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Study of Industrial Accident Based on In-Depth Investigation

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Abstract

Industrial accidents caused by static electricity were common for years. Beyond grounding and other static mitigation devices, plants often control environmental humidity and optimize production processes to reduce static hazards. This study aims to determine the causes and mechanism of an industrial accident and well-known unusual event related to static electricity, volatile organic compounds (VOC), and minimum ignition energy (MIE). Through instrument measurements and analysis methodology such as Hartmann tube, static electricity meter and fault tree, the cross factors are analyzed to complete the study systematically. Results reveal that anti-rust paint on the inner surfaces of machinery created insulating conditions, allowing static electricity to accumulate and discharge during material feeding. The induced static electricity subsequently releases a high discharge energy exceeding the MIE of the particle. When combined with VOC generation from an unexpected process interruption, it can lead to fire or explosion.

Keywords: industrial, minimum ignition energy, volatile organic compounds, static electricity

1. Introduction

A large amount of static electricity is frequently produced, accompanied by manufacturing and operational methods in industrial production, and it exists on the non-metal surface. The fire or explosion under special hazard conditions will be easily induced, consequently. Actually, the real event will happen in various situations, including production, transportation, and packaging processes. In certain special circumstances, even a machine malfunction for a few seconds or a large amount of static electricity, a fire, or a small-scale explosion may be induced. However, there is no similar problem of machine and product under the same operational mode in the past decades. It reveals that the cause of this event should be an outlier under the whole process at a subsequent time. This unusual programmer must exist because of some unexpected events.

Consequently, a detailed investigation of incident scenes is necessary to elucidate the interactions among contributing factors, which serves as the primary motivation of this study. The research background of this study is an accident that occurred in a factory producing plastic and synthetic rubber raw materials. Under normal operation, the products were packaged promptly after material intake. However, due to equipment failure, the material intended for packaging was temporarily stored in a sealed container while troubleshooting was performed. Unexpectedly, the fire accident occurred in a few ten seconds because of static electricity discharge in the container. The top venting filter bag was ignited by the flashing fire, and the burned condition is shown in Fig. 1.

Although the factory implemented strict measures for static electricity control, such as grounding, humidity control, etc. According to the recommendations of NFPA 77, all metal components of portable tanks, intermediate bulk containers, and

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non-bulk containers should be grounded to minimize static electricity. The risk of fire caused by static electricity discharge increases with the volume of the container and the volatility of the used dust. Therefore, during filling operations into a non-conductive container, the fill level should be kept as low as possible, and any metal components of the container, as well as the metal funnel (if used), should also be grounded to prevent charge build-up [1-2]. In this study, different working conditions will be verified, including the type of powder, diameter, and feed rate. Furthermore, the sizes, shape, and the projection area will affect the electrostatic discharge of the particle [3].

This study focuses on static electricity phenomena observed in dust filled with highly insulating powder. In particular, the brush discharge occurs along the settling powder and the container wall, which can also be explained by the gravity compression of charged powder particles [4]. The discharge due to gravity compression will happen expectantly when the specific charge is lower than 3×10^{-6} C/kg and within a certain range. This range decreases as container diameter decreases and powder conductivity increases [5-6]. Moreover, if the flammable dust undergoes polymerization due to cohesion and sticks to the container wall during movement, static charges may generate flammable electrostatic discharge [7-11]. In practice, the ignition of flammable dust is often attributed to static discharge when small particle powders are concentrated within the explosive range. When an explosive dust cloud is simultaneously present, such discharge can cause explosion and fire [9, 12-17].

To address industrial accidents caused by static electricity, this study first adopts tree analysis to systematically identify and separate possible error sources. Subsequently, the explosion range of dust flammability concentration, MIE measurements, and static charge accumulation mechanism are examined to investigate the relationship with discharge phenomena. This approach will help analyze the key factors contributing to the accidents. The primary objective of this paper is to develop practical methods to determine the causes of such incidents and to propose effective strategies to eliminate static charges. Although previous research focused on the ¡ncident investigation, much of it lacked experimental verification. The application of practical verification experiment and relative analysis is the main contribution and value. Finding a feasible solution to industrial accidents is the primary motivation of this paper.

The first section of the paper introduces the background and outline of the experimental objectives. In the second section, details of the relative experimental setup are provided, illustrating the methodology adopted. The measurement techniques employed and a detailed discussion of findings will be focused on in the third section. Finally, the paper concludes by summarizing the outcomes and offering insights into potential implications or future directions for research in this area. That is the whole structure of this paper. The block diagram of research progress will be indicated in Fig. 2.

Fig. 1 The Schematic of the filter bag after burning

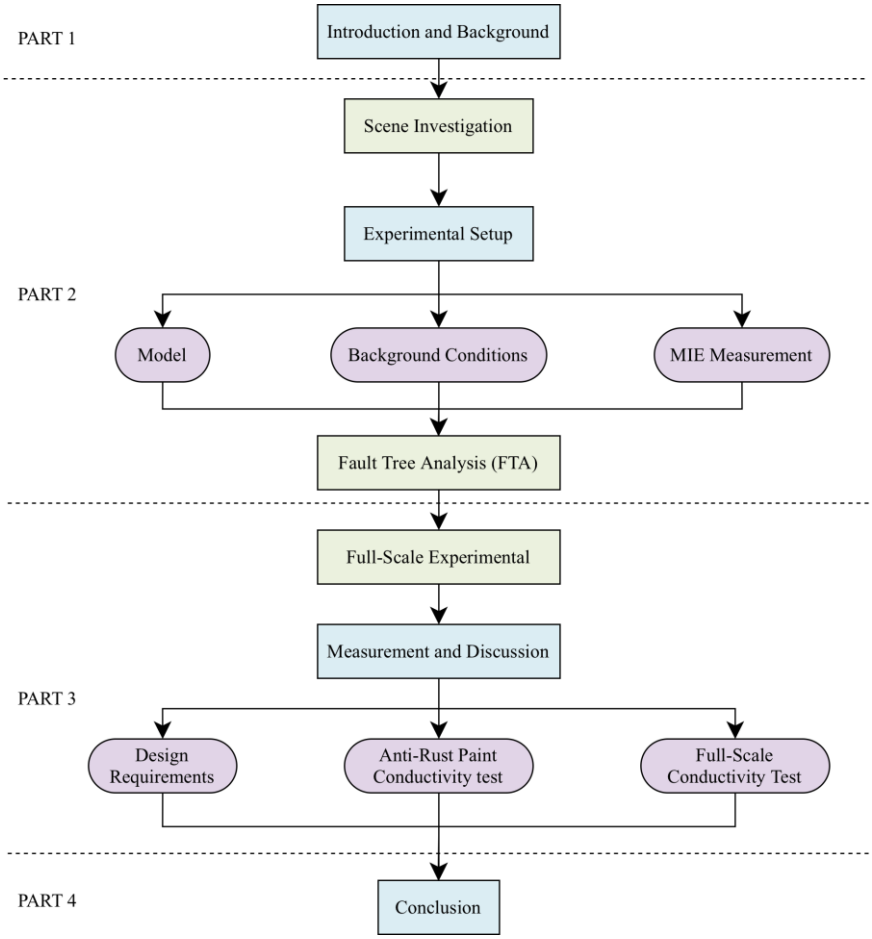


Fig. 2 The block diagram of the research process

2. Experimental Setup

In this research, a fire investigation is conducted via incident scene reconstruction to determine the causes of this incident. Due to the complex nature of fire dynamics involving multiple factors and conditions interacting with each other, the failure of any single factor can potentially lead to the event. This constitutes the mechanism of occurrence specific to the event, which will be initially analyzed through detailed fault tree analysis conducted during on-site incident investigation. After conducting this preliminary analysis, the full-scale simulation experiment will be carried out to approach the actual situation. In the experiment, the fuel, fire source, and other key factors will be mainly focused on. Consequently, the calculation of static electricity and flammable dust concentration will be used for factor analysis. And then the methodology can be established, and the final experimental results can be obtained.

2.1. Scene investigation

According to the observation in Fig. 3, the product particle will accrete on the inner surface of the container due to static electricity generated from friction against the walls during feeding and discharge. Following the material entry on-site, the maintenance access was opened to measure the static electricity accumulation on the wall via an electrostatic meter. The surface static electricity value was up to -15.6 kV, indicating the amount of internal static electricity was significant. In this study, the grounding methods for the container will also be evaluated to evaluate their feasibility and effectiveness. That is the most important argument to know the fire ignition mechanism in such an accident.

As shown in Fig. 4, the grounding method employed on-site involved cross-connect grounding, where one end of the grounding wire was connected to a metal screw on the container body. This method utilizes a metal panel to release internal static electricity. Typically, the particle will be filled up to 70 % height of the container and then excreted for packaging. The

particle products and level control inside the container are shown in Fig. 5. The height of particles will be monitored by the liquid level control recorder inside the container and the video camera setting outside. On the day of the incident, the product particles were maintained inside the container because of a power failure. The series connection of accumulated VOC and static electricity will become an important factor in causing accidents. Based on previous experiences, the accident will happen when all unexpected errors occur in series at the same time, even if the sub-devices are all under normal circumstances. To investigate the possible concatenation of factors of an accident is the primary motivation in this study.

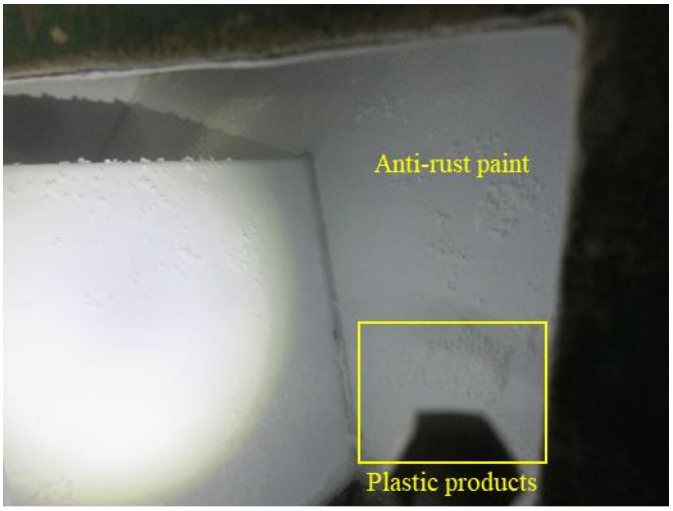
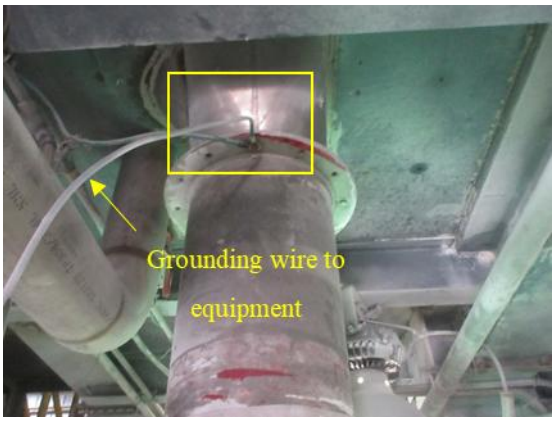
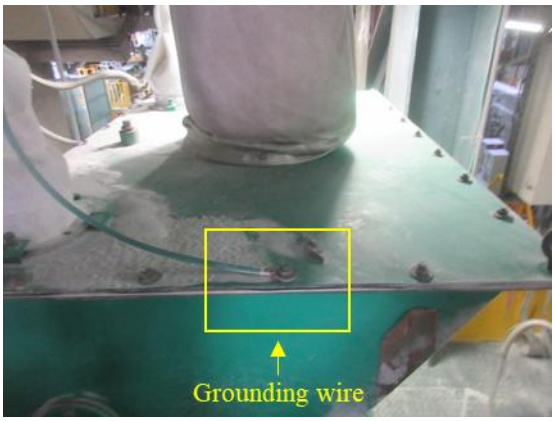


Fig. 3 Product particles attached to the inner wall of the container



(a) Grounding of the inlet pipe



(b) Grounding of the top of the equipment

Fig. 4 Grounding position of pipe and equipment

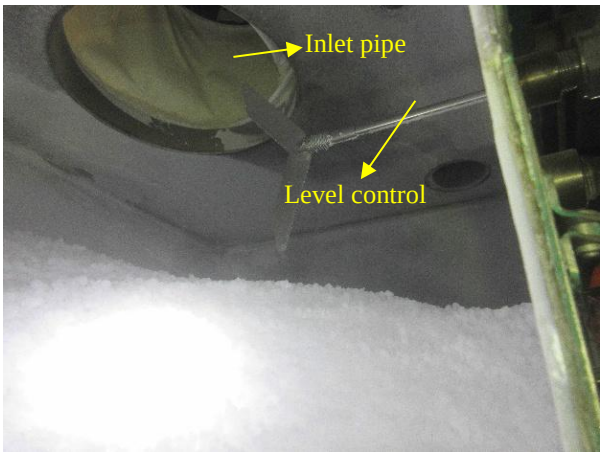


Fig. 5 The plastic products and level control inside the container

2.2. Measurement of Static Electricity

According to an on-site survey, the electrical energy (mJ) generated by dust and the inner wall under the manufacturing environment will be calculated through the data record of static electricity accumulation [18]. That energy will be compared with the Minimum Ignition Energy (MIE) of dust. The results reveal that the voltage of static electricity inside the container is about -15.6 kV. A spark discharge device based on the standard measurement method EN13821 was set up in this experiment. Enough capacitors are connected in parallel on the discharge electrode. And the calculation formula is a comment calculation method shown in the Electronics textbook.

Simply measuring the static voltage generated on the wall surfaces at the site does not provide an assessment of the energy. The number of capacitors connected in parallel to the discharge electrode is a necessary way to accurately measure the energy. Typically, a capacitor is a kind of device in which two conductors are separated by an insulator. It is commonly used for store charge and electrical energy. In the experiment, the inner wall of the container is coated with anti-rust paint to form a state similar to a parallel plate capacitor. That is the reason the above formula can be used to calculate electrical energy. Based on the basic circuit theory, the capacitor can be calculated using a theoretical formula. In fact, this is just a theoretical estimation to roughly know the value of the capacitor. Under the voltage of static electricity of -19.6 kV, the release energy of the container is about 1.1 mJ after calculation.

2.3. Analysis of Fault Tree

The Fault Tree is a systematic analytical methodology that is suitable for conducting in-depth and comprehensive analysis of potential events within a complex system or process. The likelihood and mechanisms of event occurrence by combining various potential causes and failure paths through logical gates into a structured tree format will be clearly illustrated. This clear logical structure will help to a better understanding of the mechanism and probability associated with the occurrence of an event by clarifying the logical relationship and influence among various factors.

The gate in the Fault Tree means a kind of connection of event chain, which includes “or” and “And. It plays a crucial role to know how the logic of a tree works. They connect basic events to middle events and ultimately, to the top event. A simple example of a Fault Tree is shown in Fig. 6. Events A and B have impacted the top event Q and connected it through a gate of "And". This kind of gate indicates that failure event Q will occur only if events happen in the meantime. Event B is influenced by the two basic events of C and D, which are connected to it through an "Or" gate. Furthermore, this gate implies that the failure of either event C or D would fail in the upper event [19]. Once the tree has been constructed, the branches of the tree will be analyzed in detail, and any branch that is contradictory to the available evidence will be removed.

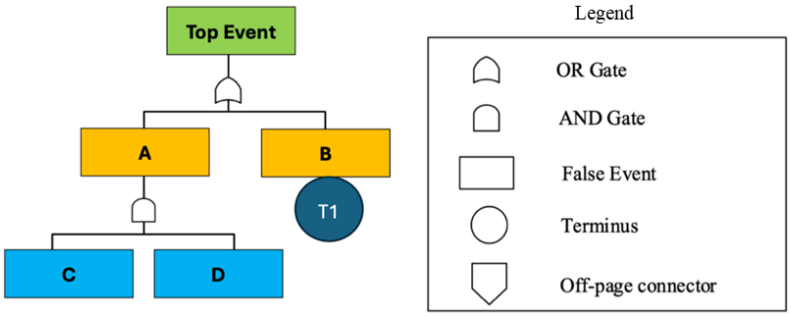


Fig. 6 A simple Fault Tree structure

After conducting an on-site investigation to identify a fundamental event and its failure path, a Fault Tree structure will be constructed based on detailed analysis. This graphical representation in the Fault Tree will facilitate qualitative analysis, which will help to understand which factors are most likely to contribute to a fire incident at the plastic factory in this study. According to the results of the fault tree analysis, as illustrated in Fig. 7, these critical factors will guide the establishment of a

comprehensive analysis in the full-scale experimental setup. In the following steps, the likelihood and potential risks associated with the fire event will be assessed. In the current site of the accident, a high accumulation of static electricity on the surface of the particle can be observed. The temperature variation in the process is not high and will not exceed the autoignition temperature of the fuel. Consequently, the effect of temperature on the fire source will be ruled out in this study. The investigation of the production of static electricity and the cause of sparks will be the primary argument. This is also the focus of this article later.

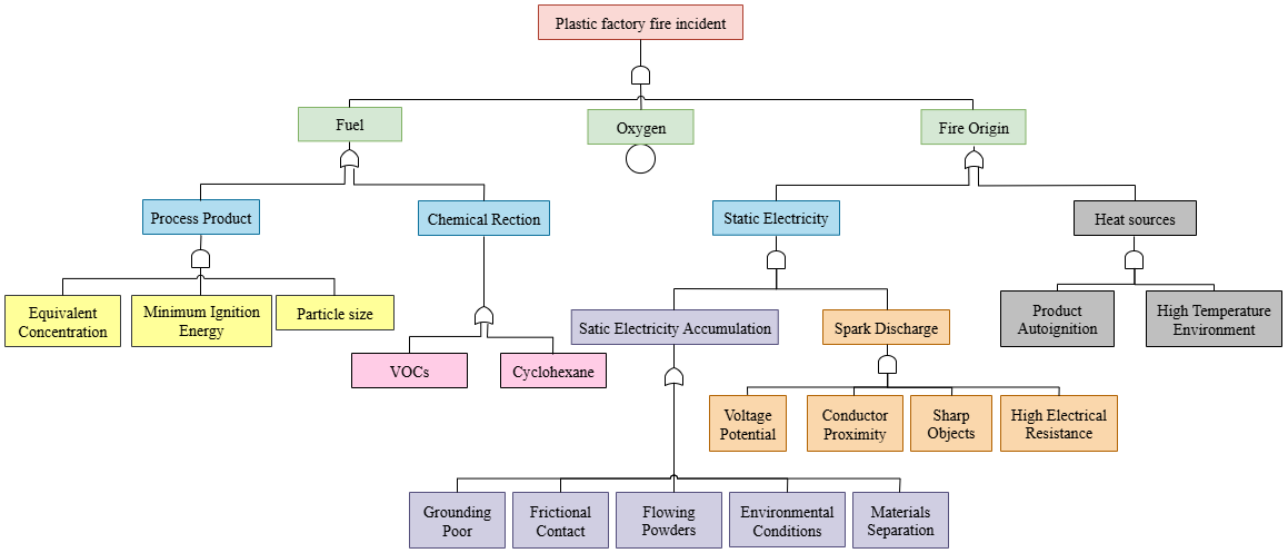
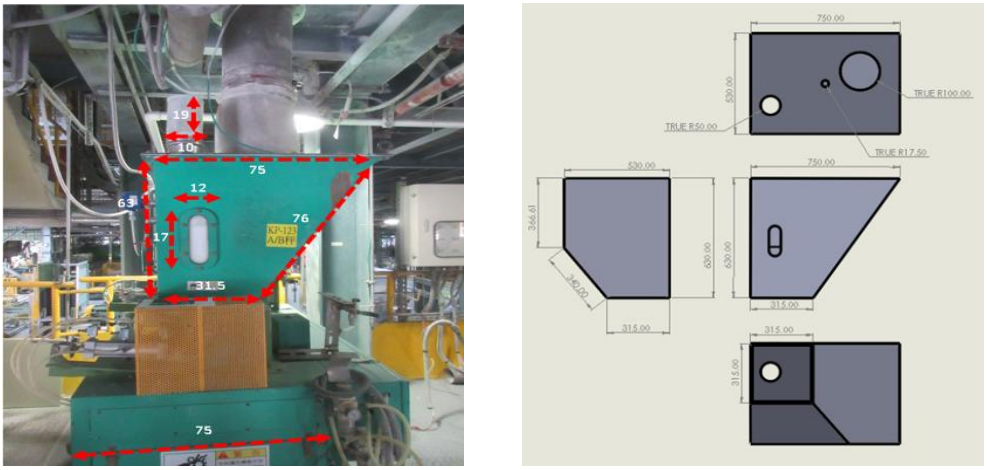


Fig. 7 Fault tree analysis for plastic factory fire incident [19]

2.4. Full-scale Experimental Setup

(1) Modelling

To enhance the accuracy, the drawings will follow the real scale of the container to evaluate the method of feeding and accumulation. The real scale and drawings are shown in Fig. 8, respectively. These models will be used for the following experiment to fit in with the actual situation. The particles will be poured into this device and then accumulate static electricity when stopped.



(a) Real scale of container (b) The drawings for modeling

Fig. 8 The scheme of the container

(2) Particularization

During the feeding process, the filter in the upper vent of the container has not been cleaned for a long time. Maybe the dust diameter in the finished product is small, the dust will not be filtered, and might rise in the air due to a shock during the

feeding process or a stop. It could cause a fire incident. Therefore, the concentration calculation of fuel will follow the steps shown below.

(a) Scenario: Because of the feed stop for 50 seconds, the dust will accumulate inside the container temporarily. In this situation, the difference is only a feed stoppage. In addition, the height of dust accumulation is about 70 % in the container, as captured by a video recorder. Consequently, the MIE will be calculated corresponding to the concentration under the volume ratio is 70 %.

(b) Experimental setup: To put the dust into 25 ml, 50 ml, and 100 ml measuring cylinders, respectively. The density of the dust of each cylinder can be calculated after weighing and measuring. The bulk density was determined. The concentration is calculated by container space and the amount of accumulation. The Hartmann tube will be adopted to compare the MIE in this study.

(c) Verification: According to the previous experimental method, the bulk density of dust is 0.42 g/ml, and the volume of the container is 0.35 m^3. The dust weight can be calculated as 1.03×10^5 g under 70 % container volume. Therefore, the concentration of accumulated dust is 2.94×10^5 g/m^3 in the container. The detailed experimental parameters are shown in Table 1.

Table 1 A simple Fault Tree structure

Density of Dust	Volume	Concentration of accumulated dust
0.42 g/ml	0.35 m^3	2.94×10^5 g/m^3

The detailed experiment setup and parameters of the MIE measurement are revealed below.

(a) The MIE experiment is mainly based on the regulations of EN13821 and ASTM E2019–03. The Hartmann tube is the primary facility for MIE measurement comparison.

(b) The pressure inside the container is 7 bar.

(c) The dust will be ignited by sparks between the two poles of glass cylinder of the Hartmann tube.

(d) The ignition energy ranges from 1 to 1000 mJ.

(e) Diameter of dust is 25~50 μm.

(f) Concentration range: 250 to 3,000 g/m^3

The minimum ignition energy MIE lies, by definition, between two energy values. For comparison between different apparatus, only one single value (E_s) instead of the energy range shall be used. This single value E_s can be estimated by the use of the probability of ignition to exactly know the true MIE. By knowing the minimum ignition energy of the product, it can predict whether the fuel will ignite along potential fire paths. This helps clarify the root causes of such fires and guides appropriate storage and operational procedures for the future.

(3) Overall experimental setup

The full-scale experimental setup is shown in Fig. 9. Dust was fed into the container through the upper feed inlet. A filter bag is installed on the left-hand side of the container. Static electricity accumulation was monitored and recorded using a probe-type electrostatic meter. In this experiment, identified potential fuels include lighter, smaller powder in the product, as well as VOC (A gas detector is used to measure concentrations). In addition, the thickness of anti-rust paint on the wall is 3.5 mm according to the actual situation. Due to a protruding level control inside the process vessel, it constitutes a sharp edge or point on a conductor in the fault tree analysis, potentially enhancing local electric field strength and leading to electrostatic discharge [20]. The purpose of the above measures is to achieve the following outcomes:

(a) Calculate static electricity accumulation and its causes.

(b) Determine the volatile organic compounds (VOCs) concentration in the product.

(c) Assess the effectiveness of grounding and conditions for generating electrostatic discharge.

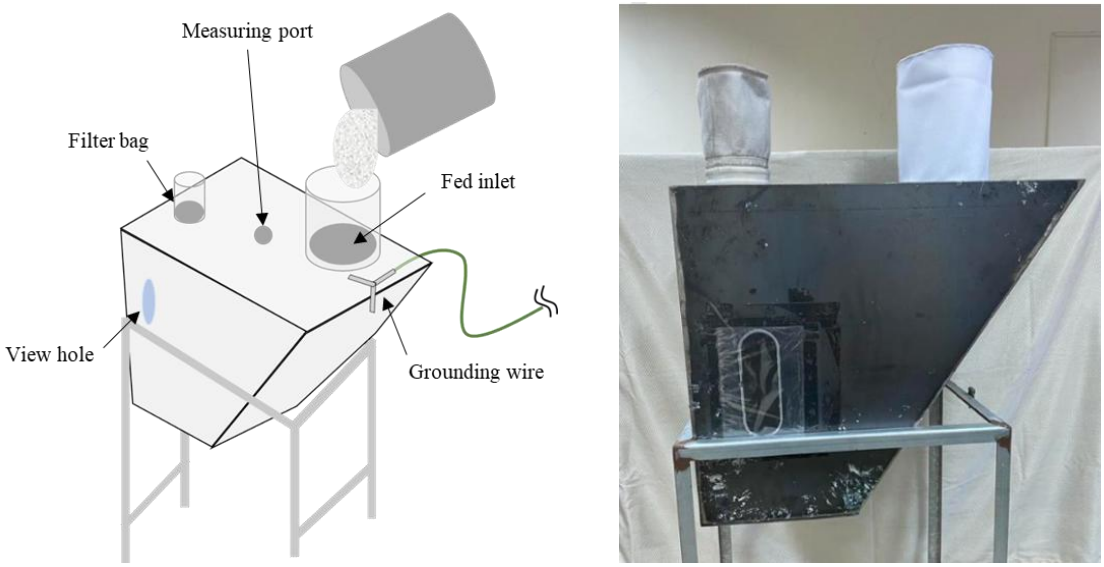


Fig. 9 The scheme comparison of actual and experimental arrangements

3. Measurements and Discussion

The present section reveals the primary issues related to measurement, which are design requirements, anti-rust paint conductivity test, and full-scale conductivity test, respectively. The detailed parameters and procedures will be illustrated in detail to support the experiment. Each conductivity test will be executed over fifty times to meet the needs of statistics and accuracy.

3.1. Design Requirements

A detailed investigation was conducted into the status of the process mixture and combustion situation on that day of the accident due to dust concentration. The MIE required to ignite a dust cloud at all parameter points was confirmed in this procedure. After sampling of actual cases, the particle amount of product dust ranging from 25 to 50 μm is minimal, with only by-product components such as Calcium stearate and Zinc stearate being used as experimental samples for the following minimum ignition energy test. In this study, the dispersion pressure and capacitance choice were 7 bar and 100 pF, respectively. The time delay depends on the capacitance choice, and the ignition will be triggered automatically after the time delay.

Based on the experimental parameters mentioned above, the results of standard minimum ignition energy detection for this Ficase product are shown in Fig. 10. The experimental results indicated that the ignition energy of Calcium stearate is typically higher than that of Zinc stearate at every test concentration. The Zine stearate at the situation of low concentration and low ignition energy cannot be ignited. Consequently, it might be preliminarily judged that the main element of dust in this case was Zinc stearate because of its easy ignition characteristic. In order to further know the difference in space and dimensions between the on-site process and the standardized measurement space for minimum ignition energy, an analysis will be carried out to compare the calculated spatial concentrations of these fine powders in the product with the testing results, which are shown in Table 2.

Through the experience formula of spark energy, the measured energy value of electrostatic discharge on site is about 1.1 mJ. And the dust accumulation concentration of 2.94×10^5 g/m^3 on the day of the accident. Therefore, the concentration of finer particles suspended in the product can be calculated by the composition percentage. As shown in Table 2, the particle concentrations of Zinc stearate and Calcium stearate all fall within the range detectable for dust ignition. Based on the

experimental results, the minimum ignition energy for Calcium stearate is 54.8 mJ. It might not be the fuel in the incident because of the energy and concentration distribution shown in Fig. 10.

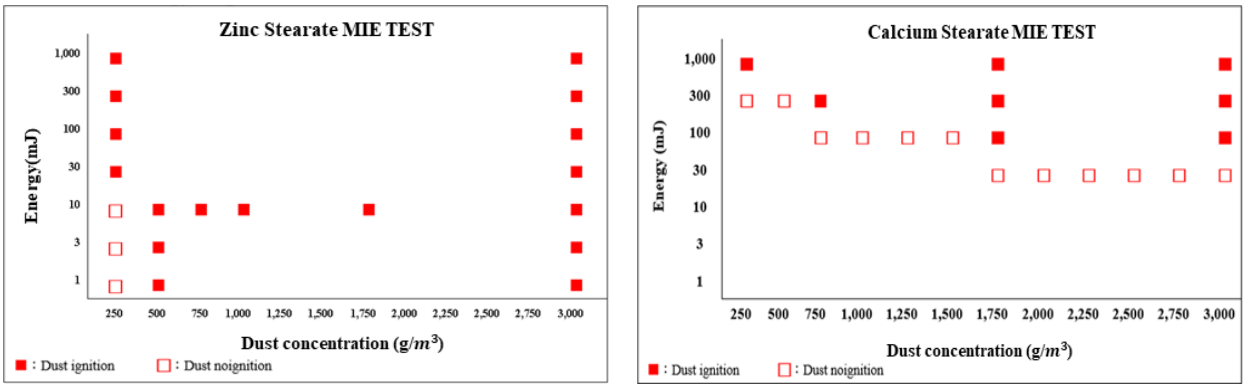


Fig. 10 The measurements of the MIE

The energy released from the site walls exceeds the minimum ignition energy of the Zinc stearate within the product (MIE < 1 mJ), but its proportion in the process is minimal. Therefore, the dust concentration of the Zinc stearate could accumulate to exceed the minimum concentration that can be ignited, and an accident occurred. For an occurrence of dust combustion, the particle concentration, air supply, and flame propagation must be maintained. It is so-called the three elements of combustion. In the industrial manufacturing processes, static electrical phenomena would be induced by different operational methods, especially in chemical, painting, plastic, etc. Despite various measures already adopted to avoid static electricity, fires due to static electricity still occur frequently. In the rich flammable gas environment, if the electrostatic discharge energy is larger than the MIE. It could become a fire or explosion source. The operational process will be simulated and inspected via an experimental method in this study.

Table 2 Measurement results for MIE testing of the product

	Percentage	Concentration of accumulated dust	MIE (mJ)	Dust ignition range
Zinc stearate	0.12~0.15 %	$352-441$	≤1	$250 < R \leq 3000$
Calcium stearate	0.10~1.00 %	$294-2940$	E_S =54.8	$1500< R \leq 3000$

3.2. Anti-rust Paint Conductivity Test

The preliminary conductivity test will be simulated using two different iron plates for two kinds of scenarios in the experiment, as shown in Table 3. The main objective is to investigate the conductivity of anti-rust paint inside the container. Firstly, most commercial anti-rust paint is insulating, and it will prevent charges from moving freely. The fire source will appear due to accumulated static electricity on the surface, which cannot be effectively removed inside the container. Therefore, two iron plates, one coated with anti-rust paint, and the other without paint, will be used, and the same connection of ground wire for the experiment. The present setup is primarily to compare each conductivity during the feeding process. Under the condition of grounding, the highest static electricity of an iron plate without anti-rust paint is -1.78 kV, while the iron plate with paint shows the highest static electricity of -2.73 kV. Results indicate that the conductivity of the iron plate with paint is poor and prove that the static electricity cannot be well removed and accumulates on the surface of the container.

Results also indicate that the plate without paint cannot release static electricity by grounding. The possible causes are plastic dust and humidity because of the open space. Another possible cause might be the dielectric strength of plastic dust. The dielectric strength refers to the maximum electric field that a material can withstand without experiencing electrical breakdown. In this case, if the plastic dust present on the unpainted plate has a high dielectric strength, it could prevent the effective discharge of static electricity even when the plate is grounded. This could contribute to the inability of the plate without paint to

release static electricity. As shown in Table 4, the values of voltage are small but show a wide variation. Relative to painted plate experiments, it can be revealed that the accumulation of static electricity is more obvious (see Table 5). These results are quite in line with those of previous discussions. The presence or absence of anti-rust paint should be the key cause of the accident.

Table 3 The scheme of the conductivity experiment

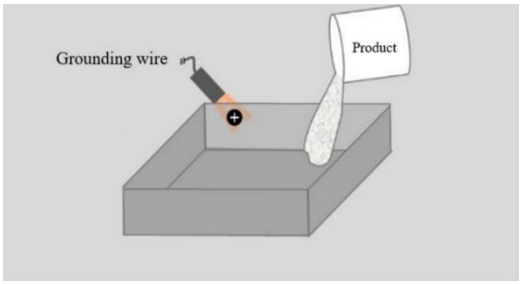
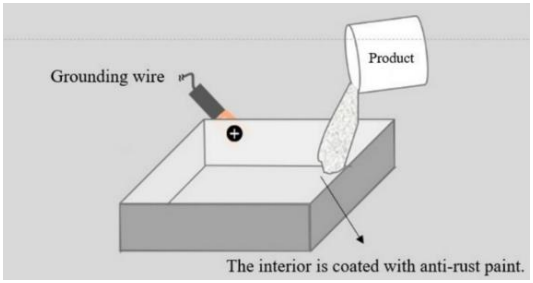
Scenarios	Without anti-rust paint	With anti-rust paint
Experiments		

Table 4 The static voltage of the iron plate without painting

	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6
Voltage	-1.52 kV	-1.33 kV	-1.71kV	-1.13 kV	-1.02 kV	-1.78 kV

Table 5 The static voltage of the iron plate with painting

	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6
Voltage	-1.11 kV	-2.73 kV	-1.92 kV	-2.25 kV	-1.41 kV	-2.66 kV

3.3. Full-scale Conductivity Test

In this experiment, a full-scale experimental site had been established beforehand, and the processed products were conveyed from the entrance to the interior of the container. The same type of filter bag provided on-site was adopted, and the product was transported from the entrance to the interior of the container to simulate both normal and abnormal filter bag usage. When powder accumulates in the container up to 70 % of the visible hole height, the VOC concentration, accumulation of static electricity in combustible dust, and paint conductivity will be recorded, respectively, in the experiment to confirm the possible key cause compared with previous results.

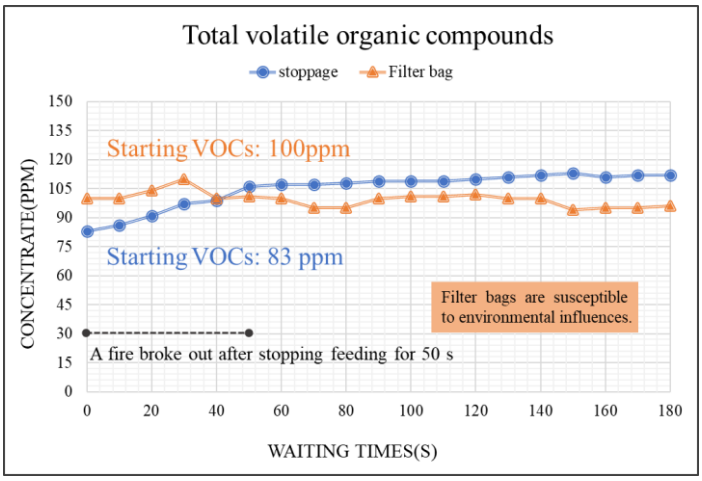


Fig. 11 The measurements of the MIE

The experimental data were recorded via a five-gas detector to track the concentration distributions of volatile organic compounds inside the container with time, as shown in Fig. 11. The results indicated that the concentration started to rise with time during the situation of stoppage. However, the concentration will decrease to a constant value after 40 seconds during the

use of the filter bag. The difference between the two situations will occur during the stopping of material supply and after 40 40-second. That is the critical moment of VOC accumulation to be the fire source.

Via experimental verification corresponding to a statistical basis, it has been indicated that the voltage of accumulated static electricity is up to -20 kV (see Table 6) when the height of powder accumulation reaches 70 % of the visible hole height. If the values of experimental electricity were substituted into the empirical formula, the maximum energy generated by dust inside the container is 1.8 mJ in this scenario. It is obvious evidence revealing that the primary case of ignition is electrostatic discharge by high voltage of static electricity, based on these experimental results. In the situation of a pause in operation, whether the filter is clogged or not, a larger amount of static electricity will be generated and accumulate on the surface of the particle. That will be the main source of fire that triggers the incident.

Experimental results also indicate that different cumulative amounts of VOC will be contained by each batch of product, which could lead to different initial concentrations in each experiment. According to the experimental investigation, it can be found that the ventilation effectiveness of the breathable filter bag used on-site is inadequate. This will minimize the difference between VOC accumulation inside the scale body and the concentration under full blockage conditions. It will potentially lead to VOC accumulation and enhance the fire risk. That is the main source of fuel in this accident. Consequently, the breathable filter bag should be improved to increase its breathability. It will efficiently decrease the concentration of VOC.

The VOC emissions do not reach the low limit of combustion at that time through experimental tests, considering the temperature of the production process and idle time were considered. According to the historical data provided by the factory, the primary component of VOC in this case is cyclohexane. In the meantime, the literature had indicated that the minimum ignition energy of cyclohexane is about 0.065 mJ [21]. It is quite consistent with the previous experimental results, which reveal that the energy generated by dust inside the AB scale can reach up to 1.8 mJ. That is the dominant evidence indicating that the produced VOC is the fuel source in this case, prominently.

Table 6 The static electricity of full-scale experimental tests

	Filter bag	Volts	Energy	Note
TEST 1	Usual (Filter bag)	-18.5 kV	1.54 mJ	Instrument limitations: (V_{max}:-20 kV)
TEST 2		-19.3 kV	1.68 mJ	
TEST 3	Unusual (stoppage)	-19.6 kV	1.73 mJ	
TEST 4		-20 kV	1.8 mJ	

4. Conclusions

In this study, the generation of VOC, accumulation of static electricity, MIE, and grounding conditions inside an enclosed container were experimentally investigated to understand the possible causes of industrial fire and explosion accidents. From the results, the conclusion can be drawn as follows:

(1) The inner walls of the container were coated with 3.5 mm-thick anti-rust paint, which caused the container to act as an insulator. This allowed static electricity to accumulate on surfaces, reaching up to -15.6 kV, and generate discharge energy of approximately 1.1 mJ, exceeding the MIE of the particles.

(2) During normal operation, static electricity and VOC were effectively exhausted during material feeding. However, an unexpected stoppage of feeding for 50 seconds allowed temporal accumulation of dust and static charge, creating conditions sufficient for a fire or explosion.

(3) The dust explosion conditions, including dust concentration, oxygen availability, ignition energy, and enclosure space, were largely satisfied during the feeding stoppage. Temporary vacuum formation in the container's upper space reduced oxygen locally, slightly lowering explosive potential, but sufficient conditions remained to trigger the accident

Future improvements and major areas of focus include enhanced monitoring and control of static electricity accumulation and VOC levels during material handling, implementation of safety procedures and grounding practices that account for unusual process interruptions, consideration of container surface treatments to minimize insulating effects, and adoption of comprehensive risk management strategies to anticipate and mitigate potential industrial accidents caused by static electricity and dust accumulation.

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Conflicts of Interest

The authors declare no conflict of interest.

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