

Experimental study on foam drainage of AFFF: Additive regulation, thermal transition, and fire-extinguishing verification

Yun Zhang

Jimei University

Zijie Yin

Jimei University

Yan Zheng

Jimei University

Fangting Tian

Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences

Yiming Xu

Jimei University

Zhongqing Liu

Jimei University

Zongheng Chen

Xiamen Aids to Navigation Department of the Eastern Navigation Service Center, Ministry of Transport

Jieqing Zheng

zhengjieqing@jmu.edu.cn

Jimei University

Meiwei Huang

Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences

Yong Guo

Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences

Research Article

Keywords: Aqueous film-forming foam extinguishing agent, Foam drainage, Additives and formulations, Temperature effects, Fire extinguishing experiment

Posted Date: June 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10039499/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

Foam drainage is crucial for maintaining foam layer stability and improving the efficiency of aqueous film-forming foam (AFFF) in extinguishing oil fires. This paper investigates the drainage kinetics of AFFF to reveal how formulation and temperature regulate drainage, establish a quantitative relationship between drainage rate and fire-extinguishing performance, and thereby provide a basis for designing high-efficiency and eco-friendly AFFF. The experimental results show that the hydrocarbon surfactant K12 and xanthan gum exhibit a nonlinear synergistic effect in retarding foam drainage, while excessive addition is detrimental. Moreover, temperature exhibits a dual regulatory mechanism on foam drainage: in high viscosity system, increasing temperature always promotes foam drainage; in the low viscosity system, the effect of temperature rise on the foam drainage is first delayed and then accelerated, resulting in a non-monotonic change in the 25% drainage time. Based on the above rules, 25 groups of formulas were designed for fire extinguishing experiments, and the effectiveness of the formula design method based on drainage control was verified. For STAR-2157/2470, the optimal range of 25% drainage time was determined to be 5.9 ± 0.2 min, and two groups of AFFF formulas that met the national fire extinguishing standards were successfully screened.

1. Introduction

Aqueous film-forming foam (AFFF) has emerged as an effective agent for extinguishing flammable liquid fires, owing to its dual mechanism of forming a water film and a foam layer on the fuel surface[1–7]. However, the water film is not pre-existing; it is continuously supplied by foam drainage after foam generation. In the actual firefighting scenarios, the foam drainage rate must be coordinated with the water film evaporation rate at high temperature to maintain the dynamic balance of water film thickness. Consequently, foam drainage behavior is a key factor to determine foam stability and fire extinguishing efficiency.

Foam is a ternary two-phase dispersion system composed of gas phase and liquid phase. Surfactants align in an ordered manner at the gas-liquid interface to form a liquid film that encapsulates gas bubbles[8–14]. The core mechanism of foam destabilization lies in reducing the system's free energy, primarily through liquid phase separation, bubble coalescence, and gas diffusion (Ostwald ripening). Macroscopically, these processes manifest as film thinning, bubble rupture, coalescence, and coarsening, ultimately leading to foam collapse[15–17]. Given the foam structure, the liquid is primarily distributed at the Plateau boundaries and nodes, with relatively little liquid content in the liquid film; therefore, liquid phase separation in the foam also occurs mainly through the Plateau boundaries and nodes. This transport process is synergistically driven by gravity and capillary pressure, while being constrained by liquid viscous resistance; its kinetic behavior can be described by the fluid flow equations within the Plateau borders and nodes[18, 19]. Depending on the driving forces and the mode of foam supply, foam drainage can be further classified into three types: free drainage, forced drainage, and pulsed drainage[20–22].

Foam drainage is a complex process influenced by multi-scale factors and has become a research focus in the development of AFFF. Previous studies have shown that the foam drainage rate is closely related to the surfactant type, and that the drainage rate of AFFF foam is generally slower than that of fluoroprotein foam[23]. Arabadzhieva et al.[24] investigated the relationship between the characteristics of surfactant adsorption layers and the drainage behavior of foam films using $C_{12}E_4$ aqueous solutions; their results showed that changes in the adsorption layer properties were synchronized with the variation of foam drainage kinetic parameters. Desbordes et al.[25] pointed out that xanthan gum molecules can retard foam drainage by accumulating in the Plateau borders, and that the drainage rate can also be regulated by adjusting the initial bubble size. Dinesh et al.[26] found a synergistic effect between nanoparticles and polymers in improving the performance of oil-displacement foams. In summary, formulation additives such as surfactant type and concentration, foam stabilizers, polymers, and nanoparticles can retard foam drainage by increasing the elasticity and strength of the liquid films and by altering the solution viscosity. However, most of these studies were conducted under ambient conditions and focused on a single variable, without directly correlating foam drainage parameters with fire-extinguishing efficiency.

The fire-extinguishing efficiency of aqueous film-forming foam depends not only on the fluorocarbon surfactant, but also on the synergistic effects of additives such as hydrocarbon surfactants and foam stabilizers[27–30]. The dynamic behavior of foam drainage is directly related to the formation and maintenance of water film and the stability of foam layer. However, current research on regulating foam drainage behavior through formulation and additives to enhance AFFF fire-extinguishing performance remains insufficient. Furthermore, AFFF is subjected to varying ambient temperatures in practical applications, and how temperature couples with formulation components to regulate foam drainage behavior and affect fire-extinguishing performance is an urgent challenge in formulation design. Therefore, this paper focuses on the drainage kinetics of AFFF, systematically investigating the regulation of foam drainage behavior by formulation composition and ambient temperature, and conducting fire-extinguishing experiments to establish a quantitative correlation between drainage rate and fire-extinguishing performance, aiming to support the design of efficient and environmentally friendly foam extinguishing agents.

2. Materials and methods

2.1. Materials

The fluorosurfactant used in this study is the commercial product STAR-2157/2470 fluoroether betaine surfactant, produced by Fujian Sanming Haishifu Chemical Co., Ltd., with a product purity of 27%. The hydrocarbon surfactants employed include decyl glucoside APG0810 (nonionic, 50% purity), cocamidopropyl betaine CAB-35 (zwitterionic, 35% purity), sodium dodecyl sulfate K12 (anionic, 99% purity), and cetyltrimethylammonium bromide CTAB (cationic, 98% purity). Xanthan gum (USP grade) is used as a foam stabilizer, and the cosolvent is diethylene glycol monobutyl ether (99% purity). The

detailed composition of the AFFF solution formulations used in the experiments is provided in the **Supplementary Materials**.

2.2. Surface and interface tension measurement

The surface tension and interfacial tension of the mixed solution were measured by the bubble pressure tensiometer BP100 and the rotary drop interfacial tensiometer SDT, respectively (KRÜSS, Germany). The interfacial tension measured in this experiment refers to the interfacial tension between the solution and n-heptane; the surface tension of n-heptane was 19.8 mN/m. All measurements were carried out at approximately 25°C, and each formulation was tested two to three times; the reported values are the averages. The spreading coefficient S of the solution was then calculated according to the formula $S = \sigma_{\text{oa}} - \sigma_{\text{wa}} - \sigma_{\text{ow}}$, where σ_{oa} is the surface tension of the oil, σ_{wa} is the surface tension of the aqueous solution, and σ_{ow} is the interfacial tension between the oil and the aqueous solution[31].

2.3. Dynamic foam analysis

In this study, a dynamic foam analyzer DFA100 (KRÜSS, Germany) was used to perform foam formation and drainage experiments on AFFF solutions with different formulations. The operating conditions were as follows: gas flow rate set to 0.3 L/min, foam generation by bubbling for 20 s, with 20 mL of foaming solution, and a data monitoring period of 0.5 h. The measured parameters included the cumulative drained liquid volume, the 25% drainage time, and the liquid content of the foam at different heights. Additionally, the foam structure was captured at 10 s intervals during drainage. Owing to the stochastic nature of foam formation, experimental data for the same formulation under identical conditions may exhibit some variation, each formulation was tested two to three times.

2.4. Temperature effects on foam drainage

Four typical AFFF formulations were selected to study temperature effects on foam drainage by varying the surface temperature of the drainage apparatus, as illustrated in Fig. 1(a). The glass funnel served as the foam container. A fiberglass heating tape with a power of 100 W/m was wound around the outside of the funnel, allowing controlled heating to achieve different wall temperatures of the glass funnel, thereby simulating the thermal effect of a hot oil surface on the foam. Additionally, a layer of thermal insulation cotton was wrapped around the funnel and the heating tape to minimize heat loss. The foam generator was an electric foam-producing device that generated bubbles of uniform size. The arrangement of thermocouples is shown in Fig. 1(a). Thermocouples #1 ~ 10 were placed symmetrically on the inner side of the glass funnel. Among them, #1 ~ 6 recorded the temperature variations at different heights along the funnel wall; #1 ~ 2 and #7 ~ 10 monitored the temperature changes at the same height but at different distances from the funnel wall. Thermocouple #11 recorded the ambient temperature, and thermocouple #12 monitored the temperature change at the middle position between the glass funnel and the heating tape.

Four formulated solutions (C-1 to C-4) with xanthan gum concentrations ranging from 0.03% to 0% were chosen, their compositions are detailed in **Table S3**. Before each test, the heating tape was adjusted to

the target temperature, and the experiment started once the thermocouples indicated that the set temperature had been reached. An electric foam generator was used to produce an appropriate amount of foam, which was discharged into the funnel. The mass of foam introduced was recorded, and timing began immediately. A container placed under the funnel collected the drained liquid. The test was terminated when foam drainage essentially ceased. After each experiment, the thermocouple temperature data and the drained liquid mass data from the electronic balance were exported. Each formulation was tested at least three times under each temperature condition.

2.5. Fire-extinguishing experimental setup

The schematic diagram of the fire-extinguishing experimental setup is shown in Fig. 1(b). The main equipment includes foam generation and supply system, such as foam solution storage tank, compressed air cylinder, gas-liquid mixer, foam gun, flow meter, valve and pipeline system, as well as standard combustion plate with an area of 0.25 m^2 , anti-burning tank and image acquisition equipment[32]. The experimental procedure was as follows: The foam concentrate was first diluted, added to the foam solution storage tank, and allowed to stand for a period. Subsequently, a pressure of 0.7 MPa was applied to the tank, and the foam flow rate was adjusted to $750 \pm 25\text{ g/min}$. The foam gun was positioned horizontally, 150 mm above the standard fire pan, to ensure forced-application of foam directly onto the center of the pan. The standard fire pan was charged with 9 L of 120# industrial solvent oil, and the burnback cup was filled with 1 L of fuel and placed in a safe location. The oil pan was then ignited. After a 1 min pre-burn, foam application was started, timing began, and the extinguishing time t_1 was recorded. After 3 min of forced foam application, regardless of whether the fire was successfully extinguished, foam supply was stopped. One minute later, the burnback cup was placed in the center of the pan and ignited, and the 100% burnback time t_2 was recorded. Meanwhile, the expansion ratio and 25% drainage time of the foam solution were measured.

3. Results and discussion

3.1. Regulation of foam drainage by additive systems

The formulation of aqueous film-forming foam must meet a variety of requirements, such as foaming performance, spreading performance, and foam stability. Therefore, AFFF solutions typically require the synergistic effects of multiple additives, like fluorocarbon and hydrocarbon surfactants, to meet fire extinguishing standards. Based on existing experimental results (see **Supplementary Materials**), among the four types of hydrocarbon surfactants, K12 was most effective at delaying foam liquid separation and maintaining foam stability, followed by CAB-35 and APG0810, while the CTAB solution performed the worst. Furthermore, xanthan gum, as a foam stabilizer, can also delay foam liquid separation, however, its optimal dosage in blended solutions containing STAR-2157/2470 has not been studied. Therefore, this study designed 16 formulations to investigate the effects of various hydrocarbon surfactant blending systems on foam liquid separation behavior. The formulation compositions are detailed in **Table S2**.

3.1.1. Solution characterization parameters

The characterization parameters of formulations B-1 to B-16, including surface tension, interfacial tension, spreading coefficient S , and the 25% drainage time measured by DFA100, are presented in Fig. 2. Figure 2(a) indicates that as the proportion of K12 in the hydrocarbon surfactant increases, the surface tension of the solution gradually increases. When the APG0810:CAB-35 ratio is 2.5:2.5, the surface tension of the solution is lowest, at approximately 16.8 mN/m, and xanthan gum has a relatively minor effect on the surface tension of the blended solutions. Figure 2(b) shows the interfacial tension between the solution and n-heptane. Overall, the interfacial tension of the solution was lowest at an APG0810:CAB-35 ratio of 2.5:2.5, at approximately 1.8 mN/m. Furthermore, when the total amount of hydrocarbon surfactants remains constant, at the same xanthan gum concentration, increasing the proportion of K12 causes the interfacial tension with n-heptane to first increase and then decrease. The interfacial tension of the blended solution with an APG0810:CAB-35:K12 ratio of 1:1:3 is actually lower than that of solutions with ratios of 2:2:1 and 1.5:1.5:2. As shown in Fig. 2(c), for the same xanthan gum concentration, increasing the proportion of K12 increases the surface tension of the solution, while the change in interfacial tension is relatively small; therefore, the corresponding spreading coefficient S also decreases. Overall, without the addition of K12, the spreading coefficient of the solution is positive and consistently greater than 1 mN/m, whereas the spreading coefficient S of the other solutions are all negative. It can thus be seen that, compared to other hydrocarbon surfactants, while K12 can maintain the stability of the foam structure, it also has a significant inhibitory effect on the solution's spreading performance.

Figure 2(d) shows the 25% drainage time of the formulated solutions measured by DFA100. Under the same operating conditions, the expansion ratios of the solutions were essentially identical, and a longer 25% drainage time indicates better foam stability. As can be seen, increasing the xanthan gum concentration generally prolongs the 25% drainage time under otherwise identical conditions. However, when the proportion of K12 is too high, the 25% drainage time of the solution containing 0.03% xanthan gum becomes shorter than that of the solution with 0.02% xanthan gum. Furthermore, at a fixed xanthan gum concentration, increasing the K12 proportion leads to a gradual increase in the 25% drainage time for two groups of formulations, while for the remaining two groups, the 25% drainage time first increases and then decreases with increasing K12 proportion.

3.1.2. Investigation of foam drainage behavior

Figure 3 illustrates the drainage behavior of formulated solutions with different xanthan gum concentrations and varying APG0810:CAB-35:K12 ratios. The data in Fig. 3(a) and (b) show that when the xanthan gum concentration is low and the total hydrocarbon surfactant content is kept constant, the foam drainage rate initially decreases with increasing K12 proportion. However, when the APG0810:CAB-35:K12 ratio reaches 1:1:3, the drainage rate unexpectedly increases, leading to a larger amount of drained liquid. This confirms that although K12 can prolong the foam drainage time, the effect is not monotonic with respect to K12 content. With a fixed total hydrocarbon surfactant content, increasing the

K12 proportion first reduces and then increases the drainage rate, and this trend is less pronounced at higher xanthan gum concentrations. Therefore, based on the data in Fig. 2(d), the hydrocarbon surfactant K12 and the foam stabilizer xanthan gum exhibit a synergistic effect in delaying foam liquid release. That is, the effect of increasing the K12 content on the foam liquid release speed varies depending on the xanthan gum concentration in the formulation solution. At lower xanthan gum concentrations, increasing the K12 content can delay foam liquid release; however, at higher xanthan gum concentrations, such as 0.03%, the effect of increasing the K12 content on delaying foam liquid release may gradually diminish. In summary, both K12 and xanthan gum can prolong the foam liquid separation time, but this effect is not simply additive, and continuing to increase the content of either component may actually have the opposite effect on prolonging the liquid separation time.

3.1.3. Foam structure-drainage rate correlation

As liquid is released from the foam, the foam structure gradually evolves through processes such as bubble collapse, coalescence, and coarsening. As shown in Fig. 4(a), when foaming ceases at 20 s, the bubbles are small and elliptical. Over time, the bubble size gradually increases, their number begins to decrease, and their shape evolves from the original elliptical form to a polygonal structure. Reference[25] demonstrates that xanthan gum has the effect of delaying liquid separation in foam; however, chemical additives such as xanthan gum ultimately delay liquid separation by influencing the viscosity of the solution or the physical structure of the foam. Therefore, in this study, the initial foam dimensions of a series of formulations with varying xanthan gum concentrations, measured by the instrument DFA100, were correlated with the 25% drainage time and the maximum liquid content S1, aiming to elucidate the influence of foam microstructure on foam drainage.

Figure 4(b) presents the relationship between the initial bubble radius and the 25% drainage time measured by DFA100 in experiments involving blended solutions of various hydrocarbon surfactant systems (B-1 to B-16). At a given xanthan gum concentration, a smaller initial bubble radius corresponds to a longer 25% drainage time, indicating an approximately negative correlation between the initial bubble size and the 25% drainage time. Comparing formulations with different xanthan gum concentrations, higher xanthan gum concentration generally leads to both a larger initial bubble size and a longer 25% drainage time. Figure 4(c) shows the relationship between the maximum liquid content S1 (i.e., the liquid content at the bottom S1 position of the foam column immediately after foam generation, measured by DFA100) and the initial bubble radius for the same set of formulations. It can be seen that a larger maximum liquid content S1 and a smaller initial bubble radius result in better retardation of foam drainage.

3.2. Analysis of temperature effects on foam drainage

In addition to the effects of additive types and concentrations in the formulation, ambient temperature is also a key factor affecting foam stability. Typical AFFF formulations with different xanthan gum concentrations (C-1 to C-4) were selected to investigate the influence of temperature on foam drainage behavior. And the temperature of the drainage apparatus surface was controlled at 26°C, 40°C, 50°C, and

60°C, respectively. The variations in cumulative drained liquid mass and 25% drainage time for each formulation at different temperatures are shown in Fig. 5(a)~(d). As seen in Fig. 5(a) and (b), overall, increasing the ambient temperature leads to a larger drained liquid mass. For formulation C-3 in Fig. 5(c), temperature changes have little effect on the drainage rate. Figure 5(d) shows that at 40°C and 50°C, the drained liquid mass is lower than that at room temperature, whereas at 60°C, it becomes higher than at room temperature.

Figure 5(e) presents the 25% drainage time of formulations C-1 to C-4 at different temperatures, showing that the drainage behavior varies with formulation composition. For Formulations C-1 and C-2, with xanthan gum concentrations of 0.03% and 0.02% respectively, increasing temperature leads to a progressive shortening of the 25% drainage time. For formulation C-3 (0.01% xanthan gum), when the temperature is raised from room temperature to 40°C, the 25% drainage time decreases; further increasing the temperature continues to reduce the 25% drainage time, albeit with a weaker decreasing trend. For formulation C-4 (0% xanthan gum), increasing the temperature from room temperature to 40°C and to 50°C causes the 25% drainage time to increase, contrary to the previous trends. However, when the temperature is further raised to 60°C, the drainage rate accelerates, and the 25% drainage time drops sharply.

The above differences arise from the dual regulatory mechanism of temperature on foam stability. In formulations containing a foam stabilizer such as xanthan gum, foam stability primarily relies on the significant increase in solution viscosity caused by xanthan gum to retard drainage. As temperature rises, the solution viscosity decreases, weakening the thickening and stabilizing effect of xanthan gum. In this case, the temperature-induced reduction in viscosity dominates, thereby accelerating drainage. When no foam stabilizer is added or its concentration is low, temperature predominantly affects the gas-liquid interface of the foam. A moderate increase in ambient temperature enhances the mobility of active molecules, strengthens the Marangoni effect, and accelerates the adsorption and movement of surfactants at the film interface, leading to a tighter surfactant arrangement and the formation of a stronger and better interfacial film. This retards foam drainage and rupture, temporarily improving foam stability. However, further temperature increase reduces the solution surface tension, which through the Marangoni effect, makes the foam films thinner and more prone to rupture. Consequently, foam stability decreases and the drainage rate accelerates. Therefore, for low-viscosity or stabilizer-free formulations, the 25% drainage time exhibits a non-monotonic behavior, first increasing and then decreasing with rising temperature.

Figure 6 shows the temperature variation at different positions of the foam layer for formulation C-4 under various ambient temperatures. As seen in Fig. 6(a), (c), and (e), the temperatures measured by thermocouples #1(2), #3(4), and #5(6) initially show a slight increase followed by a decrease, due to the delayed heat conduction from the glass funnel to the foam layer. According to the thermocouple arrangement, during free drainage of the foam in the temperature field, the temperature decrease rate at the bottom of the foam layer is lower than that at the top. Foam acts as a special porous medium composed of numerous gas-encapsulating liquid films. The thermal conductivity of air is much lower

than that of water, so the foam layer can be considered an insulating material. As the top foam drains, the expelled liquid flows downward through the nodes and Plateau borders of the foam structure under gravity and capillary forces, carrying heat from the upper to the lower foam layer. Meanwhile, the top foam is in contact with the environment, losing heat through convective heat transfer with cold air and radiative heat dissipation to the surroundings. Consequently, the temperature decrease rate at the bottom is slower than that at the top, resulting from the combined effect of the thermal insulation of the foam layer and the heat redistribution caused by foam drainage.

As shown in Fig. 6(b), (d), and (f), the closer the foam is to the wall of the glass funnel, the higher its temperature. Furthermore, the temperature measured by thermocouples #1(2) located at the funnel wall gradually decreases during free drainage and heat loss via convection and radiation to the environment, with the decreasing trend being initially fast and then slow. In contrast, the temperatures measured by thermocouples #7(8) and #9(10) both rise initially and then decrease, with the peak temperature recorded by #7(8) occurring much earlier than that of #9(10). This phenomenon is closely related to the thermal insulation properties of the foam layer and the liquid separation within the foam. Due to the low thermal conductivity of air, the further away from the glass funnel wall, the slower the heat transfer to that location. Therefore, the temperatures measured by thermocouples #7(8) and #9(10) rise first and then decrease slowly.

3.3. Analysis of fire-extinguishing experimental results

Xanthan gum maintains foam structure stability by increasing the viscosity of the AFFF solution, thereby slowing down the foam drainage rate and maintaining foam structural stability. Theoretically, a higher xanthan gum concentration leads to better prolongation of the foam drainage time. However, in actual fire-extinguishing practice, the drainage rate is not necessarily better when it is slower, an excessively slow drainage rate is detrimental to fire suppression. Therefore, an appropriate xanthan gum concentration should be selected when designing AFFF formulations. The actual fire-extinguishing experimental data for the four formulations C-1 to C-4 are shown in Table 1.

The data in Table 1 show that the spreading coefficients S of formulations C-1 to C-4 are all positive, being 1.0, 1.0, 0.8, and 0.6 mN/m, respectively, while the xanthan gum concentration decreases from 0.03% to 0%. This indicates that for the STAR-2157/2470 series formulations, increasing the xanthan gum concentration gradually increases the spreading coefficient S under otherwise identical conditions, and the increasing trend weakens at higher xanthan gum concentrations. Regarding the expansion ratio, all values exceed 10. The xanthan gum concentration significantly regulates the foam drainage rate; as shown in Table 1, the 25% drainage times of formulations C-1 to C-4 are 9.0, 7.1, 4.9, and 3.7 min, respectively. In terms of fire-extinguishing performance, none of the four foam formulations extinguished the fire within 3 min. In the fire-extinguishing tests, after 3 min of foam application, formulation C-1 still had edge flames, which self-extinguished 1 min after foam supply was stopped; formulation C-4 exhibited large edge flames after 3 min. Furthermore, when the xanthan gum concentration decreased from 0.03% to 0.01%, the burnback time t_2 reduced from 11.5 min to 6.6 min. Based on the above analysis, increasing the xanthan gum concentration gradually increases the spreading coefficient S and

prolongs the 25% drainage time as well as the burnback time, but the fire-extinguishing efficiency is not improved. According to the fire-extinguishing results of formulations C-1 to C-4, the xanthan gum concentration must be controlled within an appropriate range; either too high or too low is detrimental to fire suppression. Therefore, it can be concluded that the foam drainage rate plays a dominant role in the fire-extinguishing performance of AFFF, and an optimal drainage rate range is necessary to satisfactorily meet fire-extinguishing requirements.

Table 1
Fire-extinguishing experimental data of formulations C-1 to C-4.

Formulation	Spreading coefficient S / mN/m	Expansion ratio	25% drainage time / min	Extinguishing time t ₁ / min	Burnback time t ₂ / min	Qualified (Yes/No)
C-1	1.0	10.0	9.0	>3	11.5	No
C-2	1.0	11.0	7.1	>3	8.3	No
C-3	0.8	10.3	4.9	>3	6.6	No
C-4	0.6	10.6	3.7	>3	-	No

To verify the effectiveness of regulating the liquid-phase separation rate in enhancing fire-extinguishing performance, 25 formulations were designed for small-pan fire extinguishing experiments; the composition and characterization parameters of these formulations are shown in **Table S5** and **S6**, respectively. For each AFFF formulation, the 25% drainage time, extinguishing time t₁, and burnback time t₂ were measured, and the relationship between fire-extinguishing performance parameters and drainage performance parameters is shown in Fig. 7. According to the Chinese National Standard GB 15308 – 2006 for small-oil-pan fire-extinguishing tests of conventional AFFF solutions, the extinguishing time t₁ should be ≤ 1.2 min, and the burnback time t₂ should be ≥ 10 min[33]. Figure 7(a) and (b) present the correlations between the extinguishing time and the 25% drainage time, and between the burnback time and the 25% drainage time, respectively, for the 25 formulations. The data indicate that only two formulations meet the extinguishing time requirement, and both also satisfy the burnback time standard. The actual fire-extinguishing processes of these two AFFF formulations are shown in Fig. 8. Upon contact of the foam with the burning oil surface, the fire intensity gradually decreased. Although intermittent edge flames persisted after 30 s, formulations ZY-14 and ZY-17 eventually extinguished the small-oil-pan fire at 1.2 min and 1.0 min, respectively.

Table 2
Fire-extinguishing experimental data of selected formulated solutions.

Formulation	25% drainage time / min	Extinguishing time t_1 / min	Burnback time t_2 / min	Qualified (Yes/No)
ZY-14	5.7	1.2	11.0	Yes
ZY-15	5.5	>3.0	-	No
ZY-16	5.5	1.5	9.4	No
ZY-17	5.9	1.0	10.7	Yes
ZY-18	6.2	1.3	12.6	No
ZY-19	6.3	>3.0	9.2	No

The data in Table 2 show that the 25% drainage times of formulations ZY-14 and ZY-17 are 5.7 min and 5.9 min, respectively. Furthermore, analysis of the data reveals that modifying the formulation composition to reduce the 25% drainage time of the foam also shortens the burnback time, ultimately slowing down the fire-extinguishing efficiency. Conversely, increasing the xanthan gum concentration to retard foam drainage improves the burnback time, but the amount of drained liquid becomes too low to form a closed water film on the oil surface, which also reduces the fire-extinguishing efficiency.

The experimental results described above confirm the effectiveness of regulating foam drainage rate in improving fire-extinguishing efficiency. If the foam drains too quickly, although a closed water film can form rapidly, the foam layer rapidly loses water, bubbles coarsen and rupture, and persistent coverage cannot be maintained, leading to a significant shortening of the burnback time and easy re-ignition. If the foam drains too slowly, the foam mobility becomes poor, making it difficult to spread quickly on the oil surface; meanwhile, the water film is insufficiently replenished and rapidly thins under high-temperature evaporation, resulting in extinguishing failure. Therefore, the foam drainage rate must be controlled within an appropriate range to maintain a dynamic balance with the water film evaporation rate, ensuring both sufficient spreading speed and persistent foam coverage, thereby achieving rapid fire extinguishment. The results of this fire-extinguishing study indicate that for AFFF solutions containing STAR-2157/2470, a 25% drainage time measured according to the national standard in the range of 5.9 ± 0.2 min can meet the extinguishing requirements.

4. Conclusions

In this work, focusing on AFFF solutions containing the fluorinated ether betaine surfactant STAR-2157/2470, we systematically investigated the effects of formulation composition, additives, and ambient temperature on foam drainage behavior, and designed multiple formulations for fire-extinguishing validation. Based on these studies, the main conclusions are as follows:

(1) The concentration of the foam stabilizer xanthan gum is the primary factor retarding foam drainage, followed by the content of the hydrocarbon surfactant K12. These two additives exhibit a nonlinear synergistic effect on retarding drainage, and excessive addition of K12 may be detrimental. Moreover, the foam microstructure is correlated with the drainage rate: the smaller the initial bubble size and the higher the liquid content, the more pronounced the retardation of foam drainage.

(2) Temperature exerts a dual regulatory mechanism on foam drainage. For high-viscosity systems containing xanthan gum, increasing temperature accelerates foam drainage by reducing the solution viscosity, thereby making the foam structure more stable. For low-viscosity or stabilizer-free systems, moderate heating initially enhances the Marangoni effect by promoting surfactant adsorption and arrangement at the interface, thus retarding drainage. However, further heating reduces the surface tension, accelerates film rupture, and leads to a non-monotonic change in the 25% drainage time, which first increases and then decreases with rising temperature.

(3) The results of fire extinguishing experiment validated the effectiveness of the drainage-regulation-based formulation design approach: either too fast or too slow foam drainage is detrimental to fire suppression. For the STAR-2157/2470 series AFFF solutions, a 25% drainage time measured according to the national standard in the range of 5.9 ± 0.2 min satisfies the extinguishing requirements, and two AFFF formulations meeting the fire-extinguishing standards were successfully screened out.

Declarations

Supplementary Information

Supplementary information associated with this article can be found in **Supplementary Materials**.

Author Contribution

All authors contributed to the study conception and design. Y. Z. performed data curation and wrote the original draft. Z. Y. contributed to data curation. Y. Z. and F. T. carried out visualization. Y. X. conducted formal analysis, and Z. L. performed investigation. Conceptualization was handled by Z. C., and J. Z. was responsible for writing – review & editing, and methodology. M. H. contributed to project administration. Y. G. acquired funding . All authors read and approved the final manuscript.

Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

References

1. 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* 263:125949
2. Hinnant K, Button M, Giles S, Snow A, Ananth R (2020) Fuel effects on aqueous film formation and foam degradation and their impact on fire suppression by foams containing fluorosurfactants. *Fire Mater* 45:833–841
3. Lou M, Jia H, Lin Z, Zeng D, Huo J (2023) Study on fire extinguishing performance of different foam extinguishing agents in diesel pool fire. *Results Eng* 17:100874
4. Wu W-H, Wang J-L, Zhou Y-Q, Sun Y, Duan J, Zhang A (2023) Formulation and performance of aqueous film-forming foam fire extinguishing agent composed of a short-chain perfluorinated heterocyclic surfactant as the key component. *Chem Pap* 77:6763–6771
5. Yang Y, Peng M, Sha M, Fang J, Zhang D, Pan R, Jiang B (2022) Study on aqueous film-forming foam extinguishing agent based on fluorocarbon cationic–hydrocarbon anionic surfactants mixture system. 25:205–216
6. Wang Z, Jiang X, Yang C, Zhou B (2024) Experimental study on thermal stability and burn-back performance of aqueous film forming foam agent(AFFF) with short-chain fluorocarbon surfactant or flame retardant. *Fire Saf J* 146:104135
7. Li H, Yu X, Qiu K, Yu X, Lu S (2024) Enhanced fire-fighting performance of aqueous film-forming foam (AFFF) by tuning bubble size and expansion ratio with kenics static mixers. *Fire Saf J* 144:104117
8. Weaire D, Hutzler S (2000) *The Physics of Foams*. Oxford University Press, Oxford
9. Grassia P, Ubal S, Giavedoni M-D, Vitasari D, Martin P-J (2016) Surfactant flow between a Plateau border and a film during foam fractionation. *Chem Eng Sci* 143:139–165
10. Conroy M-W, Taylor J-C, Farley J-P, Fleming J-W, Ananth R (2013) Liquid drainage from high-expansion (HiEx) aqueous foams during and after filling of a container. *Colloids Surf A* 426:70–97
11. Zhao J, Yu Y, Wu K, Liu Y, Zhu Y, Lu H, Yue H, Liang B (2025) Experimental and molecular dynamics study of the effect of betaine surfactant structure on CO₂ foam stability. *Colloids Surf A* 709:136159
12. Anazadehsayed A, Rezaee N, Naser J, Nguyen A-V (2018) A review of aqueous foam in microscale. *Adv Colloid Interface Sci* 256:203–229
13. Pitois O, Fritz C, Vignes-Adler M (2005) Liquid drainage through aqueous foam: study of the flow on the bubble scale. *J Colloid Interface Sci* 282:458–465
14. Wang J, Nguyen A-V (2016) Foam drainage in the presence of solid particles. *Soft Matter* 12:3004–3012
15. This H (2021) Emulsions and foams: Ostwald ripening and disproportionation in practice. In: Lavelle C, This H, Killy A-L (eds) *Handbook of Molecular Gastronomy*. CRC, Boca Raton, p 8
16. Attia J-A, Kohli S, Pilon L (2013) Scaling laws in steady-state aqueous foams including Ostwald ripening. *Colloids Surf A* 436:1000–1006

17. Markworth A-J (1985) Comments on foam stability, Ostwald ripening, and grain growth. *J Colloid Interface Sci* 107:569–571
18. Koehler S-A, Hilgenfeldt S, Stone H-A (2004) Foam drainage on the microscale I. Modeling flow through single Plateau borders. *J Colloid Interface Sci* 276:420–438
19. Koehler S-A, Hilgenfeldt S, Weeks E-R, Stone H-A (2004) Foam drainage on the microscale II. Imaging flow through single Plateau borders. *J Colloid Interface Sci* 276:439–449
20. Etemad S, Kantzas A, Bryant S (2022) A systematic analysis of foam drainage: Experiment and model. *Results Eng* 15:100551
21. Kruglyakov P, Karakashev S, Nguyen A, Vilkova N (2008) Foam drainage. *Curr Opin Colloid Interface Sci* 13:163–170
22. Anazadehsayed A, Rezaee N, Naser J (2018) Exterior foam drainage and flow regime switch in the foams. *J Colloid Interface Sci* 511:440–446
23. Magrabi S-A, Dlugogorski B-Z, Jameson G-J (2002) A comparative study of drainage characteristics in AFFF and FFFP compressed-air fire-fighting foams. *Fire Saf J* 37:21–52
24. Arabadzhieva D, Mileva E, Tchoukov P, Miller R, Ravera F, Liggieri L (2011) Adsorption layer properties and foam film drainage of aqueous solutions of tetraethyleneglycol monododecyl ether. *Colloids Surf A* 392:233–241
25. Desbordes L, Grandjean A, Frances F, Lorcet H, Faure S (2021) Critical bubble diameters and Plateau border dimensions for drainage in aqueous xanthan foams. *Colloids Surf A* 612:125682
26. Joshi D, Ramesh D-N, Prakash S, Saw R-K, Maurya N-K, Rath K-B, Mitra S, Sinha OP, Bikkina P-K, Mandal A (2025) Formulation and characterisation of polymer and nanoparticle-stabilized anionic surfactant foam for application in enhanced oil recovery. *Surf Interfaces* 56:105615
27. Yu X, Yu X, Lin Y, Li H, Li G, Zong R (2023) Comparative Study on Interfacial Properties, Foam Stability, and Firefighting Performance of C6 Fluorocarbon Surfactants with Different Hydrophilic Groups, *Langmuir*, ;39: 16336–16348
28. Peng M, Sha M, Zhang D, Jiang B (2025) Study on Aqueous Film Forming Foam Extinguishing Agents Based on Perfluorobranched Short-Chain Fluorocarbon–Hydrocarbon Surfactant Complex Mixtures, *Langmuir*, ;41: 2714–2723
29. Peshoria S, Nandini D, Tanwar R-K, Narang R (2020) Short-chain and long-chain fluorosurfactants in firefighting foam: a review. *Environ Chem Lett* 18:1277–1300
30. Kang W, Yan L, Ding F, Xu Z (2021) Effect of polysaccharide polymers on the surface and foam properties of aqueous film-forming foam. *Colloid Interface Sci Commun* 45:100540
31. Kovalchuk N-M, Sagisaka M, Komiyama H, Simmons M-J-H (2024) Spreading of aqueous surfactant solutions on oil substrates: Superspreaders vs non-superspreaders. *J Colloid Interface Sci* 661:1046–1059
32. Xu Z, Guo X, Yan L, Kang W (2020) Fire-extinguishing performance and mechanism of aqueous film-forming foam in diesel pool fire. *Case Stud Therm Eng* 17:100578

Figures

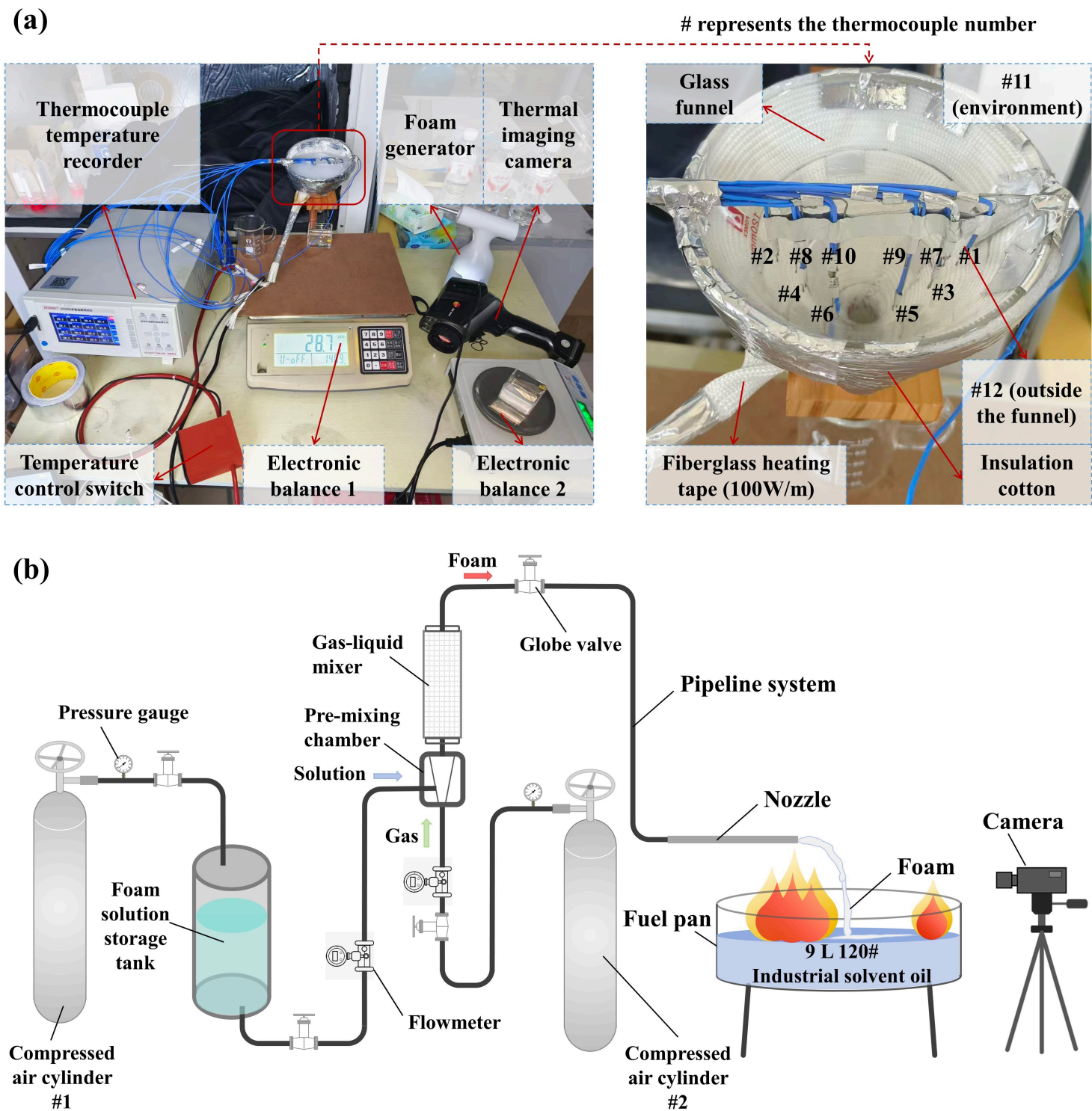


Figure 1

(a) Drainage experimental setup, (b) Schematic diagram of the fire-extinguishing experimental setup.

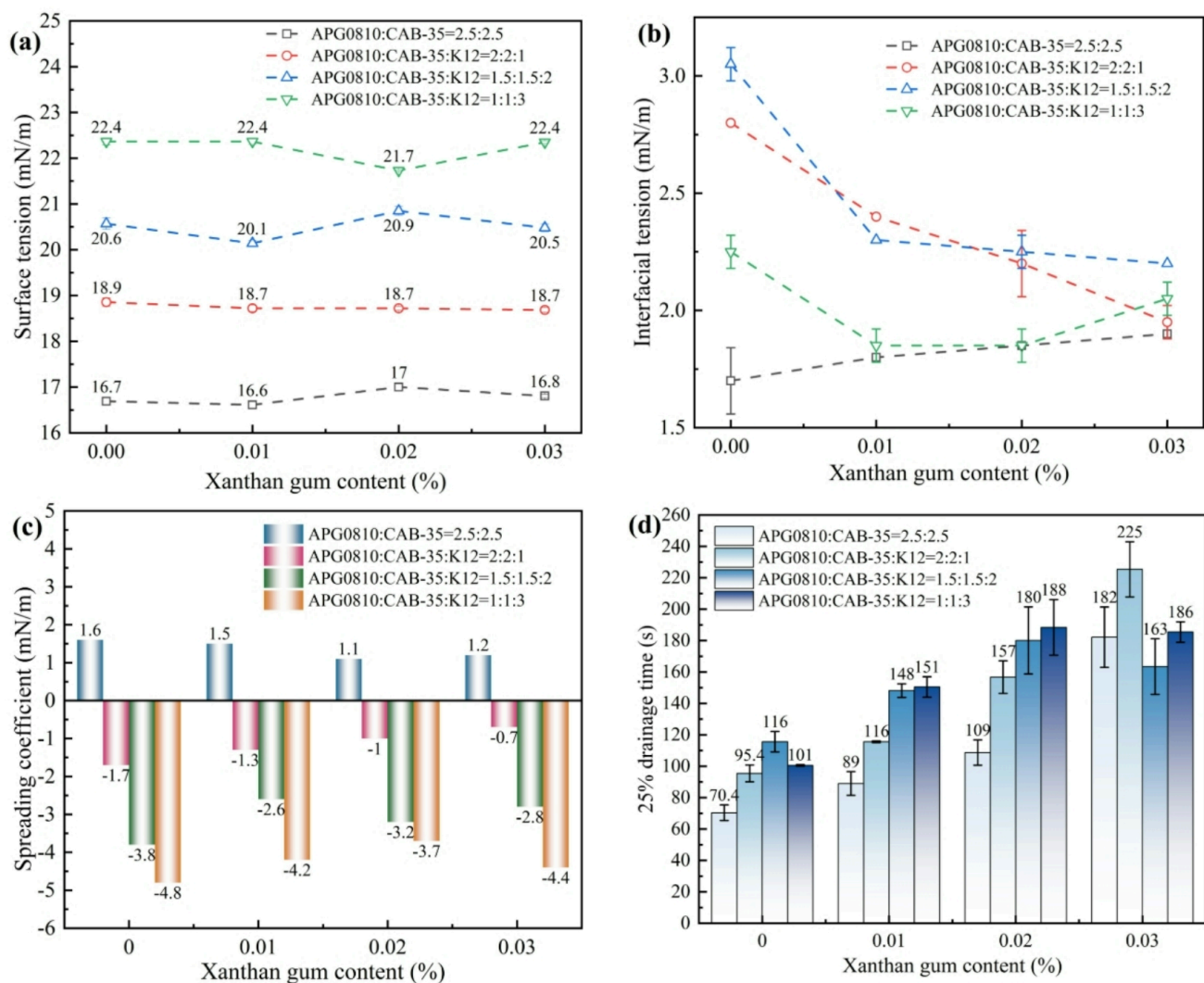


Figure 2

(a) Surface tension, (b) Interfacial tension, (c) Spreading coefficient S , (d) 25% drainage time measured by DFA100.

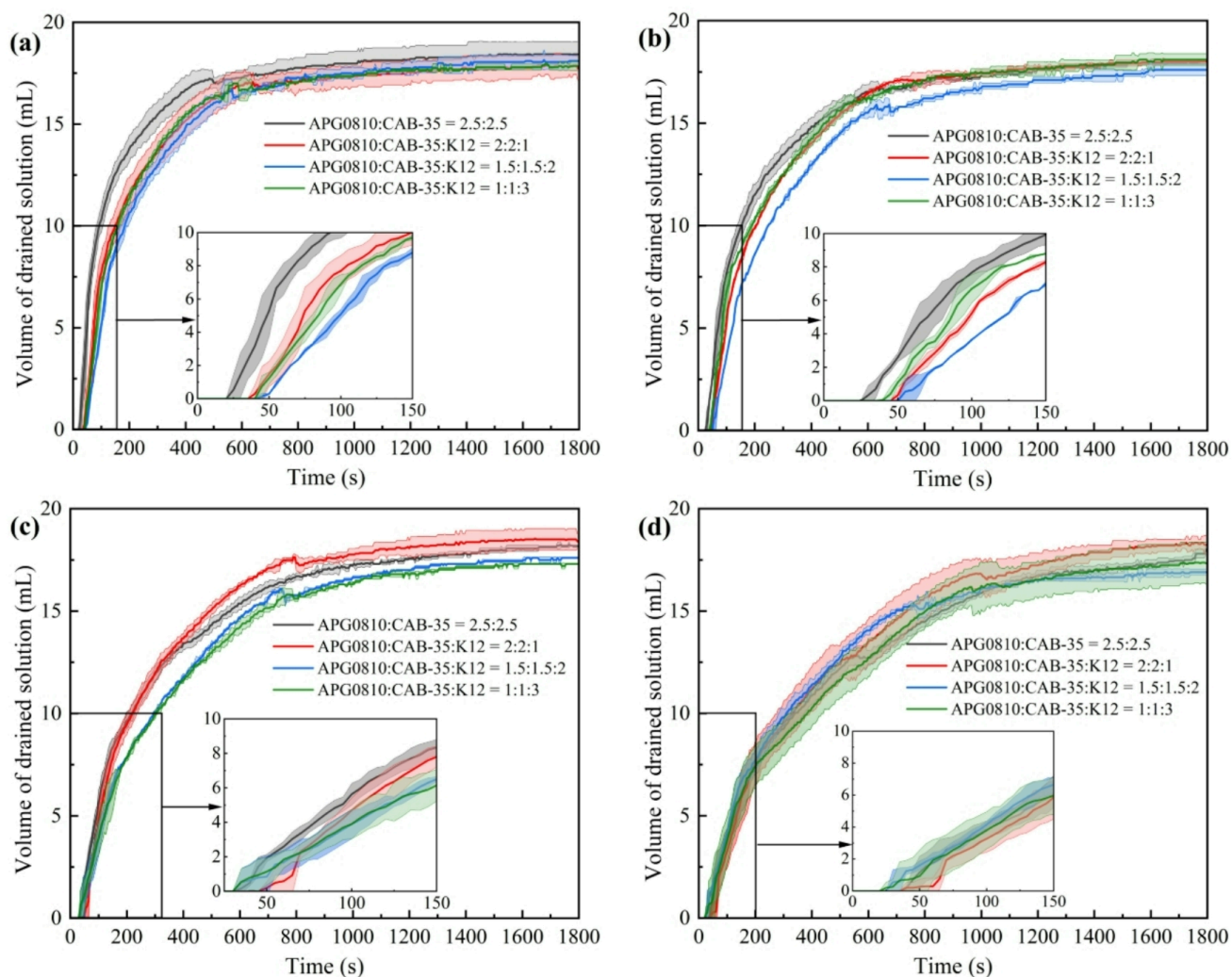


Figure 3

Time evolution of drained liquid volume after foaming for formulated solutions with xanthan gum concentrations of (a) 0%, (b) 0.01%, (c) 0.02%, and (d) 0.03%.

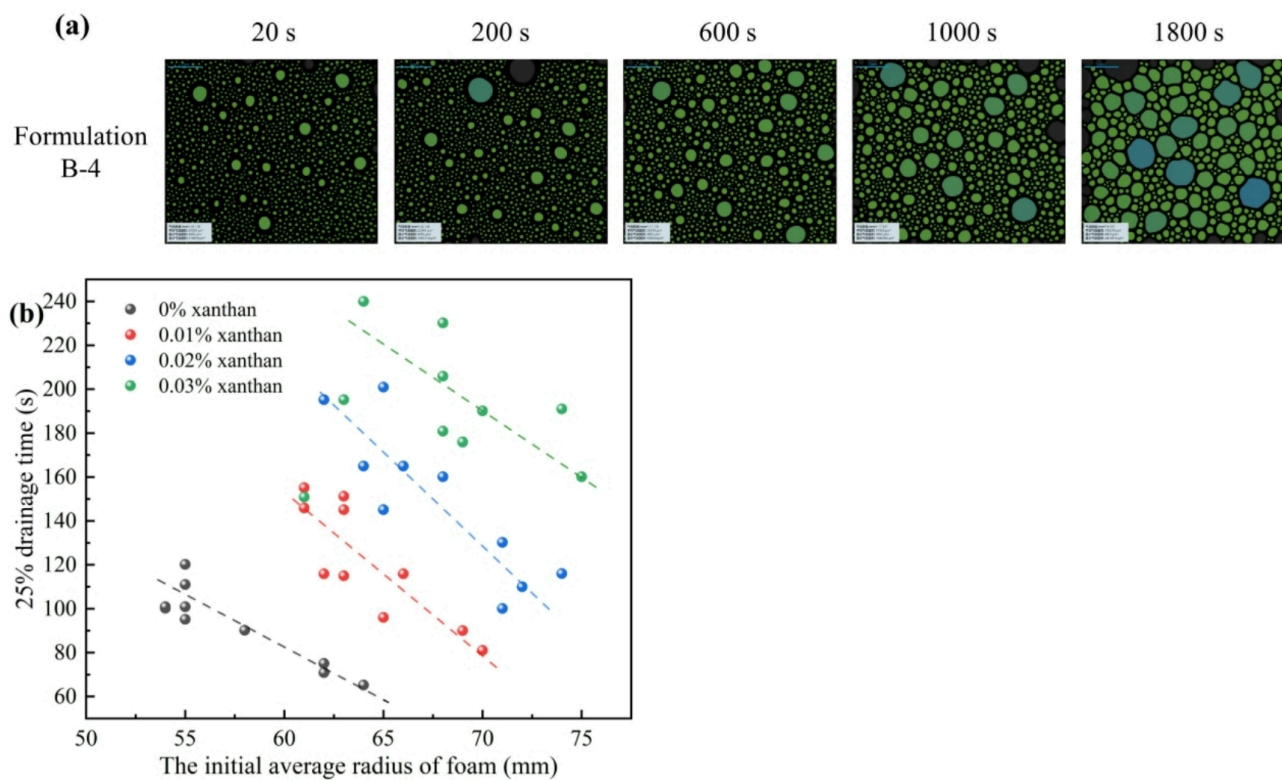


Figure 4

(a) Foam structure evolution (B-4), (b) 25% drainage time vs. initial bubble radius, (c) Maximum liquid content S1 vs. initial bubble radius.

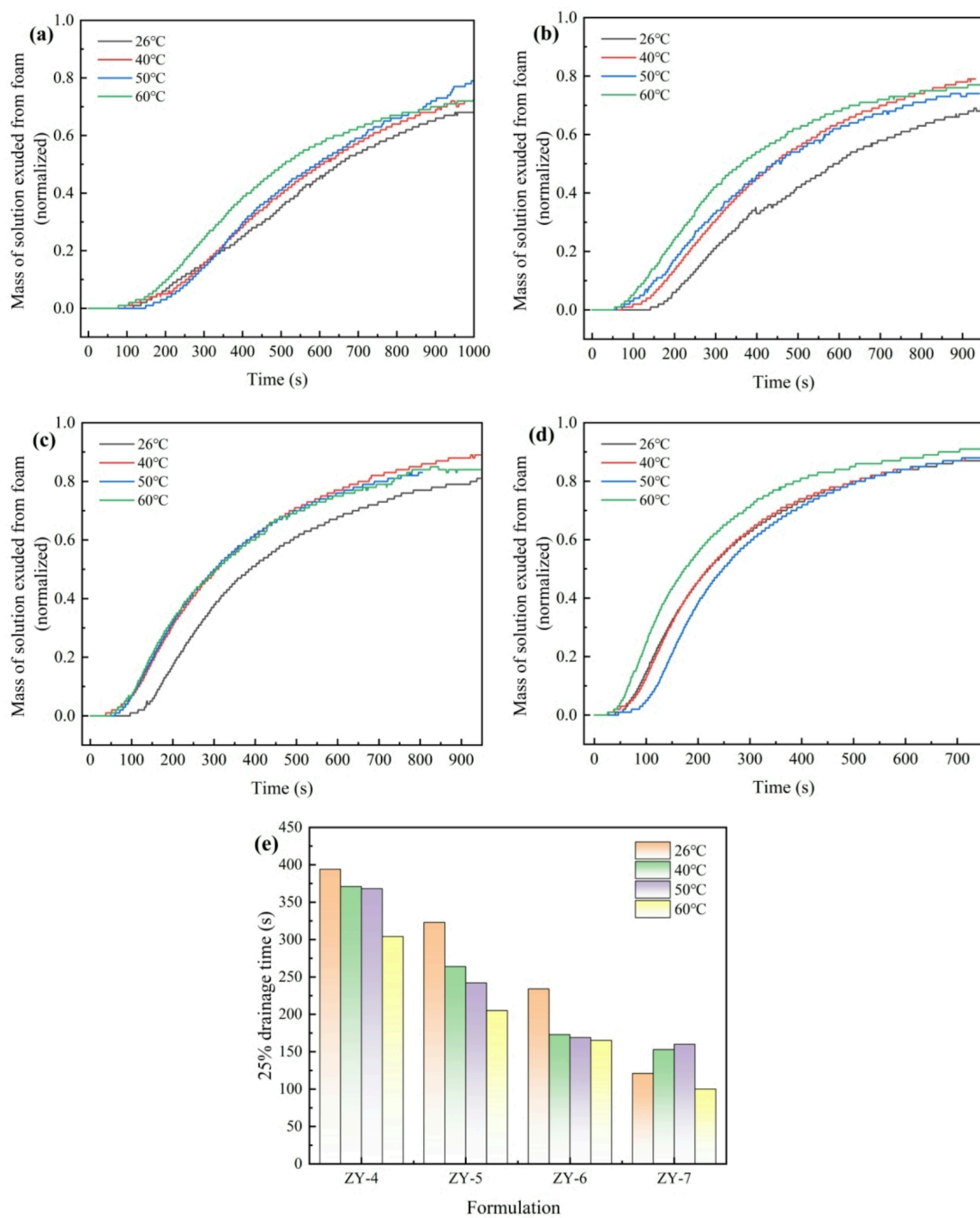


Figure 5

Time evolution of drained liquid mass from foam at different temperatures for formulation (a) C-1, (b) C-2, (c) C-3, (d) C-4; (e) 25% drainage time of formulations C-1 to C-4 at different temperatures.

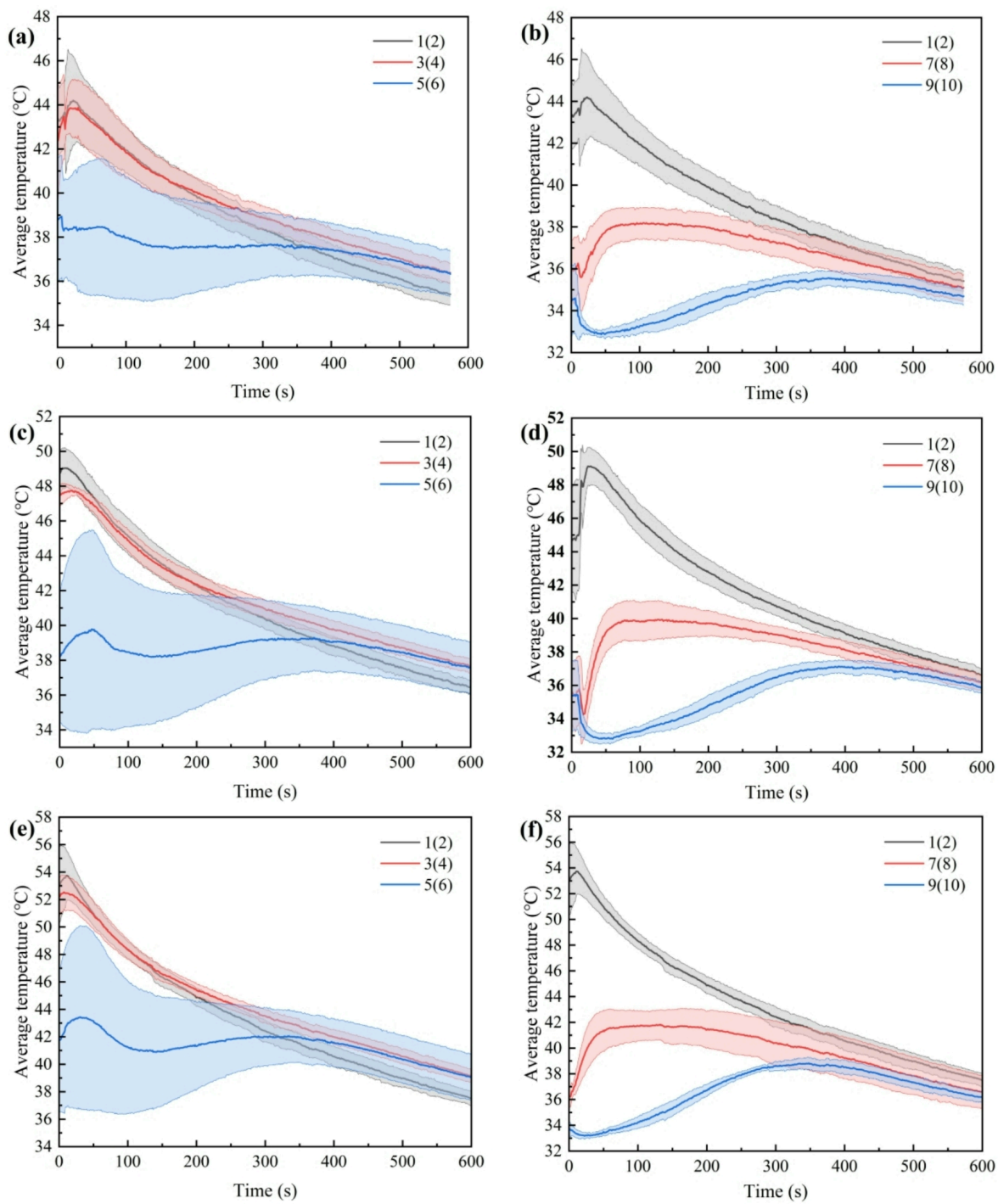


Figure 6

Temperature variation of the foam layer at different positions at (a-b) 40°C, (c-d) 50°C, (e-f) 60°C (Formulation C-4; "1(2)" denotes the average temperature measured by thermocouples #1 and #2).

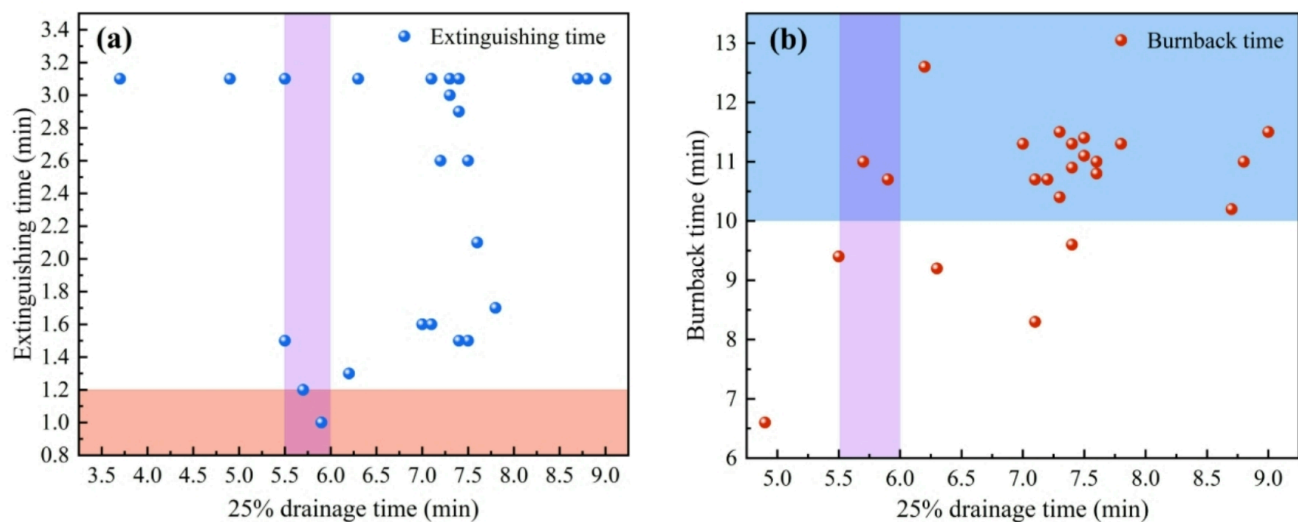


Figure 7

(a) Relationship between extinguishing time and 25% drainage time, (b) Relationship between burnback time and 25% drainage time.

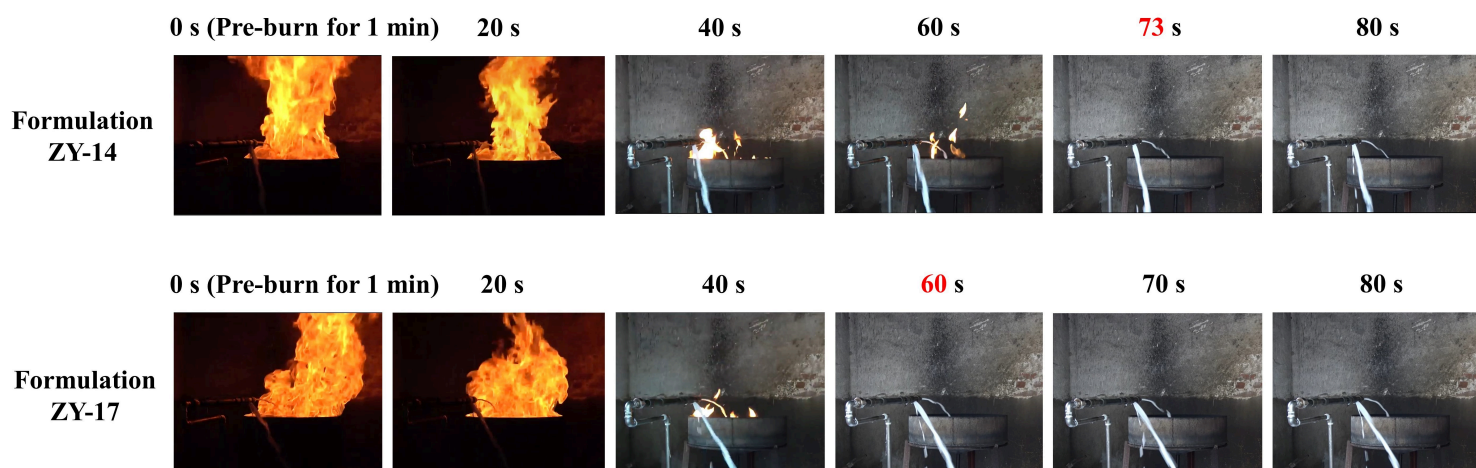


Figure 8

Fire-extinguishing process of ZY-14 and ZY-17 in small oil-pan tests.

Supplementary Files

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

- [SupplementaryMaterialsJ.Zheng.docx](#)