MALAYSIAN JOURNAL OF ANALYTICAL SCIENCES

Journal homepage: https://mjas.analis.com.my/

Research Article

Influence of particle size and dust concentration on polymer dust explosions

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Received: 11 January 2024; Revised: 10 December 2024; Accepted: 30 November 2025; Published: 28 December 2025

Abstract

A dust explosion is caused by finely divided combustible particles suspended in a sufficiently oxidised atmosphere, combined with an ignition source that triggers a combustion reaction. It is a frequent hazard in many industrial sectors with imminent potential for catastrophic consequences, including the loss of human lives and valuable properties. A number of studies have been done in the past on the factors influencing the explosions, but these studies were limited to a narrow range of combustible dust. Therefore, this research aims to evaluate the effects of particle size and dust concentration towards the severity of polyethylene (PE), melamine resin (MR) and polyethylene terephthalate (PET) dust explosions. Initially, the chemical compositions (e.g., moisture, ash, volatile matter, and fixed carbon compositions) of all three polymer dusts were identified using Thermogravimetric Analysis (TGA). Then, dust samples of different particle sizes (125 µm, 160 µm, 180 µm, 250 µm) and concentrations (250 g/m^3, 500 g/m^3, 750 g/m^3, 1000 g/m^3, 1500 g/m^3) were prepared by screening the samples through sieves of distinct pore sizes. The explosion phenomenon of each sample was observed in a Siwek 20L spherical vessel, where the data on explosion pressure and pressure rise were recorded. Additionally, the deflagration index (K_{st}) was calculated using Cubic's Law. Finally, the obtained findings were compared in terms of explosion likelihood and severity. The results showed that the explosions for all three samples were most severe at a particle size of 160 µm and the highest possible concentration (1000 g/m^3 or 1500 g/m^3). All three dusts were classified under the St_1 category, with PET exhibiting the most severe explosive effects. This finding is essential since it provides information that can be used to reduce the frequency of dust explosions and control the risk associated with combustible dust. This is especially important when conducting industrial risk assessments and proposing safety precautions.

Keywords: Dust explosion, polymer, particle size, concentration, explosion severity

Introduction

A dust explosion occurs when finely divided combustible particles are suspended in a sufficiently oxidised atmosphere with an ignition source of appropriate energy that triggers a combustion reaction. It is considered a common hazard in many industrial sectors, including coal mining, food production, plastic manufacturing, pharmaceuticals, wood processing and more. Some operations that have also been impacted by dust explosions include storage, grinding, transportation and even pneumatic conveying [1]. The explosive effects of dust explosions have the potential to cause many catastrophic incidents, including the loss of human lives and valuable properties. Among the listed hazardous materials, polymer dust has been listed as a type of combustible dust by the Occupational Safety and Health Administration (OSHA) [2].

When discussing polymer products, plastics industries are generally the centre of attention because of their role in manufacturing polymer materials that possess a certain potential to cause dust explosions. In particular, during operations to produce resins from basic raw materials, moulding compounds, a material that can cause dust explosion, are formed. These compounds are present throughout the manufacturing processes until the finished products are made [3]. As such, the mass production of polymer materials can increase the probability of combustible dust explosions occurring, especially in these industries. To prevent such detrimental events, it is necessary to take safety precautions seriously. On top of that, along with the widespread use of plastic nowadays, more raw materials are needed by the plastics industry to meet the current demand.

Therefore, opting to reduce the overall manufacture of polymers is not a sustainable option.

Several studies have been conducted to examine dust explosions [1, 4, 8, 20]. However, when these studies are analysed, it is clear that their primary focus was on carbonaceous and metal dust explosions or explosion mechanisms and preventive measures. Although many products and processes today may seem harmless, the presence of a high concentration of combustible dust under specific conditions can cause fires and explosions. Plastics, rubbers, and resin manufacturing industries are among the few areas where research on dust explosions is rarely conducted. As a result, we have a limited amount of knowledge of their potential hazards. Studies on dust explosions of polyethylene dust have been done previously by Pang et al. [21] and Cheng et al. [22]. However, studies on dust explosions of other polymer dust, such as polyethylene terephthalate and melamine resin, have not been conducted. Therefore, there is a lack of informative details and understanding supported by research findings on unspecified dust components. If the issues are not properly handled, the situation may result in unknown risks to the related companies or industries. Moreover, because of the scarce information on the topic, stakeholders cannot make precise estimations and implement proper prevention procedures to mitigate the severe consequences of dust explosions. This may eventually complicate the process of hazard identification and risk assessment.

This research investigated the effects of particle size and dust concentration on dust explosion using three different types of dust polymer: melamine resin (MR), polyethylene (PE), and polyethylene terephthalate (PET). The dust explosion characteristics (P_{max}, d_P/d_t, and K_{st}) of the selected dust polymers were evaluated for particle sizes ranging from 125 µm to 250 µm and dust concentrations between 250 g/m³ and 1500 g/m³.

Materials and Methods

Materials

This work used PE, MR, and PET dust as raw materials. Meanwhile, 5kJ chemical ignitors and sample bags were used to conduct the experiment.

Identification of dust chemical composition using TGA analysis

Thermogravimetry analysis (TGA) was conducted to identify several parameters, such as moisture content, ash, volatility, and fixed carbon composition in the dust samples. One tablespoon of each dust sample was prepared and placed in three distinct sample bags that have been labelled accordingly. The samples were then sent to the laboratory for analysis using a TGA model of Q500 V6.7 Build 203. The measurement was done at a heating ramp rate of 10 °C/min. The data on chemical composition between each sample was compared and used to predict the explosion outcome and severity.

Preparation of dust samples

PE dust was screened using a sieve with a pore size of 125 µm on a sieve analysis stand. The sample was poured into a sample bag and labelled accordingly. Afterwards, the sieved PE dust was further screened through additional sieves with pore sizes of 160 µm, 180 µm, and 250 µm, and then placed in sample bags to represent different particle sizes. Four additional samples with dust concentrations of 250 g/m³, 500 g/m³, 750 g/m³, and 1000 g/m³ were prepared at a fixed particle size of 160 µm by weighing different sample masses corresponding to a fixed vessel volume of 20L. These procedures were repeated for MR and PET, with MR having an additional 1500 g/m³ sample due to lower relative explosivity.

Experimental work on dust explosion

The Siwek 20L spherical vessel, similar to the one used in Semawi et al. [4], was used to investigate the dust explosion phenomenon of different dust polymers with distinct particle sizes and concentrations. The assessment began by switching on the main power supply, the water supply (for cooling purposes) and the KSEP software system. Next, the gas regulator was turned on and adjusted to approximately 20 bar. The top cover of the vessel was removed, and the electrodes were connected to two 5kJ chemical igniters as the source of ignition. PE dust sample with a particle size of 125 µm and concentration of 1000 g/m³ was loaded into the dust container. After the outlet was turned off, compressed air was loaded into the system until the gauge pressure reached approximately 20 bar. The delay time was set at 60ms. The dispersion of dust and the initiation of the KSEP system were performed simultaneously. The explosion phenomenon was observed, and data such as explosion pressure and pressure rise were recorded. The procedures were repeated for the remaining particle sizes of 160 µm, 180 µm and 250 µm before proceeding with different dust concentrations of 250 g/m³, 500 g/m³, 750 g/m³ and 1000 g/m³. The experiment was repeated for both MR and PET samples.

Analysis of explosion characteristic data

The spherical vessel was interfaced with a computer program to control the dispersion or firing sequence of the dust particles. The required data was collected using the KSEP control system. The data recorded includes maximum explosion pressure (P_{max}) and rate of pressure rise (d_P/d_t). These metrics were recorded and used to calculate the deflagration index (K_{st}) using Cubic's Law [4]. The characteristics of each dust explosion produced from different dust samples with distinct particle sizes and concentrations were analysed and compared in terms of their severity and hazard. Based on the findings, the dust samples were classified into their respective hazardous category. The equation to calculate the K_{st} value is given in **Equation 1**.

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

where $\left(\frac{dP}{dt}\right)_{max}$ is the maximum rate of pressure rise, and V is the volume of the test vessel.

Results and Discussion

Determination of polymer dust chemical composition

TGA is an analytical technique commonly used in the experimentation of explosions to determine a sample's thermal stability and identify the fraction of volatile components [5]. TGA provides a simple, inexpensive, yet decently accurate alternative to quantitatively evaluate the thermal characteristics of dust samples by monitoring their change in weight as a function of temperature or time. The quantitative data provided by TGA includes the percentage moisture content, volatility, fixed carbon and ash, which can be used to pre-determine the explosion severity of polymer dust [6].

According to the tabulated data in **Table 1**, the moisture content in the MR was determined to be the highest (8.04%) when compared to PE (0.17%) and PET (0.08%). The moisture content refers to the amount of water present within a substance. Depending on the level of its concentration, it may affect the ignition and dispersion behaviours of dust particles [7]. Hence, based on the moisture content of the samples, a preliminary assumption can be made that MR is expected to produce lower explosivity due to its higher moisture content.

When comparing the samples in terms of volatility, all samples were found to exhibit relatively high volatility. Specifically, PET was at the forefront with 90.58%, while MR had the least with 35.12%. Volatility or volatile components have the greatest influence on the characteristics of the explosion. Generally, high volatility lowers the minimum ignition energy (MIE) required and makes it easier for a dust sample to disperse and combust into an explosion flame [8]. Considering PET has the highest volatility, it was predicted that its explosion would be the most severe.

Another parameter determined from the analysis was the percentage of fixed carbon. Fixed carbon is a solid, flammable residue that is non-volatile. It is one of the few remaining materials after the samples have been thoroughly heated and all volatile components have been combusted. This value can be obtained by completely deducting the remaining content percentage of moisture content, volatility, and ash [9]. From **Table 1**, the amount of fixed carbon in MR was the highest at 48.37%, followed by PET (4.92%) and PE (0.6%).

The final parameter obtained from the analysis was the amount of ash. Ash refers to the combustion residue that remains after all moisture and organic matter have been removed from the substance through the heating process in the presence of oxidising agents. Even though the ash content may not significantly affect the explosion outcome, it can reduce the combustion efficiency and increase the burning duration of a sample [10]. The data showed that PE possessed the highest amount of ash (41.51%), a characteristic that can influence the explosion likelihood and severity of the sample, especially when dealing with higher particle sizes.

Effect of particle size on polymer dust explosion

An initial study was conducted to study the effect of particle size on different types of polymer dust explosions. Four distinct particle sizes (125 µm, 160 µm, 180 µm and 250 µm) with a fixed concentration of 1000 g/m^3 were used for PE and PET. As for the MR, an additional concentration of 1500 g/m^3 was included due to the reason mentioned previously. The summary of explosivity data, which describes the maximum explosion pressure (Pmax), rate of pressure rise (dP/dt) and deflagration index (K_{st}) for each set, is shown in **Table 2** for a comparative analysis.

Table 1. Chemical composition of polymer dust from TGA analysis

Sample	Moisture (%)	Volatility (%)	Fixed carbon (%)	Ash (%)
Melamine resin (MR)	8.04	35.12	48.37	8.47
Polyethylene (PE)	0.17	57.72	0.60	41.51
Polyethylene terephthalate (PET)	0.08	90.58	4.92	4.42

Since PE is a widely used polymer, its dust has been extensively studied and analysed for explosion severity. Previous researchers have pointed out the suitability of PE to serve as a standard reference for assessing the severity of unfamiliar dust samples such as MR and PET. The explosion severity of a sample can be evaluated based on three key parameters: P_{max}, dP/dt and K_{st}. The higher the values of these parameters, the greater the severity of the resulting dust explosion. According to the comparison made in **Table 2**, it can be surmised that the overall values of MR were low. This indicates that MR has a weaker explosion severity than PE. As for PET, the overall explosion severity was much higher than PE for all particle sizes except for 125 µm. The inconsistency of these results might be due to the devolatilisation effect, which could have interfered with the accuracy of the analysis.

The explosion severity peaked at the particle size of 160µm, indicating that this particle size is critical for maximum ignition potential. The severity, however, decreased drastically as the particle size was enlarged up to 180 µm and 250 µm. This is because larger particle sizes allow for smaller surface area exposure, which induces a slower reaction towards ignition than smaller particle sizes, slowing the overall explosion process [11]. Besides, smaller particle sizes promote the dispersion of dust since they are much lighter. This lightweight characteristic ensures that they remain airborne longer for a more stable explosion process to occur.

Table 2. Data of dust explosion at different particle sizes

Materials	Particle Size (µm)	Pmax (bar)	dP/dt (bar/s)	K_{st} (bar.m/s)
Melamine Resin (MR) 1500g/m^3	125	0.06	0.00025	0.0001
	160	0.08	0.0006	0.0002
	180	0.04	0.0002	0.0001
	250	0.02	0.0001	0.0000
Polyethylene (PE) 1000g/m^3	125	4.41	47	12.7578
	160	6.95	64	17.3723
	180	2.14	11	2.9859
	250	0.14	0.0008	0.0002
Polyethylene Terephthalate (PET) 1000g/m^3	125	2.14	11	2.9859
	160	7.98	126	34.2017
	180	5.46	23	6.2432
	250	0.3	0.0007	0.0002

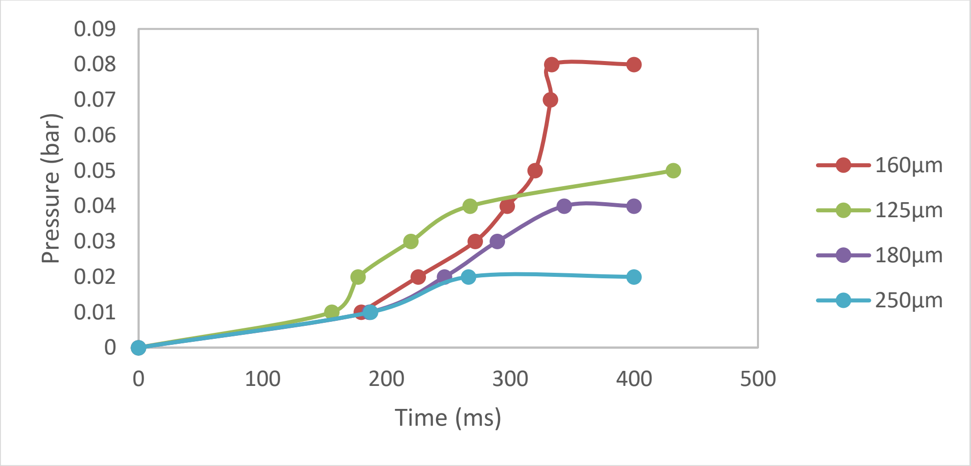

Figure 1. Effect of particle size on explosion severity of MR dust

Figure 1 presents the pressure change over time for an MR dust explosion at four different particle sizes, with a fixed concentration of 1500 g/m³. The highest explosive pressure was recorded at particle size 160µm, with 0.08 bar within the 300-350 ms time range. As for the second highest explosive, it was observed at particle size 125 µm at 0.05 bar. This was followed by 180µm (0.04 bar) and 250µm (0.02 bar). Disregarding the data for particle size of 125µm, the explosion severity, overall, decreased with increasing particle size.

Figure 2 illustrates the pressure change over time for PE dust explosions at four different particle sizes, with a fixed concentration of 1000 g/m³. Similar to MR, the highest explosive pressure was recorded at particle size 160 µm, with approximately 6.95 bar within the 300-400 ms time range. The second highest explosive pressure was produced by the particle size of 125 µm at 4.41 bar, followed by 180 µm (2.14 bar) and 250 µm (0.14 bar). Aside from the data for particle size of 125 µm, the explosion severity decreased as the particle size increased from 160µm to 250 µm.

Figure 3 shows the pressure change over time for PET dust explosion at four different particle sizes, with a fixed concentration of 1000 g/m³. The highest explosive pressure was achieved by particle size 160 µm at about 7.98 bar within the 300-400 ms time range. However, the second highest explosive pressure was recorded by the particle size of 160 µm at 5.46 bar, followed by 125 µm (2.14 bar) and 250 µm (0.3 bar). Besides the data for particle size of 125 µm, the explosion severity decreased as the particle size increased from 160µm to 250 µm.

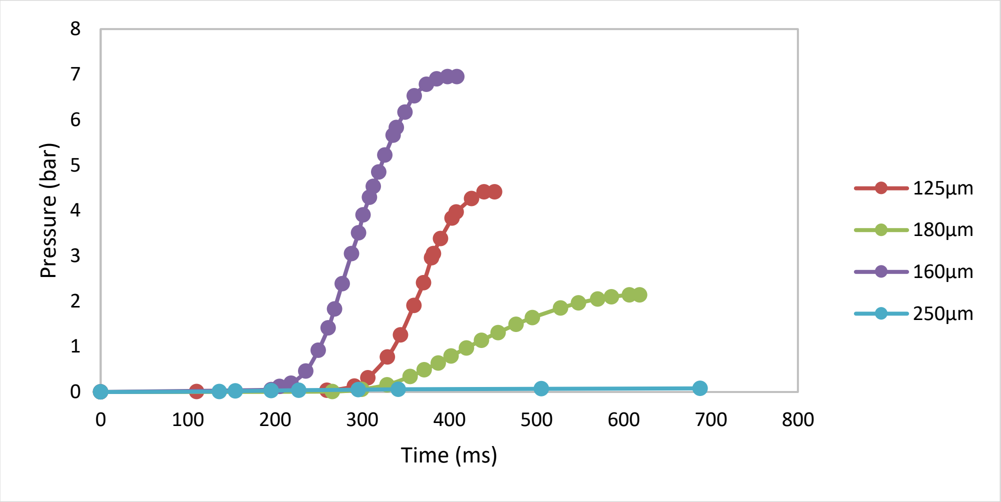

Figure 2. Effect of particle size on explosion severity of PE dust

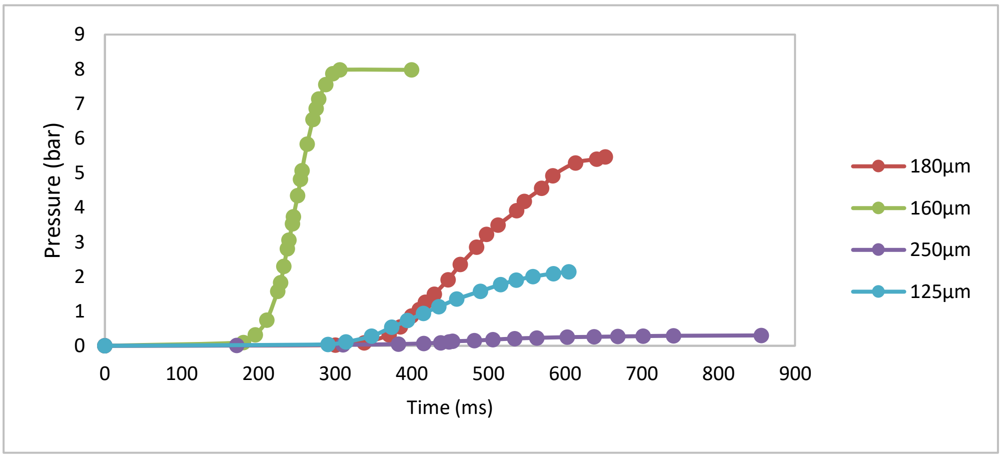

Figure 3. Effect of particle size on explosion severity of PET dust

Considering the explosion of all three dust samples, it can be concluded that particle size significantly affects the severity of the dust explosion. The trend clearly showed that the explosion severity decreased with increasing particle size. This occurred because the quantitative values (P_{max}, dP/dt and K_{st}) that describe their severity all decreased simultaneously as larger particle size samples were tested. However, the data for particle size of 125 μm across all three dust samples showed inconsistent trends, with severity being lower compared to 160 μm. This inconsistency may be attributed to the influence of devolatilisation. According to Eckhoff [12], increasing explosion severity does not continue indefinitely as particle sizes decrease. For organic materials such as polymer dust, devolatilisation or the release of combustible gas from particles precedes combustion and leads to an explosion.

Moreover, limiting the particle size to the degree where the combustion rate of a dust cloud does not increase anymore would depend on the time constants of the consecutive process devolatilisation, gas phase mixing and gas phase combustion. Particle size primarily influences the devolatilisation rate. In general, the process of devolatilisation remains the slowest step and is considered the limiting factor. This explains why further reducing the particle size would lead to greater explosions. Nevertheless, once the gas phase combustion becomes the slowest step instead of the devolatilisation process, further decrement in particle size would no longer enhance the overall combustion rate since its effects are no longer significant.

In a study conducted by Di Benedetto et al. [13] on the effects of particle size towards PE dust explosions, they found that the deflagration index decreased as dust diameter varied from 28 μm to 916 μm. The discovery suggests that the explosion pressure decreases with particle size since both explosion pressure and deflagration index are linearly related. The research on the explosion of tea dust by Nur Hikmah et al. [4] also verified this theory. From their analysis, it was determined that the explosion pressure and pressure rise escalated as the tea dust particle size dropped from 220 μm to 160 μm. However, they also discovered that when the size was the lowest at 125 μm, the explosion pressure and pressure rise were lower compared to the relatively larger particle sizes. This phenomenon occurs because, for most organic solvents, excessive particle size reductions have no significant effect on combustion rate, as devolatilization no longer dominates the determining factor of explosion severity.

Effect of dust concentration on polymer dust explosion

The effect of dust concentration on different types of polymer dust explosions was investigated using four distinct concentrations of 250 g/m^3, 500 g/m^3, 750 g/m^3 and 1000 g/m^3 at a fixed particle size of 160 μm for PE and PET. An additional concentration of 1500 g/m^3 was investigated for MR due to its low volatility, which might induce negative effects on its explosivity. The summary of explosivity data, including the maximum explosion pressure (P_{max}), rate of pressure rise (dP/dt), and deflagration index (K_{st}) for each dust sample, are presented in **Table 3**.

Table 3. Data of dust explosions at different dust concentrations

Materials	Concentration (g/m^3)	P_{max} (bar)	dP/dt (bar/s)	K_{st} (bar.m/s)
Melamine Resin (MR)	250	0	0	0
	500	0	0	0
	750	0.02	0.0001	0
	1000	0.06	0.0004	0.0001
	1500	0.08	0.0006	0.0002
Polyethylene (PE)	250	0	0	0
	500	1.84	1	0.2714
	750	5.46	23	6.2432
	1000	6.95	64	17.3723
Polyethylene Terephthalate (PET)	250	0	0	0
	500	1.59	0.0028	0.0008
	750	7.11	72	19.5438
	1000	7.98	126	34.2017

Figure 4 illustrates the effect of dust concentration on the explosion severity of MR dust at a fixed particle size of 160 µm. From the figure, the highest pressure value was obtained when the concentration was 1500 g/m^3 at 0.08 bar, followed by 1000 g/m^3 at 0.06 bar and 750 g/m^3 at 0.02 bar. This means that the higher the dust concentration present in the vessel space, the greater the overall explosion severity. For the remaining concentrations of 500 g/m^3 and 250 g/m^3, no explosion was recorded when the pressure was constantly set at zero for both concentrations. This is because the amount of dust particles present was too low to induce the explosive behaviours of the sample.

Figure 5 displays the effects of dust concentration on the explosion severity of PE dust at a fixed particle size of 160 µm. Based on the figure, the highest pressure value was obtained when the concentration was 1000 g/m^3 at 6.95 bar, followed by 750 g/m^3 at 5.46 bar and 500 g/m^3 at 1.84 bar. This meant that higher dust concentration present in the vessel space led to greater explosive readings and increased explosion severity. The concentration of 250 g/m^3 recorded no explosions as the pressure was constantly at zero, indicated by a straight line.

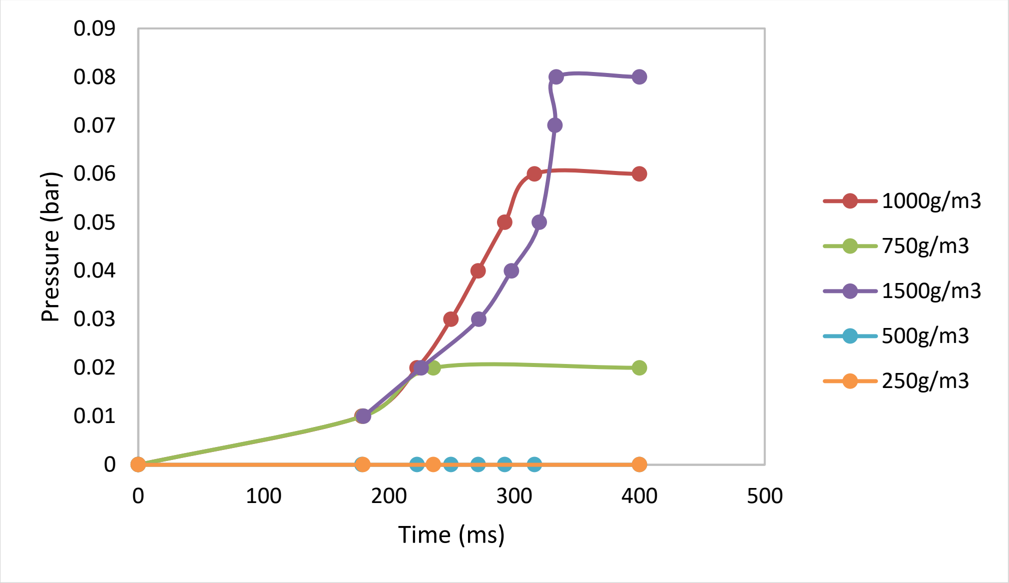

Figure 4. Effect of dust concentration on explosion severity of MR dust

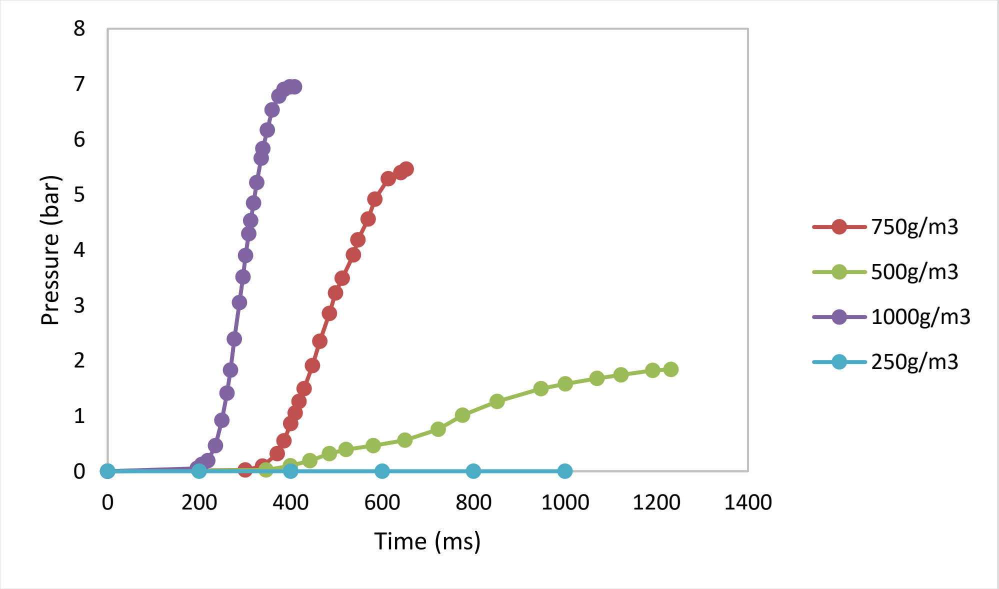

Figure 5. Effect of dust concentration on explosion severity of PE dust

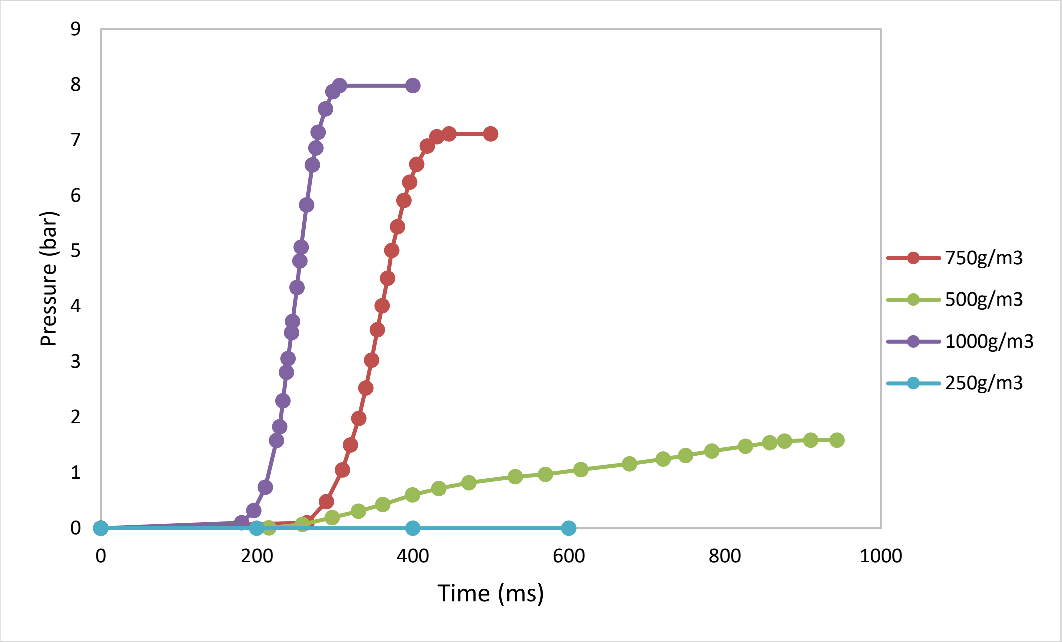

Figure 6. Effect of dust concentration on explosion severity of PET dust

Figure 6 presents the effects of dust concentration on the explosion severity of PET dust at a fixed particle size of 160 µm. It can be seen that the highest pressure value was obtained when the concentration was 1000 g/m^3 at 7.98 bar, followed by 750 g/m^3 at 7.11 bar and 500 g/m^3 at 1.59 bar. This suggests that higher dust concentration present in the vessel space led to greater explosive readings and increased explosion severity. The concentration of 250 g/m^3 recorded no explosions as the pressure was constantly at zero, indicated by a straight line.

When examining all graphs, a similar trend can be observed, in which increased dust concentration induced greater explosivity and higher characteristics in data readings. High dust concentration implies more dust particles being suspended in an enclosed environment. This situation, in turn, increases the likelihood for an explosion to occur and enhances the explosion impact incurred. However, no signs of explosion were observed for any dust sample at a concentration of 250 g/m^3, including MR at a concentration of 500g/m^3. The distinct observations are probably due to the influence of the minimum explosive concentration (MEC) of the sample [14]. A dust cloud can only explode if its concentration falls within a specific range; concentrations that are excessively high or low will prevent an explosion from occurring. This means that the 250 g/m^3 concentration was likely much lower than the MEC for all samples, resulting in no observable explosion at that concentration.

According to the coal dust explosion research done by Cao et al. [15], flame propagation can only accelerate and achieve a critical value when sufficient dust concentration is present in the reaction. As dust concentration increased from 60 g/m^3 to 250 g/m^3, there were more dust particles being confined in a fixed volume. This causes the explosion impact to increase gradually and reach a peak explosion pressure of 0.45 MPa at 250 g/m^3. As such, it is clear that the higher the combustible dust concentration, the greater the impact of the explosion produced.

Table 4. Summary of dust explosion characteristics

Materials	P_{max}	$(dP/dt)_{max}$	K_{st}	Class
MR	0.08	0.0006	0.0002	St_1
PE	6.95	64	17.3723	St_1
PET	7.98	126	34.2017	St_1

Analysis of dust explosion severity

The summary of dust explosion characteristics, including maximum explosive pressure (Pmax), maximum rate of pressure rise $(dP/dt)_{max}$ and the deflagration index (K_{st}), along with the hazard classification of each dust, is shown in Table 4. The hazard classification of combustible gas explosions was based on the deflagration index [16]. From **Table 4**, all the data for MR was much lower in comparison with PE and PET. This can be attributed to the low volatility and high moisture content of the sample, as shown in the TGA analysis. The high moisture content means that partial amounts of heat supplied from the ignition source will first be consumed by the water molecules for evaporation purposes. This reduces the amount of heat that is supplied to the dust particles, and as a result, the overall heat of combustion and explosiveness is lowered [17]. In other words, the higher the moisture content, the lower the combustion heat and explosion severity.

Based on the comparison between PE and PET, the overall explosion characteristics values for PET were significantly higher than PE. This can be correlated with its high volatility, as mentioned in the TGA analysis. An explosion is an instantaneous reaction. During the initial stage of the reaction, the volatile components that were dispersed will primarily be combusted after their first contact with the ignition source [18]. A higher volatility means more volatile components that can support a greater explosion. Higher volatility also lowers the minimum ignition energy (MIE) or the minimum amount of energy for dust ignition [19]. This makes PET dust much easier to disperse and combust into an explosion flame than PE. Although PE also had a decently high amount of volatility, the explosiveness of the dust was adversely affected by its high ash content. Ash is a material that is incombustible. Therefore, when present, it would act as an inert quality that diminishes the combustion rate of the sample. This is especially the case for larger particle sizes since ash would remain after smaller-sized volatilities are sieved. The presence of ash can greatly affect the combustion efficiency and prolong the burning duration of the sample, which explains why the explosion data obtained for PE was lower than for PET.

Conclusion

The research findings showed that the highest explosion pressure for all three samples was recorded at a particle size of 160 µm at their highest respective concentrations. MR recorded 0.08 bar at 1500 g/m³, PE recorded 6.95 bar at 1000 g/m³, and PET recorded 7.98 bar at 1000 g/m³. All three samples were categorised under the St1 class based on their respective K_{st} values. A material classified under this category generally indicates relatively weak flame intensity. Nevertheless, it must be noted that this material can have detrimental impacts under certain circumstances. When comparing the three dust samples, PET recorded the most severe explosions due to the highest data on all of the measured parameters. Overall, the research conducted was deemed successful since it managed to achieve its objective of evaluating the effects of particle size and dust concentration on different polymer dust explosions. It was determined that as particle size decreased, the explosion severity increased up to a certain point, after which further reduction in particle size no longer influenced the devolatilisation rate. As dust concentration rose, the dust explosion results became more severe. These findings are considered extremely beneficial, especially for companies that want to perform standard risk assessments regarding explosions and implement the necessary safety procedures to reduce the repercussions of such incidents.

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