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Tian, C., Zhao, J., Yang, J., Zhang, J., & Yang, R. (2023). Preparation and characterization of fire-extinguishing efficiency of novel gel-protein foam for liquid pool fires. *Energy*, 263, Article 125949. Advance online publication. <https://doi.org/10.1016/j.energy.2022.125949>

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Published in:
Energy

Publication Status:
Published (in print/issue): 15/01/2023

DOI:
[10.1016/j.energy.2022.125949](https://doi.org/10.1016/j.energy.2022.125949)

Document Version
Author Accepted version

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Preparation and characterization of fire-extinguishing efficiency of novel gel-protein foam for liquid pool fires

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Abstract: The re-ignition of large-scale storage tank fires poses one of the greatest challenges in firefighting and it is thus of practical importance to develop efficient fire extinguishing agents to suppress and control liquid pool fires. In this study, a novel gel-protein foam was prepared. The microstructure, foamability, stability and water retention capacity of the gel-protein foam were analyzed systematically to identify three best formulations, which were then used to assess their fire extinguishing and burnback performance against a commercial film-forming fluoroprotein foam (FFFP). The experimental results indicated that the gel-protein foam with the best fire extinguishing efficiency is the one with a SA/CaCl₂ ratio of 9:1 and a concentration of 0.1 wt%. The average size and water loss ratio are 124.84 μ m and 30.6%, respectively, compared to 271.92 μ m and 44.1% for FFFP. The fire extinguishing tests also confirmed that this gel-protein foam has the best cooling and burnback performance. Its 90% burnback time is 454s, a 54.42% increase that of FFFP, because it can float stably on the fuel surface to reduce the hazard of re-ignition. This work provides important data and guidance in further development of gel foams for extinguishing oil storage tank fires.

Key words: Gel-protein foam, Pool fire, Foam stability, Fire extinguishing, Burnback

1. Introduction

Several major fire and explosion accidents involving large-scale storage tanks occurred in recent years. The development of efficient fire suppression systems for such fires remains a great challenge because of the large surface burning area and the occurrence of re-ignition (Jangi et al., 2016; Chen et al., 2018; Zhao et al., 2019). Up to date, FFFP is still considered as one of the most efficient extinguishing agents for tank fires because of its good extinguishing performance. However, one of the drawbacks of FFFP is that its stability worsens under strong thermal radiation, which could result in the re-ignition of tank fires (Magrabi et al., 2002). Moreover, the fluorocarbon surfactants in FFFP also pose a great threat to the environment and public health (Rotander et al., 2015; Ananth et al., 2019). For instance, a large-scale oil storage tank fire occurred in a chemical industry plant at Gulei, Fujian Province in April 2015. It took about 56 hours to control the fire because of its large fire area (around 43910 m²) and four major re-ignitions during the accident. In the firefighting process, more than 1,600 tons of FFFP were consumed, which generated a great amount of wastewater (around 110,000 tons). Therefore, it is urgent to develop a good stability, safe, environmental-friendly extinguishing agent to control the liquid pool fires.

The stability of foams, as a key factor in the fire extinguishing process, has been studied by many scholars during the past decades (e.g., Pandey et al, 2021; Shi et al, 2022). It is well known that polymers can be used as stabilizers for aqueous foams. Bordado et al. (2007) analyzed the effect of acrylamide and 2-acrylamide-2-methyl-propane-sulphonate on the water absorption capacity of fire extinguishing agent and found that the swelling ratio could swell up to 1240 with an acrylamide/2-acrylamide-2-methyl-propane-sulphonate ratio of 3:7. Kang et al. (2021) studied the effect of xanthan gum and gelatin on the stability of a traditional aqueous film-forming foam and reported that the 25% drainage time of the foam was increased by 375.2% compared to

traditional aqueous film-forming foams without a foam stabilizer. Zhu et al. (2021) investigated the effect of welan gum and hydroxypropyl methylcellulose on the stability of an aqueous foam and showed that the foam stability could reach 96.5% with a hydroxypropyl methylcellulose/welan gum ratio of 2:8. Tcholakova et al. (2011) found that the addition of polymers in the foam can decrease the average size of the foam to around 200-300 nm, and as a result increase the foam stability. In recent years, functional particles were also used as foam stabilizers, such as silica particles (Zhou et al., 2018; Zou et al., 2019), ash fly (Lu et al., 2021; Qin et al., 2014; Shao et al., 2014; Wang et al., 2020), and Laponite particles (Sani and Mohanty, 2009; Zhang et al., 2008). These particles can increase the scattering of thermal radiation to protect the foam (Xie et al., 2013). However, the stability of the foam with polymers or functional particles are limited, because they cannot hold water efficiently, leading to poor cooling performance of the foam. In order to improve the water retention capacity, gel foams were developed. Wang et al. (2016) developed a novel gel foam with acrylic acid, soluble starch, modified alkyl glycosides and sodium dodecyl sulfate, which effectively reduced the oxidation reaction rate and heating rate of coal. Shi and Qin (2019) synthesized a gel-stabilized foam with microbial polysaccharide, galactomannan biopolymer and organic boron and found that that the average size of the aqueous foam increased from 1.19 to 3.46 mm within one hour, compared to from 1.06 to 1.30 mm for the corresponding gel-stabilized foam, which indicated that the coarsening rate of the gel-stabilized foam is slower than that of the aqueous foam. Guo et al. (2019) developed a gel foam with aluminum polyphosphate, polymeric aluminum chloride and other polymeric substances and reported that the water loss of the gel foam over 10 minutes was only 11%, which was significantly less than that of for the pure foam, 91%. Li et al. (2019) synthesized a high-water-retaining foam to control the spontaneous combustion of coal with acrylic acid and 2-acrylamide-2-methylpropanesulfonic acid and found that the product had a larger water absorption rate with good water retention and fire extinguishing efficiency. These studies clearly demonstrated that unique gel

components can improve the stability and efficiency of the foam. However, the gel components used in these studies are mainly from chemical products which are difficult to degrade and could pollute the soil and groundwater. Moreover, most of these studies focused on the fire suppression efficiency of gel foams on solid fires (mainly coal) and studies on the gel foams use for liquid fires are still very limited.

To fill in this knowledge gap, this paper is aimed at developing a novel gel-protein foam for liquid pool fires. After the screening tests on formability and stability with different surfactants, Sodium alcohol ether sulphate (AES) and Hydrolyzed protein (HP) were chosen as the compounding foaming agent, which was then use with Sodium alginate (SA) as the gelling agent and Calcium chloride (CaCl_2) as the cross-linking agent to prepare the new gel-protein foams. It is important to note that both SA and HP are environmentally friendly, non-polluting and easily degradable natural organic compounds. The microstructure, foamability, stability and water retention performance of the newly developed foams were analyzed systematically to identify the best formulations, which were then used to evaluate their fire extinguishing and burnback performance against a commercial FFFP (6%).

2. Experimental investigations and framework

2.1 Materials

The gel-protein foam is composed of surfactants, gelling agent, and cross-ling agent. Four foaming agents were examined with Hydrolyzed protein as the foaming stabilizer: (i) Sodium dodecyl benzene sulfonate (SDBS), (ii) Sodium dodecyl sulfate (SDS), (iii) Sodium dodecyl sulfonate (SLS), and (iv) Sodium alcohol ether sulphate (AES). Sodium alginate (GA) and Calcium chloride (CaCl_2) were employed as the gelling agent and cross-linking agent respectively. To evaluate the fire-extinguishing efficiency of the gel-protein foams in fire suppression and burnback tests, a commercial FFFP with 6% active matter content was also used. Detailed information of the materials used in this study is shown in Table 1.

Table 1 Detailed information of the materials.

Type	Name	Active Matter Content	Manufacturer
Surfactants	Sodium dodecyl benzene sulfonate (SDBS)	30%	Shandong Ecosol Chemical Technology Co., Ltd
	Sodium dodecyl sulfate (SDS)	92%	Shandong Ecosol Chemical Technology Co., Ltd
	Sodium dodecyl sulfonate (SLS)	99%	Fuzhou Phygene Biotech Co., Ltd.
	Sodium alcohol ether sulphate (AES)	70%	Shandong Ecosol Chemical Technology Co., Ltd.
	Hydrolyzed protein (HP)	90%	Shijiazhuang Xuermei Biotech Co., Ltd.
Gelling agent	Sodium alginate (SA)	80%	Shandong Ecosol Chemical Technology Co., Ltd
Cross-linking agent	Calcium chloride (CaCl ₂)	94%	Shandong Ecosol Chemical Technology Co., Ltd
Extinguishing agent	Film-forming fluoroprotein foam (FFFP)	6%	Suzhou Lingen Fire Technology Co., Ltd.

2.2 Microstructural analysis

The morphology of the gel-protein foam was studied using a Ruihong optical microscope (BM-500T) at room temperature. Before the experiments, a small amount of fresh foam was placed on a glass slide. The fresh foam was then secured using a coverslip for convenient viewing. ImageJ (an image analysis software) was used to analyze the size distribution and evolution process of the foam.

2.3 Foamability and stability tests

Foamability and stability are the two key parameters to assess foaming quality. The Waring Blender method was used to determine the foam expansion ratio. In the experiments, 50ml of foam solution (V_1) was injected into a container, followed by agitation at a rate of approximately 3000r/min for 2 minutes. The prepared foam was then poured into a graduated cylinder to record the foaming volume (V_2) and half-life ($T_{1/2}$). The half-life is defined as the time for the foam to separate out half of the foam solution, and is commonly used to estimate foam stability (Ju et al., 2022). The expansion ratio (E) can be found as:

$$E = V_2/V_1 \quad (1)$$

2.4 Water retention capacity test

The water loss ratio (ϕ) was used to represent the water retention capacity of the foam. The fresh foam was put into a glass beaker, and the total mass (M_t) of the beaker and foam was measured. The glass beaker was then placed in a vacuum drying chamber at a constant temperature of 100 °C. The shape of the foam was observed and the mass after dehydration (M_i) was measured every 10 minutes and the water loss ratio at different times is then calculated as:

$$\phi = (M_t - M_i)/M_t \quad (2)$$

2.5 Fire extinguishing and burnback tests

A customized gel-foam fire extinguishing system was developed in this work as shown in Fig. 1. The system consists of an air compressor, a foam generator, two containers, two flowmeters for regulating the flow rate of the foam liquid and polymer liquid respectively, a proportional regulator for controlling the ratio of the foam liquid to the polymer liquid, and a nozzle.

The fire extinguishing and burnback tests were conducted in a steel pan with a diameter of 0.8m. Before the test, 8L of water was added to the pan followed by 8L of gasoline. A K-type thermocouple with 1.0 mm wire (measurement range: 0–800 °C, accuracy: $\pm 1\%$ FS) was placed at the center of the pan and 30mm above the bottom surface to measure the temperature of the fuel surface. The distance from the nozzle to the pan center was 2m. The gasoline was ignited by a lighter and was allowed to free burn for 60s before the application of the gel-protein foam. The extinguishing time and 90% fire control time (90% of the pan area extinguished) were recorded (Chen et al., 2018). The burnback capacity of the foam was tested 5 minutes after the pool fire was extinguished. An ignition tank with a diameter of 0.2m was placed in the oil pan and 1L gasoline was then added into the ignition tank and ignited. The burnback time is determined as the time from the ignition of the burnback tank to the re-ignition of the gasoline in the oil pan and can be used to represent the fire resistance of foam (Fu et al., 2020). The whole fire suppression process was recorded by a video camera (SONY,

FDR-AX100E), and the video images were used to determine the percentage of the burnback time. In this work, the 25% and 90% burnback times were recorded, which represent 25% and 90% of the pan area re-ignited respectively. Each test condition was repeated at least three times to check repeatability and the average results are presented.

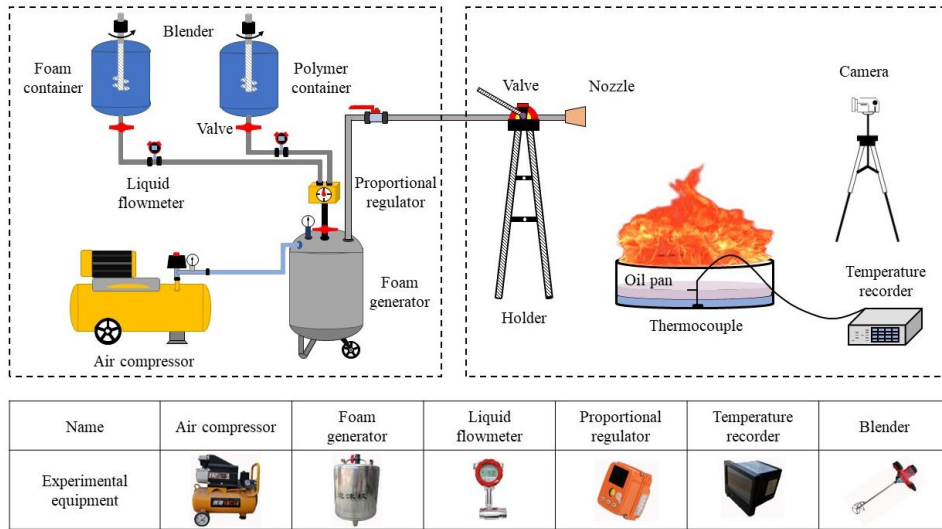


Fig. 1. The gel-protein foam fire extinguishing system

2.6 Framework

Fig. 2 shows the framework in the development and characterization of the gel-protein foam, which can be divided into three parts: (i) formulation analysis, (ii) basic features analysis, and (iii) fire extinguishing features analysis. The foamability of single surfactants and the foam comprehensive index (FCI) of compound foaming agents were examined first. The FCI was introduced in (Zhang et al., 2019) to evaluate the foam comprehensive properties and can be expressed as a function of the expansion ratio and the half-life of the compound foaming agent.

$$FCI = \frac{3}{4}ET_{1/2} \quad (3)$$

The FCI was used to screen the foaming agents and to optimize the mass fractions and mass ratios of the reagents. The best formulations of the gel-protein foam were then selected for further analysis against commercial FFFP, including (i) the basic feature analysis (microstructure and water retention tests) and (ii) fire extinguishing efficiency (fire suppression and burnback tests).

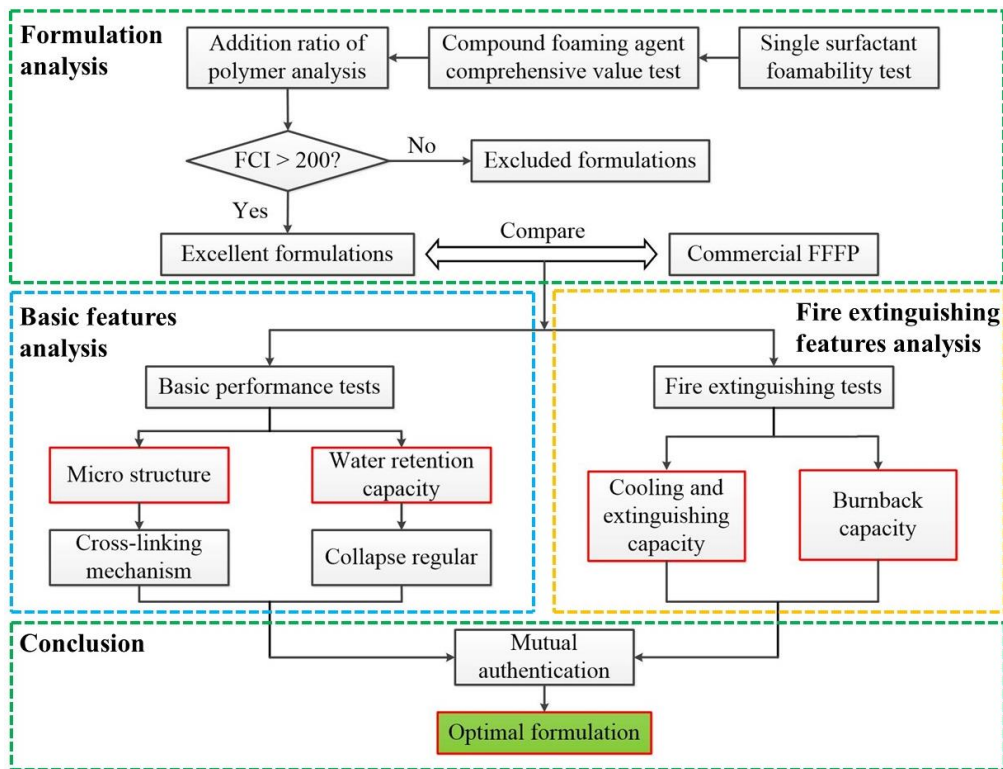


Fig. 2. The development process of gel-protein foam

3. Results and discussion

3.1 Ratio of compound foaming agents

Fig. 3 presents the measured foam expansion ratio of the four surfactants (AES, SDBS, SDS and SLS) at different mass fractions. As HP was used as a foam stabilizer, it is not considered separately. It can be noted that for all the surfactants the foam expansion ratio initially increases with mass fraction. This can be attributed to the improvement of foamability because of a decrease of surface tension. The maximum foam expansion ratio is achieved for all surfactants at a total mass fraction of 0.5 wt%, which indicates that the critical micelle concentration (CMC) has reached (Xie et al., 2011). With a further increase of mass fraction, the foam expansion ratio starts to decrease, because the surfactant molecules aggregate to form micelles when the surfactant concentration exceeds CMC, which could reduce surface activities and the foamability of the surfactant (Sharma et al., 2022). Among different surfactants, AES exhibits the best foamability with a foam expansion ratio around 16 times at a mass

fraction of 0.5 wt%. Therefore, AES was selected for subsequent compounding with HP, while the total mass fraction was kept at 0.5 wt%.

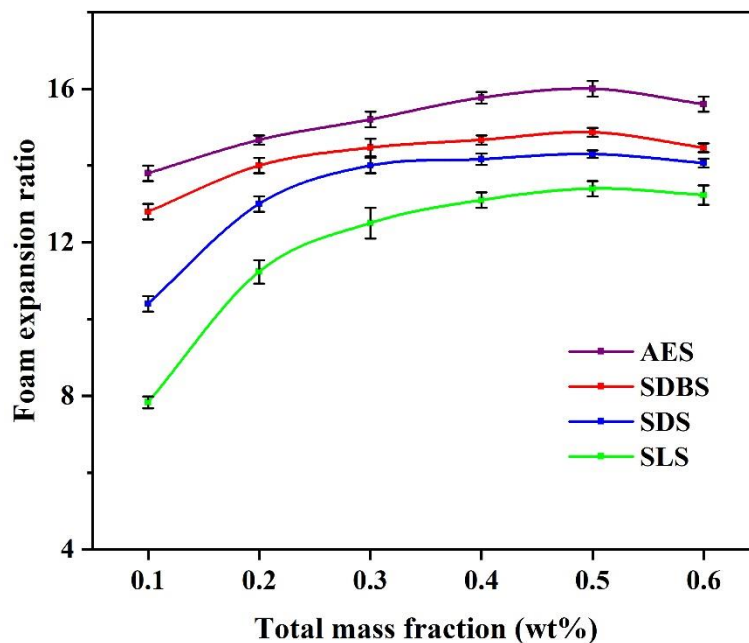


Fig. 3. Foam expansion ratio of surfactants

To determine the optimal ratio between AES and HP (η), AES was mixed with HP at different ratios as shown in Fig. 4, which presents the foam expansion ratio and half-life of the compound foaming agent. It can be observed that the foam expansion ratio increases initially with η , followed by a relative stable value. The maximum foam expansion ratio (around 16.5) is achieved as η increases to 5:5. For the half-life of compound foaming agent, it increases quickly to its maximum value (around 7.87min) at $\eta = 2:8$, followed by a steady decrease. The FCI of the compound foaming agent increases with η firstly to its maximum value when η is equal to 2:8 and then decreases slowly with a further increase of η .

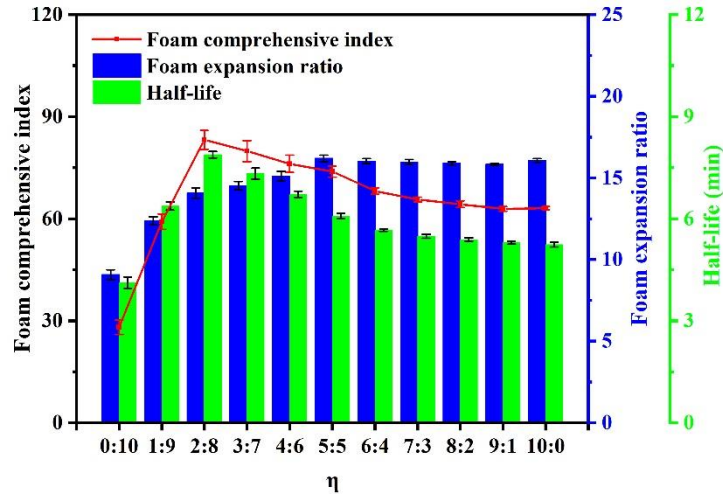


Fig. 4. The FCI of compound foaming agent with different AES/HP ratios (η)

To further confirm the optimal total mass fraction of the compound foaming agent, the influence of mass fraction of the compound foaming agent (η is fixed at 2:8) on its comprehensive properties was studied by varying mass fraction from 0.1 to 0.6 wt%. The obtained expansion ratio, half-life and FCI are shown in Fig. 5. It can be observed that FCI increases significantly with mass fraction until it reaches its maximum value at a mass fraction of 0.5 wt%, i.e., the optimal concentration of the compound foaming agent. Based on these results, the compound foaming agent with an AES/HP ratio of 2:8 and a total mass fraction of 0.5 wt% were chosen for the development of the gel-protein foam with the gelling and crosslinking agents.

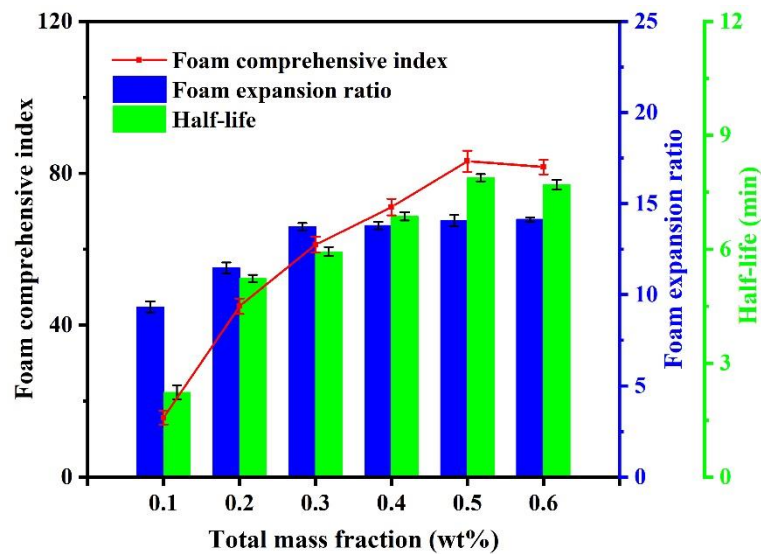


Fig. 5. The FCI of compound foaming agent with different mass fraction

3.2 Ratio of polymers

To determine the optimal ratio between the gelling and crosslink agents and mass fraction of the polymer, different ratios between SA to CaCl₂ (λ , from 1:4 to 9:1) and mass fractions (from 0.1 to 0.6 wt%) were used. It is worth pointing out that in all the formulations 0.5 wt% of the foaming agent of AES and HP at a ratio of 2:8 was used. The FCI of different formulations are shown in Fig. 6. For a fixed λ , FCI increases with mass fraction, due to the fact that the polymers provide more reaction sites for crosslinking to form a dense three-dimensional network gel structure that improves foam stability (El-hoshoudy et al., 2019; Shi and Qin, 2019). For a given total mass fraction, FCI increases initially, followed by a small decrease, but then increases again. This can be explained by noting that, when λ is less than 1, the half-life is the dominating factor, whereas the foam expansion ratio maintains a stable value. As the half-life increases gradually with the content of the gelling agent, FCI increases as well. As λ reaches a value between 1 to 1.5, the foam expansion ratio becomes the dominating factor. The viscosity of the solution increases with the content of the gelling agent, which inhibits the foamability of the surfactant. As the half-life increases slightly, FCI shows a decreasing trend. When λ is more than 1.5, the half-life becomes the dominating factor again. The foam expansion ratio drops to a relatively stable value, while the half-life increases sharply as the concentration of the gelling agent further increases, resulting in a sharp increase of FCI as shown in Fig. 6. It is important to note that in few cases when λ is large, certain formulations directly formed gel rather than gel foam because the high polymer concentration accelerates the crosslinking reaction rate, which is why no FCI was recorded for these formulations.

From Fig. 6, it can be seen that the three formulations with FCI exceeding 200 are (i) polymers concentration of 0.1 wt% with $\lambda=9:1$, (ii) polymers concentration of 0.2 wt% with $\lambda=4:1$ and (iii) polymers concentration of 0.4 wt% with $\lambda=3:1$. These three formulations will be selected for further analysis and, for simplicity, will be referred to as Formula I, Formula II and Formula III respectively.

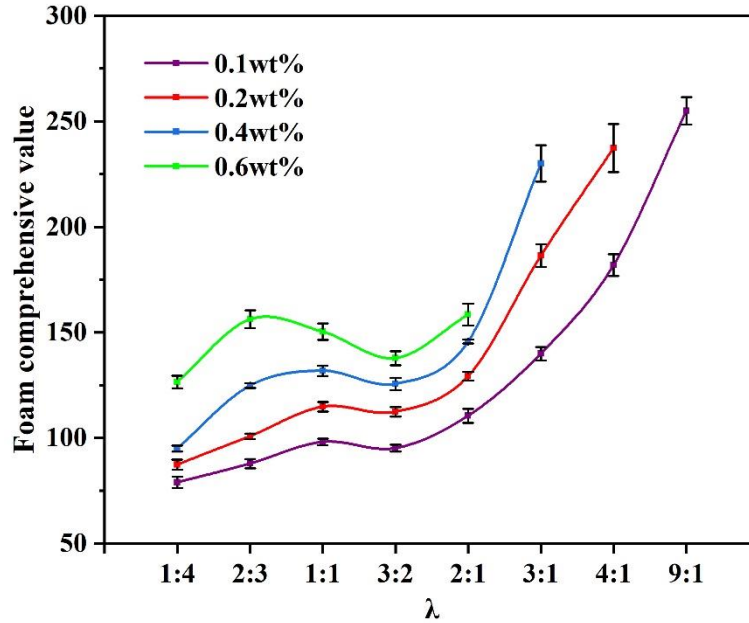


Fig. 6. The FCI with different mass fractions and SA/CaCl₂ ratios

3.3 Microscope structure and stabilization mechanism

Fig. 7 shows a comparison of the micromorphological structure of FFFP and Formula I. As Formula II and III have a similar micromorphological structure to Formula I, their results are not included here for brevity. Initially, both FFFP and Formula I show a small regular-shaped structure. The bubble size gradually increases due to liquid drainage, bubble coarsening and bubble coalescence. The liquid drainage, which plays a dominant role in the foam destabilization process, is the physical separation process of gas and liquid in the foam system with the action of gravity (Djemaa et al., 2021). The drainage results in the loss of water of the liquid film, which causes the foam film to thin and rupture. Thereby, two neighboring bubbles coalesce to a big bubble, also known as bubble coalescence (Zhou et al., 2020). Bubble coarsening refers to that gas in small bubbles will spontaneously diffuse to large bubbles through the film due to a pressure difference according to the Young Laplace law (Hill and Eastoe, 2017).

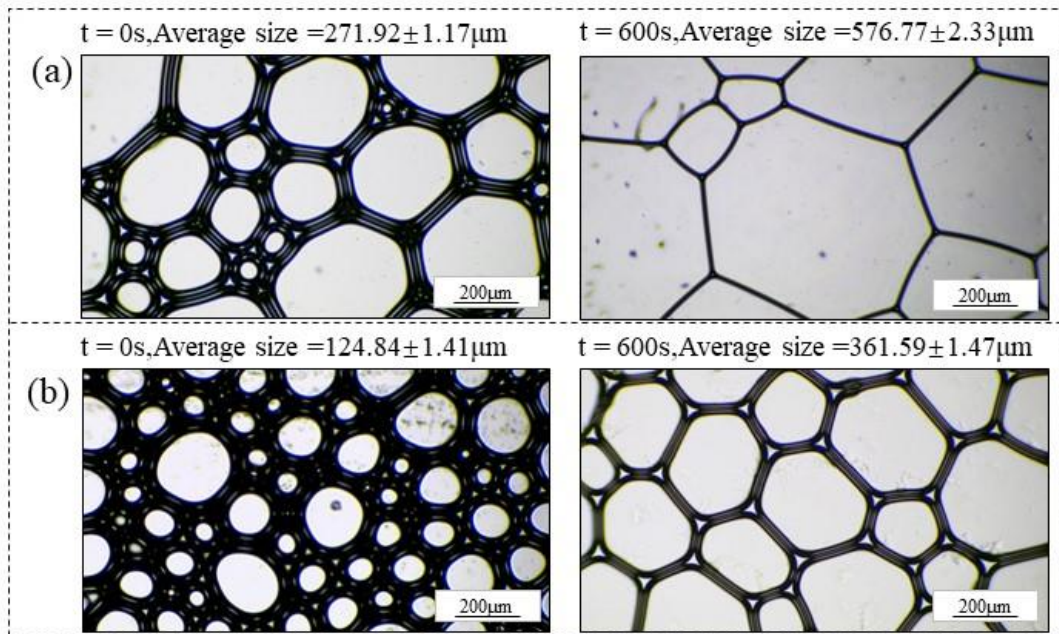


Fig. 7. Microscopic views of foam with different components: (a) FFFP, (b) Formula I

In Fig. 7, it can also be observed that the average size of the Formula I is smaller than that of FFFP, which indicates that Formula I has a better stability than that of FFFP. Furthermore, the image analysis shows that from $t=0$ to 500 s the average size of FFFP and Formula I increases from 271.92 to 576.77 μm , and from 124.84 to 361.59 μm , respectively, indicating that the growth rate of the bubble size of Formula I is lower than that of FFFP. This phenomenon can be explained by the fact that the gelling and crosslink agents (SA and CaCl_2), were introduced into the foam system. SA is a weak acid salt of organic macromolecule, which will slowly ionize Na^+ in the aqueous solution and as a result O^- can crosslink with the ionized Ca^+ in CaCl_2 , as depicted in Fig. 8. Ultimately, a thermally irreversible interpenetrating network gel structure was formed.

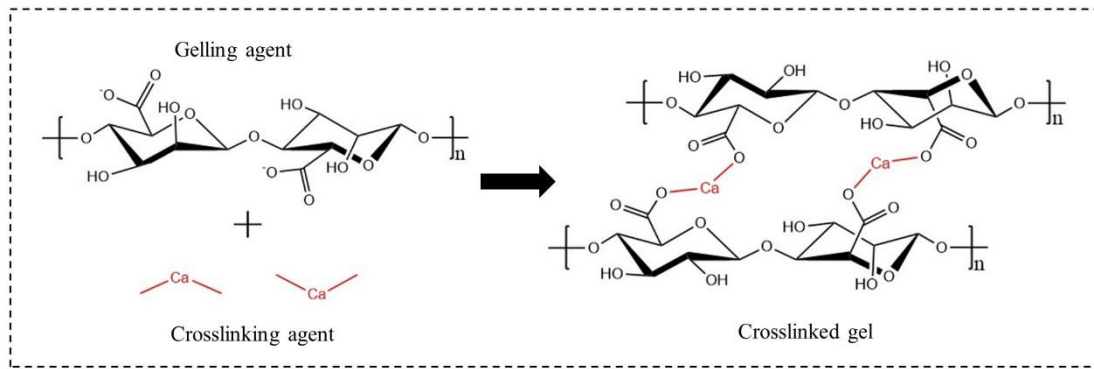


Fig. 8. The reaction mechanism of gel-protein foam

To explain the stabilization mechanism, Fig. 9 shows the three-dimensional structure of the gel-protein foam and FFFP. The gel-protein foam improves the stability of the foam by decreasing the drainage, coalescence and coarsening rate of foam, as depicted in Fig. 9a. On the one hand, gel particles are distributed in the Plateau borders, which can obstruct the drainage channel of the liquid and increase the flow resistance of liquid to decrease the drainage rate of foam (Xu et al., 2014). On the other hand, the large number of gel particles attached to the outside of the gel-protein foam can improve the elastic strength of the film to slow down the coalescence process of the foam and the diffusion of gases (Guo et al., 2019). In comparison, the Plateau borders of FFFP is blank, as depicted in Fig. 9b. This structure facilitates the flow of liquids and the diffusion of gases, which indicates that FFFP has a poor stability. In addition, the gel structure can also contribute to the attachment of water, which can improve the water retention performance and cooling capacity of the foam.

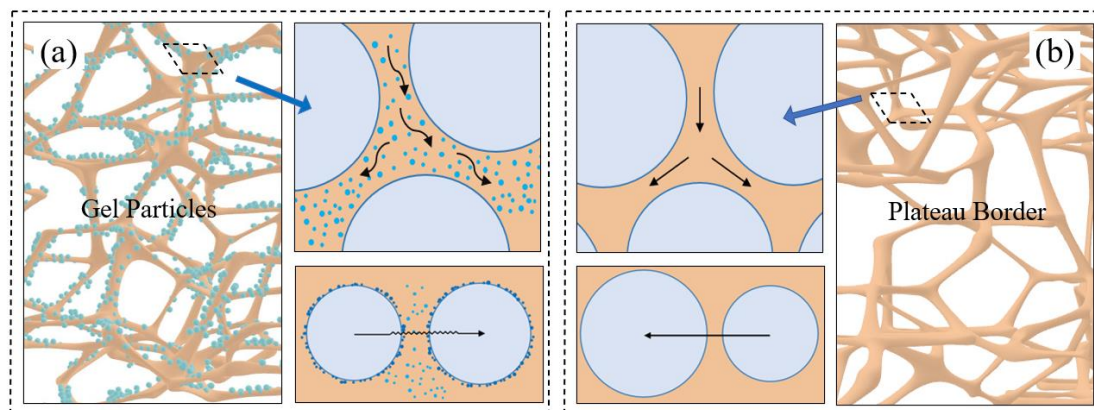


Fig. 9. Three-dimensional structure of different foams:(a) gel-protein foam, (b) FFFP

3.4 Water retention performance

Fig. 10 shows the collapse process of the gel-protein foams and FFFP. It can be found that the foam expansion ratio of FFFP was largest at the beginning but it almost defoamed completely after 20min. The quick loss of water in the foam system would weaken foam stability. In practical applications, the collapse of the foam is an inevitable phenomenon. This is ascribed to the fact that foam is a thermodynamically unstable system (Bashir et al., 2019). However, the interpenetrating network gel structure can enhance the water retention capacity of the foam. It can be seen in Fig. 10 that the gel-protein foams maintain a more stable foam structure compared to that of FFFP after 20 minutes, indicating that the gel structure can effectively inhibit the collapse of the foam in an elevated temperature environment, which would be beneficial to improve the fire extinguishing and burnback capacity of the foam.

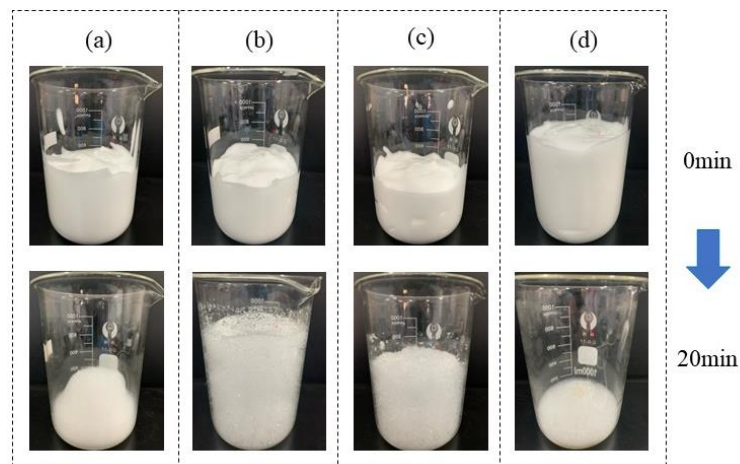


Fig. 10. Morphological changes of different types of foams: (a) Formula I, (b) Formula II, (c) Formula III, (d) FFFP

To further investigate the water retention performance, the water loss ratio of gel-protein foams was analyzed and compared with that of FFFP as depicted Fig. 11. The water loss ratio of all three gel-protein foam formulations is lower than that of FFFP, and the priority order for the water retention capacity is Formula III > Formula II > Formula I > FFFP. The water loss ratio of FFFP is 44.10% after being placed in a vacuum drying chamber for 60 minutes, compared to water loss ratios of 24.76%, 30.60% and 32.72% for Formula III, Formula II and Formula I respectively, which indicates that

the gel-protein foam has a better capacity of holding water under elevated temperature conditions. This can be attributed to the gel particles attached to the film in the gel-protein foam, which can adsorb more water by the gel structure to improve the water retention capacity of the foam.

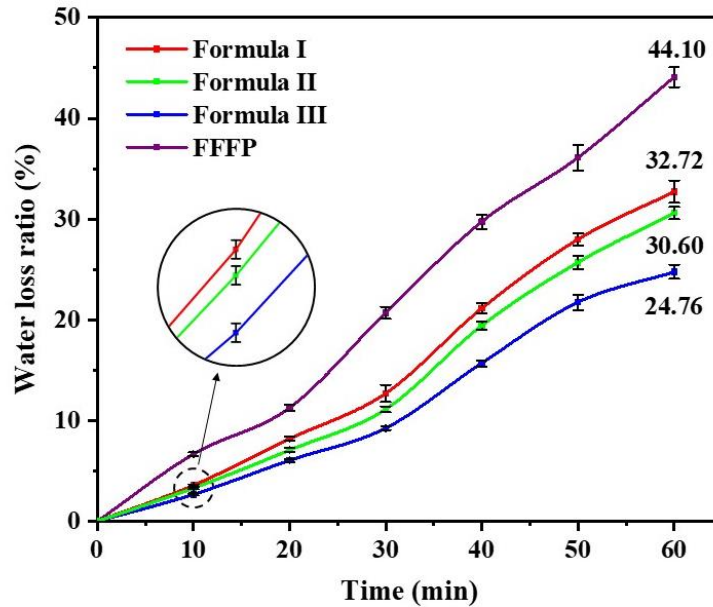


Fig. 11. Water loss ratio of gel-protein foam and FFFP

3.5 Fire extinguishing and burnback performance

Fig. 12 shows the typical images in the fire extinguishing process for Formula I and Formula II. The flame characteristics with FFFP and Formula III are similar to those of Formula I and Formula II, respectively, so their results are not included here for brevity. The fire extinguishing process can be divided into three stages: suppression, foam covering and extinguishing. In the suppression stage, the flame height decreased with the application of the foam and the gasoline pool fire was in full surface combustion. In the foam covering stage, the pool fire was in partial surface combustion due to the spreading of the foam on the fuel surface. In the extinguishing stage, the fuel surface was completely covered by the foam. It can be clearly observed that the fire suppression effect of Formula I is considerably better than that of Formula II in the entire process, as depicted in Fig. 12. For instance, at 30 seconds the flame height with Formula I is drastically decreased, whereas that with Formula II is still substantial. At 70 seconds,

the fire almost extinguished with Formula I, while it was still in partial surface combustion with Formula II.

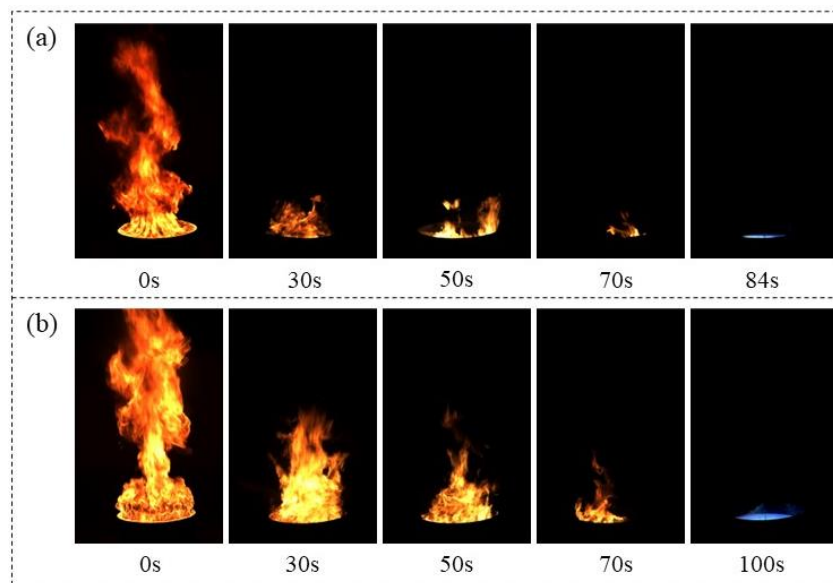


Fig. 12. Extinguishing process of different types of foam:(a) Formula I, (b) Formula II

Fig. 13a compares the 90% fire control time and extinguishing time of gel-protein foams and FFFP. The 90% fire control time and extinguishing time of Formula I and FFFP are nearly the same, whereas those of Formula II and Formula III are considerably higher. Fig. 13b displays the variation of the fuel surface temperature, which to some extent reflects the cooling capacity of the foam. The fuel surface temperature decreases quickly with the application of all foams. Among the different foams, Formula I achieves the largest reduction rate and the lowest overall temperature, which indicates that it has a better cooling capacity than the other foams. This can be attributed to the presence of gel particles which can hold more water to improve the cooling efficiency. For Formula II and Formula III, while both contain gel particles, they have a higher gelling agent content and as a result release less water to suppress the fire and cool the fuel.

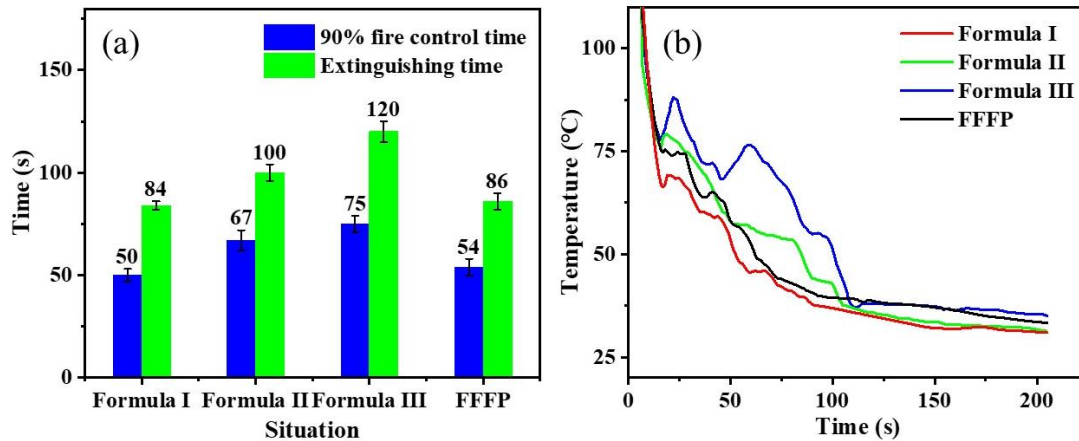


Fig. 13. Different types of foam:

(a) fire extinguishing parameters, (b) temperature variation trend

In the firefighting process, apart from the fire extinguishing and cooling efficiency, the burnback capacity of the extinguishing agent is also a key technical parameter, particularly for liquid fuel fires. Fig. 14 shows the typical images of the burnback tests with Formula I and FFFP. It can be observed that the burnback process of the foams can be divided into three typical stages: stable coverage, partial collapse and diffusion collapse, which is consistent with that in (Sheng et al., 2015). In the stable coverage stage, the fuel surface is completely covered by the foam layer. The expansion of the foam layer near the ignition tank can be observed, as shown in Fig. 10, because the gas in the foam is heated by the high temperature ignition tank. In the partial collapse stage, a discontinuous burning zone appears near the ignition tank. The collapse rate of the expanded foam is accelerated by large heat flux, leading to the overflow and burning of the fuel vapor. In the diffusion collapse stage, the discontinuous burning zone gradually turns into a continuous burning surface, because the foam layer was gradually damaged by re-ignition and burning of the pool fire, resulting in further spread of the burning surface until the foam layer completely collapsed.

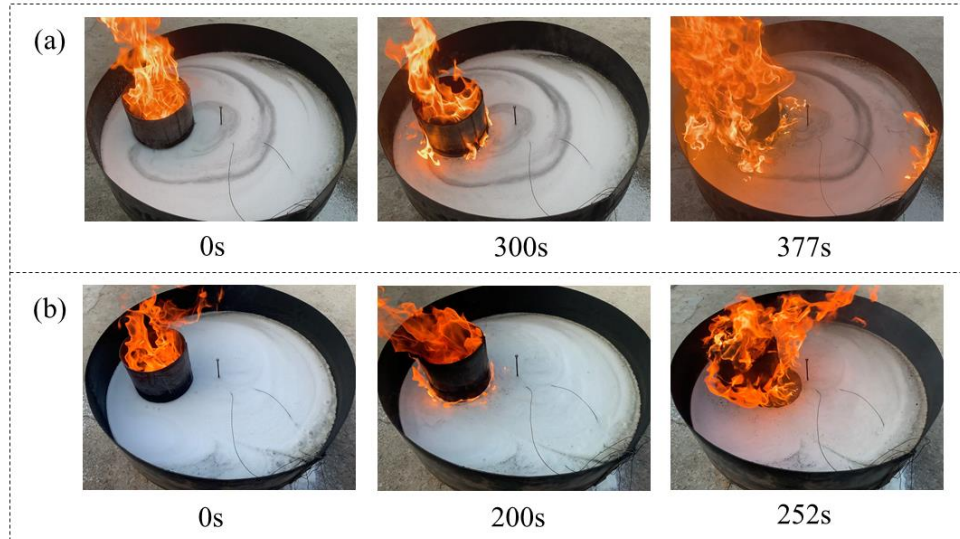


Fig. 14. Burnback process of different types of foam: (a) Formula I, (b) FFFP

To illustrate the collapse characteristics of the foams in the burnback process, Fig. 15a shows the heating rate (rate of temperature change, °C/s) of the fuel surface with gel-protein foams and FFFP. The heating rate remains slightly negative initially, followed by a gradual increase, and then increases sharply at the end. The negative heating rate in the stable covering and partial collapse stages indicates that the fuel temperature continues to decrease because of the cooling effect of the foam. The slow increase in the diffusion collapse stage is due to the gradual expansion of the re-ignition area after the foam layer is damaged. The heating rate increases sharply near the end of the test indicating the complete re-ignition of the pool fire. Fig. 15b compares the 25% and 90% burnback times of the gel-protein foams and FFFP. Compared with FFFP, the 90% burnback time of Formulas I, II and III increases by 54.42%, 27.21%, 4.76%, respectively. This can be ascribed that the gel particles in the gel-protein foams decrease the drainage and coalescence rate of the foam as shown in the detailed stabilization mechanism in Fig. 9. Overall, Formula I shows the best burnback capacity among all the foams.

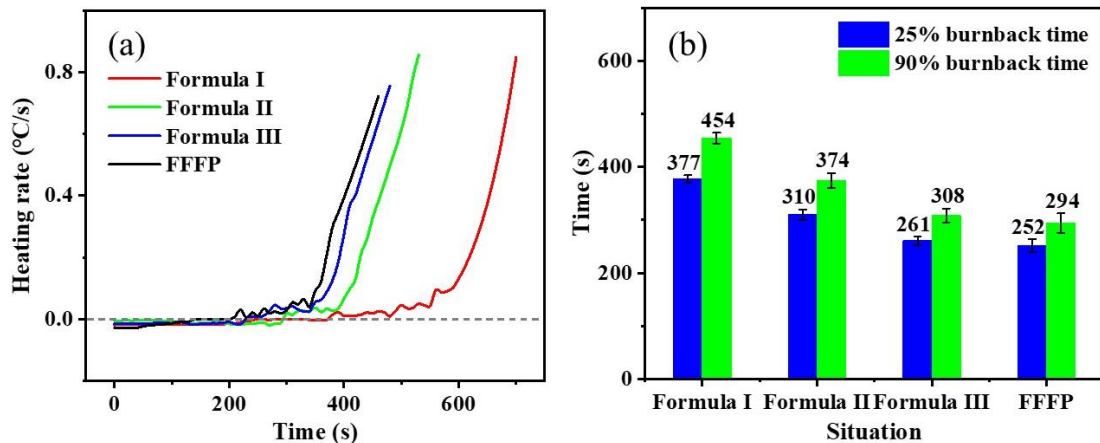


Fig. 15. With the effect of different foams: (a) heating rate of oil surface, (b) burnback parameters

4. Conclusions

In this work, a new gel-protein foam was successfully developed for suppression and extinguishing of liquid pool fires. Four surfactants (AES, SDBS, SDS and SLS) were used as the foaming agent with HP as the foam stabilizer, SA as the gelling agent, and CaCl_2 as the crosslink agent. The best compound foaming agent was found to be AES/HP at a ratio of 2:8 and a concentration of 0.5 wt%. This foaming agent was then used to determine the optimal mass fraction (wt%) and ratio (λ) of SA and CaCl_2 . Based on systematic evaluation of foam comprehensive properties, three formulations (Formula I: 0.1 wt% with $\lambda=9:1$, Formula II: 0.2 wt% with $\lambda=4:1$ and Formula III: 0.4 wt% with $\lambda=3:1$) were selected for assessing their fire extinguishing characteristics in fire suppression and burnback tests against a commercial FFFP (6%). The main conclusions are as follows:

- (1) The new gel-protein foam exhibiting the optimal fire extinguishing efficiency is Formula I, which showed excellent foam stability and water retention capacity due to the presence of gel particles. The average size and water loss ratio of this formulation are $124.84\mu\text{m}$ and 30.6%, respectively, compared to $271.92\mu\text{m}$ and 44.1% for FFFP.
- (2) For the fire suppression tests, Formula I performed slightly better than FFFP, whereas Formula II and Formula III had considerably longer fire control and

extinguishing times because both have a higher gelling agent content and as a result release less water to suppress the fire.

- (3) For the burnback tests, all three gel-protein foam formulations performed better than FFFP in terms of the burnback time and preventing the fuel from heating. Formula I showed the longest burnback time and lowest heating rate of the fuel overall as it can float stably on the fuel surface for a longer time. The 90% burnback time of Formula I is 454s, a 54.42% increase compared with that of FFFP.

In addition to better stability and fire extinguishing capacity of gel-protein foams, another key benefit of these foams is that they are environmentally friendly and easily degradable. While more tests should be conducted to verify other characteristics (such as viscosity and spread performance), this study clearly demonstrated the potential of using gel-protein foams for suppression and extinguishing of liquid pool fires.

Credit author statement

Chang Tian: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Jinlong Zhao: Resources, Supervision, Writing – review & editing, Project administration, Funding acquisition. Junhui Yang: Formal analysis, Writing – review & editing, Visualization, Funding acquisition. Jianping Zhang and Rui Yang: Supervision, Resources, Project administration, review & editing.

Acknowledges

This study was sponsored by the National Natural Science Foundation of China (No. U2033206 and No. 51906253), the Fundamental Research Funds for the Central Universities (No. 2020QN05 and No. 2021JCCXAQ01).

Appendix A. Uncertainty analysis

Due to the unavoidable measurement error and accumulated error in the process of model deduction, it is essential to quantitatively estimate their impact on the results' uncertainty. The uncertainties of the experimental parameters involved in this paper have been evaluated by adopting Moffat method (Moffat, 1985; Moffat, 1988) According to this method, the model uncertainty is described by a root-sum-square (RSS) equation.

$$\delta R = \left\{ \left(\frac{\partial R}{\partial x_1} \delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \delta x_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \delta x_n \right)^2 \right\}^{1/2} \quad (A1)$$

where x_i ($i= 1, 2, 3, \dots, n$) is the measurement, R is the experimental result which is calculated from a set of measurements, $R = (x_1, x_2, x_3, \dots, x_n)$. In this paper, the measured independent variables include foam expansion ratio (E) and half-life ($T_{1/2}$). δx_i ($i= 1, 2, 3, \dots, n$) is the uncertainty of x_i . $\partial R/\partial x_i$ is the sensitivity coefficient representing the influence weight of x_i on R . Based on Eq. (A1), the relative average uncertainties of the experimental and calculated parameters are shown in Table A1.

Table A1. Uncertainties of the measured and calculated parameters

Parameters	Source of uncertainty	Average relative uncertainties
Foam expansion ratio, E	Measurement	1.64%
Half-life, $T_{1/2}$	Measurement	1.53%
Foam comprehensive index, FCI	$E, T_{1/2}$	0.06%

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