Educational Innovation Research, 2026, Volume 4, Issue 6
https://bbwpublisher.com/journal/EIR
Online ISSN: 3029-1852
Print ISSN: 3029-1844

Analysis of Hidden Fire Hazard Factors of Dust in Laboratories and Research on Solutions

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Abstract: Aiming at the problems of hidden dust accumulation in the prevention and control of dust fire hazards in university and research laboratories, the TRIZ theory is applied to construct a systematic solution. Functional defects among the components of the laboratory system are identified via functional analysis, and the core factors leading to dust concentration accumulation are determined in combination with causal chain analysis. By using the contradiction matrix and separation principles, a solution for laboratory dust fire hazards is proposed: gradient filtration devices such as electrostatic electret filters and wire mesh filters are installed in key laboratory areas, and a pulse frequency conversion system is adopted to control the guide vane groups of variable-section ventilation ducts for automatic air duct switching, thus achieving efficient dust collection. This solution significantly reduces the risk of dust explosion and features technical and economic advantages such as low power consumption, high reliability, and easy maintenance, providing solid technical support for laboratory safety protection.

Keywords: TRIZ; Laboratory; Dust explosion

Online publication: June 26, 2026

1. Introduction

In recent years, laboratory fire accidents have occurred frequently, among which the risk of combustion and explosion caused by dust has been particularly prominent, becoming a pain point in laboratory safety management. According to statistics from the China Petroleum and Chemical Industry Federation, domestic laboratory dust-related accidents accounted for 12.5% from 2020 to 2023, and the death toll accounted for 16.7%. These accidents mostly occurred in chemical and material experiment sites [1]. The existing protection system mainly relies on ventilation and dust removal as well as operation training, but deep technical problems such as the concealed accumulation of dust and the control of static ignition sources have not been fundamentally solved. Especially in scenarios with frequent material handling and nanomaterial grinding, traditional methods are difficult to adapt to complex conditions. Therefore, it is urgent to restructure the prevention logic from the perspective of system contradictions and seek more effective innovative solutions.

This article aims to combine typical cases of laboratory dust fire hazards and apply the TRIZ innovation theory to identify the root causes and key issues of the problem through functional analysis, causal chain analysis, and resource analysis [2–3]. The use of the contradiction matrix and separation principle seeks technological breakthroughs. It provides new technical support for laboratory dust control and offers innovative ideas for the safety protection of other high-risk research environments.

2. Problem description

This article focuses on the dust fire hazards caused by long-term metal powder (such as aluminum powder) drying and screening operations in material laboratories. During such frequent operations, a large amount of fine aluminum powder inevitably remains and accumulates on the workbench surface, floor gaps, and gradually penetrates into the inaccessible corners of the equipment. Although routine daily cleaning is carried out, it is still unable to effectively remove the stubborn dust inside the equipment, resulting in repeated increases in dust concentration in local areas and even periodically reaching the explosion limit of aluminum powder, forming a potential explosive environment. More seriously, the high-speed mixing equipment equipped in the laboratory is prone to generate static sparks with energy exceeding 1 mJ during operation. Once the ventilation system temporarily fails due to faults, maintenance, or insufficient efficiency, the coupling conditions of the high-concentration dust cloud and the static ignition source will instantly form, sharply increasing the explosion risk.

3. Problem analysis

To systematically identify the fundamental causes of laboratory dust fire hazards and locate the key issues, this article uses the TRIZ tri-axis analysis method (functional analysis, causal chain analysis, and resource analysis) to conduct an in-depth analysis of the problem [4].

3.1. Functional analysis

Regarding the problem of dust fire hazards that can easily occur in material laboratories, the indoor dust collection system is taken as the research object, and it is divided into the following components: control system, fan, pipeline, and filter. The related external system components are identified: operators, other equipment, dust, laboratory, and cleaning tools. The interaction analysis among these components is carried out, focusing on identifying the key functions related to dust control and analyzing their existence. A functional model diagram, as shown in **Figure 1** (wavy lines represent harmful functions, and dotted lines represent insufficient functions), is constructed, considering the needs for improving functions and reducing costs, and initially identifying the key points to be solved in the system: dust adhesion and dust removal system.

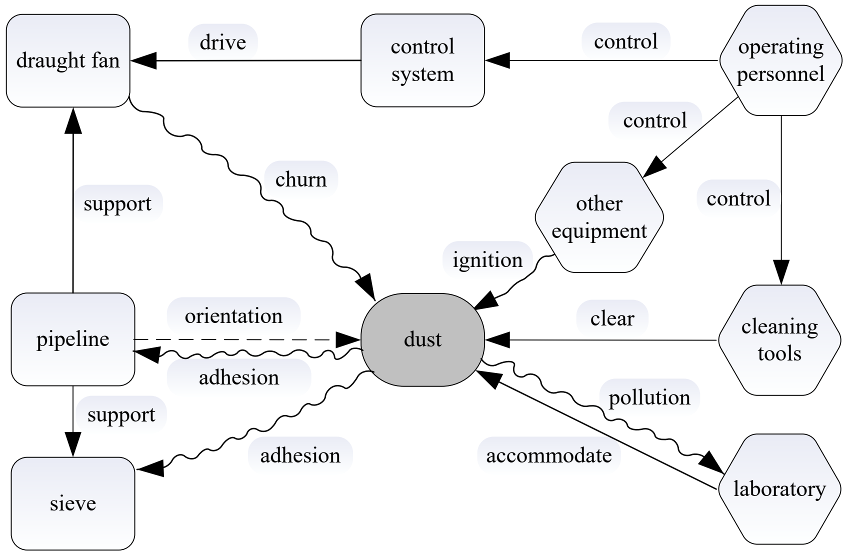

Figure 1. Functional model diagram

3.2. Causal analysis

Based on the identification of key harmful functions and deficient functions through functional analysis, the causal chain analysis tool was employed to deeply explore all possible fundamental causes leading to these functional deficiencies. By repeatedly asking "why," a hierarchical cause chain was constructed until the root of the problem was reached. This article took the initial problem "dust adhesion dust removal system" as an example and constructed a causal chain model, as shown in **Figure 2**. In the figure, the bottom layer of each branch is often the fundamental solution to the problem (**Table 1**). According to the principle of ideal degree, try to minimize changes to the engineering system and reduce costs. From **Table 1**, the key problems identified are large pore size, small motor power, and a filter that is too dense. Solving the key problems requires the assistance of external resources.

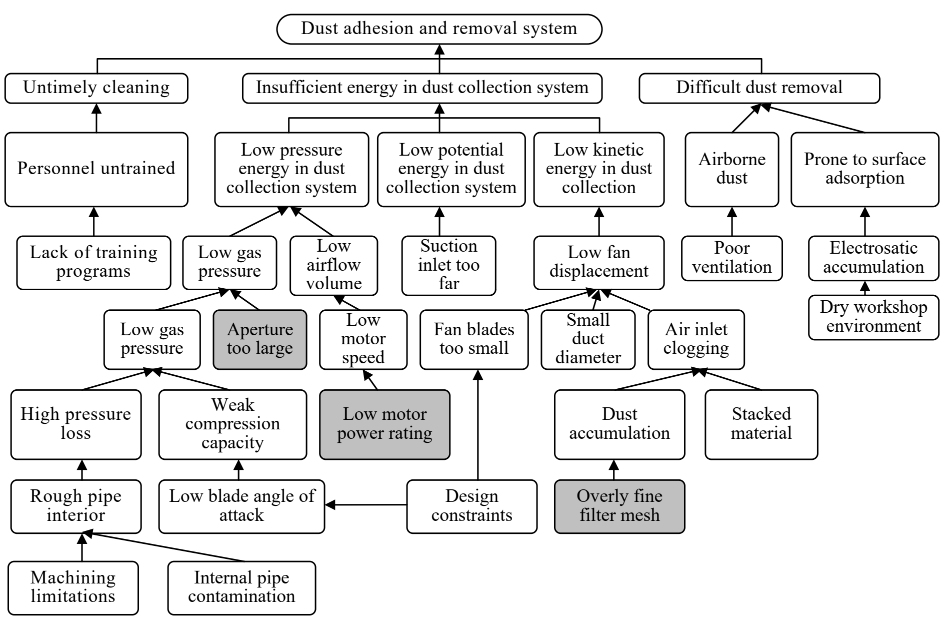

Figure 2. Cause-and-effect chain model

Table 1. List of fundamental defects of dust adhesion system

Intermediate defect	The dust was not cleaned up in time.	Insufficient energy in the dust collection system	The dust is difficult to remove.
The root cause	1. The personnel did not receive training on dust explosions during the training process.	1. Processing restrictions 2. Accumulation of debris inside the pipeline 3. Excessive pipe diameter of the dust removal system 4. Small attack angle of the fan blades 5. Low power of the fan motor 6. Excessive distance of the suction port 7. Non-compliant size of the fan blades 8. Small diameter of the air duct 9. Excessively dense filter screen at the inlet and possible obstruction by objects	1. Poor ventilation 2. Dry workshop

3.3. Resource analysis

The purpose of resource analysis is to identify the potential elements in the laboratory environment that can be used to address the fundamental flaws of the dust adhesion system. Based on the results of functional and causal analysis, the material, energy, and information resources within the existing system are deeply explored: The existing ventilation and dust removal system (pipes, fans, filters) serves as the core material foundation and has the potential for renovation, and the equipment structure and casing can accommodate additional functional components; The flow characteristics of ambient air can optimize the air flow organization. At the energy level, the gravitational field can promote dust settling, the vibration of equipment can suppress local dust accumulation, and, particularly crucially, the electrostatic field generated by high-speed mixing equipment can be transformed into an electrostatic adsorption dust removal resource through technical means from harmful ignition sources. In summary, the temporal, structural, and energy resources contained in the laboratory provide substantial support for subsequent problem-solving.

4. Problem solving

The key is to identify the physical or technical contradictions in the obtained critical issues through causal chain analysis, such as the excessive pipe diameter, insufficient motor power, and overly dense filter screens. Use the contradiction matrix and separation principle to form creative ideas. The contradiction matrix consists of 39 improvement parameters and 39 deterioration parameters, forming a rectangular array aimed at precisely recommending inventive principles. Through contradiction analysis, extract the corresponding improvement and deterioration parameters, and by querying the contradiction matrix, obtain the corresponding inventive principles.

4.1. Identification of physical contradictions and application of separation principles

Physical contradictions refer to a single parameter having opposite and reasonable requirements [5]. In the dust collection system, three sets of core physical contradictions were identified, and the TRIZ separation principle was used to solve them specifically.

4.1.1. Physical contradiction of too large ventilation duct diameter

The physical contradiction of too large a ventilation duct diameter is concentrated in the requirement that the duct structure must simultaneously meet a large diameter to reduce airflow resistance and a small diameter to enhance dust collection efficiency. Using the spatial separation principle, a variable-section ventilation duct structure was designed: The entrance section uses a large diameter to reduce initial pressure loss, and according to the continuity equation of fluid mechanics ($A_1v_1 = A_2v_2$), the section is contracted to a small diameter at the exit to increase the flow velocity, thereby separating the contradictory requirements in the spatial dimension and achieving efficient dust aggregation.

4.1.2. Physical contradiction of insufficient motor power

The physical contradiction of insufficient motor power is reflected in the need for the power system to have both high power to ensure strong suction and low power to control energy and noise. Through the time separation principle, an intelligent variable frequency control module was integrated: When the dust concentration sensor detects a value > 15 g/m³, it automatically switches to high-power mode; In normal operating conditions, it maintains low-power operation, which can reduce energy consumption and lower noise to below 65 dB(A).

4.1.3. Physical contradiction of overly dense filter screens

The contradiction point of overly dense filter screens lies in the need for the filter screen to have high density to block micrometer-sized dust and low density to maintain ventilation. Based on the spatial separation principle, a zone gradient filtration system was constructed: In the material grinding area, a static permanent magnet filter screen (with a diameter of 50 μm and high density) was configured, in the equipment transition area, a metal wire mesh filter layer (with a diameter of 100 μm and low density) was set up, and a pressure difference sensor was installed to monitor the blockage status, and when the resistance exceeds the limit, the standby air duct was automatically switched.

4.2. Identification of technical contradictions and application of inventive principles

Technical contradictions refer to an effect that simultaneously produces both useful and harmful effects. Through the contradiction matrix, two typical technical conflicts and corresponding inventive principles were identified [6].

4.2.1. Technical contradiction between dust removal efficiency and energy consumption

The technical contradiction between dust removal efficiency and energy consumption is manifested as improving dust removal efficiency (corresponding to the 39th improvement parameter in the matrix), but resulting in increased energy consumption (corresponding to the 22nd deterioration parameter in the matrix). By applying the Ashkinazi Matrix, an optimization solution can be obtained through the pre-action principle (pre-placement) and the periodic action principle (using pulses instead of continuous action): At the areas prone to dust accumulation in the ventilation ducts, pre-install detachable guide blade assemblies to guide the airflow to generate local vortices, enhancing the inertial collision and centrifugal separation effects on dust particles, thereby improving the local capture efficiency. By changing the operation mode of the dust removal system's fan from continuous constant speed to pulse frequency control mode, and switching the fan speed periodically based on real-time feedback from the dust concentration sensor or preset working thresholds, the fan speed can be adjusted. During periods of high dust concentration or high-speed operation, the fan operates at full power to ensure efficient dust capture; during periods of low concentration or low-speed operation, the fan reduces speed to maintain the basic air volume, significantly reducing standby energy consumption.

4.2.2. Technical contradictions in equipment structure

The contradiction between equipment reliability and maintenance convenience is reflected in enhancing reliability (corresponding to the 27th improvement parameter in the matrix), which leads to a deterioration in operational convenience (corresponding to the 33rd deterioration parameter in the matrix). By applying the Contradiction Matrix, an idea can be derived from the pre-action principle: Pre-embed magnetic quick-release flanges at pipe bends and connection points, and during maintenance, achieve rapid and tool-free disassembly through magnetic force adsorption devices, improving maintenance efficiency and achieving an IP65 (dust and waterproof) sealing level.

5. Final solution

Based on the systematic analysis of laboratory dust fire hazards and the application of TRIZ contradiction resolution principles: The variable cross-section ventilation duct designed by the spatial separation principle combined with the detachable guide blade assembly achieves efficient dust aggregation; The pulse frequency control system integrated by the time separation principle integrates dust concentration sensor real-time data to automatically switch power modes: In high-concentration conditions, full power is enabled to ensure suction force, and in normal conditions, low power operation is maintained; The partitioned gradient filtration device constructed based on the condition separation principle is configured with electrostatic permanent magnet filters in the material grinding area and metal wire mesh filter layers in the equipment transition area, and a pressure difference sensor is used to automatically switch the air duct when blockage occurs; Pre-embed magnetic quick-release flanges at key connection points to achieve tool-free disassembly and ensure an IP65 sealing level.

Through the above measures, the following integrated final solution is proposed: Configure electrostatic permanent magnet filters, metal wire mesh filters, and other gradient filtration devices in key areas of the laboratory, and use the pulse frequency control system to control the guide blade assembly of the variable cross-section ventilation duct, automatically switching the air duct and achieving efficient dust aggregation.

6. Conclusion

This study introduces the TRIZ innovation theory to construct a systematic safety control solution for laboratory dust fire hazards. The research has confirmed that the variable cross-section ventilation system and partitioned gradient filtration device designed by the spatial, time, and condition separation principles not only significantly reduce the risk of dust ignition but also have the characteristics of low power consumption, high reliability, and easy maintenance, forming a technically and economically superior solution. It lays a theoretical and technical foundation for the upgrade of the laboratory safety management system in universities and research institutions, and future exploration of predictive protection applications of the TRIZ theory in emerging experimental scenarios is possible.

Funding

Provincial Key Construction Discipline Project of Jiangsu Province (2016-0802 — Mechanical Engineering)

Disclosure statement

The authors declare no conflict of interest.

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