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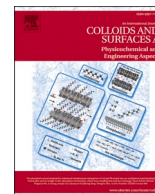
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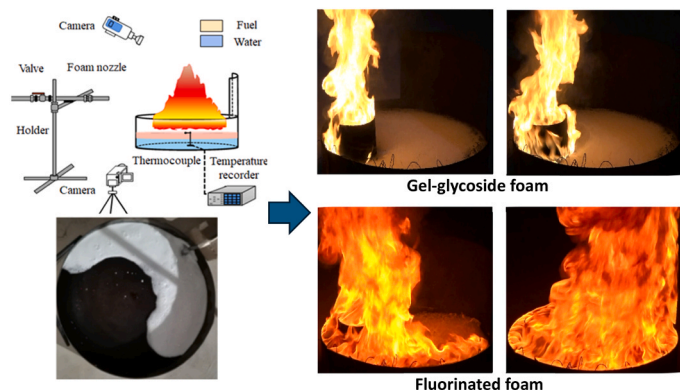
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Development of an environmentally friendly gel foam and assessment of its thermal stability and fire suppression properties in liquid pool fires

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GRAPHICAL ABSTRACT



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ABSTRACT

Large-scale tank fires are one of the most challenging firefighting scenarios and pose significant threats to the safety of personnel and the integrity of equipment. The development of effective extinguishing agents is thus of both fundamental and practical importance in the controlling, mitigation, and suppression of tank fires. In this study, a novel environmentally friendly fire suppression foam based on gel-glycoside was developed using alpha-olefin sulfonate (AOS) and alkyl ethoxy polyglycosides (AEG) as the foaming agents, and sodium silicate, and sodium bicarbonate as the gelling and cross-linking agents respectively. The optimal ratios of the foaming agents were determined firstly by examining the foam expansion ratio and foam comprehensive value. Subsequently, the foamability, thermal stability, cross-linking time, and spreadability of the optimized formulations were analyzed. Finally, the fire extinguishing effects and performance in suppressing burnback of these formulations were examined and compared with those of a traditional film-forming fluoroprotein foam (FFFP). The experimental results indicated that the gel-glycoside foam, consisting of a composite foaming agent (AOS:AEG = 1:9), sodium silicate, and sodium bicarbonate at concentrations of 0.6, 2.4 and 3.7 wt%, respectively, exhibited the best spreadability and thermal stability. This formulation also showed excellent performance in cooling and suppressing burnback in the fire extinguishing tests, with a 90 % burnback time of 485 s, 45 % higher than that of

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FFFP. The present results clearly demonstrated that gel-glycoside foams can effectively control and suppress liquid pool fires and hence reduce the risk in potential re-ignition. These findings are also important for the further development of gel foams for extinguishing large-scale oil storage tank fires.

1. Introduction

Due to large quantities liquid fuel stored in tank farms, they are prone to fire and explosion accidents, which often led to a large number of casualties and equipment failure because of the large surface burning area and strong radiation [1]. For tank fires, film-forming fluoroprotein foams (FFFPs) are widely used because of their good extinguishing performance. However, the high persistence and bioaccumulation of the fluorocarbon surfactant in FFFPs have raised serious environmental and public health concerns [2]. Moreover, the stability of traditional foams can deteriorate quickly under strong thermal radiation, resulting in re-ignition of oil tank fires [3]. For instance, an oil storage tank fire occurred in a chemical industry plant at Cangzhou, Hebei Province in May 2021. Due to intense combustion and strong radiation, it became extremely difficult to effectively apply FFFP on the fuel surface, leading to multiple re-ignitions. The fire extinguishing process lasted 84 hours with substantial consumption of FFFP and the production of 29,850 m³ wastewater. Clearly, it is of great significance to develop efficient, environmentally friendly, and high-stability fire extinguishing agents for large tank fires.

For the extinguishment of liquid fires, the use of additives in a traditional foam system to improve the stability of foam extinguishing agents has been explored by many researchers in the past decades. Zhuo et al. [4] found that nanoparticles significantly enhanced insulation performance of foam layers under radiative heating. Yekeen et al. [5] incorporated silicon oxide (SiO₂) or aluminum oxide (Al₂O₃) nanoparticles into a foam solution and reported that the foam stability improved with an increase in the nanoparticle concentration. Kang et al. [6] introduced xanthan gum and gelatin into a foam system and examined its foam stability. It was found that the foam height and 25 % drainage time were increased by 9.9 % and 375.2 % respectively, compared to the foam without. Sheng et al. [7] added nanoparticles or xanthan gum to a foam system and reported that xanthan gum could better enhance foam stability compared with nanoparticles but lead to a rapid decrease in foaming ability. Sheng et al. [8] further reported that adding SiO₂ nanoparticles to a foam solution significantly enhanced thermal stability of the foam under high-temperature conditions. Qiu et al. [9] developed an environmentally friendly firefighting foam by adding protein-metal coordination complexes to the foam system and their results showed that protein-metal coordination complexes could significantly enhance the stability of the foam. Yu et al. [10] reported that transition metal ions could substantially improve the stability of hydrolyzed rice protein foams. Furthermore, Yu et al. [11] showed that the addition of cellulose nanocrystals (CNC) could decrease the liquid discharge rate and enhance the stability of liquid foam. The above studies showed that the addition of polymers or functional nanoparticles can enhance foam stability but often lead to worsening foaming performance. Moreover, as these additives cannot retain water effectively, the cooling performance was also adversely affected [12,13]

In recent years, gel materials have been increasingly used as foam stabilizers. Han et al. [14] developed a gel foam by combining sodium alginate (SA), calcium lactate (CL), alkyl glucoside (APG), and tea saponin (TS), and showed that the gel foam had good water retention performance and as a result could significantly reduce the temperature of coal samples. Wu et al. [15] synthesized a gel foam using carboxymethyl cellulose, poly aluminum chloride, and sodium citrate, and found that the thermal stability and anti-re-ignition performance of the gel foam were better than those of a two-phase foam. Shi et al. [16] studied the half-life and fire resistance of both a gel foam and a two-phase foam and found that the gel structure significantly prolonged

the half-life of the foam while improving fire resistance compared with the two-phase foam. Tian et al. [13] prepared a gel foam using sodium alginate and calcium chloride and studied its stability and fire extinguishing performance in oil pool fires. It was reported that the gel foam had good stability and its 90 % burnback time was approximately 1.5 times that of a FFFP. It is clear from the above studies that gel materials can enhance the foam stability and improve the cooling performance, however most of gel foams have been developed primarily for solid fuels and their use in liquid fires is still limited [13]. A key difference in the extinguishing of a solid or a liquid fuel is that in a liquid fire a good foam coverage is essential, which is closely related to the spreading performance of the foam. However, gel foams are often difficult to spread freely on the fuel surface due to their rapid cross-linking and high viscosity [16,17].

To address this issue, this study aims to develop a reactive gel-glycoside foam, as is not only environmentally friendly, but also allows the controlling of the cross-linking time and hence its spreading ability when applied on a liquid surface [18–21]. Furthermore, it has been shown in [12] that these foams can maintain high thermal stability under fire conditions. In this work, alkyl ethoxy polyglycosides (AEG), alpha-olefin sulfonate (AOS), sodium silicate (Na₂SiO₃), and sodium bicarbonate (NaHCO₃) were employed to synthesize gel-glycoside foams. The gel-glycoside foam is environmentally friendly because (i) the compound foaming agent has fast natural degradation and can be decomposed into H₂O and CO₂ in a very short period of time and (ii) the gel material formed by the gelling agent and cross-linking agent can naturally degrade into H₂O and SiO₂, with the latter being a major component of sand. The optimal ratios of the foaming agents were determined firstly by examining the foam expansion ratio and foam comprehensive value. Subsequently, the foamability, thermal stability, cross-linking time, and spreadability of several optimized formulations were analyzed. Finally, the fire extinguishing and burnback performances of these formulations were evaluated and compared with those of a traditional FFFP.

2. Experimental investigations and framework

2.1. Materials

A gel-glycoside foam is composed of surfactants, gelling agents, and cross-linking agents. Four foaming agents were examined with alkyl ethoxy polyglycosides (AEG) as the foaming stabilizer: namely (i) sodium alcohol ether sulphate (AES), (ii) alpha-olefin sulfonate (AOS), (iii) sodium alkyl benzene sulfonate (SAS), and (iv) linear Alkylbenzene Sulfonates (LAS). Sodium silicate (Na₂SiO₃) was used as the gelling agent and sodium bicarbonate (NaHCO₃) the cross-linking agent. In order to evaluate the fire-extinguishing efficiency of the gel-glycoside foam, a commercial FFFP with 6 % active matter content was also used. The detailed information of the materials used in the study is shown in Table 1.

2.2. Foamability and stability tests

The foaming performance is commonly evaluated using foamability and stability. The foam expansion ratio was measured using the Waring Blender method [22]. Firstly, 50 mL of foam solution (V₁) was poured into a container and stirred at a speed of approximately 3000 rpm for 2 minutes, which was then poured into a graduated cylinder. The foam volume (V₂) and the half-life (T_{1/2}), which is defined as the time for the foam to separate half of the foam solution [13], were recorded. The

Table 1
Detailed information of the materials.

Type	Name	Active Matter Content	Manufacturer
Surfactants	Alkyl Ethoxy Polyglycosides (AEG)	50 %	Shandong Ecosol Chemical Technology Co., Ltd
	sodium alkyl benzene sulfonate (SAS)	60 %	Shandong Ecosol Chemical Technology Co., Ltd
	Sodium alcohol ether sulphate (AES)	70 %	Shandong Ecosol Chemical Technology Co., Ltd
	Linear Alkylbenzene Sulfonates (LAS)	90 %	Shandong Ecosol Chemical Technology Co., Ltd
	alpha-olefin sulfonate (AOS)	92 %	Shandong Ecosol Chemical Technology Co., Ltd
Gelling agent	Sodium silicate (Na_2SiO_3)	36 %	Tongxiang Hengli Chemical Co., Ltd.
Cross-linking agent	Sodium bicarbonate (NaHCO_3)	99.5 %	Henan Zhongyuan Chemical Co., Ltd.
Extinguishing agent	Film-forming fluoroprotein foam (FFFP)	6 %	Suzhou Lingen Fire Technology Co., Ltd.

expansion ratio (E) can be expressed as:

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

2.3. Determination of the gelation time

The gelation time was determined using the bottle test. A specified amount of gelling agent and cross-linking agent were added to a cup, followed by the addition of the compounded foaming agent to fill up to 25 mL. The gelation time was determined as the time elapsed from the start of adding the materials to that when the mixture became solid-like [23]. For each formulation, at least three tests were conducted, and the average value was used for further analysis.

2.4. Testing for foam thermal stability

The experimental device for measuring the foam thermal stability is shown in Fig. 1. The device consists of an infrared heater, a camera, a quartz glass container ($L \times W \times H = 5 \text{ cm} \times 5 \text{ cm} \times 15 \text{ cm}$), a temperature recorder and a temperature controller. The quartz glass container filled with foam was placed 6 cm below the infrared heater, and three K-type thermocouples (measurement range: 0–600 °C, accuracy: $\pm 1\%$ FS) were evenly distributed in the foam container at a separation distance of 5 cm. The top thermocouple was placed 8 cm below the radiation heat source. During the test, the infrared heating source was preheated to a

temperature of 200 °C, before the foam was added to the container. The experimental process was recorded by a digital camera (SONY, FDR-AX100E), and the video data were processed using the software Image J to obtain the variation of the foam height with the heating time.

2.5. Spreading performance test

For the spreading performance, 5 L of gasoline fuel was added to a 0.8-meter-diameter oil pan, and the foam was then slowly released from the edge of the oil pan. The entire spreading process was also recorded by the digital camera, based on which the variation of the spreading area with time was determined using Image J [24].

2.6. Fire extinguishing and burnback tests

The experimental device for the fire extinguishing and burnback tests is shown in Fig. 2. The system consists of a self-priming pump, two containers, three flow meters, a pipe mixer, a foam nozzle, an oil pan with a diameter of 0.8 m, two cameras, and thermocouples. Before the test, 5 L of water was added to the pan, followed by 10 L of gasoline. The gasoline was ignited with a lighter and allowed to burn freely for 60 s, before the gelatinous foam was applied. The extinguishing time and 90 % control time (90 % of the pan area extinguished) were recorded [25]. The burnback capacity of the foam was tested 5 min after the pool fire was extinguished. An ignition tank with a diameter of 0.2 m was placed in the oil pan and gasoline was then added into the ignition tank and ignited. The 25 % and 90 % burnback times (25 % and 90 % of the oil pan area re-ignited) were recorded. The burnback time can be used to indicate the foam's resistance to re-ignition [26,27]. The entire fire extinguishing process was recorded, and the video images were used to determine the burnback time. Each operating condition was repeated at least three times to check for repeatability, and the average result was presented.

2.7. Framework

The framework shown in Fig. 3 consists of three parts: (i) formulation analysis, (ii) basic characteristic analysis (thermal stability and spreadability), and (iii) fire extinguishing characteristic analysis. Firstly, the foaming ability of single surfactants and the foam comprehensive index (FCI) [28] of compound foaming agents were examined.

$$\text{FCI} = \frac{3}{4} \text{ETI} / 2 \quad (2)$$

The FCI and the gelation time were then used to screen the foaming agents and to optimize the mass fractions and mass ratios of the reagents. Finally, the comprehensive performance of the gel-glycoside foam was evaluated in terms of thermal stability, spreadability and fire performance in the fire suppression and burnback tests.

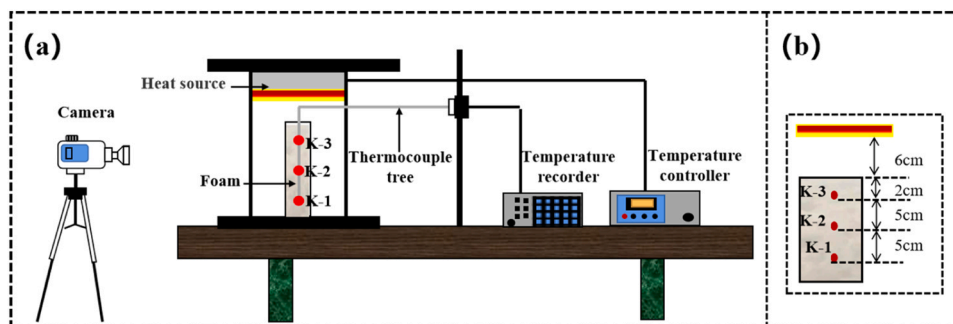


Fig. 1. Experimental apparatus for foam thermal stability.

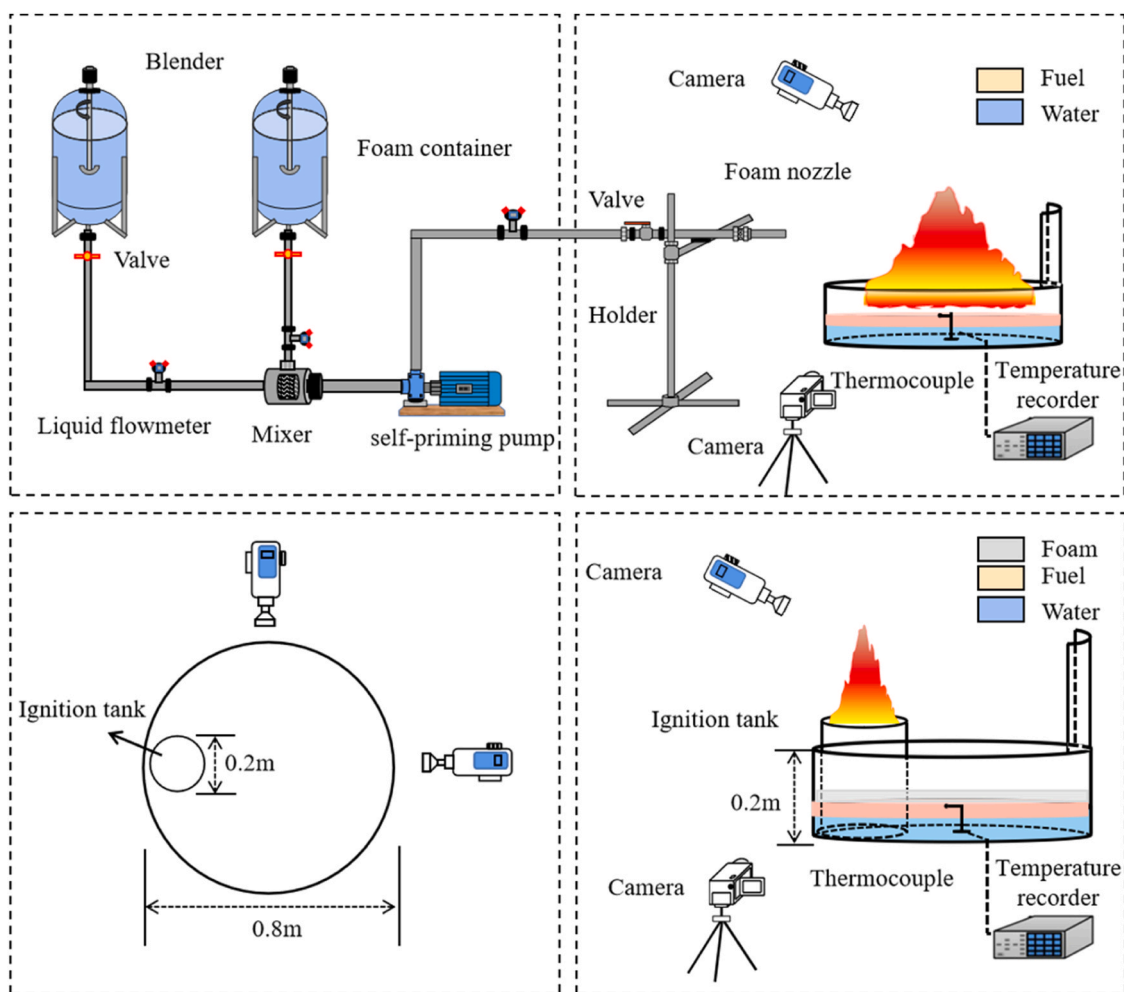


Fig. 2. The gel-glycoside foam fire extinguishing system.

3. Results and discussion

3.1. Ratio of compound foaming agents

The foam expansion ratios of the four surfactants (AES, AOS, SAS, and LAS) at different mass fractions are presented in Fig. 4. The foam expansion ratios appear to increase initially with the increase of mass fraction due to a decrease in surface tension. The maximum foam expansion ratio of AOS is achieved when the mass fraction is 0.4 wt%, indicating that the critical micelle concentration (CMC) has reached [29], after which the foam expansion ratio would decrease with a further increase in mass fraction, as the surface tension can no longer decrease. Instead, the redundant surfactant molecules aggregate and form micelles, which can lead to a decrease in the surface activity and surfactant foamability. Among the surfactants tested, AOS exhibits the best foamability, achieving a foaming ratio of 18.3 times at a mass fraction of 0.4 wt%. Therefore, AOS was selected for subsequent compounding with AEG.

In order to determine the optimal ratio between AOS and AEG (η), AOS and AEG are mixed in different proportions at a total mass fraction of 0.5 wt%. The foam expansion ratio, half-life and foam composite index are analyzed, as shown in Fig. 5. It can be observed that all three parameters first increase and then decrease with an increase of η . The maximum foam expansion ratio (20.4) is achieved at $\eta = 5:5$, whereas both the half-life and FCI reach their maximum values (7.79 min and 112.18 respectively) at $\eta = 1:9$, which is considered as the optimal ratio between AOS and AEG.

The effect of the mass fraction of the compound foaming agent (η is now fixed at 1:9) on its foam comprehensive performance was also studied by varying the mass fraction from 0.1 to 0.7 wt% and the results are presented in Fig. 6, where it can be seen that initially FCI increases with the increase of mass fraction until it reaches the maximum value at a mass fraction of 0.6 wt% (i.e., the optimal concentration), after which FCI starts to decrease indicating worsening stability. Based on the above results, a compound foaming agent with an AOS/AEG ratio of 1:9 and a total mass fraction of 0.6 wt% was selected to develop the gel-glycoside foam in combination with the gelling and cross-linking agents. For convenience, the foaming agent with only AOS and AEG will be referred to as F-0.

3.2. Ratio of polymers

Fig. 7a presents the variation of the foam expansion ratio with different concentrations of the cross-linking agent (NaHCO_3) and gelling agent (Na_2SiO_3). The foam expansion ratio decreases as the Na_2SiO_3 concentration increases for a given NaHCO_3 concentration, because the viscosity and surface tension of the foaming solution increase with increasing Na_2SiO_3 concentration, resulting in a decrease in the foam expansion ratio. It should be noted that viscosity is one of the most important parameters affecting the spreading and subsequently suppression performance of a foam and, generally, the higher the viscosity, the lower the spreading performance. Whilst the viscosity of the foams was not measured in this study, its effects are clearly shown in the spreading and fire suppression tests. Meanwhile, the foam expansion

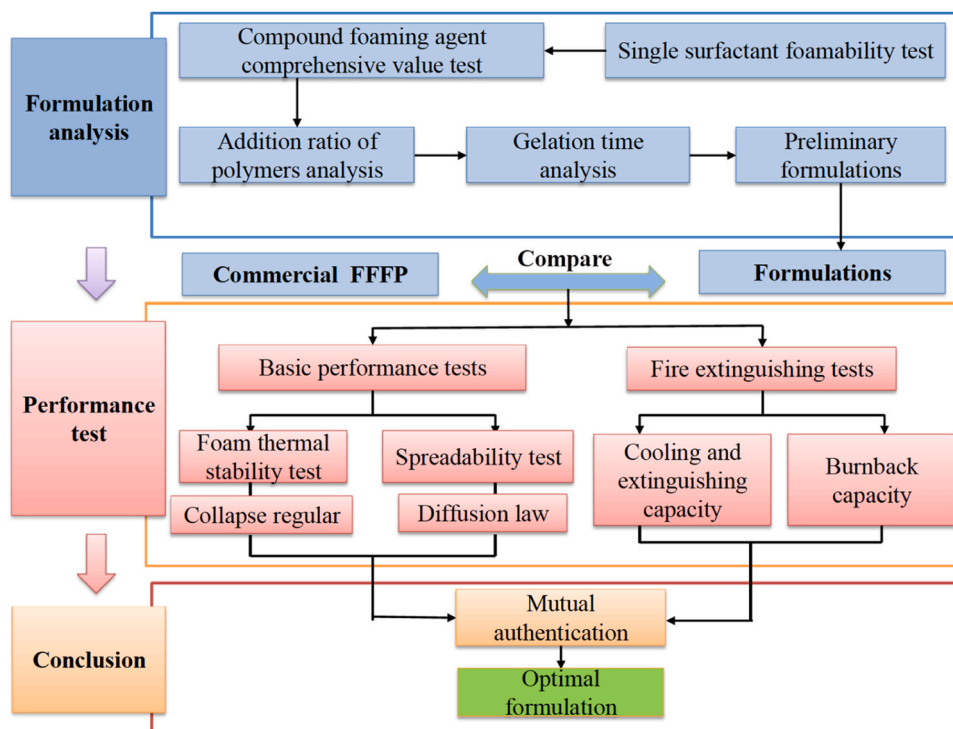


Fig. 3. The development process of gel-glycoside foam.

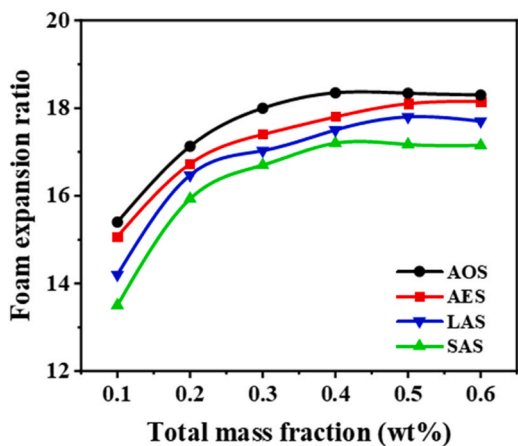


Fig. 4. Foam expansion ratio of surfactants.

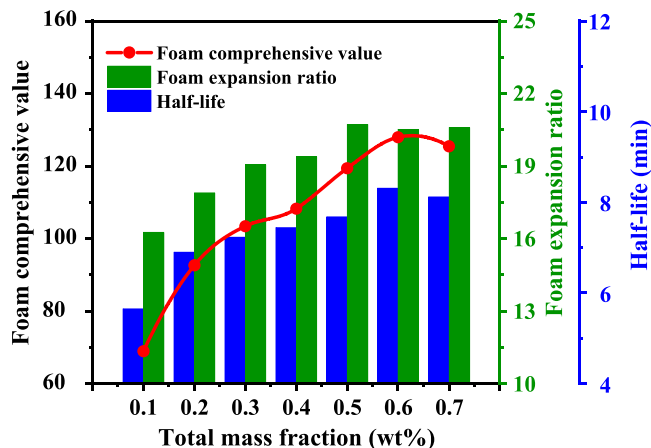


Fig. 6. The FCI of the compound foaming agent at different mass fractions.

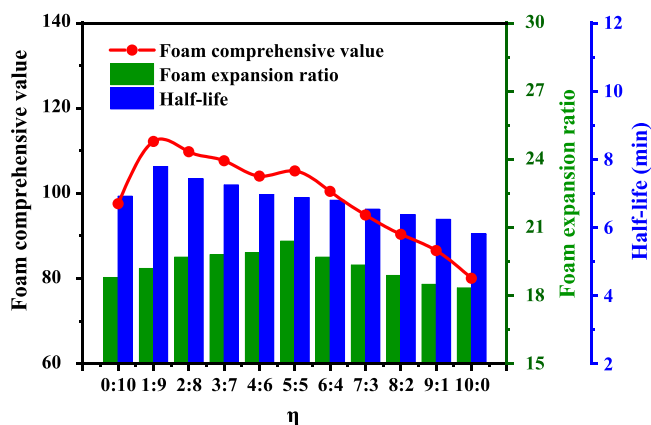


Fig. 5. The FCI of compound foaming agent with different AOS/AEG ratios (η).

ratio decreases with the increase of the NaHCO_3 concentration for a given Na_2SiO_3 concentration. This can be attributed to the rapid formation of the gel structure, which limited gas penetration into the solution. Since a further increase of the NaHCO_3 concentration leads to worsening fire performance of the foam, high concentrations of the agents were not considered in this study.

Fig.7b shows the cross-linking time (within 20 min) for different concentrations of the gelling agent (Na_2SiO_3) and cross-linking agent (NaHCO_3). It can be seen that at a constant Na_2SiO_3 concentration, the cross-linking time of the gel foam decreases with an increasing concentration of NaHCO_3 . This is mainly due to the fact that as the concentration of the gelling agent increases, a large number of hydrophilic silica groups (Fig. 8) are generated in the solution, so the reaction rate between the gelling agent and cross-linking agent is accelerated. The cross-linking time of the gel shows a shortening trend with an increasing concentration of NaHCO_3 under a constant Na_2SiO_3 concentration. This could be attributed to the rapid increase in the number of cross-linking

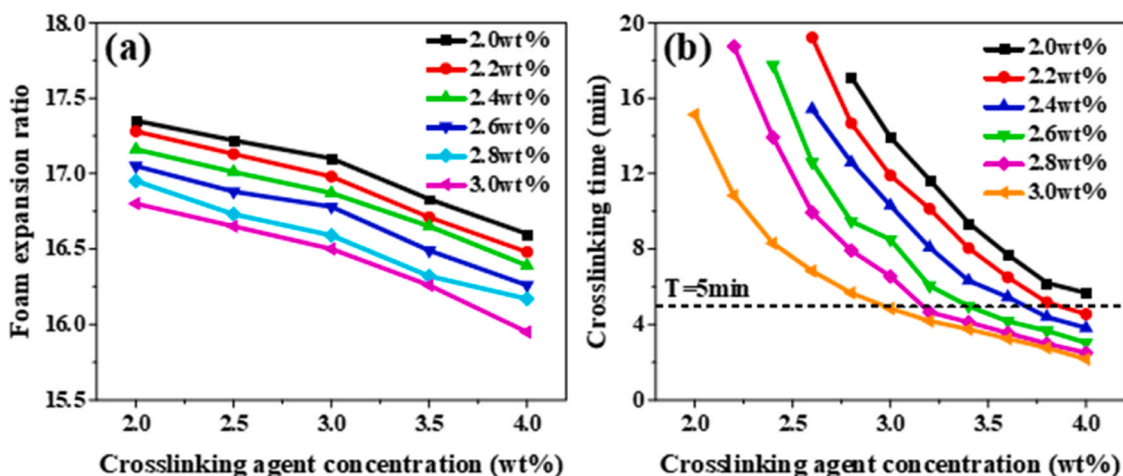


Fig. 7. The foam expansion ratio (a) and cross-linking time (b) with different mass fractions of Na_2SiO_3 and NaHCO_3 .

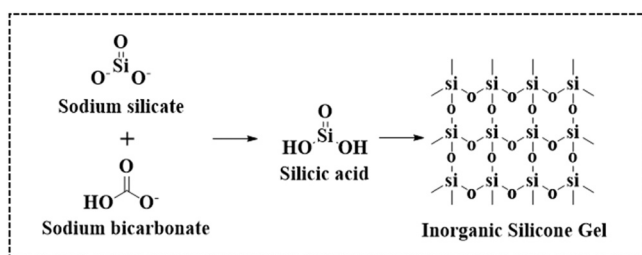


Fig. 8. The reaction mechanism of gel-glycoside foam.

ions in the foaming solution as the concentration of the cross-linking agent increases. These cross-linking ions can react quickly with the hydrophilic silicon oxygen groups and form a three-dimensional network structure (Fig. 8).

It is worth emphasizing that, although increasing the concentration of either the gelling agent or the cross-linking agent can shorten the cross-linking time of the gel foam, it has a significantly negative impact on the foam expansion ratio, as shown in Fig. 7a. Lowering the concentrations of either the gelling agent or the cross-linking agent would result in it taking longer to form the gel foam or no gel foam formed at all.

The spreading performance of the foam is a critical parameter for extinguishing liquid fires. On the one hand, the gel foam can be formed in a very short period of time when the concentration of the gelling and

cross-linking agents is high. However, the foam cannot efficiently spread on the surface of the liquid, making it impossible to extinguish the fire. On the other hand, it would take a long time to form the gel foam if the concentration of the gelling and cross-linking agents is low, resulting in poor burnback performance. In practical firefighting, 5 min was often chosen as the time limit for its effective supply of the foam extinguishing agent [30]. It is, therefore, essential for the foam to spread on the liquid surface for more than 5 minutes with a continuous supply, without adversely affecting its performance in suppressing burnback. Based on the above discussions, the formulations with a cross-linking time of about 5 minutes were selected for the fire suppression tests at different mass fractions of NaHCO_3 : Na_2SiO_3 : (i) 3 wt%: 3 wt%, (ii) 3.1 wt%: 2.8 wt%, (iii) 3.4 wt%: 2.6 wt%, (iv) 3.7 wt%: 2.4 wt%, and (v) 3.8 wt%: 2.2 wt%. For simplicity, these formulas will be referred to as F-1, F-2, F-3, F-4, and F-5, respectively.

3.3. Thermal stability of foam

The decay of the foam volume under thermal radiation is depicted in Fig. 9a for F-1. The other foams show similar trends and thus are not included here for brevity. The foam volume initially increases because of the expansion of gas in the foam during heating. Subsequently, the foam volume decreases with time, due to the rapid evaporation of liquid in the foam. Fig. 9b shows a comparison of the variation of the foam height for all the gel-glycoside foams and FFFP, where it can be seen that the foam height of all formulations experiences a small increase followed by a rapid decline. During the initial rise, the foam heights of the gel-

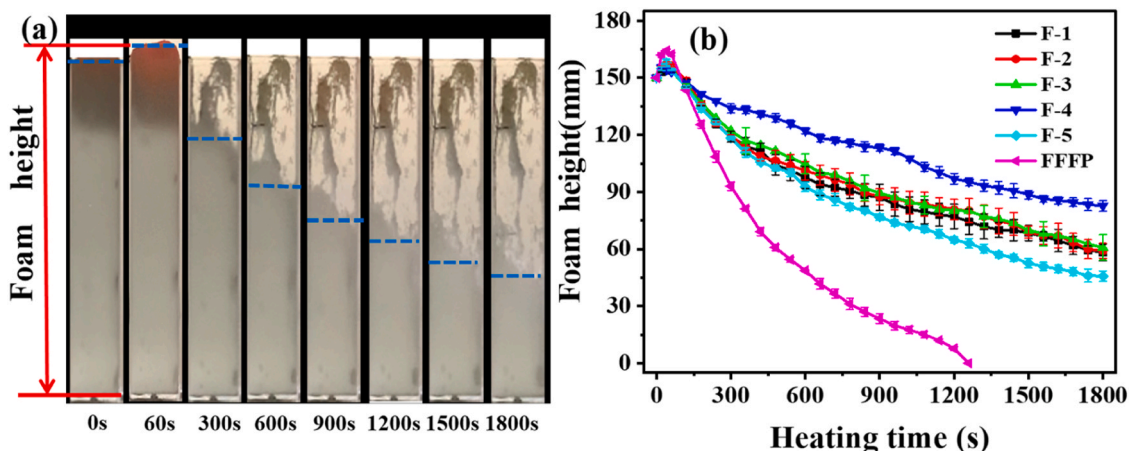


Fig. 9. Foam decay process under thermal radiation: (a) The F-1 foam decay over time; (b) Foam layer height varies with heating time.

glycoside foams are slightly lower than that of FFFP, but subsequently decrease at much lower rates than FFFP. The superior thermal stability of the gel-glycoside foams can be attributed to the gel particles adhered to the membrane in the foam, which effectively reduce the drainage and coalescence rate of the foam.

To further investigate the thermal stability of gel-glycoside foams, the temperature variation at different depths in the foam layer were analyzed. Fig. 10a displays the temperature changes at different positions inside the F-1 foam layer (K-1, K-2, and K-3 positions are shown in Fig. 2). The trends of the results for FFFP, F-2, F-3, F-4 and F-5 are similar. At K-2, the foam temperature reaches the first stable value after a short rise. This is because the poor gas diffusion among bubbles caused by slow foam coarsening can effectively prevent heat transfer from the heated gas in the upper bubbles to the lower bubbles [26]. Subsequently, the temperature rises sharply and after some time reaches a second relatively stable value, at which the thermocouple is exposed to thermal radiation due to the collapse of the foam layer. At K-1, the temperature increases slowly since the thermocouple is protected by the foam layer for the whole duration of the test. Clearly, the temperature variation at the K-2 position are best to reflect the collapse of the foam under heating conditions. Fig. 10b shows a comparison of the temperature variations at K-2 for all the formulations. The order of the foam layer collapse is: FFFP < F-5 < F-1 < F-2 < F-3. Note that the foam layer of F-4 did not completely collapse during the whole heating process. These results indicate that the foam structure of the gel-glycoside foam is more stable than that of FFFP, because the gel structure in the gel-glycoside foam can effectively inhibit the collapse of the foam layer at high temperatures. The results also reveal that F-4 foam has the highest thermal stability among all the formulations.

3.4. Spreading performance

The spreading performance of a foam determines its diffusion rate on a liquid surface, which in turn affects the efficiency of extinguishing liquid fires [31]. Fig. 11 shows the spreading process of the gel-glycoside foam F-1 on the fuel surface. It can be seen that the foam first gathers near the wall before spreading along the wall. The spreading speed of the foam increases initially, when the spreading is affected by the interaction of gravity and inertia, leading to the rapid spreading of the foam on the liquid surface. As the foam spreads further outward, the force that promotes the spreading gradually transitions from gravity to surface tension, and the force that hinders the spreading from inertia to viscosity. This results in a gradual decrease in the spreading speed. The oil surface is completely covered by the foam after 24 s as shown in Fig. 11.

To further examine the spreading performance of the gel-glycoside foam, the variation of the spreading area of the foam with time was analyzed, as depicted in Fig. 12, where it can be observed that the initial

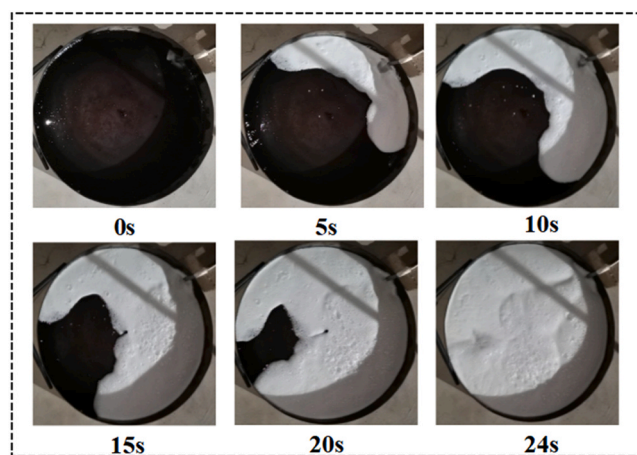


Fig. 11. Spreading process of gel glycoside foam F-1 on fuel surface.

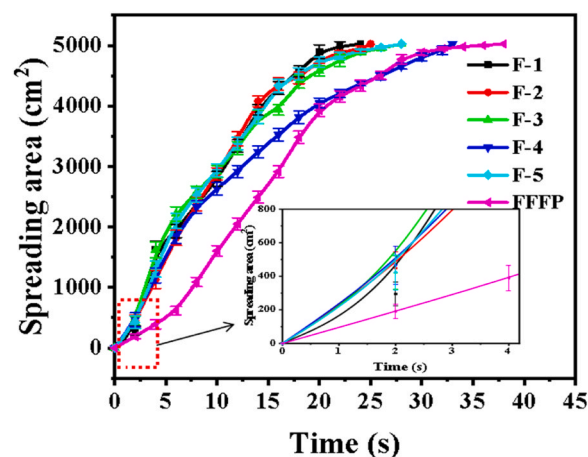


Fig. 12. The variation of foam spreading area with time.

spreading speed of F-4 is higher than other formulations. However, with the increase of the spreading time, the spreading speed of F-4 gradually becomes lower than that of other formulations, likely due to the larger content of gel particles formed in F-4 than other formulations. The spreading time of all gel-glycoside foams are lower than that of FFFP, indicating that the formation of gel particles in gel-glycoside foams can be delayed by controlling the cross-linking time, thereby enhancing the foam spreadability.

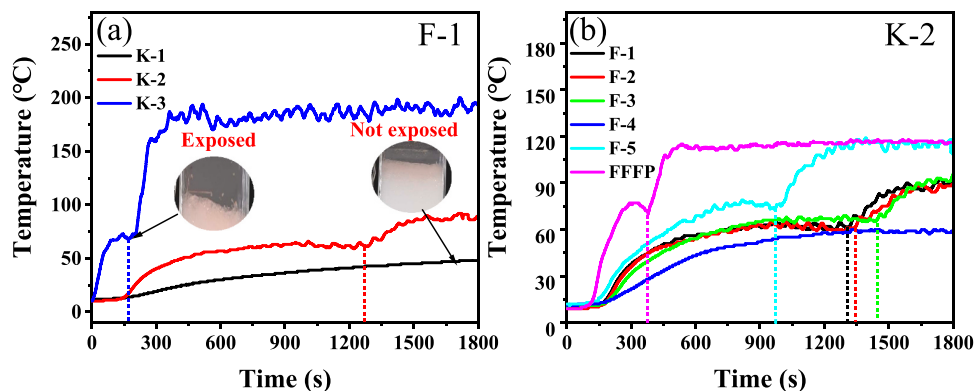


Fig. 10. Temperature variation at different depths inside the foam layer. (a) The variation of F-1 foam temperature with time; (b) The temperature variation at K-2 position.

3.5. Fire extinguishing and burnback performance

Fig. 13 displays typical images in the extinguishing process using foams F-0 and F-1 (note that F-0 is the formulation without the cross-linking or gelling agents). Clearly, the extinguishing effect of F-1 is significantly better than that of F-0, owing to the combined action of the gelling agent, cross-linking agent, and gel particles. In both cases (and similarly for other formulations), the fire extinguishing process can be divided into three stages: suppression, foam covering, and extinguishing. During the suppression stage, the flame pulsation frequency increases with the release of the foam, and the flame height is almost constant. In the foam covering stage, the flame height decreases significantly due to the foam spreading on the fuel surface, and the pool fire is in partial surface combustion. During the extinguishing stage, the fuel surface is completely covered by the foam.

Fig. 14a shows a comparison of the 90 % fire control time and extinguishing time of different foams. The extinguishing time of F-1 is reduced by 35.6 % compared with F-0. This could be attributed to the fact that NaHCO_3 , acting as a flame retardant, decomposes into carbon dioxide at elevated temperatures, which in turn dilutes the oxygen in the combustion zone, leading to improved fire extinguishing efficiency. This also explains the finding that both the 90 % fire control time and extinguishing time progressively decrease with an increase in the NaHCO_3 concentration (i.e., from F-1 to F-5). Fig. 14b presents the variation of the fuel surface temperature, a measure of the cooling ability of the foam. The fuel surface temperature decreases quickly after the application of the foam. Among all the formulations, F-4 achieves the lowest overall temperature, likely due to the presence of gel particles, which enhance the foam's cooling capacity by storing more water. Here, it is important to note that Qiu et al. [9] and Hinnant et al. [32] have shown that some commercial foams can be degraded not only by the heat from the fire but also by the hot fuel and its vapors. However, the effects of the fuel on the performance of the gel foams can be considered negligible in this work as the surface temperature of the fuel (around 100°C) is significantly lower than the flame temperature. This is also further supported by the finding that the performance of F-4 and F-5 is similar to FFFP in both the extinguishing time and cooling the fuel.

For extinguishing liquid fires, in addition to fire extinguishing capability, the burnback ability of the foam extinguishing agent is also a crucial parameter. Fig. 15 displays typical images of the burnback tests with F-4 and FFFP. It can be observed that as the ignition tank continuously heated the surrounding foam and fuel, the burnback process of the foam can be divided into three stages: foam expansion stage, foam decay stage and foam collapse stage. In the foam expansion stage, the expansion of the foam layer near the ignition tank can be observed, as depicted in Fig. 9a. This is because the gas molecules within the foam

layer are heated by the ignition tank, leading to an expansion in the foam volume as the distance between gas molecules increases. In the foam decay stage, discontinuous flames started to appear around the ignition tank. This is due to the heat flux accelerating the rate of decay of the foam layer, leading to the inability of the foam layer to inhibit the overflow and combustion of the fuel vapor. During the foam collapse stage, the foam layer was gradually destroyed by the flame, resulting in the discontinuous flame transitioning into a continuous combustion surface. With further spreading of the combustion surface, the foam began to collapse on a large scale, eventually leading to the complete re-ignition of the oil pool. It can be observed from Fig. 15 that at 354 s, whilst F-4 was still in the collapse stage, full-surface re-ignition has occurred for the case with FFFP, indicating significantly better performance of F-4 in suppressing burnback than that of FFFP.

To better understand the spreading process, Fig. 16a shows the heating rate curve (temperature change rate, $^\circ\text{C} / \text{s}$) on the fuel surface with both gel-glycoside foams and FFFP. During the foam expansion phase, the heating rate of all formulations fluctuated around $0^\circ\text{C}/\text{s}$ due to the cooling effect of the foam. In the foam decay and collapse stages, the heating rate curves of the gel-glycoside foams and FFFP show different trends. The heating rate curves of both FFFP and gel-glycoside foams initially exhibit a slow increase, due to the destruction of the foam layer, causing the fuel vapor to overflow and ignite. After some time, the heating rate curve of FFFP starts to rise and fluctuate slightly, while those of the gel-glycoside foams remain at a relatively stable value, due to the presence of gel particles, which delay the destruction of the foam layer by enhancing its stability and release water to delay the increase of the heating rate. Eventually, the heating rate curves of all formulations rise sharply, indicating complete re-ignition of the oil pool, albeit at different times. Here it is important to note that while the performance of F-4, F-5 and FFFP are similar in the fire suppression tests, F-4 shows a significant delay in the temperature rise rate compared to F-5 and FFFP, consistent with the visual observation in Fig. 15. This is also evident in the 25 % and 90 % burnback times as shown in Fig. 16b. Compared to FFFP, the 90 % burnback times of F-3 and F-4 increase by 9.85 % and 44.78 %, respectively. Despite the fact that F-1, F-2, and F-5 exhibit higher stability than FFFP, their foam expansion ratio is inhibited due to high contents of cross-linking or gelling agents, which resulted in the foam layer becoming thinner after the fire extinguished, leading to inferior resistance to re-ignition compared to FFFP. Based on the above results, it can be concluded that F-4 demonstrated the best fire extinguishing effect and burnback capability among all the formulations.

4. Conclusions

In this work, a novel gel-glycoside foam, which consists of AEG and AOS as compound foaming agents, Na_2SiO_3 as the gelling agent and NaHCO_3 the cross-linking agent, was successfully developed and applied for suppression and extinguishing of liquid pool fires. The thermal stability, spreading performance, performance in suppressing burnback and fire extinguishing performance of the gel-glycoside foams were studied systematically and compared with a commercial FFFP. The main conclusions are as follows:

(1) The ratio of the new gel-glycoside foam (F-4) showing the best performance in fire extinguishing and suppressing burnback is: 0.6 wt% compound foaming agent (AOS:AEG = 1:9), 2.4 wt% gelling agent, and 3.7 wt% cross-linking agent. This formulation also exhibits good foam thermal stability due to the presence of gel particles.

(2) In the spreading performance test, the gel-glycoside foam successfully enhanced its spreading ability on liquid surfaces by controlling the cross-linking time to delay the formation of gel particles. Compared to FFFP, the gel-glycoside foam showed better spreading performance.

(3) For the fire suppression tests, it was found that the use of NaHCO_3 can enhance the fire extinguishing effect of the gel-glycoside foam due to the release of CO_2 when it decomposes. The fire extinguishing performance of the gel-glycoside foam was improved with increasing NaHCO_3

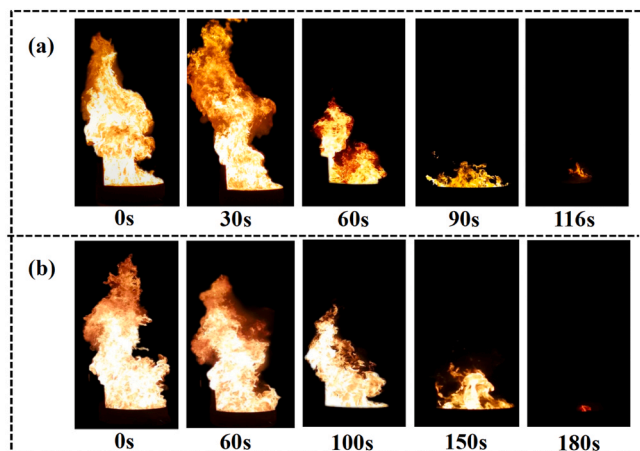


Fig. 13. Extinguishing process of different types of foam: (a) F-1, (b) F-0.

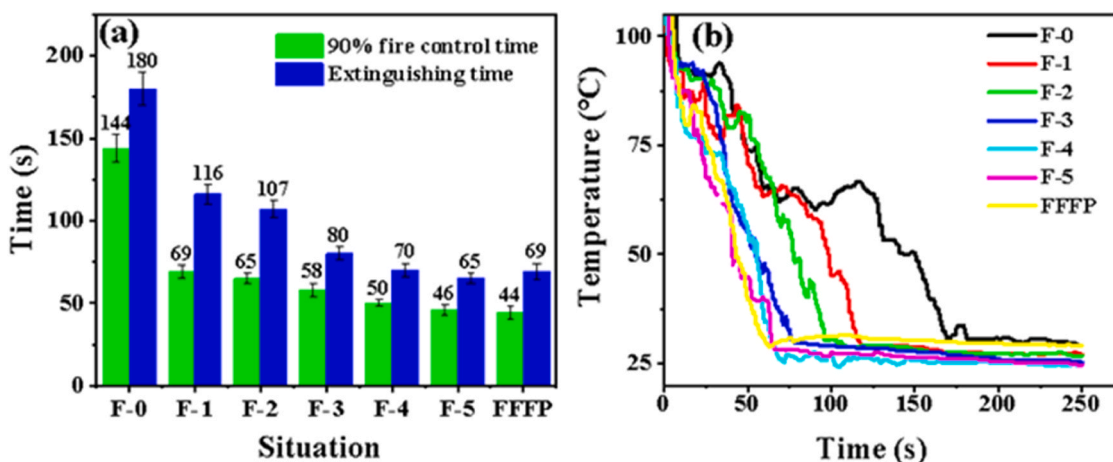


Fig. 14. Different types of foam: a) fire extinguishing parameters, (b) temperature variation trend.

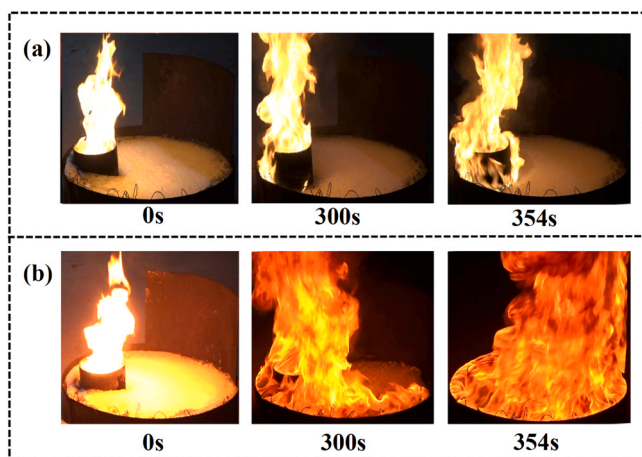


Fig. 15. Burnback process of different types of foam: (a)F-4, (b) FFFP.

concentration.

(4) During the burnback test, the 90 % burnback time of the best performing gel-glycoside foam formulation (F-4) is 485 s, an increase of 44.78 % compared to that of FFFP. However, for the other foam formulations with a higher content of either the cross-linking agent or the gelling agent, their performance in suppressing burnback worsens because of the rapid decrease of the foam expansion ratio.

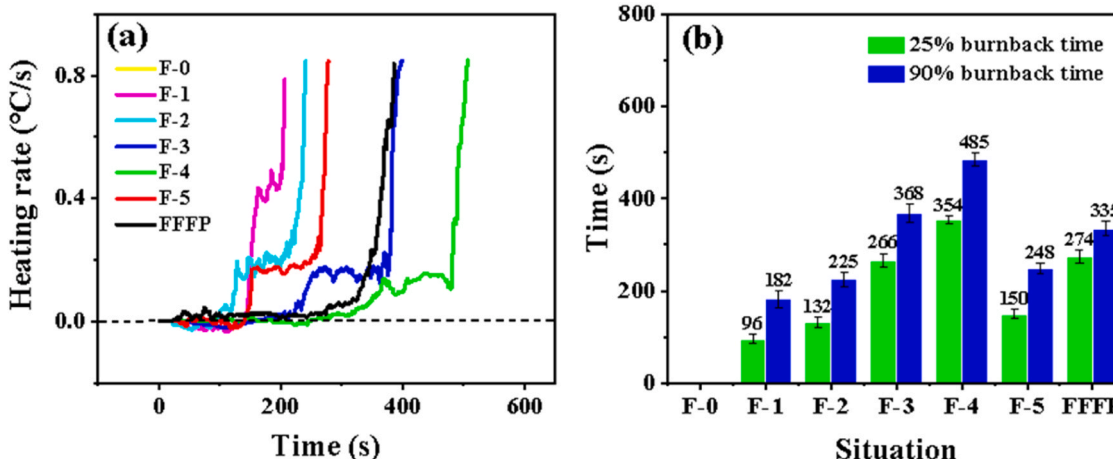


Fig. 16. Comparisons of gel-glycoside forms and FFFP on: (a) heating rate of oil surface, (b) burnback parameters.

The study has clearly demonstrated the potential of using gel-glycoside foams to suppress and extinguish liquid pool and tank fires. The primary reason for the better thermal stability than FFFP is the formation of Si-O-Si structure in the gel-glycoside foam, which can greatly slow down the drainage, coarsening and rupture rate of the foam, thereby improving its thermal stability. The improved thermal stability implies that the gel-glycoside foams can resist higher radiation and convection heat and thus, it can quickly form a stable spreading area on the fuel surface to form a protective barrier to control or extinguish the fire. More tests will be conducted in our future work with other fuels and different pan diameters for further validation of the fire extinguishing performance of the gel-glycoside foam used in this study.

CRediT authorship contribution statement

Jinlong Zhao: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Junhui Yang:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization. **Zhenqi Hu:** Visualization, Writing – review & editing. **Rongxue Kang:** Supervision, Writing – review & editing. **Jianping Zhang:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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