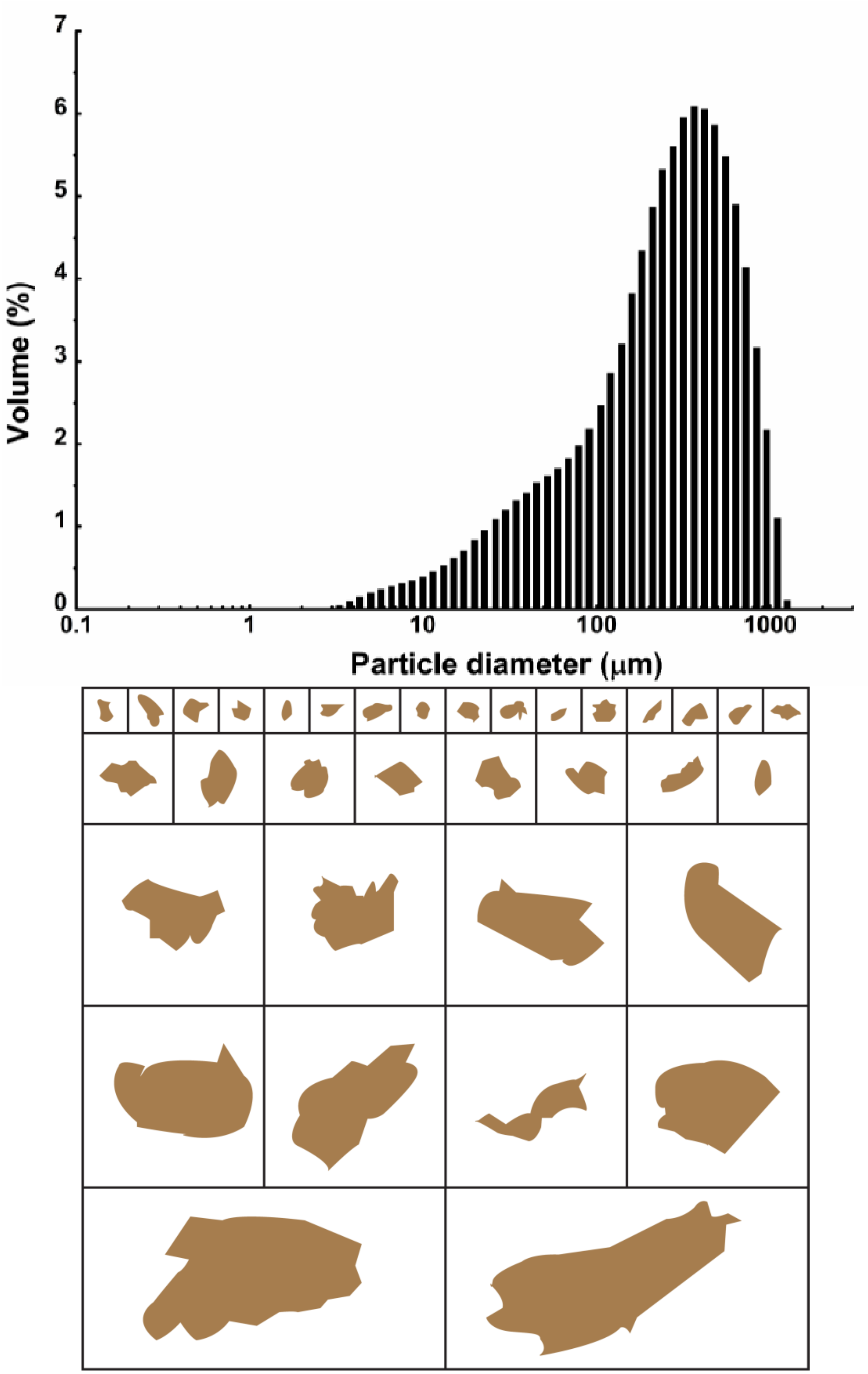
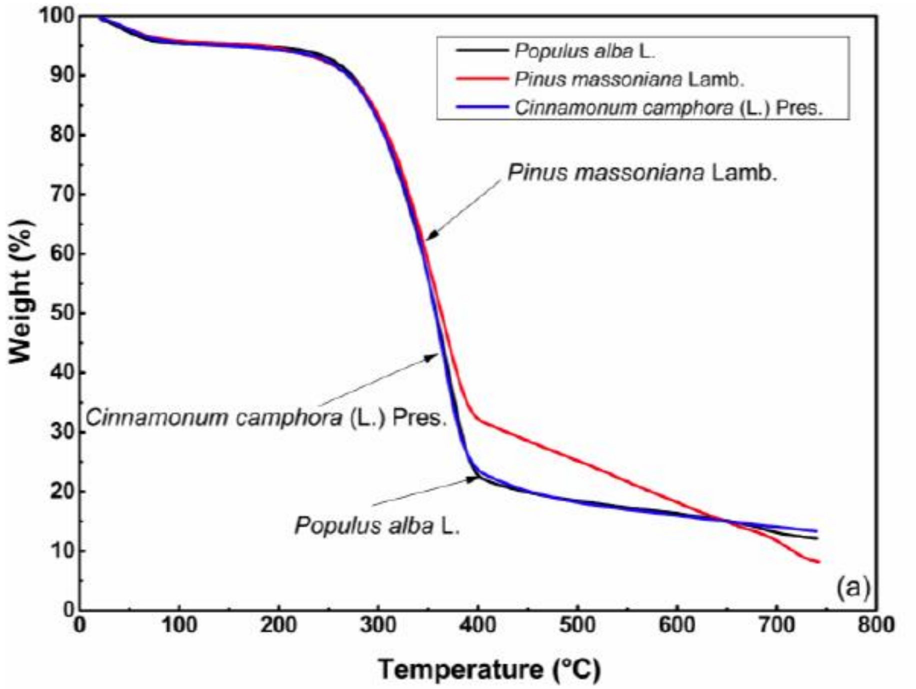


Fig. 4. Particle shapes and particle size of unsieved *Cinnamonum camphora* dust



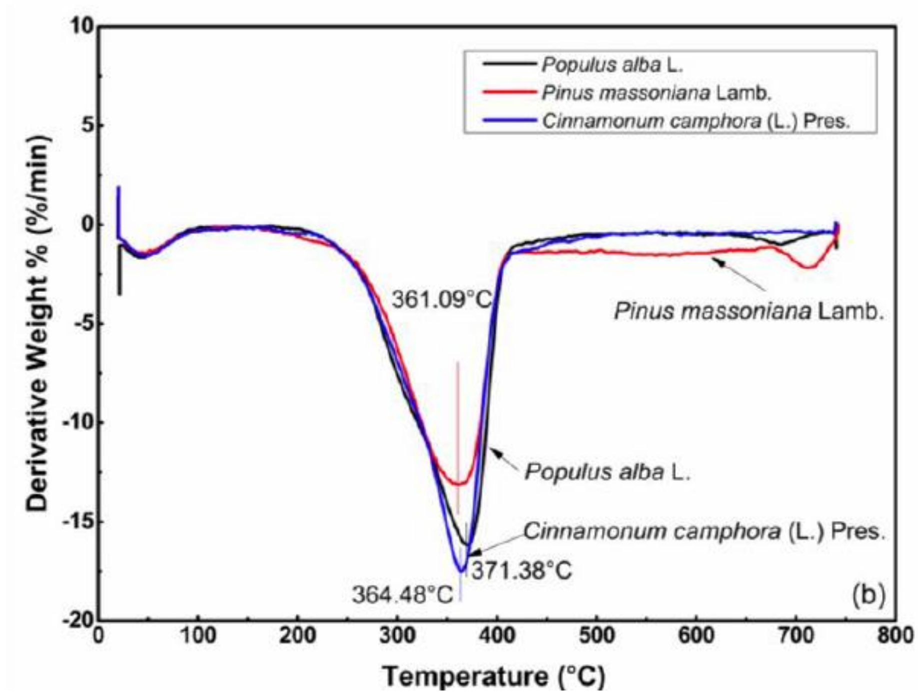


Fig. 5. a) TG and b) DTG curves for the dust samples

When the temperature reached 350 °C, the mass loss of all dust samples was about 50%, and the maximum mass loss occurred at 360 °C. However, the dust samples from *P. alba* and *C. camphora* devolatilize more than that of *P. massoniana* dust, and in the carbonation stage, the *P. massoniana* dust decomposed more than *P. alba* and *C. camphora* dust, leading to a lower content of char residue at 750 °C (Table 5). These results can be attributed to the fact that the *P. massoniana* dust contains turpentine and rosin, which start to decompose and carbonate at 300 °C (Wang *et al.* 2005).

Table 4. Elemental Composition of the Wood Dust

Elemental Composition	C (wt%)	H (wt%)	N (wt%)	S (wt%)
Populus alba	44.84	4.35	0.57	0.81
Pinus massoniana	39.78	3.33	0.32	0.53
Cinnamonum camphora	48.37	4.38	0.67	0.39

Table 5. Thermal Degradation and Char Residue Data by TGA

Sample	$T_{5\%}$ (°C)	$T_{50\%}$ (°C)	R_{peak} (%/min)	T_{peak} (°C)	Char residue at 750 °C (%)
Populus alba	159.9	358.0	15.2	371.4	12.2
Pinus massoniana	181.6	363.1	12.1	361.1	8.2
Cinnamonum camphora	148.2	357.2	16.5	364.5	13.4
$T_{5\%}$: temperature at the mass loss of 5%; $T_{50\%}$: temperature at the mass loss of 50%					
T_{peak}: temperature at the peak; R_{peak}: mass loss rate at the peak					

Explosion Characteristics of Wood Dust Samples

Effect of particle size on explosion pressure and explosion index

Figure 6 shows the pressure evolution during the explosion process for *C. camphora* dust with a particle size of 63 to 125 μm. When the dust concentrations were 500 g/m^3 and 1250 g/m^3, the explosion pressure and the pressure rise rate reach their maximum values, respectively. Similar results were also obtained by Calle *et al.* (2005). According to BS EN 14034-2 (2006), the explosion index (K_{st}) is defined as the explosion pressure rise rate (dp/dt) normalized to a 1 m^3 vessel in the explosion pressure rise rate, making the explosion pressure rise rate measured in different containers comparable. It is calculated using the cubic law in Eq. 1,

$$K_{st} = (dp/dt) \times V^{1/3} \quad (1)$$

where V is the volume of the explosive container, 20 L.

Figure 7 is the relationship between P_{max} or K_{St} of dust samples and particle size. When the particle size increased from 0-63 μm to 250-500 μm, the P_{max} and K_{St} of *Pinus massoniana* Lamb dust decreased from 7.56 bar to 6.80 bar and from 129 bar·m/s to 59.2 bar·m/s, and the decreasing rate was 10.1% and 54.1%, respectively. The dust samples from *C. camphora* and *P. alba* showed similar changing trends to that of *P. massoniana* dust. Therefore, a conclusion can be drawn that particle size affects K_{St} much more than P_{max}. This result is consistent with the literature (Calle *et al.* 2005).

In addition, it is interesting that *P. alba* dust had higher P_{max} and K_{St} values than *P. massoniana* dust and *C. camphora* dust in the selected particle size. The *P. alba* dust exhibited a relatively high length to diameter ratio which makes it tend to float in the air for a long period during the explosion test and enhance its explosive power.

For the *C. camphora* and *P. massoniana* dust, the oval-shaped particles make them relatively difficult to disperse in the air. The explosive characteristics of dust are related to its volatility content, and the more volatile the content, the greater the explosion severity of the dust (Gu and Wang 2008). From the TG curves in Fig. 5, the volatile content of the *P. alba* dust and *C. camphora* dust was significantly higher than the *P. massoniana* dust.

Finally, the sulfur elemental content and H/C ratio of the *P. alba* dust were highest among three types of dust samples. However, compared to *C. camphora*, the dust from *P. massoniana* had a higher content of sulfur, but it did not achieve higher values of

P_{max} and K_{St}. This result suggested that the effect of sulfur on P_{max} and K_{St} had been offset by the high content of rosin acid in *P. massoniana* dust.

The wood dust with similar particle size had different explosion pressure and explosion index values, and the relationship was the same as the H/C ratio of each kind of wood dust, which are ranked as *P. alba* > *C. camphora* > *P. massoniana*.

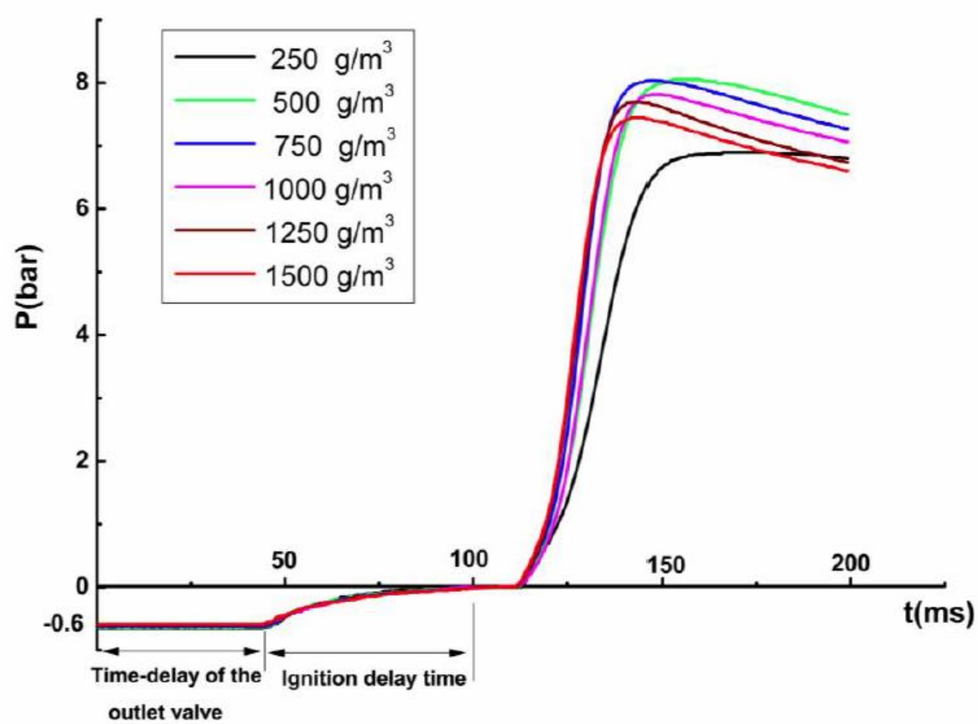


Fig. 6. Pressure / time curve (*Cinnamonum camphora* dust with particle size of 63 to 125 μm)

Effect of dust concentration on explosion pressure and explosion index

Figure 8 shows the explosion pressure and explosion index of dust samples with increasing dust concentration. As the dust concentration increased, the explosion pressure rose initially until the maximum was reached and decreased afterwards, demonstrating that the dust concentration has a threshold value. Lee *et al.* (2016) and Kordylewski and Amrogowicz (1992) obtained similar results. When dust concentration increased within the threshold, the dust involved in the explosion reaction and the heat released increased, leading to a rise in the explosion pressure.

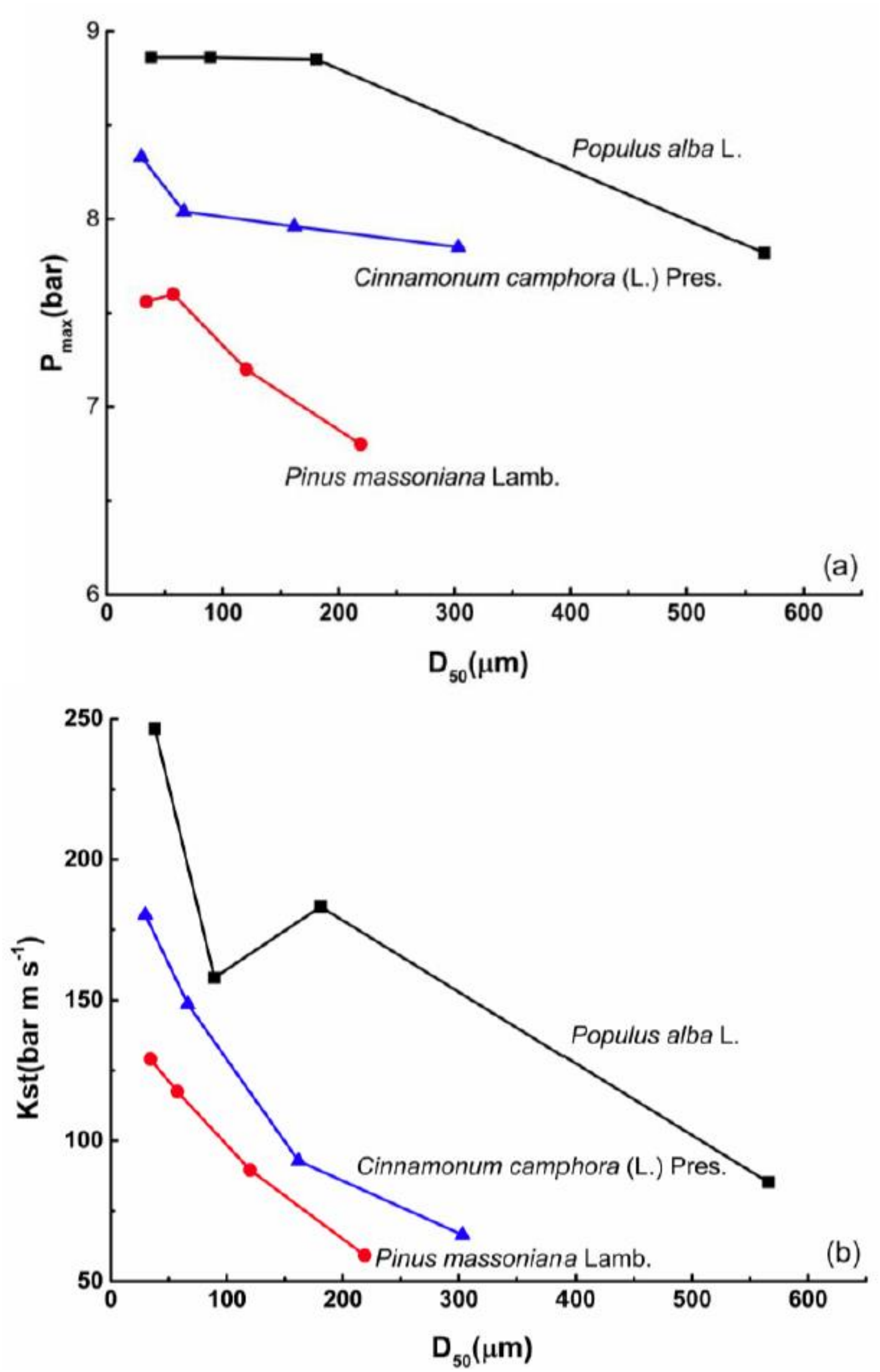


Fig. 7. Effect of wood dust particle size on a) P_{max} and b) K_{st}

Further increase in the dust concentration beyond the threshold resulted in an increase in the number of particles in the explosion sphere and an insufficient amount of oxygen, causing a reduction in the number of particles per unit volume participating in the explosion reaction and thereby decreasing the explosion pressure. On the other hand, the heat and shock waves generated by the explosion were absorbed by the excessive dust, which caused the heat released by the reaction to be less than the heat lost by the absorption. This hindered the spread of the flame and eventually lead to the downward trend of the dust explosion. Finally, the excessive dust in the explosion sphere can also reduce the explosive level and efficiency of the gunpowder.

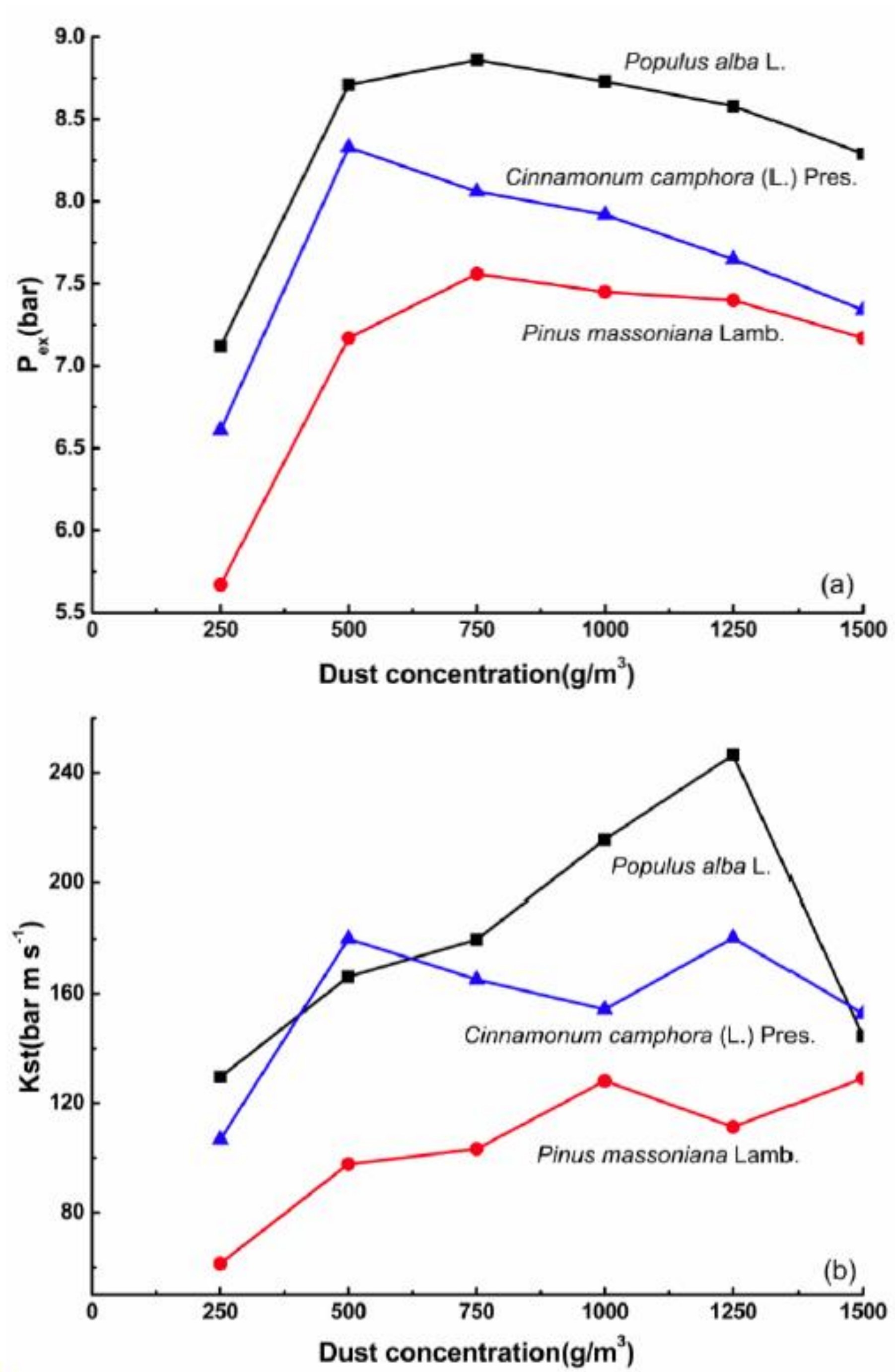


Fig. 8. Effect of dust concentration on a) P_{max} and b) K_{st} (particle size, 0 to 63 μm)

For different species, the threshold of dust concentration was not identical. For example, for the dust of *P. alba* and *P. massoniana*, the threshold, 750 g/m^3, was higher than that of *C. camphora*, 500 g/m^3. The thermal degradation data in Table 5 shows that the mass loss rate of *C. camphora* dust first reached 5% at 148 °C. The higher the concentration of *C. camphora* dust, the smaller the number of particles involved in the subsequent explosion reaction, resulting in a lower dust concentration threshold.

The dust concentration values corresponding to the maximum explosion pressure and the maximum pressure rise rate are different, as shown in Fig. 6. Obviously, the maximum speed and the maximum acceleration of the explosion reaction do not necessarily occur at the same time. Accordingly, in the testing procedure of the explosion, a series of experiments were repeated for a range of dust concentrations. This conclusion is consistent with the literature reports (Amyotte *et al.* 2012; Tascón *et al.* 2016; Cao *et al.* 2017).

Similarly, among the three types of wood dust with a particle size of 0 to 63 μm, *Populus alba* dust exhibited the highest values of P_{max} and K_{St}, and the *Pinus massoniana* Lamb dust had the lowest.

Synergistic effects of particle size and dust concentration on the explosion severity of the wood dust

Figure 8 shows that for the explosion pressure of the three types of wood dust, the threshold of dust concentration is 500 g/m^3 or 750 g/m^3. The dust concentration of 500 g/m^3 or 750 g/m^3 were used as examples to discuss the synergistic effects of particle size and dust concentration on explosion severity.

In Fig. 9, for the dust samples of *P. alba* and *C. camphora* with the same dust concentration, the explosion pressure increased with decreasing particle size. The smaller the particle size, the larger the specific surface area and the larger the contact area between dust particles and the oxygen, resulting in faster heat release during burning. Besides, the convective heat rate of the dust and the gas in the explosion sphere is accelerated with decreasing particle size, thus shorting the ignition time of the dust. However, for the *P. massoniana* dust with a dust concentration of 500 g/m^3, the explosion pressure did not reach above the changing trend, and its P_{max} corresponded to the particle size range of 63 to 125 μm instead of 0 to 63 μm. This result may be caused by the fact that the *P. massoniana* dust contains a large amount of turpentine that makes small dust reunion and thus reduces its explosion severity.

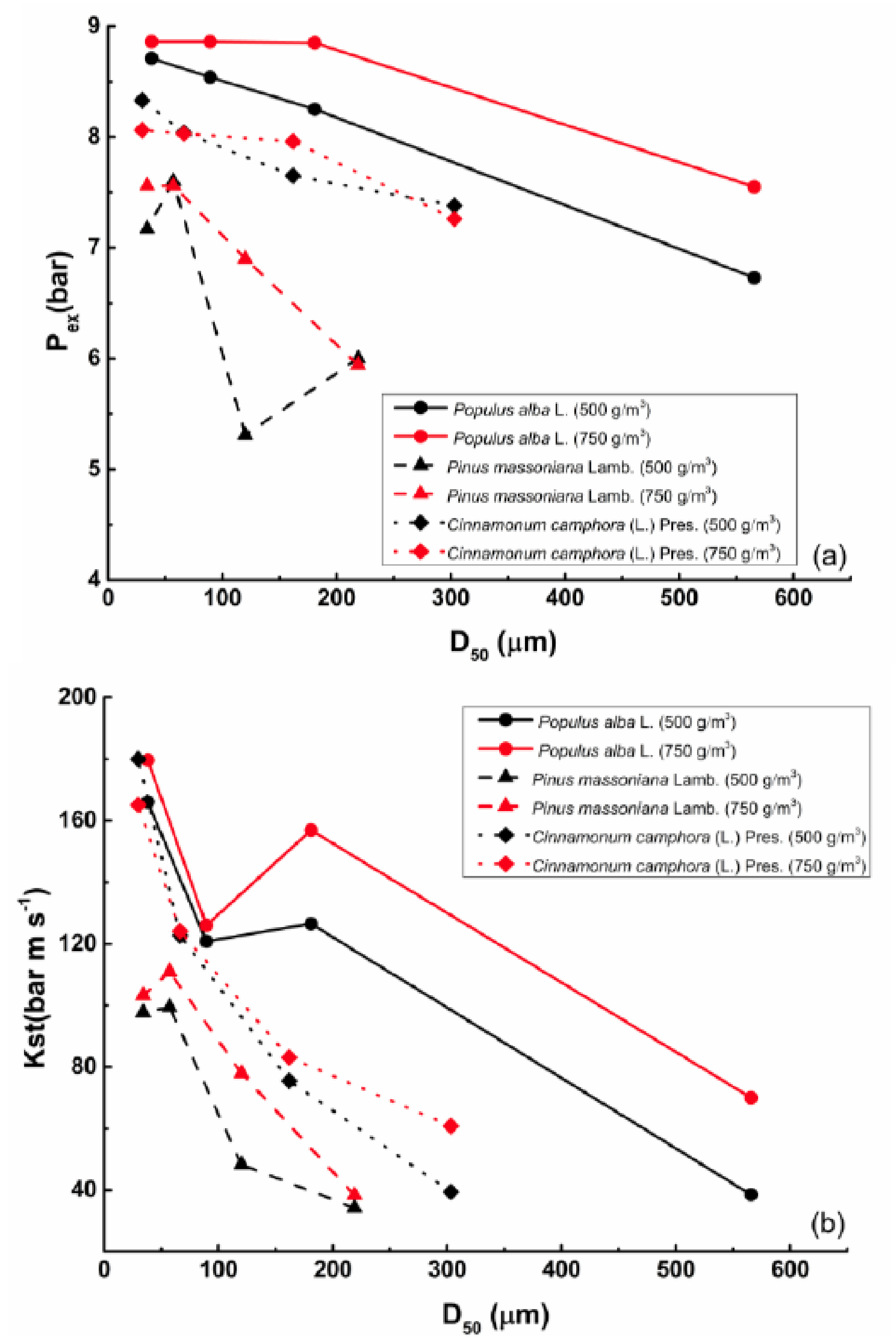


Fig. 9. Synergistic effects of particle size and concentration on a) P_{max} and b) K_{st}

In regard to the K_{st} value of selected dust samples, the maximum value corresponds to the particle size of 0 to 63 μm, except for *P. massoniana* dust. Thus, under the synergistic effect of the threshold dust concentration and the smaller particle size, it is more likely to induce an explosion accident with a high strength.

CONCLUSIONS

1. The particle size affects the explosion index (K_{St}) much more than the maximum explosion pressure (P_{max}). Both K_{St} and P_{max} present a decreasing trend with increasing particle size, and the P_{max} values are in the range of 7 to 9 bar, regardless of species.
2. For different species, wood dust with similar particle size have different explosion pressure and explosion index values, which are ranked as *Populus alba* L. > *Cinnamonum camphora* (L.) Pres. > *Pinus massoniana* Lamb.
3. For the explosion pressure of wood dust samples with same particle size, the dust concentration exhibited a threshold value that produced P_{max} values of 750 g/m^3, 750 g/m^3, and 500 g/m^3 for *Populus alba* dust, *Pinus massoniana* dust, and *Cinnamonum camphora* dust, respectively.
4. Particle size and dust concentration have a synergistic effect on the explosion pressure and explosion index. Wood dust with a smaller particle size is more likely to explode at the threshold of dust concentration.

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