Design and Research of Fire Prevention and Control Device for Train Electrical Cabinets

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Abstract. As a core and key component of trains, electrical cabinets have dense internal equipment and a closed, narrow space. Once a fire breaks out, the fire spreads extremely quickly, which will pose a serious threat to the safe operation of the train and may even trigger major safety accidents. To effectively address this potential safety hazard, this paper designs a fire prevention and control device for train electrical cabinets. The device integrates automatic and manual dual fire prevention and control modes, adopts a temperature-electricity dual-control activation mechanism, and is equipped with an environmentally friendly and efficient perfluorohexanone fire extinguishing agent to achieve real-time monitoring and rapid fire extinguishing of electrical cabinet fires. This paper elaborates on the design basis, product application, design objectives, preliminary design scheme, electrical interfaces, and verification methods of the device, and determines the agent dosage and discharge parameters through theoretical calculations. The actual vehicle-mounted operation verification shows that the device operates stably and reliably with excellent fire extinguishing performance, which can meet the strict requirements of fire prevention and control for train electrical cabinets and provide a strong guarantee for the safe operation of trains.

Keywords: Train electrical cabinets,Fire prevention and control device,Perfluorohexanone,Temperature-electricity dual-control,Fire extinguishing agent

1 Introduction

With the vigorous development of the rail transit industry, the operating speed of trains continues to increase, and its safety guarantee system faces higher requirements. As the core hub for power transmission and control of trains, electrical cabinets and medium-voltage cabinets integrate a large number of precision electronic components, lines, and electrical equipment. During operation, fires are prone to occur due to short circuits, overloads, component aging and other factors. Due to the narrow space and poor ventilation conditions of the cabinet, smoke spreads rapidly and the fire spreads quickly after a fire breaks out. Conventional fire extinguishing methods are difficult to intervene quickly, which is easy to cause serious consequences such as equipment burning, train shutdown, and even endanger the safety of passengers.

N. Malik et al. (eds.), *Proceedings of the 6th International Conference on Public Management and Intelligent Society (PMIS 2026)*, Advances in Engineering Research 301,
https://doi.org/10.2991/978-94-6239-721-7_4

Therefore, it is of great practical significance to develop a fire control device for the train electrical cabinet that can realize real-time monitoring and efficient fire extinguishing to improve the safe operation level of the train. Based on relevant national standards and industry specifications, combined with the structural characteristics and fire risk characteristics of train electrical cabinets, this paper designs a set of fire prevention and control device integrating monitoring, alarm, and fire extinguishing, aiming to achieve precise prevention and control of electrical cabinet fires.

2 Design Basis

2.1 Design Purpose

This design provides an advanced, reliable and universal fire control device for the electrical cabinet of the train, defines the functions, parameters, dimensions and installation requirements of the device, and provides a comprehensive technical basis for the R&D, production, installation and verification of the device. The device can effectively realize the real-time monitoring and efficient fire extinguishing of the train electrical cabinet fire, and ensure the safe and stable operation of the train.

2.2 Definitions/Abbreviations

Detection unit: Pressure detection unit, used to collect real-time pressure information inside the fire box and pipeline.

Solenoid valve: Temperature-electricity dual-control solenoid valve, with dual functions of automatic temperature triggering and manual electrical activation.

MVB bus: Multifunctional Vehicle Bus, used for information transmission between various train equipment.

RS485: A commonly used serial communication interface standard, used for communication between the detection unit and the smoke and fire alarm controller.

3 Product Application and Scope of Use

3.1 Product Application

When a fire is detected, the fire extinguishing system can be automatically or manually started to quickly spray extinguishing agent, suppress the spread of the fire, realize the early control and fire extinguishing of the fire, and minimize property losses.

3.2 Working Methods

Automatic Mode.

The device monitors the ambient temperature inside the electrical cabinet in real time through the fusible alloy of the solenoid valve. When the temperature inside the cabinet rises to the set operating temperature of the fusible alloy, the fusible alloy breaks, triggering the activation of the fire box. The fire extinguishing agent is automatically sprayed into the protected space through the pipeline and sprinkler head to achieve automatic fire extinguishing.

Manual Mode.

The smoke and fire alarm system monitors fire information such as temperature and smoke concentration inside the cabinet in real time, and transmits relevant data to the train network through the MVB bus. After the driver obtains and confirms the fire status through the train network, he can operate the manual start button to activate the solenoid valve, trigger the fire box to spray the agent, and implement manual fire extinguishing.

4 Design Objectives

4.1 Device Performance Parameters

The core performance parameters of this fire prevention and control device are optimally designed to meet the operating environment and usage requirements of the train. The specific parameters are shown in the table 1:

Table 1. Performance Parameters of the Fire Prevention and Control Device

No.	Item	Parameter
1	Power supply voltage	DC24V
2	Rated power	< 20W
3	Operating temperature	-40℃~70℃
4	Storage temperature	-40℃~80℃
5	Activation method	Temperature and electricity dual control
6	Agent capacity	1.5kg
7	Agent pressure	1.2~1.6MPa
8	Spraying time	5~8s
9	Protection space	$2m^3$
10	Communication method	RS485 communication
11	Fire extinguishing principle	Gasification heat absorption, oxygen insulation and suffocation, chemical reaction heat absorption
12	Total weight	< 10kg

4.2 Agent Parameters

Basic Characteristics of the Agent.

The fire extinguishing agent used in the device is perfluorohexanone (chemical formula: Dodecafluoro-2-methylpentan-3-one), which is a clear, colorless, and odorless liquid. It is stored in a liquid state and can be vaporized immediately after being sprayed, quickly filling the protected space. Its fire extinguishing principle is based on the synergistic effect of gasification heat absorption, oxygen insulation and suffocation, and chemical reaction heat absorption, with high fire extinguishing efficiency and outstanding environmental friendliness. The agent has an ozone depletion potential (ODP) of 0, a global warming potential (GWP) of 1, and an atmospheric lifetime of only 0.014 days, making it an ideal environmentally friendly chemical fire extinguishing agent at present.

Under different ambient temperature conditions, the pressure stability of this agent is better than that of traditional gaseous agents. When nitrogen is used as the filling gas, the agent pressure only increases by 0.01MPa when the ambient temperature changes in the range of -40°C~80°C, and the filling density of the agent is usually lower than 1.8 times that of the boiling point gaseous agent, which can be used stably in low and high temperature environments.

Physical Characteristics of the Agent.

Physical characteristics of the agent are shown in the Table 2.

Table 2. Physical Characteristics of the Agent

Property	Parameter
Chemical formula	Dodecafluoro-2-methylpentan-3-one
Molecular weight	316.04
Boiling point at 1atm	48°C
Freezing point	-108.0°C
Liquid density at room temperature (25°C)	1.6g/ml
Liquid density at room temperature (25°C) and 1atm	0.0184g/ml
Specific volume at room temperature (25°C) and 1atm	0.0543m³/kg
Liquid viscosity at room temperature (25°C)	0.41-0.56 centistrokes
Solubility of water in perfluorohexanone at room temperature (25°C)	< 0.001% weight percentage
Solubility of water in the agent at 21°C	< 0.001
Vapor pressure at room temperature (25°C)	0.4bar
Dielectric strength	~ 110kv

Fire Extinguishing Performance Parameters of the Agent.

Fire extinguishing performance parameters of the agent are shown in Table 3.

Table 3. Fire Extinguishing Concentration of the Agent (Unit: %)

Combustible	Acetone	Ethanol	n-Heptane	Heptane	Diesel	Methanol	2-Butanone
Agent concentration	5.6	7.2	5.9	5.6	4.5	8.5	5.9

Advantages of the Agent.

High safety: Non-toxic and harmless to the human body, can be used in places where people work;

Non-corrosive: No corrosive effect on storage materials such as rubber and metal, as well as electronic components and lines, and will not cause secondary damage;

No residue: No solid particle residue after release, no need for subsequent cleaning;

Convenient storage: It is liquid at room temperature, no need for high-pressure storage, avoiding the risk of high-pressure leakage, and the transportation safety is not restricted;

Wide application range: Strong fire extinguishing ability, has been widely used in ships, forests, navigation, construction, aviation, oil fields, natural gas, precision instruments and other fields.

Comparison and Analysis Table of Perfluorohexanone and Traditional Gaseous Fire-Extinguishing Agents.

The comparison and analysis of perfluorohexanone and traditional gaseous fire-extinguishing agents are shown in Table 4.

Table 4. Comparison and Analysis Table of Perfluorohexanone and Traditional Gaseous Fire-Extinguishing Agents

Comparison Dimensions	Perfluorohexanone	Traditional Heptafluoropropane	Traditional Carbon Dioxide
Extinguishing Efficiency per Unit Volume (m^3/kg)	1.33 (1.5 kg of agent protects 2 m^3 of space)	0.8~1.0 (2.5 kg of conventional agent protects 2~2.5 m^3 of space)	0.6~0.8 (3 kg of agent protects 1.8~2.4 m^3 of space)
Storage Pressure Requirement (MPa)	1.2~1.6 (normal temperature and low-pressure storage)	2.5~4.2 (high-pressure storage, requiring special pressure-resistant steel cylinders)	15.0 (high-pressure liquefied storage, high risk level)
Cost-Effectiveness Analysis	Initial equipment cost is slightly higher than that of heptafluoropropane systems; no high-pressure leakage risk and low maintenance cost (annual maintenance cost ≤ 500 RMB); no residue, no corrosion, avoiding secondary losses; excellent environmental performance, free from the risk of policy elimination.	Medium initial equipment cost; high-pressure steel cylinders require regular inspection (once every 3 years, single inspection cost about 800 RMB); slight corrosiveness, which may damage precision electronic components; high Global Warming Potential (GWP=2090), facing long-term restrictions from environmental policies.	Lowest initial equipment cost; high maintenance cost for high-pressure storage equipment (annual maintenance cost ≥ 1000 RMB); easy formation of condensed water after fire extinguishing, which may cause short-circuit damage to electrical equipment; has asphyxiation risk to humans, requiring personnel evacuation before activation, not suitable for manned scenarios.

The extinguishing efficiency per unit volume is calculated based on typical application parameters of each system. Due to its fast gasification rate and low extinguishing concentration (only 4.5% for diesel fires), perfluorohexanone provides a larger protection space per unit mass of agent, showing significant efficiency advantages.

In terms of storage pressure, the low-pressure characteristic of perfluorohexanone reduces safety risks during equipment manufacturing, transportation and installation, making it more suitable for installation in the narrow space of trains.

Cost-effectiveness should be evaluated based on the whole-life cycle cost: although the initial investment of the perfluorohexanone system is slightly higher, it avoids regular inspection costs of high-pressure equipment and secondary damage losses. Moreover, it conforms to the "dual carbon" policy orientation and has higher long-term application value.

5 Design Scheme

5.1 Design Principles

As a key system to ensure the safe operation of trains, the fire prevention and control device strictly follows the principles of reliability, safety, practicality, and compatibility in the design process. It adopts mature and reliable circuit design and intelligent logic algorithms, and the core components adopt redundant design to ensure the stable operation of the system under complex working conditions; fully consider the installation space and operating environment of the train, optimize the device structure and size to facilitate installation and maintenance; at the same time, ensure the compatibility of the device with the existing smoke and fire alarm system and train network of the train, so as to realize information interconnection and collaborative work.

5.2 Device Network Topology

One set of fire prevention and control device is installed in each carriage. The entire device consists of a fire box, a pressure detection unit, a temperature-electricity dual-control solenoid valve, pipelines, and sprinkler heads. Among them, the fire box and pressure detection unit are installed inside the electrical cabinet, and the solenoid valve, pipelines, and sprinkler heads are installed in the electrical cabinet and medium-voltage cabinet respectively according to the protection requirements.

The network topology of the device adopts a hierarchical design. The fire box and pressure detection unit establish a connection with the smoke and fire alarm controller through the RS485 communication interface to realize real-time transmission of pressure data and equipment status information; the smoke and fire alarm system performs data interaction with the train network through the MVB bus, and uploads fire information, equipment fault information, etc. to the train network for the driver's real-time monitoring and operation. The device is powered by a DC24V DC power supply.

5.3 Product and System Responsibilities

Pressure Detection.

The pressure detection unit collects real-time pressure data inside the fire box and pipeline, and transmits the pressure information to the smoke and fire alarm controller through RS485 communication. The train network can obtain the pressure data in real time, so it is convenient for the staff to monitor the pressure state of the fire extinguishing system and find abnormal pressure in time [1].

Automatic Fire Prevention and Control.

Through the fusible alloy of the solenoid valve to realize temperature monitoring and linkage activation, it can respond quickly at the initial stage of fire and effectively control the spread of fire [2].

Manual Fire Prevention and Control.

After the smoke and fire alarm system sends out a fire alarm, the driver confirms the fire through the train network and can start the fire extinguishing system through the manual start button. Therefore, it can be applied to the occasions where manual judgment is required to start the fire extinguishing.

Fault Diagnosis.

The detection unit has a complete fault diagnosis function, and realizes automatic fault identification and alarm through real-time monitoring of pipeline pressure information and sensor working status [3]. Details are as follows:

If the pressure sensor signal cannot be read, it is judged as a pressure sensor fault, and a fault alarm is issued in a timely manner;

When the pipeline pressure is lower than the set threshold, it is judged as undervoltage fault, and the equipment will remind the staff to check the tightness of the equipment or supplement the reagent;

When the pipeline pressure is higher than the set threshold, it is judged as overpressure fault to avoid the safety risk of pipeline rupture.

5.4 Overall Layout and Main Component Structures

Fire Box.

The fire box is a container for the storage of fire extinguishing agent, which can hold 1.5L of fire extinguishing agent. Made of high-strength materials, it has good sealing performance and pressure resistance.

Pressure Detection Unit.

The pressure detection unit is mainly used for real-time detection and data transmission of pipeline pressure.. It is equipped with a guide rail adapter and adopts a guide rail installation method, which is convenient for installation and fixation in the electrical cabinet and simplifies the later maintenance and replacement process.

Solenoid Valve.

The solenoid valve adopts the temperature and electricity dual control design, so it can be automatically triggered by the temperature through the fusible alloy or started by the manual power supply. Its installation size is optimally designed to adapt to the installation space of the electrical cabinet and medium-voltage cabinet, ensuring firm installation and reliable operation.

Sprinkler Head.

The nozzle is made of 316 stainless steel [4]. It has good corrosion resistance and can withstand high temperature, so it can adapt to the complex environment of train operation. Through the special design of spray angle and flow rate of the nozzle, it can ensure that the medicament can cover the protection space evenly.

Pipeline.

The pipeline is made of 316 stainless steel with an outer diameter of 8mm and an inner diameter of 4mm. The material has high strength and strong corrosion resistance, and can be flexibly laid according to the internal structure of the electrical cabinet and medium-voltage cabinet to ensure the smooth delivery of the agent to each sprinkler head.

5.5 Calculation and Analysis

Agent Dosage Calculation.

The electrical cabinet has a small space and concentrated equipment. According to this characteristic, a full-coverage fire extinguishing scheme is designed. The fire box is installed inside the electrical cabinet, and the fire detector (fire prevention and control device for electrical cabinet) is installed on the top plate of the electrical cabinet (only the fire detector is installed in the medium-voltage cabinet). Once a fire occurs, the agent can be sprayed to extinguish the fire through remote electrical activation (manual activation) or temperature-controlled activation. The internal space of the electrical cabinet is approximately 2m^3, and the agent dosage is calculated [5]:

Using the fire extinguishing agent dosage calculation formula:

$$m = (100 \times C \times V \times S \times K3) / 100$$

Where: S——Volume ratio, S = (K1 + K2*T) = 0.07325;V——Volume of protected object C, m^3; T——Ambient temperature, T = 25°C;K1——Uneven coefficient, K1 = 0.0664;K2——Agent loss coefficient at different temperatures, K2 = 0.000274;K3——Full-coverage fire extinguishing safety coefficient;C——Agent concentration coefficient, C = 6%

The theoretically calculated fire-extinguishing agent dosage required for the electrical cabinet is 0.25 kg.

The safety factor K3 shall meet the environmental requirements, including the reliability of equipment, the impact correction of environmental conditions and the verification of engineering practice. Details are as follows:

Risk correction factor for rapid fire: The train electrical cabinet is densely populated with electronic components and has limited heat dissipation space. Fires caused by short circuits or overloads are characterized by "second-level spread" (referring to the fire risk assessment data specified in GB/T 25119-2010 Railway Applications - Electronic Equipment for Rolling Stock).The flame temperature can rise to more than 600 °C in 3~5 seconds, so it is significantly faster than the flame propagation speed in general closed occasions. Considering that the dosage of chemicals should meet the protection requirements after rapid fire expansion, a risk correction factor of 2 times is introduced.

Compensation Coefficient for Agent Efficiency Attenuation Under Extreme Environments: The train operating environment involves complex conditions such as wide temperature fluctuations (-40°C~70°C), continuous vibration (5g RMS), and electromagnetic interference (in accordance with GB/T 21563-2018). The test data showed that the gasification rate of perfluorohexanone was reduced by 18% in the low temperature environment (-40 °C), while the local reagent residue rate in the pipeline caused by vibration was about 12%, and the overall efficiency was reduced by about 30%. Therefore, in order to compensate the efficiency loss caused by environmental factors, this paper introduces 1.5 times coefficient.

Leakage Compensation Coefficient for Incompletely Enclosed Spaces: Due to heat dissipation ventilation, cable perforations, and other factors, the train electrical cabinet is not fully enclosed, resulting in partial leakage of the fire-extinguishing agent after discharge. Simulation tests show that the agent leakage rate of a typical electrical cabinet is approximately 10%~15%. Considering engineering design redundancy, a 1-fold leakage compensation coefficient is adopted.

Reliability Redundancy Requirements for Safety-Critical Systems: In accordance with IEC 61508-2 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems,the fire protection and control system of the train shall have a safety integrity level (SIL) of 3. Even if a single fault occurs, it also needs to operate reliably. Combined with the redundancy design principle, a 1.5-fold reliability redundancy coefficient is introduced.

Based on the aforementioned constraints, the safety factor K3 is calculated as follows: Risk Correction Coefficient × Environmental Attenuation Compensation Coefficient × Leakage Compensation Coefficient × Reliability Redundancy Coefficient = $2\times1.5\times1\times1.5=6$. This ensures the sufficiency of the agent dosage and the reliability of fire extinguishing.

Thus, the required agent dosage for the electrical cabinet is 1.5 kilogram, with an agent filling pressure of 1.3~1.7 MPa.

Determination of Spraying Time.

Referring to GB50370-2005 Code for Design of Gas Fire Extinguishing Systems, by analogy with the spraying time requirement of heptafluoropropane fire extinguishing system (no more than 10s), combined with the higher fire extinguishing efficiency of the perfluorohexanone agent used in this device, the agent spraying time is set to 5~8s to ensure that a sufficient amount of agent is quickly sprayed in the early stage of the fire to suppress the spread of the fire.

6 Electrical Interface Description

6.1 Detection Unit Electrical Interface

The detection unit is powered by DC24V, and the equipment is connected with the smoke and fire alarm controller through RS485 communication interface to transmit pressure data and fault information [6] . The definition of interface pin and wiring mode shall strictly follow relevant electrical standards to ensure reliable signal transmission [7].

6.2 Fire Box Electrical Interface

The electrical interface of the fire box is mainly used to receive the activation signal of the solenoid valve, adopting a DC24V control voltage. The interface has the functions of short circuit and overload protection, so the fire box can reliably act and release the extinguishing agent after receiving the activation signal.

6.3 Solenoid Valve Electrical Interface

The solenoid valve is powered by DC24V and has two control signal input interfaces, corresponding to automatic activation (temperature triggering) and manual activation (electrical signal triggering) respectively. The interface design has good sealing and anti vibration performance, so it can meet the vibration and environmental changes during train operation.

7 Verification of the Design Scheme

The performance of the fire control device shall comply with the design requirements and actual use needs. After the design is completed, a series of routine tests and type tests are required [8], including the following test items:

Appearance and structure inspection: Check the appearance quality, dimensional accuracy, installation firmness, etc. of each component of the device;

Electrical performance test: Test electrical parameters such as power supply voltage adaptability, rated power, and communication reliability;

Environmental adaptability test: Including high and low temperature tests (operating temperature -40°C~70°C, storage temperature -40°C~80°C), shock and vibration tests (complying with GB/T 25119-2010 standard), and protection level tests (complying with GB50370-2005 standard);

Fire extinguishing performance test[9]: Under the simulated electrical cabinet fire scenario, test the device's activation response time, spraying time, fire extinguishing success rate, etc., as shown in the figure 1.

Fault diagnosis function test: simulate sensor fault, undervoltage fault and overpressure fault, and check the accuracy of fault diagnosis and timeliness of alarm;

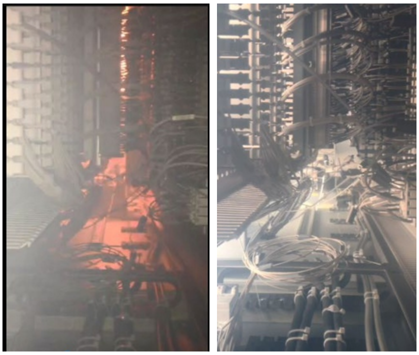

Fig. 1. Ground Electrical Cabinet Fire Extinguishing Test

Long-term reliability test: Conduct long-term continuous operation tests under rated working conditions to evaluate the service life and stability of the device.

Through the above test verification, ensure that all performance indicators of the device are normal.

8 Vehicle-Mounted Operation Status

The fire prevention and control device for train electrical cabinets has completed prototype development and test verification, and has been installed and operated on actual trains,as shown in Figure 2. After a period of actual operation assessment, the device operates stably with normal functions. It can monitor the pressure state and fire information of the electrical cabinet in real time, and can carry out fault diagnosis. In the simulated fire test, there is no fault and abnormality, and the fire extinguishing effect is good. It meets the safe operation requirements of the train and has broad promotion and application value.

Fig. 2. Actual Vehicle-Mounted Photo

9 Conclusions and Prospects

9.1 Conclusions

The fire prevention and control device for train electrical cabinets designed in this paper is based on the temperature-electricity dual-control activation mechanism, adopts an environmentally friendly and efficient perfluorohexanone fire extinguishing agent, and integrates multiple functions such as real-time monitoring, automatic alarm, rapid fire extinguishing, and fault diagnosis. Through reasonable structure and parameter design, the device has the characteristics of small volume, light weight, convenient installation and reliable operation, so it can effectively deal with the fire risk of the train electrical cabinet. The actual on-board operation results show that the device has good fire extinguishing performance, so it can provide a strong guarantee for the safe operation of the train and meet the safety development needs of the rail transit industry.

9.2 Prospects

With the continuous development of rail transit technology, higher requirements are put forward for the intelligence and integration level of train fire prevention and control systems. In the future, the device can be further optimized and upgraded in the following aspects:

Improve the intelligence level: Introduce artificial intelligence algorithms to accurately identify and predict fire signals[10], reducing false alarms and missed alarms;

Realize remote monitoring and maintenance: Through 5G, Internet of Things and other technologies[11], realize real-time remote monitoring and fault early warning of the device's operation status, facilitating staff to conduct remote maintenance and management;

Optimize agent performance: Continuously develop more environmentally friendly, efficient, and low-cost fire extinguishing agents to further improve fire extinguishing efficiency and environmental friendliness;

Expand the application range: Promote the design concept and technical scheme of the device to other types of rail transit vehicles such as urban rail transit and freight trains, as well as related fields such as industrial electrical cabinets, so as to expand the application scenarios of the device.

Declaration of AI-Assisted Technologies

The authors declare that no AI-assisted technologies were used in the writing of this manuscript, and they take full responsibility for the content of the paper.

During the writing of this manuscript, the author used AI tools during the Chinese-to-English translation process and for checking grammar. The authors take full responsibility for the use of these tools and take full responsibility for the content of the paper.

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