



## Investigation of marginally explosible dusts

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### ABSTRACT

“Marginally explosible dusts (MEDs)” are a group of combustible dusts that are distinguished by relatively low volume-normalized maximum rate of pressure rise ( $K_{St}$ ) and maximum explosion pressure ( $P_{max}$ ) values. Earlier studies have suggested that dusts with  $K_{St}$  values less than 45 bar m/s in the laboratory-scale 20-L chamber would not explode in the 1-m<sup>3</sup> chamber and therefore not on an industrial scale. Conversely, for some metallic dusts, significantly higher  $K_{St}$  values are generated in the 1-m<sup>3</sup> chamber. Industries that handle MEDs continue to search for answers to the questions “are they explosible or not?” and “should we protect or not protect against potential explosions of these dusts?”. To answer these questions, four well-characterized materials namely, carbon black, oat grain flour, urea, and zinc were tested in the current study. These materials were selected because they exhibit different combustion behaviors and also cover a range of industries. Five ignition energies (i.e., 0.5, 1, 2.5, 5, and 10 kJ) were used in the 20-L chamber tests. The results show a clear case of overdriving (as a result of the high ignition energy density in the 20-L chamber) with respect to urea and carbon black dusts. Nevertheless, the urea dust is non-explosible. The data also suggests that the choice of test chamber to generate suitable explosion data is strongly dictated by the combustion path of MEDs. However, there are exceptions. The study also establishes the importance of both chemico-physical and thermal analyses to understanding the explosion behavior of MEDs. With reference to urea dust, a new definition for MEDs has been suggested as dusts having  $P_{max} < 3.0$  bar(g),  $K_{St} < 20$  bar m/s (in the 20-L chamber),  $MEC > 1000$  g/m<sup>3</sup>,  $MIE > 1000$  mJ, and  $MIT > 600$  °C. This work provides guidelines to industries that handle MEDs on the explosibility classification of these dusts, thus addressing the existing difficulty, and informing industry on the safety strategies required when handling this group of dusts.

## 1. Introduction

Proper classification of combustible dusts as explosible or non-explosible is the first step in the dust explosion hazard and risk assessment process (Ebadat, 2010). In recent times, one group of combustible dusts that has received increased attention as a result of the uncertainty that surrounds its classification (as being explosible or non-explosible) is “marginally explosible dusts”. The term was first adopted by Palmer and Tonkin (1968), when the explosibility of phenol formaldehyde resin and magnesium oxide dusts, and their mixtures, were investigated in a vertical explosion tube. It was concluded that marginally explosible

dusts have a comparatively narrow range of flammable concentrations, generate only moderate explosion pressures, and are unlikely to cause severe explosions. Several studies have since been undertaken to investigate and understand the behavior of dusts considered to be “marginally explosible” in terms of their explosibility (Cashdollar and Chatrathi, 1993; Proust et al., 2007; Cloney et al., 2013; Thomas et al., 2013). This group of combustible dusts presents a peculiar challenge when designing dust explosion prevention and mitigation strategies. While they may appear to explode during laboratory scale tests, their explosion characteristics in industrial-size facilities can be less certain. For instance, ambiguities have been found in the results for some

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materials as determined in different-size chambers and in accordance with standardized test protocols (Proust et al., 2007; Cloney et al., 2013; Thomas et al., 2013). For example, Proust et al. (2007) concluded that a dust having a value of  $K_{St} < 45$  bar m/s measured in a standard 20-L sphere might not be explosible in a 1-m<sup>3</sup> chamber.

Several studies have attributed this behavior largely to the phenomenon of over-driving caused by energetic chemical igniters leading to false positives in smaller explosion chambers (Going et al., 2000; Rodgers and Ural, 2011; Kuai et al., 2011, 2013; Thomas et al., 2013; Portarapillo et al., 2021a). Although several studies have been conducted to understand the behavior of this group of dusts, the question of “whether these dusts are explosible or not” still remains unanswered. Hence, industries that handle such dusts either continue to employ the same prevention and mitigation measures as severely explosible dusts, or do not put in place any explosion safety measures because the dusts are deemed non-explosible on an industrial scale. Other studies (Proust et al., 2007; Bucher et al., 2012; Myers et al., 2013; Cloney et al., 2013; Taveau, 2014; Taveau, 2015a, 2015b; Taveau et al., 2019) have suggested the existence of another complication associated with the different behaviour of metallic marginally explosible dusts relative to non-metallic marginally explosible dusts. For instance, as found by Bucher et al. (2012), out of the 13 metallic dust samples tested, a significant majority of 12 dusts that tested to be explosible in the 20-L chamber with  $K_{St}$  values below 50 bar m/s, were found to have greater values of both  $P_{max}$  and  $K_{St}$  in the 1-m<sup>3</sup> vessel. Similarly, Taveau et al. (2019) indicated that  $K_{St}$  values of iron, zinc and aluminum dusts can be much more severe when measured in the 1-m<sup>3</sup> chamber relative to values measured in the more commonly used 20-L chamber. The  $K_{St}$  value of aluminum, in particular, can double in the larger vessel. This assertion has been further confirmed by Puttick (2017). The different behaviour of metallic marginally explosible dusts relative to non-metallic marginally explosible dusts can be justified by the presence of several effects affecting the standard measurements, including the triggering and heat dissipation effect of chemical igniters and the level of pre-ignition turbulence in vessels of different sizes (Portarapillo et al., 2021a, 2021b).

The current experimental study investigates the explosion behavior of marginally explosible dusts observed in the 20-L and the 1-m<sup>3</sup> chamber to attempt to provide answers to the questions “are marginally explosible dusts explosible or not?” and “should we protect or not protect against explosions of these dusts?”. Answers to these questions would help bring clarity to industries handling these dusts. The research further seeks to suggest a working definition for the term marginally explosible dusts. The current paper further explores the role of chemico-physical and thermal screening of the selected combustible dusts to fully understand the explosibility or non-explosibility of marginally explosible dusts in terms of flame propagation pathways of these dusts. Additionally, this research work discusses the influence that the specific combustion mode that controls flame propagation has on choosing the most practical explosion test chamber.

## 2. Materials and methods

Testing was performed to determine two sets of explosion characteristics namely, explosion severity parameters and explosion likelihood parameters. Explosion severity parameters, which include the maximum explosion pressure ( $P_{max}$ ) and maximum rate of pressure rise ( $(dp/dt)_{max}$ ), were determined on two test scales: the 20-L and 1-m<sup>3</sup> explosion chambers. On the other hand, explosion likelihood parameters (i.e., minimum ignition energy (MIE), minimum explosible concentration (MEC), and minimum ignition temperature (MIT)) were determined with the MIKE-3 apparatus, both 20-L and 1-m<sup>3</sup> chambers, and BAM oven, respectively. The samples were also tested to assess chemico-physical features as well as thermal properties.

### 2.1. Experimental materials

This section presents the four experimental materials used in the current testing program: carbon black, oat grain flour, urea, and zinc powders. Carbon black was supplied by Michelin Canada and is mainly used in the rubber industry, mostly in the automotive field. Oat grain flour is used as an ingredient and antioxidant in a variety of food products. Urea is a nitrogen fertilizer widely used due to its high nitrogen content. Zinc is used to galvanize metals and alloys such as brass and in the form of powder to produce zinc oxide. The selected materials represent different types of dust materials with distinct reactivities, handled by various processing industries across the globe. All four materials were procured in powder form and were tested as received.

### 2.2. Material characterization

Before testing was conducted, selected physical and chemical properties of the dust samples were determined. The properties investigated include particle size distribution given in terms of the median diameter,  $D_{50}$ , as well the 10% and 90% boundaries (i.e.,  $D_{10}$  and  $D_{90}$  respectively), polydispersity ( $\sigma_D = (D_{90} - D_{10})/D_{50}$ ) (which was calculated from the particle size distribution), and bulk density ( $\rho_{bulk}$ ). Microscopic images of all the dusts were obtained via scanning electron microscopy (SEM). The thermal behavior of the dusts was also assessed by thermogravimetric (TG) analysis using a simultaneous TG/DSC TA Instrument Q600SDT. Tests were performed in an open alumina pan. Briefly, 10 mg sample was placed in the crucible and was heated with heating rate  $\beta = 10.0$  °C/min, in both N<sub>2</sub> and airflow (100 mL/min) to assess the influence of different atmospheres. To analyze gases produced from sample degradation, an FTIR analysis was carried out through a TGA/FTIR interface linked by transfer line to the TGA furnace. The cell and transfer line of the TGA/FTIR interface were heated and kept at 220 °C. In this way, product gases from sample degradation could not condense. The output of this analysis is a Gram-Schmidt diagram and the attribution of FTIR peaks was carried out by using the OMNIC library and literature data. Additionally, proximate analyses (in accordance with ASTM D7582-15 (2015)) to measure moisture content (M%), volatile matter (VM%), ash content (A%) and fixed carbon (FC%), and ultimate analyses (using the equipment, CHN 628 LECO) to determine carbon (C%), hydrogen (H%), nitrogen (N%), oxygen (O%), hydrocarbon (H/C) and carbonates (O/C) were performed for each sample. All measurements were conducted using calibrated apparatus and standard procedures according to the respective ASTM standards.

### 2.3. Measurement of explosion parameters

Measurement of explosion parameters was performed using standardized equipment and following standardized test protocols. Prior to determining the explosion parameters in this study, all experimental apparatuses and procedures were verified by testing against a well-established standard dust (niacin). The results produced were consistent with previously published data. The niacin sample was obtained from an international round-robin campaign in 2017 (CaRo 17), in which the Dalhousie Dust Explosion Lab participated. Prior to testing, the dust samples were placed in a desiccator to prevent moisture absorption. Explosion severity parameters investigated were maximum explosion pressure,  $P_{max}$ , and volume-normalized maximum rate of pressure rise,  $K_{St}$  (determined with the maximum rate of pressure rise,  $(dp/dt)_{max}$ ). For explosion likelihood parameters, the minimum explosible concentration, MEC, minimum ignition energy, MIE, and minimum ignition temperature, MIT were determined. The test apparatuses and procedures used in this research have been described in detail in a previous study (Addo et al., 2019). Five different ignition energies (i.e., 0.5, 1, 2.5, 5, and 10 kJ) were used for the determination of explosion severity parameters ( $P_{max}$  and  $K_{St}$ ) in the 20-L explosion chamber. In the 1-m<sup>3</sup> explosion chamber, all explosion severity testing was conducted

with an ignition energy of 10 kJ and using a delay time of 600 ms, which departs from the previous study (Addo et al., 2019) where a choice between 550 ms or 600 ms was made depending on the sample's bulk density. For the measurement of MEC, an ignition energy of 2.5 kJ was used in the 20-L chamber while 10-kJ was used in the 1-m<sup>3</sup> chamber.

Table 1 gives a summary of the equipment used, standard procedure followed, and equipment location. In both the 20-L and 1-m<sup>3</sup> chambers, a rebound nozzle was used to aid dust dispersion.

### 3. Results and discussion

Results from the experimental work are presented in this section. The discussion here focuses on both the qualitative and quantitative trends observed in the extensive material characterization and experimental testing.

#### 3.1. Material characterization

Fig. 1 shows the SEM images of all four dusts, while Table 2 presents some of the determined physical properties. Of note, urea shows a non-porous, flaky structure that may behave like fibrous materials while zinc shows spherical particles with some degree of agglomeration.

#### 3.2. Explosion severity results

This section presents results of the explosion severity measurements in the two different sized explosion chambers.

##### 3.2.1. Explosion testing in both 20-L and 1-m<sup>3</sup> chambers

Table 3 gives a summary of the explosion severity results as indicated by the parameters of interest, P<sub>max</sub> and K<sub>St</sub>.

It must be noted that, according to the testing standard (ASTM E1226-12a, 2018), only P<sub>max</sub> and K<sub>St</sub> values determined with 10-kJ ignition energy are considered in the design of safety strategies (i.e.,

**Table 1**  
Summary of test equipment, standards, and equipment location.

Equipment	Output(s)	Test standard	Apparatus location
20-L explosion chamber	P <sub>max</sub> , K <sub>St</sub>	ASTM 1226-12a, 2018	Dalhousie Dust Explosion Lab
	MEC	ASTM 1515-14, 2018	
1-m <sup>3</sup> explosion chamber	P <sub>max</sub> , K <sub>St</sub>	ASTM 1226-12a, 2018	Fauske and Associates
	MEC	ASTM 1515-14, 2018	
MIKE 3	MIE	ASTM 2019-03 (2013), 2018	Dalhousie Dust Explosion Lab
BAM oven	MIT	ASTM 1491-06 (2012), 2018	Dalhousie Dust Explosion Lab
TG/DSC TA Instrument Q600SDT	Thermal behavior, Proximate analysis	ASTM D7582-15 (2015)	SaRAH Dust Lab Federico II, Naples
TGA/FTIR interface	Gas analysis	None	SaRAH Dust Lab Federico II, Naples
Scanning electron microscope	SEM images	None	Department of Chemical, Materials and Production Engineering, Federico II Naples
CHN 628 LECO	Ultimate analysis	ASTM D3176-15 (2015)	Department of Chemical, Materials and Production Engineering, Federico II Naples

preventive and mitigative measures). It can be seen that all four dusts produced an explosion in the 20-L chamber when an ignition energy of 10 kJ was used. The effect of the different ignition energies will be discussed in the following section.

Carbon black exploded in the 20-L chamber generating a P<sub>max</sub> value of 7.2 bar(g) and K<sub>St</sub> value of 63 bar m/s. Oat grain flour also exploded in the 20-L chamber generating P<sub>max</sub> and K<sub>St</sub> values of 7.2 bar(g) and 48 bar m/s respectively. The explosion pressure recorded by oat grain flour is typical for organic materials, so it is as expected. Both carbon black and oat grain flour dusts recorded K<sub>St</sub> values that are higher than the limiting value (45 bar m/s) contained in the definition of marginally explosible dusts suggested by Proust et al. (2007), thus are not marginally explosible dust. With respect to urea, it generated the weakest explosion severity compared to the three other dusts in the 20-L chamber as indicated by the P<sub>max</sub> and K<sub>St</sub> values of 3.0 bar(g) and 7 bar m/s respectively. The K<sub>St</sub> value of 7 bar m/s suggests that there was barely any propagation of the flame through the dust. These P<sub>max</sub> and K<sub>St</sub> values for urea further suggest that it may be marginally explosible, hence, it is imperative to test the urea dust in the 1-m<sup>3</sup> chamber for verification. In the case of zinc, the P<sub>max</sub> and K<sub>St</sub> values indicate an explosion in the 20-L chamber. The behavior of zinc dust in the 20-L chamber is consistent with the work of Taveau et al. (2019).

It can be seen that three dusts (i.e., carbon black, oat grain flour, and zinc) out of the four dusts produced an explosion (according to the explosion criterion in the ASTM 1226-12a, (2018)) in the 1-m<sup>3</sup> chamber as indicated by the P<sub>max</sub> and K<sub>St</sub> values. Among the three dusts that exploded, oat grain flour recorded the highest P<sub>max</sub> value while zinc recorded the lowest. The P<sub>max</sub> values of both carbon black and oat grain flour are as expected for organic materials. In terms of zinc dust, the P<sub>max</sub> value of 6.0 bar(g) is similar to the value reported by previous authors (Taveau et al., 2019) although the K<sub>St</sub> value in this current research is about 25% higher. This may be attributed to the difference in particle size distribution and the degree of passivation on the metal dust surface. The K<sub>St</sub> value of zinc in the 1-m<sup>3</sup> chamber increased by more than two-fold relative to the 20-L value. The relative increase of the K<sub>St</sub> value of zinc in the 1-m<sup>3</sup> chamber may be attributed to the large chamber volume and the longer reaction time which allowed the zinc dust to develop its full reactivity during the combustion process. Unlike the other three dusts, urea did not explode in the larger 1-m<sup>3</sup> chamber. The zero indicates that there was no flame propagation through the urea dust particles. Clearly, the behaviour of urea in the smaller chamber was as a result of overdriving and testing in the 1-m<sup>3</sup> chamber has confirmed that the urea dust is non-explosible.

##### 3.2.2. Role of ignition energy in the 20-L chamber

Pilão et al. (2006) have suggested that increasing ignition energy results in increasing explosion severity in the 20-L sphere. This behaviour has been largely attributed to "preconditioning", where the dust mixture is preheated by the strong ignition source prior to combustion (Cloney et al., 2013; Portarapillo et al., 2021a; Clouthier et al., 2019). The relatively large 10-kJ ignition energy used in the 20-L chamber may cause the explosion characteristics to be overestimated (Cloney et al., 2013; Portarapillo et al., 2021a). After testing in the 20-L chamber was completed with the 10-kJ Igniters, the ignition energy was reduced to 5 kJ, 2.5 kJ, 1 kJ, and 0.5 kJ. This was done to examine the influence of decreasing the ignition energy on the P<sub>max</sub> and K<sub>St</sub> data, assess the most appropriate ignition energy to use, and determine which chamber volume to employ. Fig. 2 presents the effect of varying the ignition energy on the P<sub>max</sub> and K<sub>St</sub> values of all four dusts. It can be noticed from both plots that decreasing the ignition energy from 10 kJ to 0.5 kJ also caused a general decrease in both severity parameters. Furthermore, the effect of varying ignition energy is more profound for K<sub>St</sub> values than for P<sub>max</sub> values.

Choosing an appropriate ignition source is important to make sure that it is energetic enough to initiate the combustion process without actively forcing an explosion by preheating the dust mixture. Previous

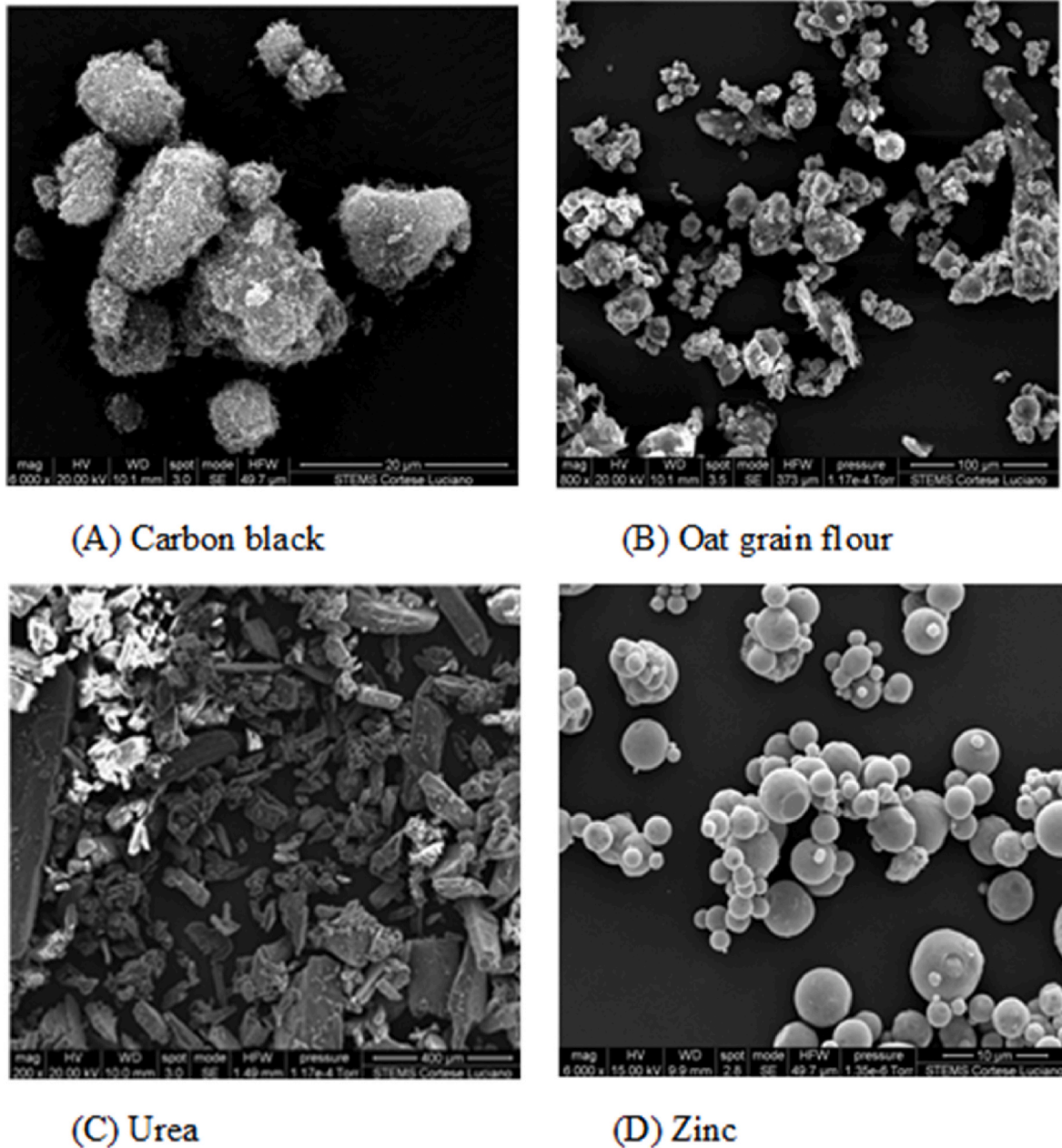


Fig. 1. Scanning Electron Microscopy (SEM) images of all four dust samples.

Table 2

Test material properties.

Material	Particle Size ( $\mu\text{m}$ )			$\sigma_D$	$\rho_{bulk}$ ( $\text{kg}/\text{m}^3$ )
	D <sub>10</sub>	D <sub>50</sub>	D <sub>90</sub>		
Carbon black	22	78	678	8.4	380
Oat grain flour	8	46	424	9.0	330
Urea	14	94	373	3.8	1340
Zinc	4	9	22	2.0	7130

work by Addo et al. (2019) suggested that, for severely explosible dusts, decreasing ignition energy from 10 kJ to 2.5 kJ in the 20-L chamber did not affect both  $P_{max}$  and  $K_{St}$  significantly. In such a case, a 5- or 2.5-kJ ignitor can give a good estimation of the explosion severity of these dusts. On the other hand, for hard-to-ignite or marginally explosible dusts, the suggestion is to use an ignition energy that is just enough to initiate the ignition process without forcibly triggering the explosion of

the dust by preheating it.

### 3.2.3. Role of chamber volume

The reproducibility values (given by  $(20\text{-L value} - 1\text{-m}^3 \text{ value}) / (1\text{-m}^3 \text{ value})$ ) for each dust sample are presented in Table 4. For three of the dusts (i.e., carbon black, oat grain flour, and zinc), the values of  $P_{max}$  did not vary significantly from the reproducibility limits as outlined in ASTM E1226-12a (2018). However, the  $K_{St}$  values varied markedly and do not fall within the 20% reproducibility limits except for oat grain flour. Considering the  $P_{max}$  and  $K_{St}$  values in the 1-m<sup>3</sup> chamber, it can be concluded that the three dusts (carbon black, oat grain flour, and zinc) are explosible. The only exception was urea, whose  $P_{max}$  and  $K_{St}$  values in the 1-m<sup>3</sup> chamber indicated that an explosion did not occur.

The larger chamber volume played an important role, with the 1-m<sup>3</sup> chamber having a volume that is 50 times that of the 20-L chamber. This means that the combustion process now has enough reaction volume available for full flame development of the dust sample. There is also

**Table 3**  
Explosion severity results.

Material	Ignition Energy (kJ)	20 L		1 m <sup>3</sup>	
		P <sub>max</sub> (bar(g))	K <sub>St</sub> (bar-m/s)	P <sub>max</sub> (bar(g))	K <sub>St</sub> (bar-m/s)
Carbon black	10.0	7.2	63	6.4	44
	5.0	7.0	59	–	–
	2.5	7.0	59	–	–
	1.0	6.7	42	–	–
	0.5	6.4	22	–	–
Oat grain flour	10.0	7.2	48	6.8	59
	5.0	6.6	29	–	–
	2.5	6.4	27	–	–
	1.0	6.3	25	–	–
	0.5	6.0	16	–	–
Urea	10.0	3.0	7	0	0
	5.0	0.0	0.0	–	–
	2.5	0.0	0.0	–	–
	1.0	0.0	0.0	–	–
	0.5	0.0	0.0	–	–
Zinc	10.0	6.2	57	6.0	129
	5.0	6.7	45	–	–
	2.5	6.4	43	–	–
	1.0	6.2	41	–	–
	0.5	5.5	40	–	–

“–” A dash means not tested.

adequate time for the combustion reaction to proceed. The larger volume requires that a longer ignition delay time (i.e., 600 ms) is used which allows the turbulence generated by the dispersion process to be distributed over the entire volume of the chamber (Portarapillo et al., 2021c).

Although the same ignition energy (10 kJ) is used in the 1-m<sup>3</sup>, the corresponding increase of dust material (i.e., 50 times the amount of dust used in 20-L chamber) causes a dilution of the energy release (Ogle, 2016). This dilution behavior is absent in the 20-L chamber, and thus its susceptibility to the overdriving effect. Table 3 also shows more than a twofold increase of the K<sub>St</sub> value of zinc between the two chambers. This is because the zinc dust needed more time to attain its stabilized combustion regime; the 1-m<sup>3</sup> chamber provides both adequate time and volume for reaching this regime. The behavior of zinc is typical of metallic dusts and similar behavior has been reported in other studies (Taveau et al., 2019).

It can therefore be suggested that scaling 20-L results for some dusts (such as metals) may not be straightforward and cannot be based only on K<sub>St</sub> values. This conclusion agrees with the previous work by Addo et al. (2019), whereby K<sub>St</sub> results for coarse polyethylene in the 1-m<sup>3</sup> chamber at an ignition delay time of 600 ms did not vary significantly from testing at an ignition delay time of 550 ms. From the results presented in this work (i.e., Table 4), a suggestion could be made for a working definition of marginally explosible dusts. Using the urea as an example,

marginally explosible dusts may be defined as dusts with P<sub>max</sub> < 3.0 bar (g) and K<sub>St</sub> < 20 bar m/s in the 20-L chamber, and that do not explode with a 5-kJ Ignitor in the 20-L chamber. This definition considers the very important conditions that affect the explosion characteristics of these dusts. As per the characteristics of marginal explosibility discussed together with the 1-m<sup>3</sup> results presented in this study, the urea dust is non-explosible.

### 3.3. Explosion sensitivity

This section presents and discusses the explosion likelihood results. Table 5 gives a summary of the explosion likelihood test results in terms of MEC in the 20-L and 1-m<sup>3</sup> chambers, MIE (with and without inductance) in the MIKE 3 apparatus, and MIT in the BAM oven, respectively.

**Table 4**  
Reproducibility limits for explosibility testing.

Samples	Reproducibility limits (%)	
	P <sub>max</sub> (bar(g)) (±10%)	K <sub>St</sub> (bar-m/s) (±20%)
Carbon black	12.5	43
Oat grain flour	5.9	–19
Urea	–	–
Zinc	3.3	–56

–no reproducibility value calculated due to no explosion recorded in 1-m<sup>3</sup> chamber.

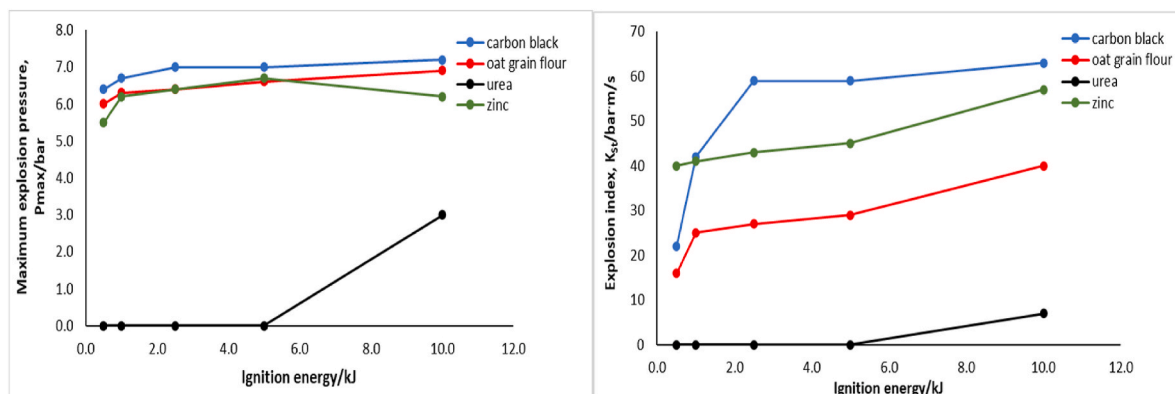
Reproducibility is calculated by (20-L value – 1-m<sup>3</sup> value)/(1-m<sup>3</sup> value).

**Table 5**  
Explosion likelihood results.

Material	MIE (mJ)		MIT (°C)	MEC (g/m <sup>3</sup> )	
	With Inductance	Without Inductance		20 L	1 m <sup>3</sup>
				2.5 kJ	10 kJ
				60 ms	600 ms
Carbon black	>1000	>1000	>600	80	250
Oat grain flour	100–300 E <sub>s</sub> = 140	300–1000 E <sub>s</sub> = 540	400	250	500
Urea	>1000	>1000	>600	750 <sup>a</sup>	>3000
Zinc	300–1000 E <sub>s</sub> = 720	>1000	>600	650	750

E<sub>s</sub> is statistic energy.

<sup>a</sup> MEC determined with ignition energy (I.E.) of 10 kJ since no explosion occurred with 2.5 kJ I.E.



**Fig. 2.** Effect of varying ignition energy on P<sub>max</sub> (left) and K<sub>St</sub> (right) values in the 20-L sphere.

### 3.3.1. Minimum explosible concentration (MEC) in both 20-L and 1-m<sup>3</sup> chambers

From Table 5, a comparison between MEC values obtained in both chambers indicates a general increase in MEC values obtained in the 1-m<sup>3</sup> chamber. Also, it can be seen that in the 20-L chamber, carbon black dust recorded the lowest MEC value followed by oat grain flour and zinc, while urea dust did not record a measurable MEC value in both the 20-L sphere (with 2.5- and 5-kJ ignitors) and 1-m<sup>3</sup> chamber (with 10-kJ ignitors). Out of the three dusts that recorded measurable MEC values, these values were very high (i.e., >100 g/m<sup>3</sup>) for oat grain flour and zinc. The only exception was carbon black dust which recorded an MEC value less than 100 g/m<sup>3</sup> in the 20-L chamber. However, the MEC value of 250 g/m<sup>3</sup> recorded in the 1-m<sup>3</sup> indicates a case of overdriving in the smaller 20-L chamber even with an ignition energy of 2.5 kJ.

Another case of overdriving the MEC value was observed for urea whereby a measurable MEC value was only recorded in the 20-L chamber when the ignition energy was increased from 2.5 to 10 kJ. Even with this large ignition energy, the MEC value of 750 g/m<sup>3</sup> is very high. The fact that there was no explosion recorded in the 1-m<sup>3</sup> chamber confirms that the MEC value for urea dust in the 20-L is as a result of overdriving. For a metallic dust like zinc, the high MEC value is as expected. This can be attributed to the relatively high density of the zinc dust. This implies that to form an explosible dust cloud, a significant number of the metal particles must be suspended in air.

It is worth noting that in addition to overdriving phenomenon, also turbulence and non-homogeneous dust distribution may influence MEC results. These phenomena play an important role in differentiating the results in the two standard vessels, as shown by the results of the CFD simulations in some recent works (Portarapillo et al., 2020; Portarapillo et al., 2021b; Portarapillo et al., 2022a). It is very likely that the lower values of the minimum explosion concentration in the 20 L vessel are due to the poorer dust distribution in the vessel. Due to the poorer distribution and the smaller vessel volume, it is possible that more dust accumulates on the generated turbulent macro vortex edges and accumulates both on the wall and in the centre of the sphere. In the centre of the sphere, it is therefore possible to obtain a local dust concentration that is much higher than the nominal concentration (Portarapillo et al., 2020; Portarapillo et al., 2021b; Portarapillo et al., 2022a).

The results in Table 5 suggest that there is no agreement between MEC values measured in the two chambers as they did not fall within the reproducibility limits outlined in ASTM 1515–14 (2018). Testing on the larger scale confirmed that all the dusts tested in this work have high MECs  $\geq 250$  g/m<sup>3</sup> thus indicating that thin layers of these dusts could not readily form combustible dust clouds if dispersed in air. In addition to the proposed definition of MEDs in Section 3.2.3, it can be suggested that marginally explosible dusts have MEC values greater than 1000 g/m<sup>3</sup> (i.e., MEC >1000 g/m<sup>3</sup>).

### 3.3.2. Minimum ignition energy (MIE)

The summary results obtained for the minimum ignition energy of all dusts tested are also presented in Table 5. MIE values were determined with and without inductance. It can be seen that oat grain flour recorded the lowest MIE values both without and with inductance. Without inductance, the remaining three dusts did not ignite at the maximum ignition energy that can be measured with the equipment (i.e., MIE >1000 mJ). However, with inductance, the MIE value of oat grain flour decreased, while the zinc dust also ignited at an MIE <1000 mJ (i.e., 720 mJ). This behavior is evidence of the impact of inductance in producing sparks with longer duration which in turn decreases the MIE of a given sample (von Pidoll, 2001; Eckhoff, 2017). The two other dusts (carbon black and urea) still did not ignite with the addition of an inductance of 1 mH since the MIE values remained unchanged (i.e., MIE >1000 mJ). The minimum ignition energy of dusts is dependent on factors including the size distribution of the dust particles, dustiness (or the ease of forming a combustible dust cloud), ease of evolution of volatile matter, and the electrical conductivity of the dust. The behavior

of oat grain flour with respect to spark ignition may be attributed to the ease of evolving volatiles for combustion as well as its dispersibility, while that of zinc may be largely attributed to its electrical conductivity. Despite the formation of a ZnO film on the surface of zinc, prolonged application of spark ignition is able to break down the film and cause the particles to ignite. The MIE results imply that oat grain flour is more sensitive to electric sparks as relative to the other three dusts, followed by zinc which is weakly sensitive when exposed to prolonged electric sparks (due to the addition of 1-mH inductance). Both carbon black and urea were insensitive to spark ignition. From the MIE results from the current study, it can be concluded that urea dust, which exhibits marginal explosibility in the 20-L chamber may be insensitive to spark ignition energies less than or equal to 1000 mJ (i.e., MIE >1000 mJ).

### 3.3.3. Minimum ignition temperature (MIT)

The summary results of the minimum ignition temperature (MIT) tests for all dusts are also presented in Table 5. The majority of the dusts (i.e., 3 out of 4) did not show an ignition when exposed to a hot surface at a temperature of 600 °C (i.e., the maximum apparatus temperature). The minimum ignition temperature of combustible dusts is strongly dependent on the ease of evolution of combustible volatiles from the dust. Generally, the greater the volume of combustible gases released relative to time, the more sensitive the material is when exposed to hot-surface ignition. The MIT results reflect the fact that hot-surface ignition processes involve different physical and chemical phenomena than those in spark ignition scenarios. Additionally, the 5-s ignition criterion for the BAM oven could lead to a sample material emitting sufficient volatiles for combustion as it sits on the bottom surface of the heated furnace. Overall, the MIT results show that only oat grain flour, out of the four dusts, can undergo hot-surface ignition at temperatures around 400 °C. This behavior is typical of traditional organic dusts like oat grain flour with respect to hot-surface ignition. From the results presented in Table 5, an MIT threshold value of 600 °C can be suggested for marginally explosible dusts.

## 3.4. Effects of material characteristics

This section discusses the results of the material properties determined in this work and how these influence the explosion behaviour of marginally explosible dusts.

### 3.4.1. Chemico-physical properties analysis

In order to fully appreciate all the phenomena and issues occurring during the testing of a specific combustible dust, it is imperative to understand the flame propagation mechanism. A complete chemico-physical and thermal characterization is required to understand their influence on the combustion behaviour and, consequently, make a judgement of which explosion vessel leads to the most realistic evaluation of explosion parameters. Through the chemico-physical characterization, which consists of the determination of particle size distribution, shape, density and molecular composition, the relaxation time can be calculated, and the role of oxygen diffusivity can be assessed. With thermal characterization, the decomposition and combustion phenomena can be investigated, and the proximate analysis can be used to mainly evaluate the moisture and volatile content. Moreover, the gaseous species produced can be distinguished by Fourier transform infrared spectroscopy (FTIR) analysis. Thermal analysis is important to understand which combustion path is predominant during flame propagation and whether a selected dust fits the definition of a marginally explosible dust. Indeed, in recent works the importance of a complete chemical-physical and thermal screening of any combustible dust was shown in order to fully understand the explosive behaviour in terms of flame propagation pathways and consequently in terms of flammability and explosion parameters (Centrella et al., 2020; Danzi et al., 2021; Portarapillo et al., 2020b, 2021d, 2022b). In particular, this approach has been used to justify the presence of synergistic effects in mixtures of

combustible dusts and to establish a new safety classification for the mixtures themselves (Centrella et al., 2020; Portarapillo et al., 2020b). In addition, this approach has been applied to non-traditional powders such as nylon and biomass powders to understand the main flame propagation pathways and the geometrical, chemical, physical, and thermal characteristics that most influence this propagation (Danzi et al., 2021; Portarapillo et al., 2021d, 2022b).

Once the predominant flame propagation path of the dust and the controlling step have been identified, it is possible to determine the vessel to be used for the explosion tests in order to obtain the most practical explosion parameters that can be applied in the design of safety strategies. If the volatiles evolved are a mixture of flammable and inert species, a phenomenon of marginal explosibility may occur if the amount of inert gases evolved is significantly high. In the case of dusts whose flame propagation is controlled by phenomena in the heterogeneous phase, the dust requires time and space for full combustion development; thus, the use of the 1-m<sup>3</sup> chamber is recommended. On the other hand, for dusts whose flame propagation is controlled by phenomena in the homogeneous phase, the 20-L chamber can produce a good estimation of the explosion characteristics (Portarapillo et al., 2021a).

### 3.4.2. Thermal analysis

To explain the behaviour of the organic dusts, thermal analysis in both inert and oxidant atmospheres was performed together with the proximate and ultimate analyses and the FTIR analysis of gaseous products. As can be seen from Table 6, both oat grain flour and urea are characterized by a high amount of volatiles that can be produced due to the thermal decomposition.

Then, oat grain flour and urea were tested with TG/FTIR analysis, with the results reported in Figs. 3 and 4. For oat grain flour, the TG (Fig. 3a) and the first-derivative of TG (DTG) (Fig. 3b) profiles are similar in nitrogen and air in the low temperature section and then differ from 450 °C. From this behaviour, it can be concluded that a heterogeneous combustion path, based on the interaction between the solid and the oxygen in the air, can take place at high temperature (>450 °C). However, at a lower temperature, 60% of the dust is already devolatilized, forming a mixture of flammable gases (hydrocarbons, carboxylic acids, and CO) and inert gases such as water and CO<sub>2</sub> (Fig. 3c and d). These flammable volatiles are released during heating and then react in the gas phase with air. It is therefore possible to conclude that the combustion of oat grain flour is mainly homogeneous, and the low K<sub>St</sub> value is mainly linked to the formation of a mixture containing inert materials which slows down flame propagation.

This concept is even more prominent in the case of urea. The profiles in an inert and oxidizing environment are identical (Fig. 4), suggesting that only the homogeneous combustion path is present in the case of urea. When subjected to heat, urea produces a mixture of flammables (isocyanic acid and ammonia) and large amounts of inert (CO<sub>2</sub>) gases. The large amount of inert CO<sub>2</sub> gas produced impedes flame propagation through the reacting gas phases, thus making urea non-explosible. In the case of carbon black, the scenario differs from both oat grain flour and urea. As can be seen in Fig. 5, the TG (Fig. 5a) and DTG (Fig. 5b) profiles in inert and oxidizing environments are very different. In an inert atmosphere, carbon black loses a percentage by weight corresponding to the sum of the moisture and volatile contents measured during the

proximate analysis (4.3 %). In the case of an oxidizing atmosphere, the sample is instead totally consumed following two reactive and strongly exothermic phenomena at 200 °C and 650 °C.

The mixture of volatiles produced in an inert atmosphere is again composed of a mixture of flammable species (ammonia, isocyanic acid) and inert CO<sub>2</sub>. In this case, the interaction with oxygen is present and active already at low temperature (200 °C) with the formation of the typical combustion products. From these results, it can be concluded that in the case of carbon black both reactive paths are active. However, due to the molecular structure of carbon and its reactivity, a surface reaction is strongly favoured. Although this organic sample presents a heterogeneous path predominant over the homogeneous one (volatile matter is only 3.8% of the total solid mass), it still seems to show a behaviour similar to marginally explosible organic dusts: i.e., the explosion parameters are greater in the 20-L sphere, while there is a decrease of explosion severity in terms of both P<sub>max</sub> and K<sub>St</sub> values in the larger vessel. This may be due to overdriving effect in the smaller 20-L chamber. It can also be related to the fact that the heterogeneous combustion is very rapid and active at a lower temperature of about 600 °C (as shown in Fig. 5a), compared to typical metallic dust behaviour whereby heterogeneous combustion reaction occurs at relatively higher temperatures (typically in excess of 900 °C).

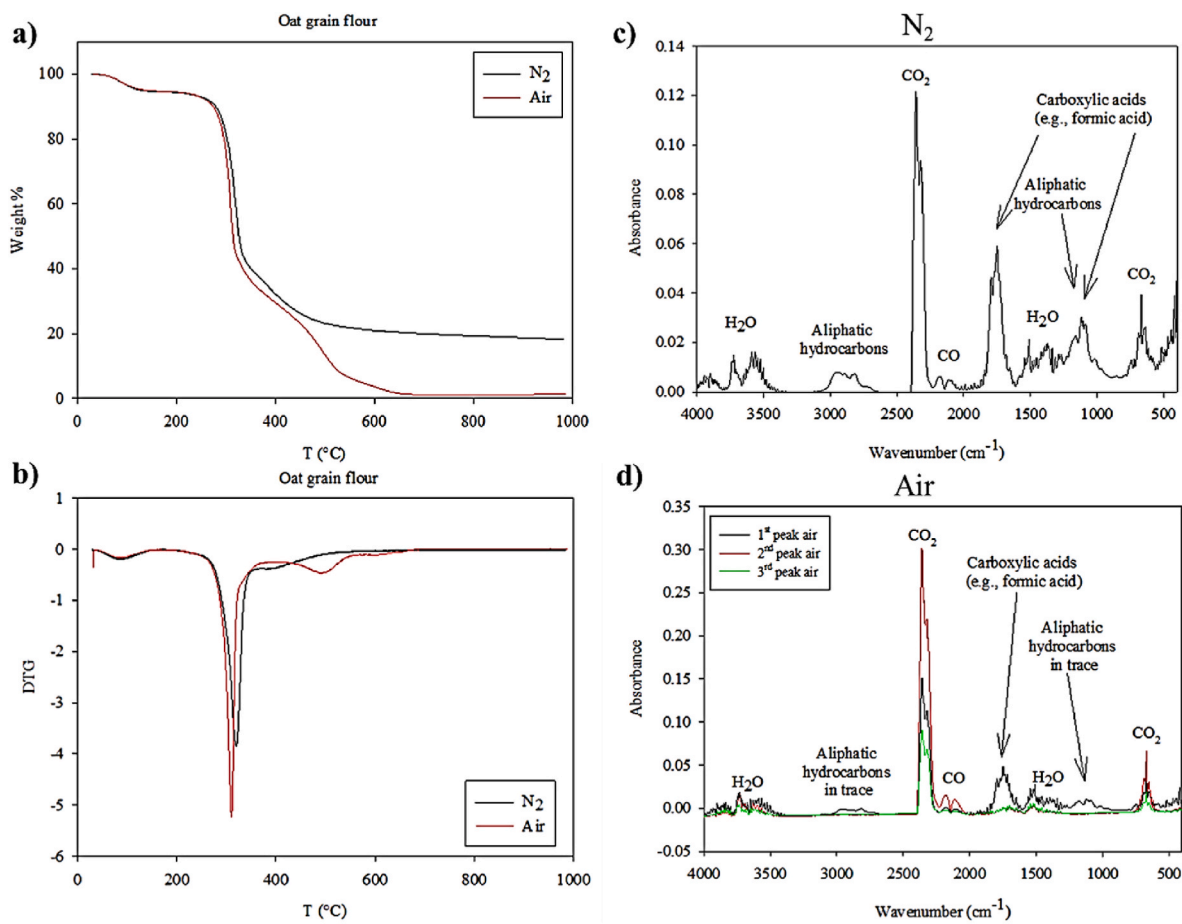
As regards zinc, it is well known that, like many metals, it oxidizes spontaneously in air because of the diffusion of oxygen species over the surface. Consequently, the solid particles are coated with a layer of ZnO covering their entire surface. While approaching the flame front, solid Zn particles are heated and the Zn core inside the solid-phase oxide layer starts to melt (melting point 420 °C). The melting point of ZnO is much higher (melting point 1970 °C), which prevents the particle from igniting immediately. Sundaram et al. (2016) suggested that ignition of metallic dusts results from layer-by-layer destruction, attributed to the thermomechanical stresses produced during the heating phase, and the melting of the oxide shell. Different from zinc, the interaction between carbon black and oxygen is faster and active at low temperature as reported in Fig. 5.

For dust materials with very low volatile content like zinc and iron, the heterogeneous path is the only responsible for ignition and flame propagation. Here, due to the low flame temperature and high evaporation temperature of zinc, there is no release of flammable volatiles during combustion, and the reaction occurs at the surface of the solid zinc particles. The combustion of zinc is complicated by the formation of a protective film ZnO which prevents further particle to particle combustion. More reaction time and volume will be required for the propagating flame to reach more of the particles and be sustained; thus, a larger chamber will be most suitable to produce explosion data that is representative of industrial situations. Moreover, as reported by Portarapillo et al., 2021a, in the 1 m<sup>3</sup> vessel, the lower level of pre-ignition turbulence inhibits heat diffusion and then the hot core generated by the chemical igniters is preserved. When dust flame propagation is controlled by particle heating, as in the case of metal dusts, the explosion parameters are higher in the 1-m<sup>3</sup> chamber than in the 20-L vessel due to the presence of thermal effect (Portarapillo et al., 2021a).

The rate of flame propagation can also be related to molecular structure. In fact, carbon black is made up of amorphous granules characterized by high surface-to-volume ratio. Unlike zinc, whose combustion is controlled by the melting of the core and the fracture of

**Table 6**  
Proximate and ultimate analysis of the tested samples.

Material	Proximate analysis				Ultimate analysis					
	M%	VM%	A%	FC%	C%	H%	N%	O%	H/C	O/C
Oat grain flour	4.0	77.6	15.7	2.7	43.27	7.21	1.45	48.06	2.00	0.83
Carbon black	0.5	3.8	3.1	92.6	92.03	0.25	0.02	7.71	0.03	0.04
Urea	0.0	99.5	–	–	19.51	6.65	44.58	29.26	4.09	1.12
Zinc	0.0	–	–	–	–	–	–	–	–	–



**Fig. 3.** Weight % (a) and DTG curves (b) as a function of temperature ( $^{\circ}\text{C}$ ) in nitrogen (black line) and air (red line) flow of oat grain flour. FTIR on gaseous species in nitrogen (c) and air (d) flow. In the case of more than one peak, black line is for the 1st peak, red line for the 2nd peak, green line for the 3rd peak and blue line for the 4th peak.

the shell that allows the diffusion of oxygen, carbon black reacts quickly with oxygen. For these reasons, flame propagation is not controlled by particle preheating as occurs in the case of metal powders. This may account for the different behaviours of carbon black and zinc dusts in the two explosion chambers.

#### 4. Choice of explosion chamber for the most suitable results

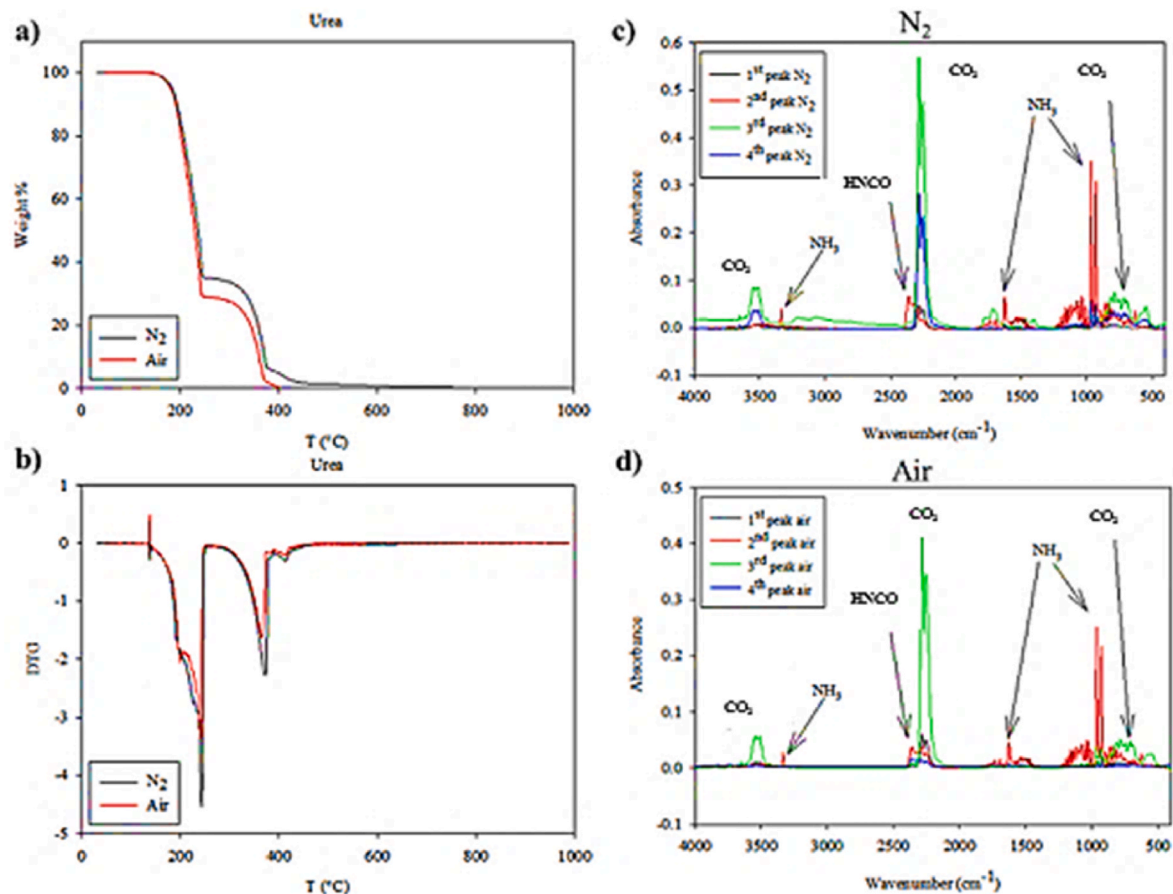
The strategy of assessing the explosion risk of dusts has been to present the worst-case scenario, or the worst conditions under which the dust being tested can cause an explosion. The problem here is that there is the possibility to overestimate or underestimate the explosion characteristics when all test conditions and procedures are not carefully considered. One important consideration in the measurement of explosion characteristics, especially in the case of marginally explosible dusts is the effect of scaling the data from the small 20-L chamber. The results of the current study (i.e., chemico-physical, thermal analysis, and experimental analysis) have suggested that the type of combustion phenomenon exhibited by a particular dust strongly dictates the choice of appropriate explosion chamber to produce acceptable explosion data. Analysis of the results in the current research has suggested that generally, dusts whose deflagration is predominantly influenced by homogenous combustion (Path A) (such as oat grain flour in this work, and other traditional organic dusts like lycopodium and niacin) may produce practical results in the 20-L chamber. Homogeneous combustion is characterized by the devolatilization of the organic dust particles followed by a gas phase combustion reaction with air.

In other words, these dusts mostly obey the “cubic root relationship”

and the data obtained from the 20-L chamber correlates well with that of the  $1\text{-m}^3$  chamber. Conversely, for dusts whose combustion phenomenon is largely dictated by heterogeneous combustion (Path B) (such as zinc dust in the current research, and iron (Fe) dust samples as tested in the work by Clouthier et al. (2019)), the 20-L is not appropriate for generating explosion data and the  $1\text{-m}^3$  should be used to provide the closest evaluation of the explosion risk to the industrial scenario. Heterogeneous combustion is characterized by surface burning of solid dust particles. Here, the flame temperature of the dust is lower than its evaporation temperature; thus, there is no release of volatiles. To be clear, under both circumstances (either homogeneous or heterogeneous), the  $1\text{-m}^3$  is appropriate to use but in the case of MED that follow a homogeneous combustion path a 20-L chamber may be more economically practical due to the limited quantity of material required, speed of testing, less combustion products released to the environment after a test, and less technician effort.

However, not all materials (either organic or metallic) follow the expected combustion paths. An example is carbon black, which is considered as an organic material but reacts in a heterogeneous combustion mode, thus making the  $1\text{-m}^3$  chamber the most suitable apparatus for testing. For urea, although organic, with flame propagation controlled by a homogeneous combustion mode, measuring the explosion characteristics according to the current standard procedure (ASTM E1226-12a, 2018) will overestimate its explosion severity. In this case, it is recommended to test the urea dust in the  $1\text{-m}^3$  to generate explosion data that is more practical and closely represents industrial scenarios. An example of a metallic dust that deviates from the expected combustion path is aluminium. Fine particles of aluminium exhibit a



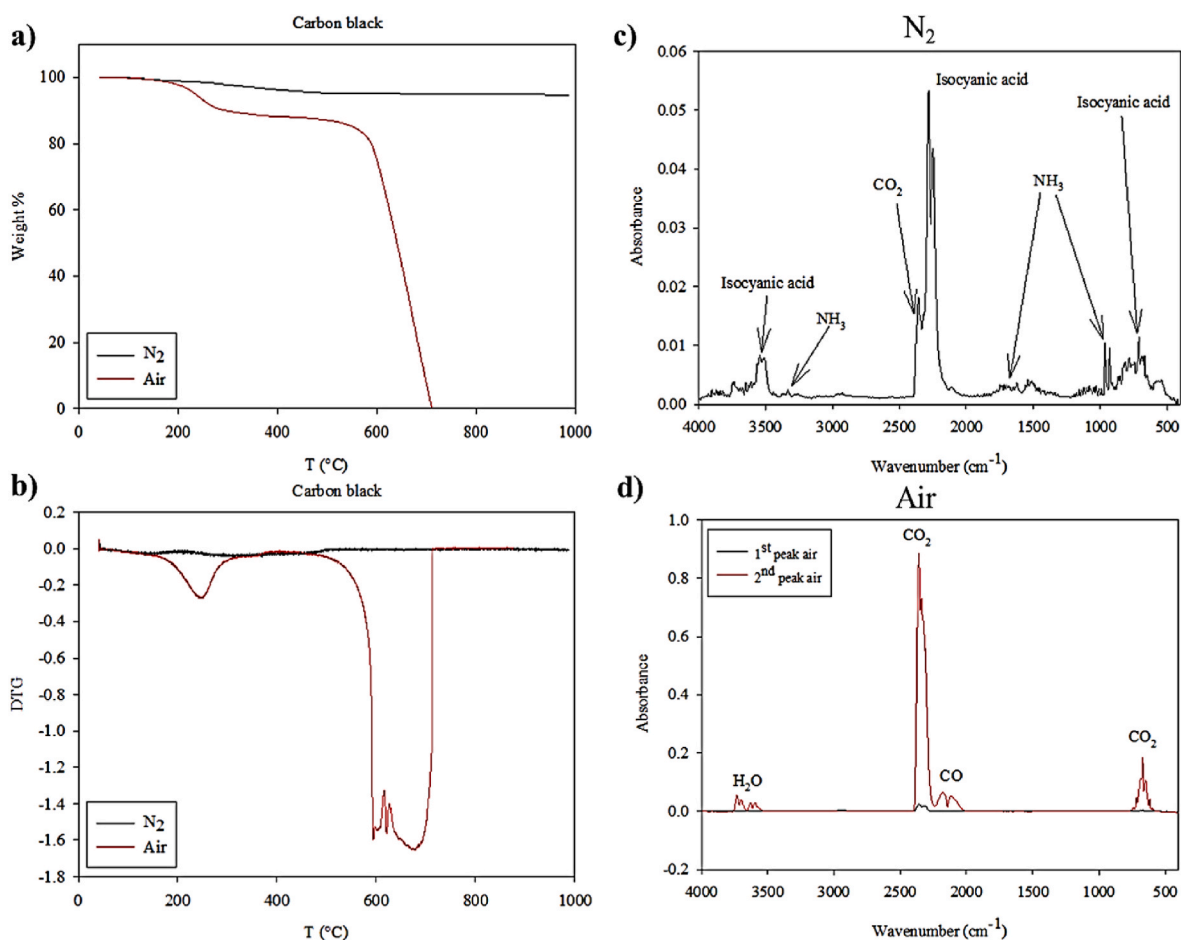


**Fig. 4.** Weight % (a) and DTG curves (b) as a function of temperature (°C) in nitrogen (black line) and air (red line) flow of urea. FTIR on gaseous species in nitrogen (c) and air (d) flow. In the case of more than one peak, black line is for the 1<sup>st</sup> peak, red line for the 2<sup>nd</sup> peak, green line for the 3<sup>rd</sup> peak and blue line for the 4<sup>th</sup> peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

combustion behaviour that is totally different from that of Fe and Zn. In the case of aluminium dust, the flame temperature is higher than the evaporation temperature so that during flame propagation, the fine aluminium particles are burned to evolve a very unstable and highly reactive aluminium gas which then reacts in a homogeneous combustion mode. This behaviour accounts for the reason why fine aluminium has a very fast combustion reaction and can reach unsafe levels during testing as can be seen in the experimental study by Clouthier et al. (2019). Similar to the behaviour of urea, the explosion of Al 100 (fine, with  $d_{50} = 5 \mu\text{m}$ ) and Al 103 (coarse, with  $d_{50} = 119 \mu\text{m}$ ) are heavily overdriven in the 20-L chamber with 10-kJ ignition energy; hence the 1-m<sup>3</sup> chamber may be more suitable for obtaining explosion severity data that represents industrial scale situations. Urea and Al 103 dusts explode in the 20-L chamber using a 10-kJ ignitor but not in the 1-m<sup>3</sup> chamber; thus, these two dusts fit the definition of marginally explosible dusts. Additionally, both do not have measurable MEC, MIE and MIT. For the medium-sized aluminium dust (Al 101,  $d_{50} = 28 \mu\text{m}$ ) tested in Clouthier et al. (2019), the  $K_{St}$  value (328 bar m/s) in the 1-m<sup>3</sup> chamber is more than three times the  $K_{St}$  value (98 bar m/s) in the 20-L chamber. This behaviour is at variance with the suggestion in the NFPA 484 (2019) to simply double the 20-L  $K_{St}$  value of aluminium dust for vent design calculations. Clearly, in the case of Al 101, applying the suggestion in the NFPA 484 (2019) would have resulted in underestimating the actual associated risk and undersized vent design considerations. With respect to the Fe dust samples, explosion severity was found to be higher in the 1-m<sup>3</sup> chamber compared to the 20-L chamber. This shows a clear underestimation of the explosion risk of the Fe dust samples in the 20-L chamber. Also, the test result indicate that all the three sizes of Fe dust were explosible although they produced low  $K_{St}$  values in both

chambers (Clouthier et al., 2019). The combustion of aluminium and other materials has been further explained by Cloney (2019).

To demonstrate further how the combustion modes of dusts can serve as a guide to choosing a suitable test chamber that gives more practical explosion data, additional materials have been considered. The materials are niacin, lycopodium, two different sizes of polyethylene (PE) dust (from the research work by Addo et al. (2019)), three sizes of Fe dust and three sizes of Al dust (from the study by Clouthier et al. (2019)). Typically, plastics such as PE dusts burn to evolve flammable gases (such as C<sub>2</sub>H<sub>2</sub>) which then reacts with air in a gas/gas phase reaction following a homogeneous combustion path. However, for the coarse PE (with  $d_{50} = 131 \mu\text{m}$ ), there is a flame propagation limitation due to the increasing particle size, thus requiring a larger vessel volume and relatively longer reaction time such as in the 1-m<sup>3</sup> chamber for full flame development. This is not the case for the fine PE (with  $d_{50} = 42 \mu\text{m}$ ); hence the 20-L vessel may be more practical for generating suitable explosion data. Lycopodium and niacin dusts are typical organic dusts that burn to release flammable volatiles which then react with air in a homogenous combustion mode. The 20-L chamber may be suitable for determining practical explosion data. Table 7 shows a summary of the dusts analysed in the current work and previous works by Addo et al. (2019) and Clouthier et al. (2019), together with the relative flame propagation paths (A and B) as well as the vessels recommended to obtain the most realistic  $K_{St}$  values. Table 7 may serve as a guide for choosing the explosion test chamber that is more practical to produce the most suitable set of explosion severity data. There is clearly opportunity to study the combustion modes of more dust materials to build a more comprehensive guide.



**Fig. 5.** Weight % (a) and DTG curves (b) as a function of temperature (°C) in nitrogen (black line) and air (red line) flow of carbon black. FTIR on gaseous species in nitrogen (c) and air (d) flow. In the case of more than one peak, black line is for the 1st peak, red line for the 2nd peak, green line for the 3rd peak and blue line for the 4th peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## 5. Industrial implications

This work has provided data and explanations that are aimed at providing guidance to process industries that handle marginally explosible dusts (MEDs). The behavior of urea in this work has provided a basis for the explosibility classification of these dusts, thus addressing the existing difficulty of handling MEDs. However, it is important to evaluate the risk of more dusts that are truly marginally explosible to make a firmer conclusion. With the current behavior of urea in both chambers, it can be suggested that marginally explosible dusts are indeed capable of propagating a dust flash fire but not an explosion. Based on this information, it can be suggested that process industries put in place safety measures and strategies required to prevent flash fires when handling urea. It must be stressed that the most accurate method of classifying any dust as explosible or non-explosible is by testing in standard test apparatuses and using standard procedures. Thus, the explosion characteristics of individual dusts must be measured to assess their risk of explosion.

With such guidance (as provided in Table 7), selecting the most practical explosion test chamber can be cost effective for industry, even for the larger 1-m<sup>3</sup> chamber. For instance, in cases of overestimation or underestimation of explosion severity parameters in the 20-L chamber, making explosion prevention and mitigating design decisions based on these data may be costly in the end. Overestimation of explosion severity parameters may result in situations including protecting dusts that may not actually be explosible and oversized vent designs. On the other hand, underestimation may result in problems such as inadequate or no

protection for dusts that may be explosible and undersized vent designs. In such cases, testing in the 1-m<sup>3</sup> chamber may prove to be the best option, and would save precious dollars that would have been used to mitigate the effects of overestimation or underestimation of explosion severity parameters in the 20-L chamber.

## 6. Conclusions

The discrepancy that results from scaling 20-L explosion data is real, especially for marginally explosible dusts. The current study investigated the problem posed by so-called marginally explosible dusts by assessing the explosion risk of four well-characterized combustible dusts in the 20-L and 1-m<sup>3</sup> chambers. The research also conducted detailed chemico-physical and thermal analyses to further understanding the fundamental behaviors that underly the mechanisms of flame propagation with respect to MEDs. The effect of varying the ignition energy in the 20-L chamber, and the effect of scaling the 20-L data were investigated as well. Finally, this work considers how the type of combustion reaction mode (either homogeneous or heterogeneous) influences the choice of appropriate test chamber in order to produce practical results. It also identifies that in some instances, testing in the 1-m<sup>3</sup> chamber can actually be cost effective. This study further contributes to our understanding of the fundamental mechanisms that govern the explosion behavior of MEDs and the implications for industry. The following points summarize the major findings from the current study:

**Table 7**  
Summary of investigated dusts and relative flame propagation path.

Material	Flame propagation path		Comments	For most practical $K_{St}$ value	References
	PATH A	PATH B			
Carbon black	No	Yes	Low flammable volatile content and rapid heterogeneous combustion	1-m <sup>3</sup>	This work
Oat grain flour	Yes	No	Mainly homogeneous combustion	20 L	This work
Urea	Yes	No	Homogeneous combustion but overdriven (MED)	1-m <sup>3</sup>	This work
Zinc	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	This work
Al 100	Yes	No	Homogeneous combustion but overdriven	1-m <sup>3</sup>	Clouthier et al. (2019)
Al 101	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	Clouthier et al. (2019)
Al 103	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	Clouthier et al. (2019)
Fe 101	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	Clouthier et al. (2019)
Fe 102	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	Clouthier et al. (2019)
Fe 103	No	Yes	Layer-by-layer heterogeneous combustion	1-m <sup>3</sup>	Clouthier et al. (2019)
Niacin	Yes	No	Mainly homogeneous combustion	20 L	Addo et al. (2019)
Lycopodium	Yes	No	Mainly homogeneous combustion	20 L	Addo et al. (2019)
Fine PE	Yes	No	Mainly homogeneous combustion	20 L	Addo et al. (2019)
Coarse PE	Yes	No	Mainly homogeneous combustion but underdriven	1-m <sup>3</sup>	Addo et al. (2019)

- Both chemico-physical and thermal analyses are important to understand the explosion behavior of MEDs.
- Carbon black and urea dusts are clearly overdriven in the 20-L chamber with a 10-kJ ignitor.
- Although carbon black and urea seem to fit the definition of MEDs in the 20-L chamber, carbon black is explosible while urea is non-explosible as indicated by data obtained from the 1-m<sup>3</sup> chamber.
- Oat grain is explosible and has explosion characteristics typical of a traditional organic dust.
- Comparing the explosion data from both chambers shows good agreement in terms of  $P_{max}$  values, but no agreement in terms of  $K_{St}$  values except for the oat grain flour.
- Explosion severity of metal dusts such as zinc may be underestimated in the 20-L chamber. Explosion severity of metal dusts can more than double in the 1-m<sup>3</sup> chamber due to factors such as increased volume, time to full flame development, and thermal effects.
- Marginally explosible dusts have low ignition sensitivity as can be seen by the MEC, MIE and MIT results for urea.

- With reference to urea dust, a new definition of MEDs has been suggested:  $P_{max} < 3.0$  bar(g),  $K_{St} < 20$  bar m/s,  $MEC > 1000$  g/m<sup>3</sup>,  $MIE > 1000$  mJ, and  $MIT > 600$  °C.
- For dusts whose flame propagation is dictated by a homogeneous combustion (Path A), the 20-L chamber is generally recommended. However, for dusts whose flame propagation is controlled by heterogeneous combustion (Path B), the 20-L chamber may not be appropriate to generate suitable explosion data, and the 1-m<sup>3</sup> chamber is generally recommended. However, there are dust materials such as carbon black (from the current work) and aluminum (from other studies) whose combustion mode deviates from what is expected. The possibility of overdriving or underdriving can also affect the choice of an explosion test chamber.

### CRediT authorship contribution statement

**Albert Addo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Maria Portarapillo:** Investigation, Resources, Writing – review & editing. **Almerinda Di Benedetto:** Writing – review & editing. **Yajie Bu:** Writing – review & editing. **Yuan Chunmiao:** Writing – review & editing. **Ashok Dastidar:** Investigation, Resources, Writing – review & editing. **Faisal Khan:** Writing – review & editing. **Paul Amyotte:** Resources, Supervision, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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