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Coal Dust Severity in a Power Plant: In-Situ, Analytical, and Numerical Assessments

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ABSTRACT

One of the most serious occupational hazards in the coal industry is coal dust. Previous research revealed that the vast majority of coal dust assessments were conducted in coal mines, resulting in a lack of understanding of the severity of coal dust during coal handling activities in power plants. Therefore, the severity of combustible coal dust in one of Malaysia's power plants was assessed using a comprehensive analysis that included qualitative observations, in-situ measurements, numerical simulations, laboratory tests, and data analysis. The designated locations include the coal conveyor hall (Zone 1, 2A, and 2B), milling (Zone 3), and bunkering areas (Zone 4). Relevant safety limits, as recommended in National Fire Protection Association (NFPA) 654, were used as guidelines where comparisons with the site data were made. The high coal dust accumulation rate in Zone 1 was revealed to be largely the result of inefficient ventilation performance, as confirmed by in-situ measurement and numerical simulation. Direct referencing to the relevant NFPA 654 guidelines finds the zones encompassing the coal conveyor hall are at "high risk" of fire and explosion. Further laboratory assessments on the dust samples in Zone 1 however reduces the earlier assessment to "medium risk" with the potential of "low risk" with regular housekeeping. Zones 3 and 4 were found to be "low risk" areas due to insignificant accumulation and good air flow management. Overall, the evaluation of the severity of combustible coal dust was successful in establishing the risk mapping for all zones. Cleaning frequencies were also proposed based on the coal dust accumulation rates and the risk mapping.

1. Introduction

Coal is a flammable sedimentary rock that is also a versatile fossil fuel, consisting of a complex and heterogeneous mixture of mostly organic matter [1-3]. Because of its combustibility, coal is one of the most important energy sources, and it plays an important role in the global economy [4-6]. The use of coal as a fuel source, on the other hand, has a significant impact on both air quality and climate change [7,8]. As a result, while the coal industry is necessary for societal growth, it can also cause significant damage to the public environment and endanger the physical health of the workers [4,7]. Coal dust is one of the most serious occupational hazards in the coal industry [4] not only

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because it is harmful to one's health, but also because it can act as a medium for the transportation and distribution of pollutants in the surface environment [9]. Another negative effect of coal dust is poor air circulation, which reduces air quality and visibility [10]. The suspended coal dust poses a significant risk of explosion [11]. Every year, unintentional coal dust explosions cause massive property damage and casualties all over the world [11]. The coal dust cloud, also known as suspended coal dust, is a homogeneous and well-mixed fuel-air mixture that can be ignited if sufficient ignition energy is applied [11]. The initial burning of coal dust in confined spaces, such as a power plant's coal conveyor hall, may result in an explosion, resulting in a chain reaction [11]. As a result, the challenges of ensuring safety in coal handling operations are exacerbated when these activities are performed in the presence of explosive coal dust [12].

Aside from suspended dust, settled coal dust occurs at various stages of the coal handling process, such as coal preparation, milling, transportation, and storage [13]. When settled dust comes into contact with oxidisers and an ignition source, it can cause thermal runaway, which can spark smouldering flames, generate hot nests, and, in some cases, ignite coal dust explosions [13]. Thermal runaway is a phenomenon caused by supercritical self-heating and spontaneous igniting of solid fuel dust when enough energy is supplied to the dust, triggering exothermic reactions and causing a significant temperature increase [13,14].

Previous research revealed that the vast majority of coal dust assessments were carried out in coal mines. Tong *et al.,* [4] used a probabilistic risk assessment approach and Monte Carlo simulation to assess the levels of exposure and health risks of coal dust in a coal mine in Shanxi Province, China. The assessment discovered that the duration of coal dust exposure has the greatest impact on health risk [4]. Ishtiaq *et al.,* [11] investigated the presence of probable hazardous elements (PHEs) in coal dust and the risk to human health near mining sites in Cherat, Pakistan. PHE concentrations were discovered to be close to the threshold levels. Coronado-Posada *et al.,* [1] discovered that mining dust has phytotoxic effects on plant growth, indicating that coal dust should not be considered an inert material. Smirniakov *et al.,* [13] conducted an in-depth analysis of coal dust explosion factors in Russian coal mines.

All of these findings point to a lack of understanding about the severity of coal dust during coal handling activities in power plants. As a result, an in-depth assessment of the risk of flammable coal dust in power plant coal handling facilities is urgently required. Because the handling and transport of coal has a high potential for releasing significant amounts of coal dust, these facilities are frequently associated with the discharge of massive amounts of coal dust particles. Only a comprehensive analysis involving in-situ measurements, analytical laboratory tests, and numerical simulations can determine the severity of combustible coal dust. The study's findings will provide critical insight into the risk level of combustible coal dust in power plant coal handling facilities, and plant operators may find them useful in implementing dust control measures. The current coal dust evaluation results are directly linked to the applicable recommendations in the National Fire Protection Association (NFPA) 654 to evaluate its coal dust scenarios.

2. Methodology

The coal dust assessment was conducted at one of Malaysia's power plants. The coal dust assessment methodology consists of seven major activities. These include qualitative observations, documentation reviews from actual power plant data, the establishment of the zone of interest, coal dust sample collection, in-situ measurements and numerical analysis, analytical fuel tests, and data analysis. The following sections go through each of these main activities in depth.

2.1 Qualitative Observations

In the early stages of the assessment, qualitative observations were conducted at the zones of interest to gain an initial understanding of the severity of the coal dust dispersion. The zones of interest include the coal handling facilities within the coal conveyor hall, pulverises (mills), and coal bunkering zones. Specific zones, particularly near electrical equipment, were marked for detailed in-situ measurements to be performed later. Existing coal dust accumulation was removed in order to measure coal dust thickness and rate of accumulation. Any hot works that could potentially pose a fire or explosion risk were identified and taken into account when determining the zone's risk rating.

2.2 Documentation Review

Several key documents were obtained from power plant personnel in order to gain a better understanding of the overall activities in the zone of interest. Important documents include housekeeping procedures and engineering drawings. In-situ observations, log-book examination, and interviews with relevant power plant personnel were carried out to evaluate housekeeping related to dust accumulation within the area of concern.

2.3 Division of the Zone of Interest

To effectively carry out the assessment activities, zones of interest for coal dust assessment were defined, as seen in Figure 1. Zones 1, 2A, 2B, 3, and 4 are the five zones where assessment activities were carried out, as shown in Figure 1. Zones 1, 2A, and 2B are the three zones related to the conveyor hall. Zones 3 and 4 surround the coal mill and coal bunker, respectively.

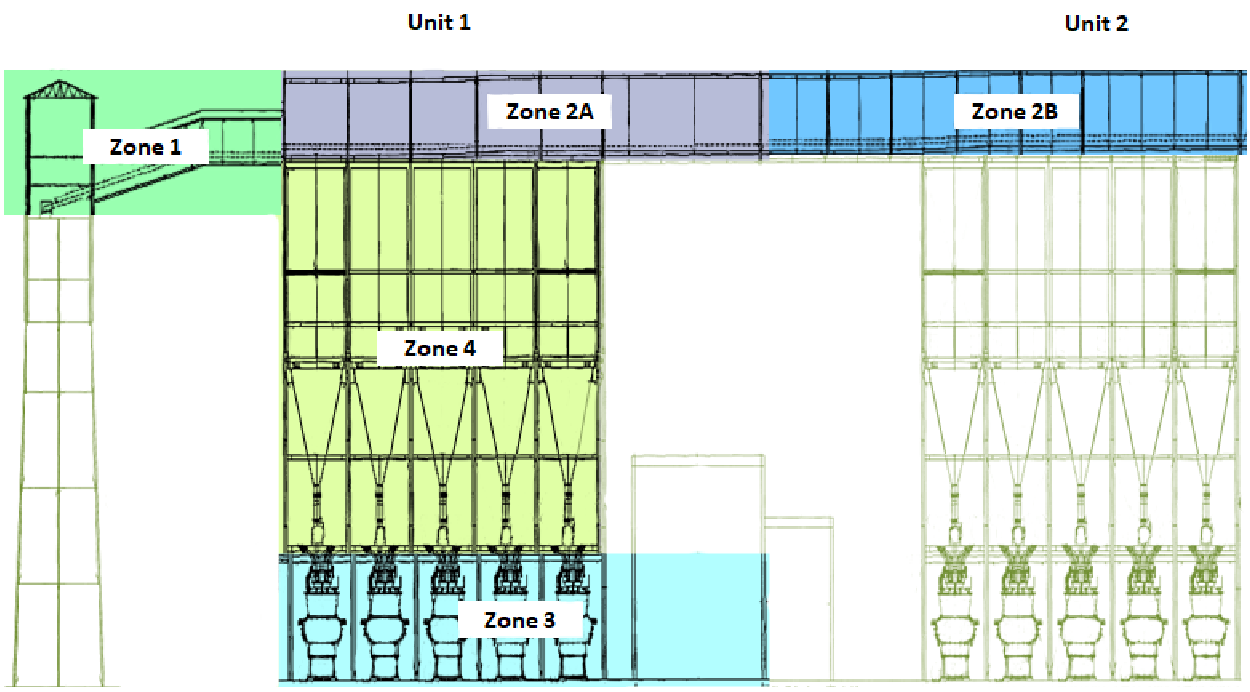


Fig. 1. Zones of interest for the coal dust assessment

2.4 Coal Dust Sample Collection

One of the most important activities during the assessment was collecting coal dust samples from each of the zones shown in Figure 1. Dust collection equipment with filtering capabilities was strategically placed near the areas of interest. There were two filtering methods used: one for suspended coal dust, which used the Minivolume Sampler (negative pressure), and the other for settled dust, which is driven by gravity. The equipment was placed in the areas of interest for 24 hours to collect coal dust. The coal dust samples collected from various zones were then weighed on a laboratory weighing scale to determine the accumulation rates of coal dust. The measured rates were then used to determine the severity of the coal dust suspension and accumulation, with a recommended cleaning frequency being considered as an actionable measure.

2.5 In-situ Measurements and Numerical Simulations

A series of in-situ measurements were performed in order to obtain specific data for the comparative assessment with the NFPA 654 threshold risk level. During the assessment period, in-situ measurements included the depth of coal dust layers, the percentage of coal dust coverage to footprint area, air velocities at exhaust fans and openings, and temperature measurements.

To evaluate the conveyor hall's ventilation management, a computational fluid dynamics (CFD) simulation was run with the measured air velocities and temperatures at the access doors and exhaust fans as boundary conditions. Using as-built dimensions obtained from the power plant, the three-dimensional (3D) geometry of a coal conveyor hall was created. In order to save computational time and cost, the conveyor hall geometry was simplified to capture important features while leaving out non-critical components. Figure 2 depicts a representative image of the conveyor hall's boundary names. The boundary designations K1 to K7 and Door 1 to Door 4 represent the exhaust fans and access doors, respectively.

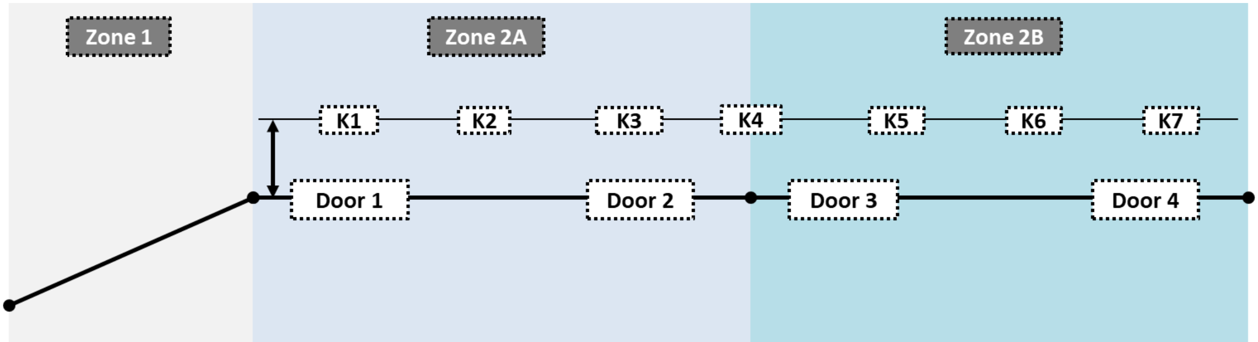


Fig. 2. The representative image of the modelled coal conveyor hall, displaying all boundary condition locations

Table 1 displays the corresponding boundary conditions derived from on-site measurements. It is important to note that the exhaust fan K5 was damaged during the measurement period, resulting in significantly lower air velocity than the others.

Table 1
Velocity and temperature for each boundary

Boundary names	Door 1	Door 2	Door 3	Door 4	K1	K2	K3	K4	K5	K6	K7
Velocity (m/s)	1.63	1.87	2.26	2.72	1.68	1.51	9.88	11.17	1.09	10.75	13.04
Temperature (°C)	32.2	32.6	33.0	32.3	30.0	30.0	30.0	30.0	30.0	30.0	30.0

The CFD simulation was carried out using a commercial CFD software package, ANSYS Fluent V.19 R1. The ANSYS Fluent solver is frequently used for ventilation simulations, and these simulation techniques have been thoroughly validated [15]. As a result, this is a viable approach for simulating air dispersion phenomena. The pressure-based solver is used to solve the governing equations. The coupled technique was used to solve the pressure-velocity coupling. The coupled technique solves both mass conservation and momentum conservation simultaneously, allowing these equations to be interdependent. Because the pressure-based technique is used in this study, the first law of thermodynamics for energy conservation will be addressed sequentially.

The SST k - ω model derives the steady Reynolds-averaged Navier-Stokes (RANS) equations by separating the instantaneous flow variables into fluctuating and steady components and applying Reynolds averaging techniques to the Navier-Stokes (NS) equations. Following the Reynolds averaging method, new terms known as Reynolds stresses appear to reflect the effects of turbulence. To close the RANS equations, the Boussinesq hypothesis is used to relate the Reynolds stresses to the mean velocity gradients. The term turbulence viscosity derives from this relationship. The SST k - ω model is used to resolve turbulent viscosity. As a result, turbulent viscosity is computed as a function of turbulence kinetic energy, k, and specific dissipation rate, in the SST k - ω model. Menter *et al.,* [16,17] provide detailed information on the formulations and constants used in the SST k - ω model. The use of RANS simulations has been shown to produce results that are comparable to air dispersion experimental data, as seen in Kumar *et al.,* [15] and Rahman *et al.,* [18].

To obtain good spatial convergence accuracy, the grid independent test was used. Meshes (elements) were created with orthogonal quality and skewness in mind to represent mesh quality because mesh quality influences the level of spatial discretisation error [19]. To ensure adequate mesh qualities, the orthogonal and skewness features of all generated meshes evaluated in the grid independent test were controlled. When the mesh number at the conveyor hall model is increased from 3.18 million to 4.75 million, the velocity profiles almost no longer vary by less than 1%. As a result, 3.18 million meshes make up the burner model.

2.6 Analytical Laboratory Testing

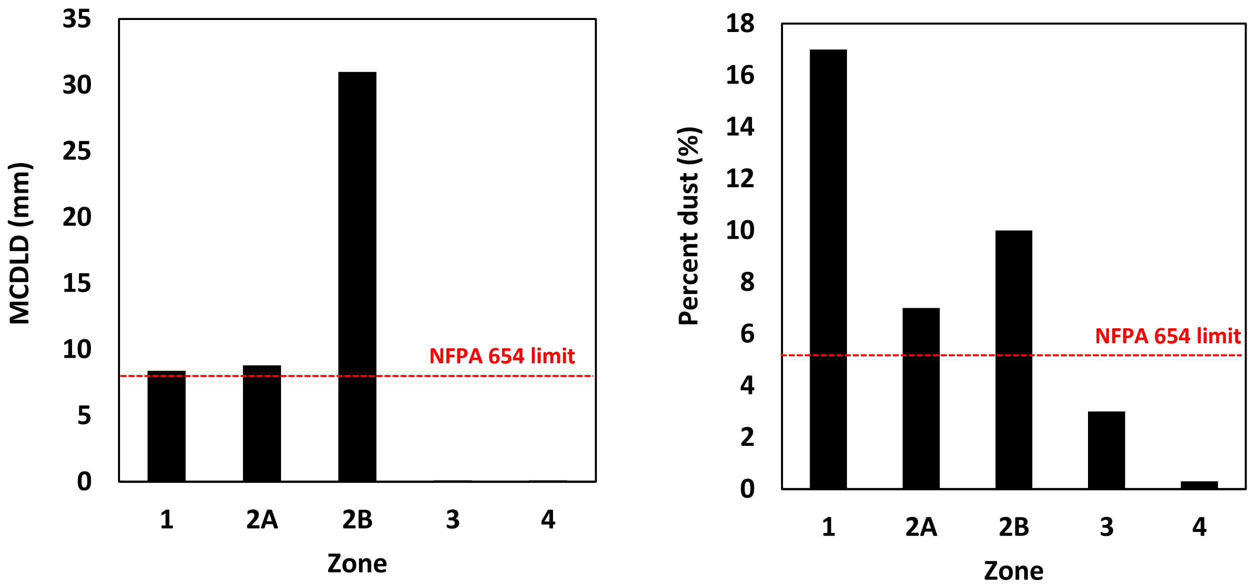
Several parameters, including coal bulk density, particle size distribution (PSD), and minimum ignition temperature (MIT), were determined before the combustibility and level of coal dust hazards could be established for a specific zone of interest. Laboratory tests were performed on coal dust samples collected to determine the aforementioned parameters.

3. Results
3.1 Maximum Coal Dust Layer Depth (MCDLD)

The MCDLD from each zone was measured and the results were compared to the NFPA 654 limit, as shown in Figure 3(a). The MCDLD procedure and calculation can be found in NFPA 654 [20]. The MCDLD from the zones representing the coal conveyor hall is higher than the MCDLD from the remaining zones, exceeding the NFPA 654 limit. The accumulation of settled dust in the coal conveyor hall is caused by the transportation of coal on a conveyor that takes place within the hall's enclosed space. Zones 3 and 4 are open space zones with high air movement that allow for better ventilation performance. The MCDLD in Zone 2B has the highest value among the zones due to a massive outburst of coal dust near the end of the conveyor belt.

3.2 Percentage of Coal Dust Coverage to Footprint Area (Percent Dust)

The percent dust in each zone was measured and compared to the NFPA 654 limit. Figure 3(b) shows that the percent dust from the zones surrounding the coal conveyor hall is higher than the rest of the zones, exceeding the NFPA 654 limit. As a result, the findings back up the MCDLD's previous findings. Zone 2B has a higher MCDLD than Zone 1, but Zone 1 has a higher dust percentage. Zones 1 and 2B mark the beginning and end of the conveyor belt, respectively. The massive outpouring of coal dust at the beginning and end of the conveyor belt has been the primary cause of the increased coal dust discharged from these two zones.



(a) MCDLD (b) Percent dust

Fig. 3. MCDLD and percent dust from each zone

3.3 Numerical and In-Situ Assessments of Settled and Suspended Coal Dust

Using the coal dust samples collected, the accumulation rates of coal dust for the zone encompassing the coal conveyor hall were calculated. The CFD simulation results of the ventilation condition in the coal conveyor hall, as shown in Figure 4, were then used to validate the measured dust accumulation rates. The code designations B1 to B6, C1 to C10, and D1 to D10 indicated areas in Zones 1, 2A, and 2B where settled coal dust accumulation rates were monitored, respectively. In contrast, the code designations B7501 to B7504, 2A7501 to 2A7504, and 2B7501 to 2B7504 reflected the locations where the suspended coal dust accumulation rates were measured in Zones 1, 2A, and 2B. All of these locations are close to electrical equipment that has been identified as a potential ignition source.

According to in-situ measurements, Zone 1 has the highest coal dust accumulation rate (both settled and suspended dust). The results of the in-situ measurement can be validated by CFD simulation in the coal conveyor hall, where a reduced air flow velocity in Zone 1 has been demonstrated. Hence, the high coal dust build-up rate in Zone 1 is primarily due to poor ventilation performance.

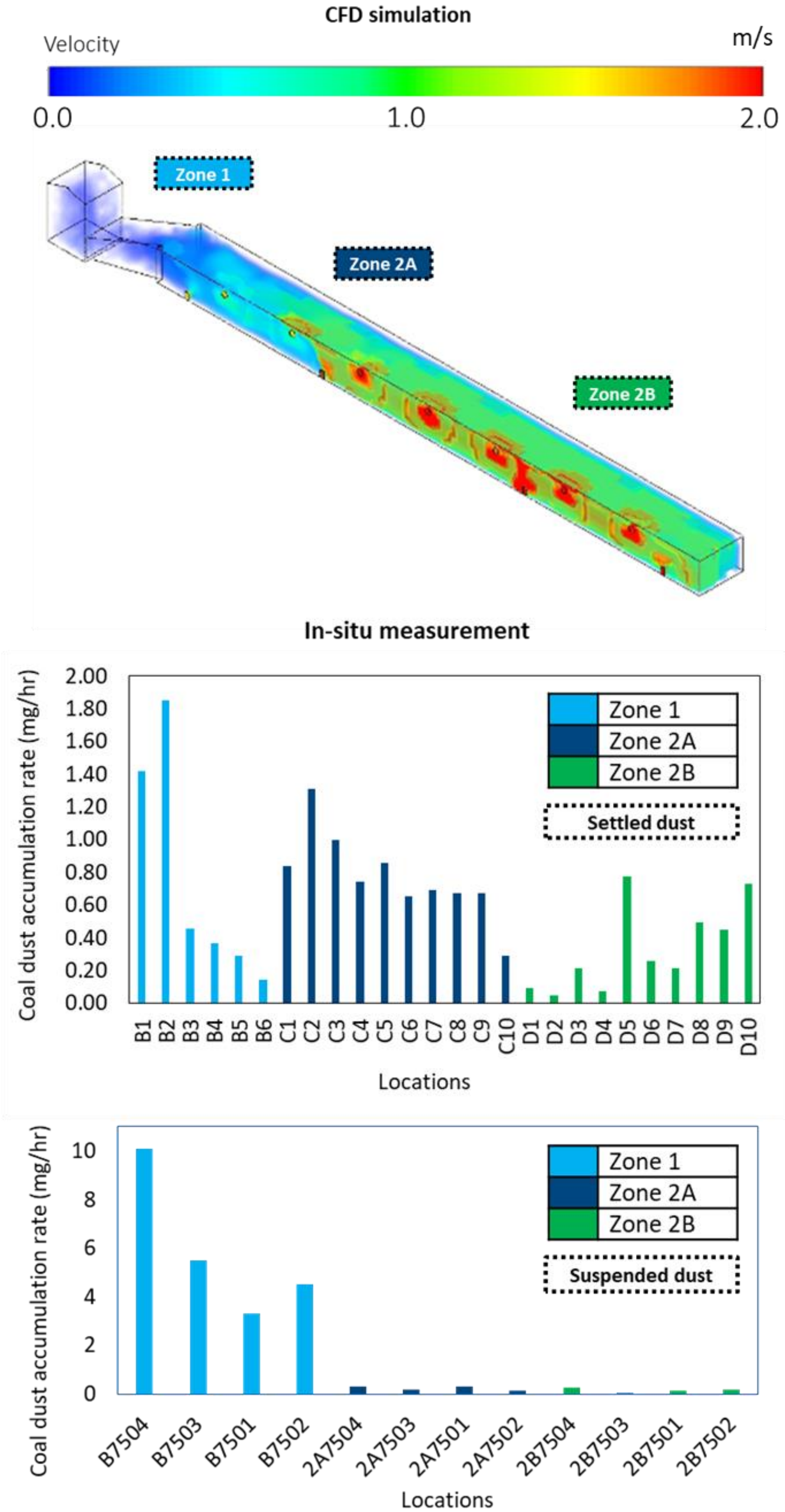


Fig. 4. Comparison of air flow CFD simulation and in-situ measurements of coal dust accumulation rates

3.4 Coal Bulk Density, Particle Size Distribution (PSD) and Minimum Ignition Temperature (MIT)

The measurement of coal bulk density is an important indicator for assessing the risks of facilities to coal dust [20]. Because measuring the bulk density of coal dust requires a large sample amount, sampling was done at Zone 1, which had previously been found to have the highest accumulation of all the zones studied. The bulk density of coal was determined to be 553.5 kg/m^3. The coal bulk density was calculated in accordance with ISO 23499 [21]. The value represents fine coal dust and is used to calculate risk assessment markers for combustible coal dust severity. Aside from risk assessments, the bulk density value can be used as an indicator for cleaning frequency [20], which will be discussed in detail in the Recommendation section.

Particulates smaller than 10 µm in size are considered inhalable in terms of coal particle size [22]. This particle matter is commonly known as PM10. The coal dust particulates may be considered safe in terms of health, safety, and the environment (HSE) requirements because the median size of coal dust particle from the PSD test (coal dust samples in Zone 1) was 27 µm. The PSD testing procedure is based on the work of Xu *et al.,* [23]. Personal Protective Equipment (PPE) is still required to perform tasks in all zones, particularly the coal conveyor hall.

The MIT is another important indicator for determining the risk of flammable coal dust [20]. Figure 5 depicts the assessment results using the same coal dust samples collected from Zone 1. The MIT testing procedure follows the ASTM E1491 - 06 Standard Test Method for Minimum Autoignition Temperature of Dust Clouds [24].

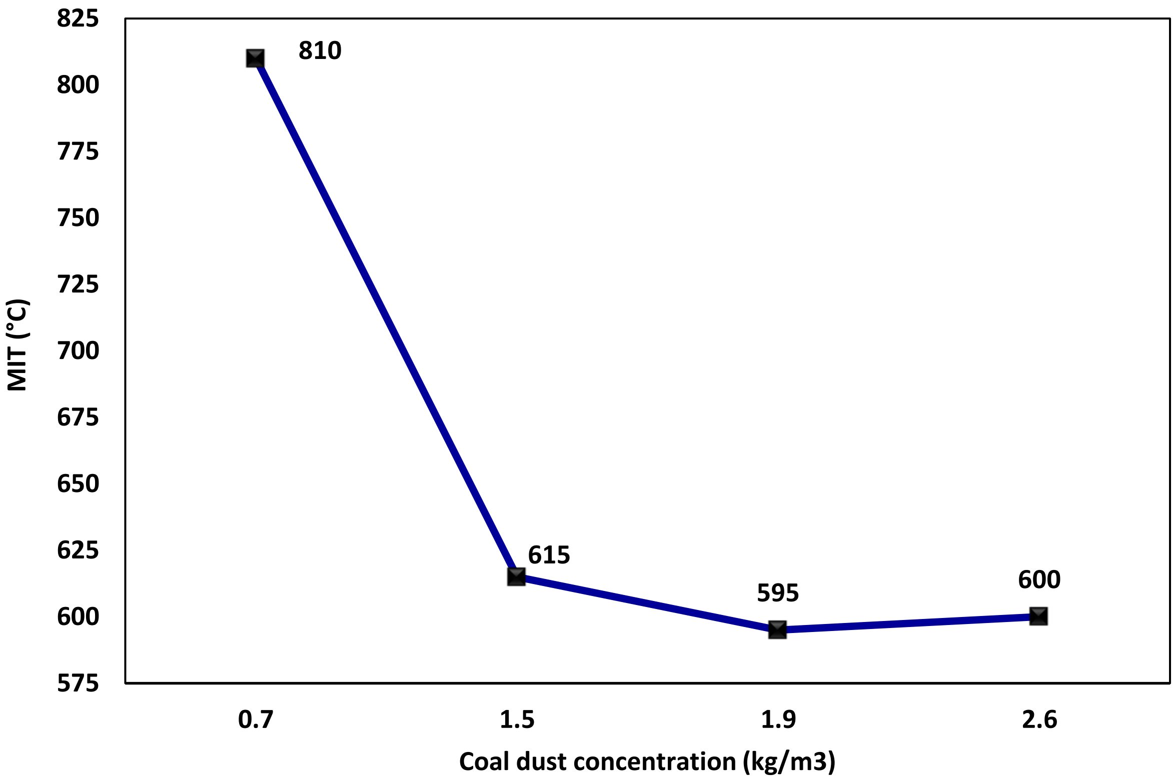


Fig. 5. MIT of coal dust samples in Zone 1

The lowest MIT found was 595°C for a coal dust concentration of 1.9 kg/m^3. The risk of ignition is approximately 300 times lower for the previously determined coal dust bulk density of 553.5 kg/m^3, as indicated by the MIT dust concentration. Another sign of low risk is the maximum environment temperature measured during the assessment period, which was 40°C, which is significantly lower than the temperature required for ignition, which is 540°C. However, the MIT guidelines do not rule out the possibility of an external spark in the vicinity, which would increase the likelihood of spontaneous combustion.

3.5 Coal Dust Risk Mapping

Figure 6 depicts the coal dust risk mapping for the zones studied. The colours red, yellow, and green represent the risk scales, with red and green representing the highest and lowest levels, respectively.

The red colour, in particular, also denotes a scenario or value that exceeds the NFPA 654 limit/risk. As previously indicated, the MCDLD and percent dust for the zones surrounding the conveyor hall exceed the NFPA 654 limit. The almost enclosed conveyor hall has a poorer ventilation performance than the other zones, with Zone 1 having the lowest ventilation performance. Zone 1 is the only zone where the coal bulk is sufficient to proceed with the bulk density measurement. Therefore, it indicates that this zone contains a significant amount of coal dust. Because of the severity of the coal dust discovered from the in-situ measurement, the MIT and PSD were only measured for the coal dust sample in Zone 1. However, as previously noted, the danger of auto-ignition is considerably low based on the results of MIT. Furthermore, the median size of coal dust particle from the PSD demonstrates an appropriate value in terms of HSE concern, implying a lower health risk.

Referring to Figure 6, qualitative observations were made by observing the coal dust cloud, which is a dust flash-fire danger. A dust flash-fire danger is linked with any location where combustible dust accumulates on exposed or concealed surfaces, external to equipment or containers, or any area where a hazardous concentration of dust exists [20]. Significant coal dust clouds were noticed during housekeeping activities in Zone 1. Significant quantities of coal dust accumulation were also discovered during the assessment, covering a number of electrical compartments across all zones. Nonetheless, all electrical components are concealed, and the interior components are not in direct contact with the coal dust. All of these components, however, require frequent checks to ensure that the equipment's safety is not jeopardized.

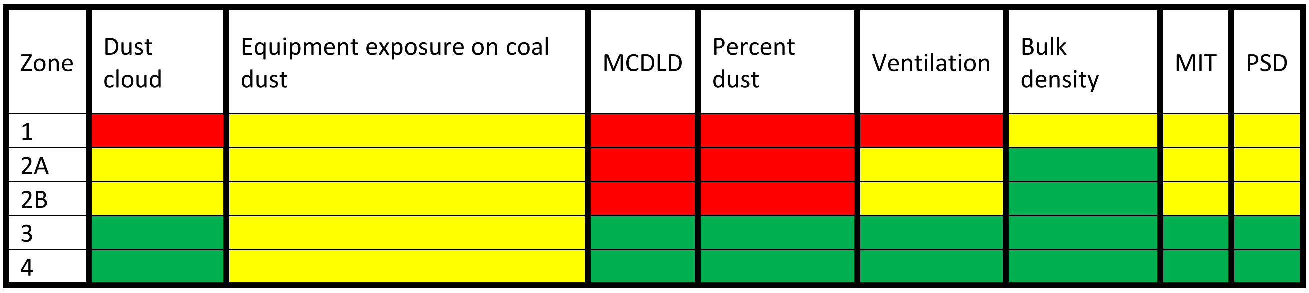


Fig. 6. Risk mapping of all zones

3.6 Recommendation: Cleaning Frequency

Unscheduled housekeeping should be executed to limit the time that a local coal dust spill or short-term accumulation of dust is allowed to remain before the local area is cleaned to less than the threshold coal dust accumulation [20]. The criteria of maintaining the MCDLD below 0.8 mm was based on a reference bulk density of 1200 kg/m^3. Taking note of the lower coal bulk density found in the current study, some flexibility may exist for the cleaning frequency as proposed in the NFPA 654, as shown in Table 2.

Table 2
Proposed cleaning frequencies

MCDLD (bulk density 1200 kg/m^3)	MCDLD (bulk density 481 kg/m^3)	Longest Time to Complete Unscheduled Local Cleaning of Floor-Accessible Surfaces	Longest Time to Complete Unscheduled Local Cleaning of Remote Surfaces
>3.3 mm	>8.3 mm	1 hour	3 hours

Table 2 should be taken as a guide to cleaning frequency. Nonetheless, if power plant operators intend to operate the coal conveyor hall with less than the MCDLD defined in Table 2, the cleaning frequency shall be established to ensure that the MCDLD level does not exceed the threshold MCDLD in Table 2. Hence, the measured coal dust accumulation rates can be utilised to provide an early estimation of the cleaning frequency required to keep the coal dust depth below 8.3 mm.

Table 3 shows the recommended cleaning frequency for Zones 1, 2A, and 2B based on the average and maximum coal dust accumulation rates.

Table 3
Proposed cleaning frequencies based on the coal dust accumulation rates

Zone	Cleaning frequency	
	Average dust accumulation rates	Maximum dust accumulation rates
1	≈ Every 5 hours	≈ Every 3 hours
2A	≈ Every 40 hours	≈ Every 24 hours
2B	≈ Every 93 hours	≈ Every 40 hours

Zone 1 requires more frequent cleaning than the other Zones because of the extreme coal dust scenario. The proposed cleaning frequency is inapplicable for Zones 3 and 4 since the measured coal dust depths are less than the NFPA 654 threshold level.

4. Conclusions

An assessment of the severity of combustible coal dust in one of Malaysia's power plants was completed successfully. The specified locations are the coal conveyor hall (Zones 1, 2A, 2B), milling (Zone 3), and bunkering areas (Zone 4). The assessment methodology consisted of qualitative observations, in-situ measurements, numerical analyses (CFD), analytical laboratory tests, and data analysis. Relevant safety limits, as recommended in NFPA 654, were used as guidelines where comparisons with the site data were made.

The high coal dust accumulation rate in Zone 1 was discovered to be largely the result of inadequate ventilation performance, as confirmed by in-situ measurements and CFD simulations in the coal conveyor hall. As Zones 3 and 4 are open space zones, higher air movement in the open area resulted in improved ventilation performance, reducing the overall coal dust accumulation. Direct referencing to the relevant NFPA 654 guidelines finds the zones encompassing the coal conveyor hall are at “high risk” of fire and explosion. Further tests and laboratory assessments on PSD and MIT however reduces the earlier assessment to “medium risk” with the potential of “low risk” with regular housekeeping.

Overall, the evaluation of the severity of combustible coal dust was successful in establishing risk/severity mapping for all zones within the power plant coal handling facilities. Cleaning frequencies were also proposed based on the coal dust accumulation rates and the risk mapping.

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