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A Proposed Firefighting and Post-Fire Vbscene Control Procedure for Wood Pellet Processing Facilities to Prevent Flash Fire and Secondary Dust Explosions

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ABSTRACT: The biomass wood pellet industry is inherently exposed to a high risk of fire and explosion because fine wood dust is continuously generated and accumulated throughout the production process. This paper analyzes the thermodynamic and aerodynamic mechanisms underlying flash fire and secondary dust explosions in wood pellet processing facilities. On that basis, it proposes a safe and technically appropriate firefighting procedure tailored to this type of industrial occupancy. The findings contribute to strengthening the scientific basis for developing specialized operational guidelines for fire suppression and rescue forces in Vietnam.

KEYWORDS: flash fire; secondary dust explosion; wood pellets; combustible wood dust; firefighting tactics; smoldering fire; inert gas; fog nozzle; compressed air foam system; NFPA 660.

1. INTRODUCTION

Against the backdrop of the global energy transition and increasing pressure to reduce carbon emissions, wood pellets are being used more widely as a biomass fuel capable of partially replacing fossil fuels in thermal power plants, industrial combustion systems, and domestic applications. Wood pellets are biofuels manufactured from plant-based residues such as rice husks, corn stalks, sawdust, and other wood residues. These materials are by-products remaining after sawn timber production, wood processing, and the processing of other agricultural products. Under the combined effects of heat and pressure, natural binders in the raw material enable pellet formation without the need for additives. Owing to several advantages, including abundant feedstock from surplus wood residues, relatively simple production and operating technology, low labor demand, high calorific value with low ash generation, more stable prices than fossil fuels, and strong market demand, the number of wood pellet production facilities has continued to increase. In Vietnam, the wood pellet processing industry has expanded rapidly in recent years due to the abundant availability of wood and forestry by-products, while also playing an increasingly important role in the country's biomass export sector. Recent industry reports indicate that Vietnam is among the world's leading wood pellet exporters; in 2024 alone, wood pellet exports reached approximately 6 million tons, valued at more than USD 800 million, with Japan and South Korea as the principal markets [1, 2].

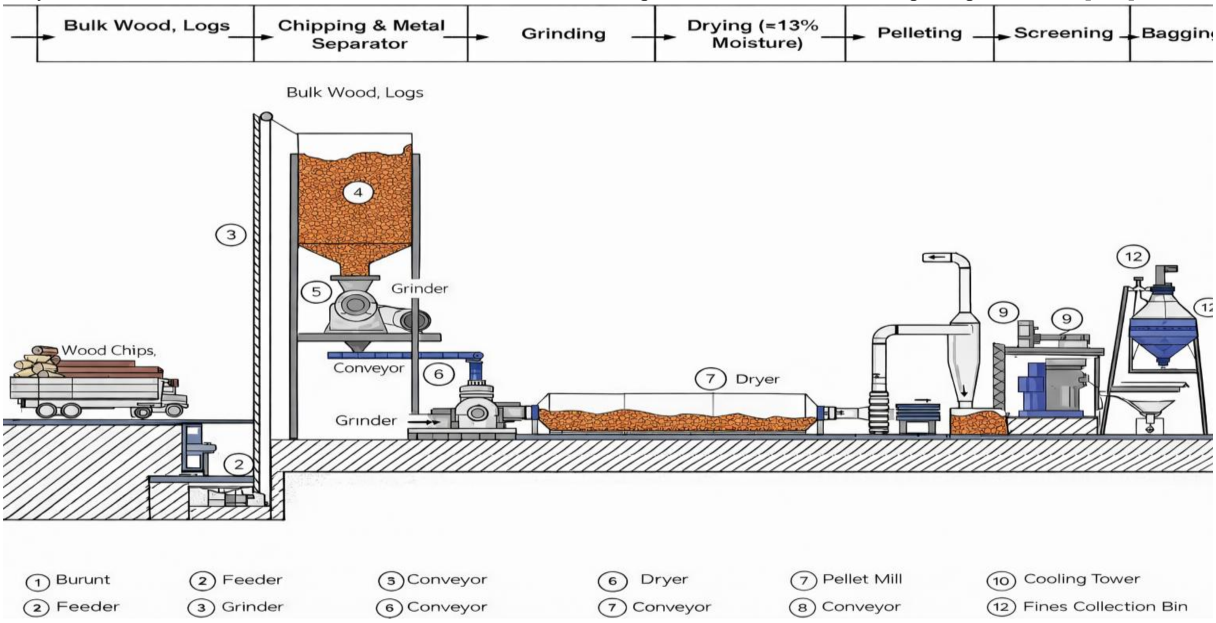

Figure 1. Wood pellet production process

In wood pellet manufacturing, the stages of chipping, grinding, drying, and pelletizing generate large quantities of fine wood dust, typically with particle sizes below 500 µm. By nature, wood dust is a particulate combustible material characterized by a high specific surface area, low ignition energy, and a strong tendency toward rapid flame propagation when dispersed in air. Consequently, wood pellet processing facilities present a high fire and explosion hazard if settled dust, ignition sources, and process-space conditions are not adequately controlled [3–6].

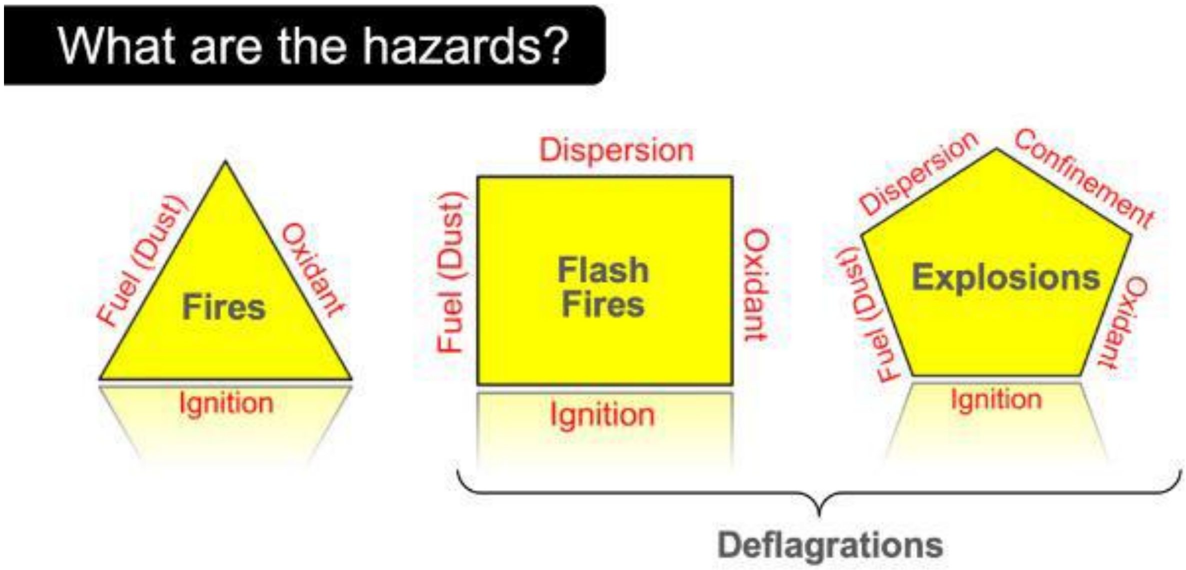

Figure 2. Progression of fire and dust explosion hazard models

Hazardous phenomena associated with wood dust can generally be classified into three principal levels: dust fire, flash fire, and dust explosion. At the lowest level, a dust fire occurs when wood dust exists as a settled layer and is exposed to a sufficiently strong heat source. The combustion mechanism follows the fire triangle, consisting of fuel, oxidizer, and an ignition source such as open flame, hot surfaces, friction, electrical sparks, or electrostatic discharge. The second hazard level is flash fire, which may occur when dust is dispersed in air, thereby satisfying four conditions: fuel, oxidizer, ignition source, and suspended combustible dust. Once settled dust is disturbed and forms a dust cloud, ignition may occur because the contact area between dust particles and oxygen increases abruptly. The third and most severe hazard level is dust explosion, which becomes possible when confinement is present, thereby completing the explosion pentagon. If a burning dust cloud develops within an enclosed space or a space with restricted air exchange, the rapidly generated pressure cannot be relieved in time, resulting in a dust explosion. Within this sequence, primary dust explosions generally originate inside process equipment such as grinders, baghouse dust collectors, cyclone separators, or enclosed conveyors. Secondary dust explosions typically follow when the pressure wave from the primary event dislodges settled dust throughout the facility, forming a much larger dust cloud that is subsequently ignited by residual flames or heat sources [3–6].

In practice, when a localized fire occurs in a wood pellet production facility, the first three elements of the dust explosion pentagon - fuel, oxidizer, and ignition source - are often already present. The determining factor leading to flash fire or secondary dust explosion is usually dust dispersion, which may inadvertently be caused by firefighting operations themselves if the extinguishing agent or discharge pattern is selected inappropriately. Therefore, investigating the mechanisms that lead to flash fire and secondary dust explosion, and proposing a specialized firefighting procedure for this type of facility, is both practically significant and urgently needed [4, 6, 7].

2. RESEARCH CONTENT

2.1. Thermodynamic and aerodynamic mechanisms of secondary dust explosions

When firefighters apply a solid water stream directly onto a fire involving accumulated wood dust, the stream not only delivers a large water flow but also entrains high-velocity air, thereby creating turbulent flow in the impact zone. This aerodynamic action may generate shear stresses that exceed the adhesion forces between dust particles and the surfaces on which they have settled. As a result, dust may be dislodged from floors, equipment, structural beams, or roof members and become suspended in the air. From a fire and explosion safety perspective, this mechanism is particularly dangerous because firefighting operations may inadvertently complete the “dust dispersion” element of the dust explosion pentagon [3, 4, 7].

Once the dust is dispersed and its airborne concentration reaches or exceeds the minimum explosible concentration, the original flame front or heated surfaces in the fire area may act as ignition sources for the newly formed dust cloud. Because wood dust possesses a large surface area, combustion can occur simultaneously over a large number of particles, causing the rate of heat release to increase very rapidly. Numerous studies have shown that wood dust typically falls within the ST1 explosion class, with Kst values commonly in the range of 100–200 bar·m/s, sufficient to cause severe damage to equipment and structures in confined spaces [3, 4, 6].

If the fire or primary explosion occurs within enclosed equipment such as a dust collection system, ductwork, conveyor, or grinding chamber, the resulting pressure wave may propagate into adjacent spaces, shake structural components, and loft long-settled dust throughout the workshop. Under these conditions, a secondary dust cloud, often far larger in volume than the original dust cloud inside the equipment, is formed and may be ignited by flames from the initial event or by residual hot surfaces. Because the mass of dust suspended within the building is often considerably

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greater than that involved in the primary event, secondary dust explosions are typically more destructive than primary dust explosions in terms of overpressure, extent of damage, and the level of danger posed to firefighting personnel [4–7].

In essence, secondary dust explosions in wood pellet processing facilities are the combined outcome of two interacting processes: an aerodynamic process that disperses dust and a thermodynamic process through which heat sources ignite the suspended dust cloud and promote rapid flame propagation. From this perspective, controlling the mechanical impact of discharge streams and limiting dust dispersion during firefighting are fundamental requirements for preventing the transition from a localized fire to a flash fire or secondary dust explosion [3, 4, 7].

2.2. Firefighting tactics according to the stage of fire development in wood processing facilities and dust-handling systems

In wood processing facilities, biomass pellet plants, and industrial dust collection systems, firefighting tactics should be selected according to the stage of fire development, the extent of combustible dust accumulation, and the characteristics of the process space. Unlike ordinary fires, fires in environments containing wood dust always carry the potential to escalate rapidly from localized burning to fire spread, flash fire, or secondary dust explosion if the extinguishing agent or discharge mode is not appropriately selected. OSHA guidance indicates that, in facilities containing combustible dust, unsuitable extinguishing agents or discharge methods may both disturb settled dust and introduce additional air into the fire zone, thereby increasing the likelihood of flash fire and secondary dust explosions in process equipment, conveyors, cyclone separators, baghouse dust collectors, and storage silos [6, 7]. On this basis, firefighting tactics may be categorized into three levels: Level 1 for small fires and smoldering combustion; Level 2 for medium-scale fires involving open flames; and Level 3 for extensive fires or fires within enclosed process spaces [6, 7].

Level 1

At this level, the fire usually exists as smoldering combustion within piles of sawdust, layers of accumulated wood dust around equipment, or small localized fires on machinery surfaces. At this stage, the principal hazard lies not in high heat release but in the possibility that settled dust may be disturbed if a high-momentum water stream is used. OSHA clearly notes that, when firefighting in combustible dust environments, solid water streams should be avoided because they may disperse surface dust into the air and thereby form dust clouds. Moreover, even fog nozzles operated at excessive nozzle pressure may introduce air into the fire zone. Accordingly, the preferred approach is to use a fog nozzle or a medium- to wide-angle spray pattern, combined with low nozzle pressure, while directing the stream upward at an oblique angle so that water falls gently onto the fuel rather than striking it directly with a solid stream. This approach is consistent with the operational principle of water mist fire protection systems. Its effectiveness is primarily attributed to two mechanisms: first, smaller droplets exert less mechanical force, thereby reducing the risk of dust-cloud formation; second, the larger total surface area of the droplets enhances heat transfer and evaporation efficiency, allowing smoldering hot spots to be cooled more rapidly before they develop into sustained flaming combustion [7, 8].

Level 2

Once the fire has spread to conveyors, feed areas, or raw-material staging zones and involves open flames together with high thermal radiation, the fog nozzle alone is no longer the optimal option. Under these conditions, firefighting tactics must do more than cool the surface; they must also increase the penetration of the extinguishing agent into the fuel bed while establishing a separating barrier between the fuel and the oxidizer. The appropriate tactical shift is therefore to use a compressed air foam system in combination with Class A foam or wetting agents. These additives reduce the surface tension of water and thereby improve its spreading and penetration into densely packed cellulosic materials such as sawdust, dry wood dust, and wood pellets [7, 9].

From a tactical standpoint, compressed air foam systems produce a foam blanket with improved adhesion and longer retention on the fuel surface, thereby enhancing cooling performance, isolating the fuel from oxygen, and reducing the dispersion of combustible dust particles. For Level 2 fires, firefighters should avoid direct frontal attack using high - momentum water streams. Instead, an indirect blanket-application technique should be used, for example by directing the stream onto a hard surface above or in front of the fire so that the foam can flow and spread over the burning material. In addition to suppression effectiveness, the current edition of NFPA 11 emphasizes the need to address health, safety, and environmental considerations in the selection, use, and disposal of firefighting foams. Accordingly, the use of compressed air foam can only be regarded as sustainable when accompanied by chemical management measures and containment of post-fire runoff to prevent environmental release [9].

Level 3

When fire spreads throughout the workshop or occurs within enclosed process equipment such as storage silos, bins, baghouse dust collectors, cyclone separators, and similar confined spaces, firefighting principles must be adapted to the specific scenario. At this stage, the priority is no longer simply to increase the application rate of extinguishing agent, but rather to control the mechanical force of the discharge stream, minimize disturbance of settled dust layers, limit the introduction of additional air into the fire zone, and prevent flash fire or secondary explosion. OSHA specifically recommends the use of medium- to wide-angle spray patterns, low pressure, and an upward oblique discharge direction so that water falls onto the burning surface from a safe distance, instead of using direct solid water streams [7].

However, when smoldering combustion develops inside silos or enclosed equipment, opening the equipment or applying water directly into the smoldering zone may increase the risk of flash fire and secondary dust explosion. In such cases, inerting measures may be more appropriate, namely the injection of inert gases such as nitrogen or carbon dioxide into the fire area in order to reduce fuel and oxygen concentrations below the critical threshold for ignition. NFPA 69 identifies oxidant concentration control as one of the fundamental methods of explosion prevention, while OSHA notes that inerting is effective only when the appropriate inert gas is selected and introduced by a safe method [7, 10].

A critical point is that introducing inert gas into silos, tanks, or enclosed hoppers may create an oxygen - deficient atmosphere that poses an immediate threat to the life and health of firefighting personnel. According to OSHA 29 CFR 1910.146, any firefighting operation involving entry into permit-required confined spaces must be strictly controlled with respect to internal atmospheric conditions, entry procedures, and the availability of a dedicated rescue plan. In addition, Hedlund reported that, in some smoldering fires in wood pellet silos, the injection of carbon dioxide into the headspace above the stored material may generate static electricity and thereby increase the risk of explosion. This finding indicates that inert gases should not automatically be assumed to offer the same level of operational safety in all circumstances [11, 12].

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Taken together, these three tactical levels demonstrate that the essence of firefighting in wood pellet processing facilities lies not merely in choosing an appropriate extinguishing agent, but in selecting tactics that correspond to the mechanism of fire development and the dispersion state of combustible dust. Level 1 prioritizes cooling and suppression of smoldering combustion without disturbing dust; Level 2 emphasizes penetration, surface coverage, and fuel isolation; and Level 3 focuses on controlling flash fire and secondary explosion hazards, oxygen concentration, and the safety of firefighting operations in enclosed spaces. This tiered approach is highly relevant to Vietnam because it enables the standardization of operational procedures according to risk level, reduces reliance on subjective experience, and provides a scientific foundation for specialized guidance applicable to fires involving wood dust, biomass pellets, and industrial dust collection systems [6–12].

2.3. Post-fire control and safe scene clean-up

Even after the main fire has been brought under control, smoldering combustion may persist within compacted wood materials, sawdust, or accumulated layers of burned dust, thereby creating a continuing risk of rekindle, flash fire, and secondary explosion. Under oxygen - deficient conditions, smoldering may continue to generate combustible gases such as carbon monoxide, hydrogen, and methane. If the fuel bed is suddenly raked, disturbed, or turned over, oxygen may rapidly penetrate the smoldering zone and re-establish the conditions necessary to sustain combustion. For this reason, post-fire control in wood pellet processing facilities should be regarded as an integral phase of firefighting operations rather than merely as a clean-up activity following fire suppression [5–7].

From the standpoint of scene management, the first requirement is to maintain continuous surveillance of areas in which smoldering may still be occurring beneath the fuel layer. Monitoring should be conducted using thermal imaging cameras to identify temperature differentials, detect smoldering zones through visible indicators such as smoke emission or localized heat, and track heat migration within the fire area. This should be combined with continuous monitoring of carbon monoxide concentrations in order to assess the extent of pyrolysis and the possible persistence of hidden hot spots. Based on these monitoring results, raking and overhaul should be performed progressively in thin layers, from the outside inward and from the top downward. As each layer of charred material or fuel is disturbed, it should be cooled immediately with a fine water spray and moved without delay to a safe outdoor area for continued temperature monitoring and prevention of rekindle. This approach minimizes sudden disturbance of the fuel mass while also reducing the likelihood of simultaneously releasing combustible dust and combustible gases into the fire scene [5, 7].

At the same time, post-fire clean-up operations must strictly comply with safety requirements applicable to combustible dust environments. Both OSHA and NFPA warn that blowing dust with compressed air or dry sweeping with brooms may generate dust clouds and thereby increase the risk of flash fire and secondary dust explosion. Accordingly, neither compressed - air blowdown nor vigorous dry sweeping should be used. More appropriate methods include controlled wet cleaning using fine spray to moisten, stabilize, and collect residual dust and combustion products, or the use of specialized industrial vacuum cleaners suitable for dust - hazard areas. Vacuum equipment and dust - conveying components should be electrically conductive or properly grounded in order to reduce the accumulation and discharge of static electricity during the collection of fine wood dust [6, 7].

Where firefighting foam has been used during suppression, post-fire control must also encompass the management of fire water, foam solution, and post-fire runoff. NFPA 11:2024 emphasizes the need to consider health, safety, and environmental aspects simultaneously in the selection, use, and disposal of firefighting foam residues. In parallel, the U.S. Environmental Protection Agency updated its interim guidance in 2024 on the destruction and disposal of PFAS and PFAS-containing materials, highlighting the need to manage these waste streams in ways that minimize environmental release. Therefore, where firefighting foam has been applied, especially fluorinated foam, all wash water, residual foam, and foam-contaminated waste should be collected, isolated, temporarily stored, and treated in accordance with applicable environmental regulations. Such materials should not be discharged directly into public drainage systems or receiving waters without proper control measures [9, 13].

3. CONCLUSION

This study demonstrates that the risk of flash fire and secondary dust explosion in wood pellet processing facilities depends not only on the combustibility and explosibility characteristics of wood dust, but also directly on the firefighting tactics selected and the methods adopted for post -fire scene control. The use of inappropriate extinguishing agents or discharge patterns may disturb settled dust, introduce additional air into the fire zone, and thereby create the conditions for a localized fire to escalate into a flash fire or secondary dust explosion. Based on an analysis of the thermodynamic and aerodynamic mechanisms involved, this paper proposes a three - level firefighting procedure corresponding to smoldering combustion, open-flame fire, and fires occurring in enclosed process spaces. The study further emphasizes that post - fire control, hot - spot monitoring, safe industrial cleaning, and the management of contaminated fire water and firefighting foam are integral components of the firefighting process in facilities exposed to combustible dust hazards. In practical terms, the proposed procedure may serve as a scientific basis for the development of specialized operational guidance for fire suppression and rescue forces in Vietnam in relation to wood pellet processing plants and other industrial facilities presenting similar dust explosion hazards.

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