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Flammability and explosion characteristics of softwood dust

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Abstract
In technical terms, wood is a natural composite material with a polymer matrix, reinforced with fibres made of uniaxially oriented longitudinal cells. Due to the ease of obtaining and relatively low technological requirements related to its processing, wood is a common material used for various types of construction materials. An experimental investigation was carried out to determine the evolution of the ignition sensitivity and the explosion of three types of softwood dusts. Two of those dusts come from conifers and one from a deciduous tree. Complete fire characteristic requires several parameters describing wood dust behaviour under fire conditions including heat release rate (HRR), ignition time, or fire growth index. To determine those parameters, a cone calorimeter was used. Explosion characteristic was tested for representative wood as a dust sample in 20-L spherical vessel. Minimum ignition energy (MIE) was tested on MINOR II apparatus, which is a modified Hartman's tube. Minimum ignition temperatures were tested with the use of layer ignition temperature apparatus and Godbert–Greenwald apparatus for minimum ignition temperature of a dust layer and dust cloud (MIT), respectively. Dust with the highest K_{ST} value, lowest MIE in the widest concentration range, and lowest MIT was pine wood dust. It also shows the shortest ignition time and a timespan between ignition and HRR peak.

Keywords Softwood · Wood dust · The lower explosive limit · Minimum ignition energy · Minimum ignition temperature

Introduction

A dust explosion is the rapid combustion of a solid reactant in the form of fine particles. Thus, the size and composition of the dust particles are important parameters in defining the reaction. Much has been postulated in the literature about the relationship of particle size and dust explosion, and some studies have been performed on various types of dust [1–4]. Most of the industrial dusts with appropriate grinding and concentration in the air and a suitable ignition source can create flammable and explosive atmospheres [5, 6]. Wood is a multi-layer material, it is divided into early and late, i.e., growing in spring and growing in summer. Late wood, compared to early wood, has more fibres and has coils and vessels with smaller diameters and thicker walls. Due to this heterogeneity in the structure of the wood, both layers have a different hardness. In addition, the hardness of the wood also depends on the density and moisture content. Wood density, i.e., its mass, is the ratio of the mass to the volume of wood, and it is a correlated value with hardness. The heavier wood is, the harder it is. The hardness of the wood is measured by the resistance of the wood when pressing a steel ball of a strictly defined size (Janka hardness test). The hardness depends on the species of tree the wood comes from. The hard species include larch, black locust, or locust tree (incorrectly called acacia), beech, oak, hornbeam, sycamore, and elm and for the softest: linden, alder, aspen, and poplar. Softwood is much easier to work with, but is it safer to work with too. From an ecological perspective, wood is an almost ideal material because it is fully renewable and biodegradable. Moreover, no substitute for it has yet been found. Wood has over 30,000 applications, including in furniture, construction, railways, haberdashery, mining, paper industry, energy, and boatbuilding. Each year sawmill cut hundreds of millions of cubic metres of wood creating millions of tons of wood dust which is explosive at the right concentration and conditions. Industrial plants use many safeguards, but failures related to an explosion or fire of wood dust occur

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often. In 2021, over 25% of all combustible dust fires and explosions involved wood products' industry [7]. In Germany, Austria, and Switzerland, as many as 79 events were recorded between 2015 and 2017. The aim of the study was to examine the explosion characteristics, minimum ignition temperatures, and minimum ignition energies of three selected types of a softwood dusts. The basic criterion for selecting tree types was their use in industry.

Experimental setup

Materials

Grinding and sieving

Tested materials were gained from the sawmills. Before testing, all wood dust samples were dried for 12 h at 30 °C temperature, powdered by an industrial mill, and subjected to a sieve analysis. Particle size distribution of the all powders was determined with a RETCH analyser. Gained powder was further used in the research.

Research methods

Flammability test

Parameters characterizing behaviour of analysed compounds in the presence of flame were studied using cone calorimeter (FTT Limited) according to standard ISO 5660–1 [8]. Three samples of equal mass, for each wood dust, were placed in aluminium foil form (100 mm × 100 mm × 25 mm). Each sample was treated with external heat flux (HF) value of 35 kW m^{-2} simulating the thermal exposure during the first phase of fire. Following parameters were estimated: Heat release rate—HRR (kW m^{-2}), peak of heat release rate—pHRR (kW m^{-2}), time to peak of heat release rate—t-pHRR (s), total heat release—THR (MJ m^{-2}), ignition time—TTI (s), total smoke release—TSR (m^2), fire growth rate—FIGRA (kW $m^{-2}s^{-1}$).

Smoke density test

The smoke density characteristics in a closed vessel can be described by two main parameters: smoke optical density (SOD) and VOF4. SOD parameter determines visibility reduction and is the determinant of an amount of smoke produced during the first ten minutes of thermal degradation of tested material. VOF4 describes increasing rate of smoke density during the first four minutes, which are crucial during evacuation process. Valeur Obscurcissement Fumée (VOF4) is a smoke evaluating parameter generated by the summation of the optical density over the first 4 min.

All parameters were measured using smoke density chamber (FTT Limited, West Sussex) according to standard ISO 5659–2 [9]. Three samples, of equal mass for each tested compound, were covered with aluminium foil (75 mm × 75 mm × 10 mm) and treated with external HF of 25 kW m^{-2}. Due to the high flammability of the test compounds, even in the absence of the ignition source (electric spark), two relevant comparative parameters were added: time to maximum smoke density (t-MSOD).

Explosion characteristics

The explosion characteristics of tested wood dusts were estimated with the use of 20-L spherical vessel which is a laboratory version of a 1-m^3 vessel for testing dusts, according to EN-14034 standards [10–14].

Minimum ignition energy (MIE)

One of the most important parameters defining the vulnerability of a dust cloud to ignition is minimum ignition energy (MIE). A MIE test was performed using MINOR II apparatus, which is a modified Hartman tube (MIKE 3 analogue). The construction of the apparatus as well as the method and criteria for measurements are presented in standard ISO/IEC 80079–20-2 [10].

Minimum ignition temperature of a dust cloud (MIT)

To complete dust–air mixture experimental data, the MIT apparatus was used for the determination of the minimum ignition temperature of a dust cloud to measure the susceptibility of a dust cloud to auto-ignition in a heated environment [15]. The measurement procedure was defined according to ISO/IEC 80079–20-2 [10].

Results and discussion

Determination of fire behaviour

The result of the measurements was to obtain the values of the determined values which characterized the behaviour of materials under the influence of the intense heat radiation, namely: The heat release rate is a very important parameter needed to assess the fire hazard that the materials and products of their decomposition represent. It allows draw conclusions about the size of the fire, the rate of its growth, and as a consequence quantity and quality of the smoke released. The average values of the determined calorimetric parameters describing the behaviour of softwood dust under the influence of heat flux with a density (35 kW m^{-2}) are presented in Table 1.

Table 1 Calorimetric parameters of the tested softwood dust

Sample	TTI s	MARHE kW/m^{-2}	FIGRA $kW/m^{-2}s^{-1}$	HRR kW/m^{-2}	pHRR kW/m^{-2}	t-pHRR s	THR MJ/m^{-2}	TSR m^2/m^{-2}
Pine	8	103	7.85	73.4	157	20	28.7	266.9
Spruce	10	95.3	8.3	63.1	151	18	25.9	48.9
Alder	18	90.3	5.8	71.3	133	25	27.0	58.8

Pine dust ignites in a shorter time than spruce or alder dust. Both dusts from the coniferous trees are characterized by short ignition times, higher pHRR parameters, and shorter time to obtain the maximum heat release rate t-pHRR. Coniferous wood dusts have a shorter TTI, influenced perhaps by the higher content of flammable volatiles that are included in the resin. Faster ignition due to the release of flammable volatiles influenced the time to reach the HRR peak for coniferous wood dust compared to deciduous wood (alder). At the same time, the achievement of higher HRR peaks for coniferous wood poses a higher fire hazard as determined by the FIGRA parameter. In particular, pine dust appears to be the dust that poses a particular fire risk, as it reaches the highest values of the parameters tested.

This is probably due to the higher resin content, which also translates into more heat generated. The time to ignition of alder dust is relatively long, and the combustion parameters are low. The total amount of heat released is higher than for spruce dust, see Fig. 1. As each of the tested samples had the same mass (20.0 ± 0.1 g). The tested dust particle sizes were a 50/50 mixture of dust in the range of 20–71 µm and 71–125 µm, the only element that differed in the samples seems to be the chemical composition. Analysing the amount of ash after burning the softwood dust, it was found that after burning alder dust, approx. 1.9 ± 0.1 g of ash was left, pine dust 3.0 ± 0.2 g of ash, and spruce dust 2.5 ± 0.1 g of ash. Comparing these data with the amount of generated heat, it can be concluded that the THR value for alder dust is related to 90% mass loss. The smaller amount of resin present in deciduous trees explains in this case the low amount of ash and the fumes generated during combustion.

Smoke density test

The insulated smoke density test chamber is widely used in all industrial sectors to determine the density of smoke produced by solid materials during interaction with external heat radiation under controlled conditions. The results of the measurements were the parameters characterizing the behaviour of materials under the influence of intense heat radiation, namely:

- smoke optical density in 1.5 min of the test—SOD1.5;
- smoke optical density after 4 min of the test—SOD4.0;
- smoke optical density after 10 min of the test—SOD10;
- maximum value of smoke optical density—MSOD;
- time to obtain the maximum value of smoke optical density—t-MSOD (s);
- the cumulative value of the smoke density in the first four minutes of the test—VOF4.

Averaged values of parameters obtained during measurements min. three samples of each of the tested dusts are presented in Table 2.

The obtained results indicate that despite the relatively rapid increase in the optical density of the fumes. Already

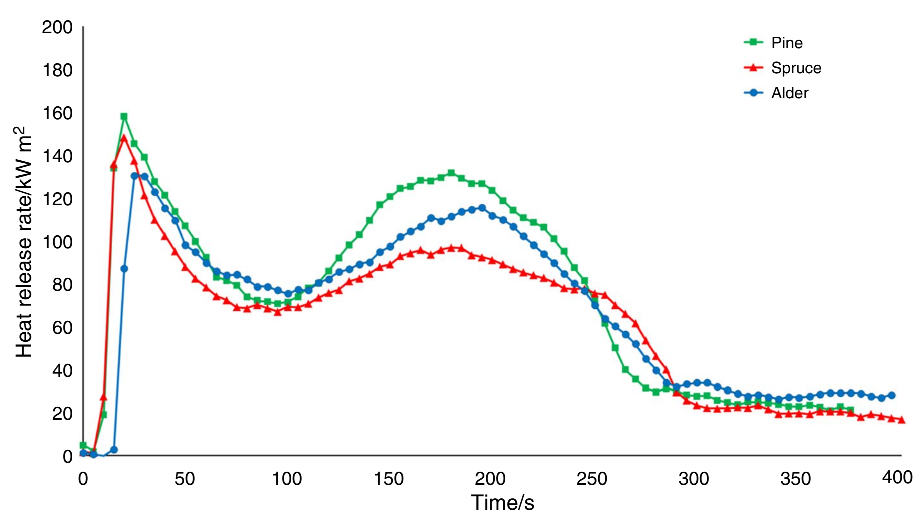

Fig. 1 Heat release rate as a function of time for tested wood dusts

Table 2 Smoke optical density of softwood dust

Sample	SOD1.5	SOD4.0	SOD10	MSOD	t-MSOD	VOF4
HF—25 kW (m^{-2})						
Pine	211	412	443	565	389	918
Spruce	197	418	381	545	353	897
Alder	160	416	387	563	328	800

in the first minute of the test, none of the dust ignited in contact with thermal radiation from the cone heated to a temperature of about 520 °C. Assuming that the amount of smoke released during the test of all three types of dust after ten minutes is relatively similar. It can be concluded, in accordance with the results obtained in calorimetric tests, that alder dust is characterized by the highest thermal resistance. The value of the SOD1.5 parameter for this dust is the lowest, which in comparison with the ignition time obtained from the cone calorimeter indicates the correctness of this assumption. Another explanation may be that the higher moisture content, which has a significant impact on the ignition time and the smoke density. Water evaporation process is endothermic that requires a lot of energy. Before the test, all dusts underwent a drying process; therefore, the amount of moisture in the dust was reduced as much as possible. Moreover, from the presented graph of the dependence of smoke density and mass in time, it does not appear that there was a mass loss without a significant increase in the smoke density in the first phase of the study. Therefore, the moisture content can be dismissed as an alternative explaining the noticeable difference in the SOD1.5 parameter values. It is worth noting that both during the study of the flammability parameters and the smoke density, the amount of remaining ash for softwood is approx. 50% higher than for hardwood dust. It is characteristic of deciduous wood dust to reach lower SOD values in the first minutes of the test. Large differences are noticeable between alder dust and the other dusts for SOD1.5, while subsequent SOD values show similar values. It can be concluded that the smoky character of alder dust is shorter but more intense. After 4 min of testing, the values achieved for all dusts are similar. However, alder wood dust reached the MSOD value in the shortest time, and for this parameter, the values for all dusts were similar. The later smoke release of alder wood dust contributes to the lower VOF4 values.

Determination of explosion characteristics

The result of the measurements was obtaining the characteristics of the explosion of softwood dust. The following parameters were determined during the tests:

- maximum explosion pressure—P_{max} (bar);
- deflagration index—K_{ST} (bar•m s^{-1});
- lower explosion limit for dust—LEL (g m^{-3}).

On the basis of the obtained results, individual dusts were assigned to explosion classes according to OSHA (Occupational Safety and Health Administration) in Table 3. It was found that all the tested dusts are characterized by low values of the lower explosion limit. For alder and spruce dust, the LEL values decrease with the reduction of the particle size. Alder dust with a particle size of 20–71 µm reaches the lowest LEL value of 40 g m^{-3}, which is the lowest determined value for the tested dust. A specific dependence of the maximum explosion pressure on the particle size was observed for the dusts of conifers and deciduous trees. In the case of alder dust, the increase in particle size resulted in a significant decrease (almost 1 bar) of the P_{max} parameter. On the other hand, in the case of coniferous dust, a slight increase in the explosion pressure was observed in both cases. This is an interesting observation because it is only noticeable for coniferous wood dust. Furthermore, it can be seen that an increase in particle size resulted in a decrease in the P_{max} value. The increase in *P*max, despite the increase in particle size, can be attributed to the intensive evaporation of volatile substances absorbed and chemically bound in the wood structure. This leads to a reduction in temperature and thus in maximum pressure. Many sources indicate a decrease in P_{max} with increasing particle size, which is also noticeable for alder dust [5]. It is worth mentioning that the P_{max} value depends both on the increase in the number of moles of gaseous products in a constant volume, but also on the temperature inside the

Table 3 Explosion characteristics of softwood dust in two particle size ranges

Sample	P_{max} bar	Conc. /g m^{-3}	K_{ST} bar/m s^{-3}	ST class –	LEL /g m^{-3}
20–71 µm					
Pine	7.5	1000	194	ST 1	50
Spruce	7.5	500	212	ST 2	50
Alder	7.5	500	175	ST 1	40
71–125 µm					
Pine	7.7	1000	180	ST 1	50
Spruce	7.7	500	188	ST 1	60
Alder	6.7	1250	101	ST 1	60

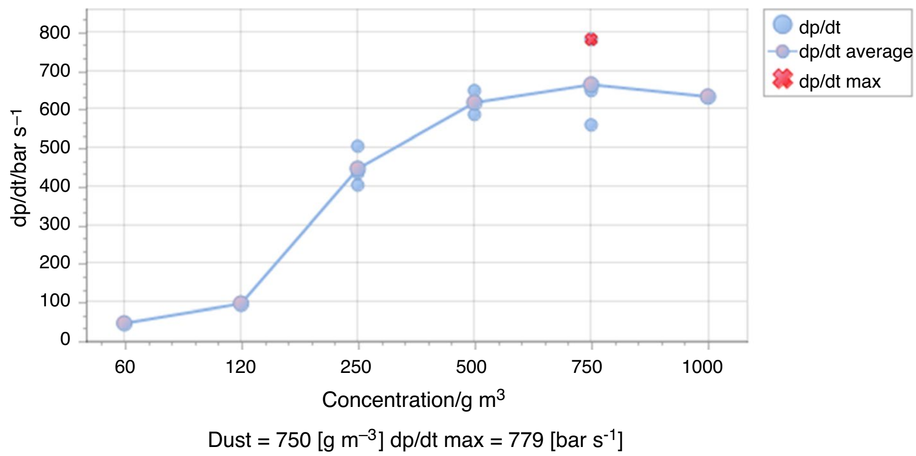

Fig. 2 Diagram of the dependence of pressure increase per unit of time on concentration for spruce dust with particle size in the range of 20–71 μm

test system. Therefore, the effect mentioned above may be due to the fact that for coniferous wood dusts with smaller particles, volatiles are evaporated in the first stage of combustion, which can result in a lower temperature, lowering the P_{max} value. For the larger particles of these dusts, despite the lower values of the rate of pressure rise (K_{ST}), the temperature lowering effect is lower, probably due to the smaller surface area of the dust, the evaporation does not take place as quickly. Part of the flammable vapours is burned off during this time, while the rest continues to evaporate. Therefore, the temperature reduction is not as noticeable, which translates into higher P_{max} values.

Another observation is that the maximum pressure values in the case of conifers were observed at the same concentrations for both particle size ranges, while for alder dust, the maximum pressure was determined at a concentration 2.5 times higher. This is probably due to the fact that the maximum pressure for deciduous wood dust is set in the initial phase of combustion, making it necessary to increase the specific total surface area of the dust particles. As mentioned earlier, as the particle size increased, there was a decrease in the (dp/dt)max value. For spruce dust with a particle size of 20–71 µm, the determined maximum value of the K_{ST} parameter exceeded 200 bar·m s^{-1}, Fig. 2. This allows the dust to be classified as ST2 explosion class (strong explosive properties). A slightly lower value was obtained for spruce dust, and although 200 bar·m s^{-1} (classification to the ST2 explosion class) was not exceeded. K_{ST} value of 194 bar·m s^{-1} means that this dust is on the border between the ST1 and ST2 classes. Once again, a discrepancy in the behaviour of coniferous and deciduous dusts with an increase in particle size was observed. The K_{ST} values for pine and spruce dust decreased by approx. 10–15%, while for alder dust, the value of the K_{ST} parameter decreased by approx. 40% with the increase in particle size. This is further evidence of the differences in the explosion characteristics of deciduous and coniferous wood dust. This may be influenced by the content of combustible volatiles released in the first stages of combustion.

Table 4 Values of the MIE for the tested dusts

Dust	MIE mJ
20–71 μm	
Pine	10–30
Spruce	10–30
Alder	30–100
71–125 μm	
Pine	30–100
Spruce	30–100
Alder	30–100

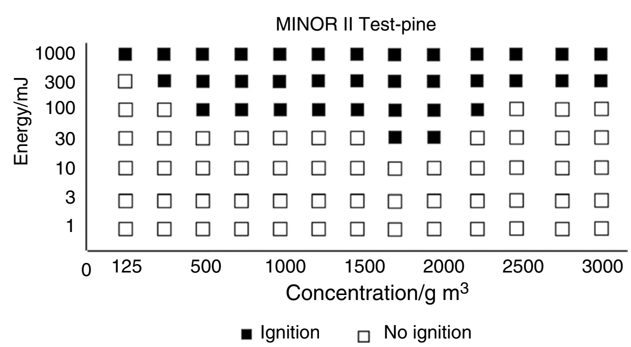

Fig. 3 Graphical interpretation of the minimum ignition energy test

Determination of minimum ignition energy (MIE)

The result of the minimum ignition energy test is the lowest value of the energy that, in contact with the dust–air mixture, it ignites. The results of tests carried out for all tested wood dust samples are summarized in Table 4.

Analysing the obtained results, it can be concluded that both pine and spruce are ignited by an electric spark with energy in the range of 10–30 mJ, Fig. 3. This value increases in the range of larger particle sizes up to 30–100 mJ. This increase is due to the greater mass of a single particle. The same amount of energy from the spark is distributed in this case by a greater number of chemical molecules that are part of the organic material, causing a lower temperature to increase in the entire system. In addition, the greater mass of the dust causes the contact surface between the heated material and the originating oxygen from air is smaller, and thus, the initiation of a self-sustaining combustion process is much more difficult. Alder dust in both particle size ranges is ignited by a spark in the same energy range of 30–100 mJ. A higher value of MIE for the finer dust fraction than in the case of coniferous dust partially correlates with the calorimetric values. Despite the fact that a 50:50 mixture of dusts with different particle sizes was used for calorimetric tests, the ignition time largely depends on the heating speed of the smallest particles present in the sample. It can, therefore, be assumed that the ignition times partially correlate with the minimum ignition energy obtained in the tests with the use of the MINOR 2 apparatus. The obtained results confirm the high susceptibility of softwood dusts to ignition from an electric spark of relatively low energy, in particular for wood dust of conifers with a particle size range of 20–71 µm.

Table 5 Values of the minimum ignition temperature for the tested substances

Dust	MIT °C
20–71 µm	
Pine	450
Spruce	495
Alder	485
71–125 µm	
Pine	450
Spruce	500
Alder	490

Determination of minimal ignition temperature of a dust cloud (MIT)

The test of the minimum ignition temperature of the dust cloud was carried out in accordance with the [10] standard at the Central Mining Institute. The results obtained for softwood dust samples in both particle size ranges are summarized in Table 5. The lowest value of the dust cloud ignition temperature, at the level of 450 °C, was obtained for pine dust at both particle size ranges. The ignition temperature of spruce and alder dust has similar values in the range of 490–500 °C. In both cases, the difference between MIT for the different particle size ranges is 5 °C. The lack of a significant difference in ignition temperature as a function of particle size may also indicate that fineness is not the only determining factor for ignition. The difference in sensitivity to ignition initiator and particle size in the MIE test may indicate that particle size has a greater influence on sensitivity to initiating stimuli in the case of sources acting locally (spark igniting the entire dust volume). Compared to agents acting on the entire dust volume, (thermal radiation emitted by the heated walls of the furnace through which the dust is blown).

Conclusions

During this research, three types of wood dusts were investigated for their flammability, explosion characteristics, and minimum ignition temperatures and energy. Based on gained results, it can be concluded that pine shows the highest values of almost all parameters, from tested dusts. Pine can grow into a large fire, emitting over four times as much smoke than alder. Both dusts from the conifer group are characterized by shorter ignition times, higher pHRR parameters, and shorter time to obtain the maximum heat release rate t-pHRR than alder. The results obtained during the tests with the use of the smoke test chamber indicate that the optical density of the fumes in the first ninety seconds of the test (SOD1.5) is the lowest for alder dust, which in comparison with the ignition time obtained from the cone calorimeter indicates the correctness of this assumption. It is observed that alder wood dust, which initially emits the lowest amount of smoke, is the earliest to obtain a value for the MSOD parameter, the values of which are similar for each dust.

Analysing the results obtained during the determination of the explosion characteristics of individual dusts in two variants of fragmentation. It was found that alder dust with particle sizes in the range of 20–71 µm reaches the lowest value of the lower explosion limit of 40 g m^{-3}, it is the lowest determined value for the tested dusts. For spruce dust with a particle size of 20–71 µm, the determined maximum value of the deflagration index (K_{ST}) exceeded 200 bar·m s^{-1} which qualifies it to ST2 explosive class with a high explosive characteristic. An unexpected increase in P_{max} for coniferous wood dust with increasing particle size was also observed, and for alder dust (deciduous tree), the results showed the expected relationship. The K_{ST} values for all dusts clearly indicated a relationship between dust particle size and the rate of pressure increase. This makes the results of the P_{max} values all the more surprising. The lowest value of the dust cloud ignition temperature, at the level of 450 °C, was obtained for pine dust at both particle size ranges. The ignition temperature of spruce and alder dust has similar values in the range of 490–500 °C. It can be concluded that greater sensitivity to ignition sources will be achieved by dusts with smaller particle sizes. However, this effect is greater for point-acting ignition sources, where energy is concentrated on individual particles such as an eclectic spark. The analysis of all obtained results and the relationships between them suggests that there are large discrepancies between the results obtained for the dusts of deciduous and coniferous trees in the softwood trees group.

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Declarations

Conflict of interest Authors are required to disclose financial or non-financial interests that are directly or indirectly related to the work submitted for publication. Please refer to "Competing Interests and Funding" below for more information on how to complete this section.

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