Key Performance Regulation of Perfluorohexanone Microcapsules for Active Fire Suppression of Electrical Equipment

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ABSTRACT Polyurethane-based core-shell microcapsules loaded with perfluorohexanone were fabricated via interfacial polymerization in this paper. Four core regulation indicators were defined targeting the operating conditions of electrical equipment: encapsulation efficiency, thermal triggering temperature, long-term storage stability at room temperature, as well as insulation and fire extinguishing performance. Four types of process variables were systematically adjusted in contrast experiments, namely the mass ratio of shell monomers, core-shell mass feeding ratio, emulsification stirring speed and doping dosage of nano-silica. Multiple characterization methods including gas chromatography (GC), thermogravimetric analysis (TGA), withstand voltage insulation tester and simulated electrical cabin fire platform were adopted to establish quantitative correlations between process parameters and key performances of microcapsules. Test results show that optimal comprehensive performance is achieved when the mass ratio of isocyanate to diethylenetriamine is 2.2:1, core-shell feeding ratio is 1:3.5, stirring speed is 1200 r/min and SiO_2 doping content is 3 wt%. Under this condition, the encapsulation efficiency reaches 83.7%, the rupture triggering temperature stabilizes within 110–115 °C, the core material retention rate hits 87.2% after 60 days of storage at ambient temperature. In simulated switch cabinet fire tests, the fire suppressant can be released within 0.6 s and flames are completely extinguished in 7 s. The insulation resistance maintains at the level of 10^{13} Ω without corrosion on circuit boards and metal conductive components.

INDEX TERMS electrical equipment; active fire suppression; perfluorohexanone; microcapsule; performance regulation; interfacial polymerization; power big data for electrical fire early warning

I. INTRODUCTION

A. RESEARCH BACKGROUND

The ownership of power systems, industrial electrical control devices and new energy energy storage equipment keeps growing in China[1-3]. Electrical fires account for over 30% of total annual fire accidents. Fire statistics released by the Ministry of Emergency Management reveal that 85% of electrical fires occur inside narrow closed spaces, such as low-voltage switch cabinets, cable trays, photovoltaic combiner boxes, lithium battery energy storage cabins and charging piles[4, 5]. Three prominent drawbacks restrict the application of traditional fire protection technologies in these scenarios.

First, early ignition is hard to detect manually. Local high temperature generated by aging insulation layers, loose wiring terminals and capacitor thermal runaway only exists inside equipment cavities[6, 7]. Conventional external smoke and temperature detectors suffer detection delays, and flames have already spread when external alarms are triggered.

Second, traditional fire suppressants show poor adaptability. Dry powder fire extinguishers block contacts of precision circuit boards; water-based suppressants cause secondary short circuits and explosions due to electrical conductivity; long-term use of heptafluoropropane brings greenhouse gas emission risks[8]. Third, passive fire suppression systems fail once power cuts off[9]. Pipe network fire extinguishing devices driven by sensors and electromagnetic valves will completely lose fire suppression capacity if short circuits cut off power supply.

Perfluorohexanone is a clean fluorinated ketone fire suppressant. It features electrical insulation and zero solid residues, with short atmospheric lifetime. Upon heating, it decomposes into fluorine free radicals to rapidly capture H· and OH· active radicals in combustion reactions, while absorbing massive heat through vaporization to cool down burning objects. These characteristics perfectly match the fire suppression requirements of electrical equipment[10]. However, pure liquid perfluorohexanone has extremely strong volatility; direct coating or filling leads to complete volatilization within several months, so it cannot be pre-embedded inside equipment for long-term fire monitoring.

Microcapsule technology encapsulates liquid perfluorohexanone inside micron-scale polymer shells to form self-temperature-triggered fire suppression units[11]. When the internal temperature of equipment rises to a preset dangerous threshold, the shell melts and ruptures to release fire suppressant instantly for in-situ active fire suppression. The whole process requires no external power supply or external signal trigger, which makes it a passive self-inductive fire protection material.

Nevertheless, existing perfluorohexanone microcapsules face unbalanced performance issues: excessively thin shells cause leakage at room temperature, overly thick shells greatly raise triggering temperature, insufficient core loading leads to inadequate fire suppression efficiency, and systematic performance regulation schemes targeting electrical operating conditions are still absent.

Aiming at the working conditions of electrical equipment including long-term static storage at room temperature, instant local high-temperature ignition and high insulation requirements, this paper systematically investigates the regulation rules of preparation processes on four core performances of microcapsules, and optimizes preparation parameters suitable for power industry scenarios. Meanwhile, this study integrates early warning ideas based on power big data for electrical fire risks, and constructs an integrated safety scheme combining hidden danger pre-identification and automatic flame extinction. The research provides practical guidance for the industrial application of built-in passive active fire suppression materials in power equipment.

B. RESEARCH STATUS

1) Research Progress on Preparation and Performance of Perfluorohexanone Microcapsules

Microcapsule technology is a novel encapsulation method that fully wraps solid, liquid or gas substances inside thin films composed of natural or synthetic polymers[12]. Its core purpose is to store and protect trace substances. By adopting different polymer compounds as wall materials to fully wrap target substances (core materials or internal phases), the technology can improve core material stability, control release rate and enhance safety.

Yang Binbin et al. [13] conducted detailed research on perfluorohexanone microcapsule technology, covering preparation methods, performance evaluation, process technologies and commercial application prospects, laying a technical foundation for further development and application of perfluorohexanone fire suppressants.

Microcapsulation can shield fire suppressants from environmental interference and realize rapid release for fire suppression when needed[14, 15].

2) Application Status of Power Big Data in Electrical Fire Prevention and Control

Power big data collects massive real-time data including current, voltage, contact temperature, electric leakage and arc characteristics through distribution terminals and sensors. Machine learning algorithms are adopted to establish equipment fire risk grading models for early identification of hidden dangers such as wire aging and overheated terminals.

Zhao Jiaxing et al. [16] studied a power grid fire early warning algorithm based on fuzzy neural networks.

The literature constructed a multi-source perception big data platform for distribution networks, integrating real-time temperature and electrical parameters of switch cabinets and cables to build a three-level fire risk early warning threshold model. The model can predict local overheating hidden dangers 72 hours in advance and provide forward risk guidance for active fire suppression materials.

However, existing big data early warning systems only send alarm information and cannot independently handle early fires.

C. RESEARCH CONTENTS

1.Determine four core performance indicators of perfluorohexanone microcapsules for active fire suppression of electrical equipment, and clarify constraint thresholds of each indicator under power operating conditions;
2.Fabricate polyurethane-based perfluorohexanone microcapsules via low-temperature interfacial polymerization, and carry out orthogonal contrast experiments with four types of regulation variables;
3.Complete sample performance tests through GC, TGA, insulation resistance tester and simulated electrical fire cabin, and analyze the influence rules of single factors and interaction factors on material performances;
4.Obtain optimal preparation processes balancing high core loading, stable storage, precise thermal triggering and superior insulation;
Design an integrated joint prevention and control scheme combining big data early warning model and in-situ active fire suppression of microcapsules for electrical equipment.

D. INNOVATIONS

1.A four-performance synchronous regulation system is established targeting electrical equipment operating conditions, which simultaneously constrains encapsulation efficiency, triggering temperature, core retention rate during storage and insulation resistance. This system makes up for the defect of single-performance optimization in existing research;
2.Nano-silica hybrid modification is introduced to polyurethane shells, solving the contradiction between shell strength and adjustable thermal triggering temperature;
3.A hierarchical matching scheme of microcapsule triggering temperature is proposed by integrating power big data

fire risk early warning algorithms, realizing the combination of hidden danger early warning and passive in-situ flame extinction.

II. EXPERIMENTAL SECTION

A. EXPERIMENTAL RAW MATERIALS AND TESTING INSTRUMENTS

1) Raw Materials

Core material: perfluorohexanone (industrial grade, purity 99.5%, boiling point 49 °C, electrically insulating and non-conductive); Shell monomers: trimethylhydroxypropyl triisocyanate (TMPTI, oil-phase monomer), diethylenetriamine (DETA, water-phase crosslinker); Dispersant: polyvinyl alcohol (PVA, 5 wt% aqueous solution, reduces interfacial tension and stabilizes emulsion); Modification filler: nano silicon dioxide (SiO_2, particle size 30 nm, surface hydroxyl modified to improve shell compactness); Cleaning media: deionized water, anhydrous ethanol.

2) Testing Instruments

Electronic balance, digital constant-temperature stirring emulsifier, low-temperature water bath reactor, vacuum drying oven; Gas chromatograph (GC): measures free perfluorohexanone content to calculate encapsulation efficiency; Simultaneous thermogravimetric analyzer (TGA-DSC): nitrogen atmosphere, heating rate 10 °C/min, measures microcapsule rupture triggering temperature and thermal weight loss curves; Ultra-high insulation resistance tester: tests insulation performance of microcapsule coatings; Simulated closed electrical fire test cabin: simulates short-circuit ignition environment inside switch cabinets, records fire suppressant release duration and flame extinguishing time; Constant temperature and humidity storage box: simulates temperature and humidity in southern power distribution rooms to test core material retention rate after 60 days.

B. MICROCAPSULE PREPARATION PROCESS VIA INTERFACIAL POLYMERIZATION

1.Water phase preparation: Dissolve a certain amount of PVA in deionized water, add diethylenetriamine and stir until fully dissolved. Add nano-SiO_2 with corresponding mass fraction according to experimental groups, and conduct ultrasonic dispersion for 30 min.

2.Oil phase preparation: Mix TMPTI isocyanate monomer and perfluorohexanone core material according to preset core-shell mass ratio, and stir slowly to form uniform mixture.

3.Emulsification and dispersion: Maintain water bath temperature at 40 °C, drop oil phase into water phase slowly, and emulsify continuously for 15 min under corresponding stirring speed to form stable oil-in-water emulsion.

4.Low-temperature polymerization: Keep water bath at 40 °C and stir at low speed for 3 h. Isocyanate and amine monomers crosslink to form polyurethane shells at oil-water interfaces, wrapping perfluorohexanone droplets to generate microcapsules.

Post-treatment: Stand for stratification, clean the mixture three times with deionized water and anhydrous ethanol to remove free monomers and unencapsulated core materials on particle surfaces. Conduct vacuum drying at 40 °C for 8 h to obtain white powdery perfluorohexanone microcapsules.

C. TEST METHODS FOR CORE PERFORMANCES

1) Test of Encapsulation Efficiency and Core Loading Rate

Immerse 1 g microcapsule powder in anhydrous ethanol, break shells via ultrasonic treatment to release all core materials, and measure total mass of perfluorohexanone by GC. Take another 1 g sample without shell breaking, soak in ethanol to dissolve only free core materials on particle surfaces, and measure free core mass by GC.

Calculation formulas:

$$\text{Encapsulation efficiency} = \left(1 - \frac{\text{Mass of free core material}}{\text{Total mass of core material}}\right) \times 100\%$$

$$\text{Core loading rate} = \frac{\begin{array}{c}\text{Mass of perfluorohexanone}\\ \text{inside microcapsules}\end{array}}{\text{Total mass of microcapsules}} \times 100\%$$

2) Test of Thermal Triggering Temperature

Carry out TGA-DSC synchronous thermal analysis under nitrogen protection with temperature rising from room temperature to 300 °C at constant speed. The initial temperature corresponding to the first sharp weight loss on curves is defined as thermal rupture triggering temperature of microcapsules. Electrical equipment requires triggering temperature within 105–120 °C. Temperature below 105 °C leads to false triggering under normal operating temperature of equipment; temperature above 120 °C delays fire suppressant release after flame spread.

3) Test of Storage Stability at Room Temperature

Seal all groups of microcapsules inside constant temperature and humidity box (25 °C, relative humidity 60%) for 60 days. Take samples every 15 days, measure residual core material content by GC and calculate core retention rate. Power equipment has a service life of at least 5 years, so the core retention rate after 60 days of accelerated test should exceed 85% to meet long-term storage requirements.

4) Combined Test of Insulation and Fire Extinguishing Performance

1.Insulation test: Mix microcapsules with silicone rubber to prepare 1 mm thick coatings. Apply 500 V DC voltage via insulation resistance tester and record insulation resistance value. The threshold for electrical scenarios is $\geq 10^{12}$ Ω.

2.Simulated fire suppression test: Install copper bar short-circuit heating source inside closed test cabin, pave microcapsule fire suppression coatings inside the cabin, and record the time consumed for fire suppressant release after temperature rises to triggering threshold and total time to completely extinguish flames.

D. DESIGN OF ORTHOGONAL EXPERIMENTAL VARIABLES

Four core regulation variables with multiple levels were selected in this paper, and a total of 16 groups of samples were tested: Variable A: mass ratio of shell monomers (TMPTI:DETA), Level 1 (1.5:1), Level 2 (2.2:1), Level 3 (2.8:1), Level 4 (3.5:1); Variable B: core-shell feeding mass ratio (perfluorohexanone: total mass of shell monomers), Level 1 (1:2), Level 2 (1:3.5), Level 3 (1:5), Level 4 (1:7); Variable C: emulsification stirring speed, Level 1 (600 r/min), Level 2 (1200 r/min), Level 3 (1800 r/min), Level 4 (2400 r/min); Variable D: mass fraction of nano-SiO_2 additive, Level 1 (0 wt%), Level 2 (1.5 wt%), Level 3 (3 wt%), Level 4 (4.5 wt%).

III. ANALYSIS OF TEST RESULTS AND PERFORMANCE REGULATION RULES

A. REGULATION RULES OF SINGLE VARIABLES ON MICROCAPSULE ENCAPSULATION EFFICIENCY

The regulation rule of single-factor variables on the encapsulation efficiency of microcapsules is shown in Table 1.

Three clear regulation rules can be concluded from data in Table 1.

First, the mass ratio of shell monomers has an optimal range. Insufficient TMPTI leads to incomplete crosslinking, numerous micropores on shells and permeation loss of core materials, with encapsulation efficiency only 62.4%. When TMPTI proportion exceeds 2.2:1, excessive monomers form massive free resin impurities covering microcapsule surfaces, blocking shell pores and reducing effective core loading space, which causes slight decline of encapsulation efficiency. The optimal ratio is 2.2:1 with compact and complete crosslinking network and few free monomers.

Second, core-shell feeding ratio directly determines the upper limit of core loading. When core-shell ratio is 1:2, insufficient shell monomers fail to fully wrap oil droplets, leading to massive free perfluorohexanone in emulsions. The ratio of 1:3.5 can form uniform thin shells to hold core materials sufficiently. Further increasing shell monomer proportion to 1:5 and 1:7 continuously thickens shells, reduces core proportion under the same total mass and lowers encapsulation efficiency synchronously.

Third, stirring speed and nano-SiO_2 produce synergistic promotion effects. Low speed of 600 r/min causes inadequate emulsification with large differences in oil droplet sizes and incomplete wrapping of large droplets. When speed rises to 1200 r/min, emulsion monodispersity improves significantly and microcapsules show regular spherical morphology. Speed exceeding 1800 r/min breaks oil droplets via high shear force to generate massive tiny free core materials, resulting in decreased encapsulation efficiency. Adding 3 wt% nano-SiO_2 fills crosslinking gaps of polyurethane and blocks core permeation channels, lifting encapsulation efficiency by 12% compared with samples without fillers. Fillers over 3 wt% trigger nanoparticle agglomeration to form shell defects and slightly reduce encapsulation efficiency.

Comprehensively considering encapsulation efficiency, the combination A2, B2, C2, D3 (monomer ratio 2.2:1, core-shell ratio 1:3.5, stirring speed 1200 r/min, SiO_2 dosage 3 wt%) achieves peak encapsulation efficiency of 83.7%, meeting the high core loading requirement for electrical fire suppression.

B. REGULATION RULES OF PROCESS PARAMETERS ON THERMAL TRIGGERING TEMPERATURE

Electrical equipment operates at 40–80 °C for long-term service, and the maximum steady temperature inside closed switch cabinets can reach 95 °C in summer. Microcapsule triggering temperature must stay above 95 °C and below 120 °C to release fire suppressant at the early stage of thermal runaway. Table 2 records rupture triggering temperature of each sample group.

Analysis of regulation rules:

1.Crosslinking density of shells dominates triggering temperature. Higher proportion of isocyanate monomers increases polyurethane crosslinking density, improves shell heat resistance and synchronously raises melting rupture temperature. Ratio of 1.5:1 forms loose crosslinking structure, and shells soften and leak at 102 °C. Ratio exceeding 2.8:1 leads to over-compact crosslinking, and shells rupture only above 128 °C. Fire suppressant is released after temperature rises over 130 °C, which allows flame spread and fails early active fire suppression.

2.Nano-silica fillers improve shell thermal stability. Sample S5 without SiO_2 has triggering temperature of 107 °C, barely avoiding the maximum normal operating temperature of equipment. After adding 3 wt% SiO_2, inorganic particles disperse inside polymer networks and inhibit thermal sliding of polymer chains, stabilizing triggering temperature at 113 °C and leaving a safe temperature buffer zone to prevent false release under high-temperature operation in summer. Excessive filler agglomeration causes local stress concentration, leading to premature local shell cracking under high temperature and large fluctuation of triggering temperature.

3.Core-shell ratio affects shell thickness. Higher feeding amount of shell monomers thickens shells, slows heat conduction to internal core materials and raises overall triggering temperature. Samples with core-shell ratio 1:7 reach triggering temperature of 136 °C, completely unsuitable for fast temperature-rise scenarios such as switch cabinets and charging piles.

The optimal triggering temperature range of 110–115 °C corresponds to process parameters of monomer ratio 2.2:1, core-shell ratio 1:3.5 and SiO_2 dosage 3 wt%, which fully matches the optimal parameters for encapsulation efficiency, realizing synchronous compliance of two core performances.

TABLE 1. Comparison of Influences of Four Types of Process Variables on Microcapsule Encapsulation Efficiency

Group No.	A Monomer Ratio	B Core-Shell Ratio	C Stirring Speed (r/min)	D SiO_2 Dosage (wt%)	Encapsulation Efficiency (%)
1	1.5:1	1:2	600	0	62.4
2	1.5:1	1:3.5	1200	1.5	71.6
3	2.2:1	1:3.5	1200	3	83.7
4	2.8:1	1:5	1800	3	79.2
5	3.5:1	1:7	2400	4.5	68.5

TABLE 2. Thermal Triggering Temperature of Microcapsules under Different Process Parameters

Sample No.	Shell Monomer Ratio	Core-Shell Ratio	SiO_2 Dosage (wt%)	Triggering Temperature (°C)	Suitability for Electrical Working Conditions
S1	1.5:1	1:2	0	102	Too low, prone to false triggering
S2	2.2:1	1:3.5	3	113	Fully suitable
S3	2.8:1	1:5	3	128	Too high, delayed fire suppression
S4	3.5:1	1:7	4.5	136	Excessively high, not applicable
S5	2.2:1	1:3.5	0	107	Marginally suitable

C. STORAGE STABILITY REGULATION: CORE MATERIAL RETENTION RATE AFTER 60 DAYS AT ROOM TEMPERATURE

Power equipment needs long-term static storage after delivery. Microcapsules pre-embedded inside equipment cavities should maintain effective fire suppression capacity for at least 3 years. Accelerated storage test for 60 days at ambient temperature can predict long-term leakage risks. Table 3 shows core retention rate after 60 days of storage under constant temperature and humidity.

Data analysis:

1.Emulsification stirring speed determines spherical integrity of microcapsules. Low speed of 600 r/min generates irregular droplets with uneven shell thickness, and core materials slowly permeate through thin positions during long-term storage, leaving only 72.5% effective fire suppressant after 60 days. Speed of 1200 r/min produces emulsion with optimal monodispersity, regular spherical microcapsules and uniform shell thickness with few leakage channels. Stirring speed over 1800 r/min creates tiny shell cracks via high shear force, and cracks expand gradually under long-term humid conditions to accelerate core material loss.

2.Nano-SiO_2 hybridization acts as the core measure to promote storage stability. Polymer chains of pure polyurethane shells contain gaps, allowing small perfluorohexanone molecules to penetrate shells and volatilize slowly. 3 wt% silica fills crosslinking gaps to form dense barrier layers and greatly reduce core permeation rate, lifting 60-day retention rate from 79.1% to 87.2%. Excessive filler agglomeration forms tiny internal cavities inside shells and accelerates leakage conversely.

3.Storage leakage has strong coupling correlation with encapsulation efficiency. Samples with encapsulation efficiency below 70% generally suffer severe leakage due to incomplete shell wrapping and rapid volatilization of free core materials. Samples with encapsulation efficiency over 80% modified by silica show controllable loss during long-term storage and meet the long-term service requirements of power equipment.

D. REGULATION OF INSULATION PERFORMANCE AND SIMULATED FIRE SUPPRESSION PERFORMANCE IN ELECTRICAL CABINS

Two exclusive constraints exist for electrical scenarios: fire suppression materials cannot reduce equipment insulation level, and fire suppressant shall be released rapidly after ignition to extinguish flames within short time and avoid continuous high-temperature damage to circuit boards. Table 4 synchronously records three indicators including coating insulation resistance, fire suppressant release time and total flame extinguishing duration.

Regulation rules:

1.Nano-silica modification simultaneously improves insulation and fire suppression efficiency. Pure polyurethane shells contain trace conductive ion channels with insulation resistance only 1.2×10^{12} Ω. Uniform dispersion of 3 wt% SiO_2 inorganic fillers blocks conductive paths and raises insulation resistance by one order of magnitude to 1.5×10^{13} Ω, fully meeting insulation standards of high-voltage electrical components. Excessive filler agglomeration generates conductive impurity particles and slightly decreases insulation performance.

2.Samples with stable triggering temperature achieve faster release response. Microcapsules prepared under optimal process have concentrated triggering temperature at 113 °C with synchronous shell melting and rupture, releasing all internal perfluorohexanone within 0.6 s. Samples with scattered triggering temperature and uneven shell thickness rupture in batches with release delay over 1 s, extending flame burning time on circuit boards.

Microcapsule encapsulation does not significantly weaken fire suppression capacity. Pure liquid perfluorohexanone extinguishes flames in only 4.2 s but cannot be stored for long periods. The optimal microcapsule sample takes 7 s for fire suppression, merely increasing the time by 2.8 s, while possessing advantages of long-term passive embed-

TABLE 3. Core Material Retention Rate of Microcapsules after 60 Days of Storage at Room Temperature

Test Group	Stirring Speed (r/min)	SiO_2 Filler (wt%)	Core Retention Rate after 60 Days (%)	Leakage Grade
T1	600	0	72.5	Severe leakage
T2	1200	0	79.1	Slight leakage
T3	1200	3	87.2	No obvious leakage
T4	1800	3	84.6	Trace leakage
T5	2400	4.5	78.3	Slight leakage

TABLE 4. Insulation and Simulated Fire Suppression Test Results of Microcapsule Coatings

Sample Formula	Insulation Resistance (Ω)	Fire Suppressant Release Response Time (s)	Total Flame Extinguishing Time (s)
Without SiO_2 modification	1.2×10^{12}	1.1	12.3
1.5 wt% SiO_2	4.6×10^{12}	0.8	9.1
3 wt% SiO_2	1.5×10^{13}	0.6	7.0
4.5 wt% SiO_2	9.2×10^{12}	0.9	10.5
Pure liquid perfluorohexanone (control group)	3.8×10^{13}	Instantaneous	4.2

ding. Its comprehensive adaptability far exceeds liquid fire suppressants.

No solid residues remain inside cabins after fire suppression, copper bars and printed circuit boards suffer no corrosion or conductive residues, eliminating risks of secondary electrical faults.

E. COMPREHENSIVE PERFORMANCE VERIFICATION TEST OF OPTIMAL PROCESS

Based on regulation rules summarized from the first four tables, the optimal preparation process parameters are confirmed as follows: mass ratio of shell monomers TMPTI:DETA = 2.2:1, core-shell feeding mass ratio 1:3.5, emulsification stirring speed 1200 r/min and nano-SiO_2 dosage 3 wt%. Three parallel repeated tests were conducted to verify performance stability, and results are shown in Table 5.

Performance fluctuations of three parallel samples are extremely small, and all indicators reach standard stably, verifying excellent repeatability of this regulation process suitable for large-scale industrial production. All indicators fully satisfy rigid requirements of active fire suppression materials for electrical equipment: encapsulation efficiency over 80% guarantees sufficient fire suppressant supply; triggering temperature of 113 °C avoids normal equipment temperature rise and activates fire suppression precisely at early thermal runaway stage; 60-day core retention rate of 87.2% ensures low loss during long-term service; insulation resistance at 10^{13} Ω level protects electrical safety; flames are fully extinguished within 7 s to safeguard precision electronic components.

IV. JOINT PREVENTION AND CONTROL SCHEME INTEGRATING POWER BIG DATA AND MICROCAPSULE ACTIVE FIRE SUPPRESSION

A. FIRE RISK GRADING LOGIC BASED ON POWER BIG DATA ([16])

Grade I (Low Risk): Equipment temperature stably stays below 85 °C, no arc or leakage signals, low wire aging degree;

Grade II (Medium Risk): Steady terminal temperature ranges from 90 to 100 °C, occasional weak arcs, slight aging of wire insulation;

Grade III (High Risk): Local temperature continuously exceeds 105 °C, frequent arcs and leakage, high risk of insulation layer damage.

Traditional systems only push graded early warning information and rely on manual on-site disposal, leading to delayed response.

Combined with temperature-sensitive regulation characteristics of microcapsules, this paper designs a hierarchical matching layout scheme.

B. DIFFERENTIATED REGULATION AND LAYOUT OF MICROCAPSULES BASED ON RISK GRADING

Adjust microcapsule triggering temperature processes according to big data risk grades to realize targeted hierarchical protection:

1.Grade I low-risk switch cabinets and conventional cable trays: Adopt standard microcapsules with triggering temperature of 113 °C embedded inside cavities to cope with accidental short-circuit ignition;

2.Grade II medium-risk aging circuits and old terminal boxes: Fine-tune process parameters to reduce triggering temperature to 108 °C for early intervention of local overheating and prevent hidden danger expansion;

3.Grade III high-risk energy storage cabins, charging piles and photovoltaic combiner boxes: Adopt composite double-layer microcapsule coatings. Bottom layers with 108 °C low triggering units suppress early temperature rise, while surface layers with standard 113 °C units handle open flames to realize dual active fire suppression guarantee.

TABLE 5. Comprehensive Performances of Three Parallel Samples Prepared by Optimal Process

Parallel Sample	Encapsulation Efficiency (%)	Triggering Temperature (°C)	60-Day Core Retention Rate (%)	Insulation Resistance (Ω)	Total Fire Extinguishing Time (s)
Sample A	83.5	112	87.4	1.4×10^{13}	6.9
Sample B	83.9	114	87.0	1.6×10^{13}	7.1
Sample C	83.7	113	87.2	1.5×10^{13}	7.0
Average Value	83.7	113	87.2	1.5×10^{13}	7.0

The big data platform updates equipment risk grades in real time. Operation and maintenance staff can customize microcapsule fire suppression patches and coatings with corresponding triggering temperatures instead of adopting unified specification materials, balancing protection effects and application costs.

C. COMPLETE JOINT PREVENTION AND CONTROL PROCESS

1.Perception and data collection: Distribution terminals and temperature sensors continuously upload electrical operating parameters to power big data cloud platform;
2.Data analysis and judgment: Fuzzy neural network model calculates fire risk grades in real time and marks high-risk equipment positions;
3.Hierarchical layout: Operation and maintenance personnel select optimized perfluorohexanone microcapsule materials with corresponding triggering temperatures according to risk grades, and paste or spray them on hot spots of equipment;
4.Passive in-situ fire suppression: Local thermal runaway occurs inside equipment, shells rupture to release perfluorohexanone when temperature reaches microcapsule preset threshold, with 0.6 s response time and full flame extinction within 7 s;
5.Post-event data backtracking: The big data platform records temperature and current characteristics of this fire accident, updates neural network model parameters and optimizes subsequent risk prediction accuracy.

This scheme forms a closed loop of "hidden danger prediction – customized material preparation – in-situ fire suppression – model iteration", solving the passive defect of traditional fire protection that handles flames only after ignition. It is applicable to large-scale electrical fire prevention scenarios including transformer substations, industrial and commercial power distribution rooms and new energy energy storage stations.

V. CONCLUSIONS

A. MAIN CONCLUSIONS

1.For active fire suppression scenarios of electrical equipment, four core performances of perfluorohexanone microcapsules need synchronous regulation: core encapsulation loading rate, precise thermal triggering temperature within 110–115 °C, storage stability at room temperature and ultra-high insulation performance. Polyurethane interfacial polymerization system modified by 3 wt% nano-silica hybridization can realize coordinated optimization of all four indicators.
2.Four types of process parameters have a definite optimal combination: mass ratio of isocyanate shell monomers to amine crosslinkers at 2.2:1, core-shell feeding mass ratio of perfluorohexanone to shell monomers at 1:3.5, emulsification stirring speed of 1200 r/min and nano-SiO_2 dosage of 3 wt%. Microcapsules prepared under this process have average encapsulation efficiency of 83.7%, stable triggering temperature of 113 °C, 60-day core retention rate of 87.2%, coating insulation resistance of 1.5×10^{13} Ω, and can extinguish flames inside simulated switch cabinets within 7 s without conductive residues or corrosion on electrical components.
3.Clear regulation rules of process variables are summarized: crosslinking density of shells determines triggering temperature and barrier capacity of shells; emulsification speed controls spherical integrity of microcapsules and directly affects core leakage loss during long-term storage; nano-silica fills polymer crosslinking gaps to simultaneously improve encapsulation efficiency, thermal stability and insulation performance. Particle agglomeration occurs when filler dosage exceeds 3 wt%, leading to reverse decline of all performances.

Combined with three-level fire risk early warning model based on power big data, differentiated regulation of microcapsule triggering temperature can be realized. Low-temperature triggering microcapsules are adopted for high-risk equipment and standard temperature-sensitive microcapsules for conventional equipment. An integrated electrical fire prevention system combining hidden danger prediction and passive in-situ flame extinction is constructed, making up for the defect that traditional early warning systems cannot independently handle fire accidents.

B. LIMITATIONS

1.This paper only carries out 60-day accelerated storage tests at room temperature, lacking long-term natural aging test data of 3–5 years. The aging law of shells under long-term humid conditions and cyclic temperature fluctuation still needs supplementary research.
2.Experiments only simulate single short-circuit ignition scenarios inside switch cabinets, without tests on composite fire hazards such as lithium battery thermal runaway and arc explosion inside high-voltage switch cabinets.

Mechanical properties of composite materials formed by mixing microcapsule powder with silicone rubber and epoxy resin have not been systematically studied, and quantitative data on coating cracking and peeling risks are absent.

C. FUTURE RESEARCH PROSPECTS

1.Conduct long-term cyclic aging tests to establish a performance attenuation model of microcapsules with 10-year service life, and improve evaluation standards for long-term fire protection materials of power equipment.
2.Carry out composite fire hazard tests under multiple scenarios, adjust core composite systems of microcapsules to adapt to complex electrical fires including lithium battery thermal runaway and high-voltage arcs.
3.Optimize composite formulas of microcapsules and polymer substrates to enhance adhesion and vibration resistance of fire suppression coatings, adapting to mobile electrical equipment such as high-speed train traction boxes and vehicle-mounted charging piles.
4.Integrate edge computing power terminals to realize local real-time risk identification via small-scale data, independently adjust layout strategies of microcapsule fire suppression modules on site and reduce transmission pressure of cloud big data.

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