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ASSESSMENT OF THE IMPACT OF SPRUCE WOOD PARTICLE SIZE AND WATER CONTENT ON THE IGNITION TEMPERATURE OF DUST CLOUDS

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This paper aims to assess the impact of water content and particle size of Norway spruce (*Picea abies* (L.) Karst.) wood dust on the ignition temperature of dust clouds. Dust samples were divided into four size fractions: less than 71 µm, from 71 to 150 µm, from 150 to 200 µm, and from 200 to 250 µm. Three different water contents, i.e. 0, 4 and 8 wt%, were analysed for each fraction. Ignition temperatures were determined for three different sample weights: 0.1, 0.2 and 0.5 g and for three different values of air pressure: 20, 30 and 50 kPa according to EN 50281-2-1:1998. The results showed that minimum ignition temperature (400 °C) was measured for a sample of 0.5 g weight and air pressure of 30 and 50 kPa. The determined ignition temperatures under the examined conditions were evaluated using one-way analysis of variance followed by Duncan's multiple range test. The results of the analyses indicate that water content in the examined interval does not have a significant impact on ignition temperature. On the other hand, ignition temperature increases almost linearly with the increasing particle size.

Keywords: dust cloud, dust fire, explosion, fire risk assessment, ignition temperature, Norway spruce wood, wood dust

INTRODUCTION

Dust explosion is one of the major causes of industrial accidents. With the development of wood process industry, the probability of dust explosion increases and its consequences are much severer than before.[1-2] In 22% of industrial dust explosions, explosive atmosphere consists of wood dust clouds.[3]

In a working environment, dust occurs in two forms: as settled dust (dust layer) or dispersed dust (dust cloud), and it can change its status from one form to another very easily. Settled dust can be dispersed very simply (*e.g.* by vibrations or air flow), while a dust cloud becomes settled via the sedimentation process.[4-5] The fire hazard of wood dust depends on its form. Settled dust has a tendency for spontaneous combustion and flameless combustion (smouldering). Flameless combustion (smouldering) is dangerous due to the production of a high amount of toxic combustion products, primarily carbon monoxide.[6-9] However, from the viewpoint of fire safety, a dust cloud is a more dangerous form since it is a potential source of explosion risk.[10]

In wood industry, the risk of dust explosion can be reduced to a minimum by the principles of inherent safety. Inherent safety is a proactive approach to process safety in which hazards are eliminated or lessened so as to reduce the risk without engineered (add-on) or procedural intervention. Four basic principles are available to attain an inherently safer design: minimisation (use minimum quantities of hazardous materials if the use of such materials cannot be avoided), substitution (replace substances with less hazardous materials or processing procedures with methods that do not involve hazardous materials), moderation (use hazardous materials in their least hazardous form) and simplification (design processes, processing equipment and procedures to eliminate errors by eliminating excessive use of add-on safety features and proactive devices).[11]

In wood processing, the first three principles of risk reduction of wood dust explosion are practically not applicable, or are applicable only to a very limited extent. Hence, simplification remains the only efficient principle. Operating procedures and equipment that reduce the risk of explosion are selected on the basis of technical and safety parameters of wood dust.

Technical and safety parameters are divided into parameters describing the probability risk of dust cloud explosion (minimum ignition temperature, lower explosion limit, and minimum initiation energy) and parameters describing explosion effects (maximum explosion pressure and maximum increase rate of explosion pressure). Lower explosion limit and minimum ignition temperature have the highest informative value for preventing dust cloud explosion. Lower explosion limit represents the probability of creating an explosive atmosphere, and minimum ignition temperature reflects the probability of ignition of the explosive atmosphere. The stated technical and safety parameters greatly depend on the characteristics of combustible dust and external conditions. The most important properties of combustible dust are its chemical composition, concentration, particle size, water content and the presence of additive substances used for the protection of material, from which the dust particles were created.

Technical and safety parameters of dust are mostly affected by its chemical composition. It has a decisive impact on dust flammability and on the mechanism of dust degradation and combustion during explosion. Eckhoff[12] and Rockwell and Rangwala[13] made a distinction between two types of dust flames: the Nusselt flame and the volatile flame. In the Nusselt flame, strictly heterogeneous combustion occurs at the surface of the particles, sustained by diffusing oxygen towards the particles' surface. In the volatile flame, particles produce vapour before combustion. When mixed with air, these gases and vapours burn as a premixed gas. Wood dust typically follows the second type of behaviour. During the combustion of a wood dust cloud, its degradation and the combustion of degraded gaseous products occur followed by the combustion of the solid residue.[14]

The differences in chemical composition of different tree species primarily result from the variability of the content of its main components (cellulose, hemicellulose and lignin), and the content of extractives and their chemical composition. However, the changes in the content of the main components do not primarily cause the variability in technical and safety parameters of wood dust. The variability results mainly from the differences in physical characteristics, and in the content and chemical composition of extractives. Physical characteristics of wood primarily depend on its structure. Significant differences in wood structure, content, and chemical composition of extractives are mainly between native (European) and exotic tree species (from Africa, Asia and Southern America).

In the case of similar chemical composition of dust clouds, their technical and safety parameters are primarily influenced by their concentration in the atmosphere, particle size and their water content. A number of works[15-20] have dealt with the impact of the stated parameters on explosion, while the majority of them focused on coal, food, and metal dust. Nevertheless, the conclusions presented in these works can be generalised to any combustible dust.

Dust clouds reach minimum ignition temperature, maximum explosion pressure and flame temperature at concentrations close to the stoichiometric ratio.[4,15-19] However, the results of Li *et al*.[20] indicate that not all dust clouds approaching the stoichiometric ratio show the maximum rate of increase of the explosion pressure.

In the interval from the lower explosion limit to the concentration of the stoichiometric ratio, the ignition temperature of a dust cloud decreases exponentially with its increasing concentration.[15] The lower explosion limit increases exponentially with the increasing particle size. The increase of the lower explosion limit is milder in more volatile materials than in less volatile materials. The relationship of the minimum ignition energy to the particle size is linear, while the relationship to dust concentration is quadratic (with the minimum at the concentration close to equivalent ratio).[21] The minimum ignition temperature of a dust cloud increases almost linearly with the increasing particle size.[15]

Only a few scientific works[10,21] have dealt with the exact assessment of the combined effect of particle size and wood dust moisture on the minimum ignition temperature. The evaluation of the impact of particle size on the minimum ignition temperature is usually based on the generally accepted theorem that minimum ignition temperature increases with the increasing particle size. In the case of a large range of particle sizes (*i.e.* several hundreds of micrometers) this assumption is accurate, but if dust consists of particles with size differences of several tens of micrometers only, this conclusion is not always valid. The invalidity of the generally accepted theorem in the particle size interval of several tens of micrometers is documented by Martinka *et al.*,[10] and Mitall and Guha.[15-16]

The impact of water content on the minimum ignition temperature of dust clouds has not been exactly assessed yet. Nevertheless, the results presented by Ladomersky *et al.*,[22] Zachar and Skrovny,[23] Terenova,[24] Shi and Chew,[25] Liesiene and Kazlauske[26] and Suty *et al.*[27] indicate a significant impact of water content in wood on its ignition and combustion. Hence, it can be expected that minimum ignition temperature of dust clouds will significantly increase with the increasing water content.

The parameters of the ignition source (temperature, energy, and time of exposure) and the properties of the oxidising atmosphere (flow rate and flow character – laminar or turbulent, temperature, oxygen concentration and relative air humidity) belong to the most important external conditions affecting technical and safety parameters of dust clouds. The influence of the parameters of the ignition source and the oxidising atmosphere was thoroughly addressed by Wu *et al.*,[28] Martinka *et al.*,[29] Majlingova *et al.*,[30] and Xu *et al.*[31]

The aim of the present paper is to assess the combined impact of water content and particle size of Norway spruce (*Picea abies* (L.) Karst.) wood dust on the minimum ignition temperature of dust clouds.

EXPERIMENTAL

Materials

The samples of Norway spruce (*Picea abies* (L.) Karst.) wood dust were divided into four different particle size fractions (less than 71 µm, from 71 to 150 µm, from 150 to 200 µm, and from 200 to 250 µm). All fractions were measured at three different water contents (0, 4 and 8 wt%).

The samples were prepared from compact wood with a density of 432 kg.m^{-3} (at water content 12 wt%) by grinding with a hand-held belt sander. Afterwards, the samples were dried at a temperature of 103 ± 2 °C to water content of 0 wt% for 24 hours. Consequently, they were sieved in order to divide the samples into the analysed fractions and again dried to absolute moisture of 0 wt% (because water content had risen during sieving). Next, the samples were divided into three groups. The ignition temperatures of the first group of dust clouds were measured at water content of 0 wt%. The second and the third groups were conditioned to water contents of 4 wt% and 8 wt%, respectively, prior to the measurements.

Equipment and procedure

The ignition temperatures of the analysed samples were determined with the Godbert-Greenwald furnace apparatus according to EN 50281-2-1:1998[32] using a modified test procedure. The modification referred to the particle size of the analysed dust samples that differed from the requirements of the cited standard. The above-mentioned technical standard demands testing of dust samples that fall through a test sieve with square openings of nominal size 71 µm. In this work, the ignition temperatures of dust clouds were determined for the dust composed of the particles with the size above and below 71 µm. The ignition temperatures were determined for the samples weighing 0.1, 0.2 and 0.5 g ± 5% and air pressures of 20, 30 and 50 kPa ± 5%. The chosen testing conditions allowed exact assessment of the impact of particle size and water content on the ignition temperature of spruce wood dust clouds. A detailed description of the applied testing apparatus is presented by Mittal and Guha.[16]

Every test (for each sample weight, air pressure, particle size, and water content) was repeated ten times at the given ignition temperature and at the temperature lower by 10 °C than the ignition temperature. The temperature was considered to be the ignition temperature if the ignition occurred at least once, while at the temperature lower by 10 °C no ignition occurred.

RESULTS AND DISCUSSION

Table 1 presents the ignition temperatures of Norway spruce (*Picea abies* (L.) Karst.) wood dust clouds for the analysed sample weights (0.1, 0.2 and 0.5 g), air pressure values (20, 30 and 50 kPa), four fractions of particle size (less than 71 µm, from 71 to 150 µm, from 150 to 200 µm, and from 200 to 250 µm), and three water content values (0, 4 and 8 wt%).

According to EN 50281-2-1:1998,[32] the minimum ignition temperature of dust clouds of the analysed samples was 400 °C (the cited standard considers as minimum ignition temperature a value of temperature decreased by 20 °C, at which the ignition of the dust sample with the particle size less than 71 µm occurs). According to Kasalova and Balog,[33] the minimum ignition temperature of spruce dust cloud is 410 °C. The difference between the values is caused by the higher water content in the samples of the cited authors compared to our samples. According to Turekova *et al.*,[34] and Zachar *et al.*,[35] the minimum ignition temperature of a settled spruce dust layer and compact spruce wood is 380 °C and 400 °C, respectively. The presented values (Table 1) show that the ignition temperature of spruce wood does not vary much regardless of its form and the assessment method.

Fig. 1 presents the values of mean ignition temperatures of spruce wood dust clouds with the standard deviation for the given categories of particle size and water content. The values in Fig. 1 indicate that water content (within the analysed range from 0 to 8 wt%) does not have a significant impact on the ignition temperature, while the effect of particle size is significant. The stated hypothesis about the effect of water content and particle size was tested with one-way analysis of variance (ANOVA) performed in MS Excel 2010. The calculated criterion $F = 0.7875 < F_{\text{crit}} = 3.0829$ at $\alpha = 0.05$ significance level suggests that null hypothesis of the identity between mean values of ignition temperatures of spruce wood dust clouds with water contents of 0, 4 and 8 wt% can be accepted. The conclusion that the ignition temperature does not depend on water content is valid only for the examined interval of water content. Other works of Ladomersky *et al.*,[8,22] Terenova,[24] Shi and Chew[25] and Macindoe and Leonard[36] demonstrate that water content in tens of wt% has a significant impact on the ignition and the combustion of wood and wood materials. In addition, according to Dzurenda,[37] who refers to the results of the state laboratory in Ostrava-Radvanice, wood dust with water content above 40 wt% is non-combustible.

Table 1

Ignition temperatures of spruce dust clouds for the analysed sample weights, air pressure, water content and particle fractions

Sample weight (g)	Air pressure (kPa)	Water content (wt%)	Ignition temperature (°C)			
			Particle size (μm)			
			<71	71-150	150-200	200-250
0.1	20	0	470	500	500	520
0.1	30	0	460	470	490	490
0.1	50	0	450	460	490	510
0.1	20	4	480	500	510	510
0.1	30	4	460	480	480	510
0.1	50	4	460	470	480	510
0.1	20	8	460	480	510	520
0.1	30	8	460	480	500	510
0.1	50	8	460	470	500	530
0.2	20	0	460	490	500	500
0.2	30	0	430	470	480	500
0.2	50	0	430	440	470	490
0.2	20	4	450	460	490	500
0.2	30	4	440	450	480	500
0.2	50	4	430	460	480	490
0.2	20	8	450	480	490	520
0.2	30	8	450	470	470	500
0.2	50	8	450	470	470	500
0.5	20	0	440	450	480	490
0.5	30	0	420	450	460	500
0.5	50	0	420	450	460	490
0.5	20	4	430	450	470	490
0.5	30	4	430	450	470	470
0.5	50	4	430	450	470	470
0.5	20	8	440	470	480	500
0.5	30	8	430	460	470	480
0.5	50	8	440	460	480	490

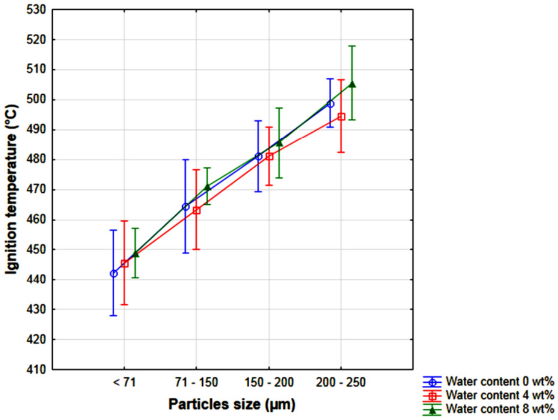

Figure 1: Relationship between the ignition temperature of spruce wood dust cloud and particle size at three different water contents (vertical bars denote +/- standard deviations)

Table 2

Results of ANOVA examining the impact of particle size of spruce wood dust clouds (with water contents of 0, 4 and 8 wt%) on the ignition temperature (significance level $\alpha = 0.05$)

ANOVA coefficients	Water content (wt%)		
	0	4	8
F	19.1812	15.6444	31.4553
F_{crit} (-)	2.9011	2.9011	2.9011

The results of the analysis of variance aimed at testing the impact of particle size (at all analysed water contents) on the ignition temperature of spruce wood dust clouds are presented in Table 2. The data in Table 2 show that $F > F_{\text{crit}}$ for all analysed water contents. Thus, the null hypothesis of the identity between mean values of ignition temperatures of dust clouds composed of spruce wood particles of all different sizes (less than 71 µm, from 71 to 150 µm, from 150 to 200 µm, and from 200 to 250 µm) was rejected at $\alpha = 0.05$ significance level. Hence, particle size has a significant influence on the ignition temperature at all analysed water contents (0, 4 and 8 wt%).

The analysis of variance was followed by Duncan's multiple range test. Duncan's test was performed using StatSoft Statistica 10. The results are presented in Tables 3 to 5. Duncan's test p values evaluate the statistical significance of the difference between the means of the ignition temperature of dust clouds composed of particles of different fractions. The difference between ANOVA and Duncan's test is that ANOVA examines if there is a significant difference between the ignition temperatures of two to n samples in a statistical set consisting of n samples (that differ in the size of their particles). The results of ANOVA do not allow revealing which two samples are significantly different from each other. However, Duncan's test is able to indicate the samples (that differ in the size of their particles) with significant differences between their mean ignition temperatures. Significant difference is indicated by Duncan's test p value that is lower than 0.05.

The data presented in Tables 3 to 5 show that there are significant differences between the mean ignition temperatures of dust clouds composed of particles of different fractions for all analysed water contents. The data in the tables and in Fig. 1 document that the mean ignition temperature increases linearly with the increasing size of particles. An almost linear relationship between the minimum ignition temperature and the size of dust particles was also found by Mittal and Guha[15-16] and Cao *et al.*[18] The only exception was identified for the dust with water content equal to 4 wt% composed of particles of sizes from 150 to 200 µm, and from 200 to 250 µm, for which no significant difference between their mean ignition temperatures was revealed. This fact can result from two possible causes. The first possibility is uneven distribution of particle sizes in the fractions from150 to 200 µm and from 200 to 250 µm (i.e. that in both fractions particles with the dimensions close to 200 µm may be dominant). However, this is highly improbable, since the samples of all four fractions were homogenised prior to moisture conditioning. This means that if the uneven distribution of the particle sizes in the fractions had been the primary cause of the above-stated fact, it would also have been observed for other water content values (0 and 8 wt%). Therefore, the impact of water content on the ignition temperature of dust cloud seems to be a more probable cause of the observed results. According to Bardon and Fletcher,[14] the combustion (explosion) of a wood dust cloud is coupled with its degradation and combustion of gaseous degraded products followed by the combustion of the solid residue. Hence, the combustion mechanism of the wood dust cloud is similar to the mechanism of solid wood. Carbon monoxide (CO) is one of the most significant products of thermal degradation and partial wood oxidation. According to Balog,[38] the combustion rate of CO mixed with oxygen is a monotonous function of hydrogen or hydrogen compounds. The studies of Ladomersky *et al.*[9,22] and Martinka *et al.*[39] document that the combustion of the oven-dry wood does not take a perfect path and releases a relatively high amount of CO. The reason is the low amount of hydrogen and hydrogen compounds (in the case of oven-dry wood their proportion is only around 6.3 wt%). Hence, wood burns with maximum efficiency only at optimum moisture, which depends on wood density, content of extractives and external conditions. Optimum moisture is usually equal to unit values of wt% (most commonly between 4 and 8 wt%). Therefore, it is probable that the optimum water content had a significant impact on the combustion rate of CO during the ignition and subsequent explosion of the spruce wood dust cloud composed of particles with the dimensions from 150 to 200 μm and from 200 to 250 μm. The increase of the CO combustion rate caused the difference between the mean ignition temperatures of the two fractions to diminish and to be insignificant.

The assumption that 4 wt% is the optimum water content for the ignition of the spruce wood dust cloud is partially documented by the data shown in Fig. 1. This figure illustrates that for all fractions except for the fraction less than 71 μm the lowest ignition temperatures were observed at water content of 4 wt%. In addition, Duncan's test coefficient of the two discussed fractions (i.e. from 150 to 200 μm, and from 200 to 250 μm) was only slightly greater than the critical value (0.05). Hence, non-significant difference between the mean ignition temperatures of spruce wood dust cloud composed of particles with the dimensions from the intervals between 150 and 200 μm, and between 200 and 250 μm, may be ambiguous.

Table 3
Duncan's test *p* values used to assess the impact of particle size of spruce wood dust cloud (with water content of 0 wt%) on the ignition temperature

Particle size (μm)	Duncan's test *p* value (-)			
	<71	71-150	150-200	200-250
<71	-	0.007734	0.000087	0.000055
71-150	0.007734	-	0.040421	0.000208
150-200	0.000087	0.040421	-	0.029541
200-250	0.000055	0.000208	0.029541	-

Table 4
Duncan's test *p* values used to assess the impact of particle size of spruce wood dust cloud (with water content of 4 wt%) on the ignition temperature

Particle size (μm)	Duncan's test *p* value (-)			
	<71	71-150	150-200	200-250
<71	-	0.025987	0.000128	0.000055
71-150	0.025987	-	0.025987	0.000442
150-200	0.000128	0.025987	-	0.089372
200-250	0.000055	0.000442	0.089372	-

Table 5
Duncan's test *p* values used to assess the impact of particle size of spruce wood dust cloud (with water content of 8 wt%) on the ignition temperature

Particle size (μm)	Duncan's test *p* value (-)			
	<71	71-150	150-200	200-250
<71	-	0.000972	0.000062	0.000055
71-150	0.000972	-	0.022584	0.000064
150-200	0.000062	0.022584	-	0.002392
200-250	0.000055	0.000064	0.002392	-

The measured data were used for the prediction of the ignition temperature for the samples weighing from 0.05 to 0.55 g under different values of air pressure from the interval between 15 and 55 kPa. The prediction was performed with the distance weighted least squares model in StatSoft Statistica 10 software environment. The results are presented in Figs. 2 to 4.

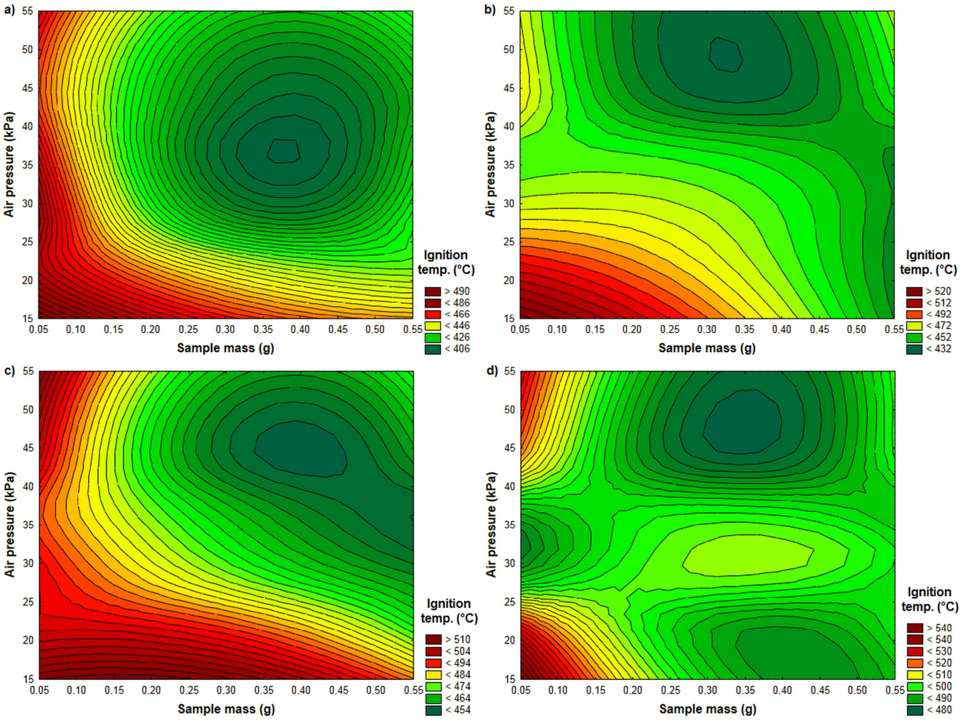

Figure 2: Prediction of ignition temperatures of spruce wood dust cloud (with 0 wt% water content) composed of particles of sizes: a) less than 71 μm; b) from 71 to 150 μm; c) from 150 to 200 μm; d) from 200 to 250 μm

The assessment of the risk of wood dust cloud explosion should also account for other factors that can have a significant impact on the ignition temperature. The most significant factors affecting the ignition temperature include the presence of fire retardants.

Fire retardants, used to reduce the flammability of solid wood or chipboard wood materials from which dust originates, have a great effect on the technical and safety parameters of dust clouds. The influence of fire retardants on the technical and safety parameters depends mainly on their chemical composition and application method.

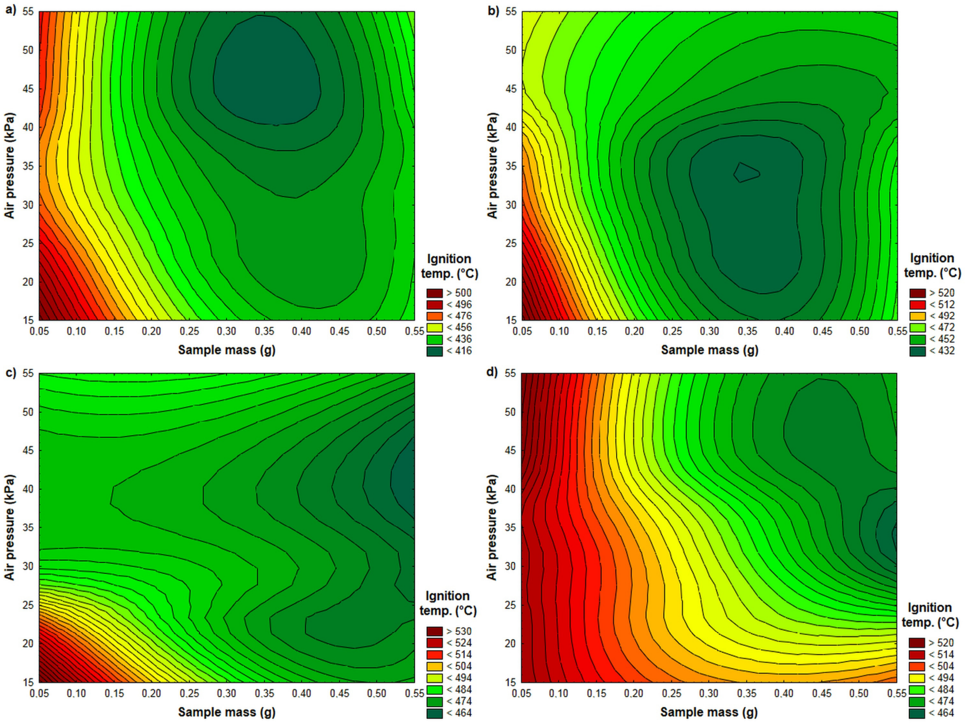

Figure 3: Prediction of ignition temperatures of spruce wood dust cloud (with 4 wt% water content) composed of particles of sizes: a) less than 71 μm; b) from 71 to 150 μm; c) from 150 to 200 μm; d) from 200 to 250 μm

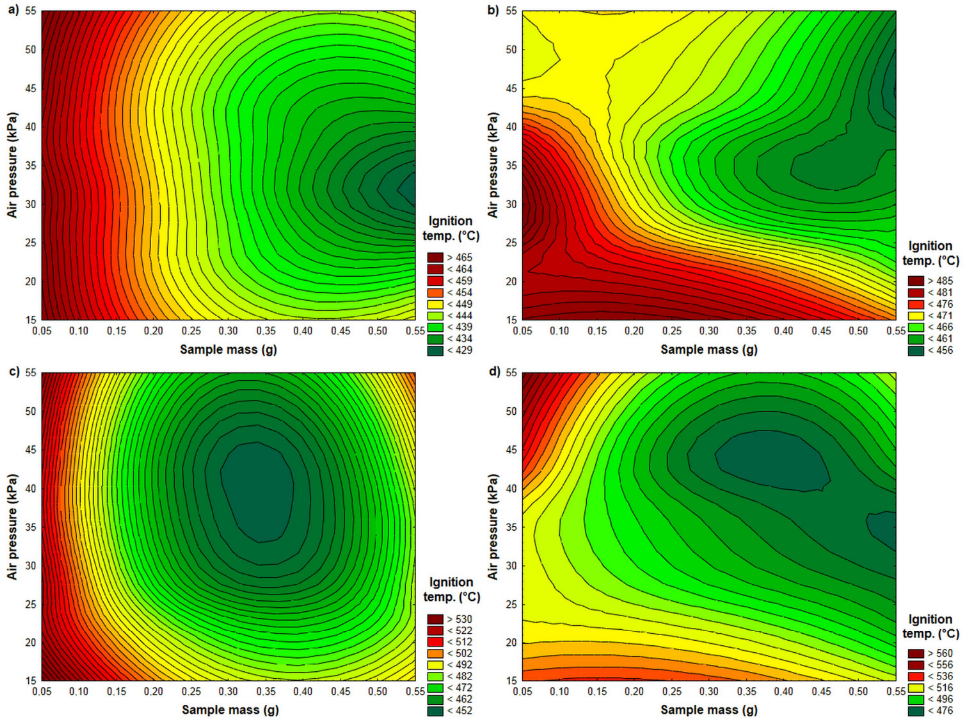

Figure 4: Prediction of ignition temperatures of spruce wood dust cloud (with 8 wt% water content) composed of particles of sizes: a) less than 71 μm; b) from 71 to 150 μm; c) from 150 to 200 μm; d) from 200 to 250 μm

In spite of the fact that the effect of most retardants on the minimum ignition temperature of dust clouds has not been exactly determined, it can be predicted from the mechanism of their functioning and from their efficiency to reduce the flammability of compact wood materials. The effect of fire retardants on the flammability of wood and other organic polymers has been described in Qu *et al.*,[40] Zhang *et al.*,[41] Osvaldova-Makovicka and Osvald,[42] Cazacu *et al.*,[43] Volf *et al.*,[44] and Rybakowski *et al.*[45] Apart from fire retardants, other chemicals used for chemical protection of wood (*e.g.* biocides) may also have a great effect on technical and safety parameters.

CONCLUSION

Wood dust represents one of the most common explosive atmospheres in industry. The ignition temperature of a dust cloud is a technical safety parameter that characterises the sensitivity of the explosive atmosphere consisting of dust cloud to ignition by hot surface. The ignition temperature of dust depends not only on the chemical composition, but also on the particle size and water content.

The obtained data document that the mean ignition temperature of spruce wood dust cloud increases almost linearly with the increasing particle size. On the contrary, water content between 0 and 8 wt% does not have a significant impact on the ignition temperature.

Apart from particle size and water content, the minimum ignition temperature is also significantly affected by the content and the chemical composition of fire retardants and other chemicals used for the chemical protection of wood. The exact assessment of their impact on the ignition temperature will be a subject for future research.

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