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Environmentally Friendly Firefighting Foams Used to Fight Flammable Liquid Fire

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Abstract. The application of conventional aqueous film-forming foam (AFFF) has been restricted due to the environmental hazards caused by long-chain fluorocarbon surfactants. Environmentally friendly firefighting foams are urgently needed. In this study, AFFFs based on a long-chain fluorocarbon surfactant and a short-chain fluorocarbon surfactant, and fluorine-free foams based on a silicone surfactant and a mixture of foam stabilizers are prepared. The critical properties, including film-forming ability, foam stability, and foam spreading property, of foams and a commercial AFFF are investigated systematically. The fire extinguishing and burn-back performances are evaluated by a small-scale test method. Results indicate that the removal of fluorocarbon surfactants from AFFF leads to an apparent decrease in film-forming ability, foam stability, foam spreading property, and corresponding fire extinguishing performance. AFFF based on short-chain fluorocarbon surfactant shows excellent extinguishing and burn-back performances even if its film-forming ability, foam stability, and foam spreading are slightly worse than those of conventional AFFF. Although FfreeF cannot form an aqueous film and exhibits poor foam spreading, it demonstrates satisfactory fire extinguishing performance and optimal burn-back performance depending on its superhigh stability. This study can provide guidance in the development of environmentally friendly firefighting foams.

Keywords: Firefighting foam, Environmental-friendly, Film-forming, Foam drainage, Foam spreading, Fire extinguishing

1. Introduction

Liquid fuel has been widely used in many industrial fields, such as diesel, heptane, gasoline, crude oil, and so on. During the production, transportation, storage, and use of fuel, liquid fire often occurs due to the accidental leakage of fuel [1–4]. The characteristics of liquid fire, such as fast burning rate, long duration, and intense heat radiation, can cause serious damage to the surrounding environment [5–10]. In addition, the tendency of liquid fire to produce harmful and toxic materials, such as CO, sulfur oxides, nitrogen oxides, and some hydrocarbons, can lead to serious environmental impacts. Thus, studies on efficient and environmentally

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*Correspondence should be addressed to: Youjie Sheng, E-mail: youjies@xust.edu.cn; Xiangrong Liu, E-mail: liuxiangrongxk@163.com friendly fire extinguishing agents used for liquid fire are crucial to reduce the losses from fire.

Foams have been extensively used to arrest various fuel fires [11–13], and aqueous film-forming foam (AFFF) is an efficient extinction agent used to suppress liquid fire. AFFF efficiently extinguishes liquid fire while relying on the joint effect of a foam layer and an aqueous film layer on the liquid fuel surface. Many properties of AFFFs, including self-sealing ability [14], foam spreading [15], foam stability [16–18], fire extinguishing, and burn-back properties [19–21], were investigated to understand their relation to fire suppression. However, the use of AFFF containing fluorocarbon surfactants has been restricted by the United Nations Environment Program due to their severe ecological hazards [22–24]. Thus, the development of environmentally friendly firefighting foams for extinguishing liquid fire is an urgent task.

To reduce the use of conventional fluorocarbon surfactants, two main research ideas were used. The one is to decrease the number of carbon atoms in a perfluorinated radical from C8–C10 (long chain) to C4–C6 (short chain) [25], that is, replace long-chain fluorocarbon surfactants in AFFF with short-chain fluorocarbon surfactants. However, studies on the properties of firefighting foam containing short-chain fluorocarbon surfactants are limited. Whether conventional AFFF and foams based on short-chain fluorocarbon surfactants can fight liquid fire with similar efficiency remains unclear. The other is to develop fluorine-free firefighting foam (FfreeF) [26–28]. Several parameters of FfreeF formulations have been the main focus of research: foam spreading [15], bubble coarsening [29], foam degradation [30], and dynamic surface and interfacial tension [31]. However, the studies on the properties of the firefighting foams developed based on the two ideas were few, especially the fire extinguishing performance and mechanism. Determining the real fire extinguishing mechanism of newly developed and environmentally friendly firefighting foams is still unclear due to the lack of the related data and direct comparison of fire extinguishing performance. Moreover, no applicable commercial formulation has been reported so far. We don't know if either of the two ideas will work or which one is the better. Therefore, considerable studies focused on the relation between components and performance of the firefighting foams still need to be conducted.

In the present study, AFFFs containing long-chain and short-chain fluorocarbon surfactants were synthesized. FfreeFs were prepared using the mixture of hydrocarbon and silicone surfactants as the main components. The critical properties of AFFFs, FfreeFs, and a commercial AFFF, including film-forming ability, foam stability, and foam spreading property, were investigated systematically. The fire extinguishing and burn-back performances were evaluated through a small-scale test method. The fire extinguishing mechanism of the environmentally friendly firefighting foams was revealed in detail. This study provides practical guidance for developing environmentally friendly firefighting foams to extinguish liquid fire.

2. Experimental

2.1. Materials

Five firefighting foam formulations (three AFFFs and two FfreeFs) were used in the present study. Table 1 shows the main components and concentrations of the foam formulations. FC-134 is a long-chain fluorocarbon surfactant purchased from Wuhan Changjiang Fluorine Technology Co., Ltd with C8 in its perfluorinated radical. Capstone® FS-50, a short-chain fluorocarbon surfactant with C6 in its perfluorinated radical, was purchased from Dupont. FfreeF F-3# was prepared using the formulation of F-1#, but the component of fluorocarbon surfactant was removed. F-5# containing long-chain fluorocarbon surfactant with high concentration (above 3%) was purchased from Yangzhou Jiangya Fire Equipment Co. Ltd.

Notably, the hydrocarbon surfactant in F-1#, F-2#, and F-3# was zwitterionic lauryl imidazoline, and the stabilizer was xanthan gum. For F-4#, the hydrocarbon surfactants consisted of 2% sodium dodecyl sulfate, 15% lauryl imidazoline, and 10% N-dodecyl-N,N-dimethylglycine, whereas the stabilizers consisted of 5% PEG-200, 1% lauryl alcohol, 1% isobutanol, and 0.3% xanthan gum. Foam solutions were synthesized by mixing foam concentrates with fresh water at a volume ratio of 3:97.

2.2. Experimental Apparatus and Methods

2.2.1. Aqueous Solution Properties of Firefighting Foams A fully automatic surface tension meter (QBZY-3) was used to measure the surface and interfacial tension of foam solutions. A DV-1 digital viscometer was used to measure the dynamic viscosity of foam solutions. The spreading coefficient was used to characterize the film-forming ability of AFFF in almost all the standards related to firefighting foams, such as BS EN 1568-3-2008 [32], DEF (AUST) 5706 [33], NFPA [34], and MOD 42-40 [35]. It is expressed as follows:

$$S = \gamma_{\mathrm{o}} - \gamma_{\mathrm{w}} - \gamma_{\mathrm{ow}}, \tag{1}$$

where S is the spreading coefficient, γ_o is the surface tension of liquid fuel, γ_w is the surface tension of foam solution, and γ_{ow} is the interfacial tension between the foam solution and liquid fuel. The foam solution can form an aqueous film on the liquid fuel surface if $S > 0$.

2.2.2. Generation and Property Measurement of Firefighting Foams In this study, the compressed air foam was created using a self-established system. The system consisted of air cylinders, mixing chamber, flow meters, pipes, and valves and is shown in the black dotted box in Figure 1. The mixing chamber was a cylindrical container made of quartz glass (D = 80 mm, L = 200 mm), and its interior was filled with quartz beads (D = 3 mm). Foams were created in the mixing chamber after the foam solution was mixed with air at the ration of 15/75L/h. The expansion ratio (ER) of the compressed air foam was calculated by the Eq. (2).

Table 1
Composition of Firefighting Foam Concentrates

Item	Hydrocarbon surfactant	Fluorocarbon surfactant	Silicone surfactant	Ethylene glycol	DGME	Carbamide	Stabilizers	Water
F-1#	30%	2% (FC-134)	1%	20%	5%	3%	0.3%	39.7%
F-2#	30%	2% (FS-50)	1%	20%	5%	3%	0.3%	39.7%
F-3#	30%	0	1%	20%	5%	3%	0.3%	41.7%
F-4#	27%	0	3.3%	15%	5%	5%	7.3%	37.4%
F-5#	Commercial AFFF formulation							

DGME refers to diethylene glycol monobutyl ether

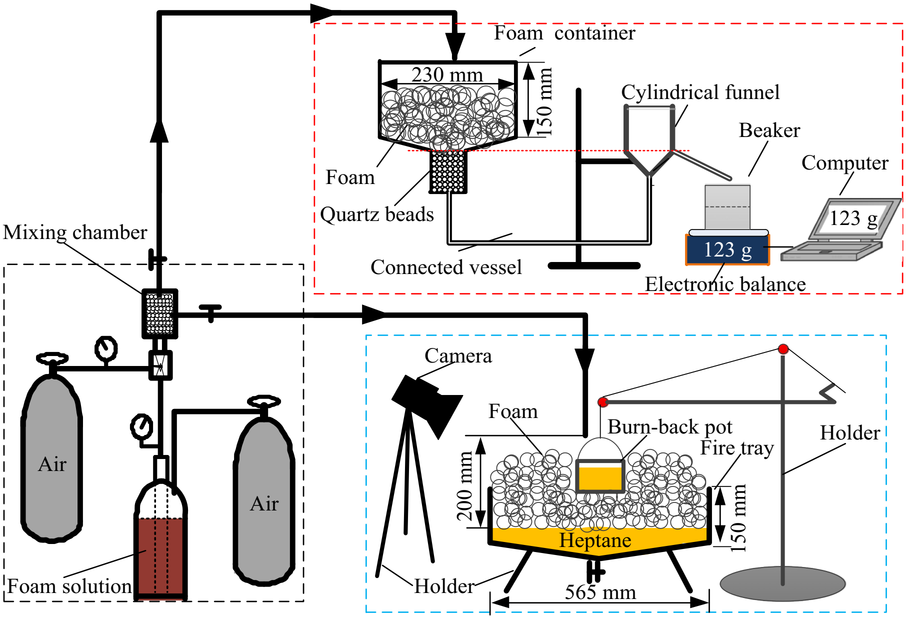


Figure 1. Apparatus for foam generation and measurement of foam stability, spreading, fire extinguishing, and burn-back performance.

$$\mathrm{ER} = V_{Foam}/(m_2 - m_1), \tag{2}$$

where ER is expansion ratio, V_{Foam} is volume of foam, m_1 is mass of foam container, m_2 is total mass of foam container and foam solution used to create foam. In this study, the created foam had a fixed expansion ratio of 12.

An apparatus to measure foam stability was established by using the law of connected vessel, as shown in the red dotted box in Figure 1. At the start of each experiment, foam was applied to the container for 90 s at the same mass flow rate. The instantaneous mass data of solutions drained out of foams were collected by an electronic balance. Similar to previous studies, the foam drainage mass and drainage rate were used to characterize foam stability [18, 19, 37].

Foam spreading on the liquid fuel surface is a critical parameter affecting fire extinguishing performance. However, studies on the foam spreading property are limited. Heptane was used as a standard liquid fuel to verify fire extinguishing and burn-back performance in most of the international standards, such as BS EN 1568-3-2008 [32], DEF (AUST) 5706 [33], NFPA [34], and MOD 42-40 [35]. Thus, heptane was chosen to conduct foam spreading experiments on liquid fuel surface in this study. The foam spreading process on the heptane surface was recorded using a CCD camera, and the spreading process was quantitatively analyzed with a MATLAB code. The foam spreading property was evaluated using the foam spreading area and foam spreading rate.

Small-scale tests for the fire extinguishing and burn-back properties of firefighting foams were performed according to the Chinese standard GB15308-2006 [38]. The testing apparatus and size of the fire tray, which are similar to that provided by the standards [32, 33, 35], are shown in the blue dotted box in Figure 1. At the beginning of the tests, 9 L of n-heptane was added to the fire tray and ignited at 0 s. Foam was supplied to the fire tray with a mass rate of 750 g/min after 60 s of pre-burning. The time when the flame extinguished completely was set as the fire extinguishment time. Foam application stopped after 180 s. The burn-back pot (D × H = 120 mm × 80 mm) with 1 L of n-heptane was ignited at 240 s. The location of the burn-back pot was dynamically adjusted to ensure that the upper surface of the foam layer and the pot lip were on the same level. The duration from the ignition of the pot to the time when the flame covered the entire fire tray denoted 100% burn-back time. All the fire extinguishing and burn-back experiments were repeated three times.

3. Results and Discussion

3.1. Aqueous Solution Properties

The surface tensions, interfacial tensions, and spreading coefficients of the foam solutions are shown in Figure 2. The surface and interfacial tensions of AFFF solutions were clearly lower than those of the two FfreeFs. Specifically, the order of surface tension was F-1# > F-2# > F-5# > F-4# > F-3#, whereas the order of interfacial tension was F-1# > F-5# > F-2# > F-4# > F-3#. Thus, AFFFs

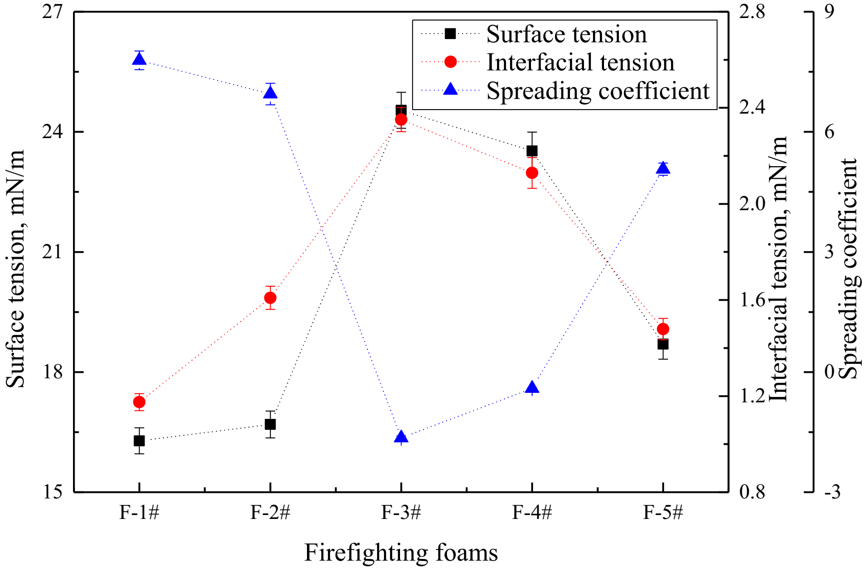


Figure 2. Surface tension, interfacial tension, and spreading coefficient of foam solutions.

demonstrated higher surface activity than FfreeFs due to the addition of fluorocarbon surfactants into AFFFs.

The order of the spreading coefficient in the foam solutions was F-1# > F-2# > F-5# > F-4# > F-3#. Notably, the spreading coefficients of AFFF solutions were positive, but those of FfreeF solutions were negative. The three AFFF solutions could theoretically form an aqueous film on the cyclohexane surface, but the FfreeF solutions could not. Notably, the viscosities of F-1#, F-2#, F-3#, F-4#, and F-5# were 1.89, 1.83, 1.37, 1.93, and 1.12 mPa s, respectively.

3.2. Foam Properties

3.2.1. Firefighting Foam Stability Figure 3 shows the drainage mass and the drainage rate of foams. The drainage mass increased gradually versus time in all the foams. F-5# showed the highest drainage mass curve, which implied that F-5# had the worst foam stability. The drainage mass curve of F-2# was slightly higher than that of F-1#, thereby indicating that the short-chain fluorocarbon surfactant was slightly worse in stabilizing the foam compared with its long-chain counterpart. The drainage mass curve of F-3# was higher than that of F-1#. This finding suggested that foam stability decreased once the fluorocarbon surfactant was removed from the AFFF components. Notably, the drainage mass curve of F-4# was much lower than those of AFFFs, which demonstrated that F-4# had higher foam stability than AFFFs.

The drainage rate of the three AFFFs and F-3# increased rapidly and then sharply decreased, as shown in Figure 3b. The maximum drainage rates of F-1#, F-2#, F-3#, and F-5# were 0.87, 1.24, 1.47, and 1.73 g/s at 135, 73, 37, and 102 s, respectively. At the early stage of drainage, the order of drainage rates of foams was F-5# > F-3# > F-2# > F-1#. The size of the drainage rate is mainly dependent on the surface tension and viscosity of the stage. The low surface tension and increased viscosity primarily caused the slow drainage [19, 39–41]. However, the order was F-5# < F-3# < F-2# < F-1# at the late stage, because foam drainage is driven by the liquid fraction at this stage [42]. The drainage rate curve of F-4# was lower than that of AFFFs at an early stage. The drainage rate of F-4# increased slowly, following a value near zero for approximately 250 s. The drainage rate curve of F-4 became stable until 1000 s after the maximum value of 0.19 g/s was obtained at 293 s. At a later stage, the drainage rate curve of F-4# was higher than that of AFFFs because of its high liquid fraction [42].

3.2.2. Foam Spreading Property on the n-Heptane Surface Figure 4 shows the typical foam spreading process on the heptane surface. The case of F-2# on the heptane surface was taken as an example. At the first 5 s, foam spread rapidly in a circular form and then scattered gradually in a noncircular shape. Foam spreading decelerated after one edge of the foam blanket touched the wall of the fire tray. Finally, the foam slowly covered the tray. These results suggested that the foam spreading process was inconsistent with the assumption of foam spreading models [43, 44].

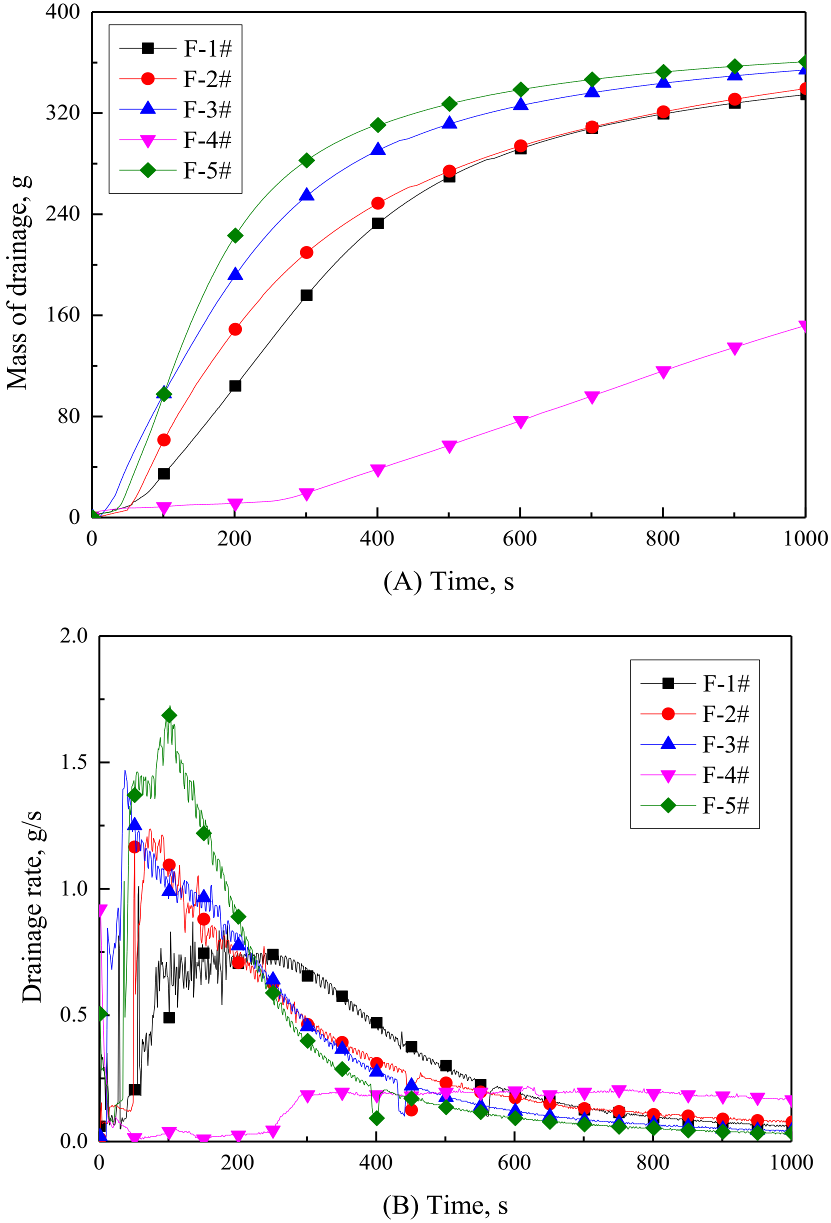


Figure 3. Variation in the drainage (a) mass and (b) rate of firefighting foams versus time.

Figure 5 shows the quantitative process of foam spreading using the MATLAB code. Figure 5a, b present the original and processed images, respectively. The white region in the blue circle in Figure 5b shows the foam spreading area. The

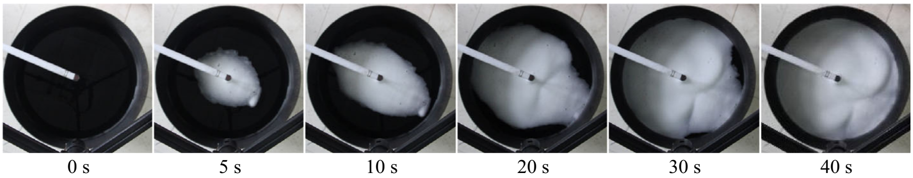


Figure 4. Typical spreading process of firefighting foam on the heptane surface.

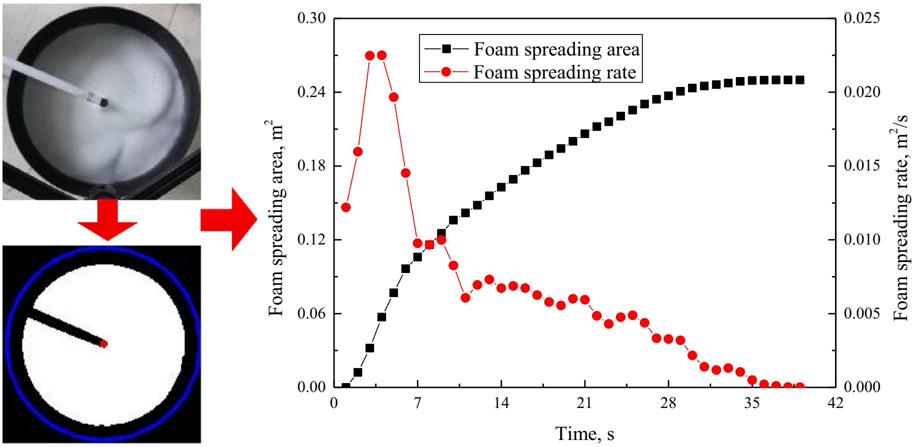
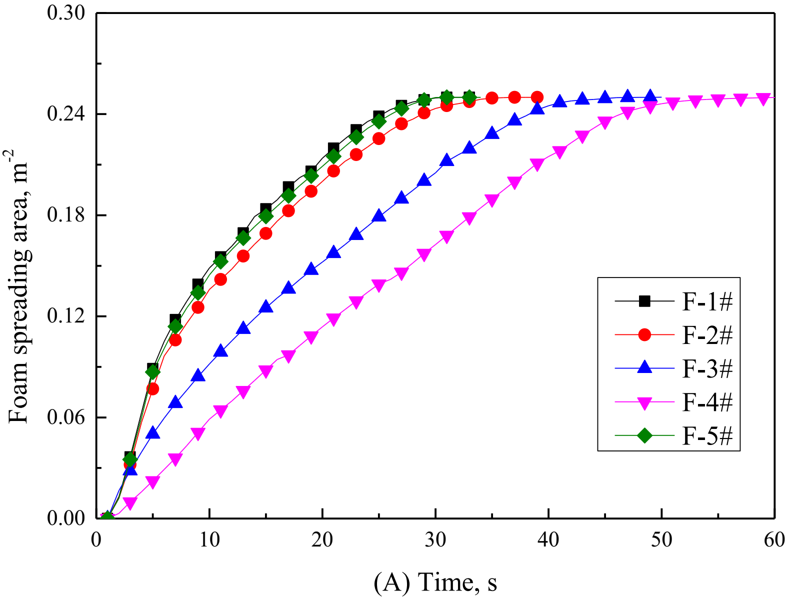


Figure 5. Quantitative description of the foam spreading process of F-2#.

area of the blue circle is a known value. The foam spreading area in Figure 5a was calculated through the blue circle area in Figure 5b. Figure 5c shows the curves of the foam spreading area and the foam spreading rate of F-2# versus time after running the MATLAB code. The foam spreading area increased rapidly over time and then increased slowly after the linear increasing stage. The foam spreading rate of F-2# increased rapidly and then decreased gradually after reaching the maximum value.

The foam spreading area of the five firefighting foams versus time is plotted in Figure 6a. The foam spreading area curves of the three AFFFs exhibited a similar change trend; they increased rapidly and then increased slowly after the linear increase stage. Notably, the curves almost overlapped one another, thereby indicating that short-chain fluorocarbon surfactants can enhance the foam spreading property similar to their long-chain counterparts. No rapid increase in the spreading area curves of FfreeFs was found. The spreading area curves of F-3# and F-4# increased gradually from the beginning and then increased slowly until the maximum value was reached. The spreading area curve of F-3# was lower than that of F-1#, which implied that the removal of fluorocarbon surfactants from



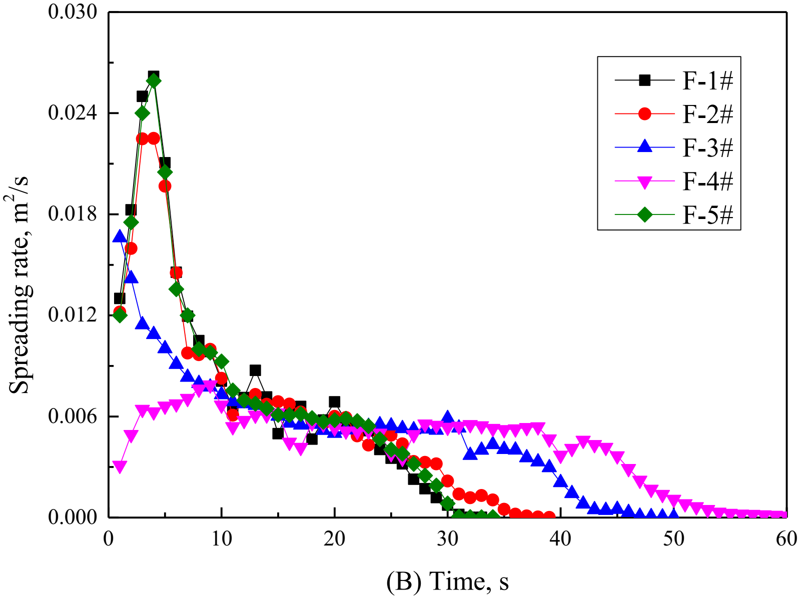


Figure 6. Variation in the foam spreading (a) area and (b) rate of firefighting foams versus time.

AFFF reduced foam spreading ability. The time required for F-4# to cover the entire fire tray was longer than that for other foams mainly due to the low surface activity and high viscosity of the F-4# solution [15].

The foam spreading rate of the three AFFFs decreased sharply after a rapid increase and then gradually reduced to zero after the steady stage, as illustrated in Figure 6b. The maximum foam spreading rates of F-1#, F-2#, and F-5# were similar to one other at 0.0262 m^2/s, 0.0225 m^2/s, and 0.0259 m^2/s, respectively; the corresponding time for them to reach the maximum spreading rate of foam was the same value (i.e., 4 s). By contrast, FfreeFs exhibited different change trends. The spreading rate of F-3# remained stable after a rapid decrease and then gradually decreased to zero. The foam spreading rate of F-4# remained stable after a transient increase and then slowly decreased to zero. The maximum foam spreading rate of F-4# was 0.0079 m^2/s, which was reached at 9 s. Several troughs were noted on the spreading rate curve of F-4# at the stable stage. This phenomenon was caused by the spread of foam in both vertical and horizontal directions [15]. A high number of troughs indicated a slow foam spreading rate. The absence of troughs in the spreading rate curves of AFFF further suggested that their foam spreading property was better than FfreeFs. The high surface activity and low viscosity of AFFF solutions were the key factors leading to their good foam spreading property.

3.3. *Fire Extinguishing and Burn-Back Performances*

3.3.1. Typical Process of Fire Extinguishing and Burn-Back Tests All the firefighting foams showed the same fire extinguishing process as F-1# (Figure 7). Heptane was ignited at 0 s and burned steadily after 60 s. Foam was added into the fire tray, and it gradually spread on the heptane surface. Flame pulsation frequency increased with the gradual increase in foam amount. Flame height declined rapidly when the foam covered the entire fire tray at around 83 s. The flame could not cover the whole tray with increasing foam layer thickness at 90 s. Finally, the flame disappeared due to the continuous application of foam.

The burn-back tests of the five foam samples generally showed a similar phenomenon. Figure 8a shows the burn-back process of AFFF (F-2#). At the early stage, the foam layer showed an apparent expansion because of the heated air inside the foam; this stage was denoted as stage I (0 s–360 s). Subsequently, the upper part of the foam blanket became very dry and disappeared gradually over

Figure 7. Typical process of the fire extinguishing test of firefighting foam.

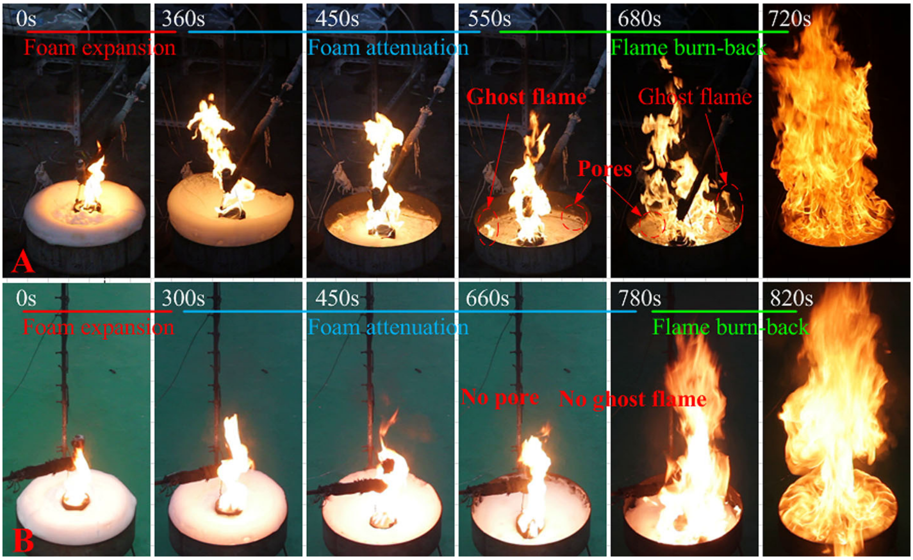


Figure 8. Process of the burn-back test of firefighting foams (a) AFFF F-2# and (b) FfreeF F-4#.

time; this stage was known as stage II (360–550 s). At the late stage, heptane inside the burn-back pot underwent boiling combustion. The foam layer accelerated decay, and heptane in the fire tray burned again; these events comprised stage III (550–720 s). Figure 10b shows the burn-back test of FfreeF (F-4#). F-4# exhibited a similar burn-back phenomenon to F-2# with foam expansion (0–300 s), attenuation (300–780 s), and reburning (780–820 s).

However, a significant difference was noted between AFFFs and FfreeFs at the late stage. Specifically, many pores developed on the foam blanket surface of AFFFs at the late stage. Fuel vapor overflowed from the broken pores and frequently created "ghost flames" after igniting. However, these "ghost flames" were extinguished rapidly due to the excellent self-sealing capacity of AFFFs. As time passed, an increasing number of pores burst, leading to additional "ghost flames," followed by steady flames. These phenomena were in accordance with previous studies [19, 45], and they were a result of heptane being a low boiling fuel [45]. For F-3# and F-4#, pores or "ghost flames" were absent during foam decay even though the foam blanket on the heptane surface was very thin. A small flame was observed on the edge of the fire tray as time passed. The foam blanket could not effectively inhibit the small flame due to its inadequate seal-healing capacity. The small flame evolved into a steady and large flame, resulting in the complete reburning of n-heptane in the fire tray.

3.3.2. Fire Extinguishing and Burn-Back Times The fire extinguishing and burn-back times of foams are shown in Figure 9. All the foams could extinguish the heptane fire rapidly. F-2# had a longer fire extinguishing time than F-1# but sig-

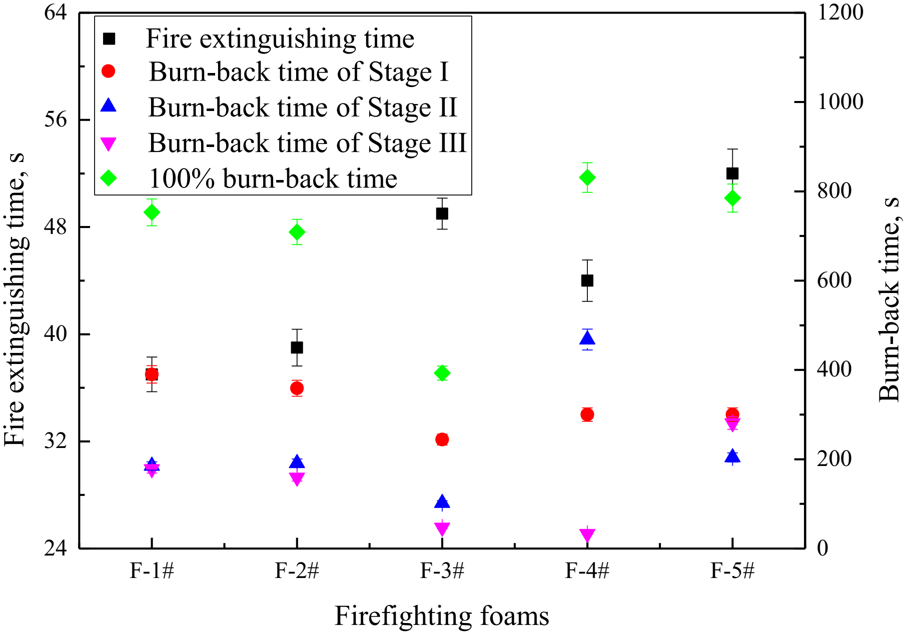


Figure 9. Fire extinguishing and burn-back times of firefighting foams.

nificantly shorter time than F-5#. These results indicated that short-chain fluorocarbon surfactants demonstrated excellent fire suppression performance in AFFF, which was similar to that of AFFF containing long-chain fluorocarbon surfactants. Surprisingly, FfreeF F-3# showed a shorter fire extinguishing time than F-5#, thereby implying that the direct removal of long-chain fluorocarbon surfactants led to relatively good fire extinguishing performance. FfreeF F-4# showed slight poor fire extinguishing performance compared with F-1# and F-2# but better performance than F-3# and F-5#. Thus, F-4# displayed good performance in fighting heptane fire.

The burn-back times of F-1#, F-2#, F-4#, and F-5# exceeded 600 s, which met the requirements of the GB15308-2006 standard [38]. The burn-back time of F-3# was 393 s, which was much lower than the standard's requirement of 600 s. F-2# showed a similar burn-back time to F-1# and F-5#, which implied that AFFFs containing short-chain fluorocarbon surfactants had the same burn-back performance as conventional AFFFs. In particular, FfreeF F-4# showed the maximum burn-back time although its solution could not form an aqueous film on the heptane surface due to the superhigh foam stability.

Notably, the three AFFFs F-1#, F-2#, and F-5# demonstrated similar burn-back times at the three stages of the burn-back tests. This finding implied that AFFF containing short-chain fluorocarbon surfactant exhibited the same burn-back regimes as AFFFs with long-chain fluorocarbon surfactant. Among the samples, F-3# presented the worst burn-back performance in all the three stages of the burn-back test. However, the time FfreeF F-4# lasted at stage I of the burn-back test was similar to that of AFFFs. Moreover, the time F-4# lasted at stage II was much longer than that of AFFFs. Few liquids drained out of F-4# due to its superhigh foam stability at stage II, and the "wet" foam could inhibit the fuel vapor for a long time. Furthermore, the time F-4# lasted at stage III was shorter than that of AFFFs, and this result was ascribed to the poor self-sealing capacity of F-4#. Unlike F-4#, AFFFs could extinguish a small flame rapidly by relying on its self-sealing capacity at stage III.

3.3.3. Comparative Analysis of the Fire Extinguishing Mechanism As we know, AFFFs extinguish flame mainly depending on the oxygen isolation of foam layer and aqueous film layer on liquid fuel surface, and the cooling effect caused by the rapid evaporation of water in AFFF. But, the different firefighting foams used in our study have the same initial liquid content, as they have the same expansion ratio. Thus, for these foams used in the present study, the cooling effect caused by the rapid evaporation of water can be considered to be the same to each other. The cooling effect is not the reason for the different fire extinguishing efficiency of the several environmentally friendly fire fighting foams used in this study. The main mechanism of fire extinguishment is the high-efficient inhibition of foam layer and aqueous film on fuel vapor. Therefore, we just focused on the effect of foam layer and aqueous film layer during the analysis of the fire extinguishing mechanism in Figure 10.

The fire extinguishing performance of AFFFs F-1#, F-2#, and F-5# was dependent on the aqueous film and foam layer on the fuel surface, as illustrated in Figure 10a. In the process of extinguishing fire, the foam spread rapidly and covered the liquid fuel. Meanwhile, the relatively poor stability of AFFFs caused a considerable amount of liquid to drain out. A small amount of drained liquid formed the aqueous film on the fuel surface. The rapid spread of the foam blanket and aqueous film led to the fast extinguishment of flames. However, the excess drained

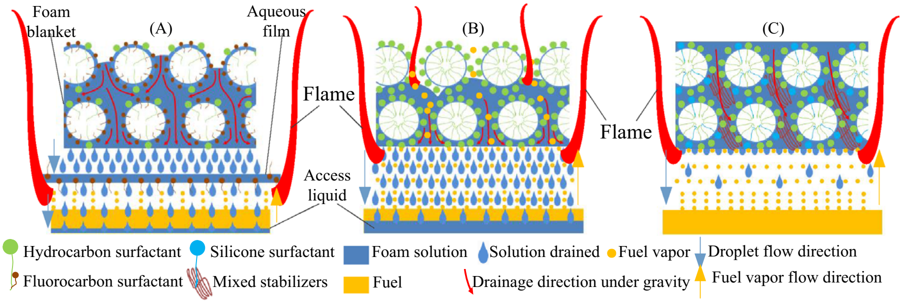


Figure 10. Comparison of the fire extinguishing mechanism of the following environmentally friendly firefighting foams: (a) AFFF, (b) unstable FfreeF, and (c) highly stable FfreeF.

liquid sank to the bottom of the liquid fuel after the aqueous film formed because its density was higher than that of heptane [36]. The ability of the foam blanket to isolate liquid fuel vapor declined with the rapid decrease in liquid content. Thus, the burn-back performance of AFFFs was worse than that of F-4#.

For the FfreeFs in which the fluorocarbon surfactant was removed directly from the AFFF formulation, similar to F-3#, no aqueous film formed on the liquid fuel surface and foam stability was relatively poor. The foams extinguished the flame by relying only on the foam blanket with poor stability (Figure 10b). A large amount of liquid drained out of the foam blanket and sank to the bottom of the liquid fuel due to the poor foam stability. The inferior foam blanket had difficulty in isolating the liquid fuel vapor. Small flames may occur over the foam blanket because liquid fuel vapor may occasionally penetrate foam blanket and be ignited, which resulted in the faster collapse of foam blanket, as described in Figure 10b. Thus, the foam exhibited poor fire extinguishing and burn-back performances.

The fire extinguishing mechanism of FfreeF F-4# differed from that of AFFFs (Figure 10c). During fire extinguishment, minimal draining was observed in F-4# due to its high foam stability. The majority of liquids remained in the foams, and the foam layer was “wet”. It is difficult for liquid fuel vapor to penetrate the “wet” foam layer upon foam covered fuel surface. The foam could cover the entire fuel surface and rapidly extinguish the flame. Thus, FfreeF can effectively fight flammable liquid fire without an aqueous film. In terms of burn-back performance, much more heat was absorbed by foam F-4# compared to other foams with bad foam stability. The high liquid content enhanced the ability to resist thermal radiation. Moreover, foams with high liquid content could efficiently inhibit liquid fuel vapor and effectively cool the fuel surface. Therefore, the superhigh foam stability provided by the mixture of surfactants and foam stabilizers in F-4# led to its excellent burn-back performance.

4. Conclusions

Unlike FfreeF solutions, AFFF solutions can form an aqueous film on the cyclohexane surface. AFFF solutions containing long-chain fluorocarbon surfactants show slightly better film-forming property on the cyclohexane surface than those containing short-chain fluorocarbon surfactants.

Long-chain fluorocarbon surfactants have better foam stabilizing ability than their short-chain counterparts. Foam stability decreases once fluorocarbon surfactants are removed directly from the AFFF components while other components remain unchanged. FfreeFs containing a mixture of foam stabilizers demonstrate significantly higher stability than AFFFs.

AFFFs have better foam spreading properties than FfreeFs. The removal of fluorocarbon surfactants from AFFF leads to a reduction in foam spreading ability. Short- and long-chain fluorocarbon surfactants both enhance the foam spreading property. The high surface activity and low viscosity of AFFF solutions are important factors that lead to good foam spreading properties.

Conventional AFFFs and the environmentally friendly firefighting foams F-2# and F-4# can extinguish flammable liquid fires and resist flame radiation. AFFFs based on short-chain fluorocarbon surfactants exhibit the same fire extinguishing and burn-back mechanisms as conventional AFFFs. These mechanisms rely on the foam blanket and aqueous film on the liquid fuel surface. FfreeFs based on silicone surfactants and the mixture of foam stabilizers extinguish liquid fires with high efficiency depending on their superhigh foam stability.

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