MODERATION OF EXPLOSION LIKELIHOOD AND CONSEQUENCES OF NON-TRADITIONAL DUSTS

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The research presented in this paper is focused on dust explosions of coarse and fine flocculent (or fibrous) samples of wood and polyethylene. Hybrid mixtures of fibrous polyethylene and admixed ethylene were also studied. Experimentation was conducted by following standardized test procedures and using standardized apparatus for determination of maximum explosion pressure, size-normalized maximum rate of pressure rise, minimum explosible concentration, minimum ignition energy, and minimum ignition temperature. A general trend was observed of enhanced explosion likelihood and consequence severity with a decrease in material diameter, as well as enhanced consequence severity with admixture of a flammable gas to the combustion atmosphere. The same phenomena are well-established for dusts composed of spherical particles; this highlights the importance of inherently safer design and the principle of moderation in avoiding the generation of fine sizes of flocculent dusts and hybrid mixtures of such materials with flammable gases.

KEYWORDS: Dust explosions, flocculent material, hybrid mixtures, moderation, inherent safety

INTRODUCTION

As defined by the US National Fire Protection Association in NFPA (2007), a *dust* is any finely divided solid, 420 μm or 0.017 in. or less in diameter (i.e., material capable of passing through a US No. 40 Standard Sieve). There could therefore be a tendency to consider flocculent substances (fibrous or "fluffy" materials in which the fibres are better characterized by a length-to-diameter ratio than by a characteristic diameter) as "non-traditional dusts" – if they are considered to be dusts at all.

In this context, it is pertinent to note the NFPA definition of a *combustible dust* – a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentration, regardless of particle size or shape (NFPA, 2007). This latter definition with no limitations on particle shape or particle size is relevant to the field of flocculent material explosibility, which is the subject of the current paper.

Frank (2004) illustrates the importance of research on the explosibility of flocculent materials in his description of the 1995 Malden Mills explosion involving nylon fibres (flock). Recent papers by Marmo and Cavallero (2008) and Marmo (2010) provide details on the acquisition of nylon fibre minimum ignition energy data and a further case study, respectively. Piccinini (2008) describes a case study of a dust explosion in a wool factory, and papers by von Pidoll (2001, 2002) address the issue of ignition of flocculent textiles.

While there is thus some understanding of the explosible nature of flocculent particles, there remains a need for further research and data generation. As noted by Marmo and Cavallero (2008), fibre ignition has not been studied to the same extent as dust (particle) ignition and there is a lack of quantitative data to describe the behaviour of fibre dispersion. Febo (2010) has demonstrated the

requirement for explosibility testing of flocculent materials and has commented that simple visual observation of a material is not a reliable means of identifying a combustible dust hazard.

To help address these research needs, the current paper presents explosibility data for different sizes of fibrous materials alone and also with admixed flammable gas. Thus, the work has relevance to the inherently safer design principle of *moderation* in terms of avoidance of both hybrid mixtures and finely-sized particulate matter (Amyotte et al., 2009a). The test results are discussed with respect to their implications for the likelihood and consequences of explosions arising from fibrous (or flocculent) particulate matter, and conclusions are made to facilitate better understanding of the explosion risk presented by such materials.

EXPERIMENTAL

Bulk samples of fibrous wood and polyethylene were obtained for testing. The explosibility parameters investigated were maximum explosion pressure (P_{max}), size-normalized maximum rate of pressure rise (K_{St}), minimum explosible concentration (MEC), minimum ignition energy (MIE), and minimum ignition temperature (MIT).

Aside: K_{St}, the size-normalized maximum rate of pressure rise for a constant-volume explosion, is the product of the maximum rate of pressure rise, $(dP/dt)_{max}$, and the cube-root of the volume, V, of the chamber in which the explosion tests were conducted. The units of K_{St} are therefore units of (pressure)(length)/(time); conventional units are bar · m/s. As noted below, standardized equipment (volume of 20 L) and standardized test procedures were used in the current work, thus enabling the measured $(dP/dt)_{max}$ values to be converted to K_{St} values.

Table 1. Particle size distributions for fibrous wood (FW) samples

Sample	<500 μm [weight %]	<75 μm [weight %]
FW-1 Bulk	41	0.3
FW-2 −35 Mesh (<500 μm)	100	0.7
FW-3 −200 Mesh (<75 μm)	100	100

MATERIALS

Table 1 gives the particle size distribution (PSD) of the bulk fibrous wood sample, designated as FW-1 (moisture content of 0.6 weight %). Also shown in Table 1 are the PSDs of −35 mesh and −200 mesh wood samples designated as FW-2 and FW-3, respectively. Sample FW-2 was prepared by sieving a portion of the bulk FW-1 sample, while FW-3 was prepared by pulverizing a portion of FW-1 and then sieving through a 200-mesh screen. All PSDs reported in Table 1 were determined by sieve analysis.

Table 1 indicates that FW-1 was comprised of 59 weight % +35 mesh material (nominally > 500 μm) and 41 weight % −35 mesh material (nominally < 500 μm). A qualitative sense of this bulk material composition is given in Figures 1 and 2, which show photographs for each fraction. Even with the aid of only a digital camera the non-spherical nature of the particles is clearly visible in Figures 1 and 2.

Table 2 gives the PSD of the bulk fibrous polyethylene sample (designated as FPE-1) as well as that for a −200 mesh sample termed FPE-2. This finer size was obtained by sieving a portion of the bulk FPE-1 sample. The PSD of FPE-1 was determined by sieve analysis while the PSD of FPE-2 was measured by Malvern (light-scattering) analysis. Table 2 shows material > 200 mesh for FPE-2, likely because of material passing through the 75-μm sieve with fibre length being longer than fibre width (i.e., the fibrous particles orient themselves during

Figure 1. Digital photograph of +35 mesh wood sample

Figure 2. Digital photograph of −35 mesh wood sample (FW-2)

the sieving process so as to pass through the screen openings via the smaller dimension). The Malvern apparatus does not distinguish between different particle shapes and assumes all signals are generated by spherical particles.

Table 3 gives the PSDs for six size fractions of powdered (i.e., spherical or near-spherical) polyethylene. Explosibility results for these samples were previously reported by Amyotte et al. (2008); details are included here because of the subsequent comparison in the current work with the fibrous polyethylene samples (Table 2). In Table 3, SPE-1 represents the coarse (bulk) sample from which SPE-2 and SPE-3 were prepared by sieving. Similarly, SPE-4 is the fine (bulk) sample from which SPE-5 and SPE-6 were prepared by sieving. All PSDs in Table 3 were determined by Malvern analysis with the exception of that for SPE-1 which was measured via a combination of sieve and Malvern analyses. All samples of polyethylene (FPE and SPE) were dried before testing to a bone-dry state.

The fibrous and spherical polyethylene samples could be easily distinguished by the naked eye in their coarse (bulk) states – FPE-1 and SPE-1, respectively. FPE-1 was clearly composed of strands of material with a significant length-to-diameter ratio whereas SPE-1 was clearly more a powder with spherical/near-spherical particles. This distinction was not readily apparent for the finer sizes of FPE and SPE. With the aid of a scanning electron microscope (SEM), however, the different particle shapes can again be observed. Figures 3 and 4 show SEM micrographs for the nominally −200 mesh polyethylene samples (FPE-2 and SPE-5, respectively), in which the flocculent and particulate shapes of the samples are visible.

APPARATUS AND PROCEDURES

American Society for Testing and Materials (ASTM) test protocols were followed using standard dust explosibility test equipment manufactured by Adolf Kuhner, Switzerland. Details on the equipment and method of operation can be found on the manufacturer's web site (www.kuhner.com).

Table 2. Particle size distributions for fibrous polyethylene (FPE) samples

Sample	<1000 μm [weight %]	<500 μm [weight %]	<250 μm [weight %]	<150 μm [weight %]	<75 μm [weight %]
FPE-1 Bulk	82	73	49	27	8
FPE-2 −200 Mesh (<75 μm)	100	100	99	94	65

Table 3. Particle size distributions for spherical polyethylene (SPE) samples (Amyotte et al., 2008)

Sample	D(v,0.5) [μm]	D(4,3) [μm]	D(v,0.1) [μm]	D(v,0.9) [μm]
SPE-1 Coarse (Bulk)	916	900	455	1252
SPE-2 −40 Mesh (<420 μm)	276	276	107	433
SPE-3 −70 Mesh (<212 μm)	171	159	84	252
SPE-4 Fine (Bulk)	103	146	35	334
SPE-5 −200 Mesh (<75 μm)	49	48	24	78
SPE-6 −400 Mesh (<38 μm)	28	29	20	38

D(v,0.5) = volume median diameter; D(4,3) = volume mean diameter
D(v,0.1) = diameter > 10 volume % of particles; D(v,0.9) = diameter > 90 volume % of particles

The experiments for P_{max}, K_{St} and MEC were performed using a Siwek 20-L explosion chamber. This apparatus consists of a spherical vessel into which the sample dust is dispersed and subsequently ignited by a centrally-mounted chemical ignitor(s). Figure 5 shows a schematic of the chamber and ancillary equipment. Testing with the larger-sized flocculent samples (FW-1 and FPE-1) at higher concentrations necessitated placing the sample directly in the explosion chamber prior to testing, rather than in the external dust storage reservoir. The ignition delay time was fixed at 60 ms for all tests; ignition energy was 5 kJ for MEC determination and 10 kJ for P_{max}/K_{St} testing (in accordance with the relevant ASTM methodologies). Hybrid mixture testing for the FPE samples was conducted with admixture of approximately 1 volume % ethylene to the combustion atmosphere by means of the partial pressure method.

The MIE experiments were conducted using a MIKE 3 apparatus consisting of a 1.2-L cylindrical glass chamber into which dust is dispersed and then ignited by an electrical spark of known energy (maximum value of 1 J). Spark energy, ignition delay time and dust concentration were systematically varied during the test procedure. MIE values were determined without inductance in the spark circuitry and also with an inductance of 1 mH; the latter case results in a protracted spark and the potential for a lower MIE than would be measured using no inductance.

The MIT experiments were conducted using a cylindrical furnace known as a BAM oven. In the operation of this apparatus, a dust cloud is generated by squeezing a
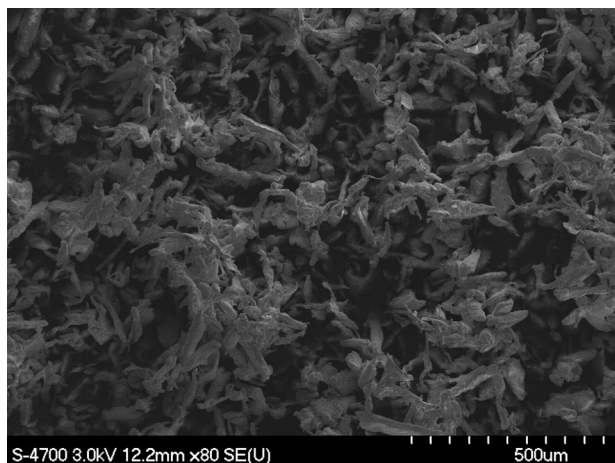

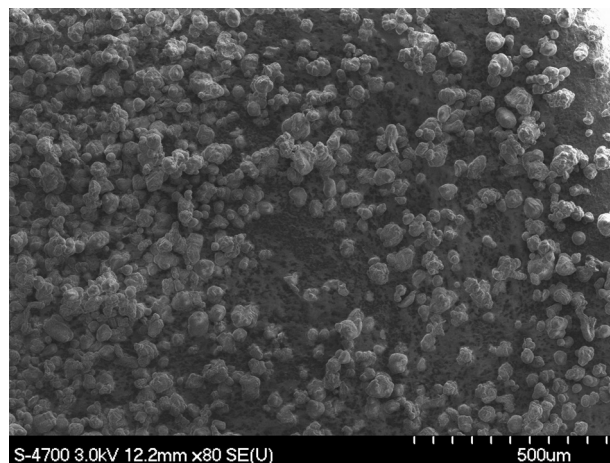**Figure 3.** SEM micrograph of −200 mesh fibrous polyethylene sample (FPE-2)

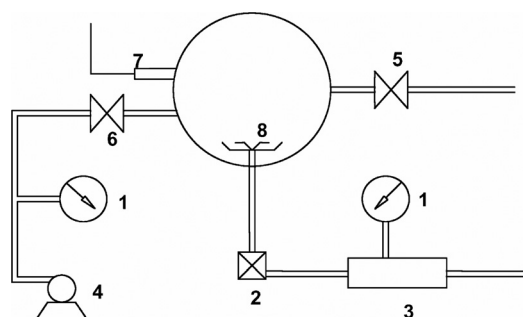**Figure 4.** SEM micrograph of −200 mesh spherical polyethylene sample (SPE-5)

Figure 5. Schematic diagram of Siwek 20-L chamber (1 – Pressure Gauge; 2 – Solenoid Valve; 3 – Dust Storage; 4 – Vacuum Pump; 5 – Exhaust Valve; 6 – Vacuum Valve; 7 – Transducers; 8 – Rebound Nozzle)

rubber bulb (previously charged with sample) which directs the dust against a circular, concave metal plate of about 20 cm^2 area and known temperature (maximum value of 580°C).

RESULTS AND DISCUSSION

The results of explosibility testing for the fibrous wood and polyethylene samples are given in Tables 4 and 5, respectively. For comparison purposes, spherical polyethylene explosibilty data from Amyotte et al. (2008) are summarized in Table 6. A long dash in Tables 4–6 indicates that the particular parameter was not measured for the given sample. Also, the MIE results are given as a range; this is an artifact of the MIKE 3 apparatus, with the lower number being the spark energy at which no ignitions were recorded and the higher number being the spark energy at which at least one ignition occurred.

In terms of the risk posed by the hazard of the various materials studied, the parameters in Tables 4–6 that pertain

to the likelihood of occurrence of a dust explosion are MEC, MIE and MIT. Parameters relevant to the severity of the consequences resulting from a dust explosion are P_{max} and K_{St}. These points are discussed in the following sections for the fibrous wood and polyethylene samples.

FIBROUS WOOD SAMPLES

Figures 6 and 7 show the influence of particle (mesh) size on the maximum values of explosion pressure and rate of pressure rise, respectively, for the fibrous wood samples FW-2 and FW-3. All explosion pressure data are given in Figure 6 while, for the sake of clarity, only the highest value of rate of pressure rise measured for a given dust concentration and sample is shown in Figure 7.

Figures 6 and 7 demonstrate that at a given dust concentration, a decrease in size from FW-2 to FW-3 has a greater impact on the magnitude of rate of pressure rise than explosion pressure. This effect ultimately manifests itself in the final values of P_{max} and K_{St} as discussed shortly. Also apparent in Figures 6 and 7 is the attainment of peak values of explosion pressure and rate of pressure rise at leaner dust concentrations for the finer-sized FW-3 sample. Thus, a decrease in particle size (i.e., fibre diameter) reduces the rate-limiting effect of this material property on the combustion process. These observations for the fibrous wood samples tested are consistent with the work of Denkevits and Dorofeev (2006) on spherical graphite dusts and Amyotte et al. (2009b) on spherical polyethylene samples.

In terms of explosion likelihood, Table 4 shows that minimum explosible concentration, ignition energy and ignition temperature all display a general trend of decreasing values as particle size decreases and more fines are therefore present in the sample. In particular, FW-3 has an MEC of only 20 g/m^3 and an MIE within the range of energies developed by typical electrostatic discharges. FW-2, with less than 1 weight % −200 mesh material, has a

Table 4. Explosibility data for fibrous wood (FW) samples

Sample	P_{max} [bar(g)]	K_{St} [bar·m/s]	MEC [g/m^3]	MIE (inductance) [mJ]	MIE (no inductance) [mJ]	MIT [°C]
FW-1	7.2	41	100	300–1000	300–1000	>580
FW-2	7.8	80	30	300–1000	>1000	420
FW-3	8.2	149	20	10–30	30–100	410

Table 5. Explosibility data for fibrous polyethylene (FPE) samples

Sample	P_{max} [bar(g)]	K_{St} [bar · m/s]	MEC [g/m^3]	MIE (inductance) [mJ]	MIE (no inductance) [mJ]	MIT [°C]
FPE-1	5.8	22	450	100–300	> 1000	460
FPE-1 + C$_2$H$_4$	5.8	50	50	–	–	–
FPE-2	7.2	75	60	10–30	100–300	490
FPE-2 + C$_2$H$_4$	7.2	102	10	–	–	–

Table 6. Explosibility data for spherical polyethylene (SPE) samples (Amyotte et al., 2008)

Sample	P_{max} [bar(g)]	K_{St} [bar · m/s]	MEC [g/m^3]	MIE (inductance) [mJ]	MIE (no inductance) [mJ]	MIT [°C]
SPE-1	Explosions in only 1/3 of tests from 250–1250 g/m^3	Explosions in only 1/3 of tests from 250–1250 g/m^3	No explosions from 500–2750 g/m^3	>1000	>1000	–
SPE-2	Explosions in only 2/3 of tests from 250–1250 g/m^3	Explosions in only 2/3 of tests from 250–1250 g/m^3	No explosions from 500–2750 g/m^3	>1000	>1000	–
SPE-3	5.8	15	500	>1000	>1000	–
SPE-4	6.9	78	40	10–30	100–300	410
SPE-5	6.7	104	10	10–30	100–300	400
SPE-6	6.9	137	20	10–30	30–100	370

somewhat lower likelihood of explosion, but not by a significant amount in terms of MEC and MIT. Even FW-1 (a near equal mix of the fractions shown in Figures 1 and 2) has a relatively low MEC of 100 g/m^3 and was ignitable by electric sparks of 1 J energy.

Consequence severity displays a similar trend with respect to a decrease in particle size. As illustrated by the data in Table 4, the influence of a greater percentage of fines is more pronounced for P_{max} than for K_{St}. Again, this is an expected result based on testing of spherical particulate material such as the SPE-4, SPE-5 and SPE-6 samples shown in Table 6 (Amyotte et al., 2008) and other spherical polyethylene samples (Amyotte et al., 2009b). Further, the P_{max}/K_{St} results in Table 4 are consistent with the work of Febo (2010) who determined that a fibrous wood sample with 48 weight % < 500 μm was explosible, whereas a sample of the same material with 22 weight % < 500 μm was not explosible (based on 20-L chamber testing).

Moderation of the explosion hazard for fibrous or flocculent materials by avoidance of fine size fractions is therefore of critical importance. While it is not always possible to employ this fundamental principle of inherently safer design (e.g., when the fine material is the desired end-product), the implications of finely sized flocculent dusts for explosion likelihood and consequence severity should be well-understood. Particle size considerations are also of great importance in selecting a representative dust sample from a process for explosibility testing (Amyotte and Eckhoff, 2010).

FIBROUS POLYETHYLENE SAMPLES

From an explosion likelihood perspective, the results in Table 5 for the fibrous polyethylene samples follow the same general trends as those just discussed for the fibrous wood samples. A pronounced effect of a reduction in size from FPE-1 to FPE-2 is observed for MEC and MIE, with an order of magnitude reduction in both parameters.

With respect to consequence severity, increases in P_{max} and K_{St} with a decrease in particle size are again evident in Table 5. For a given size fraction (FPE-1 or FPE-2), admixture of approximately 1 volume % ethylene to the combustion atmosphere has no net effect on P_{max}
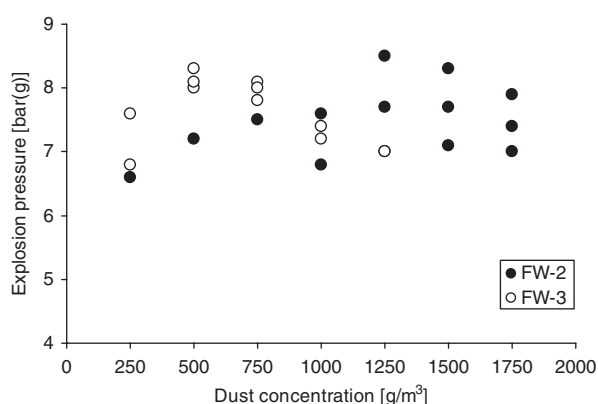
Figure 6. Influence of particle size on explosion pressure for fibrous wood samples
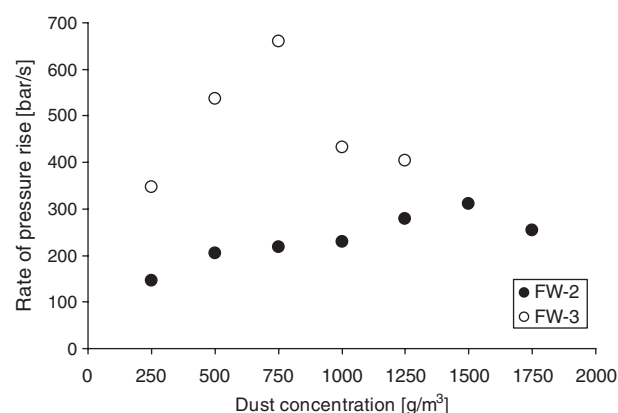
Figure 7. Influence of particle size on rate of pressure rise for fibrous wood samples

but a significant influence on K_{St}. These are expected results and are consistent with the dust and hybrid mixture testing reported by Amyotte et al. (2009b) for spherical polyethylene samples and admixed ethylene, hexane and propane. The maximum explosion pressure, P_{max}, is a thermodynamic parameter and is therefore largely dependent on initial and final test conditions; $(dP/dt)_{max}$ and hence K_{St}, on the other hand, are kinetic parameters and are influenced to a far greater extent by factors such as particle size reduction and flammable gas admixture which enhance rate-limiting combustion steps.

Application of the inherent safety principle of *moderation* in the case of the fibrous polyethylene samples would again necessitate the avoidance of fine size fractions. Additionally, the polyethylene/ethylene data given in Table 5 demonstrate the need to monitor and alter processing methods wherever possible to eliminate the potential for hybrid mixture formation. There are also clear implications of these findings with respect to explosion mitigation measures such as venting and automatic suppression. Such measures designed for a coarse dust in the absence of a flammable gas would be inadequate for protection from the effects of an explosion of a hybrid mixture of a fine dust and admixed flammable gas.

The data in Table 5 for fibrous polyethylene can be compared with the results shown in Table 6 for spherical polyethylene. The comparison is general and must be viewed in relative terms only for the following reasons: (i) although both the fibrous and spherical samples are indeed polyethylene, the composition of each was not determined in the current work, and (ii) size comparisons based on mesh size involve the use of a particle "diameter", which is the sole dimension of interest for a spherical particle but only one of three dimensions of interest for a fibrous particle (the others being length and to a lesser extent, thickness).

With the above limitations in mind, FPE-1 is seen to be closest in size (in terms of a mean or median diameter) to SPE-2 and its explosibility data generally compare well with those for SPE-3. Similarly, FPE-2 is closest in size to SPE-5 and its explosibility data generally compare well with those for SPE-4. The validity of these observations is supported by the work of Marmo and Cavallero (2008) who noted in their work on ignition energies for flocculent material that the influence of diameter on MIE was greater than that of the fibre length. Although length does have an effect, diameter is the rate-controlling variable affecting mass and heat transfer processes occurring in the fibres (Marmo and Cavallero, 2008).

What the above comparison also shows is that there is no apparent reason to expect a particular material to be non-explosible or less explosible simply because it is composed of strands or fibres that do not conform to the notion of dusts being made up of spherical or near-spherical particles. Referring again to the remarks made by Febo (2010): . . . *simply looking at a dust is not necessarily a reliable way to identify a combustible dust hazard.*

CONCLUSION

The current work has used bulk samples of fibrous wood and polyethylene to demonstrate that particle shape, in addition to particle size, is an important material property affecting dust explosibility. Flocculent materials were observed to display the same general trend of increasing explosion likelihood and consequence severity with a decrease in fibre diameter as is displayed by materials having a more spherical shape. The test results obtained in the current work also show that like spherically-shaped powders, flocculent materials experience a heightened explosion severity with admixture of a flammable gas. Thus, the explosible nature of fibrous substances should not be discounted solely on the basis of their particle shape not being that of a "traditional" dust.

Reliance on bulk samples as in the present study means that while particle or fibre diameter can be controlled to some extent by appropriate sieving procedures, fibre length remains an indeterminate variable. Parametric studies incorporating both diameter and length are required to yield fundamental information on the influence of both geometric dimensions. Such work is currently being planned for the corresponding author's laboratory.

ACKNOWLEDGMENT

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