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Experimental investigation of the minimum auto-ignition temperature (MAIT) of the coal dust layer in a hot and humid environment

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Ventilation Air Methane (VAM) abatement technology is recognized as a promising and value adding technique for reducing fugitive methane emissions, however, it also increases the potential fire and explosion risks of overheated coal dust. To eliminate these risks from the abatement systems it is necessary to determine the critical combustion characteristics of the minimum auto ignition temperature (MAIT) for a coal dust layer.

This study investigates the auto-ignition behavior of coal dust layers in a humid environment with Relative Humidity (RH) $>80\%$. The MAIT of four different coal dust samples (Australian coal) with particle sizes below 212 µm and dust layer thicknesses of 5, 12 and 15 mm were measured using a dust layer auto ignition temperature apparatus in accordance with the ASTM E2021 standard.

It was concluded that the MAIT of the coal dust layer significantly decreases with decreasing particle size. The MAIT for the coal samples with a smaller D50 size were observed to be lower in comparison with samples with a larger D50 size. The dust layer thickness was shown to significantly impact on the MAIT. The MAIT increased proportionally with the increasing thickness of the coal dust layer. The effect of the coal dust moisture content and humidity on the MAIT for compacted dust layers was noticeable, whereas, this effect was less important with loose dust layers. In addition, this work investigated and compared the MAIT for a typical coal dust sample based on the existing ASTM and International Electrotechnical Commission (IEC) standard procedures for ignition of coal dust layers.

1. Introduction

Dust explosions and ignition hazards are major safety concerns in a majority of industries which have dusty environments, such as silos and food factories, and in the coal mining and petrochemicals industries. Accidental fires and explosions caused by the ignition of combustible dust and gas lead to massive property damage and loss of life around the world every year. In 2005 alone, 13 explosions were reported in agricultural factories in the United States [1,2]. Between 2000 and 2012, five catastrophic explosions occurred in the United States mining industry resulting in 350 deaths and over 1000 people being injured. The total of the financial assets damages to the mines was in excess of $560 million. In addition, each mine was out of operation for a couple of months, significantly impacting on profits, and in some cases the lost production is likely to exceed the total cost of the assets damage [3]. The indirect costs of these accidents, such as the trauma imposed on families due to the loss of loved ones, however, cannot be expressed in financial terms. Hence, to prevent these accidents from happening it is vital to have a better understanding of the driving mechanisms which result in fire and explosion events.

There are numerous studies in the open literature in the field of fires and explosions in the industrial processing industries. The majority of these studies have been conducted on combustible metal dusts, such as aluminum powder [4–6] and cereal dusts, such as wheat dust in silos [7–9]. Underground coal mines are classified as highly hazardous areas from the point of view of fires and explosions. Despite the application of highly restrictive safety rules and continuous monitoring, fire and explosion accident avoidance is not always successful. This is mainly due to the variability in the characteristics of underground coal mines. The coal dust explosion severity depends on the coal type, the coal particle properties and the environmental conditions [10–15]. Despite the large number of studies on fires and explosions in coal mines [3,6–9,11,12,16,17], there remain shortcomings in the knowledge, such as around the impacts of the properties of coal dust (such as C/H, volatiles) on the initiation of explosions under

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certain conditions. Sapko et al. [16] examined the variations of coal particle size in the ventilation air samples from eleven coal mines in the USA. They observed that approximately 60–77% (± 14) of the particles were below 212 μm and that approximately 26–39% (± 11) of the particles were below 75 μm [16]. Based on the study by Sapko et al., it can be concluded that the majority of the coal dust particles that are emitted from the mines' shaft ventilation air are below 212 μm in size. Chen [17] conducted research to examine the components present in Ventilation Air Methane (VAM). He examined four VAM systems in Australia, including in the Hunter Valley, NSW, and the Bowen Basin, QLD. He noted that the relative humidity in the VAM systems were above 75% and in some cases reached 100%.

For a fire and/or explosion to occur in a coal mine, in addition to having a proper mixture of air and fuel, an ignition source with adequate energy is also necessary. The ignition may come from different sources such as electrical sparks, mechanical impact, open fires, hot surfaces and coal dust auto-ignition. Coal dust is a potential source of ignition due to the exothermic oxidation of coal, which has the potential to exceed the auto-ignition temperature. As such, it is important to investigate the possibility of coal dust as an ignition source as well as the environmental properties which may impact on this behavior.

The hazards of a combustible dust deposited on a hot surface was first referred to by Plamer [18], whose experimental work was carried out using a heated steel plate on which dust was set in conical heaps. Coal dust and dusts from other materials were used. It was observed that the minimum ignition temperature of coal dust varied with the depth of the bed and the composition of the dust, while no effect of packing density was noted. Nagy [19] examined the auto-ignition temperature for Pittsburgh coal dust layers. He used a typical laboratory muffle furnace to examine the variations in auto-ignition temperatures with particle size, bed depth and packing pressure for dust particle sizes ranging from 74 μm to 210 μm. He observed that the minimum auto-ignition temperature increased from 160 °C to 230 °C as the particle sizes increased from 74 μm to 212 μm. However, the minimum auto-ignition temperature (MAIT) increased as the bed depth decreased from 25.4 mm to 3.175 mm. Bowes and Townshen [20] used the same apparatus designed by Plamer et al. and observed that the particle size had a minimal effect on the MAIT while only the depth of the dust layer had a significant impact. They used coal dust samples with particles size diameters of less than 840 μm, and the coal dust particles were packed inside 5, 10 and 20 mm stainless steel rings. The minimum auto-ignition temperatures observed were 235 °C, 205 °C and 173 °C, respectively, for each thickness of steel ring. Miron [21] applied the Notational Academy of Sciences (NAS) procedure to determine if there was any correlation between the MAIT and the particle size. He examined explosive dusts such as coal dust, metal dust and oil shale for this purpose. He observed that there is a direct correlation between the MAIT and the particle size. The MAIT is higher for larger particles and a thinner dust layer [21]. These agree with the results presented by Bowes et al. [20]. Miron et al. also observed that the volatile content and chemical composition of each coal sample had a significant impact on its MAIT. Reddy [22] performed experiments on two types of coal samples: Princes coal from Cape Berton and Pittsburgh coal. The experiments were performed following the ASTM E2021 standard, with coal dust layer thicknesses of 5, 10 and 15 mm. He observed that the exothermic reactions (self-heating) gradually disappeared as the thickness of the coal dust layer increased. The first exothermic reaction was attributed to the release of volatile organic compounds and volatile matter combustion, while the second exothermic reaction refers to the char combustion. Moreover, despite the Prince and Pittsburg coals being of the same rank and the same size range (below 75 μm), there was a noticeable difference of 20 °C in terms of the MAIT. Park [23] conducted a series of experiments using samples from the Pittsburgh coal seam to measure the MAIT for different bed thicknesses of 6.4, 12.7, 19.2 and 25.4 mm, in order to develop a mathematical equation to predict the critical point of the ignition of the dust layer. The ignition for the bed thicknesses mentioned took place after approximately 2500, 4000, 6000 and 8000 seconds, respectively. Park, in an earlier study [24], examined the effects of the air flow on the test procedure for the ASTM E2021 standard and recommended that the air flow over the coal bed surface be minimized. He concluded that 33 cm/s air flow over the test bench was enough to increase the MAIT for Pittsburgh coal from 220 °C to 230 °C.

The effects of the relative humidity of the air on the MAIT of dust layers are as yet unclear. Morios [21] indicated that a small quantity of humidity increases the heating, while a large quantity (over 5%) retards the heating of the coal dust. The drying and wetting of coal dust also accelerates the heating process [25].

In underground coal mines, layers of coal dust can accumulate on a hot surface, especially if the surface is enclosed. The accumulation of the coal dust may cause compression, leading to an increase in the density of the dust layer. This has the potential to change the MAIT of the compacted coal dust layers. Nagy and Verakis [15] tested layers of three different materials (including Pittsburgh coal) to determine how the density affects the MAIT.

In the case of the Pittsburgh coal dust, increasing the density of the dust layer did not present a noticeable impact on the MAIT. Without testing at different layer thicknesses, it cannot be assumed that this behavior is synonymous with all thicknesses. In the testing of beech sawdust, Bowes and Townshend [20] found that only thin layers were affected by density changes. Other studies [26–31] addressed the effects of weathering on the spontaneous ignition of coal dust. In a study by Kucuk [26], the effect of moisture on the spontaneous ignition of a coal dust layer was investigated. A water concentration by mass of 25% was added to a coal dust sample followed by air drying (at 90 °C) until all the added moisture was evaporated. It was concluded that the real effect of humidity on the minimum ignition temperature of coal cannot be determined as the temperature impacts on the active functional groups and reduces the oxygen by enhancing the oxidation process [32,33]. Beamish [34] established a relationship between the spontaneous ignition of coal dust with the self-heating rate, called "R70", which was first introduced by Humphreys [35]. Beamish [36] investigated the effects of moisture on the self-heating of eleven coal dust samples. He concluded that moisture defers the self-heating for a specific time, depending on the amount of moisture in the coal sample. In addition, he observed that the moisture trapped in the coal sample prolonged the evaporation stage. As such, the entire process, which includes the intense oxidation and self-ignition, was extended. Despite the importance of the relative humidity effects and the coal dust moisture content on the self-heating of coal dust layers, there are not many studies to address this shortcoming in the knowledge. As such, a comprehensive study was conducted at the University of Newcastle, Australia, to examine these effects further. The aims of this study are to: (1) investigate the effects of relative humidity on the MAIT of coal dust layers; (2) determine the MAIT deposited in the proposed VAM capture duct; (3) examine the correlation between the MAIT and the physical and chemical properties of the coal dust; and (4) examine the effect of the packing density on the MAIT of the coal dust layers inside the proposed VAM capture duct.

2. Methodology and technique

2.1. The experimental setup

The experimental apparatus used to determine the MAIT of the coal dust layers is shown in Fig. 1. It consists of a flat surface furnace, data logger, computer program, and some accessories. The hot plate furnace was comprised of a circular aluminum plate of 25.4 mm thickness and 203 mm diameter. A circular stainless steel ring of 5 mm height and 50.8 mm diameter was used to keep the coal dust particles at the center of the furnace plate. Three K-type thermocouples were used to continuously measure the coal dust layer and the plate temperatures. All the input and output information was handled and recorded by a data logger and computer system. The experimental setup and the experimental procedure followed were in accordance with the ASTM E2021 standard.

In addition to the MAIT dust layer apparatus, a Thermogravimetric analysis (TGA) apparatus was employed to give precise measurements for the weight loss and heat flow of the coal dust ignition under different conditions (see Fig. 2). The TGA balance sensitivity was less than 1 μg, and the temperature precision was 0.5 K.

The sample weight used for the TGA analysis was 4.6 mg for the ignition of the coal samples, and instrument air was introduced to the samples at a flowrate of 80 ml/min under dynamic conditions at a heating rate of 10 °C/min. The ignition temperature was raised from room temperature to 700 °C.

2.2. Experimental procedure

The ASTM E2021 standard was used as a guideline to conduct the experiments. The furnace was calibrated to assure the accuracy of the plate temperature for any given set point. A calibration was conducted after every ten experiments. The hot plate furnace was then set at a pre-defined temperature according to the experimental schedule. The coal sample with known physical and chemical properties was placed inside the stainless steel ring over the hot plate furnace. The surface of the coal dust layer was then smoothed out by using a small flat trowel.

Typically, each experiment took approximately an hour. If no self-heating or ignition was observed at a given plate temperature, then no ignition was considered to have occurred at that set point temperature. The experiment was then repeated with a fresh sample of the same coal at successively higher temperatures. This process was continued until auto-ignition occurred. The temperature at which the ignition occurred is considered as the MAIT. In contrast, if the coal sample ignited at the initial set temperature, then the experiments were repeated with fresh samples at a lower plate temperature. This process was continued until no ignition was observed. The lowest temperature at which ignition was observed was considered the MAIT. To confirm the accuracy of the test, each experiment was conducted three times. The temperature ramp up/down for each step was 5 °C. Based on the ASTM E2021 standard, the ignition of the coal dust layer on the hot plate is considered to have occurred once a glow with a cracking sound and a corresponding temperature rise of 50 °C above the plate initial temperature is observed [24,37–39]. However, the International Electrotechnical Commission (IEC 61241) considers the MAIT to be reached when the sample temperature rises 20 °C above the plate temperature for particle sizes below 212 μm [7–19]. Finally, all experiments were conducted at 25 °C.

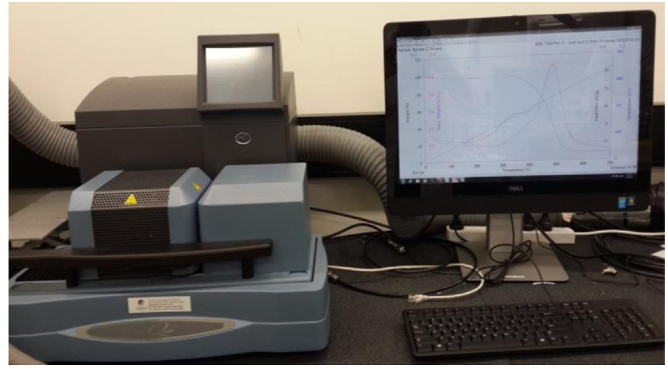

Fig. 2. Thermal Gravity Analysis (TGA) apparatus.

2.3. Sample preparation and analysis

The experimental study was carried out using four coal dust samples sourced from four different coal mines (A, B, C and D) in Australia. To eliminate environmental effects, the coal samples were kept in a cool area in sealed containers. The coal samples were then sieved using a series of sieves and a sieve shaker. The average particles size (D50) obtained from the sieving process were < 74 μm, 74–125 μm and 125–212 μm. A MALVERN Particle Size Analyser was used to determine the particle size distribution of the coal dust samples. The particle size distributions for each coal sample are shown in Table 1.

The analysis clearly indicated that, for D50 averages, Mine C had the largest average particle size (65.89 μm) followed by Mine B (29.91 μm), Mine D (21.8 μm) and Mine A (20.79 μm).

Table 2 indicates the ultimate and proximate analyses for the coal dust samples used in this study.

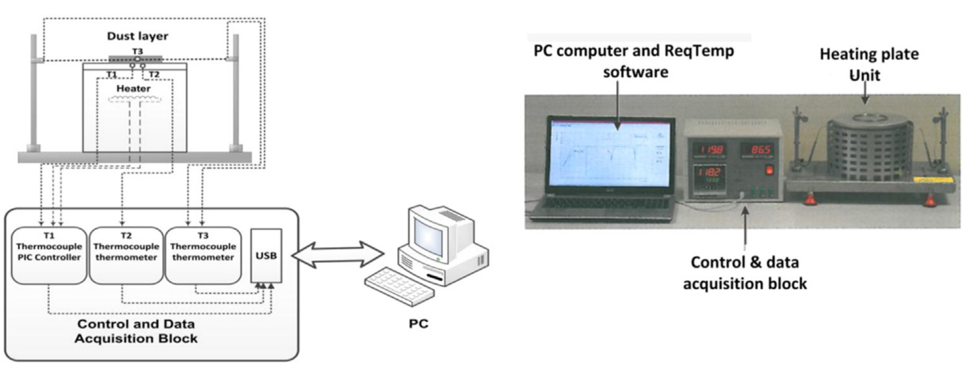

Fig. 1. Experimental setup.

Table 1
Coal dust sample particle size distributions.

	A	B	C	D
D90	64.02	111.73	189.79	65.85
D50	20.79	29.91	65.89	21.8
D10	3.04	4.5	9.26	2.91

Table 2
Proximate analysis of coal dust samples.

Coal samples v	A	B	C	D
Moisture (wt%)	3.1	1.1	2.6	4.1
Ash (wt%)	21.4	10.3	9.4	20.6
Volatile matter (wt%)	28	31.7	36.3	27.5
Fixed Carbon (wt%)	47.5	56.9	51.7	47.8

3. Results and discussion

3.1. The effects of particle size on the MAIT

Fig. 3 shows the variation of the MAITs with particle size for the coal dust samples below 212 μm from Mine B. The coal dust layer thickness for these sets of experiments was 5 mm.

As observed, the MAITs significantly increased with increasing particle size. The MAIT for coal dust particle sizes below 74 μm was approximately 235 °C, while the MAIT increased to 250 °C and 270 °C for the 74–125 and 125–212 μm size fractions, respectively. The MAITs reduced by about 13% as the particle sizes decreased from 125–212 μm to <75 μm.

There are three valid reasons for the drop in the MAITs. Firstly, the finest particles are more able to trap the generated heat from the oxidation at a faster rate than the coarse particles. Additionally, the finest particles liberate volatile matter at a higher mass flow-rate than the coarsest particles, which accelerates the auto-ignition of the coal particles. Finally, the finest particles have a larger surface area for oxidation than the coarsest particles. All of these reasons led to the reduced MAITs for decreasing coal dust particle sizes. These results are in good agreement with the findings reported by Miron et al. and Brown et al. [20,21].

3.2. The effects of volatile matter and the average particle size on the MAIT

The variations of the MAIT with the volatile matter content and

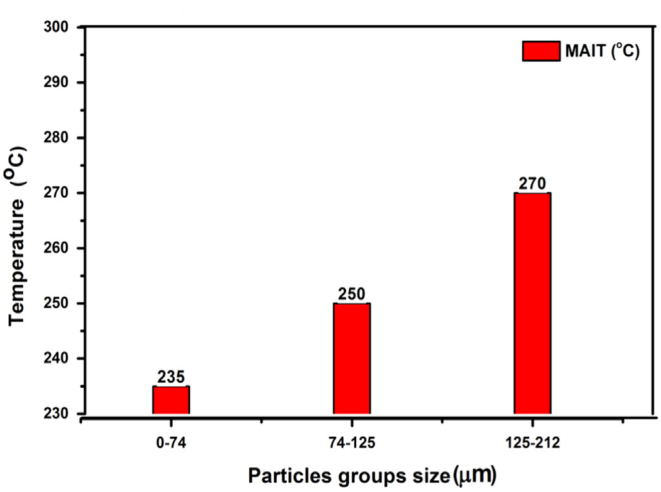

Fig. 3. MAIT of Mine B sample for three particle size groups (<74 μm, 74–125 μm, and 125–212 μm).

average particle size (D50) for the four coal dust samples collected from different coal mines (i.e., A, B, C and D) are presented in Figs. 4(a) and 3(b), respectively, and the ordinate X-axis (Mines samples) is arranged according to the D50 values from lowest to highest.

The Mine B sample had the lowest MAIT of 235 °C, while the MAITs for the A and D samples were 240 °C. The MAIT for sample C was approximately 245 °C. The average size D50 for samples A, B and D were around 25 μm and for sample C was 65 μm (see Fig. 3 (b)). The effect of the volatile matter content on the MAITs is more dominant than the particle size for particle sizes below 50 μm and particle sizes are more dominant than the volatile matter content for particles larger than 50 μm. This is clearly shown for the coal dust sample B (Fig. 3(a)). In this sample, despite having the same particle size as Mine samples A and D, the higher volatile matter content, in comparison with the A and D samples, resulted in a decreased MAIT (by ~5 °C). In contrast, the mine sample C had a particle size >50 μm and yet the MAIT increased with increased volatile matter contents. From these results, it is attributed that the MAIT is dependent on both the chemical and physical properties of the coal particles. The change in the particle size's influence at approximately 50 μm can be attributed to the volatile matter travel distances from the voids to the surface, as well as the weak capillary action due to the larger particle sizes. The capillary width for the alignment of coal particles is usually wider for the coal bed layers made of larger particles. As such, the cohesive force between the volatile matter and the coal particles is small. This, therefore, leads to a slower release of volatile matter. In small particle size beds, the volatile matter is therefore released more quickly from the voids. However, the travel distance from the particle surface to the combustion zone is longer for small particle sizes and shorter for large particle sizes. With changing particle sizes, the rate of change of the volatile matter released and the travel time of the volatile matter from the particle surface to the combustion zone, therefore, have different rates of change. The particle size and the rate determining step will therefore change with the particle size, which was found to be approximately 50 um for the samples tested. The evidence of the rate of the volatile matter release, measured by the heat released as a function of temperature in the TGA experiments, is discussed in Sections 3.2.2 and 3.5.3.

3.3. The effects of humidity on the MAIT

The effects of humidity on the MAIT were investigated as a part of this study. For this purpose, the coal dust samples collected from Mine B were exposed to air of 80% RH for durations of 2, 4 and 24 h. The initial observations of the mass changes (approximately 1.1%) showed that the maximum moisture adsorption occurs within the first 2 h of humidification (see Fig. 5).

The moisture adsorption rate substantially reduced as the time of the exposure was prolonged, becoming saturated after 24 h of exposure. The extent of the water adsorbed by the coal particles depends on the morphology and the pre-existing level of water on the coal particles. The particles with a greater number of open pores and lower surface moisture can absorb more water in comparison with those that have fewer open pores and are less saturated. After saturation is reached, no more water can be absorbed by the coal particles, therefore the mass remains constant.

Fig. 6 indicates the effects of humidity on the MAIT for a coal dust layer collected from Mine B. These coal particles were exposed to air of 80% RH for a period of up to 24 h.

Fig. 6 shows the three size ranges tested for their MAITs with variable time exposures to humid air. The <74 μm sample showed a constant MAIT of 235 °C for the four samples tested after humid air exposure times of 0 h, 2.5 h, 4 h and 24 h. The 74–125 μm

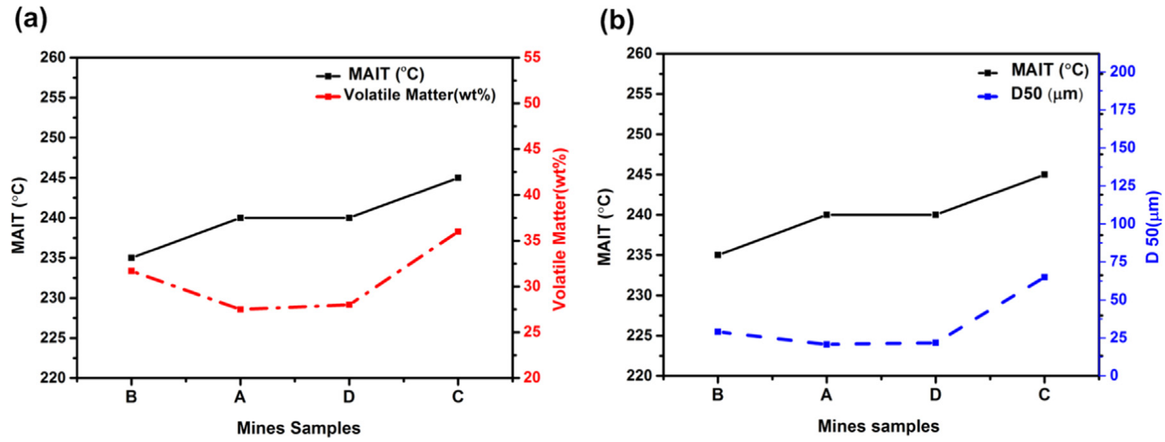

Fig. 4. MAITs for mine A, B, C and D samples (−74 µm) for variable (a) volatile matter (wt%) and (b) average size D50.

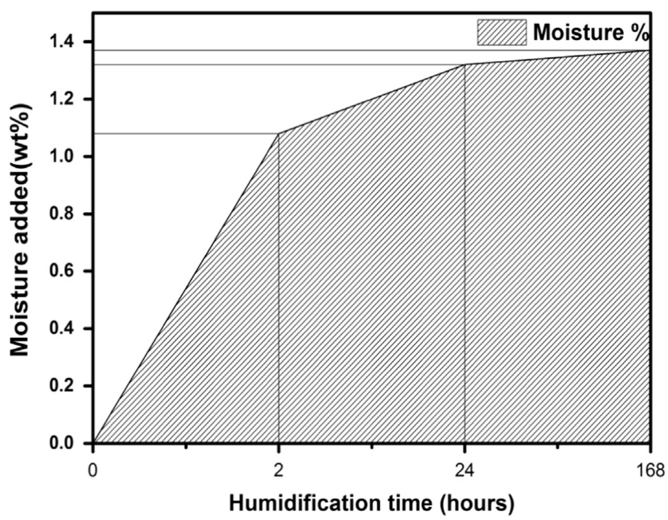

Fig. 5. Moisture absorption versus exposure time for the Mine B sample (below 74 µm>).

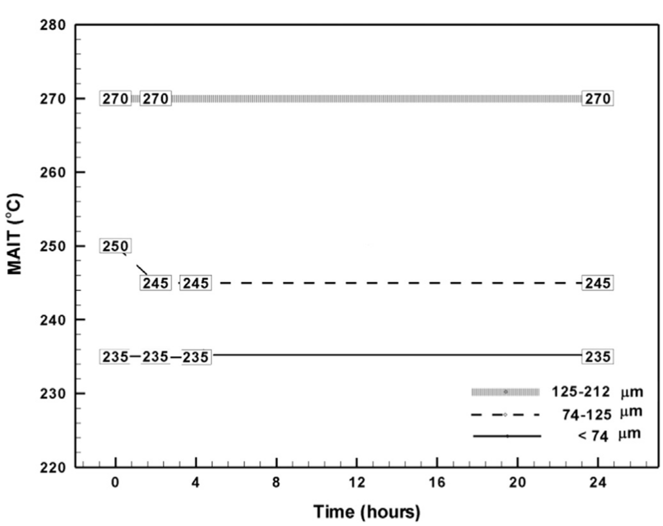

Fig. 6. MAIT versus exposure time to humid air for the Mine B samples.

samples showed an approximately constant MAIT across the four exposure times and similarly, the 125–212 µm samples showed a constant MAIT across three different exposure times. The MAIT, therefore, does not change for either small particles (<74 µm) or large particles (125–212 µm). However, the MAIT for the 74–125 µm samples varied slightly (5 °C) between 0 h and 2.5 h of exposure time.

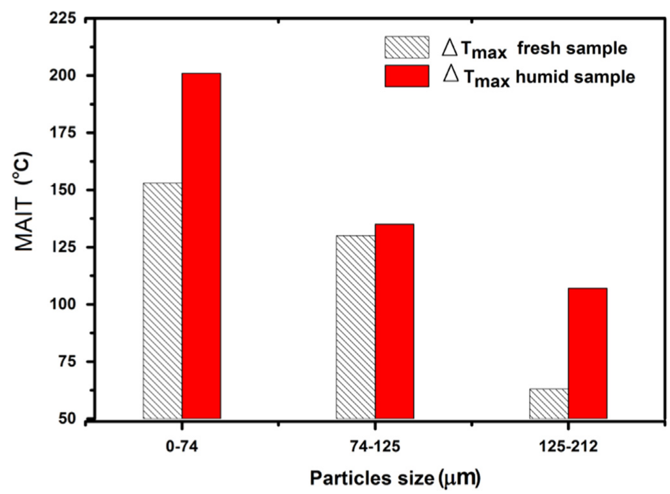

Fig. 7. MAITs of different sizes for fresh and humid samples.

Fig. 7 illustrates the difference between the maximum temperature of an ignited coal dust layer and the plate temperature for the two fresh and mummified coal dust samples collected from Mine B. In this figure the temperature differences are shown as ΔT_{MAX}. As observed, the ΔT_{MAX} varied with the coal dust particles sizes. The ΔT_{MAX} for the coal dust particles below 74 µm was 201 °C and 153 °C for the humidified and fresh samples, respectively. It shows an approximately 23% lower heat liberation from the humidified samples when compared with their fresh sample counterparts. For larger particles (i.e., 74–125 µm), however, the ΔT_{MAX} variation was minimal. The ΔT_{MAX} for these ranges of particles was approximately 128 °C and 130 °C for the fresh and humid samples, respectively. While the middle size range particles showed similar values for both the fresh and humid ΔT_{MAX} samples, the very coarse particles (i.e., 125–212 µm) had substantial ΔT_{MAX} variations of 40%. For the very coarse fresh and humidified samples, the ΔT_{MAX} are approximately 63 °C and 107 °C, respectively. From the results presented in Fig. 7, it is deduced that the ΔT_{MAX} variations are significantly influenced by the size of the coal dust particles constructing the coal dust layer. The oxidation process and heat generation occurs on the surface of the coal dust particles. Beds made of fine particles have larger surface areas in comparison to coarser particle beds. Therefore, the surface area available for oxidation is greater, and more heat will thus be liberated for finer particles.

Generally, the volatile matter diffusion and travel to the combustion zone occurs in two stages. In the first stage, the volatile compounds inside the coal particles diffuse out through the interconnected channels and reach the surface of the particle. In stage two, the released volatiles from stage one accumulate and travel through the micro sized channels formed by the particles' alignments. It usually takes longer for the volatiles to reach a particle's surface in larger particles than in smaller particles as the volatiles need to travel a longer distance. In addition to the travel distance, the volatile diffusion rate depends highly on the heating process and the heating increments ramping up. The physical structure of coal particles is prone to change due to continuous heating. It is often manifested in the form of partial surface annealing and the formation of coke inside the particles. This structural change leads to deformations and/or the blockage of the interconnected channels inside the coal particles. Therefore, the liberated volatiles may be trapped inside the particle for a longer time and gradually diffuse out. Unlike in coarse particles, the liberation and diffusion of volatile compounds is much quicker in fine particles. This happens due to the quicker heat penetration inside the coal particles as well as the short travel distance for the volatiles to reach the surface.

The inflation of the ΔT_{MAX} for the humidified samples, in comparison to the fresh samples, can be attributed to the expansion of the particle's surface area as well as the increase in the active surface. During the humidification process, a thin layer of water molecules envelops the surface of the coal particle. Upon the initiation of the thermal process, the pores open up and the layer gradually evaporates from the sample surface, resulting in an increase in the total surface area. Moreover, a negative pressure is created on the particle surface with water evaporation. This negative pressure, to some extent, unbinds and liberates the volatiles trapped inside the particle. The expansion of the surface area and liberation of volatiles results in a noticeable increase in the size of the active zones on the surface of the particle (see Fig. 7). Hence, the heat release from the combustion process is enhanced for the moist samples [26,40].

To conclude, the humidification of the VAM stream, smaller particle sizes and the higher compositions of volatile matter in the coal dust particles lowers the MAIT of the coal dust layer in VAM streams, leading to an increase in the probability of an explosion by increasing the energy ignition.

3.4. The effects of the packing density on the MAIT

Table 3 tabulates the obtained results for the effects of the packing density on the MAIT for coal dust samples collected from Mine D. In this exercise, coal dust layers of different thicknesses were compressed by applying a pressure of 1249 N/m^2 for durations of one minute. The results corresponding to the coal dust bed density showed a nearly linear correlation between the MAIT, the coal dust layer thickness and the compression. The MAIT for the uncompressed samples increased as the thickness of the dust layers decreased. For the 12.7 and 15.0 mm thick samples, the compressed coal dust required an extra 10 °C to self-ignite than for the loosely packed coal dust samples. Whereas, the 5 mm thick sample required only an extra 5 °C to self-ignite when compressed.

Table 3
Packing density effects on the MAIT.

Layer thickness (mm)	MAIT for normal bed (°C)	Packing density (g/cc)	Volume change (%)	MAIT for compacted bed (°C)
5.0	240	0.480	11.0	245
12.7	210	0.525	17.7	220
15.0	205	0.540	25.0	215

Table 4
Particle size distributions of the unpacked and packed coal dust samples.

PSD characterize (μm)	Unpacked coal sample	Packed coal sample
D90	65.85	61.81
D50	21.8	20.22
D10	2.91	3.03

These disparities occur due to the fact that thicker layers are able to trap heat more efficiently than thinner layers. Consequently, lower temperatures are needed to ignite the thicker layers. In comparison, Nagy's [19] research findings reported that the packing density had no effect on the MAITs for 5 mm thick coal dust layers with a measurement accuracy of 10 °C. While, in this study, the experiments extended beyond a thickness of 5 mm and were conducted on three different thicknesses of coal dust layers (5, 12.7 and 15 mm) with a MAIT measurement accuracy of 5 °C. In agreement with Nagy, there were negligible changes in the MAITs for the compacted and uncompacted samples of 5 mm thick coal dust layers(see Table 3).

The effects of the packing force on the particle size distribution have been reported for 5 mm layer thicknesses by using a MALVERN Particle Size Analyser (see Table 4).

3.5. Temperature-time profile

3.5.1. The effects of humidity on the temperature-time profiles

Fig. 8(a)–(d) indicate the temperature-time profiles and the ΔT_{MAX} for coal dust samples collected from Mine B. The coal samples for particle sizes below 74 μm were exposed to humid air (RH 80%) for durations of 2, 4, and 24 h.

Fig. 8(a) shows the typical temperature-time profile for the coal dust particles before humidification. t_1 t_2 and t_3 refer to the time needed to achieve the highest temperature for self-heating, first ignition and second ignition, respectively. The first peak (ΔT_1) arises due to the self-heating reactions when the generated heat in the bed is higher than the heat loss to the surroundings. At this point, the combustion does not proceed as the generated heat is not enough to ignite the coal dust. The highest peak in the temperature-time profile (ΔT_2) was observed at approximately 1300 seconds after the initial ignition. The bed temperature then gradually reduced below the plate temperature [24,25].

Fig. 8(b) shows the temperature-time profile for the coal dust particles after two hours of humidification. Three distinct temperature peaks were observed. The presence of these peaks can be attributed to the dust layer's initial self-heating, and the first and second ignitions. The time required to achieve ΔT_1 was similar (450–500 s) to that of the non-humidified sample. While the time between the first and second ignitions (t_3) were approximately 900 s.

Fig. 8(b)–(d) show the temperature-time profiles for the coal dust particles after four and twenty four hours of humidification, respectively. In Fig. 8(c), it was observed that t_3 (2 h humidification) occurred approximately 2000 s after the initiation of the test, which is more than twice of that observed in Fig. 8(b) (4 h humidification). The t_3 value is even higher (3000 s) for the sample that was subjected to 24 h humidification (Fig. 8(d)). This set of experiments, therefore, indicates a clear correlation between the t_3 ignition peak time in the temperature-time profile and the coal dust moisture content. For the fresh sample (not heat and/or moisture treated) only two temperature peaks were observed, while increasing the moisture content by at least 1% (equivalent to 2 h humidification in this study) resulted in multiple ignition peaks being observed in the temperature-time profiles. In addition, the time span between the two ignition peaks increased with

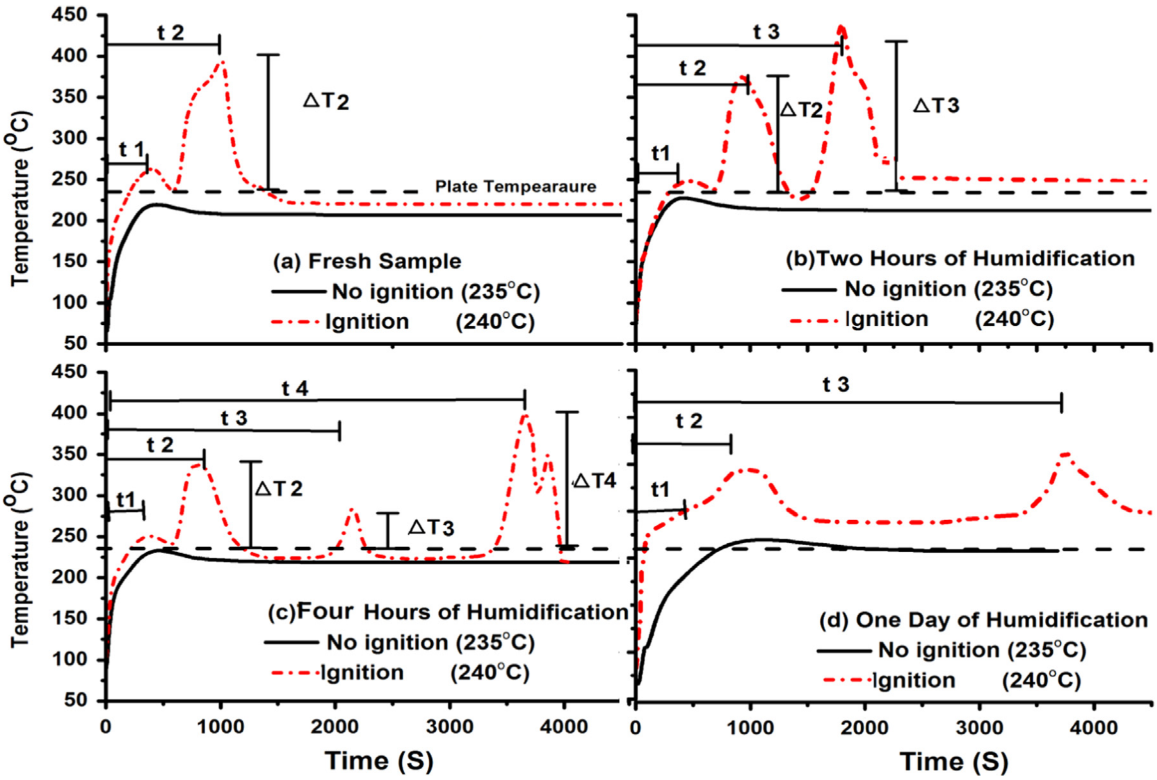

Fig. 8. Time-temperature profiles for Mine B samples, below 74 μm (a) fresh sample, (b) two hours humidification, (c) four hours humidification, (d) one day humidification.

the duration of the humidification. Furthermore, as shown in Fig. 8 (d), the self-heating peak was delayed and merged with the first ignition peak caused by the moisture content, as originally reported by Beamish 2005 [41]. These findings agree well with the results presented by Beamish and Reddy [22,41].

Fig. 9(a)–(c) show the appearances of the coal dust layer surfaces during the heating process. Fig. 9(a) is an image taken from the coal dust layer during the self-heating phase. The predominant sign of the initiation of an ignition at this stage is smoldering. At this stage, a white colored smoke rises up from the surface of the coal dust layer which is comprised of water vapor and some combustion products (e.g., CO_2). During the first ignition stage some small cracks began to appear on the surface of the coal dust layer (Fig. 9(b)) and gradually increased in size and number during the second ignition stage (Fig. 9(c)).

The first ignition occurs due to the partial ignition of the coal dust layer only. At this stage, some of the generated heat from the self-heating reactions is consumed by the evaporation of the adsorbed moisture. The lower layers evaporate first and are dry enough to ignite earlier than the upper layers, which are not completely evaporated. The heating of the coal dust layer further results in the second ignition phase, which usually happens after all the moisture has been evaporated and sufficient heat is generated. Detecting the initial temperature rise in a coal dust layer is crucial, from a fire safety point of view, as it provides the system and/or people with sufficient time to stop the dust layer reaching the ignition stages (cracking).

3.5.2. *The effects of drying on the temperature-time profiles*

The effects of heating and drying on temperature-time profiles were investigated as a part of this study. Fig. 10(a) and (b) indicate the temperature–time profiles for the coal dust samples with sizes ranging below 74 μm collected from mine D. the coal dust samples were exposed to a hot environment with an approximate temperature of 50 °C in an adiabatic oven for two hours. the thermal treated samples were then used for the MAIT experiments. the results corresponding to the temperature-time profiles show that the MAIT is not affected by exposure to the hot environment.

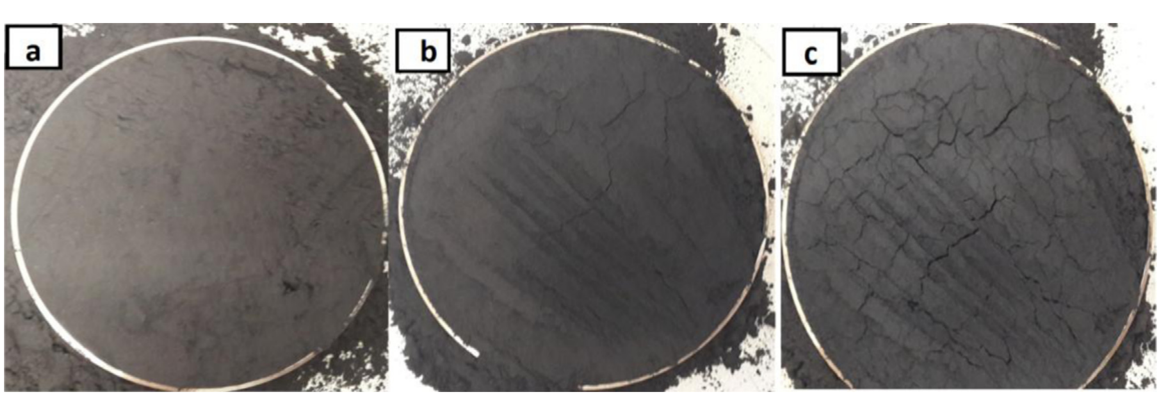

Fig. 9. Coal dust layers during (a) self-heating, (b) first ignition, and (c) second ignition.

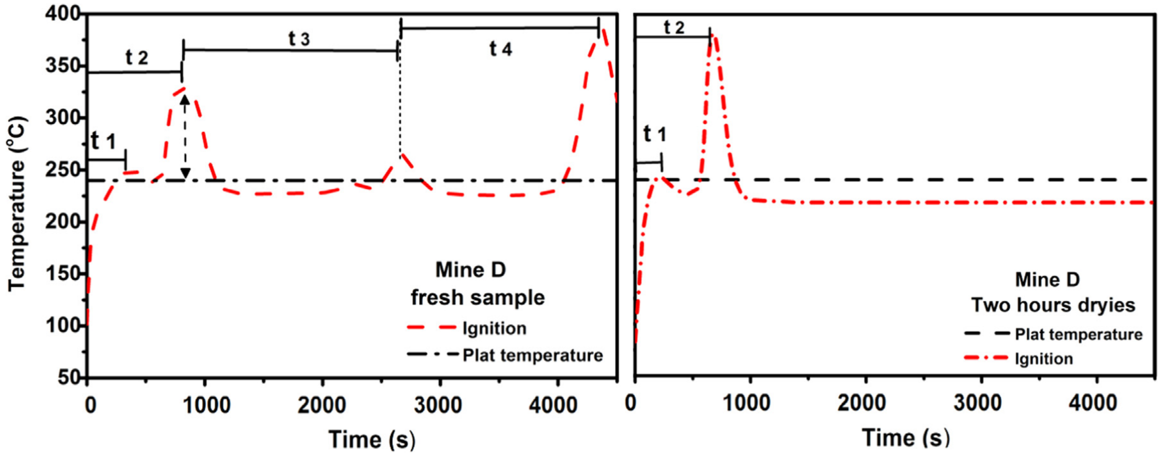

Fig. 10. Temperature-time profiles for Mine D samples below 74 μm (a) fresh sample, (b) dried sample.

Mine D samples inherently contain a relatively high amount of moisture (4.1%). Fig. 12(a) shows the behavior of the ignition of the fresh sample and clearly depicts two behaviors. Firstly, multiple ignition peaks can be observed. Secondly, the maximum temperature difference (ΔT) for the last peak is higher than that for the other peaks. After the sample was dried for two hours, the ignition showed two different behaviors to the non-dried samples (see Fig. 10(b)). Only one ignition peak was observed, and the value of t_1 was relatively shorter for the dried than for the fresh samples because of the moisture evaporation [42].

The results of the TGA analysis of the fresh and dry samples from Mine D are shown in Fig. 11(a) and (b), which show the weight conversion (weight loss%) and the nominal heat flow as a function of time, respectively.

It was observed from the microbalance of TGA Fig. 11(a) that the samples significantly started losing mass at a temperature of around 360 °C, which indicated the commencement of the fixed carbon and residual char oxidation of the coal dust. The sample continually lost weight until around 590 °C, which indicated the ending of oxidation. The percent of ash and non-combustible residual after combustion was around 16% for both the fresh and dry samples. The pattern of the weight conversions corresponding to the temperatures doesn't show any significant change or the influence of the moisture on the coal ignition. The nominal heat flow (Fig. 11(b)) shows three stages of coal dust combustion. The first stage starts from the room temperature until 150 °C. In this stage, the sample gains energy to evaporate the free moisture from the coal sample. Beyond 150 °C, the oxidation of the volatile matter and the active sites emerge. The total nominal heat released in the second stage is 4084 W/g and 4178 W/g, respectively, for the fresh and dry samples. In the last stage, the residual char oxidation emerged at around 360 °C and the total nominal heat released at this stage was 4785 W/g and 4960 W/g, respectively, for the fresh and dry samples. The nominal heat flow data shows slight differences between the fresh and dry samples, which may be attributed to the differences in the sample moisture. The TGA analysis doesn't show significant changes to the coal dust ignition behavior between the fresh and dry samples. This fact emphasized that the observed multi-ignition is not a result of the effects of moisture on the ignition behavior of single particles. The multi-ignition phenomenon, however, may be attributed to the partial ignition of the dust layer samples. As the moisture evaporates from the particles closest to the hot plate surface upwards through the sample, the upper particles are restrained from ignition. The upper particles are ignited when enough energy reaches them, which causes the multi-ignition phenomenon.

3.5.3. *The effects of particle size on the temperature-time profiles*

As the coal dust layer is considered as an ignition source, predicting and understanding the time of ignition is a crucial factor in the designing of the mitigation system in VAM. The effect of a particle's size on the time of ignition is clarified in Fig. 11.

Fig. 12(a)–(c) present the temperature-time profiles and the ΔT_{MAX} for the Mine B coal dust samples ranging between <74 μm, 74–125 μm, and 125–212 μm. The temperature-time profiles show that the self-heating and ignition behaviors of the samples are

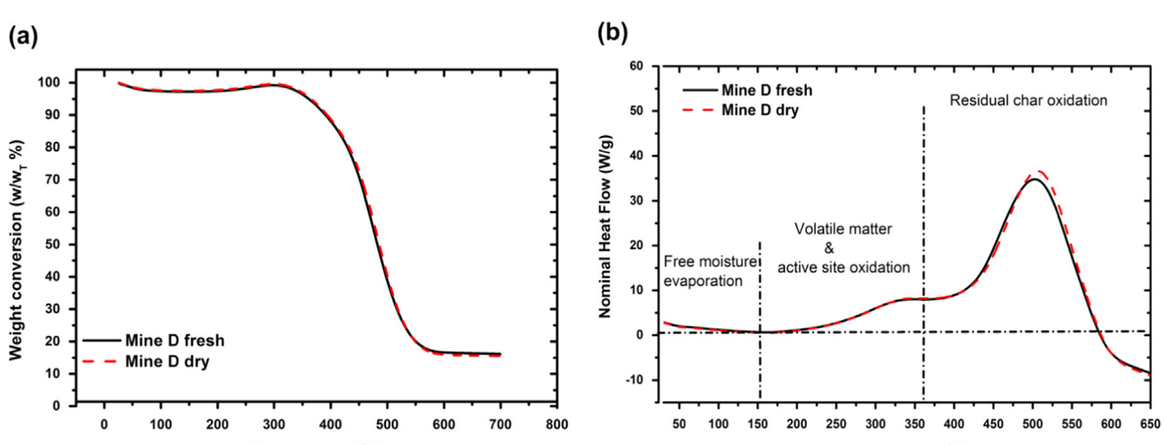

Fig. 11. TGA analysis for fresh and dried samples from Mine D (a) weight conversion, (b) nominal heat flow.

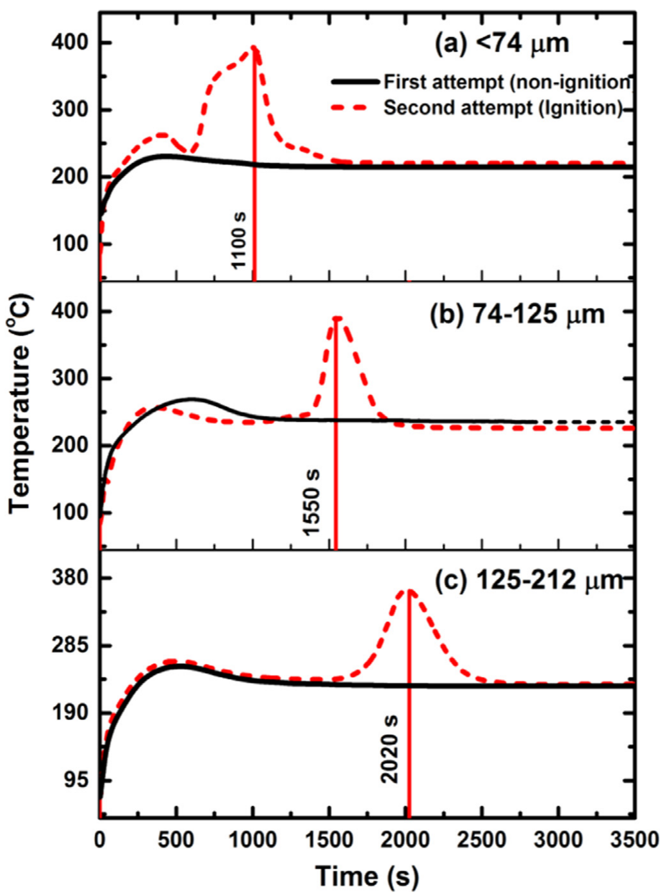

Fig. 12. Time-temperature profiles for Mine B samples (a) below 74 μm, (b) 75–125 μm, and (c) 125–212 μm.

similar for all the size fractions. The temperature–time profiles show that ignition is achieved after 1100 s for particles <74 μm, 1550 s for particles between 74–125 μm, and finally 2020 s for the largest particles in this study (125–212 μm). For all three size fractions (<74 μm, 74–125 μm and 125–212 μm) the highest temperature reached for self-heating falls within a 500–750 s time span. However, the required time (t_2) to reach ignition differs with the particle size. From the obtained results, it is inferred that the time of ignition alters with the particle size. The heating rate is governed by the convective heat loss and the rate of volatile matter diffusion from the coal particles, which is noticeably higher for the finer coal particles [43].

The results of the weight conversion and the nominal heat flow as a function of the reaction temperature are shown in Fig. 13 (a) and (b), respectively.

The weight % conversion as a function of the reaction temperature (Fig. 13(a)) shows the weight conversion of the large particles shifted by around 40 °C when compared to the small (<75 μm) particles. The results showed good agreement with the previous literature [44,45]. Additionally, the results of the nominal heat flow as a function of the reaction temperature (Fig. 13(b)) showed three stages of coal ignition. The three stages are the moisture evaporation, the volatile matter and active site oxidation, and the residual char oxidation. The three particles sizes showed similar patterns in the free moisture evaporation stage. The nominal heat flow patterns in the second stage, nonetheless, showed the finest particle sizes releasing higher heat flows as compared to the coarsest particles. Heat flows of 871 W/g, 696 W/g and 662 W/g were released, respectively, from the B <74 μm, B 74–125 μm and B 125–212 μm size fractions. The nominal heat flow from the last stage showed significant reductions in the heat released from the fine particles as compared to the coarse particles. In summary, the differences in the heat emitted shifted in the thermogravimetric analysis with changing particle sizes. The shift can be attributed to two main facts, firstly, the volatile matter is released at a higher rate across the particle's surface [45]; and secondly, the oxidation of the volatile matter and the active sites restrains the oxygen from accessing the residual char.

3.6. *Comparison of the MAIT definition between the ASTM E2021 and IEC 61241 standards*

All the experiments in this study were conducted to comply with the ASTM E2021 standard. The ASTM standard, however, considers coal dust layer sizes of <74 μm, while this study also considers coal dust layers up to 212 μm. In addition, the ASTM standard defines the occurrence of ignition when the dust layer exceeds the plate temperature by 50 °C. The IEC standard, on the other hand, includes guidelines for coal dust layers of size >212 μm and defines the occurrence of ignition as when the dust layer exceeds the plate temperature by 20 °C. Therefore, a comparison was done to determine if there would be any differences in the determination of the MAITs according to the definitions proposed by the ASTM E2021 and IEC 61241 standards. Table 4 shows the MAITs for the different coal samples from Mine B according to the ASTM and IEC definitions.

It can be seen that for nearly all the samples the acquired values for the MAITs for both the ASTM and IEC standards were equal (Table 5).

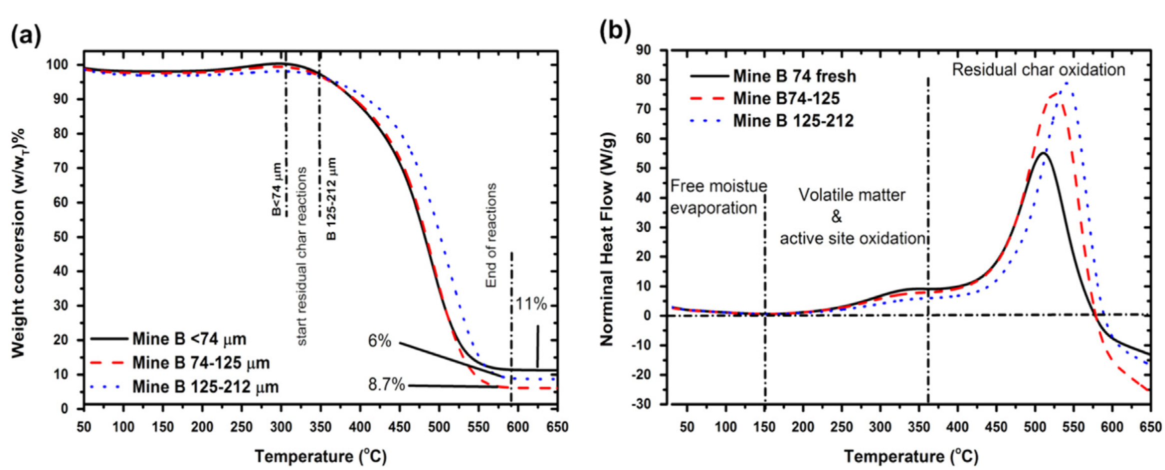

Fig. 13. TGA analyses for coal samples from Mine B with three particles sizes (a) weight conversion, (b) nominal heat flow.

Table 5
Comparison between MAITs according to the ASTM and IEC standards.

Particle size (μm)	Humidification duration (h)							
	0		2		4		24	
	ASTM	IEC	ASTM	IEC	ASTM	IEC	ASTM	IEC
< 74	235	235	235	235	235	235	235	235
74–125	250	250	245	245	245	245	245	245
125–212	270	265	270	270	270	270	270	270

4. Conclusion

- The MAITs for coal dust layers significantly increases with increasing particle sizes. The MAITs changed for particle sizes both above and below 74 μm. For particle sizes in the range of 74 μm to 212 μm, the MAITs varied between 15 °C to 35 °C. The effect of the particle sizes on the time needed to ignite also varied from 1500 s, for the finest particles, to 2400 s for particles below 212 μm.
- The effect of the particle sizes on the severity of the ignition indicates that for coal beds consisting of particle sizes of < 74 μm, the ΔT_{MAX} reached was around 436 °C, while the maximum temperature that was recorded in all the experiments for large sized particles was 377 °C. Moreover, the ΔT_{MAX} for humid coal was much higher than for the fresh samples. For example, the higher ΔT_{MAX} for a humid sample is 201 °C versus only 163 °C for a fresh sample for the finest particles size.
- Exposing the coal bed to relative humidity (at 10 °C for 2, 4, 24 h and a week) had no significant effect on the coal's MAIT. For coal particle sizes < 125 μm, the MAIT varied arbitrarily by 5 °C.
- The humidification of the coal bed increases the possibility of the appearance of the phenomenon of double ignition in the time-temperature profile. The time between ignitions for an exothermic peak also vary with the humidification's duration as a result of an increase in the moisture in the coal dust bed. For hot environments, the phenomenon of multiple ignitions disappeared for inherently humid samples (Mine D) after removing the moisture from the particles.
- The mean diameter particle size (D50) has a large impact on the MAIT in comparison to both the volatile matter and the fixed carbon compositions. The results showed that the effects of the volatile matter and fixed carbon on the MAITs are greater for smaller sized (D50) coal dust particles.
- Regardless of the distinct differences between the definitions of ignition between the ASTM and IEC standards, in terms of their interpretations of the MAIT, it was found that all the coal samples which satisfied the IEC ignition temperature (ΔT=20 °C) were also able to be ignited as defined by the ASTM standard (ΔT=50 °C).
- Applying a packing force on the coal dust layer (up to 1225 N/m^2) increased the MAIT by 10 °C, in spite of the fact that this force does not have a significant impact on the single particle size.
- The TGA analysis showed that there is no significant impact of moisture (in the range of 4%) on the weight loss conversion % pattern of coal dust ignition, and only slightly increased the heat released from fresh samples than from dry ones. Additionally, the impacts of the particle size are obvious, in terms of the weight loss conversion and the nominal heat released, where the finest particles released higher energies than the coarse particles in the volatile matter and active site ignition stages. Notwithstanding this, the coarse particles (74–125 μm and 125–212 μm) released higher energies than the smaller particle bed size < 74 μm.

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