

Preparation of Microcapsule Perfluorohexane and Study on Its Fire Extinguishing Performance

Miao Yu

Guizhou Power Grid Co., Ltd.

Zhang Hengrong

Guizhou Power Grid Co., Ltd.

Liu Anjiang

Guizhou Power Grid Co., Ltd.

Wu Peng

Guizhou Power Grid Co., Ltd.

Zhang Wancheng

Guizhou Power Grid Co., Ltd.

Liu Wenming

liuwenming0226@163.com

Shanghai Puyuan Technology Co., Ltd.

Research Article

Keywords: Microcapsule fire extinguishing agent, Perfluorohexanone, Thermal response, Oil pool fire

Posted Date: August 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10427122/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

As a commonly used fire extinguishing agent, perfluorohexanone has limitations such as high boiling point, poor diffusibility, and strong dependence on external driving forces, which restrict its application in complex scenarios. In this study, a perfluorohexanone microcapsule fire extinguishing agent with a gelatin-phenolic composite shell was innovatively prepared. The particle size characteristics, thermal response law, and fire extinguishing performance in semi-open spaces were systematically investigated using a laser particle size analyzer, thermogravimetric analyzer, and oil pool fire experiment. The results show that the microcapsules have a concentrated particle size range of 400–600 μm , with intact surfaces and uniform morphology; they start thermal response at approximately 75°C and decompose completely at 145°C, and the heating rate can regulate their release behavior. Compared with liquid perfluorohexanone, the microcapsules have the advantages of targeted penetration and delayed release. After fire extinguishing, the shells deposit on the oil surface to form a physical barrier, which effectively inhibits fuel volatilization and delays re-ignition, providing a new technical solution for solving fire extinguishing problems in complex scenarios.

1. Research Background

Perfluorohexanone ($\text{C}_6\text{F}_{12}\text{O}$) is a novel clean fire extinguishing agent and a substitute for halon. It achieves efficient fire suppression through the synergistic effects of multiple mechanisms, including chemical inhibition, in which fluorine radicals are released to interrupt the combustion chain reaction; thermal dilution, in which its high specific heat capacity and vaporization absorb heat; and oxygen isolation. Depending on the type of fuel, its minimum extinguishing concentration can be as low as 4.5%–7% by volume. In addition, perfluorohexanone has an ozone depletion potential (ODP) of zero, a global warming potential (GWP) of only 1, and an atmospheric lifetime of approximately two weeks. These characteristics are significantly superior to those of traditional halons and other emerging alternatives. In recent years, perfluorohexanone has been widely applied in data centers, power facilities, aerospace, cultural heritage protection, and precision electronics^{1–4}.

However, despite its excellent fire extinguishing performance and environmental friendliness, perfluorohexanone still faces several limitations in practical engineering applications. First, compared with most fire extinguishing agents, its relatively high boiling point of 49.2°C gives it a certain degree of liquid-state stability under normal temperature and pressure¹⁵. As a result, after discharge, its vaporization rate is relatively slow, leading to limited diffusion performance and making it difficult to rapidly cover the entire flame region within a short period of time⁵. Zou Jun⁶ et al. pointed out that the amount of pressurizing gas and the volume of the gas chamber have a significant influence on the spraying performance of perfluorohexanone fire-extinguishing devices. Their study indicated that improper matching between these two parameters may lead to poor spraying performance or even failure of the extinguishing device to operate normally. By reasonably regulating the amount of gas used, the spraying efficiency and atomization performance of the extinguishing device can be significantly improved, thereby enhancing its fire-extinguishing effectiveness. To address the above technical

bottlenecks, this study proposes a perfluorohexanone microcapsule fire-extinguishing agent based on gelatin and phenolic polymer materials. In this approach, a gelatin–phenolic composite system is used as the shell material to construct a typical core–shell structure, in which perfluorohexanone is effectively encapsulated within a thermally responsive shell, forming micron-sized microcapsule particles^{7–9}. During the fire-extinguishing process, the microcapsules can be carried by an inert gas to penetrate the turbulent region surrounding the flame and reach the combustion core directly. Owing to its high-temperature-responsive characteristics, the gelatin–phenolic composite shell undergoes thermal decomposition upon contact with the flame, thereby releasing the extinguishing agent^{16–20}. This enables targeted delivery and temporal control, significantly improving the precision of the extinguishing process and the adaptability of the system in complex environments. Wu Yan⁹ et al. reported that microcapsules prepared by encapsulating halogenated hydrocarbons with gelatin-based wall materials exhibited good sealing performance at room temperature, effectively suppressing the volatilization and leakage of the extinguishing agent and significantly improving its storage stability. He Gensheng⁸ found in his study that microcapsule fire-extinguishing agents can rapidly release extinguishing gases once a certain temperature is reached, and can quickly extinguish fires upon contact with open flames or smoldering surfaces, thereby achieving automatic activation and automatic fire suppression. Based on the above studies, microencapsulation technology demonstrates considerable potential and may effectively compensate for the performance limitations of perfluorohexanone^{10, 11}.

In summary, the fire-extinguishing technology system based on perfluorohexanone microcapsules represents an evolution from conventional liquid spraying toward structured and intelligent fire-extinguishing materials. By integrating rapid response, effective flame suppression, and environmental adaptability, this technology provides an important theoretical basis and an engineering solution for efficient fire suppression in future complex fire scenarios.

2. Experimental and Testing Methods

2.1 Preparation of Perfluorohexanone Microcapsules

The first wall layer was prepared as follows. A mixture of 10.5 mL of perfluorohexanone, 32 mL of 5% gelatin solution, and 20 mL of a dispersion containing 0.25% nano-SiO₂ and 0.75% nano-TiO₂ was fully emulsified at 25°C and 1300 rpm. Subsequently, 4.8 mL of 5% sodium hexametaphosphate solution was added dropwise, and the system was allowed to undergo coacervation for 20 min, followed by ice-bath treatment for 1 h. Then, 5 mL of 10% glutaraldehyde solution was added dropwise, and the reaction was carried out at 35°C and pH 7 for 40 min. After that, 5.2 mL of 15% resorcinol solution was added dropwise, and the reaction proceeded at 35°C and pH 2–3 for 15 min. Finally, 8 mL of 37% formaldehyde solution was added dropwise, and the reaction was maintained at 35°C for 35 min to obtain single-layer microcapsules^{21–23}.

The polymer for the second wall layer was prepared as follows. Urea was added to a 37% formaldehyde solution at a molar ratio of 1:1.8, and the pH of the system was adjusted to 9.5. The reaction was carried out at 75°C for 1 h to obtain a linear urea–formaldehyde prepolymer. After cooling and dilution with deionized water, the prepolymer was slowly added to the single-layer microcapsule system. The pH was then adjusted to 2.5, and the temperature was raised to 40°C for curing for 2 h. The solution in the three-necked flask was filtered, and the product was repeatedly washed three times with deionized water until neutral. Finally, the product was thoroughly dried to obtain perfluorohexanone microcapsules^{23–25}.

2.2 Characterization Methods for Perfluorohexanone Microcapsules

The morphology of the perfluorohexanone microcapsules was characterized using scanning electron microscopy (SEM) and a laser particle size analyzer. The structural composition of the perfluorohexanone microcapsules was analyzed by Fourier-transform infrared spectroscopy (FT-IR) and X-ray photoelectron spectroscopy (XPS). The thermal stability of the perfluorohexanone microcapsules was evaluated using a Hitachi STA200 thermogravimetric analyzer^{26–29}. The tests were conducted in a nitrogen atmosphere using alumina crucibles, with the gas flow rate controlled at 50 mL/min. Four different heating rates, namely 10, 20, 30, and 40 K/min, were applied to simulate the different temperature-rise conditions that may occur in fire scenarios. The temperature range was from room temperature to 800°C. The mass of each sample was controlled at 4 ± 0.2 mg. To improve the accuracy and repeatability of the data, all tests were repeated three times under the same conditions, and the average values were used.

2.3 Fire-Extinguishing Experiment in a Semi-Open Space

A typical pool-fire combustion and spray fire-extinguishing experimental platform was designed in a semi-open space with dimensions of 1 m × 1 m × 1 m, as shown in the figure below. A multi-source data acquisition system was used to monitor and analyze the temperature and image information during the fire-extinguishing process. The extinguishing agent was driven by high-purity nitrogen, and a static pressure of 1.0 MPa was applied to achieve high-speed release^{30–34}. Analytical-grade n-heptane (C₇H₁₆) was selected as the fuel. After measurement, 30 g of n-heptane was accurately weighed and injected into the oil pan as the combustion source. The oil pan had dimensions of 10 cm × 10 cm × 10 cm and was made of high-temperature-resistant stainless steel, providing excellent thermal stability and suitability for repeated fire-extinguishing experiments³⁵.

A total of eight K-type armored thermocouples were arranged in the experiment. All thermocouples were connected to a temperature acquisition system, and the data sampling frequency was set to 10 Hz, enabling stable recording of high-frequency temperature variations throughout the fire-extinguishing process. A high-speed camera was used for visible-light imaging of the entire fire-extinguishing process, while an infrared thermal imager was employed to record two-dimensional temperature distribution images^{37,38}. These measurements were used to obtain the spray cooling range, the disappearance

process of hot spots, and the evolution of the spatial temperature distribution before and after fire extinguishment.

Schematic diagram of the n-heptane fire-extinguishing apparatus: 1. Computer; 2. Temperature data acquisition instrument; 3. Thermocouple tree; 4. Oil pan; 5. Fire extinguisher; 6. High-definition camera/infrared thermal imager.

3. Results and Discussion

3.1 Structural Characterization of Perfluorohexanone Microcapsules

Figure 1 shows the particle size distribution and SEM surface morphology of the prepared microcapsules. The results indicate that the particle size of the microcapsules was mainly concentrated in the range of 400–600 μm , with a narrow distribution and good particle uniformity. The SEM images show that the microcapsules had intact surfaces, clear outlines, and good dispersibility, with no obvious agglomeration or collapse. This indicates that the encapsulation structure was stable and that the emulsification process was uniform. The excellent morphology control can be attributed to the gelatin–phenolic composite shell system used in this study.

The FT-IR spectrum and XPS survey spectrum of the perfluorohexanone microcapsules are shown in Fig. 2. In Fig. 2a, the absorption peak at 1737 cm^{-1} corresponds to the stretching vibration of the $\text{C}=\text{O}$ group in the perfluorohexanone core material. The peaks at 1303 cm^{-1} and 1260 cm^{-1} are assigned to the stretching vibrations of CF_3 and CF_2 groups in the perfluorohexanone core, respectively. The characteristic infrared absorption peaks in the range of $2800\text{--}3000\text{ cm}^{-1}$ are attributed to the stretching vibrations of CH_3 and CH_2 groups in the shell material. As shown in Fig. 2b, a binding energy peak appears at 682.2 eV, corresponding to the F 1s signal of the C–F groups derived from the perfluorohexanone core material³⁹.

Therefore, the perfluorohexanone microcapsules were successfully prepared. After the perfluorohexanone microcapsules were ground and dried in an oven at 100°C to a constant weight, the encapsulation efficiency of the microcapsules was measured to be approximately 60%.

3.2 Analysis of the Thermal Decomposition Behavior of Perfluorohexanone Microcapsules

To simulate different temperature-rise-rate environments that may occur in actual fire scenarios, heating rates of 10–40 K/min were adopted to investigate the pyrolysis behavior of the microcapsules. Figures 3a and 3b show the thermogravimetric curves and reaction rate curves of the microcapsule fire-extinguishing agent, respectively^{41–44}. The mass loss curves indicate that the microcapsule shell began to undergo thermal decomposition at approximately 75°C , after which the core material,

perfluorohexanone, was gradually released and became available to react with free radicals in the flame. This suggests that the microcapsules exhibit good thermal stability under room-temperature storage conditions, while being able to respond rapidly under thermal radiation or local temperature rise, thereby satisfying the requirements for early-stage fire suppression.

As the temperature further increased, the decomposition reaction of the shell intensified and was completed at around 145°C. At this stage, perfluorohexanone was completely released and the shell was fully decomposed, thereby maximizing the fire-extinguishing effect. This release behavior enables the extinguishing agent to gradually release chemical species capable of capturing flame radicals during the early stage of fire development, while avoiding system instability caused by sudden and intense release. In addition, the complete decomposition of the shell at approximately 145°C allows the extinguishing agent to achieve maximum delivery before the fire source is fully developed. Moreover, this release behavior is highly consistent with the temperature-rise process in actual fire scenarios, demonstrating good temperature-responsive performance and enabling the microcapsules to adapt to various application scenarios.

The reaction rate curves further verify the above analysis. As the heating rate increased from 10 K/min to 40 K/min, the peak reaction rate of microcapsule pyrolysis decreased significantly, indicating that the thermal release process became more gradual. This phenomenon can mainly be attributed to the hysteresis effect between heat conduction and thermal response within the shell, which prevents the release of the core material from occurring as a sudden burst and instead results in a certain sustained-release behavior. Such a buffering response to temperature variation helps reduce the risk of local overheating and avoids flame deflagration or system instability caused by instantaneous large-scale release, thereby improving the overall thermal safety of the system.

The microcapsules exhibited higher thermal response sensitivity under medium and low heating rates, making them more suitable for rapid identification of and active intervention in early-stage fire sources. This contributes to enhancing the adaptability and response performance of the fire-extinguishing system in multiple scenarios. In addition, several weak shoulder peaks were observed at the edges of the main reaction peak. The fundamental reason for this phenomenon is that the inherent microstructure of the gelatin–phenolic composite shell varies slightly at different positions, resulting in a certain degree of non-uniform thermal response, which is a normal feature of the preparation process. Furthermore, gelatin forms a flexible network structure through hydrogen bonding and crosslinking agents, whereas phenolic resin constructs a dense rigid framework through thermal curing reactions. Therefore, the two components exhibit significant differences in thermal stability and decomposition mechanisms.

3.3. Fire Extinguishing Application in a Semi-Open Space

In this study, the fire extinguishing performance of liquid perfluorohexanone and its microencapsulated form against pool fires in a semi-open space was compared to reveal the differences between the two release modes in terms of thermal responsiveness, coverage and diffusion capability, and fire

suppression effectiveness. Figure 4 shows the temperature variation at each measurement point over time after the flame became stable and the extinguishing agent was discharged. To ensure the comparability of the experimental data, perfluorohexanone was discharged only after the flame was fully established and had reached a quasi-steady state in all tests. After the n-heptane in the oil pan was ignited, the temperatures at both the flame center and the flame edge increased rapidly, and the temperature peak was higher at positions closer to the fuel surface.

Among them, thermocouple No. 1 at the flame center, located near the bottom of the flame core, responded first. Its temperature increased sharply within a short period and reached a peak close to 600°C before the extinguishing agent was released. After perfluorohexanone was sprayed into the flame, the temperature dropped abruptly and rapidly decreased to below 200°C within approximately 30 s, indicating the strong cooling effect and chain-reaction inhibition capability of the extinguishing agent in the flame core region. Similarly, thermocouple No. 1 at the flame edge also showed a rapid temperature rise after ignition, with the temperature eventually stabilizing at around 400°C. Subsequently, within a few seconds, approximately at 6 s, the temperature quickly dropped to below 200°C due to coverage by the extinguishing agent spray. The earlier cessation of temperature increase in this region may be attributed to its location at the flame edge, where airflow disturbance was relatively strong. Under the limitations of heat release intensity and local oxygen concentration, the temperature was suppressed after reaching a plateau.

The other measurement points, including thermocouples No. 2–4 at the flame center and No. 2–4 at the flame edge, exhibited similar trends. During the initial stage of flame development, the temperature increased gradually. After the extinguishing agent was discharged, all measurement points showed a significant and synchronous rapid decrease in temperature. This indicates that the perfluorohexanone spray had good spatial diffusion and coverage capability, enabling it to act comprehensively on both the flame core and surrounding regions within a very short time. Overall, the results demonstrate that perfluorohexanone can rapidly suppress the heat release reactions in both the flame center and flame edge regions after discharge and significantly reduce the system temperature within a short period, confirming its rapid fire extinguishing effectiveness in a semi-open space.

Figures 5 and 6 sequentially present the image sequences of the entire process from ignition, combustion growth, and extinguishing agent discharge to flame extinction, visually reflecting the temporal evolution of the flame geometry, brightness, and expansion behavior during the fire extinguishing process. When the flame was not disturbed by the extinguishing agent, it underwent a typical free-burning process, during which its morphology gradually intensified. This was mainly reflected in the continuous increase in flame height, the expansion of the lateral spreading range, and the gradual enhancement of flame brightness, which corresponded to an increase in temperature. This process is consistent with the heat release characteristics of n-heptane pool combustion. Fuel vapor continuously accumulated and was ignited, producing a stable and intense diffusion flame with typical luminous flame features.

When the perfluorohexanone discharge device was activated and the agent first came into contact with the combustion region, the images showed a transient “expansion” phenomenon within a very short period. Specifically, the flame volume increased instantaneously, the flame boundary became blurred, and the brightness was enhanced. This phenomenon may be jointly driven by the following two mechanisms. The first is the momentum impact effect. Since perfluorohexanone is stored in liquid form, the discharge process is driven by high-pressure nitrogen to form a high-speed gas–liquid mixed spray jet. When this jet first acts on the flame region, the large momentum impact associated with it can disturb the flow boundary and turbulent structure of the flame, causing the flame to be temporarily “blown up” or to expand upward and outward. The second is combustion-promoting transitional behavior. Previous studies have shown that, at low concentrations and under high-temperature conditions, perfluorohexanone may partially undergo thermal decomposition to generate combustible or mildly reactive intermediates, such as $\text{CF}_3\cdot$ and $\text{C}_2\text{F}_5\cdot$. Meanwhile, before its cooling effect becomes fully effective, the reaction rate of the local combustible mixture may be temporarily enhanced¹². In addition, due to the high density of perfluorohexanone itself, 1.6 g/cm^3 at 25°C , it tends to deposit in the lower region of the flame after initial injection and form a new reaction zone with unburned fuel vapor, which may also contribute to the transient intensification of the flame.

However, as the extinguishing agent spray continued to be released and accumulated in space, its concentration rapidly increased to the effective fire suppression range. The images show that the flame volume began to shrink significantly, the brightness gradually weakened, and the flame boundary became increasingly blurred until the flame was completely extinguished. The fire extinguishing behavior at this stage was mainly governed by the synergistic effects of three core mechanisms. First, chemical inhibition occurred. Under high-temperature conditions, perfluorohexanone releases fluorine-containing radicals, which can react with key radicals such as $\text{H}\cdot$ and $\text{OH}\cdot$ in the combustion chain reaction, thereby interrupting the radical chain reaction and rapidly reducing the flame reaction rate. Second, thermal dilution and cooling effects played an important role. The liquid droplets of perfluorohexanone vaporized at high temperature and absorbed a large amount of latent heat. Owing to its high specific heat capacity, perfluorohexanone can significantly reduce the local gas-phase temperature within a short period, thereby suppressing the combustion reaction. Third, shielding and oxygen isolation effects were also involved. In spray form, perfluorohexanone forms a dense aerosol cloud in the space, effectively diluting the surrounding oxygen concentration and blocking the supply of air to the flame core region, thereby weakening the conditions required to sustain the flame^{6, 13, 14}.

Finally, under the combined conditions of sufficient extinguishing agent concentration, cooling of the heat source, and restricted oxygen supply, the flame was rapidly extinguished. In the images, this was manifested as the disappearance of the flame, homogenization of the background temperature, and a stable state with no residual luminous flame. This process fully demonstrates that nitrogen-driven perfluorohexanone has the potential for rapid response and efficient fire suppression, especially in semi-open spaces where high extinguishing speed and broad coverage are required. The image analysis is consistent with and further supports the thermocouple temperature data discussed above.

Figure 7 shows the variation process of the oil pool flame temperature after the discharge of perfluorohexanone microcapsules, comprehensively reflecting the thermal response characteristics of the microencapsulated extinguishing agent when acting on an n-heptane pool fire in a semi-open space. Overall, the temperature curves at the measurement points in both the flame center and flame edge exhibited a typical “rise followed by decline” trend. Compared with liquid perfluorohexanone, the temperature decrease was more gradual and showed a certain delay effect.

Taking thermocouple No. 1 at the flame center as an example, its temperature increased rapidly after ignition and reached a maximum of approximately 480°C. After the microencapsulated extinguishing agent was discharged, the temperature gradually decreased and dropped below 200°C within approximately 33 s. Compared with the liquid perfluorohexanone shown in Fig. 4, although both agents could achieve effective cooling, the microencapsulated extinguishing agent exhibited a longer response time and a lower cooling rate, indicating that its initial cooling effect was weaker than that of the liquid form. This is mainly related to the structural characteristics of microcapsules. During discharge, liquid perfluorohexanone can directly vaporize and absorb heat, thereby producing a strong instantaneous cooling effect. In contrast, the microencapsulated structure must undergo thermal decomposition or rupture of the shell material before release, resulting in a certain time delay in the release of the extinguishing agent.

However, the microcapsules also exhibited unique advantages. Since perfluorohexanone is encapsulated by polymer materials, the particles have a relatively small size and low mass transfer resistance, allowing them to penetrate the outer flame more stably in a quasi-solid or droplet form and reach the flame core region. This “targeted penetration” characteristic is beneficial for achieving more precise inhibition of the chain reaction and improving the fire extinguishing efficiency per unit dose.

In addition, a transient “decrease followed by increase” fluctuation appeared in the temperature rise curve of thermocouple No. 1 at the flame center. Based on the actual experimental conditions and the response characteristics of the sensor, this anomaly was most likely caused by error factors such as thermocouple response delay, local shielding, or electrical signal disturbance, and does not reflect the true thermal behavior of the flame itself. For thermocouple No. 1 at the flame edge, the temperature remained at a high-temperature plateau for a period after reaching approximately 420°C and then decreased rapidly after contact with the extinguishing agent, indicating that the microencapsulated extinguishing agent also had a good cooling effect in the flame edge region.

The remaining thermocouple measurement points, including flame center No. 2–4 and flame edge No. 2–4, exhibited similar trends, indicating that the extinguishing agent was uniformly distributed in the space and that the overall coverage range was stable. In summary, although perfluorohexanone microcapsules are slightly inferior to the liquid extinguishing agent in terms of initial fire suppression response, they possess unique advantages such as strong penetration capability, delayed release, and targeted action in the flame core region. Therefore, they are particularly suitable for scenarios with complex flame spatial structures where spray coverage is difficult to achieve comprehensively.

Figures 8 and 9 respectively present the image sequences of the entire process from flame ignition, natural growth, and perfluorohexanone microcapsule release to flame extinction, visually revealing the dynamic evolution characteristics of the flame structure during fire suppression. As shown in the images, the flame was rapidly established after ignition and underwent an initial natural expansion stage, during which its height and brightness gradually increased, forming a typical diffusion flame. In the absence of interference from the extinguishing agent, the fuel, n-heptane, continuously evaporated and mixed with the surrounding air for combustion, producing a stable and intense luminous flame.

When the perfluorohexanone microcapsules were first sprayed into the flame region, the images clearly showed a pronounced “expansion” phenomenon within a very short period. The flame height, area, and brightness all increased sharply, and the flame boundary expanded significantly. This phenomenon was more intense than that observed during the discharge of liquid perfluorohexanone. The instantaneous “explosive growth” of the flame can be attributed to the following synergistic mechanisms. First, the gas momentum disturbance effect occurred: during discharge, the high-speed jet generated by nitrogen as the driving gas disturbed the flame base and promoted the rapid diffusion of the flame plume. Second, the gas release effect induced by thermal decomposition was involved: under the action of the high-temperature flame, the polymer shell of the microcapsules underwent pyrolysis or cracking and released a certain amount of gas. This process not only increased the gas-phase volume but also exerted an expansion effect on the flame structure. Third, the concentrated vaporization and release effect of the extinguishing agent also contributed to this behavior. Since some microcapsules were directly transported into the flame core region, the perfluorohexanone carried by them rapidly vaporized. The volume expansion during vaporization and the formation of a vapor cloud temporarily enhanced the flame, especially by generating strong local convection near the flame base, thereby further intensifying the expansion of the flame structure. Fourth, although phenolic resin and gelatin possess certain flame-retardant properties, the shell materials may still exhibit a degree of combustibility under high-temperature or oxygen-enriched conditions. This combustibility may temporarily enhance the flame or release additional heat, thereby reducing the fire extinguishing efficiency.

Although the flame growth observed at this stage appears abnormal, it is essentially a transitional response before the effective release of the microencapsulated extinguishing agent, characterized by short duration and localized influence. Subsequently, as the amount of released extinguishing agent gradually accumulated and its concentration increased, its fire suppression mechanisms began to take effect. The images show that the flame gradually shrank, its brightness decreased, and it was eventually completely extinguished. This process indicates that, despite the initial disturbance effect, the microencapsulated extinguishing agent can still achieve effective fire suppression through combined mechanisms, including vaporization heat absorption, radical scavenging, dilution, and shielding.

Figure 10 shows the state of the oil pool surface after fire extinguishment. As can be clearly observed, a large number of microcapsule shell fragments were deposited and adhered to the oil pool surface, forming a discontinuous but densely distributed solid isolation layer. This structure played an important role as a “residual fire suppression barrier” after extinguishment. The microcapsule shell covering layer

effectively reduced the evaporation rate of the fuel, inhibited the re-release of flammable vapor, and further prevented the possibility of flame reignition.

4. Conclusions

To address the limitations of perfluorohexanone, including its high boiling point, poor diffusivity, and strong dependence on external driving force, this study proposed a perfluorohexanone microcapsule fire extinguishing agent based on a gelatin–phenolic resin composite shell. Systematic tests were conducted on the particle size, thermal response behavior, and fire extinguishing performance of microencapsulated perfluorohexanone in a semi-open space. The results showed that the gelatin–phenolic resin composite shell achieved structural advantages by combining good film-forming ability with thermal stability. The prepared perfluorohexanone microcapsules exhibited a particle size mainly concentrated in the range of 400–600 μm , with intact surfaces and uniform morphology, which improved their thermal responsiveness and environmental adaptability.

The microencapsulated perfluorohexanone began to respond at approximately 75°C and completely decomposed at approximately 145°C. Increasing the heating rate made the shell response more uniform, indicating that its release behavior was controllable and that it possessed excellent thermally regulated performance. Compared with liquid perfluorohexanone, the microencapsulated form showed a slightly slower initial response, but it offered unique advantages, including targeted penetration, delayed release, and prolonged action duration. Therefore, it is suitable for scenarios with complex flame structures or where spray coverage is difficult to achieve. After fire extinguishment, the microcapsule shells were deposited on the oil surface, forming a physical isolation layer that suppressed fuel evaporation and reduced the risk of reignition.

Declarations

Notes

The authors declare no competing financial interest.

Author Contribution

Yu Miao and Hengrong Zhang conceived the research framework, performed data analysis, and drafted the complete main manuscript text. Anjiang Liu was responsible for experimental design, data visualization, and prepared Figures 1–3. Peng Wu and Wancheng Zhang assisted in literature collection, experimental testing, and revised the manuscript for logical consistency and expression. Wenming Liu supervised the whole research work, put forward valuable revision suggestions, and checked the integrity of all data and content. All authors have carefully read, reviewed, and approved the final version of the submitted manuscript.

ACKNOWLEDGMENTS

The work was financially supported by the Southern Power Grid Technology Project: (060000KC23110057).

References

1. Wang P, Du Q, Zhao Y, Sun JA (2024) Novel Fire Extinguishing Agent—Perfluorohexanone (C₆F₁₂O). *China Sci Technol Inform* (18), 156–158, 162
2. Guo G, Zhan X, Hou L, Zhang S, Shen J (2019) Optimization Method for Distribution Network Fault Mitigation Measures Based on Importance Ranking and Life Cycle Assessment. *Electr Power Big Data* 22(5):81–87
3. Wang L (2014) Hazard Analysis of Fire, Flood, and Personal Accidents in Substations. *Guizhou Electr Power Technol* 17(2):73–74
4. Cai X, Zhu Y, Jiang K, Xi X, Zhang Y, Lin W Application of Perfluorohexanone Gas Fire Extinguishing Systems in Prefabricated Lithium Iron Phosphate Battery Energy Storage Cabins
5. Chen Y, Zhao C, Huang Q, Li S, Huang J, Ni X, Wang (2023) Jian, Investigation on the temperature variation of novect-1230 and halon 1301 in a discharge system. *Case Stud Therm Eng* 50:103421
6. • Zou J, Wang G, Tan X, Bi Y (2025) Study on the Effects of Gas-Generating Agents and Gas Chambers on Perfluorohexanone Fire Extinguishing Devices. *Fire Sci Technol* 44(1):30–34
7. Rao Z (2023) Preparation and Properties of Functional Gelatin Hydrogels. *M.S. Thesis*, Zhengzhou University, Zhengzhou, China
8. He G (2021) Preparation and Performance of Halocarbon Fire Extinguishing Agent Microcapsules Coated with Poly(methyl methacrylate). *M.S. Thesis*, Nanjing Normal University, Nanjing, China
9. Wu Y (2020) Preparation and Performance of Halocarbon Fire Extinguishing Agent Microcapsules. *M.S. Thesis*, Nanjing Normal University, Nanjing, China
10. Han Z, Li Z, Yang J (2025) Highly effective suppression of accidental combustion and explosion on B/ KNO₃ by perfluorohexanone microcapsule. *Fuel* 386
11. Xue C, Jiang H, Zhu C, Gao, Wei (2023) A novel dry water with perfluorohexanone for explosion suppression of AlH₃. *Chem Eng Sci* 271
12. Xing H, Lu S, Yang H, Zhang, Heping (2022) Review on research progress of C₆F₁₂O as a fire extinguishing agent. *Fire* 5(2):50
13. Ma J, Zhao Q, Wang H, Yang F (2025) Experimental Study on the Fire Suppression Performance of a Locally Applied Perfluorohexanone Fire Extinguishing System. *Fire Sci Technol* 44(8):1097–1102
14. Wang K, Wang D, Zhou B, Wang X, Chen (2025) Tao, Study on the synergistic extinguishing effect of perfluorohexanone-nitrogen. *Case Studies in Thermal Engineering* 71
15. Li C, Bian H, Ding D, Huang F, Zhu Z (2024) Enhancing Safety in Small Confined Spaces with Thermally Triggered Fire-Extinguishing Microcapsules from Microfluidics. *Lab Chip* 24(4):904–912

16. Liu H, Zhang T, Zhang M, Zhang C, Guo Z, Zhang Y, Chen H, Wu Y, Zhang G (2024) Preparation and Thermal Responsiveness of Microencapsulated Fluorinated Liquids for Automatic Fire Extinguishing. *Heliyon* 10 (5), e27454
17. Kim S, Choi H, Song YK, Kim S, Noh SM, Lee KC (2024) Thermoresponsive Microcapsules with Fire-Extinguishing Composites for Fire Prevention. *ACS Appl Polym Mater* 6(6):3373–3378
18. Wang C, Liu J, Liu Y, Sun H (2026) Perfluorohexanone Fire-Extinguishing Microcapsules Prepared with Double Layer: Urea-Formaldehyde Resin and Poly(methyl methacrylate). *ACS Appl Eng Mater* 4(6):2726–2739
19. Guo Y, Gao J, Zhou X, Zhang H (2025) Self-Triggered Fire-Extinguishing Microcapsules with Pronounced Performance in Suppressing the Thermal Runaway of Lithium-Ion Batteries. *J Mater Chem A* 13:32460–32470
20. Han Z, Yang J, Yu Y, Zhang X (2025) Preparation and Characterization of Novel Core-Shell Microcapsules Containing C6F12O for Initial Fire Suppression. *Process Saf Environ Prot* 193:772–780
21. Zhou G, Li Y, Liu Y, Zhang Q, Wei Z, Li S, Yang S, Yuan S, Fan T, Huang Q (2024) Preparation of a Novel Environmental-Friendly Lithium-Ion Battery Fire Suppression Microcapsule and Its Fire Extinguishing Mechanism in Coordination with ABC Dry Powder. *J Clean Prod* 448:141438
22. Said AO, Stoliarov SI (2021) Analysis of Effectiveness of Suppression of Lithium Ion Battery Fires with a Clean Agent. *Fire Saf J* 121:103296
23. Takahashi F, Katta VR, Babushok VI, Linteris GT (2021) Numerical and Experimental Studies of Extinguishment of Cup-Burner Flames by C6F12O. *Proceedings of the Combustion Institute* 38, 4645–4653
24. Pagliaro JL, Linteris GT (2017) Hydrocarbon Flame Inhibition by C6F12O (Novec 1230): Unstretched Burning Velocity Measurements and Predictions. *Fire Saf J* 87:10–17
25. Lee DH, Kwon S, Kim YE, Kim NY, Joo JB (2022) Double-Layered Polymer Microcapsule Containing Non-Flammable Agent for Initial Fire Suppression. *Materials* 15(21):7831
26. Xing H, Lu S, Yang H, Zhang H (2022) Review on Research Progress of C6F12O as a Fire Extinguishing Agent. *Fire* 5(2):50
27. Liu Y, Yang K, Zhang M, Li S, Gao F, Duan Q, Sun J, Wang Q (2022) The Efficiency and Toxicity of Dodecafluoro-2-methylpentan-3-one in Suppressing Lithium-Ion Battery Fire. *J Energy Chem* 65:532–540
28. Sun H, Zhang L, Duan Q, Wang S, Sun S, Sun J, Wang Q (2022) Experimental Study on Suppressing Thermal Runaway Propagation of Lithium-Ion Batteries in Confined Space by Various Fire Extinguishing Agents. *Process Saf Environ Prot* 167:299–307
29. Zhao J, Xue F, Fu Y, Cheng Y, Yang H, Lu S (2021) A Comparative Study on the Thermal Runaway Inhibition of 18650 Lithium-Ion Batteries by Different Fire Extinguishing Agents. *iScience* 24 (8), 102854

30. Xu J, Guo P, Duan Q, Yu X, Zhang L, Liu Y, Wang Q (2020) Experimental Study of the Effectiveness of Three Kinds of Extinguishing Agents on Suppressing Lithium-Ion Battery Fires. *Appl Therm Eng* 171:115076
31. Liu Y, Duan Q, Xu J, Li H, Sun J, Wang Q (2020) Experimental Study on a Novel Safety Strategy of Lithium-Ion Battery Integrating Fire Suppression and Rapid Cooling. *J Energy Storage* 28:101185
32. Yuan S, Chang C, Yan S, Zhou P, Qian X, Yuan M, Liu K (2021) A Review of Fire-Extinguishing Agent on Suppressing Lithium-Ion Batteries Fire. *J Energy Chem* 62:262–280
33. Sun J, Mao B, Wang Q (2021) Progress on the Research of Fire Behavior and Fire Protection of Lithium Ion Battery. *Fire Saf J* 120:103119
34. Meng X, Jiang L, Duan Q, Wang S, Duan P, Wei Z, Zhang L, Jia Z, Jin K, Wang Q (2023) Experimental Study on Exploration of Optimum Extinguishing Agent for 243 Ah Lithium Iron Phosphate Battery Fires. *Process Saf Environ Prot* 177:138–151
35. Liu L, Du Z, Zhang T, Guo Z, He M, Liu Z (2019) The Inhibition/Promotion Effect of $C_6F_{12}O$ Added to a Lithium-Ion Cell Syngas Premixed Flame. *Int J Hydrog Energy* 44(39):22282–22300
36. Yu J, Chen H, Yu Z et al (2023) Inhibition/Promotion Effect of $C_6F_{12}O$ Addition on Premixed RP-3/Air Flame. *ACS Omega* 8(3):3429–3440
37. Mu X, Cong H, Yuan Z, Bi Y, Bi M (2023) Study on the Inhibitory Effect and Mechanism of Perfluoro(2-methyl-3-pentanone) on the Combustion of Gasoline Blended with Biomass Additives. *Fuel* 349:128768
38. Fan R, Pan Y, Shi X, Lu Y, Wang Z (2023) Investigation on the Suppression Effect of High Momentum $C_6F_{12}O$ (Novec-1230) Flow on Hydrogen Jet Flame. *J Loss Prev Process Ind* 84:105128
39. Xing H, Lu S, Tao J, Zhou Y, Zhao J, Zhang H (2025) Insight into $C_6F_{12}O$ Fire Suppression Mechanism on Coaxial *n*-Heptane Flame: Combined Experimental and ReaxFF Molecular Dynamics Simulation. *Process Saf Environ Prot* 200:107383
40. Yu Z, Li G, Jia H, Dong H, Zhao J, Zhang H (2026) Enhancing Atomization and Fire-Suppression Efficiency of Perfluorohexanone Using Swirl Nozzles across a Range of Injection Pressures. *J Loss Prev Process Ind* 99:105802
41. Pan Q, Sang N, Zhou T, Wu C, Si T, Huang F, Zhu Z (2025) Array-Structured Microcapsule Fibers for Efficient Fire Extinguishing in Confined Spaces. *Lab Chip* 25(9):2193–2204
42. Wang K, Wang D, Zhou B, Wang X, Chen T (2025) Study on the Synergistic Extinguishing Effect of Perfluorohexanone-Nitrogen. *Case Stud Therm Eng* 71:106215
43. Liu Z, Li Y, Li Q, Fei B, Pan R, Zhou X (2026) Water-Resistant and Flame-Retardant Waterborne Polyurethane Coating Based on Hydrophobic SiO_2 and Microcapsule Perfluorohexanone: With Automated Intelligent Fire Early Warning and Fire Protection. *Prog Org Coat* 210:109659
44. Gao J, He Y, Wei R, Huang S, Liu M, Li J (2026) Analysis of Two Typical Fire-Extinguishing Microcapsules Prepared via Microfluidics. *Case Stud Therm Eng* 83:108101

Figures

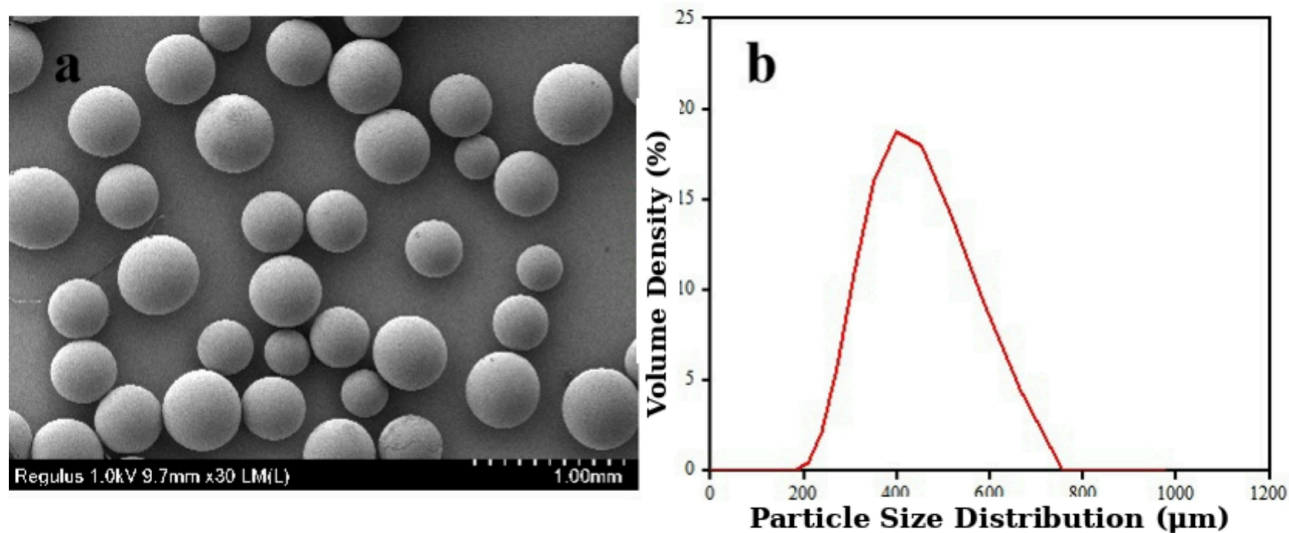


Figure 1

Microscopic morphology and particle size distribution of perfluorohexanone microcapsules.

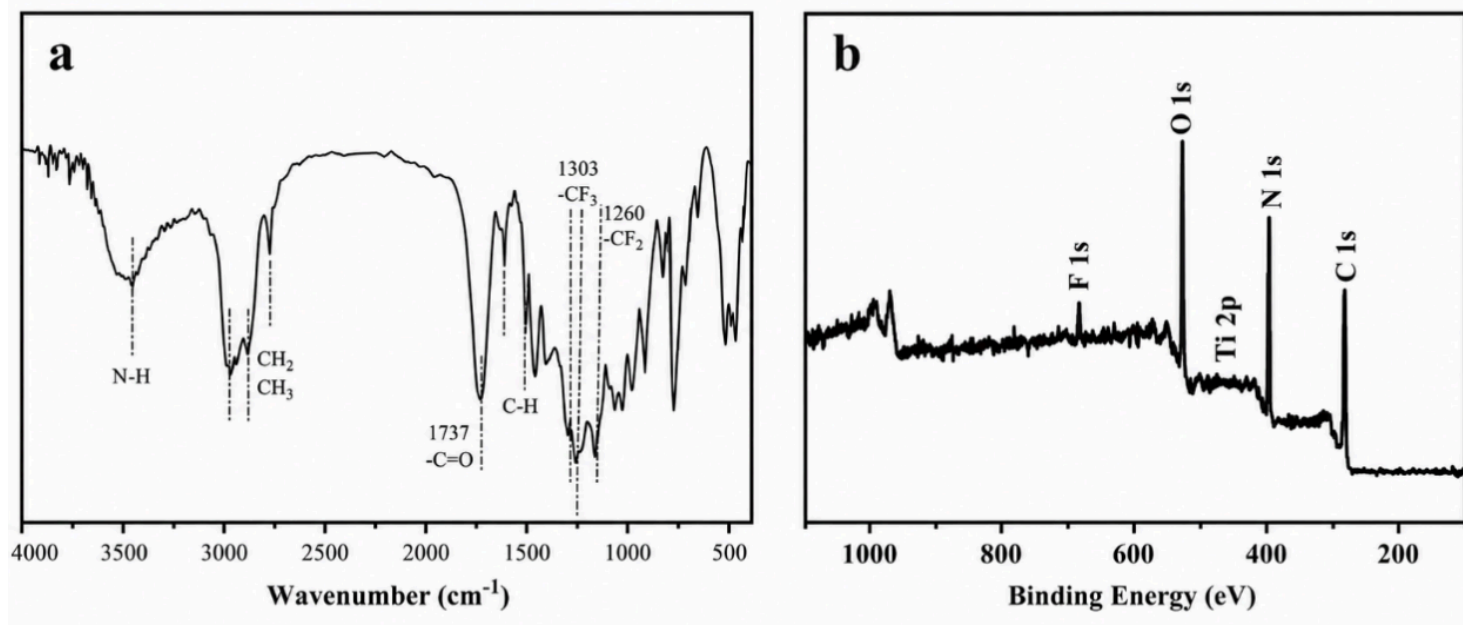


Figure 2

FT-IR spectrum and XPS survey spectrum of perfluorohexanone microcapsules.

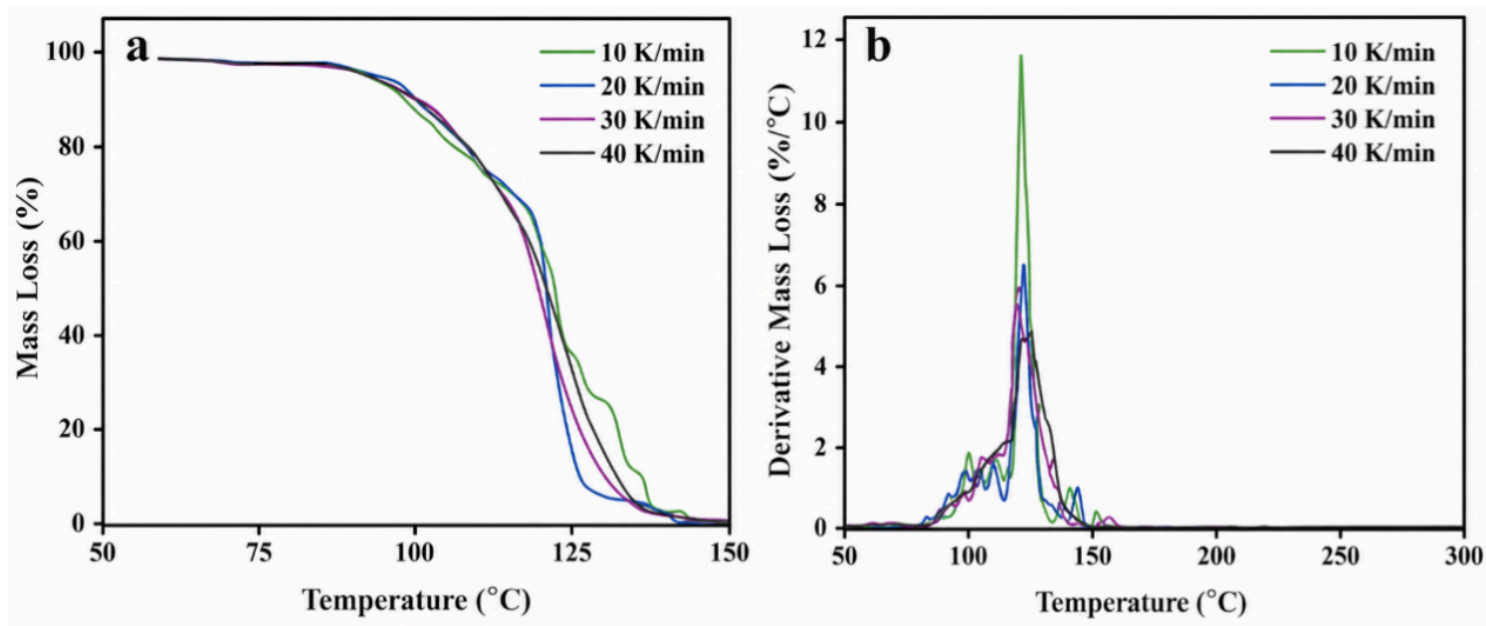


Figure 3

Thermogravimetric curves of the microcapsules.

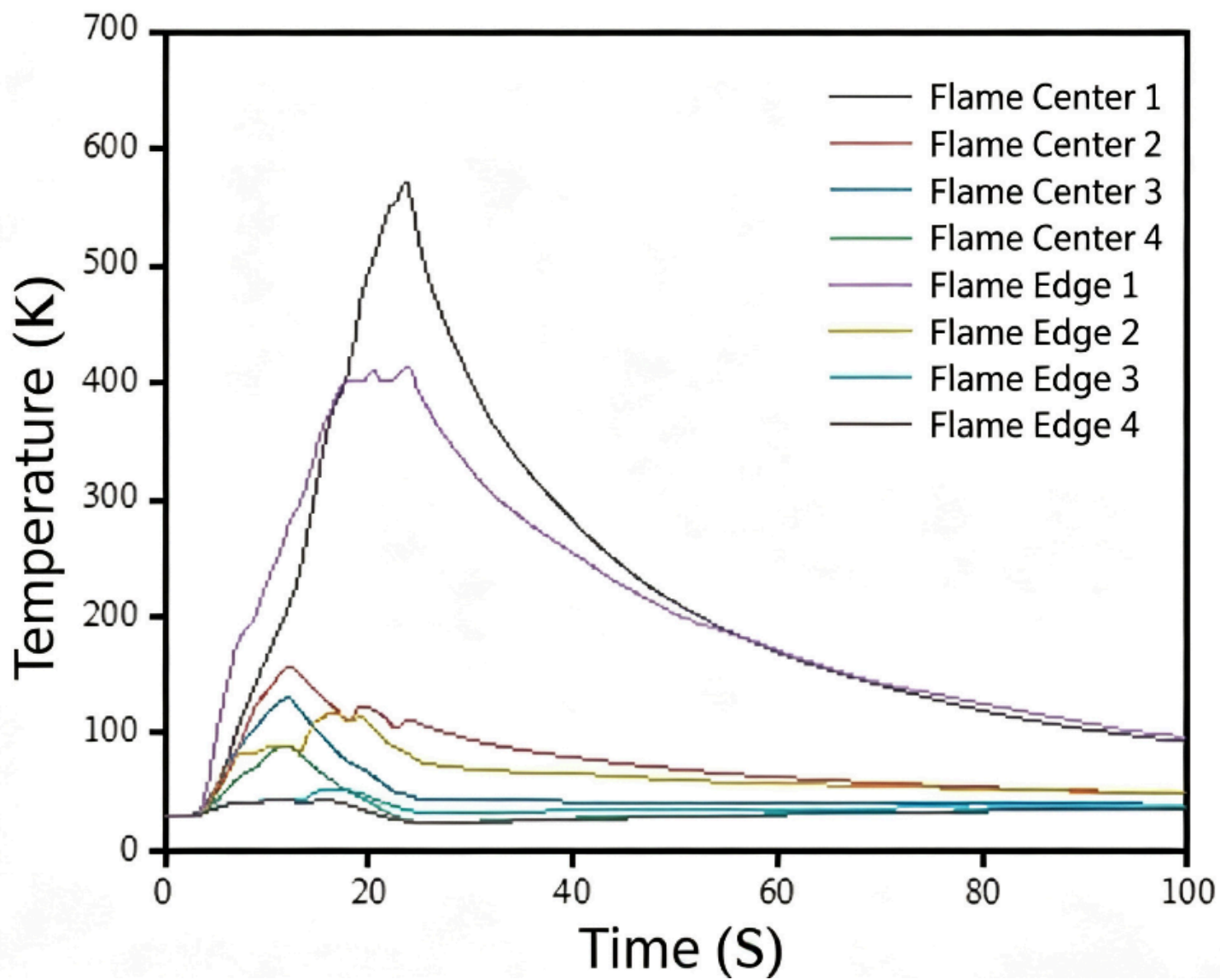


Figure 4

Temperature variation of the flame after the release of perfluorohexanone



Figure 5

Morphological changes of the flame after the release of perfluorohexanone

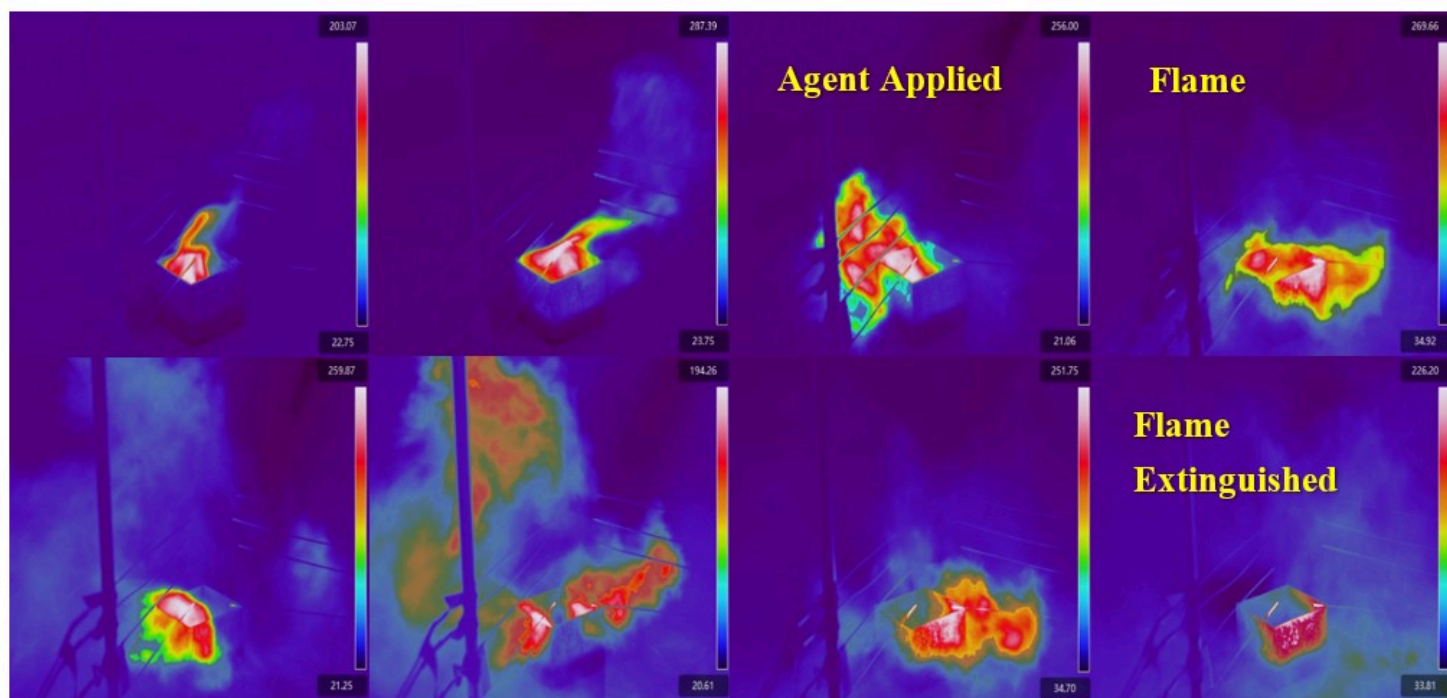


Figure 6

Changes in infrared images of the flame after the release of perfluorohexanone

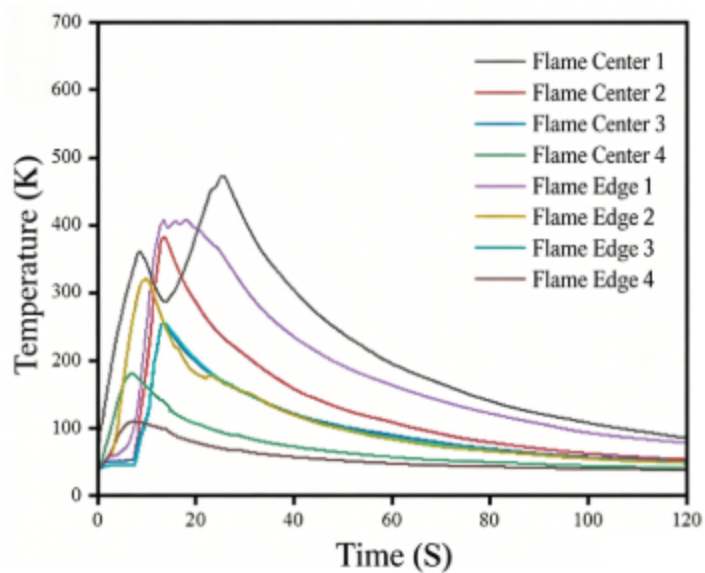


Figure 7

Temperature variation of the flame after the release of perfluorohexanone microcapsules



Figure 8

Morphological changes of the flame after the release of perfluorohexanone microcapsules

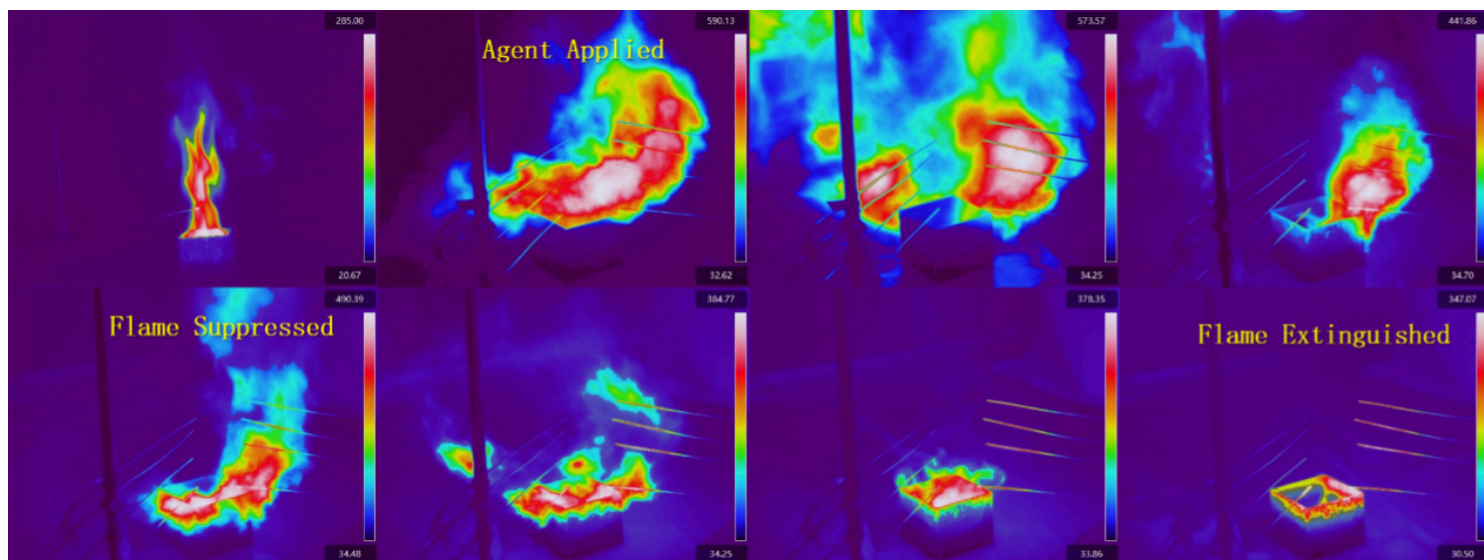


Figure 9

Changes in flame temperature images after the release of perfluorohexanone microcapsules



Figure 10

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [floatimage1.png](#)