Explosion characteristics of biomass dust – comparison between experimental test results and literature data

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ABSTRACT

The design of explosion mitigation strategies e.g. vent design is mainly based on dust explosion characteristics such as the maximum explosion pressure ($P_{\max}$) and the deflagration index (K_{St}) of dust cloud, which are defined in various standards.

The wood dust explosion characteristics can be directly obtained by performing standard tests, and test results are also available in the literature. However, the parameters for one type of dust may vary substantially in the literature. For example, the K_{St} value for one wood dust is 11.4 times higher than another wood dust in Gestis-Dust-Ex database. The reason for such large variation in explosion parameters is due to factors such as material properties, particle size distribution, particle shape, moisture content, turbulence level during tests and so on.

The objectives of this paper are (i) to carry out dust explosion tests for $P_{\max}$ and K_{St} for two wood dusts with well-described material parameters such as particle size distribution and moisture content according to European standards, (ii) to perform statistical analysis of wood dust explosion characteristics including $P_{\max}$ and K_{St} in the literature, (iii) to identify the effects of dust material parameters such as particle size and moisture contents on $P_{\max}$ and K_{St} and (iv) to highlight the variation in $P_{\max}$ and K_{St} and the importance of obtaining knowledge about these properties of an individual dust, e.g. via dust explosion tests.

KEYWORDS: biomass, wood dust, explosion, explosion overpressure, deflagration index.

NOMENCLATURE

D_{10}	particle size at which 10% of particles by mass are less than this value (μm)	P_{ex}	maximum explosion overpressure for a single test (bar)
D_{32}	Sauter Mean Diameter (μm)	$P_{\max}$	maximum explosion overpressure (bar)
D_{50}	median particle size based on mass (μm)	P_0	atmospheric pressure (1 bar)
D_{90}	particle size at which 90% of particles by mass are less than this value (μm)	S_u	burning velocity (m/s)
		V	volume of the vessel (m^3)
K_{St}	deflagration index (bar·m/s)	Y_{H2O}	moisture content in mass (%)

INTRODUCTION

Biomass, e.g. produced from wood, can be used as a fuel in the form of e.g. pellets. During the pellets production and transportation process, wood dust is formed in the process equipment such as

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 366-375
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: 978-5-7422-6496-5 DOI: 10.18720/spbpu/2/k19-69

conveyors, storage silos and hoppers. With the presence of oxygen and ignition source, dust explosion can occur; see several recent accidents in Sweden [1-3].

The design of explosion mitigation strategies e.g. vent design [4] is mainly based on dust explosion characteristics such as the maximum explosion pressure ($P_{\max}$), the deflagration index (K_{St}), the Lower Explosion Limit (LEL), the Limiting Oxygen Concentration (LOC) of dust cloud, Minimum Ignition Energy (MIE), Minimum Ignition Temperature (MIT) of dust cloud and dust layer, which are defined in various standards. For example, $P_{\max}$ and K_{St} can be tested according to European e.g. EN 14034 parts 1 and 2 [5, 6] and American standards, e.g. ASTM E1226-10 [7].

The wood dust explosion characteristics can be directly obtained by performing standard tests. Alternatively, these parameters can be obtained in an online database [9], scientific publications [10-15] and technical reports [16, 17]. However, the wood dust explosion characteristics for one type of dust may vary substantially in the literature. For example, the K_{St} value for one type of wood dust is 11.4 times higher than another wood dust in Gestis-Dust-Ex database [9]. The reason for such large variation in explosion parameters is due to factors such as material properties, particle size distribution, particle shape, moisture content, turbulence level during tests, test apparatus and so on.

The objectives of this paper are (i) to carry out dust explosion tests for $P_{\max}$ and K_{St} for two wood dusts with well-described material parameters such as particle size distribution and moisture content according to European standard EN 14034 parts 1 and 2 [5, 6], (ii) to perform statistical analysis of wood dust explosion characteristics including $P_{\max}$ and K_{St} in the literature, (iii) to identify the effects of dust material parameters such as particle size and moisture content on $P_{\max}$ and K_{St} and (iv) to highlight the variation in $P_{\max}$ and K_{St} and the importance of obtaining knowledge about these properties of an individual dust, e.g. via dust explosion tests.

This paper is organized as follows. First, the measurement of the dust explosion characteristics $P_{\max}$ and K_{St} for two wood dusts with well-described material properties in a 20 L vessel are reported. Second, statistical analysis of totally 57 wood dust samples from the literature and this work are performed, followed by the conclusions.

MEASUREMENT OF EXPLOSION CHARACTERTIRISTICS OF WOOD DUSTS

In this section, the dust explosion characteristics $P_{\max}$ and K_{St} of two well characterized wood dust are measured in a 20 L vessel. The first wood dust was sampled in the filter of the dust collecting system at a furniture workshop, where they deal with different kinds of wood materials, e.g. Medium Density Fiberwood (MDF) board and massive wood. The second wood dust came from balsa tree for the use as a structural core material for composite laminates. In this paper, we name the first and the second wood dust as furniture wood dust and balsa wood dust, respectively. Only the detailed test results for the furniture wood dust will be presented, whereas the balsa wood dust results will be reported due to the limitation of length of paper.

Dust sample characteristics

Particle size distribution was measured at RISE Chemistry lab using a seive shaker manufactured by Retsch of series AS200 control with sieve mesh sizes of 63, 75, 125, 180, 250, 350, 500 μm and sieve frame diameter of 200 mm. The sieves were arranged as a sieve stack with the coarsest sieve at the top and finest seive at the bottom. The top seive was filled up with almost one third of volume by the dust mateiral. By shaking the material away from the seive mesh surface in a 3D direction, only the particles larger than the seive mesh size will be remained in the repecitve seive. The mateiral weight in the respecitve seive was weighed and a particle size distribution was determined. In this test, the seive shaker ran for 5 min with interval operation of 15 s and a shaking amplitude of

1.5 mm. The test results was shown in Fig. 1 based on three series of tests with a totoal dust mass of 115.17 g. With the assumption of a linear distribution of particle size within each particle size range, and based on the sieving results one can obtain the characteristic particle size in Table 1.

The moisture content of dust sample was measured by keeping the dust sample in an oven under temperature of 105 °C until the mass of sample was not reduced with a maximum duration of 24 h. The measured moisture content in the furniture wood dust sample is 7.9%.

Table 1. Characteristic particle sizes of furniture wood dust

Particle size parameters	D_{10}	D_{50}	D_{90}
Value [μm]	13	64	113

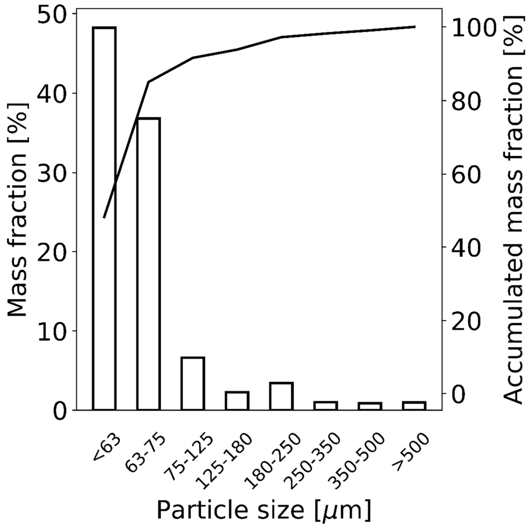


Fig. 1. Particle size distribution of furniture wood dust. Note the bars correspond to mass fraction, whereas the solid line corresponds to accumulated mass fraction.

Experimental setup

The dust explosion characteristics $P_{\max}$ and K_{St} were obtained in a 20 L vessel manufactured by Anko in accordance to European and American standards; see the design of the 20 L spherical vessel in Fig. 2. First, a vacuum pressure of -0.6 bar gauge was formed by pumping air outside of the spherical vessel. The dust sample was placed in a pressurized container at a pressure of 20 bar gauge. The dust sample was then injected into the spherical chamber via a fast actuating valve and with the assistance of a rebound V-shape nozzle. Accordingly, a relatively homogenous dust air mixture was formed. The pressure in the vessel after the dust injection was around 1 atm. A pair of pyrotechnical igniters with a total energy of 10 kJ ignited the dust cloud after an ignition delay time of 60 ms (the time between dust injection and ignition). The pressure curve was then recorded by two dynamic pressure sensors by Kistler. The pressure rise rate was processed by taking the derivative of the pressure-time curve.

RESULTS AND DISCUSSIONS

In this section, the important dust explosion paramters are presented first, followed by the measurement results.

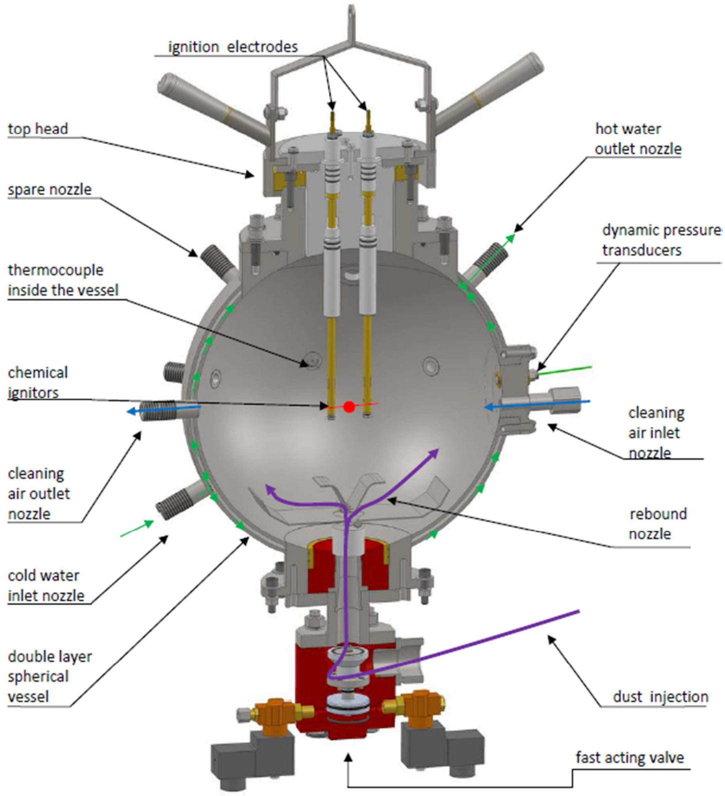


Fig. 2. The design of 20-litre spherical vessel from Anko user manual [18].

Definition of dust explosion parameters

P_{ex} is defined as the maximum explosion overpressure, i.e. above the pressure in the vessel at the time of ignition, for a single dust concentration explosion test. Tests are run with different dust concentrations first, and then tests are repeated two more times to obtain a average value of P_{ex}. Note that P_{ex} is corrected to consider the effects of water cooling and chemical ignitors according to the European standard EN 14034 parts 1 and 2 [5, 6]. $P_{\max}$ is defined as the maximum explosion overpressure obtained during dust/air mixture explosion at the optimum dust concentration, i.e. the maximum value of averaged P_{ex} for different dust concentrations as follows

$$P_{\max} = \max((\sum_{i=1}^{i=3} P_{ex,ij})/3), \quad (1)$$

where, subscript i is the number of test series performed; j is the number of dust concentrations performed in each test serie.

The deflagration index K_{St} is defined as the volume-dependent maximum pressure rise rate at the the optimum dust concentration as follows

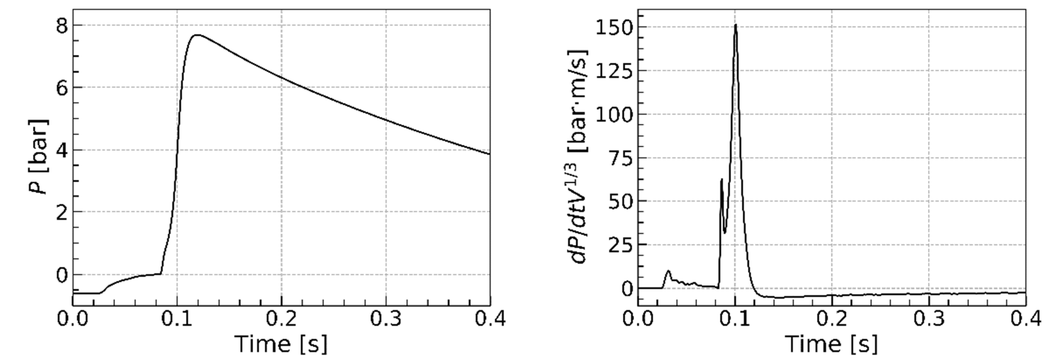
$$K_{St} = \left(\frac{dP}{dt}\right)_{\max} V^{1/3}, \quad (2)$$

Measurement of P_{max} and K_{St}

A representative furniture wood dust explosion at concentration of 500 g/m^3 is shown in Fig. 3. In Fig. 3 (a) the overpressure increases slightly up to around 0 bar which corresponds to the end of dust injection process. Later the overpressure curve increases substantially mainly due to the dust explosion process. There are three peaks in the volume-dependence pressure rise rate; see Fig. 3 (b). The first peak is due to the dust injection, whereas the second and third peak is due to pyrotechnical igniters and dust explosion, respectively.

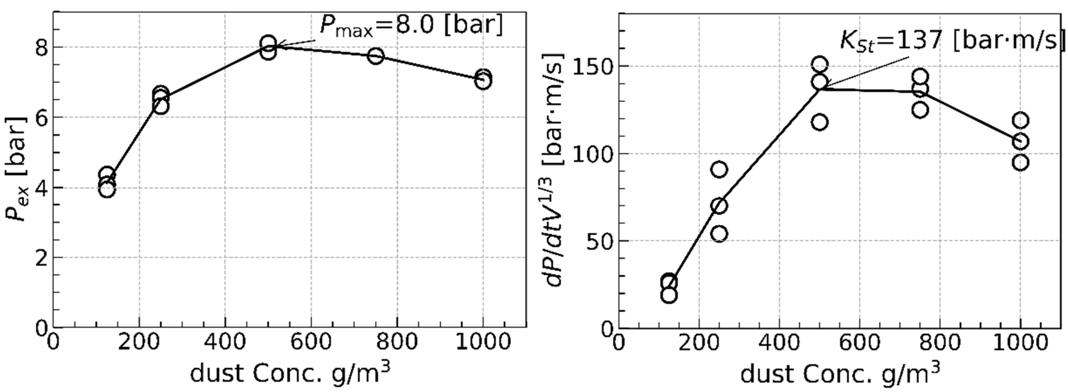
For the furniture wood dust, the maximum explosion overpressure $P_{\max}$ is 8.0 bar occurring at a dust concentration of 500 g/ m^3, and the deflagration index K_{St} is 137 bar·m/s occurring at the same dust concentration; see Fig. 4. It is worth noting that the $P_{\max}$ and K_{St} does not necessarily occur at the same dust concentration.

The balsa wood dust is characterized by a moisture content of 7% and a mass median diameter of 192 μm. The maximum explosion overpressure $P_{\max}$ is 7.6 bar occurring at a dust concentration of 750 g/m^3, and the deflagration index K_{St} is 100 bar·m/s occurring at a dust concentration of 1000 g/ m^3. The detailed data plots are not shown here due to the limitation of length in this paper.



(a) Overpressure (b) Volume-dependence pressure rise rate

Fig. 3. Explosion overpressure (without correction) and volume-dependence pressure rise rate versus time for furniture wood dust with concentration of 500 g/m^3 in 20 L vessel.



(a) Overpressure (b) Deflagration index

Fig. 4. $P_{\max}$ and K_{St} in 20 L vessel for furniture wood dust.

ANALYSIS OF BIOMASS DUST EXPLOSION CHARACTERISTICS IN LITERATURE

The wood dust explosion characteristics can be directly obtained by performing standard tests, and the test results are also available in an online database [9], scientific publications [10-15] and technical reports [16, 17]. The data for $P_{\max}$ and K_{St} for wood dusts is shown in Fig. 5. Bubble size corresponds to D_{50} of dust samples, whereas bubble color corresponds to the moisture content. White bubbles indicate missing information about moisture content, whereas cross symbols indicate missing information of either particle size or moisture content. Current results are shown as diamond symbols. As can be seen in Fig. 5, the data is very scattered. The reason is that the tests were performed with dust sample from different kinds of woods, such as beech, jute, Spanish pine, Norway spruce etc, different particle size distribution, different moisture content and different test methods, such as 20 L and 1 m^3 vessels. However, a general trend is that with the increase of $P_{\max}$, the K_{St} increases.

A closer observation in Fig. 5 shows that smaller and red coloured bubbles tend to reside in the upper right corner of the graph, whereas larger and blue coloured bubbles tend to reside in the lower left corner of the graph. Such a trend is in agreement with the fact that smaller and dryer dusts are more reactive than larger and moist dusts. The current test results lie close to other test results with similar moisture content and particle size; see diamond symbols in Fig. 5.

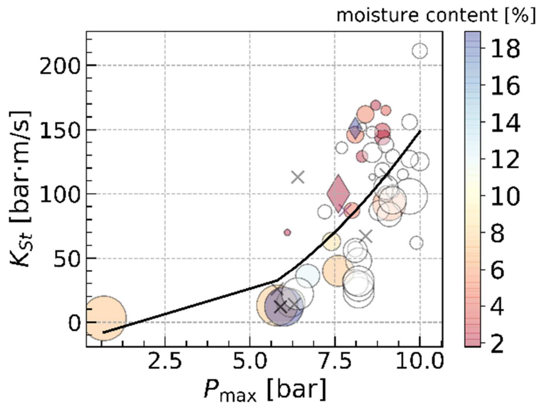


Fig. 5. Correlation between $P_{\max}$ and K_{St} for 57 wood dust samples from literature [9-17] and this work. Bubble and diamond sizes correspond to D_{50} of dust samples, whereas bubble and diamond color corresponds to the moisture content. White bubbles indicate missing information about moisture content, whereas cross symbols indicate missing information of either particle size or moisture content. Current test results are shown in diamond symbols.

Correlation between $P_{\max}$ and K_{St}

The next question is: Can we find a correlation between $P_{\max}$ and K_{St} so that the test engineers can roughly estimate if their test result is reasonable or not? The cubic law is commonly used in standardized dust explosion tests for comparing maximum pressure rise rate between vessels of different size as follows [5-8, 19]

$$\left(\frac{dP}{dt}\right)_{\max} V^{1/3} = \text{const}, \tag{3}$$

By using the classical combustion theory in a constant volume system and assumptions of ideal conditions which will be discussed later, the cubic law can be rewritten as follows [20, 21]

$$\left(\frac{dP}{dt}\right)_{\max} V^{1/3} = 4.83\left(\frac{P_{\max}+1}{P_0} - 1\right) P_{\max} S_u = \text{const}, \tag{4}$$

Equation (4) can be used to correlate the K_{St} and $P_{\max}$ for dust explosion under ideal conditions such as (i) the vessel size is large compared to the dust flame thickness or the ignition source, (ii) the flame is spherical and smooth, (iii) a constant burning velocity S_u is assumed, and (iv) this burning velocity only depends on material properties, pressure, temperature and turbulence level.

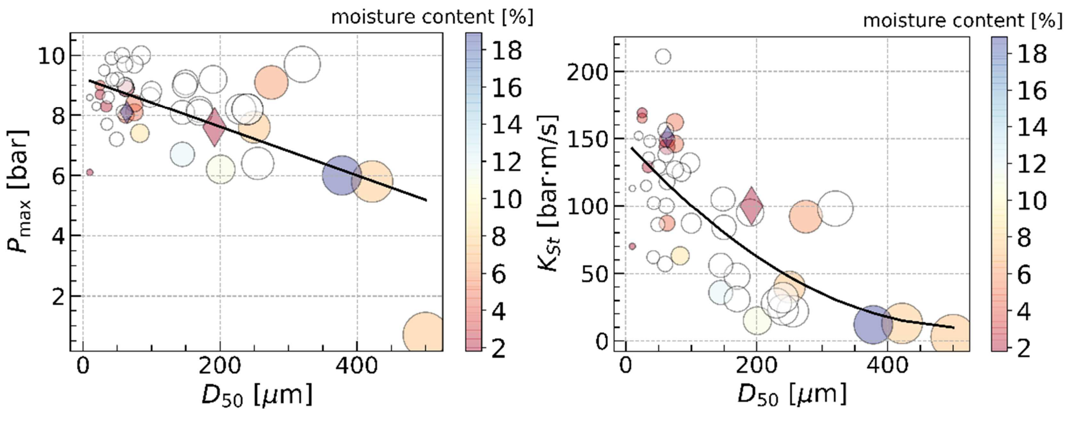
Based on the cubic law in Eq. (4), the $P_{\max}$ and K_{St} values for wood dust obtained in Gestis-Dust-Ex database [9] and some other literature [10-15, 16, 17] are approximated using a second-order polynomial. In this paper if no special comments are made, the tool for approximating dust explosion database is *numpy.polyfit* in *python* program by minimizing the squared error. A correlation between $P_{\max}$ and K_{St} based on 57 wood dust samples with a mean relative error of 68% is as follows

$$K_{St} = 2.13P_{\max}^2 - 5.96P_{\max} - 4.75. \quad (5)$$

Effect of particle size on $P_{\max}$ and K_{St}

The effect of particle size on the dust explosion characteristics were studied in the literature [21-25]. The general trend is that smaller particles yield higher $P_{\max}$ and K_{St} for micrometer particles such as coal [21], iron [21], aluminum [22, 25] and magnesium [23, 24] dusts. The reason is that smaller particles are characterized by a larger specific surface area which in term increases the volitilization and burning rate [22].

The mass median size, D_{50}, is frequently used to characterizing the average size of dust particles, and it is defined as the particle size where half of the particles in mass resides above this point and half resides below this point. It is suggested by other researchers that the Sauter Mean Diamter (SMD or D_{32}) may be more appropriate for quantifying the average size of dust particles [22, 25] since it indicates the volume to surface area ratio in a statistical point of view. However, to obtain SMD, it requires optical method, and such results are seldom available in the literature. The current analysis focuses exclusively on the effect of mass median size D_{50}.



(a) Correlation between $P_{\max}$ and D_{50} (b) Correlation between K_{St} and D_{50}

Fig. 6. Correlation between dust explosion characteristics and D_{50} for 49 wood dust samples from literature [9-17] and this work. Symbol size corresponds to D_{50} of dust samples, whereas symbol color corresponds to the moisture content. White bubbles indicate missing information about moisture content. Current results are shown as diamond symbols.

With the increase of D_{50}, the $P_{\max}$ decreases slightly (see Fig. 6 (a)), whereas K_{St} decreases strongly with the increase of D_{50} (see Fig. 6 (b)) for wood dusts. Such finding is inline with the finding by Cashdollar for coal and iron dusts [21]. The reason for the weak effect of D_{50} on $P_{\max}$ may due to the fact that $P_{\max}$ highly depends on the energy released by the constant volume system [25] and partly depends on the combustion efficiency which is connected to the particle size. In contrast, the K_{St} has a strong dependence on D_{50}, and the reason is that larger surface area of smaller particles increases the burning rate. The solid lines in Fig. 6 are approximations based on 49 wood dust samples, with mean relative error for $P_{\max}$ and K_{St} being 22% and 51%, respectively, which are reported as follows

$$P_{\max} = -8.09 \times 10^{-3} D_{50} + 9.23, \quad (6)$$

$$K_{St} = 5.01 \times 10^{-4} D_{50}^2 - 0.53 D_{50} + 147.79 \, . \quad (7)$$

Effect of moisture content on $P_{\max}$ and K_{St}

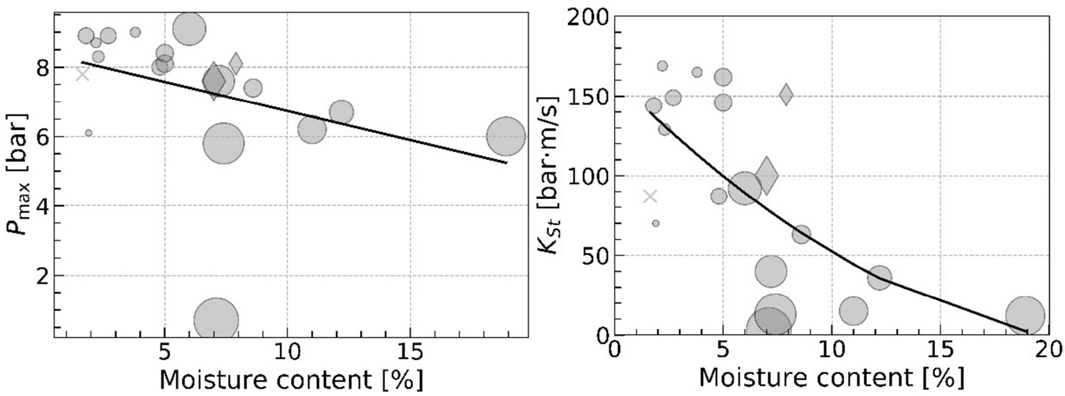
Winter dry season promotes dust explosions since dusts has low moisture contents and are more easily dispersed. Statistical analysis by U.S. Chemical Safety Board shows that seven out of eight combustible dust explosions between 1995 and 2009 occurred during winter season [26]. According to the ASTM standards, the moisture content in the dust sample should be less than 5%. However, no recommendation is made in the European standards. The moisture content of dust has substantial effect on the dust explosion characteristics and the effect depends on the material. For example, with the increase of relative humidity at which the aluminium dust is preserved, the $P_{\max}$ and K_{St} increases [25]. This promotion of explosion is related to the hydrogen production reaction between aluminium and water [25]. More frequently the dust explosion violence decreases with the increase of moisture content in the dust sample such as for maize flour [27] and coal dusts [28].

It can be seen in Fig. 7 that for the wood dust with the increased moisture content the $P_{\max}$ and K_{St} decrease, which is inline with the findings by Yuan et.al. [28] for coal dust. The solid lines in Fig. 7 are approximations based on 20 wood dust samples, with mean relative error for $P_{\max}$ and K_{St} being 56% and 187%, respectively,

$$P_{\max} = -0.17 Y_{H2O} + 8.41, \quad (8)$$

$$K_{St} = 0.28 Y_{H2O}^2 - 13.75 Y_{H2O} + 161.40 \, . \quad (9)$$

Figure 7 also indicates that smaller dust particles tend to reside above the correlation line, whereas larger dust particles tend to reside below the correlation line, which is inline with the finding of effect of particle size on explosion characteristics.



Correlation between $P_{\max}$ and moisture content (b) Correlation between K_{St} and moisture content

Fig. 7. Correlation between dust explosion characteristics and moisture content for 20 wood dust samples from literature [9-17] and this work. Bubble and diamond sizes correspond to D_{50} of dust samples. Cross symbol indicates missing information of particle size. Current results are shown as diamond symbols.

CONCLUSIONS

The dust explosion characteristics $P_{\max}$ and K_{St} for two wood dusts with well-described dust material properties, i.e. particle size distribution and moisture content were measured in a 20 L vessel according to European standard EN 14034 parts 1 and 2.

The explosion characteristics $P_{\max}$ and K_{St} of 57 wood dust samples, from both literature and test results in this paper, were analysed. A substantial scatter in the data highlights the importance of performing wood dust explosion tests for each single dust sample due to the variation in the dust sample characteristics such as material composition, particle size characteristics and moisture content.

Although there is a substantial scatter in the data, several trends are observed. The value of K_{St} increases with $P_{\max}$ quadratically for the wood dust samples studied in this paper. The value of $P_{\max}$ decreases linearly with the median dust particle size and moisture content, whereas the K_{St} decreases non-linearly with the particle size and moisture content. The reason is that $P_{\max}$ is mainly related to the energy released in the constant volume system and partly depends on the combustion efficiency which is connected to the particle size. In contrast, K_{St} depends on more complicated factors such as burning velocity, which is related to particle size and turbulence level non-linearly.

ACKNOWLEGEMENT

The authors would like to thank the Fuel Safety Storage competence platform at RISE Research Instititutes of Sweden for providing financial support, Sven-Ove Vendel at RISE for providing support in dust sampel moisture content measurement, Nijaz Smajovic at chemistry department of RISE for providing support in dust particle size characterization and Bolander & Schön for providing wood dust sample.

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