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Experimental study on the quantitative evaluation of the thermal stability performance and heat insulation characteristics of fire-fighting foam

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Abstract

Foam extinguishing agents are crucial for the suppression of flammable liquid fires. Their thermal stability performance and heat insulation characteristics are critical indicators to evaluate the efficiency of the fire-fighting foam. There have been some studies focused on exploring the behavior of fire-fighting foams exposed to radiant heating. However, the decay mechanisms and heat transfer behaviors of the foam at the micro-scale are still unclear and require further clarification. Therefore, in this study, the volume reduction coefficient, falling time of foam column height, and the temperature profiles of the foam layer under the thermal radiation environment of different conditions are discussed. The results indicate that the high temperature generated by the radiative heat flux will accelerate the collapse rate of the foam layer. The stability of the foam structure will be seriously damaged. There is a relationship between heat radiation intensity and foam attenuation coefficient. The empirical model for reflecting the fire-fighting foam collapse process under the fire environment with high heat radiation flux is modified. Moreover, the average collapse rate and temperature difference gradient are used to characterize the thermal stability performance and heat insulation characteristics of the foam. Analysis of the micro-scale foam structure parameters from the foam scans has revealed that the thermal stability performance and heat insulation characteristics of the foam are stronger when the surface tension of the foam is within the range of 17.4–20.4 mN/m.

KEYWORDS
fire-fighting foam, heat insulation characteristics, micro-scale foam structure, surface tension, thermal stability performance

1 | INTRODUCTION

Oil products are extremely important energy raw materials, which are used widely in many industries.[1–3] However, based on a wide range of application scenarios, oil products easily trigger large-scale fire accidents. They can not only cause a large number of casualties, but also bring heavy financial losses and environmental pollution.[4] Many fire-fighting events have proved that foam extinguishing agents are crucial method for the extinguishment of flammable oil fires.[5–10] Thermal stability performance and heat insulation characteristics are critical indicators to evaluate the efficiency of the fire extinguishing foams.[11,12] Both of them determine the life of the foam covering the soil surface. Unfortunately, for large-scale oil fire scenarios, with high fire temperature and extremely rapid fire propagation, the two-phase foam is thermodynamically unstable under the effect of radiant heating. As a result, the foam would collapse quickly, which is not conducive to rapidly reducing the spread process of the large-scale fire. Therefore, a foam with better thermal stability performance and heat insulation characteristics is especially needed to improve the efficiency of the fire-fighting process in the oil industry.

Previous studies mainly focused on exploring the behavior of fire-fighting foam exposed to radiant heating. Perrson[13] observed the whole collapse behavior of fire-fighting foam during radiation heating. The foam drainage and evaporation rates were measured with radiant heat fluxes up to 35 kW/m^2. The evaporation rate is proportional to the incident radiation level. The drainage rate increases when the foam is heated by radiation. Boyd and Di Marzo[12] developed a one-dimensional steady-state model to predict the evolutionary behavior of fire-fighting foam exposed to radiation heating. Foam properties and temperature distribution of the foam layer were calculated under the given radiant heat. The results show that the energy balance played a crucial role for heat absorption and foam evaporation. However, the results of the above two scholars mainly consider the foam collapse behavior exposed to a single thermal radiation environment. Furthermore, Lu et al.[14] carried out a series of experiments on the preparation of a highly stable foam aqueous solution based on analyzing the characteristics of foaming agents. Through the thermal radiation resistance test, the results showed that, when the temperature was 135°C, a small amount of water content began to evaporate, and the height of the foam began to decline. The rate of water evaporation increased with the increase in temperature. Through the change of viscosity, it is concluded that the prepared water-based foam can still maintain the shape of foam at 220°C. On this basis, Zhou et al.[15] studied the thermal stability, volume expansion ratio, and temperature distribution inside the foam layer when it is exposed to a high-temperature environment. The results showed that high ambient temperature is beneficial to foaming, but reduces the stability of the foam. Due to the different heat transfer characteristics in the depth direction, the foam layer exposed to continuous radiation heating presents three continuous stages, namely, the initial stage, the equilibrium stage, and the collapse stage. Yu et al.[16] studied the relationship between foam stability, oil film interaction, and fire extinguishing performance of fluoride-free and fluorinated foams. The results showed that the fire extinguishing performance of non-fluorinated foam can be equivalent to that of fluorinated foam by adjusting the expansion ratio of the foam. Xie et al.[17] carried out a series of experiments and found that adding opaque particles to the foam can improve the effect of absorbing and scattering heat and enhance the heat resistance of the foam layer. The present literature has clarified that the thermal radiation intensity has a strong impact on the thermal stability performance and heat insulation ability of the foam. However, there are no quantitative characterization methods for the thermal stability performance of the foam and the heat insulation ability of the foam layer, and a lack of discussion on the decay mechanism of the foam under thermal radiation environments of different intensities. On the other hand, the influence of basic indicators in the test (such as foam drainage rate, foam expansion ratio, and evaporation rate) on its thermal stability and thermal insulation ability during the test process has been clarified from a macroperspective. However, with the progress of scientific research equipment, it is necessary to explore the morphological and structural characteristics of foam at the micro-scale and further explain the evolution mechanism of thermal stability and insulation capability.

In this paper, the volume reduction process of fire-fighting foams under different radiant heating environments was explored by cone calorimeter tests. Quantitative experimental results are used to modify empirical model of the foam collapse process and evaluate its predictive capability under a high-temperature fire environment. Furthermore, quantitative indicators used to characterize the thermal stability performance and heat insulation characteristics of the foam have been based on the characteristics of the volume reduction coefficient and the temperature profiles. Moreover, when using a tensiometer and foam scan to obtain micro-scale foam structure parameters, factors such as the surface tension, average foam radius at the initial stage, average foam radius at the end of liquid film drainage, the proportion of liquid content, and the number of bubbles per square millimeter should be considered. The effects of foam structure parameters on foam thermal stability and heat insulation characteristics have been evaluated. These results can provide useful guidance for the preparation of efficient fire extinguishing foam.

2 | EXPERIMENTAL SETUP

2.1 | Foam solution preparation and foaming procedure

An aqueous film-forming foam (AFFF), a water additive agent forming foam (WAF), and a foam for Class A standard fire (CAF) are used as the test samples in this experiment. These are the foam types commonly used to suppress flammable liquid fires.[18] Detailed information on the test foams is listed in Table 1. Initial foam concentrates are mixed with deionized water according to volume ratios, and then, the mixture solution is diluted into an AFFF solution through a magnetic stirring machine. The rotating speed is maintained at 1000 r/min and the stirring lasts 20 min. After obtaining the foam solution, the high-speed stirring foaming method is used to make the two-phase foam in this study. Low-expansion foam is mainly used to extinguish open-area flammable oil fires. So, the thermal

TABLE 1 Material category.

Order	Foam extinguishing agent	Type
#1	Water additive agent forming foam	3% mixture solution
#2	Aqueous film-forming foam	3% mixture solution
#3		3% mixture solution (alcohol resistant)
#4		6% mixture solution
#5		6% mixture solution (alcohol resistant)
#6	Foam for Class A standard fire	1% mixture solution

stability performance of low-expansion foam is discussed in this study. The foam-forming times could be affected by the mixing rate. To ensure that the final volume of different types of foam is consistent, the rotating speed is set up at 2000 r/min. The two-phase foam is obtained by pouring the foam solution (180 mL) into a quartz beaker, after stirring for 5 min. The foam volume is 900 mL, and the volume expansion ratio can be regarded as five times.

2.2 | Thermal stability performance test platform setup

The test platform is composed of a cone calorimeter, quartz beaker, height-adjustable support, thermocouple, and HD camera. The thermal stability performance of the foam is measured by the cone calorimeter, as shown in Figure 1. The cone test method mainly meets the requirements of the international standard (ISO 5660-1). The size of the cone calorimeter apparatus is 1800 mm (width) × 900 mm (depth) × 2650 mm (height), and its weight can attain 350 kg. This study only explores the influence of radiant heat of different intensities on the thermal stability performance of the foam, so it is not necessary to obtain the combustion parameters of materials. The nominal power of the heater in the cone is 5000 W, and the heat radiation output range is 0–100 kW/m^2. Before the test, it is necessary to calibrate the radiation power level. According to previous research,[19,20] generally speaking, the heating temperature of the heater should be set to 625°C when the heat radiation value is 25 kW/m^2. A heat flux meter (HFM) is used to calibrate the radiation power level on the surface of the sample. The measurement range of this meter is 0–100 kW/m^2, with an accuracy of ±3% and a data repeatability of ± 0.5%. This experiment needs to be repeated 3–4 times. When the heat radiation value on the surface of the sample stabilizes at 25 kW/m^2, it indicates that the cone has reached basic accuracy.

Furthermore, the temperature resistance of the quartz beaker can be up to 1000°C, making the quartz beaker an appropriate container to be filled with foam and set on the adjustable lifting platform. The opening of the beaker is 3 cm away from the radiation cone,[15,21] which can ensure that the foam in the beaker will receive all heat radiation with limited shielding. The thermal insulation effect of the foam during volume reduction process is evaluated, using a thermocouple inserted in the bottom of the beaker to record the temperature of the liquid while the foam layer is gradually consumed. The electronic balance is used to record the mass change of the foam before and after the test. The HD camera is used to observe the volume reduction value of the foam during the whole test process.

FIGURE 1 The cone calorimeter and testing platform.

2.3 | Key parameters of micro-scale foam test and working condition setting

The surface tension of the foam solution is measured with a tensiometer (K-100, China), with the test setup shown in Figure 2. A platinum sheet of fixed size is moved down slowly and is immersed in the foam solution, at which point, the sheet will be pulled downward by the liquid due to the effect of surface tension. As the platinum plate moves downward, the surface tension gradually increases. The surface tension is calculated according to the balancing force and the surface area of the platinum sheet.[22,23] A foam scanner (Kruss, Germany) is used to obtain the microscopic foam structure characteristic parameters, as shown in Figure 3. With the help of optical instruments, the height attenuation of foam can be monitored in time and the bubble size distribution at the micron level can be obtained. Based on the discussion about the theoretical model and test method, the working condition setting in this paper is given in Table 2. Each group of tests was repeated five times, and the average value was taken for study.

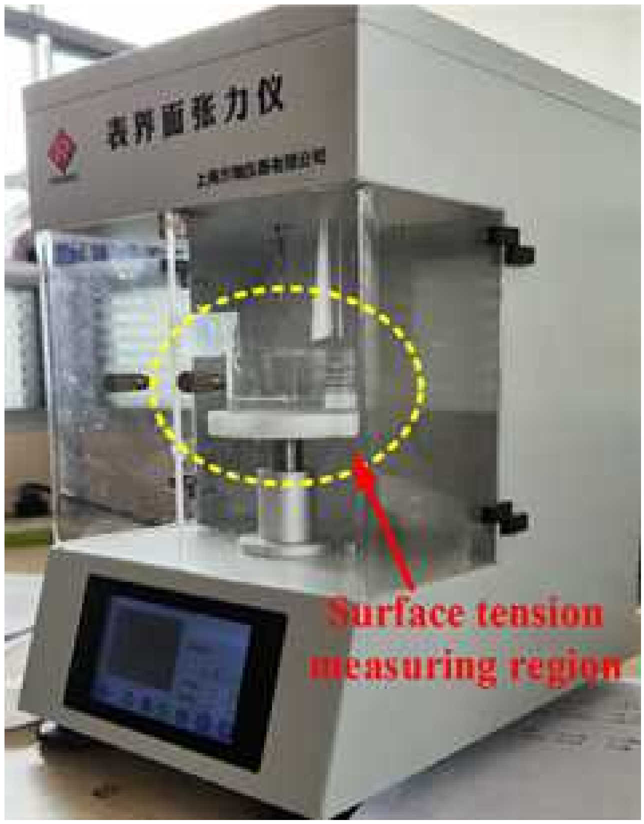


FIGURE 2 Operation scenario of tensiometer.

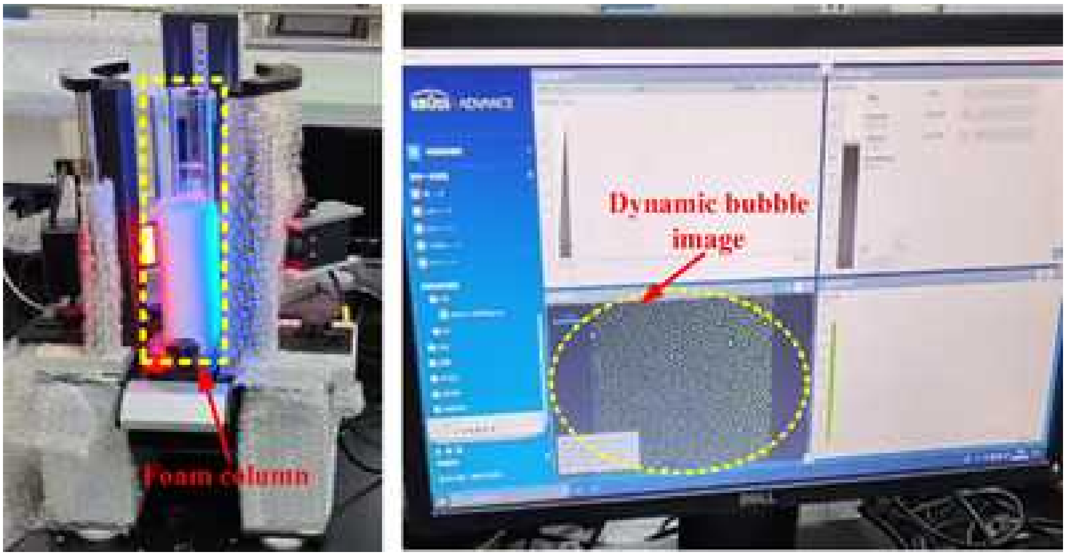


FIGURE 3 Operation scenario of foam scanner.

TABLE 2 Working conditions.

Test no.	Sample types	Radiation heat flux (kW/m^2)	Volume expansion ratio
1–5	WAF (3%)	15/20/25/30/35	5
6–10	AFFF/AR (3%)	15/20/25/30/35	
11–15	AFFF (3%)	15/20/25/30/35	
16–20	AFFF (6%)	15/20/25/30/35	
21–25	AFFF/AR (6%)	15/20/25/30/35	
26–30	CAF (1%)	15/20/25/30/35	

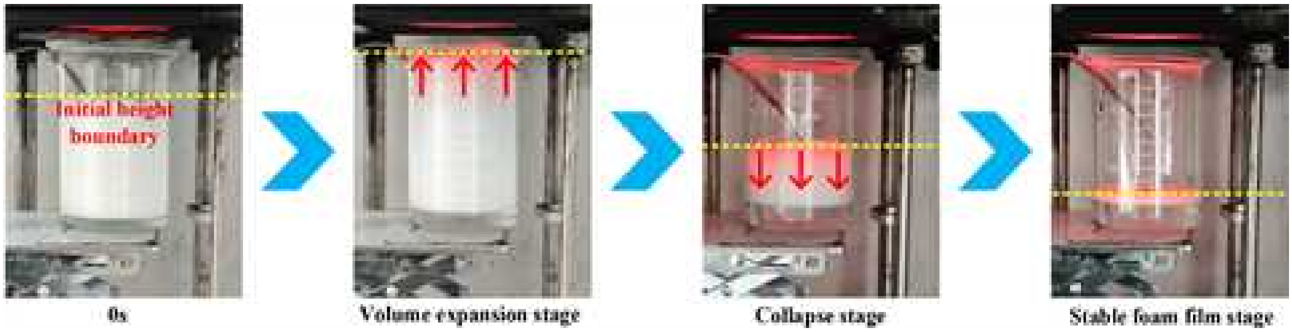


FIGURE 4 Volume reduction phenomena of the foam exposed to radiant heating.

3 | RESULTS AND DISCUSSION

3.1 | Effect of thermal radiation intensity on the fire-fighting foam

3.1.1 | Volume reduction process of the foam

The effect of heat radiation released by the cone on the foam column is shown in Figure 4. According to different volume reduction phenomena, the whole process can be divided into three stages. In the beginning, there is the volume expansion stage. The liquid contained in the upper layer foam column will vaporize generating a large amount of steam when the upper foam layer receives heat from the cone. Thermal buoyancy will also make the foam column float upward. Therefore, the foam layer will first expand rapidly for about 30 s, before it collapses. Second is the collapse stage. During this stage, the thermal stability performance gradually weakens under the continuous effect of heat radiation. The foam volume gradually decreases due to the continuous collapse of foam and drainage of liquid. The last stage is named the stable foam film stage. Only a layer of foam water film with a volume of about 20 mL remains on the liquid surface, and the foam has no heat insulation ability. According to the change of foam volume during the test, when the foam layer in the beaker drops to about 200 mL, it marks the end of the whole test process. The expiration time of the thermal stability performance can also be captured by this process.

In a previous study,[12] two vertical gas-fired panels are used as radiant heat input. The panels are oriented at a 30° angle, which helped to produce a uniform radiation on the foam. The mixture of natural gas and air can make the heat fluxes of the foam surface positioned at the gas-fired panels up to 15–18 kW/m^2, which is the same as the radiation heat flux value in a real fire environment. However, for some enclosed spaces or environments with higher fuel loads, the thermal radiation intensity will increase significantly. As a result, the initial radiation heat flux is set at 15 kW m^{-2} and then gradually increased to simulate the impact of higher heat radiation flux fire environment on the life of the foam layer.

The whole volume reduction process of the foam layer under different thermal radiation intensities is shown in Figure 5. For all foam samples, as the heat radiation intensity increases from 15 to 35 kW/m^2, it can be seen that the time required for the complete failure of the foam layer is also gradually decreasing. This transformation shows that the high temperature generated by the radiation heat flux will accelerate the collapse of the foam layer. The stability of the foam structure will also be seriously damaged. Furthermore, for the six foam samples selected in this paper, it can be seen that the difference in the fire-fighting foam volume reduction time corresponding to different radiation heat fluxes is gradually decreasing when the thermal radiation intensity exceeds 25 kW/m^2, and the curves of foam volume reduction in the range of 30–35 kW/m^2 coincide. This indicates that, when the heat radiation intensity exceeds 30 kW/m^2, its impact on the collapse rate of fire-fighting foam is decreasing, having reached the minimum critical value.

3.1.2 | The modified empirical model of the foam collapse process

Based on the above analysis, the heat radiation intensity has a great influence on the collapse process of the foam. In other words, the relationship between the heat radiation intensity and the decay time of the foam layer should be further characterized quantitatively. In previous research,[24] an empirical model has been proposed by expressing the foam collapse rate as follows:

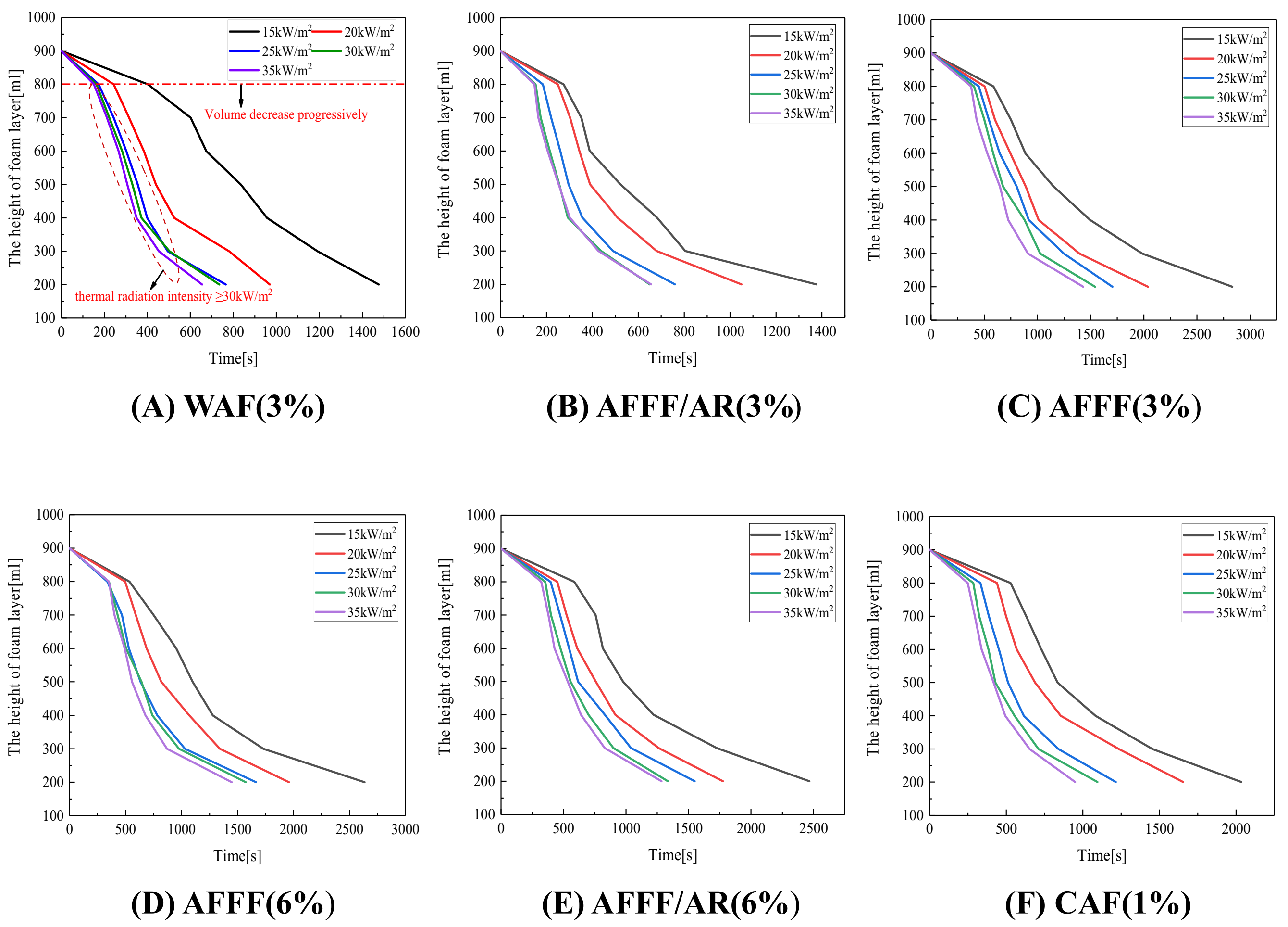


FIGURE 5 The effect of thermal radiation intensity on the foam volume.

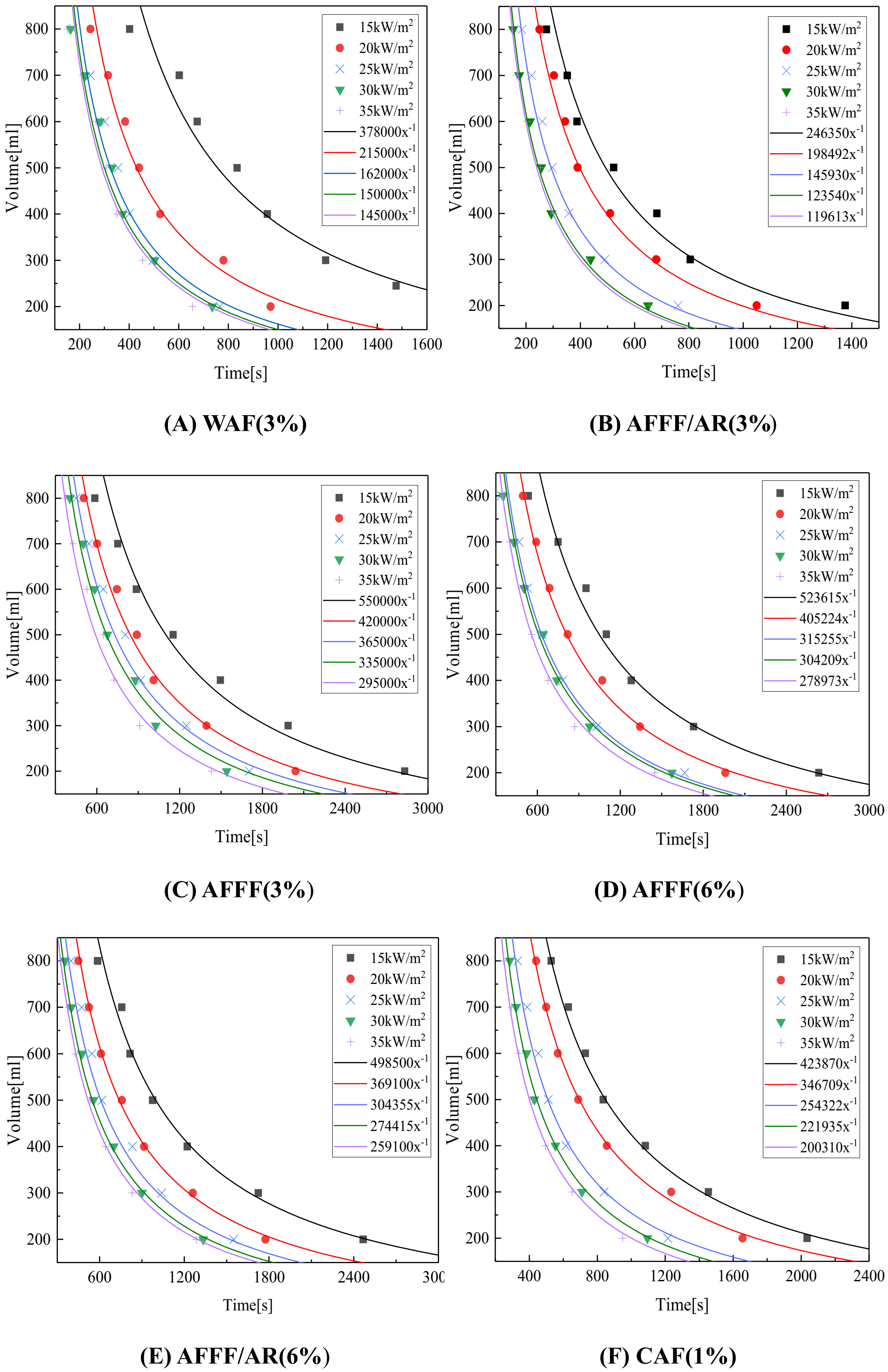


FIGURE 6 The decay curve for different radiant heat flux conditions.

TABLE 3 Foam attenuation coefficient under different thermal radiation intensity scenarios.

Heat flux	WAF	AFFF/AR (3%)	AFFF (3%)	AFFF (6%)	AFFF/AR (6%)	CAF
15 kW/m^2	k_0	k_0	k_0	k_0	k_0	k_0
20 kW/m^2	$0.56k_0$	$0.80k_0$	$0.76k_0$	$0.77k_0$	$0.74k_0$	$0.81k_0$
25 kW/m^2	$0.43k_0$	$0.59k_0$	$0.66k_0$	$0.60k_0$	$0.61k_0$	$0.60k_0$
30 kW/m^2	$0.39k_0$	$0.50k_0$	$0.57k_0$	$0.58k_0$	$0.55k_0$	$0.52k_0$
35 kW/m^2	$0.38k_0$	$0.48k_0$	$0.53k_0$	$0.53k_0$	$0.52k_0$	$0.47k_0$

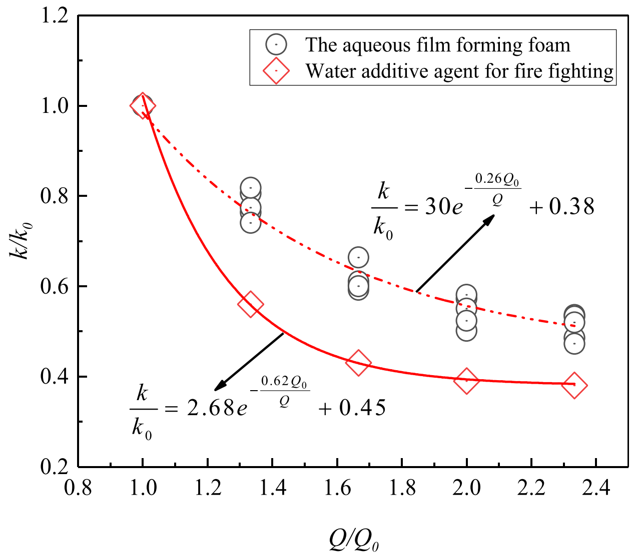


FIGURE 7 The relationship between the thermal radiation intensity and attenuation coefficient.

$$\frac{dH}{dt} = -\frac{k}{t} \tag{1}$$

Here, k is the attenuation coefficient, which is related to the chemical composition of the foam, and t is the decay time of the foam layer. However, according to the foam volume reduction condition in Figure 5, the collapse rate of foam under a high-temperature fire environment is not properly simulated by this model. To better describe the influence of heat radiation intensity on different kinds of fire-fighting foams, a correlation is developed using the data after the foam volume has dropped by 100 mL. With this approach, the attenuation coefficient and decay curves could be obtained for different fire-fighting foam samples, as shown in Figure 6. It can be seen that the decay curves of the foam layer under different thermal radiation intensity scenarios differ greatly, and smaller thermal radiation intensities correspond to larger decay coefficients. This indicates that there is a relationship between thermal radiation intensity and the foam attenuation coefficient. Therefore, a correction factor based on the proportional relationship of thermal radiation intensity and attenuation coefficient needs to be proposed, as follows:

$$\frac{k}{k_0} \propto a\left(\frac{Q}{Q_0}\right)^n \tag{2}$$

The proportional relationship of the foam attenuation coefficient under different thermal radiation intensity scenarios is shown in Table 3. The proportional values in the range of 15–35 kW m^{-2} are similar for the AFFF extinguishing agent and the compressed air foam extinguishing agent. The difference is within ± 0.05. Otherwise, the attenuation coefficient of the water foam extinguishing agent is quite different from that of other samples. Therefore, the data distribution trend in the two cases needs to be fitted separately, as shown in Figure 7. The fit accuracy (R^2) is 0.97. Therefore, the correction factor based on the proportional relationship between the thermal radiation intensity and attenuation coefficient can be expressed as Equation (3). Substituting Equation (3) into Equation (1) yields the modified empirical model for fire-fighting foam collapse process under radiant heat flux from a fire.

$$\frac{k}{k_0} = \begin{cases} 30e^{-\frac{0.26Q_0}{Q}} + 0.38 \\ 2.68e^{-\frac{0.62Q_0}{Q}} + 0.45 \end{cases} \tag{3}$$

$$\frac{dH}{dt} = \begin{cases} \frac{k_0}{t}\left(30e^{-\frac{0.26Q_0}{Q}} + 0.38\right) & \text{for AFFF\&CAF} \\ \frac{k_0}{t}\left(2.68e^{-\frac{0.62Q_0}{Q}} + 0.45\right) & \text{for WAF} \end{cases} \tag{4}$$

3.2 | Thermal stability performance of fire-fighting foam

Since the volume reduction process is characterized by three stages to properly describe the thermal stability performance of foams, it is necessary to analyze their collapse behavior in each stage. The collapse time required to the different proportions of foam volume deterioration is shown in Figure 8. It can be seen that all samples follow a bathtub trend, firstly decreasing and then increasing, which is consistent with the behavior in Figure 4. At the initial stage (for proportion of foam volume deterioration decreases from 11% to 22%), because the liquid drainage process of foam has not yet started, the foam column can maintain higher stability performance in this stage, so the height of the foam column decreases slowly and it takes longer for the foam layer to collapse. Otherwise, in the last stage (for proportion of foam volume deterioration from 67% to 78%), due to the fact that only a layer of foam water film with a volume of about 20 mL remains on the liquid surface, the concentration of liquid components in the foam is too high, which increases the collapse time again. However,

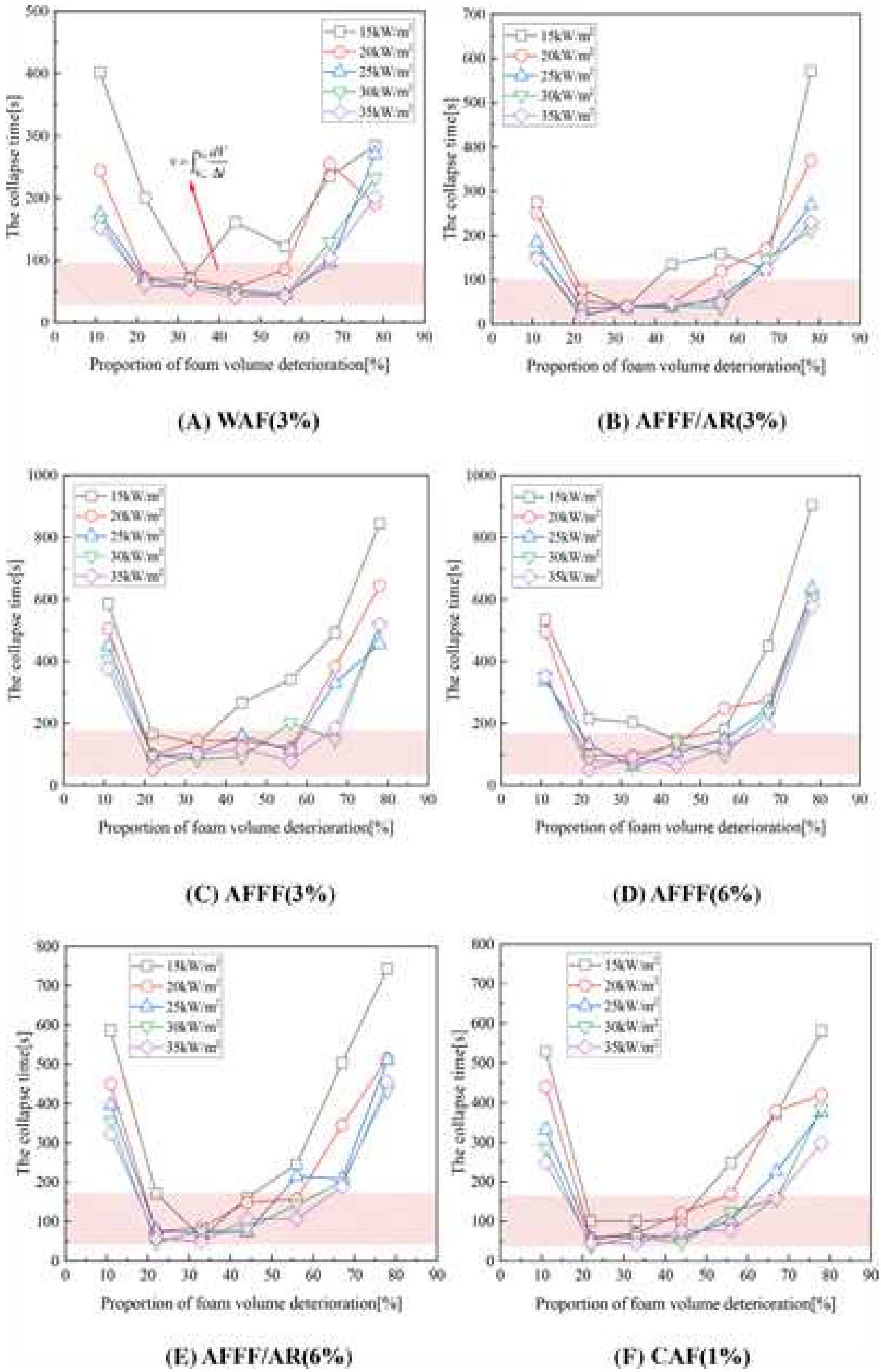


FIGURE 8 The collapse time required to the different proportion of foam volume deterioration.

TABLE 4 The distribution of the average collapse rate [ml/s].

Heat flux (kW/m^2)	WAF (3%)	AFFF/AR (3%)	AFFF (3%)	AFFF (6%)	AFFF/AR (6%)	CAF (1%)
15	0.83	1.36	0.50	0.55	0.83	0.84
20	1.45	1.83	0.81	0.81	0.96	1.14
25	1.82	2.42	0.89	1.01	1.14	1.50
30	1.96	3.06	0.95	1.09	1.36	1.82
35	2.07	3.12	1.26	1.37	1.43	1.76

when the volume reduction process of the foam column is within the range of 22%–67%, the collapse time curve for the decline function of foam column height is the same. This indicates that, when the extinguishing foam is in a high thermal radiation environment, its collapse time is stable for most of the time during the decay process. Based on the above physical characteristics, the volume collapse rate can be obtained as follows:

$$v = \frac{V_0 - V_{cr}}{\Delta t}. \quad (5)$$

Here, v is used to characterize collapse rate, with units of ml/s. dV is the differential volume during foam loss. V_0 is the foam volume value when the fraction of foam loss is 22%, V_{cr} is the corresponding volume value when the proportion of foam volume loss is 67%, and Δt is the time elapsed between those conditions. The value of this average collapse rate is reported in Table 4. It can be seen that the strength of the thermal stability characteristics of fire-fighting foam is positively related to the size of its average collapse rate. When the foam type is fixed, the collapse rate of different foam samples all shows a gradually increasing trend with the increase in thermal radiation intensity. However, when the heat radiation intensity is fixed, the collapse rate of different types of fire-fighting foam has certain differences.

The surfactant is the main component of the foam extinguishing agent. Its interfacial properties in the gas–liquid interface directly affect the surface tension of the foam solution. A previous study has shown that maintaining proper surface tension can enable the fire-fighting foam to have a good spreading ability on the gas–solid or gas–liquid interface, to obtain better thermal stability.[25,26] Therefore, surface tension is an important reference index for evaluating the fire extinguishing efficiency of foam. Some test standard documents point out that the surface tension of foam extinguishing agents should not exceed 24 mN/m to ensure high fire extinguishing efficiency, but there is no clear requirement for a lower limit.[27] The surface tension of the six types of fire-fighting foam samples selected in this paper and the corresponding foam collapse rate distribution under the different thermal radiation conditions are shown in Figure 9. It can be seen that, when the surface tension of fire-fighting foam is <17.4 mN/m, its thermal stability will also be significantly reduced. For fixed heat radiation intensity, when the surface tension of the foam is in the range of 17.4–20.4 mN/m, the collapse rate is at its lowest and the numerical change trend is relatively stable. This shows that the thermal stability performance of the fire-fighting foam is stronger within the indicated surface tension range.

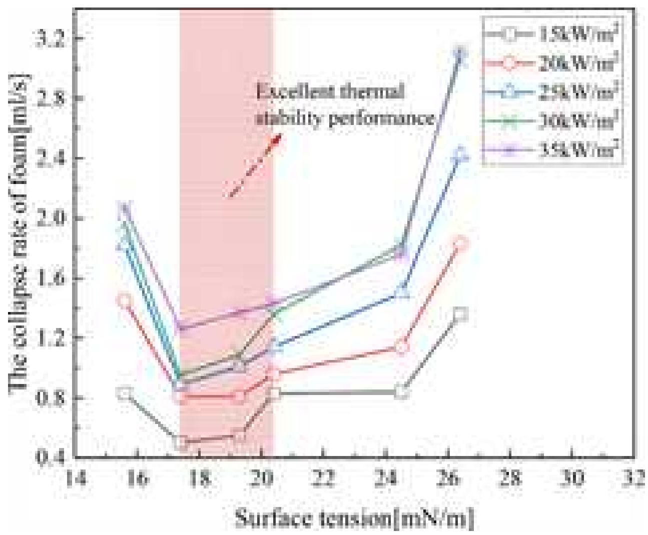


FIGURE 9 Relationship between surface tension and the collapse rate of fire-fighting foam.

Based on the microscopic image captured by the optical lens in the foam scan, as shown in Figure 10, it can be seen that at the initial stage of the collapse process, there is no obvious difference in the bubble size of various samples. However, with the influence of gravity and the continuous effect of higher temperatures, the foam drainage phenomenon is further accelerated,[28] causing the radius and distribution of foam bubbles to become significantly different. In this stage, fire-fighting foams with surface tension <17.4 mN/m, or >20.4 mN/m, will have serious coalescence (due to the rupture of liquid film between adjacent bubbles) and coarsening (there is a pressure difference between bubbles of different sizes, and the gas diffuses from small to large bubbles).[29] Therefore, it is impossible to maintain relatively stable structures and the thermal stability is significantly weakened.

3.3 | Heat insulation characteristics of fire-fighting foam

The temperature of the liquid was measured by inserting the thermocouple at the bottom of the beaker when the foam layer falls to different heights. Since the heater is located on the upper position of the foam column, generous heat will contact the foam column at the first time. As the height of the foam column decreases, its heat insulation

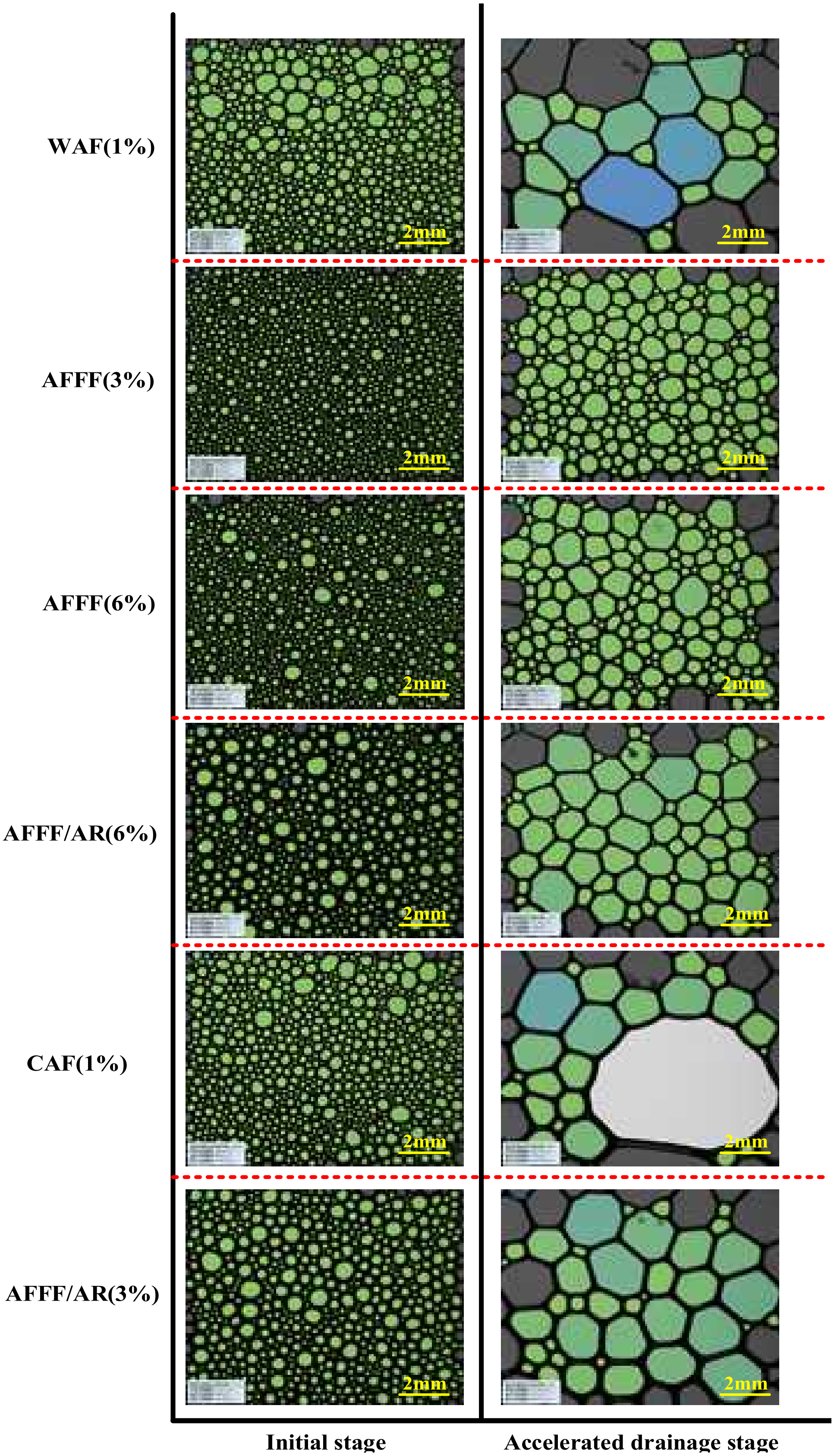


FIGURE 10 The microscopic image captured by the foam scan at different stages.

characteristics also change. In addition, the transient heating effect during the heat transfer process can also cause an increase in the temperature of the liquid at the bottom of the beaker, but this paper mainly compares the heat insulation characteristics of different types of fire-fighting foam, because the experimental conditions are the same, which means that the impact of the transient heating effect on

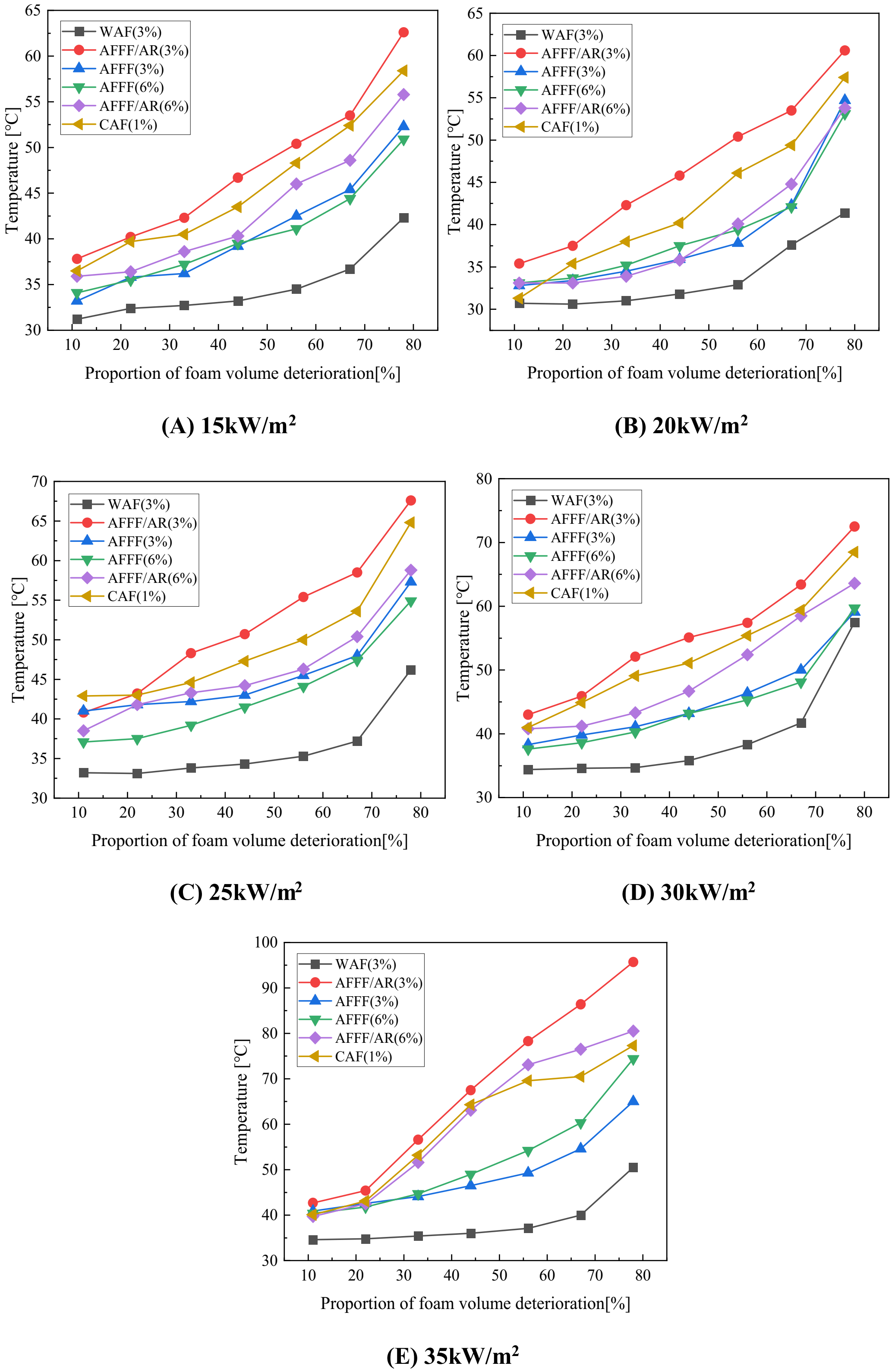


FIGURE 11 The temperature distribution for different proportions of foam volume deterioration.

the liquid at the bottom of the beaker is also the same. Therefore, the heat insulation characteristics of different types of fire foam can still be compared by this method. To make a comparison with the collapse rate of the foam, the temperature variations for the same values of foam volume loss are also analyzed. The temperature of the bottom liquid in the beaker keeps rising with the increasing proportion of foam volume loss, as shown in Figure 11, which indicates that the heat insulation characteristics of fire-fighting foam are gradually weakening. In addition, it can be seen that the bottom liquid temperature curve presents a linear growth trend. Therefore, the temperature difference between the initial collapse stage (proportion of foam volume deterioration≈10%) and complete collapse stage (proportion of foam volume deterioration≈80%) can be used to quantitatively analyze the heat insulation characteristics of different types of fire-fighting foams by calculating the quantity defined, as follows:

$$\overrightarrow{\Delta T} = \frac{|T_{initial} - T_{complete}|}{N}. \quad (6)$$

Here, ΔT is used to characterize temperature difference gradient, and the unit of temperature difference gradient is °C/%. The temperature at the initial collapse stage is recorded as $T_{initial}$, and the temperature at the complete collapse stage is recorded as $T_{Incomplete}$. N is the proportion of total foam volume loss. The thermal insulation performance can be evaluated by the temperature difference gradient, as shown in Table 5. It can be seen that the different types of fire-fighting foam have different values for this quantity when the heat radiation intensity is fixed. Therefore, it is necessary to further elaborate on the foam formation mechanism according to the microscopic key structural parameters of the foam.

Based on the data obtained with the foam scan, the foam structure parameters were tested from a micro-perspective, which include the average foam radius at an initial stage, the average foam radius at the end of liquid film drainage, the proportion of liquid content, and number of bubbles per square millimeter, as shown in Table 6. The influence of these crucial parameters on the fire-fighting foam heat insulation characteristics is described.

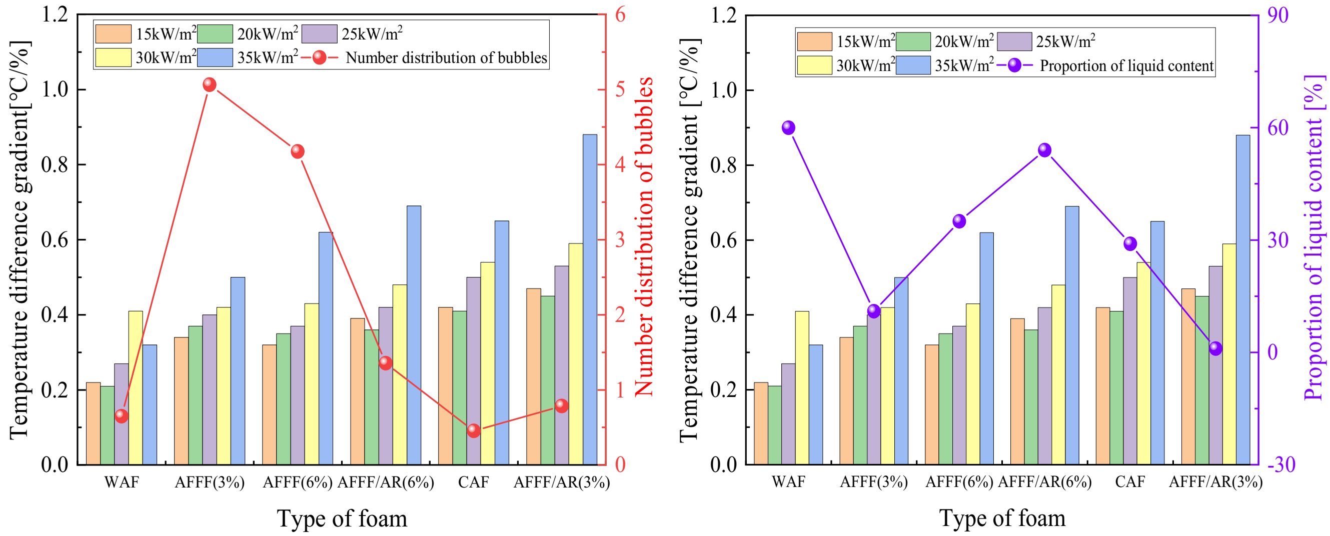
Both the number distribution and the size of the bubbles can affect the heat insulation characteristics of the foam layer. The average foam radius at different stages is shown in Table 6. It can be seen that, when the surface tension of the foam is within the range of 17.4–20.4 mN/m, the average radius of bubbles is significantly smaller than that of others, which means that more bubbles are distributed in the foam layer with same volume. As shown in Figure 12A, when the surface tension of the foam is within the range of 17.4–20.4 mN/m, the number of bubbles per square millimeter is kept at 1.4–5.1. This quantity is significantly higher than for other conditions, and the temperature gradient value is smaller; this result indicates that the foam with surface tension of 17.4–20.4 mN/m has stronger insulation performance. The main reason is that the stability of the structure will be reduced if the foam bubble radius is too large. The liquid drainage rate of the foam will be faster under this condition, which will cause collapse of the foam to accelerate. On the contrary, the foam with a smaller scale structure is more stable, due to the greater number of bubbles, which leads to the arrangement in the foam layer to be more dense, and the layer has stronger heat insulation characteristics. In addition, the proportion of liquid content of the foam layer will also affect the heat insulation characteristics, because too much liquid will accelerate the process of heat dissipation. For the WAF sample, as shown in Figure 12B, the reason behind the excellent heat insulation performance is mainly the higher liquid content (60%), which provides higher cooling performance. Because of the above research results, when the surface tension of a fire-fighting foam is within the range of 17.4–20.4 mN/m, its heat insulation characteristics are relatively higher.

TABLE 5 The distribution of the temperature difference gradient [°C/%].

Heat flux (kW/m^2)	WAF (3%)	AFFF/AR (3%)	AFFF (3%)	AFFF (6%)	AFFF/AR (6%)	CAF (1%)
15	0.22	0.47	0.34	0.32	0.39	0.42
20	0.21	0.45	0.37	0.35	0.36	0.41
25	0.27	0.53	0.40	0.37	0.42	0.50
30	0.41	0.59	0.42	0.43	0.48	0.54
35	0.32	0.88	0.50	0.62	0.69	0.65

TABLE 6 Summary of microstructure parameters of foam.

Samples	Surface tension (mN/m)	Average foam radius at the initial stage (μm)	Average foam radius at the end of liquid film drainage (μm)	Proportion of liquid content (%)	Number of bubbles per square millimeter
WAF	15.6	53	565	60%	0.6
AFFF/AR (3%)	26.4	70	538	1%	0.8
AFFF (3%)	17.4	63	216	35%	5.1
AFFF (6%)	19.3	61	230	54%	4.2
AFFF/AR (6%)	20.4	78	420	29%	1.4
CAF	24.5	54	590	11%	0.5



(a) Number of bubbles per square millimeter (b) Proportion of liquid content

FIGURE 12 The effect of microstructure parameters of foam on the heat insulation characteristics.

4 | CONCLUSION

Fire-fighting foam with better thermal stability performance and heat insulation characteristics is especially needed to improve the efficiency of fire-fighting to safeguard process operations. In this study, the thermal stability performance and insulation characteristics of fire-fighting foams with different components were evaluated and compared. A modified empirical model of the foam collapse process was proposed by discussing the relationship between thermal radiation intensity and attenuation coefficient. Moreover, the effects of micro-scale foam structure parameters on thermal stability performance and heat insulation characteristics were also evaluated. Based on these studies, the following conclusions can be obtained:

1. The heat radiation intensity has a great influence on the collapse process of fire-fighting foam. Its impact on the volume reduction time of the foam layer is decreasing when the heat radiation intensity exceeds 30 kW/m^2.
2. A new correction factor based on a proportional relationship between the thermal radiation intensity and attenuation coefficient is proposed. This correction factor was used to modify the empirical model of the fire-fighting foam collapse process under a heat radiation flux fire environment.
3. The fire-fighting foam collapse behavior is stable when the volume reduction process is within the range of 22%–67%. The average collapse rate of the foam can be obtained by calculating the parameters in this process and also used to characterize the thermal stability performance. Based on the microscopic image captured by the foam scan, there is no obvious difference in the bubble size of various samples at the initial stage of the collapse process. With the influence of gravity and the continuous effect of higher temperatures, the drainage of the foam is further accelerated, causing the radius and distribution quantity of foam to change significantly. The thermal stability performance of a fire-fighting foam is stronger when the surface tension of the foam is in the range of 17.4–20.4 mN/m.
4. The temperature difference gradient between the initial collapse stage (proportion of foam volume deterioration ≈10%) and complete collapse stage (proportion of foam volume deterioration ≈80%) was used to quantitatively analyze the heat insulation characteristics of different fire-fighting foam samples. Both the number distribution and the size of the bubbles can affect the heat insulation characteristics of the foam layer. The foam with a higher liquid content can also have a higher cooling performance. The heat insulation characteristics are relatively higher when the surface tension of fire-fighting foam is within the range of 17.4–20.4 mN/m.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Xuepeng Jiang, upon reasonable request.

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