Journal of Building Construction and Planning Research, 2026, 14(2), 115-131
https://www.scirp.org/journal/jbcpr
ISSN Online: 2328-4897
ISSN Print: 2328-4889

False Alarm Prevention System for Automatic Fire Shutters in Cold Storage: Focusing on Air Sampling and Waterproof Fixed Temperature Detectors

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How to cite this paper: Lee, D.-C., Yang, C.-K. and Choi, Y.-J. (2026) False Alarm Prevention System for Automatic Fire Shutters in Cold Storage: Focusing on Air Sampling and Waterproof Fixed Temperature Detectors. *Journal of Building Construction and Planning Research*, **14**, 115-131.
https://doi.org/10.4236/jbcpr.2026.142006

Received: June 23, 2026
Accepted: June 27, 2026
Published: June 30, 2026

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Abstract

This study investigates the prevention of false alarms in automatic fire shutter systems within cold storage warehouses, which are frequently triggered by condensation and frost. Despite the advancement of fire safety regulations from basic smoke and heat detectors to photoelectric and flame-type sensors, the high-humidity and low-temperature environments of cold storage facilities still present significant reliability challenges. To address these issues, this paper proposes a hybrid interlock system that utilizes an Air Sampling Detector (ASD) as the first-stage trigger and a Waterproof Fixed Temperature Detector as the second-stage trigger. The proposed ASD system incorporates a dedicated water trap designed to effectively separate and remove moisture from the sampled air, thereby preventing sensor malfunctions caused by water droplets. In smoke response tests on five sampled units, fire signals were transmitted within 15 - 32 s, well below the 120 s maximum transport time. During a 105-day field monitoring period, 19 of the 20 installed ASDs recorded no false alarms, and the single false alarm was traced to an improper sensitivity setting rather than condensation, whereas 12 false alarms caused by condensation and frost occurred in adjacent areas equipped with conventional spot-type smoke detectors. However, the second-stage spot-type heat detectors were mounted at a ceiling height of approximately 10 m, which exceeds the 8 m limit for spot-type heat detectors under the Korean fire detection code (NFTC 203); their role in this study is therefore limited to demonstrating environmental durability, and regulatory compliance of the second stage at high ceilings remains an open issue. These findings suggest that the proposed first-stage ASD can improve the operational reliability

of fire shutters in specialized logistics environments.

Keywords

Cold Storage, Automatic Fire Shutter, False Alarm,
Air Sampling Detector (ASD), Water Trap

1. Introduction

With the recent rapid growth of the fresh food delivery market and the expansion of the logistics industry, the construction of cold storage warehouses has increased significantly both domestically and internationally. Cold storage warehouses require high levels of thermal insulation and airtightness to maintain stable internal temperatures. However, when doors are opened for loading and unloading operations, the influx of warm, humid outdoor air comes into contact with the cold air inside, resulting in severe condensation and frost formation [1] [2]. These unique environmental conditions have a detrimental effect on fire detection systems. In particular, photoelectric smoke detectors operate on the principle of light scattering and may misinterpret fine water vapor particles caused by condensation as fire smoke, frequently triggering false alarms [3]. Malfunctions of fire shutters caused by false alarms not only interrupt logistics operations and result in economic losses but also contribute to a phenomenon known as *alarm fatigue*, in which on-site workers become desensitized to alarms and may ignore them during an actual fire. This poses a potential risk of significant loss of life.

Previous studies have demonstrated that conventional spot-type detectors have considerable limitations in providing early fire detection in large-scale warehouses with high ceilings. The study entitled "A Study on the Method of Calculating Fire Detection Time Considering Photoelectric Smoke Detection Characteristics" [4] empirically demonstrated that, as ceiling height increases, smoke becomes increasingly diluted through mixing with the surrounding air during its upward movement. Furthermore, airflow disturbances near the ceiling may prevent smoke particles from entering the detector chamber, resulting in delayed detection. These physical limitations hinder rapid responses during the early stages of a fire and are a major factor in reducing the reliability of the interlocking operation of automatic fire protection systems, including fire shutters.

Recently, in response to the strengthening of relevant regulations, including Article 14-4 of the *Rules on Standards for Evacuation and Fire Protection Structures of Buildings* and the *National Fire Safety Technical Code for Warehouse Facilities (NFTC 609)* [5], the installation of smoke detectors or flame detectors as first-stage detectors for the activation of automatic fire shutters has become mandatory. In addition, a two-stage interlocking system must be established in which heat detectors initiate the second-stage operation, resulting in complete closure of the fire shutters as the fire progresses and spreads. Accordingly, the need for fire detection technologies that are suitable for low-temperature environ-

ments and high-ceiling conditions while effectively suppressing false alarms has become increasingly urgent.

Therefore, this study proposes a combined fire detection system consisting of an air-sampling smoke detection system (ASD) equipped with a water trap and waterproof fixed-temperature heat detectors to address condensation-related problems in cold storage warehouses [6]. A total of 20 systems were installed at an operational cold storage warehouse, and five key locations were selected for sample-based empirical fire response experiments. In addition, long-term operational logs from the fire alarm control panel were analyzed over a 105-day monitoring period (December 3, 2025 to March 17, 2026). The objective of this study is to propose an optimized approach for reducing false alarms in cold storage warehouses by evaluating the fire response performance of the proposed detection system and analyzing its operational reliability under actual field conditions.

2. Literature Review

2.1. Environmental Characteristics of Cold Storage Warehouses by Temperature Zone

Cold storage warehouses are subject to strict temperature control to maintain the freshness of stored products, and the environmental factors affecting detector operation vary depending on the designated temperature of each area. In this study, the warehouse environment was classified into the following three zones for analysis.

2.1.1. Room Temperature Area

The room temperature area typically maintains a temperature range of 1˚C to 25˚C and primarily includes loading docks and packaging work areas. Although the atmosphere in this area is relatively stable under normal conditions, rapid changes in airflow occur at the boundary where incoming outdoor air mixes with the cold air inside the warehouse when external doors are opened.

Under standard environmental conditions, conventional photoelectric spot-type smoke detectors operate normally. However, when large volumes of hot and humid outdoor air enter the warehouse during the summer, the relative humidity rises sharply, potentially causing the internal chamber of the detector to reach the dew point. The fine water droplets formed under these conditions exhibit scattering behavior similar to that of smoke particles, creating a potential source of false alarms.

2.1.2. Cold Storage Area

The cold storage area maintains a temperature of approximately 0˚C to 10˚C and represents the environment in which condensation, the primary phenomenon of interest in this study, occurs predominantly. During the continuous operation of unit coolers and the dehumidification process, moisture in the air may remain suspended in the form of fine airborne droplets or particles.

Photoelectric smoke detectors measure the intensity of light scattered by parti-

cles entering the detector chamber. In this process, moisture particles can exhibit light-scattering characteristics similar to those of smoke particles generated during a fire [7]. In particular, because the relative humidity in cold storage warehouses is frequently maintained at 85% or higher, condensed moisture can remain within the labyrinth structure of the detector for extended periods, resulting in repeated malfunctions.

These malfunctions can cause problems beyond isolated false alarms, including situations in which the fire alarm control panel cannot be restored to its normal operating state. They can also lead to substantial economic losses, such as disruptions to timely deliveries caused by the unintended activation of fire shutters.

2.1.3. Deep-Frozen Area

The deep-frozen area maintains extremely low temperatures of −18˚C or below, where frost formation and freezing become prominent as moisture solidifies rapidly (**Figure 1**). Moisture entering the detector can accumulate and freeze at the air inlet or on internal optical components, degrading detection performance. Over time, these conditions may also cause equipment failures due to circuit corrosion and the freezing of internal components.

Furthermore, rapid temperature fluctuations during defrosting operations in refrigeration systems repeatedly cause the detector housing to contract and expand, potentially resulting in cracks. The formation of ice layers on the detector surface can also cause the detector head to become physically immobilized, making inspection and maintenance difficult. Consequently, the deep-frozen area represents an extremely harsh operating environment for conventional fire detection equipment.



(a) (b) (c)

Figure 1. Frost and ice formation on detectors in a deep-frozen environment.

2.2. Review of Regulations and Interlocking Requirements for Automatic Fire Shutters

2.2.1. Two-Stage Interlocking Mechanism

In accordance with the relevant laws and regulations, automatic fire shutters must operate using a two-stage interlocking mechanism according to the progression of a fire [8].

First-stage operation: When a smoke detector or flame detector detects a fire at an early stage, the shutter descends to a predetermined height above the floor to prioritize securing an evacuation route for occupants.

Second-stage operation: Subsequently, when a heat detector detects the thermal energy generated by the fire, the shutter descends completely to the floor, forming a fire compartment that prevents the spread of fire through full closure.

2.2.2. Detector Suitability According to Installation Height and Regulatory Gaps

Cold storage warehouses often feature high-ceiling structures exceeding 8 m to accommodate large volumes of stored goods. However, according to the requirements of NFTC 203 presented in Table 1 [9], spot-type heat detectors, including fixed-temperature spot-type detectors, are listed only for mounting heights below 8 m (special class or class 1 between 4 m and 8 m), and at mounting heights of 8 m or more only a limited range of detectors is permitted. Products that have obtained separate type approval for a higher mounting height may be used within the approved range [9].

Consequently, a regulatory gap arises between the requirements of the Ministry of Land, Infrastructure and Transport, which govern the complete closure of fire shutters during the second stage of operation, and the detector selection criteria stipulated under fire safety regulations [9].

Table 1. Detector adaptability and compliance by installation height.

Step	Legal Basis	Installation Height (H)	Technical Fact	Compliance
1st	(Smoke)	(No Limit)	[ASD] (Buoyant particle sampling)	O (Pass)
2nd	(Heat)	(<8 m)	[Heat] (Thermal activation)	O (Pass)
Gap	(Building Rules) (NFTC 203)	(≥8 m)	[Limit] (Thermal Plume Dilution)	X (Fail)

The *Rules on Standards for Evacuation and Fire Protection Structures of Buildings*, Article 14-4, requires the use of heat detectors for the operation of fire shutters. However, the National Fire Safety Technical Code for Fire Detection and Alarm Systems (NFTC 203) does not list spot-type heat detectors for mounting heights of 8 m or more [9], creating a regulatory gap for the second stage of fire shutter operation in high-ceiling warehouses. This limitation arises because of the thermal plume dilution phenomenon, in which the heat generated by a fire mixes with the surrounding cold air and cools as it rises toward higher ceilings, potentially preventing heat detectors from activating. In contrast, an air-sampling smoke detection system (ASD) is a photoelectric smoke detection system that operates on the principle of light scattering. Unlike heat, which dissipates as it rises, smoke particles can continue to rise toward the ceiling, where they can be actively drawn into the detection system for identification. Therefore, an ASD can satisfy the first-stage (smoke) requirement even in high-ceiling environments. The second-stage (heat) requirement, however, is not resolved by the ASD and depends on where the heat detectors are mounted; this issue is examined in Sections 3.1 and 4. This approach also helps mitigate smoke stratification, in which smoke remains suspended at an intermediate height rather than reaching the ceiling,

thereby improving the operational reliability of fire shutters.

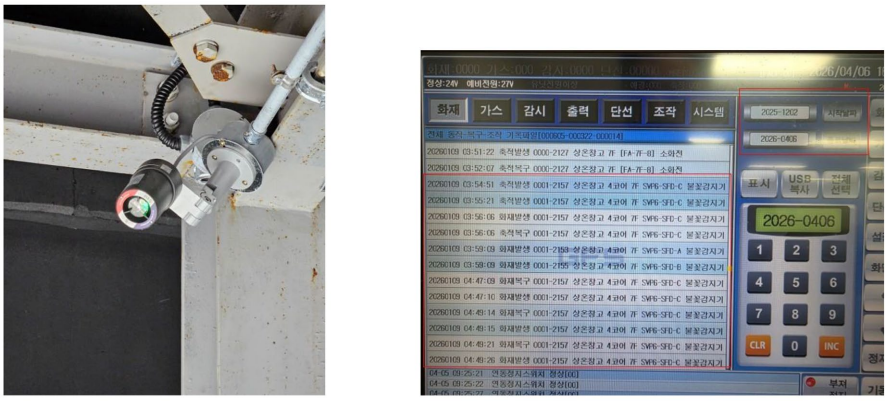
2.2.3. Technical Limitations of Flame Detectors in Cold Storage Warehouses

Although flame detectors are permitted as first-stage detection devices under current regulations, their application in cold storage warehouses presents several critical limitations.

First, visual obstruction caused by stored goods can compromise detection performance. Flame detectors require a clear line of sight to directly receive the radiant energy emitted by a fire. However, high-density racking systems and stored cargo can create blind spots through the shadowing effect, making early fire detection impossible in obstructed areas.

Second, condensation and frost formation in low-temperature environments can impair detector performance. When warm, humid outdoor air entering the warehouse during loading and unloading operations comes into contact with the cold internal environment, condensation may form on the detector lens. This can significantly reduce optical transmittance across the relevant wavelengths, resulting in a reliability failure in which the detector fails to recognize flames during an actual fire.

Frequent false alarms also cause substantial operational disruptions. An analysis of actual field records revealed that a total of 38 malfunction events were recorded over a three-month period, from December 2025 to February 2026, in traffic lanes where vehicle movements occurred frequently (**Figure 2**). These events were attributed to optical interference from sources such as forklift warning lights and LED lighting. Such false alarms can trigger unnecessary fire shutter operations, significantly reducing operational efficiency.



(a) (b)

Figure 2. Flame detectors in cold storage: (a) installation of flame detectors; (b) false alarm logs from the fire receiver.

These limitations stem from the inherent operating characteristics of flame detectors, which passively wait to receive a fire signal. In contrast, an air-sampling smoke detection system (ASD) actively draws air into the system using a fan. This

active sampling mechanism provides a distinct engineering advantage by reducing dependence on direct visibility and enabling the early collection of smoke from the interior of racking systems, where conventional flame detectors may be ineffective because of visual obstructions or optical interference.

Consequently, combining an air-sampling smoke detection system (ASD) with waterproof fixed-temperature heat detectors is essential for compensating for the environmental vulnerabilities of flame detectors and improving overall system reliability.

2.2.4. Technical Feasibility of the Proposed System

This study proposes a combined system consisting of an air-sampling smoke detection system (ASD), which operates on the photoelectric principle and is listed for installation at mounting heights of 20 m or more when an analog-type unit is used [9], and waterproof fixed-temperature heat detectors that are resistant to condensation. The primary-stage ASD is classified as a smoke detector under the type approval requirements [6], allowing its installation in high-ceiling environments. The secondary-stage waterproof fixed-temperature heat detector minimizes the effects of moisture in low-temperature environments through its sealed structure, thereby improving the reliability of the interlocking system. Because it is a spot-type heat detector, however, its use is covered by NFTC 203 only at mounting heights below 8 m, unless separate type approval for a higher mounting height has been obtained [9].

2.3. Comparative Analysis of Detector Performance According to Environmental Characteristics

Table 2. Performance comparison of fire detectors in cold storage environment.

Items	Spot-type (Smoke)	Spot-type (Heat)	Proposed (ASD)	Proposed (Waterproof)
Detection Method	Passive Diffusion	Passive Diffusion	Active Sampling	Passive Diffusion
Response Time	Moderate	Slow	Fast (Laser)	Moderate
Moisture Resistance	Very Low	Low	High (Water Trap)	Excellent (Sealed)
Durability (Frost)	Vulnerable	Vulnerable	High (External)	High (IP67)
Maintenance	Difficult (High)	Difficult (High)	Easy (Floor Level)	Moderate
Legal Compliance[a]	Compliant (1st)	Conditional (2nd; < 8 m)	Compliant (1st)[b]	Conditional (2nd; < 8 m)

Note: [a]: Compliance with the mounting-height limits of NFTC 203 [9]. Spot-type heat detectors, including the waterproof type, are listed only for mounting heights below 8 m unless separate type approval for a higher mounting height has been obtained. [b]: At mounting heights of 20 m or more, only analog-type air-sampling detectors are permitted.

Considering the unique environmental conditions of cold storage warehouses, the performance characteristics of conventional spot-type detectors were compared with those of the system proposed in this study, which combines an air-sampling smoke detection system (ASD) with waterproof heat detectors. The results of this comparative analysis are presented in Table 2.

As shown in Table 2, conventional spot-type smoke detectors have a high probability of generating false alarms due to moisture in low-temperature environments and present maintenance challenges when installed in high-ceiling areas. In contrast, the air-sampling smoke detection system (ASD) proposed in this study provides high reliability in cold storage warehouse environments through its active air-sampling mechanism and moisture separation capability using a water trap.

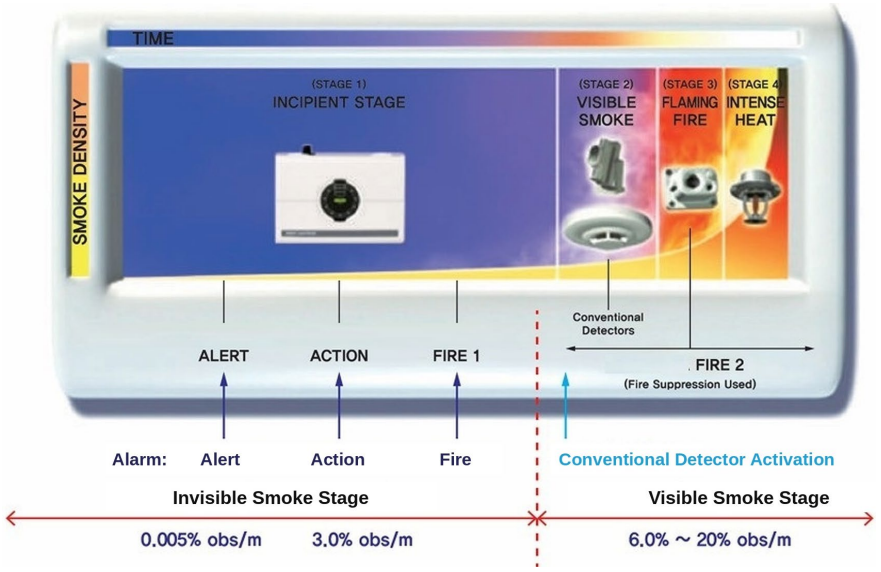


Figure 3. Comparison of fire detection stages between ASD and conventional detectors.

Referring to Figure 3, conventional spot-type smoke detectors typically operate when the smoke concentration reaches the visible smoke stage, corresponding to an obscuration level of 6.0% - 20% obs/m. In contrast, the proposed air-sampling smoke detection system (ASD) can detect a fire at concentrations as low as 0.005% obs/m, corresponding to extremely fine airborne particles [6]. This early fire detection capability provides a key technical basis for rapidly distinguishing actual fires from false alarm conditions and activating interconnected fire shutters, even in cold storage environments where condensation and water vapor occur frequently, thereby minimizing potential losses of life and property [4] [6].

Furthermore, as illustrated in Figure 4, the proposed secondary-stage fixed-temperature waterproof heat detector features a fully sealed enclosure with an IP67 protection rating, preventing equipment failures in deep-freezing environments while serving as the heat detector required for second-stage closure under Article 14-4 of the *Rules on Standards for Evacuation and Fire Protection Struc-*

tures of Buildings. This compliance is conditional on a mounting height below 8 m under NFTC 203 [9].

The fixed-temperature waterproof heat detector operates on the principle that an internal bimetal element bends in response to the heat generated by a fire, physically connecting electrical contacts to trigger fire detection. To protect the internal circuitry in cold storage environments characterized by high moisture levels and frost formation, critical components are completely sealed using materials such as epoxy resin, achieving an IP67 protection rating.

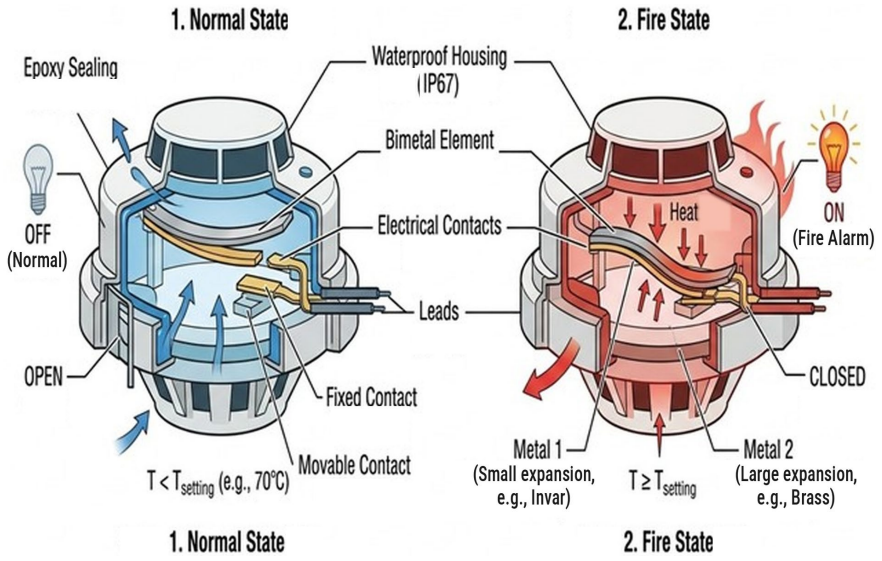


Figure 4. Structure and mechanism of the waterproof heat detector.

This configuration fundamentally prevents malfunctions (false alarms) caused by condensation while ensuring reliable activation of fire shutters during an actual fire. Therefore, the proposed combination of detectors is considered an optimal alternative for preventing unintended fire shutter activation and maximizing fire detection performance in cold storage warehouses characterized by challenging environmental conditions [8] [9].

3. Empirical Experiments

3.1. Configuration of a Fire Detection System Optimized for Cold Storage Warehouses

The first photograph (**Figure 5(a)**) shows the main unit of the air-sampling smoke detection system (ASD), which is the core device of this study. This device employs the photoelectric smoke detection principle, satisfying the requirements for a first-stage smoke detector under applicable regulations [8]. Its internal filters and smoke concentration analysis algorithms effectively suppress malfunctions caused by water vapor [3] [6].

The second photograph (**Figure 5(b)**) shows the sampling pipes and various fittings used for air collection. This piping network, installed along the ceiling of

the cold storage warehouse, serves as an air-sampling pathway. The water trap installed midway along the piping physically separates condensed water from the sampled air, preventing moisture from entering the detector unit.

The third photograph (**Figure 5(c)**) shows the waterproof fixed-temperature heat detector used for second-stage interlocking. This detector features a fully sealed enclosure with an IP67 protection rating, protecting its internal circuitry from extreme moisture and frost in low-temperature environments. In the test facility, the heat detectors were mounted on the ceiling at a height of approximately 10 m, together with the ASD sampling pipes. This mounting height exceeds the 8 m limit that NFTC 203 sets for spot-type heat detectors, and the detectors used had no separate type approval for a higher mounting height [9]. Accordingly, the second-stage results of this study are limited to the environmental durability of the heat detectors (the absence of condensation- and frost-induced faults); they do not demonstrate thermal response performance or regulatory compliance at this height.



(a) (b) (c)

Figure 5. System configuration of the ASD and waterproof heat detector: (a) ASD main unit; (b) sampling pipes and fittings; (c) waterproof fixed-temperature heat detector.

3.2. Field Installation and Condensation Prevention Structure

Sampling pipes were installed inside an operational cold storage warehouse maintained at temperatures ranging from 0˚C to 10˚C. Given the characteristics of low-temperature environments, a water trap was installed at the lowest point of the piping system, as illustrated in **Figure 6,** to prevent condensation inside the pipes from entering the main detector unit. This configuration physically separates moisture from the sampled air, thereby improving the operational reliability of the detection system [2].

The first photograph (**Figure 6(a)**) shows the installation of the air-sampling smoke detection system (ASD) main unit, mounted on the wall of a cold storage warehouse, together with the sampling pipes connected to the overhead ceiling. This configuration is designed to facilitate early fire detection and improve maintenance accessibility in high-ceiling environments.

The second photograph (**Figure 6(b)**) presents a detailed view of the water trap, which is designed to collect condensed water by gravity before it enters the detector chamber. By physically separating condensation generated in low-temperature

environments, this structure helps prevent false alarms caused by water vapor.

The third photograph (**Figure 6(c)**) shows the sampling pipes and waterproof fixed-temperature heat detector mounted on the warehouse ceiling. The active air-sampling mechanism of the ASD and the physical contact-based detection mechanism of the waterproof heat detector work in an integrated manner to maximize overall system reliability [8] [9].



(a) (b) (c)

Figure 6. Installation of the sampling network and moisture drainage system: (a) ASD main unit and sampling pipes; (b) water trap; (c) sampling pipes and waterproof heat detector on the ceiling.

3.3. Verification of Smoke Response and Actual Detection Performance

In this study, field experiments were conducted to verify whether the proposed system could accurately distinguish water vapor from fire smoke under the unique environmental conditions of cold storage warehouses. Smoke was generated inside an operational cold storage warehouse, and the responses of the air-sampling smoke detection system (ASD) and waterproof fixed-temperature heat detectors were monitored in real time. The results showed that the ASD accurately responded to actual smoke particles and transmitted an alarm during the early stages of a fire. The system used a water trap and an internal filter to physically separate moisture entering the system under high-humidity conditions. In particular, condensed water within the sampling pipes was initially collected by the water trap before reaching the optical sensors inside the detector chamber. This configuration prevented interference with light scattering caused by water vapor, thereby eliminating a major source of false alarms [3] [7].

Meanwhile, the waterproof fixed-temperature heat detector installed for second-stage interlocking maintained a stable standby state without corrosion or short circuits, even in environments where condensation occurred frequently, owing to its epoxy-sealed enclosure with an IP67 protection rating [9]. When a fire occurs, the conversion of thermal energy into mechanical displacement by the bimetal element establishes electrical contact. This mechanism provides a high degree of operational certainty for fire shutter closure because it is not susceptible to electronic noise in the same manner as signal-processing circuits. These characteristics help ensure the reliability of the detector's internal components while minimizing the possibility of malfunction under low-temperature

conditions.

The empirical test results demonstrated that the combination of first-stage active early detection using the ASD and the second-stage confirmation signal provided by the waterproof heat detector established a complementary two-stage detection system. This configuration addressed the persistent problem of condensation-induced false alarms at the first stage, and the ASD removed the installation-height limitation for first-stage smoke detection [4] [9]. The installation-height limitation for second-stage heat detection, however, was not resolved, because the heat detectors were mounted above 8 m and their thermal response was not tested in this study. These findings indicate that optimizing detector combinations can directly improve fire safety reliability in logistics facilities subject to severe environmental constraints. Consequently, the proposed system configuration was demonstrated to be a promising alternative for overcoming the environmental limitations of cold storage warehouses and maximizing the accuracy of fire shutter interlocking operations.

The first photograph (**Figure 7(a)**) shows the installation of the ASD sampling pipes, incorporating a water trap, and waterproof fixed-temperature heat detectors on the ceiling of a cold storage warehouse. The components were positioned in accordance with the system design drawings.

The second photograph (**Figure 7(b)**) illustrates the empirical testing procedure used to simulate an actual fire scenario. An aerial work platform was used to reach a height of approximately 10 m near the ceiling, where smoke representing a simulated fire source was directly introduced through a sampling hole in the ASD sampling pipe. This procedure was designed to measure the response time at each stage of system operation when actual smoke particles entered the piping network under conditions characterized by severe condensation.

The third photograph (**Figure 7(c)**) records the operating status of the ASD, showing the sequential illumination of the front-panel LEDs in response to smoke entering the system. The detector progressed through four alarm stages: Alert, Action, Fire 1, and Fire 2, ultimately transmitting a fire signal [8]. The accurate transition between these four stages as the smoke concentration increased indicates that the system was monitoring the progression of a simulated fire rather than simply responding to random environmental interference.



(a) (b) (c)

Figure 7. Smoke response and alarm operation test in cold storage: (a) installed sampling pipes and heat detectors; (b) smoke injection test; (c) ASD alarm-stage indication.

Of the 20 systems installed at the facility, all five sampled units exhibited the expected sequential illumination of the fire alarm indicators. These results provide evidence of the system's operational reliability and early fire detection capability for applications involving fire shutter interlocking [2] [6].

3.4. Analysis of Experimental Results and Reliability Verification

3.4.1. Fire Response Time According to Sampling Pipe Distance

To analyze the fire response characteristics of the proposed system, smoke was generated at designated locations in a low-temperature environment (−1˚C), and the time elapsed until the detector issued its first alarm was measured. A total of five experiments were conducted, using the sampling pipe distance (21 - 27 m out of a maximum length of 100 m) as the experimental variable. The detailed experimental conditions and results are presented in Table 3.

Table 3. Measured fire response time in cold storage test.

Test Case	Set Temp. (˚C)	Sampling Pipe Distance (m)	Response Time (s) (max. 120 s)	Status
Case 1	−1	27	32	Success
Case 2	−1	25	27	Success
Case 3	−1	21	15	Success
Case 4	−1	25	23	Success
Case 5	−1	25	23	Success

The experimental results showed that the air-sampling smoke detection system (ASD) successfully operated and transmitted a fire signal under all test cases. The correlation between sampling pipe distance and response time was analyzed, and the results are presented in Figure 8.

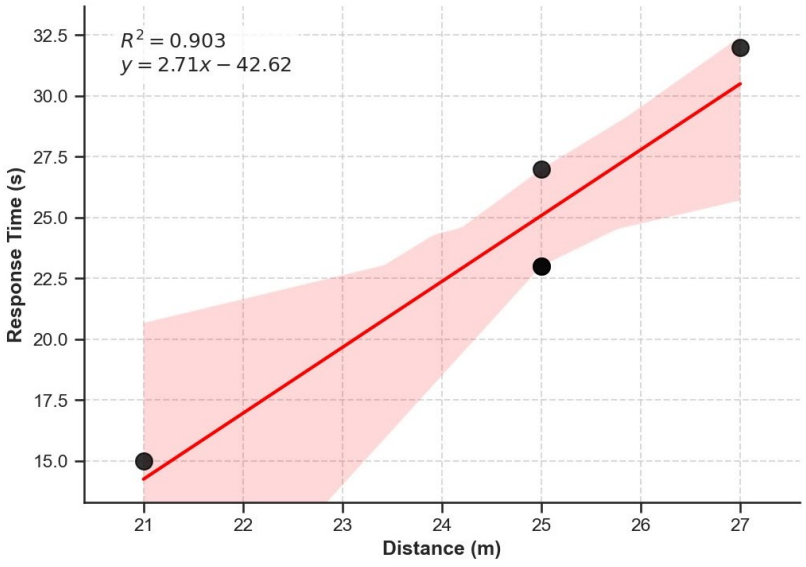


Figure 8. Correlation between sampling pipe distance and response time.

The linear regression analysis presented in **Figure 8** yielded a coefficient of determination (R^2) of 0.903, indicating a strong correlation in which the response time increased linearly with increasing sampling pipe distance. Even at the maximum distance of 27 m (Case 1), the response time was 32 seconds, which was substantially below the maximum transport time of 120 seconds specified in the ASD design guidance [2], representing a response approximately 3.75 times faster than the maximum allowable time. In particular, Cases 2, 4, and 5, which involved the same sampling distance of 25 m, produced consistent response times ranging from 23 to 27 seconds. These results demonstrate that the proposed system maintains highly stable detection reliability even in cold storage warehouse environments characterized by complex airflow patterns.

3.4.2. Verification of False Alarm Suppression through Fire Alarm Control Panel Log Analysis

To verify the actual false alarm suppression performance and field adaptability of the proposed system, a total of 20 air-sampling smoke detection systems (ASDs) designed for fire shutter applications in cold storage warehouses were installed in areas where fire shutters were interconnected with the fire detection system in an operational cold storage warehouse. The complete log records stored in the fire alarm control panel over the 105-day monitoring period from December 3, 2025 to March 17, 2026 were examined and analyzed (**Figure 9**). The results are as follows.

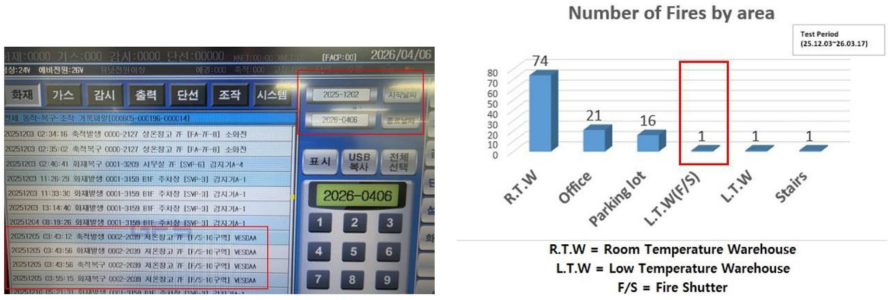
First, in adjacent areas equipped with conventional photoelectric spot-type smoke detectors, a total of 12 false alarm events occurred during the monitoring period due to condensation and frost formation, disrupting logistics operations.

Second, among the 20 ASDs installed for fire shutter applications in this study, 19 units recorded no malfunctions attributable to environmental factors such as condensation or water vapor. This finding indicates that the water traps installed at the lowest points of the sampling pipes effectively suppress the primary causes of false alarms characteristic of cold storage warehouses by physically separating and removing moisture from the sampled air.

Third, one false alarm event was recorded in one of the 20 installed detectors. An analysis of the cause revealed that the event was not attributable to optical interference caused by water vapor but rather to an improper detector sensitivity setting, identified as a configuration error [8]. During field installation, the alarm threshold had been configured at an excessively sensitive level without adequately accounting for the airflow characteristics of the installation area. After the sensitivity parameters were adjusted to the manufacturer's recommended standard values, the detector maintained a stable standby state without any further malfunctions.

These results demonstrate that the ASD system designed for fire shutter applications in cold storage warehouses can successfully overcome condensation-related problems through its hardware configuration. Furthermore, the findings indicate that, in practical field applications, overall system reliability depends not

only on the physical performance of the equipment but also on the precise configuration of operating parameters based on environmental data.



(a) (b)

Figure 9. Field monitoring results: (a) fire history log from the fire receiver; (b) false alarm ratio of fire shutter detectors.

4. Conclusions

This study proposed an optimized fire protection system combining an air-sampling smoke detection system (ASD) designed for fire shutter applications in cold storage warehouses with waterproof fixed-temperature heat detectors to address false alarms and malfunctions caused by condensation and frost under the distinctive environmental conditions of cold storage facilities. The principal conclusions derived from the empirical experiments and data analysis are as follows.

First, fine water vapor particles generated in cold storage environments maintained at temperatures ranging from 0˚C to 10˚C were found to interfere with the light-scattering principle of conventional photoelectric spot-type smoke detectors, resulting in frequent false alarms [3]. The ASD system introduced in this study demonstrated its technical feasibility in addressing this problem by physically separating and removing moisture from the sampled air through a water trap installed at the lowest point of the sampling pipe. This configuration effectively prevents malfunctions attributable to water vapor.

Second, smoke response tests conducted in an operational cold storage warehouse demonstrated that the proposed system achieved a rapid response time of less than 25 seconds on average, even under high-ceiling and low-temperature conditions. This performance supports the system's ability to meet applicable fire signal interlocking requirements and enables the prompt activation of fire shutters during the early stages of a fire, thereby helping prevent fire spread and the development of large-scale fires.

Third, to verify system reliability, a total of 20 ASDs designed for fire shutter applications in cold storage warehouses were installed, and five units were selected for detailed response testing. Subsequently, the operational performance of all 20 units was monitored over a 105-day period (December 3, 2025 to March 17, 2026). The results showed that, whereas 12 false alarm events occurred in areas equipped with conventional detectors, 19 units incorporating the proposed system experienced no condensation-related malfunctions.

Fourth, one false alarm event recorded during the monitoring period was attributed to an improper detector sensitivity setting, identified as a configuration error, rather than to environmental factors. This finding indicates that successful implementation of an ASD system in cold storage warehouses requires not only hardware improvements, such as water traps, but also precise software configuration and parameter setting that account for complex airflow patterns within the facility.

Fifth, the regulatory gap for second-stage heat detection in high-ceiling cold storage warehouses was not resolved in this study. In the test facility, the waterproof fixed-temperature (spot-type) heat detectors were mounted at approximately 10 m, above the 8 m limit for spot-type heat detectors under NFTC 203 [9]. The field results therefore support only their durability under condensation and frost, not their compliance or thermal response at that height. To achieve a compliant second stage, the heat detectors should be mounted below 8 m near the fire shutter where the building geometry permits, a heat detector type listed for the actual mounting height should be selected, or a product with separate type approval for that height should be used. Experimental verification of the thermal response of the selected configuration remains a subject for future research.

In conclusion, the proposed combination of an air-sampling smoke detection system and waterproof fixed-temperature heat detectors has the potential to substantially reduce persistent false alarm problems in cold storage warehouses. By improving the reliability of fire protection systems and the accuracy of fire shutter interlocking operations, the proposed approach is expected to contribute to minimizing casualties and property damage caused by fires in cold storage logistics facilities.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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