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TECHNICAL NOTES

Influence of particle size and moisture content of wood particulates on deflagration hazard

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FOREWORD

For many revision cycles NFPA 664 Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities, has used a median particle size to distinguish between particulates that should be considered a potential deflagration hazard from those that can be safely assumed to not pose a deflagration hazard. With a numerical median size criterion in the standard, a physical inspection can be employed to identify which portions of the process stream represent a potentially hazardous condition and which do not. The standard defines “deflagrable wood dust” on the basis of mass median particle size and moisture content. This makes the standard much easier and less-costly to use. Question has been raised over the suitability of both the numerical value of the mass median particle size and the moisture content. The other dust standards rely entirely on dust testing in accordance with ASTM E 1226 with no explicitly identified gross physical parameter quantified. Consequently, one cannot know if a particulate is hazardous without testing it. But the test method relies upon modifying the particulate to accommodate the test apparatus. This can result in the overstatement of the hazard in some cases. It can also result in circumstances where the particulate is impossible to test in the current ASTM method and no conclusion is achievable. In that case compliance with the requirements of the standard becomes impossible. Naturally, this situation erodes the confidence in the standard as a whole.

The overall goal of this project is to develop a data set from published literature that may provide basis for substantiating mass median particle size and moisture content criterion for distinguishing wood particulates that are extremely unlikely to pose a deflagration hazard from those that should be submitted for testing.

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EXECUTIVE SUMMARY

Dust explosions are a common and frequent hazard in the wood processing industry. Trying to avoid these events, several researchers have determined the main parameters affecting explosions, so they can be controlled and reduced. Among a list of them, particle size and moisture content are considered two of the most influential ones.

The Standard, NFPA 664 for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities quantified these parameters, providing numerical limits that should not be surpassed to ensure safety operations in the industry. In this frame, the overall goal of this project was to develop a data set from published literature that might provide basis for substantiating mass median particle size and moisture content criterion for distinguishing wood particulates that are extremely unlikely to pose a deflagration hazard from those that should be submitted for testing.

However, when starting to look at the available data for the wood industry, it became evident how scarce this data is. Companies and facilities are testing these materials, but the data is not available, and the general public cannot access it. Nevertheless, this lack of availability is not the only problem that needs to be solved. First, this report shows an urgent need in the wood industry to develop and implement a new methodology to classify the risk of deflagration depending on the particle size and the moisture content. However, as we have shown along the present document, to achieve this goal there are several steps that need to be performed in advance: new parameters to define particle size and a consensus on the methodologies used to determine these parameters, as well as an effort on make the obtained data available to other users, are key to this end.

This investment and collaboration is essential to make safer conditions. Nonetheless, we believe that assigning a single value for all the different wood species and the different facilities and situation that we can encounter would be too simplistic and not accurate enough.

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Influence of particle size and moisture content of wood particulates on deflagration hazard

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Introduction

The influence of particle size and moisture content on the behaviour of dust explosions has been thoroughly studied for coal, and it is well known that smaller and drier products cause easier-to-ignite clouds and that the resulting deflagration are more violent. Several researchers have satisfactorily worked on describing these influences, both experimentally and computationally. However, with the increase on the use of new energy materials such as biomass, this behaviour needs to be revised and reconsidered to ensure safe working spaces.

When starting to look at the available data for the wood industry, it became evident how scarce this data is. Companies and facilities are testing these materials, but the data is not available, and the general public cannot access it.

However, this lack of availability is not the only problem that needs to be solved. Biomass was treated as any previous studied fuels, mainly fossil fuels, and assumptions were made in order to use the already stablished knowledge in this case. However, there is a fundamental difference between coal and biomass particles that leads to several gaps of knowledge that need to be filled: the effect of particle morphology should be understood. Coal particles have always been treated as spherical particles, and all the studies regarding their deflagration behaviour is based on this. Nevertheless, biomass particles are not spherical, one of the dimensions often being much larger than the other two. This implies the need of a change in the parameters used to define the particle size of these materials, and a new complete study on how this change influences the deflagration behaviour of dusts.

Secondly, and no less important, the lack of consensus on the use of a determined experimental procedure to measure the particle sizes increases the uncertainty around the values, and the impossibility of comparing the obtained results.

The influence of moisture is clearer in this case. Moisture can promote the explosibility of certain materials, but in the case of wood, an increase on the moisture content causes a decrease of both the tendency to ignite and the severity of the explosions.

The process to fill these research gaps has already started, but it needs to accelerate, and we need to make sure that it is done, because it is the only way of ensuring safe working spaces.

The standard NFPA 664 defines the values of particle size and moisture content of wood particulates that cannot be surpassed in order to avoid explosions.

In the present document, we analyse the existing knowledge on particle size, shape and distribution, and moisture content in dust explosions; we study the different experimental procedures used to determine the particle size, which lead to an inconsistency of the obtained results; we report the data collected regarding the particle size; and we end up giving some advice on future needs.

Clarification on terminology

During the process of writing of this document, the authors and the panel members have noticed a systematic misunderstanding between the terms explosion and deflagration. The use of these terms in different part of the world present some differences that are important to clarify and that need to be understood for the present report.

To avoid any confusion, we would like to clarify these two definitions according with the in-use NFPA standards, and to establish that these are the ones used in the present report.

An explosion is "the bursting or rupturing of an enclosure or a container due to the development of internal pressure from a deflagration"

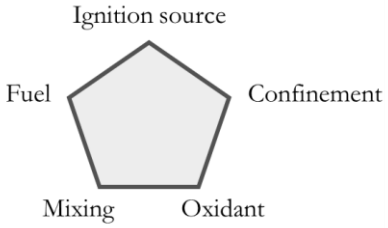
A deflagration is the "propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium".

Dust explosions

Even though the most known explosions are those caused by combustible gases, dust explosions are as frequent and damaging as the first one, and *"both types of explosions have the potential to cause loss of life, personal injury, property damage, business interruption, and environmental degradation"* [1].

When we study dust explosions, the first obstacle that we face is the definition of dust. As Amyotte points out in this book [1], historically a 420 μm or less in diameter was used to define dust [2]. However, they define combustible dust as a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size. And this is only the first time that we face a problem with quantifying the data.

What we know is that, in order for a dust explosion to start, five factors have to come together to make what has been called the dust explosion pentagon [3]:



i. Presence of combustible dust in finely divided form
ii. Availability of oxidant
iii. Presence of an ignition source
iv. Some degree of confinement
v. State of mixed reactants

Figure 1. Explosion pentagon

After the explosion occur, confinement is not needed for a deflagration to propagate through the fuel/air mixture. Furthermore, we know that any combustible material that poses a fire hazard in its solid form, will also pose a deflagration hazard if dispersed in air as dust. In addition, some materials that are not normally considered combustible can still be explosible when in dust form, such as metals [4]. This makes a long list of hazardous materials that need to be studied, characterised and classified.

Main factors influencing dust deflagrations

The main factors that influence the characteristics and consequences of dust deflagrations have been previously studied, mainly for fossil fuels. However, even when their importance is well-known, it is difficult to quantify it and their relative influence needs to be further studied, as well as how a combination of several factors affects these processes. Moreover, some of these parameters may present unexpected behaviours for different materials. That is why, due to the rise of new fuels, they need to be deeply studied and characterise.

Nevertheless, the parameters that are listed below represent the main ones that need to be always determine in order to study the characteristics and consequences of dust deflagrations.

Chemical composition

Volatiles, ash and moisture contents are basic parameters influencing the explosibility of dust clouds. An increase on the first one produces an increase on the explosibility of clouds, while the effect of ash and moisture are just the opposite [5] [6]

Particle size

Fine particles facilitate the flame propagation, and both the easiness of ignition and the severity of the explosion increases with their presence.

Dust concentration

This concentration must be in the range formed by the lower explosive limit and the upper explosive limit (flammable range) to be ignitable. In the case of dusts, the upper explosive limit is not very often used. [7]

Ignition source

The type, energy, time, volume of sample affected by this energy and its spatial distribution can affect the characteristics of the explosion.

Initial temperature and pressure

A higher initial temperature or pressure cause a reduction of the mass of air available for combustion and a reduction of the moisture of the sample, which produces an increase on the explosion severity [8].

Turbulence

Turbulence will remove heat from the ignition zone by rapid convection, so ignition requires higher energies and temperature. On the other hand, turbulence increases the violence of the explosion [9].

Gas presence

Depending on the gas mixed with the dust, the explosion can be prevented (carbon dioxide) or promoted (methane).

The effect of particle size

The explanation of the differences between dust and gas or vapour explosions can be simplified by the heterogeneity of the clouds that are formed. Dispersed dust is continuously in a movement-deposition situation, caused by air currents and turbulence, which largely depends on the particle size.

The quantitative and qualitative dependence of the violence of explosion on particle size is strongly affected by the interplay of phenomena controlling the combustion/heating of solid material [10]. Eckhoff observed that the general trend in dust deflagrations shows that a decrease on the particle size causes an increase on the deflagration hazard. However, this trend does not continue indefinitely as the particles get smaller. Deflagration of dust clouds consists on three consecutive processes: devolatilization, gas-phase mixing, and gas-phase combustion. Particle size influences the devolatilization rate, so that the lower the particle size, the higher the devolatilization rate. However, a lower limit in this depends on the ratios between the three processes, and not in any of them individually. Above this critical particle size, the devolatilization process becomes the critical factor in the flame propagation, but below it, devolatilization is so fast that the combustion is controlled by gas mixing and gas combustion.

Gao et al. [11] theoretically proved that the flame propagation mechanisms during dust explosions transited from kinetics-controlled to devolatilization- controlled as increasing the particle size. They observed that when kinetics controls the flame propagation, the flame front formed was smooth and its shape is similar to the premixed gas explosions. The flame zone consisted of premixed blue flame at the leading zone and luminous flames behind it. Opposite, when devolatilization controls the flame propagation, the flame front had a complicated structure. The flame zone consisted of blue spot flames at the leading zone and luminous flames behind them. The yellow luminous zone formed in the two different flame propagation regimes was explained as follows: around the particles, local high-concentration regions of fuel existed; when those particles burned without sufficient oxygen, soot particles were formed, and these particles emitted yellow flame. Because the particles were scattered, the pyrolysis fuel concentration was not uniform. The Damkoler number defines the transition between kinetics-controlled and devolatilization-controlled, which is proportional to the particle size. Dobashi and Senda [12] pointed out that the flame structure was dependent on the relation between gasification rate and flame propagation velocity.

In general, it can then be said that smaller particles pose a greater deflagration risk than larger particles. Small particles are more easily dispersed and will stay suspended for longer. Moreover,

because the particles are small, they are heated to the point of devolatilization or pyrolysis by less energy, are therefore more easily ignited, and can better propagate a flame. Based on the assumption that pyrolysis or devolatilization is very fast when the particle size is small enough, gas combustion becomes the controlling factor [13].

On the other hand, larger particles require more heat to devolatilize, often resulting in incomplete combustion and a continued risk of deflagration. The controlling factor for what speed a flame can propagate through a dust cloud will therefore be devolatilization, once the particle size passes a critical value [13]. The severity of the explosion will decrease as the particle size increases. As an example, Rice et al. [14] observed that coal dust particles above 850 μm ceased to take part in the explosion.

This dependence on particle size has been observed in relation to several used to characterise the ignition sensitivity and explosion severity of dusts. The effects of an increase in explosible dusts' particle size are numerous and well-established; these include, for example, a decrease in the maximum explosion pressure, P_{max}, potentially significant decrease in the maximum rate of pressure rise, $(dP/dt)_{max}$, and an increase in the minimum explosive concentration (MIE) [10]. "Increasing particle size is a classic application of inherent safety". Some other effects are explained below.

Calle et al. [15] observed the influence of particle size on the maximum pressure of explosion of wood dust with a decrease of explosion pressure when the range of particle size increases.

Fumagalli et al. [16] developed a model that shows the strong reduction of the explosion index K_{St} when the dust mean diameter increases.

The minimum ignition temperature (MIT) is affected due to the inefficient exchange of heat between the gas and dust particles when the dust particles are coarser, requiring more temperature to undergo devolatilization and thereby ignition. Eckhoff [10] studied this influence in coal dust and observed that there is also a limiting particle size (38 to <75 μm) below which there is no significant change in MIT. He then determined that the limiting size for coal dust is in the order of 50 μm, but several factors affect this limiting size, such as oxygen concentration, moisture content, porosity, discharge pressure, etc.

The minimum explosive concentration (MEC) for combustible dusts is the concentration of dust in air that is just enough to support flame propagation. MEC corresponds to the lower flammability limit (LFL) used for fluid fuels. Lower and upper flammability limits (LFL and UFL) for flammable gases and vapours are easily found in standardized laboratory test [17]. For dusts, the MEC can

also be determined in laboratory tests by observing the success or failure of a flame propagating through dust suspended in a tube or sphere. It is possible then to observe which concentrations can support the combustion, and therefore may pose a deflagration risk. Some discrepancies in the results have occurred when comparing tests with the same concentration, but different direction of flame propagation [17] (these tests are often performed in a vertical tube). This is believed to be due to gravity, when the suspended dust is ignited at the top the flame will be moving downward as the dust particles fall away from the flame front, thus making the effective concentration lower. The opposite is true when dust is ignited at the bottom, it will then be falling towards the flame, increasing the effective concentration.

For combustible dusts the MEC can be determined with some certainty, however the maximum explosible concentration is more difficult. Theoretically there is an upper concentration limit, or rich limit, though experiments in a 20 L-sphere have showed that it is possible to get an explosion from both coal dust and polyethylene at concentrations above 4000 g/m^3 [18]. For comparison the rich limit for methane is 200-300 g/m^3 [18].

The inter-particle distance in a dust cloud will also be larger at lower concentrations, leading to inefficient particle to particle heat transfer and deflagration propagation. Hence, more heat will be required to be transferred to the dust cloud for ignition and explosion propagation. In other words, in the case of lower dust concentrations, the MIT will be higher than that of the higher concentrations. Conversely, as the dust concentration increases, the number of particles per unit volume increases, leading to a decrease in inter-particle distance and efficient heat transfer between the particles. As a result, there will be more particles at a raised temperature causing a vigorous explosion even at a lower MIT. However, there is a restriction to the MEC, which is not clearly defined, probably due to its dependence on a number of factors [19].

Particle size also heavily influences the minimum ignition energy (MIE) of dust clouds, as Eckhoff reported in his book for three materials: aluminium, optical brightener and polyethylene [10]. In 1979, Kalkert and Schecker [20] developed a theory indicating that the MIE is proportional to the cube of the particle diameter. However, this relationship has not been confirmed, and different researches have obtained different results, probably due to the presence of fine size fractions in the dusts, which shows the need for considering the entire size distribution rather than just a mean size [10].

Nevertheless, the influence of particle size in MIE cannot be neglected, as Eckhoff showed with the results of three different dusts whose MIE decreases systematically with particle size. [21]

Focusing on the wood processing industry, the influence of particle size was observed at the wood processing industry, and reported by Amyotte et al. [22] from a facility that suffered a dust explosion. Trying to investigate the accident, explosibility analyses on a Siwek 20-L sphere were developed. They observed the inadequacy of designing the safety measurements of the facility only taking into account the coarse particles, even when they are present much more frequently. In this case, pockets of fine dust were found in a dead-space in the process unit header, and these fine particles present almost twice the value of maximum pressure of deflagration and the K_{St} increased from 9 for coarse particles to 130 for the fine ones. This shows the importance of detecting and analysing small particle sizes, and designing the measurements always considering these parameters to avoid non desirable consequences.

In general, it is considered that bulk materials (wood chips or coal) do not present that high risk compared to their fine forms, since they are difficult or even impossible to put into suspension, so dust clouds are not expected. However, it is important to keep two facts in mind. First, bulk materials can break into smaller particles or into dust from just being handled, so they should always be treated as a potential dust when prevention and protection measurements are considered. Second, there is an important risk of ignition from layers that can act as ignition sources. In that case, both dust and bulk materials can ignite, in some cases with the same probability and risk [23].

Particle size distribution

A dust sample is rarely composed of mono-particles, which is the term used for particles with the same shape and/or size. Therefore, not only particle size is important, but also the size distribution of the dust sample or deposit, which defines the relative amount of particles present according to the size. Particle size distribution (PSD) is an important factor for determining the deflagration risk of a dust cloud. If the fraction of very small particles is substantial this will carry an increased deflagration hazard, as was explained in the section before. However, this is not the only characteristic that influences the risk of deflagration, reason that leads in the definition of new parameters.

PSD has commonly been determined only by the parameter D_{50}, known as the median particle size. D_{50} is defined as the diameter below which 50 % of the cumulative mass or volume is present. Clearly, D_{50} by itself does not reflect the true shape of the distribution curve as it is only one value. To compensate for this, researchers are using D_{10} and D_{90} along with the D_{50} to get a more complete description of the dust in question, representing the diameter below which 10 % and 90 % of the cumulative mass is present, respectively.

During a long time, these three parameters (D_{10}, D_{50} and D_{90}) where used as independent numbers in order to provide the PSD of dusts. Furthermore, these values can be used to express the span of particle sizes, a factor known as the polydispersity index, σ_D, and defined by equation 1.

$$\sigma_D = \frac{D_{90} - D_{10}}{D_{50}} \qquad (1)$$

The influence of PSD in flame propagation was studied in 2013 by Wei Gao et al. [24], using octadecanol dust of different size distributions. The dust was heated and sprayed (in liquid form, though it cooled quickly and solidified) into a testing chamber. 50 ms after spraying the dust was ignited and the flame propagation was captured by a high-speed camera. The experiment was repeated with 3 different particle size distributions, each one with a concentration of 142 g/m^3. They named the different distribution types A, B and C, being type C the one with the largest portion of larger particles. Results showed that for type A (smaller particles) the flame propagated with an even front, leaving nothing behind. The assumption is that all the particles were pyrolyzed or evaporated before the flame passed, and so acting very similar to a pre-mixed gas explosion. The propagation through type B was more complex: blue spot flames appeared ahead of the main flame front, and some of the particles were not fully burnt.

Castellanos et al. [25] adopted a novel approach in the field of dust explosion research showing the high correlation existing between polydispersity and P_{max} and K_{st}. Defining polydispersity as a measure of the width of the particle size distribution characterized by the span of the size distribution, they observed an increase on the severity of the explosions with increasing the polydispersity.

However, a different researcher, Tascon observed that the polydispersity index has not been found to correlate consistently with explosion severity [26]. It only takes into account the width of the distribution (and the D_{50}) and fails to consider if for example a wider span is due to an increase in D_{90} or a decrease in D_{10}. In other words, two distributions can have the same poly-dispersity index and still be vastly different.

Additionally, these terms were appropriate while the studied particles had round or almost-round shapes, but it became a problem when new materials started being on the spot. Biomass materials have generally elongated shapes, making difficult to determine a mean diameter that represents all the particles.

Another approach has been to use the surface weighted mean (d[3,2]) and the volume weighted mean (d[4,3]) to define the particle size distribution. D[3,2] is the diameter of the sphere that has the same volume/surface area ratio as the particle of interest, and d[4,3] is the diameter of the sphere of equal volume to the particle. These are parameters that can be determined directly by some equipment, like laser diffraction, but they have not shown strong correlations with the dust explosion's parameters that we are studying here.

This made the need for new definitions of parameters that should be used clear, but there is still no agreement on which one(s) will provide the best information.

A well-known parameter that has been used before and has showed a correlation with the behaviour of dust explosions is the specific surface area. Specific surface area is defined as the total superficial area that a particle has. It is an important parameter regarding deflagrations of dusts because many of the reactions that occur during a deflagration take place in the surface of the particle, so the bigger these areas are, the greater the reaction rates are, and the more likely a deflagration is.

Another parameter that has shown a coherent relation to both maximum pressure and pressure rise is skewness. Skewness is how the distribution graph compares to a normal distribution, it expresses the degree of asymmetry. The skewness index [-1, 1] indicates which way the distribution

is skewed. A negative skew means the distribution curve has a tail to the left, in the negative direction. If the skew is positive, the distribution curve had the tail on the right, a tail of coarse particles. A perfectly symmetric distribution curve has skewness index $Sk = 0$. In a study from 2013, Tascón [26] compared the skewness index with the polydispersity index by using two existing studies (Castellanos et al. [27] and Li et al. [28]) that focused on the polydispersity index. They both found that there was a relation between explosion severity and polydispersity, however, their results are contradictory: Castellanos et al. found that an increase in the polydispersity index gives an increase in P_{max} and $(dP/dt)_{max}$, while Li et al.'s results indicated that a *decrease* in size polydispersity increases the explosion severity. Tascón applied a graphic skewness index to the data sets collected in the two studies, and found a coherent relation to P_{max} and $(dP/dt)_{max}$. Equation (2) shows the formula for finding the graphical skewness. The equation was implemented in a program called GRADISTAT.

$$Sk_G = \frac{\ln D_{16} + \ln D_{84} + 2\ln D_{50}}{2(\ln D_{84} - \ln D_{16})} + \frac{\ln D_5 + \ln D_{95} + 2\ln D_{50}}{2(\ln D_{95} - \ln D_5)} \qquad (2)$$

It is important to note that Tascón points out that the median diameter is still a significant factor. Its effect on deflagration parameters is far more evident than that of the skewness index. Skewness only has a notable effect when comparing dust samples with a very similar D_{50}. Tascón also insists that while particle size determination is certainly important, the diverging results and lack of repeatability is also a common problem. The main reason for this is the use of different instruments that are based on different physical properties, other factors include sampling methods, particle dispersion or agglomeration as well as software settings. [26].

The importance of particle shape

While coal dust particles may be considered spherical, this is commonly not true for biomass particles. This causes some difficulties since a lot of testing equipment and procedures seems to be designed to handle spherical particles. Particle size measurements also treat spheres as the standard shape, since the diameter is very often the parameter that is reported. Biomass can be fibrous, needle-like, flat flake-like, or any other shape, which can make it difficult for the particles to fit through holes such as in testing equipment or when sieving.

This causes an enormous inaccuracy on the definition of D_{10}, D_{50} and D_{90} as the parameters describing the particle size. The influence of particle shape in the definition of these parameters can be easily seen by the determination of particle size through sieving. If the studied particle has one of its dimensions larger than the sieve's size and the other two smaller, depending on how it falls on the sieve, the particle will go through it, or will not. If the movement is helped by a vibrational system, the probabilities of this particle going through the sieve are even larger. However, the particle's size could be considered bigger than the sieve's size, as illustrated in figure 2, which illustrates how a particle with length a and width b can or cannot pass through a sieve with a size mesh d (bigger than b but smaller than a) depending on the relative position to the mesh.

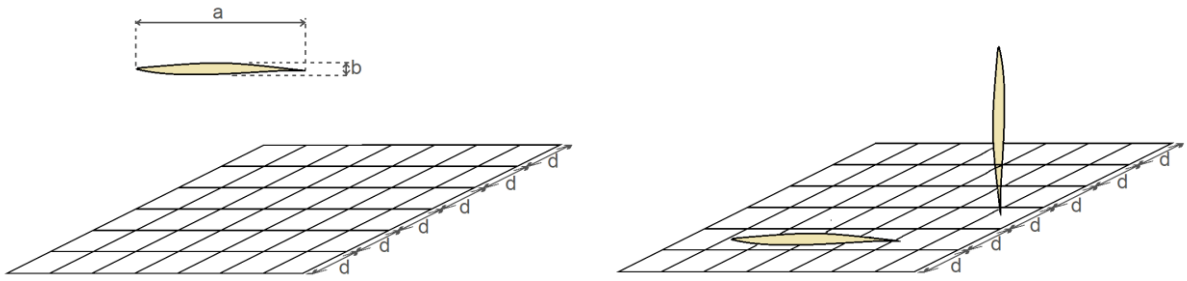


Figure 2. Influence of particle shape on the sieving method

For unevenly shaped particles an equivalent diameter is sometimes used. Meaning simply that the diameter is given as it would have been had the particle been a perfect sphere. However, to find a particle's equivalent diameter one must choose what parameter to keep constant. One can use the same surface-to-volume ratio, the same volume or the same projected area and the result is likely to vary significantly [17].

In his book [1], Amyotte refers to a study [29] of dusts' dispersibility properties, which is described as a "dust's tendency to form clouds". This tendency is affected by several parameters, chiefly particle size, particle specific surface area, dust area moisture content, dust density, particle shape,

and agglomeration. Klippel et al. [29] divided dust into six groups of "dustiness", that is how easily dispersed a dust is. The main five forces influencing the dustiness of particles are: buoyancy (due to gravity), drag force (proportional to the slip velocity), turbulent dispersion force (affected by the fluid velocity and dependent on the Reynolds number), pressure gradient force (caused by fluid acceleration) and the virtual mass force (because of the particle in motion that accelerates some of the surrounding fluid).

Group 1 have a minimal tendency to stay airborne, while group 6 is the opposite. Examples of dusts from the different groups are given in the book, and include sanding dust in group 2, and potato starch in group 6, thus saying that potato starch is likely to stay airborne longer than the sanding dust [1].

And so, the particle shape is an important factor in dust's dispersibility properties as it affects both the specific surface area and the agglomeration process of the dust, as well as directly affecting the dispersibility itself. The specific surface area is thought of as increasing with decreasing particle size, however it will also increase when considering any other particle shape than spherical. This is because spheres have the lowest surface to volume ratio of any shape, therefore all other shapes must have higher specific surface area. With increased specific surface area, whether due to small particle size or uneven particle shape, a dust's dispersibility will increase because of greater drag force, or air resistance, acting on the particles. The same is true for particles with a textured surface. Asymmetric shape and uneven surface have been shown to give lower terminal settling velocity due to rotational settling and eddy formation [1]. For dusts that consists of fibrous or flake-like particles the rate of settling would depend on the particles' orientation.

In the case of biomass dust, the particles' shape complicates testing procedures. For example, the 1 m^3 ISO chamber that among other things is used to find the minimum explosible concentrations for dusts, does not function optimally for biomass or other particles of a more uneven shape. The mechanism for feeding fuel into the explosion chamber consists of a fuel container and a tube. The tube is shaped like a 'C' and is lining the periphery of the sphere and has 5 mm openings. In a research article from 2013 Huéscar Medina et al. outlines the problems of the ill adapted testing equipment [30]. Fibrous and elongated biomass particles do not fit well through the holes and can clog the pipe, hindering effective flow. There is also an issue with the low mass density of many biomass dusts. Around 750 g/m^3 have been found to be the most reactive concentration for biomass dusts. The dust pot that holds the fuel prior to injection has a volume of 5 litres. To hold 750 g/m^3 of a 100 kg/m^3 material the dust pot would need to be 8,5 litres.

Agglomeration

Particle size, moisture content, particle size distribution and particle shape are the main factors affecting the agglomeration of dusts, pointing out the importance of this factor on the risk of explosions of organic dusts.

When particles are suspended (or not), they will often collide and stick together in lumps. This is referred to as agglomeration, or sometimes coagulation. In this situation, the particle size determined in a laboratory for this sample would still be the same, but the effective particle size will increase, reducing the ignition tendency of the sample, in other words the agglomerates will act as larger particles. Finer dust and dust with more moisture, have a higher tendency to form agglomerates and thus modifying their ignition behaviour [19].

Agglomeration of dust particles has two aspects that are important to consider: attraction forces between particles in dust layers, and rapid coagulation in dust clouds. Agglomeration in dust layers will make dispersing the dust more difficult, and the dust is less likely to form a dust cloud of primary particles (single particles, not agglomerates). The second aspect, coagulation taking place in dust already suspended, means that even if the dust is well dispersed larger agglomerates may still form [1].

Interparticle forces that cause agglomeration of dust particles:

- Van Der Waals forces
- Electrostatic forces
- Interparticle forces due to moisture

Interparticle forces due to moisture is what makes agglomeration more present when moisture content is higher. Electrostatic forces depend on the material and whether or not it is conductive. Van der Waals' forces is affected by particle size. As the dust gets finer the importance of van der Waals' increases. In a 2011 article [21] Eckhoff gives several equations, one of them for calculating van der Waals' forces, F_W,between two particles:

$$F_W = \frac{A}{a^2} * \frac{x_1 x_2}{x_1 + x_2} \qquad (3)$$

In the equation above A is a constant, a is the smallest distance between the sphere surfaces and x_1 and x_2 are the diameters of the two particles.

The following equations are found in Eckhoff's article *Influence of dispersibility and coagulation on the dust explosion risk presented by powders consisting of nm-particles* from 2013 [31]. n is the number of

particles per cm^3 at the time t, and n_0 is the number of particles in the moment the cloud was formed. The coagulation constant K is material dependent, table 1 in the article gives examples for some materials and the values range between 0,49 and 0,83 $\cdot 10^9 cm^3 s^{-1}$. The equation was first resolved experimentally in the 1930s, Whytlaw-Gray and co-workers were able to count the number of particles per unit volume of dust cloud and plotted this against time. For a wide range of materials this plot formed a straight line.

$$\frac{1}{n} - \frac{1}{n_0} = Kt \qquad (4)$$

$$-\frac{dn}{dt} = Kn^2 \qquad (5)$$

The equations are not valid in the earliest stages of coagulation, this is because the agglomeration will happen much more rapidly than the coagulation constant predicts. The initial stage is also difficult to follow experimentally, especially for very small particles.

It should also be noted that the original coagulation equations assumed all particles were spherical, which is rarely the case, especially for biomass dusts. However, minor irregularities will not significantly impact the mobility of a suspended particle and should therefore only have a minor on the coagulation rate. It has been experimentally confirmed that coagulation rates in dust clouds are not very affected by particle shape, though there are exceptions (like for chain-like structures). [31].

As a dust cloud will never be 100 % mono-disperse, it will instead consist of particles in a variety of sizes, often a wide variety. According to research referenced by Eckhoff it has been experimentally found that the wider the range of the size distribution the faster a dust cloud will coagulate. [31]. It has however, proven quite difficult to precisely calculate the effect of poly-dispersity.

Moisture has a significant impact on a dust's dispersibility properties. Experience suggests that dry dusts are more easily dispersed than moist dust. Any amount of liquid will increase the interparticle forces, sometimes increasing the attraction by a great deal. As the moisture level rise the excess water will start to form "liquid bridges" between particles and eventually these bridges will completely fill the space between particles. At this point the capillary forces between the particles are the main source of the cohesion. Further increase of moisture content will result in the dust being suspended in liquid. [21].

Agglomeration is generally not taken into account when the risk of explosion of solid materials is studied. It is true that, regarding safety, the worst scenario should always be considered, which in this case means the drier and with smaller particle size. However, by moisturizing the samples, the risk can decrease, and the amount of water needed in order to reduce it highly depends on the agglomeration tendency of the dusts.

The influence of moisture

Water has been widely used in the suppression of gas fire and explosions [32, 33], being a low cost alternative for inert materials, with no environment impact, no toxicity and relatively low cost. It has been normally used as a way of preventing dust explosions. Amyotte et al. [34] proposed the control of moisture in pipes and silos as one of the measurements to prevent dust explosions [35, 36].

However, moisture is one of the main parameters due to its antagonistic effect in the dust explosion mechanism. Depending on the chemical composition of the dust, the moisture can inhibit or promote the ignition of dusts and the severity of the explosion. On the one hand, the inhibition can be caused by agglomeration, heat sink effect, water vapour inerting or inhibition of mass transfer at particle surface. On the other hand, an increase of the ignition and explosion characteristics could be observed when the water presence leads to violent chemical reaction with the dust or when its adsorption chemically modified the particle surface and improves the species diffusion, which can lead to explosion risks higher than for the dry dust [37].

At lower moisture content, the moisture would mainly consume the reaction heat of dust explosion by temperature rise and phase change. In this situation, because the heat consumption is proportional to the mass of moisture, the measured explosion severity reduces gently and linearly with the rising moisture content. Nevertheless, as the moisture content continues to rise, due to the stronger interparticle cohesion between particles, besides consuming heat, the existence of moisture would also cause the agglomerations of dust particles and, thereby, increase the effective particle size of dusts and weaken dispersion of dust clouds, so that the reduction of flame propagation becomes more remarkable and even dust cloud cannot ignite [38].

By increasing the moisture content, an increase on the MIT, an increase on the MEC and a decrease on the P_{max} can be observed, causing both an increase on the ignition sensitivity and on the explosion severity: explosions would be easier to occur and their consequences would be more dramatic [38]. However, there is not a consensus on the limit of moisture content that would ensure the non-occurrence of explosions, being difficult to find any fix number at this respect. Lees [39] stablished that the explosibility of the dust decreases with dust moisture content above 30%.

It is also a general practice in industry to treat moist dust as less dangerous than the dry one, and it is generally correct to do so. However, it is difficult to define the limiting value at which a dust has to be considered wet or dry. First, solid particulates have four different types of water

associated: intracellular water, floc water, capillary water and free water. The methods used to determine the moisture content make a differentiation on the type of water that is actually being measured, making the first need to characterise, define and determine these types of moisture. By moisturising the dust, the moisture content that is probably mainly affected is the free water, but this hypothesis should be tested and the influence of this moisturising in the particles and the explosion risk should be studied.

NFPA 664: Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities.

The NFPA (National Fire Protection Association) is a non-profit organisation based in the USA whose declared mission is to eliminate death, injury, material or economic loss due to fire, electrical or related hazards. This work includes having published 300 codes and standards. [41]

The NFPA 664 is, as the name suggests, focused on preventing fires and explosions in wood processing and woodworking industries. Its purpose is to provide minimum requirements for the design, operations and maintenance with regards to the safety of life, property protection and mission continuity from fire and explosion. The standard applies to all new facilities and to new processes in existing facilities. It does not apply to facilities that were built or approved to be built before the standard were published in 2017.

Chapter 3 of the standard gives some definitions of relevant terminology. A deflagration is "propagation of a combustion zone at a velocity less than the speed of sound". And a deflagration hazard is determined to exist either if a certain amount of deflagrable wood dust covers upward facing surfaces or if deflagrable wood dust is suspended in the air under normal operating conditions in amounts greater than 25 % of the MEC. There is also included a wide definition of wood: Cellulosic materials derived from trees, wheat straw, flax, bagasse, coconut shells, corn stalks, hemp, rice hulls, paper or other fibres used as a substitute or additive to wood.

The most relevant of the definitions (at least as concerns to this article) are perhaps the definitions of deflagrable and non-deflagrable wood dust. Deflagrable wood dust is any dust that will propagate a flame front, thus presenting a fire or explosion hazard, when suspended in air or other oxidizing medium. Wood particulate with a mass median particle size of 500 μm or less, with a moisture content of less than 25 % are considered deflagrable. A non-deflagrable dust is a dust with the same moisture content (25 %), but a mass median particle size greater than 500 μm.

Chapter 4.4 determines when a deflagration hazard exits. This is when the average thickness of a layer of flammable dust is over 3,2 mm or, for smaller areas if the layer exceeds 3,2 mm in at least 5 % or the area. There is some flexibility in the 3,2 mm criteria should the dust in question have a settled bulk density other than 230 kg/m^3. The following equation is to be used for finding the correct allowable dust layer thickness (this is eq. 4.4.2b in the standard, eq. 4.4.2a is the same equation, but using U.S. customary units):

$$T = \frac{(3{,}2\ mm)(320\ kg/m^3)}{(Settled\ Bulk\ Density, kg/m^3)} \quad (6)$$

where:

$T =$ the allowable thickness (mm)

Chapter 8 follows up stating that there is also a deflagration hazard anywhere deflagrable wood dust is, or could be, suspended in air during operation at a maximum concentration above 25 % of the MEC. The annex to this chapter warns that all wood waste in an enclosed dust collector should be considered as potentially deflagrable. According to the standard, wood waste usually has a deflagration risk if the mean particle size is less than 420 μm and where as little as 10 % of the dust has a diameter of less than 80 μm. However, the standard claims that if the mean particle size exceeds 420 μm, only weak deflagrations are likely.

The following is a list from Ch. 8.4.1.2 of the physical properties of particulates that should be considered when evaluating the hazard of particle size reduction equipment.

1. Minimum explosible concentration (MEC)
2. Minimum ignition energy (MIE)
3. Particle size distribution
4. Moisture content as received and tested
5. Maximum explosion pressure at optimum concentration
6. Maximum rate of pressure rise at optimum concentration
7. K_{St} (normalized rate of pressure rise) as defined in ASTM E1226, *Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts*
8. Layer ignition temperature
9. Dust cloud ignition temperature
10. Limiting oxidant concentration (LOC) to prevent ignition
11. Electrical resistivity
12. Charge relaxation time
13. Chargeability

Available testing methods

For particle size

The methods used for finding and defining particle size and size distribution are diverse. Sieving is a recurring method and is often used in combination with other methods, such as laser diffraction or image analysis. Possibly because sieving does not give a definite particle size, but rather a range or size distribution. There are at least three standards regulating sieving procedures.

EN 15149-2:2010 is a European standard for how to determine the particle size distribution of solid biofuels using a vibrating sieve tower. The aperture is described as a stack of seven sieves with a collection pan below. The sieve openings are given in mm as 3,15; 2,8; 2,0; 1,4; 1,0; 0,5; 0,25.

The standard also gives an equation to calculate the median particle size, D_{50}, by linear interpolation:

$$D_{50} = C_2 + (50 - S_2) \times \frac{C_3 - C_2}{S_3 - S_2} \qquad (7)$$

Image analysis has two steps, first take a picture or scan of a prepared sample and then interpret the image, this is usually done by a computer.

Following in this chapter are the methods used to measure particle size and particle size distribution of biomasses described in different research articles.

Analysis of standard sieving method for milled biomass through image processing. Effects of particle shape and size for poplar and corn stover [42]

For this 2014 paper Gil, Teruel and Arauzo has tested two types of biomass: SRF poplar and corn stover. Poplar is described as a woody material, while corn stover is herbaceous. The authors do not go into detail about their method, but instead refer to the standards they followed for the different procedures. The samples were collected and prepared according to standards EN 14778-1:2011 for poplar and EN 14780:2011 for corn stover. European standards were also followed when analysing the samples' moisture content[1] and particle size[2].

[1] EN 14774-1:2009
[2] EN 15149-2:2010

A vibrating screen machine with six sieves [3] was used for particle size distribution. The sieves had opening sizes of (0,1; 0,25; 0,5; 1; 2; 5) mm. Before sieving a series of trials were made to determine sieving time, to ensure that the sieving was complete. The material was weighed on an electronical balance with ±0,001 gram accuracy. The sieving was deemed complete when the mass change between two sieves was less than 0,3 % of the total mass per minute. (0,3 % min^{-1}). This happened after 20 minutes.

For each size range two samples were taken for image analysis. The particles were dispersed, attempting to avoid overlapping. 24 2D-images were obtained by a scanner. For the smallest particles (those that fell through the bottom sieve) the resolution was 3200 dpi, for all other size-groups 600 dpi was used. The images were analysed to find morphological characteristics of the 100s to 1000s of scanned particles. The original colour images were enhanced and turned black and white. A filter was applied to automatically remove blobs that may correspond to more than one particle. Particles not fully in the picture were also removed.

Machine vision-based particle size and size distribution determination of airborne dust particles of wood and bark pellets [43]

Airborne dust samples from pelleting operations were collected from a baghouse deposit. The samples were of pine in the shape of pelleting sawdust and pelleting ground bark. The two materials are treated separately throughout the study. Each of the materials were made into three subsamples by sieving them. A sieve with mesh 230 (63 μm) were used to divide the samples in two, the third subsample was unseparated. Each of the total 6 subsamples were kept in separate bags (in an air-conditioned lab, at 22 °C and 55 % RH) before the tests.

To perform the test the samples were shaken and about a spoon's worth (2-3 g) were heaped onto clear paper. A thin piece of cardboard was used to spread out the material into a thin layer. (cardboard was chosen because there is no electrostatic attraction of the particles). Using the cardboard still, a small squared area was separated out then moved over to a flatbed scanner (Cano-scan 4400F) with a ¾" flat art brush. The scanner bed was lined with a "high quality overhead projector transparent sheet", making removing the sample easy. Once on the scanner bed a pointy knife was used to assure that no particles were touching or overlapping. This was described as time-consuming but practically achievable. For a black background an oil painted art paper (with a normal quality paper the fibre would be visible in the image, an could possibly affect the results) were placed carefully on top of the *singulated arrangement* of wood dust. For each layout like this, 10

[3] ISO 3310-1

pictures were taken, each focusing on a small square (50,8 mm × 50,8 mm). With three layouts per material this makes 60 pictures to be processed.

In chapter 2.7 in the paper the authors state that particles can easily be measured accurately and separated based on any selected parameter (e.g. length width, area) with image processing methods, but not by standard mechanical sieving.

Influence of the size distribution and concentration on wood dust deflagration: Experiments and reaction modelling [15]

In this 2005-study by Callé et al. the explosibility of wood dusts with different particle size distributions and concentrations are tested. The material was produced by sanding pieces of beech and oak. The sanding resulted in a very wide size distribution and the dust was sieved into four ranges: 25-45 μm, 45-71 μm, 71-90 μm and 90-125 μm. A mean diameter was found for each of the ranges, though the report does not specify by which method.

Use of tube flow fractionation in wood powder characterisation [44]

Laser diffraction/optical image analysis, tube flow fractionation.

In this research paper, by Laitinen and Karinkanta, tube flow fractionation was used to determine particle size of sawdust from Norwegian Spruce (picea abies). After the wood material was collected it was stored in a freezer. Later the saw dust was dried in an oven at a temperature below 105 °C. The dried material was sieved using a vibrating screen with aperture size of 4 mm. Any particles too large to pass through the sieve were discarded and not used in the research. The remaining material was sent through a milling system consisting of an air classifier mill (100 ATP) and an integrated rotor impact mill (50 ZPS).

To dilute the milled material, 1 g of wood powder were mixed in deionised water to a 0,2 % particle concentration. Before dilution a dispersant was added to the wood powder, to keep the powder from forming agglomerates. Laser diffraction was used to measure volumetric particle size distribution according to ISO13320.

For the tube flow fractionation, a sample is injected into a tube, and initially the particles are randomly distributed in the flow, but they are intended to sort themselves out. Particles with one or multiple long dimensions are more likely to be caught by the faster middle flow, thus the larger particles tend to concentrate at the front of the flow and exit the tube first.

In the tests a 5 cm^2 sample at consistency 0,2 % was fractioned for 100 s at an average flow rate of 7,3-8,5 cm^3/s in a long plastic tube (D=4mm). Based on 23 parallel sample analyses the standard

deviation of the combined sample fractionation and optical image analysis was determined to be 4,5 %. The variables of interest in the fractionation procedure are flow velocity, pressure, temperature, sample volume and consistency. These were to be kept constant.

Effects of particle shape and size on devolatilization of biomass particle [45]

Sieving (multiple sieves), aerodynamic classifier, sieving (single sieve), friction plate, 3D image analysis.

This study from 2008 has made a considerable effort to categorize and separate biomass particles by shape and size. Two types of biomass were used: hardwood sawdust particles (≤300μm) and poplar dowels (≥2mm). The particles were categorized as either spherical, cylindrical or flakes. Particles were supposed to have different shapes, but similar volume/mass. The preparation of the samples consisted of four steps:

1. Separation with sieve shaker: A series of sieves were stacked with the finest mesh on the bottom and the coarsest one on top, mesh sizes ranging from 25-80[4]. A sample is poured on to the top sieve and the shaking last for 40-45 minutes. The material collected from each sieve is bagged separately. This step is mainly to separate the particles by size.
2. Aerodynamic classification: they tested it with a tunnel separator. In the bottom of the tunnel four trays are placed to collect the dust. The dust is injected through an opening at the top of the tunnel. Compressed air enters through a vertical distribution pipe and spreads the dusts as it enters. Each particle's trajectory is determined by its shape. More drag forces work on particles with a bigger surface area or lower density, these will end up in tray 4, furthest from the distributor. Trays 2 and 3 collect cylinder and flake-like particles, while tray 1 gets the more equant particles. Samples collected in the trays are sometimes run through the tunnel separator more than once.
3. Shape separation by sieve: samples collected in trays 1, 2 and 3 in the aerodynamic classifier are separated into near-spherical, flake-like and cylinder-like particles. The samples are put in a new sieve shaker[5], in this step time is the variable. The particles with smaller aspect ratio will fall through more quickly, leaving the flakes and cylinders behind for longer. By lengthening the shaking time, more particles with higher aspect ratio will pass the sieve.
4. Further shape separation by friction plate: This was done by placing a 2-foot-long board clad in 600 grit sand paper at a 30° angle. One or two samples were then poured onto the high end of the board to allow the sawdust to fall the length of the board. Only the most

[4] Doesn't say how many sieves.

[5] Appears to be only a single sieve, though there is no mention of what mesh size is used.

spherical make it all the way down, thus the different shapes will sort themselves along the board.

After the samples had been through all four steps (sometimes repeatedly) particles were individually photographed from orthogonal angles. As part of the project the researchers developed an algorithm for reconstructing particle shapes based on the three images taken from different angles. The algorithm includes three major steps: image acquisition and processing, image contour alignment, and surface generation.

Experimental research on shape and size distribution of biomass particle [46]

This study from 2011 looks at 4 different kinds of biomass: pine, bean stalk, rice straw and reed. In preparation for the test, each sample was dried and ground for 3 minutes in a batch knife mill pulveriser FW177. The samples were then sieved into 5 particle size ranges: 83-106 μm, 106-150 μm, 150-180 μm, 180-300 μm and 300-425 μm. The content of the sieves was weighed to find the particle size distribution. The sieving process was repeated three times for all the materials and the average value (amount of material in the sieves) was used. From each of the ranges, 300 particles were randomly chosen for examination. Using a Nikon E200 microscope the chosen particles were magnified 300 times, and the images was analysed by Image J software. The software was able to measure the length and width for each individual particle.

Sieve analysis of biomass: accurate method for determination of particle size distribution

A recent study [47] of three different biomasses (hemp, miscanthus and pine sawdust) concluded that sieve analysis only gave a reliable result for one of the materials (pine sawdust). In the test they used a horizontal vibrating sieve shaker Retsch 2000. The experimental set up consisted of seven sieves and a collection pan at the bottom. The opening sizes for the sieves were 0.63, 1.5, 3.15, 4.5, 6.7, 8 and 10 mm. The sieves were sorted so that the coarsest, with the largest openings, was on top and then decreasing opening size for each sieve. The bottom pan would collect any particles sufficiently small to fall through all the sieves.

Before performing the test, the sieves were individually weighed. The material sample were placed in the top sieve and the sieve tower were then shaken for 30 minutes, with an amplitude of 30 mm/g applied. After shaking, each of the sieves were weighed again and the weight of the sieve were subtracted to find the amount of material the sieves had collected. Each material was tested twice, and the arithmetic median value was used.

For hemp the result was that more than half (56,16 %) of the material were left on the top sieve. The authors believed this to be due to the elongated fibrous characteristics of hemp particles.

The miscanthus particles were described as needle-shaped. This resulted in the top four sieves capturing a total of less than 1,3 % of the material. Normally (for spherical particles), this would indicate that almost all the particles had a diameter of less than 3,15 mm (the opening size of the 3rd sieve), which is not entirely untrue, however it is inaccurate.

The test worked well for sawdust. The pine particles are described as more spherical and the results show a greater disparity, that is more even distribution among the sieves.

Summary

The following table gives a short summary of some of the opportunities and limitations of each of the methods described in this chapter.

Method	Opportunities	Problems/limitations
Sieving	Widespread use, several standards, can be used in combination with other methods, finds PSD, multiple sieve sizes available. Inexpensive equipment	Not ideal for non-spherical particles; does not give the size of individual particles, but rather a range;
Image analysis	Good for different shapes, can be used to find several parameters length, width, diameter SSA, aspect ratio etc. Often used as a second step, after separating the dust into size ranges	Usually a 2D image. Standards?
Laser diffraction	Gives volumetric particle size and other parameters directly	
Aerodynamic classification	Separates by shape/surface area	Not commonly used. Seems complicated. Standards? Repeatability?
Friction board	Separates by shape/surface area more than size	Not very accurate, no standard, no defining limits (like sieves have), not commonly used.
Tube flow fractionation	Separates by shape/surface area	

For deflagration metrics

The 1 m³ sphere

The 1 m^3 sphere is a constant volume explosion vessel used for finding P_{max} and K_{St}. It is also the method preferred by standards and the method other methods are calibrated against. Use of the 1 m^3 sphere is outlined in the standard EN BS 14034.

The apparatus consists of an external 5 L fuel container, linked to the explosion chamber by a 19 mm diameter tube. There is also equipment to record the pressure development over time. From the recorded information the deflagration index K_{St} can be derived by using equation (8). [48]. The testing procedure starts with filling the dust container and pressurising it to 20 bar. On activation a fast-acting valve releases the dust into the explosion chamber through a multi-hole 'C' tube. The dispersed dust is then ignited.

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} \cdot V^{1/3} \qquad (8)$$

Through literature review and some experiments of their own, a group of researchers, Medina et al. [30], saw that the fuel dispersion system in the standard sphere was not ideal for biomass, and sought to modify the equipment to be more suitable for biomasses. The original dispersion system, the 'C' ring, did not allow fibrous biomass to pass through, even when it was milled down to a diameter of less than 63 μm, (openings in the 'C' ring are 5 mm each [30]). Among all the cases they studied only one presented a type of biomass that could pass though the standard dispersion system. These were found by Sattar et al. and were nut shells from walnuts, pine nuts and pistachios. For their own experiments the researchers swapped the 'C' ring with a spherical nozzle, they also changed the fuel container for a 10 L version to accommodate low bulk density biomass. The new set up was calibrated for its ignition delay using cornflour to give the same K_{St} with the standard 'C' ring disperser and the 10 L external dust store and spherical nozzle disperser.

The 20L sphere

As the 1 m^3 sphere was quite expensive both to build and to operate, researchers started experimenting with smaller versions of the explosion chamber. This resulted in the Siwek 20L explosion chamber. Testing showed that vessels smaller than 20 litres were not suitable, likely because the heat loss from the flame front to the walls of the chamber would be relatively greater than for a larger vessel. [49]. The ISO 1 m^3 explosion chamber is the reference standard for finding K_{St} and P_{max}, however as the 20 L sphere can be calibrated to give the same results it is recognised by standards as well. In addition, it only needs the dust sample to be 1/50 of the mass compared

to the larger sphere, which is a significant contributing factor to the 20L sphere being more commonly used than the 1 m^3 sphere. [48].

United States Bureau of Mines (USBM) developed their own version of the 20L vessel. The USBM vessel is operated by placing the dust sample in the dispersion nozzle instead of in a separate fuel container, the dust is then dispersed by an air pulse [50]. And later the University of Bergen made a hybrid sphere, combining the USBM vessel with the Siwek dispersion system. [49].

The Hartmann tube

The Hartmann tube is an explosion chamber which operates on mainly the same principles as the spherical explosion chambers described above but has the shape of a cylinder. The cylinder has an internal diameter of 61 mm and length 322 mm giving it a volume of about 1,96 L, which is significantly smaller than even the 20 L sphere [51]. Originally, the Hartmann tube was the apparatus for testing carbonaceous dusts' explosibility. Now it's used for finding the minimum ignition energy and can also be used to investigate the minimum explosible concentration as it gives similar results as the spherical explosions chambers. On P_{max} and K_{St} the tube apparatus does not give reliable results, this is in large part due to the extensive contact between the flame and the tube walls, which leads to heat loss and a lowering of both the peak pressure and the rate of pressure rise. [48].

Other methods

36L vessel, 2018. In 2018 a group of researchers constructed and calibrated a 36L to give results corresponding to both the 1 m^3 and the 20L dust explosion chambers [49]. The paper details the process of calibrating the apparatus, as well as simulating the airflow inside both the 36L-vessel and the 20L-vessel by using CFD. The newly constructed dust explosion chamber had a maximum allowable working pressure and a maximum allowable temperature of 70 bar and 260 °C. The apparatus was equipped with vacuum, dispersion, ignition and data acquisition systems. Operation of the apparatus was based on the ASTM E1226-12a standard: First a known mass of dust is placed in the fuel container, then the vessel is closed and evacuated. The air reservoir is pressurized, and a fast-acting valve opens for 50 ms to let the air flow disperse the dust in to the explosion chamber. There is a delay time of 25 ms before the dust is ignited. The explosions pressure development is recorded.

For moisture content

Finding the moisture content of any dust is simply a matter of drying a wet sample and comparing the weights to find out how much water was originally in the sample.

To find the moisture content a 25 g wet sample is placed in an oven on 103°C for 24 hours. The sample is then weighed again, and the mass percentage of moisture can be found with the following equation. Equation (9) for moisture content is given by Yang in *Image and Sieve Analysis of Biomass Particle Sizes and Separation after Size Reduction* [52]:

$$MC = \frac{Loss\ weight \cdot 100}{Wet\ sample\ weight} \qquad (9)$$

Data

The following table contains the data that have been found in the course of this literature review. As is evident from the holes in the table the researchers focus on different aspects.

Material	D5	D10	D16	D25	D30	D50	D60	D75	D80	D84	D90	D95	D100	SSA	Moisture content (%)	Explosion tested	Source
Fine wood pellets		43,4				152,9					378,9			0,069			[53]
Coarse wood pellets		1200				3000					5500						
Fine wood chips		46,5				146,6					404,1			0,307			
Coarse wood chips		400				1100					1800						
Fine torrefied wood pellets		22,3				104					326,9			0,130			
Coarse torrefied wood pellets)		2300				3500					6400						
Wood pellet airborne dust	0,0119	0,0197	0,028	0,0395	0,0466	0,0814	0,1041	0,1519	0,1749	0,1978	0,2476	0,3234				No	[43]
Bark pellet airborne dust	0,0092	0,0132	0,0193	0,0283	0,0333	0,0591	0,0815	1434	0,1774	0,2126	0,29	0,4226				No	
Wood						95										Yes	[54]
Bark						57										Yes	
Spanish pine						247										Yes	
Pine (avg. length)						320,9									9,3	No	[46]
Pine (avg. width)						230,2									9,3	No	
Wood dust from the production of particleboard (silo dust)		18,96				56,02					113,07				1,74	Yes	[55]
Wood dust from the production of particleboard (hammer mill dust)		4,43				15,96					37,74				3,88	Yes	
Radiata Pine		37,25				92,08					210,1				1,18	Yes	
Raw Norway spruce		28				149					603				5,8	Yes	[56]
Torrefied Norway spruce		15				67					281				2,8	Yes	

Norway spruce						148,5								0,65	5,8	Yes	[7]
Torrefied Norway spruce						38,8								2,10	2,7	Yes	
Southern pine						53,2								1,71	5,0	Yes	
Torrefied southern pine						36,6								1,47	3,3	Yes	
Loblolly pine (unseparated)						201,8							420			No	[57]
Loblolly pine (coarse)						291,1							420			No	
Loblolly pine (medium)						189,5							180			No	
Loblolly pine (fine)						68,2							90			No	
Miscanthus						18 mm									41,6	No	[58]
Miscanthus						18 mm									20,2	No	
Pine sawdust						0.25 mm										No **	[59]
Pine wood chips						10 mm										No **	
Wood											700					Yes	[48]
Bark											700					Yes	
Forest residue											500					Yes	
Spanish pine											500					Yes	
Barley straw											500					Yes	
Miscanthus											350					Yes	
Sorghum											650					Yes	
Rape seed straw											500					Yes	
Wood dust – beech oak mix											125					Yes	
Forest residue – wood + bark						275										Yes	
Wood dust chipboard											43					Yes	

Wheat grain dust													500			Yes	
Cellulose											125					Yes	
British Colombia wood pellets						<63*										Yes	
Nova Scotia wood pellets						<63*										Yes	
Southern yellow pine						<63*										Yes	
Fibrous wood						<75*										Yes	
Dry Douglas fir and Western red cedar						250*										Yes	
Dry mountain pine and Lodgepole pine						200*										Yes	
Dry spruce and pine and fir											200					Yes	
Southern pine											739					Yes	
Norway spruce											603					Yes	
Oak wood						62,9									7,7	Yes	[60]

*The source does not specify the parameter studied, so we assume they are referring to the median diameter of the particles.

Conclusions

This report shows an urgent need in the wood industry to develop and implement a new methodology to classify the risk of deflagration depending on the particle size and the moisture content. However, as we have shown along the present document, to achieve this goal there are several steps that need to be performed in advance.

First, we have shown that working exclusively with the mean diameter of the sample does not seem to be enough to characterise them. Assuming the sphericity of particles was a general practice for coals, but it does not seem to adjust to the specific characteristic of wood particles. We need to take into account the different on length that the three dimensions of the particle can have.

Second, there is a need on designing and implementing a common methodology on the way of determining the particle size of the materials. Samples should always be collected in similar locations to ensure that all the possibilities are studied, even the finest particles that are formed by abrasion. A complete set of particles should be tested to obtain a complete range of possible values that are probable to appear in the facilities. Once these samples are collected, testing should also be homogenised. We have shown several procedures and equipment used for determining particle size. This equipment is not based in the same principles, so the out coming results are not comparable and may substantially differ. A standard procedure should be established to clarify this.

We believe that assigning a single value for all the different wood species and the different facilities and situation that we can encounter would be too simplistic and not accurate enough. This is why, once these steps have been clarify, a great improvement in the field would be to create a mathematical model to define the risk of deflagration of wood dusts, which can simulate the behaviour in the particular case of each facility and in different moments of the process.

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