

PAPER • OPEN ACCESS

## AFFF spread over liquid surface under external radiation conditions

To cite this article: Baowei Wang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **257** 012020

View the [article online](#) for updates and enhancements.

# AFFF spread over liquid surface under external radiation conditions

Baowei Wang<sup>1,2</sup>, Shenshi Huang<sup>1</sup>, Qize He<sup>1</sup>, Shouxiang Lu<sup>1</sup>, and Ruichao Wei<sup>1</sup>

1 State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China

2 Fire Department of Ministry of Public Security, Beijing, China

E-mail: ustcwbw@163.com

**Abstract.** Aqueous film forming foam (AFFF) is effective in extinguishing oil fires. The extinguishing effect generally depends on the foam spread process and its coverage area. In this study, the foam spread process under external thermal radiation is investigated. Firstly, based on the axisymmetric foam spread model, the relationship of radiation and foam thickness is discussed. Then foam spreading experiments under pool fire condition were carried out, to simulate the actual extinguishing process of AFFF. Finally, the foam spread model considering the external radiation flux is developed which may provide theoretical guidance for fire suppression using AFFF.

## 1. Introduction

AFFF is one of the most effective and widely used extinguishant to put out liquid fire [1]. An important feature of the foam is that, its density is less than general oil. On the one hand, AFFF can cool down the fuel; on the other hand, the foam cuts off the contact between combustible gas and air. Therefore, it is very efficient in extinguishing oil fires.

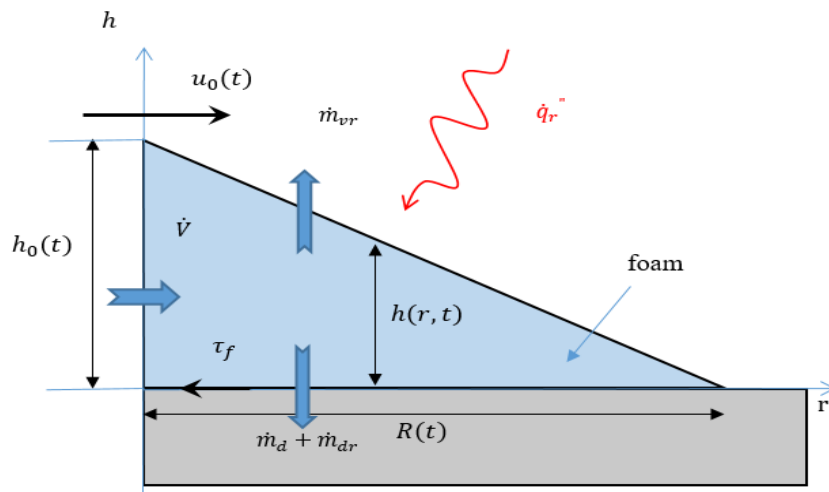
The study of fire extinguishing process of foam has been a top topic in recent years, because it help to comprehensively evaluate the fire extinguishing efficiency of foam. Williams et al. [2] indicated that the AFFF agent shows different extinguishing effect on over different burning liquid. Although fire suppression effect is much related to the flash point of fuel, the foam coverage area is the most critical factor. Persson et al. [3,4] considered the foam spread process and the foam mass loss due to fire heat radiation independently. The basic foam spread model over liquid surface was proposed. In our previous study [5], we continued to develop the axisymmetric spread model and measured the key parameters by carrying out experiment.

In this study, the model of AFFF spread over liquid surface was investigated, with the condition of external thermal radiation. Based on the axisymmetric foam spread theory, the foam loss under heat radiation was considered. Also, the experiment was carried out to simulate the actual extinguishing process of AFFF, to give reference to the spread model. This study can finally will provide further understanding of the AFFF foam spread in fire condition and contribute to fire suppression work using AFFF.

## 2. Axisymmetric foam spread theory

In the previous studies [5,6], the axisymmetric foam spread theory has been developed. When putting out the oil fire, AFFF was sprayed from the hose and spread start from a point source over the whole liquid surface. Therefore the foam spread process can be illustrated as Figure 1, and the AFFF spread model without external radiation can be expressed by Equation (1).





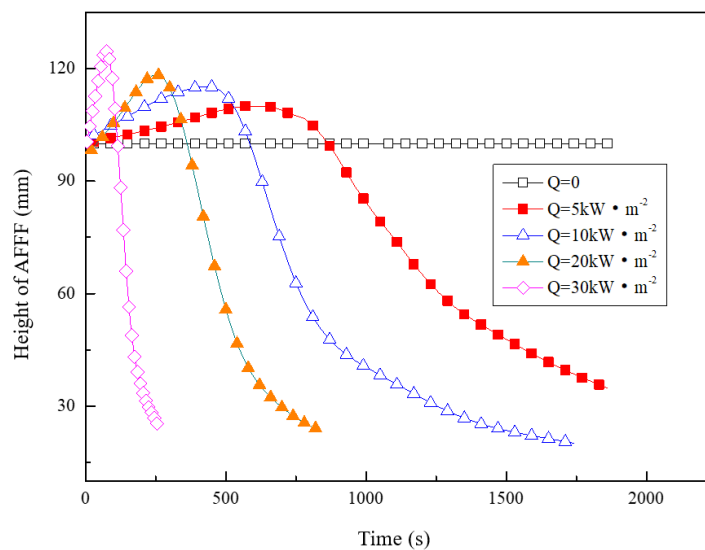
**Figure 1.** Illustration of foam spread process.

$$\begin{cases} h_0 = \left( \frac{27\dot{V}^3}{4\pi^3\beta^2R_0^2} \right)^{1/7} \cdot t^{1/7} \\ R = \left( \frac{18\beta R_0\dot{V}^2}{\pi^2} \right)^{1/7} \cdot t^{3/7} \end{cases} \quad (1)$$

Where,  $h_0$  is the foam thickness at the source point;  $R$  is the front radius;  $\dot{V}$  is the volume flow rate of foam;  $\beta$  is the friction parameter; and  $R_0$  is the initial radius of foam. Therefore, both the thickness  $h_0$  and the radius  $R$  grow as a power function over time  $t$ .

This axisymmetric foam spread model has been validated by a series of experiments in previous study. It is found that with the foam expansion about 10.0, the value of the parameter  $\beta R_0$  was calculated as  $2.06 \times 10^{-5}$  m/s. With determined foam flow rate  $\dot{V}$ , the relationship foam coverage area and time can be expressed as

$$A = 0.0033[10^{-24/7} \times (\text{m/s})^{2/7}] \dot{V}^{4/7} t^{6/7} \quad (2)$$



**Figure 2.** The height of AFFF under the condition of different external thermal radiation fluxes. ( $S = 13.5$ ,  $h = 100$  mm).

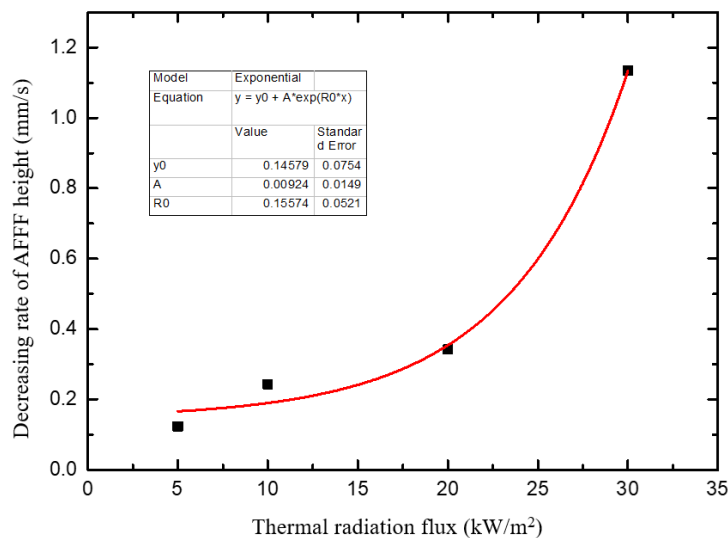
### 3. Radiation flux and foam thickness

In the case of external fire source radiation, the water in the foam can gradually evaporate after being heated, and the foam accelerates to collapse, thus reducing the thickness of the foam layer.

Wu et. al. studied the characteristics of typical AFFF under the condition of external thermal radiation. Figure 2 shows the change rate of AFFF height with initial foam height of 100 mm and the foam expansion of 13.5. The external thermal radiation flux was set to be 5 kW/m<sup>2</sup>, 10 kW/m<sup>2</sup>, 20 kW/m<sup>2</sup>, and 30 kW/m<sup>2</sup> respectively. It can be seen from the figure that, the decreasing rate of foam height varies greatly under different radiant fluxes.

After exposed to the thermal radiation, the foam will expand at first and the foam thickness will increase slightly. Then, due to the effect of evaporation and defoaming, the foam thickness starts to decrease rapidly. The maximum decreasing rate of foam height is obtained by differentiating the change of foam thickness, as shown in Figure 3. It is found by data fitting that, the maximum height decreasing rate of foam height presents an exponential relationship with thermal radiation flux, which can be expressed as Equation (3)

$$\left(\frac{d\delta}{dx}\right)_{max} = 0.0092 \cdot e^{0.1557q_r} + 0.1458 \quad (3)$$

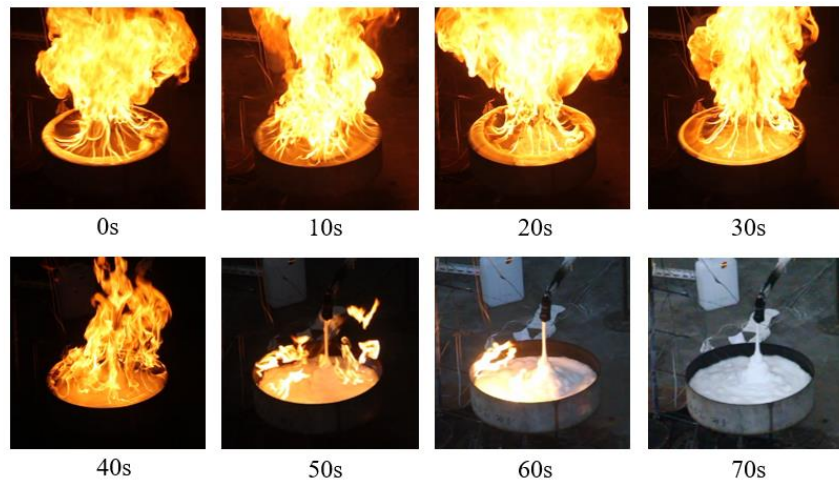


**Figure 3.** The relationship between decreasing rate of AFFF height and radiation flux ( $S = 13.5$ ,  $h = 100$  mm).

### 4. AFFF extinguishing experiment

In order to understand the actual process of AFFF extinguishing, the experiment was carried to put out a pool fire. The experiment simulated the case that foam injection from the central of the oil pan, which is similar to the real situation. In the experiment, the kerosene was used as fuel and 0.5 L heptane was used as the ignition agent. After ignition, it is ensured to have a one-minute-long pre-burning time, to generate a stable pool fire. After the pre-burning, AFFF extinguishing agent was sprayed on the oil pan.

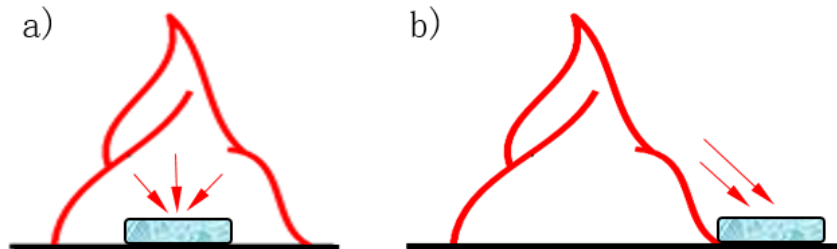
Figure 4 shows the process of AFFF extinguishing experiment, from the time when the AFFF was applied on the fire. It can be observed from the image that the foam began to accumulate in the central of the pan gradually, while the flame shape was not significantly affected. The phenomenon was similar to the flame aggregation of the ring oil pool fire. As the foam spread over the entire surface of the pan, the flame went noticeably weaker and gradually died out. It is also found from the results that, with the external radiation, it took far longer time for the foam spread over the entire liquid surface. It can be inferred that, the heat radiation reduced the thickness of the foam, so that the volume of foam decreased, thereby the spread speed of foam was reduced.



**Figure 4.** The process of AFFF extinguishing experiment ( $S=13$ ,  $\dot{V}=150$  ml/s).

### 5. AFFF spread model with external radiation

In order to obtain the model of foam weight, the radiation flux should be determined first. As the relative position of foam and the fire flame has a great impact on the radiation flux, it need to be discussed in several cases, as shown in Figure 5. When the foam is inside the fire flame, the flame shape will not be changed significantly as the experiment indicates. When the foam is outside the flame, the fire will be weakened as the foam spread and overlaps with oil surface.



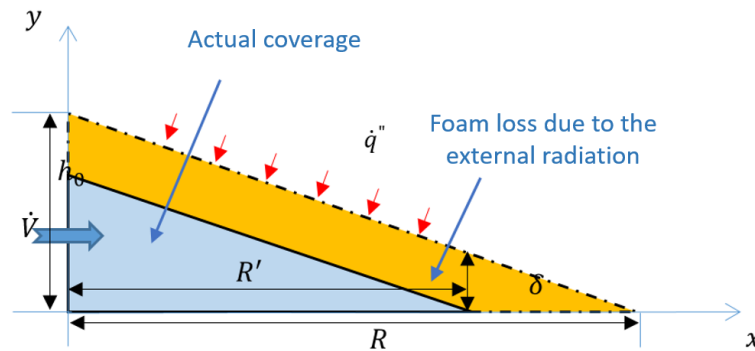
**Figure 5.** The relative position of fire flame and foam: a) inside; b) outside.

Using the solid flame model to calculate the fire radiation, it is calculated that view factor of fire flame to the foam surface can be expressed as Equation(4), with the cylinder flame shape assumed.

$$F_{\text{fire},H} = \frac{B-1/s}{\pi(B^2-1)^{1/2}} \tan^{-1} \left( \frac{(B+1)(s-1)}{(B-1)(s+1)} \right)^{1/2} - \frac{A-1/s}{\pi(A^2-1)^{1/2}} \tan^{-1} \left( \frac{(A+1)(s-1)}{(A-1)(s+1)} \right)^{1/2} \quad (4)$$

Where,  $s = L/R_f$ ,  $h = H/R_f$ ,  $A = (h^2 + s^2 + 1)/2s$ , and  $B = (s^2 + 1)/2s$ .  $L$  is the distance between the fire flame to foam front,  $H$  is the flame height, and  $R_f$  is the radius of fire flame.

Therefore, the model of foam loss can be obtained. The spread and the evaporation of the foam contribute to the increase of the coverage, and their dynamic balance determines the foam coverage area, as described in Figure 6. The spread model determines the maximum area that the foam is able to cover. When the foam is exposed to external radiation, the thickness reduction rate can be calculated by this foam loss model. The actual foam coverage area can be obtained by subtracting the radiation loss area from the total foam area calculated from the axisymmetric spread model.



**Figure 6.** Illustration of foam spread process with external radiation.

It can be inferred from Figure 6 that, the key to solving the foam coverage area under external thermal radiation is to calculate the foam radius where the foam height is  $\delta(t)$ . And, this  $\delta(t)$  is directly related to the reduction rate of foam layer thickness at this location, which can be expressed as

$$\delta(t) = (0.0092 \cdot e^{0.1557\dot{q}_r''} + 0.1458) \cdot t \quad (5)$$

For the case of both effects from foam spread and external thermal radiation, it is considered that the thermal effect can be calculated from the actual foam coverage radius  $R'(t)$ .

$$R'(t) = R(t) - \frac{R(t)}{h_0(t)} \delta(t) \quad (6)$$

Thus, substituting the Equation(1), the actual foam coverage radius  $R'(t)$  can be written as

$$R'(t) = \left(\frac{18}{\pi^2} \beta R_0 \dot{V}^2\right)^{1/7} \cdot t^{3/7} - \left(\frac{8}{3} \pi \beta^3 R_0^3\right)^{1/7} \cdot \dot{V}^{-1/7} \cdot t^{2/7} \delta(t) \quad (7)$$

If the foam injection is stopped, the only condition will be the thermal radiation. Assuming that previous foam injection time is  $t_0$ , similarly, the  $R'(t)$  can be described as

$$R'(t) = R(t_0) - \frac{R(t_0)}{h_0(t_0)} \delta(t) \quad (8)$$

Substituting the Equation(1) into Equation (8), the actual foam coverage radius  $R'(t)$  can be obtained, thereby the actual foam coverage area can be calculated by  $A' = \pi R'^2$ .

$$R'(t) = \left(\frac{18}{\pi^2} \beta R_0 \dot{V}^2\right)^{1/7} \cdot t_0^{3/7} - \left(\frac{8}{3} \pi \beta^3 R_0^3\right)^{1/7} \cdot \dot{V}^{-1/7} \cdot t_0^{2/7} \delta(t) \quad (9)$$

## 6. Conclusion

The model of foam loss under external thermal radiation is focused on in this study. By analysing the experimental data of foam thickness change under thermal radiation, the relationship between foam thickness reduction rate and radiant flux is obtained. Finally, the actual AFFF spread process under external thermal radiation is modeled based on the cylindrical flame radiation theory. Taking into account both foam spread and foam loss under external thermal radiation, the fire extinguishing effect of AFFF is determined. It is believed that the results of this study can provide theoretical guidance for fire suppression using AFFF, especially in calculating the amount of extinguishing agent in different fire scenarios.

## 7. Reference

- [1] Kuchta, Joseph M., and Robert G. Clodfelter. Aircraft mishap fire pattern investigations. GREEN
- [2] Williams, B. A., Sheinson, R. S., & Taylor, J. C. (n.d.). Regimes of Fire Spread Across an AFFF-Covered Liquid Pool, 1–10.

- [3] Persson, B., & Dahlberg, M. (1994). A Simple Model For Predicting Foam Spread Over Liquids. *Fire Safety Science*, 4, 265–276.
- [4] Persson H., "Fire Extinguishing Foams - Resistance Against Heat Radiation", SP Report 1993-54, 1993.
- [5] Wang, B. W., Huang, S. S., He, Q. Z., & Lu, S. X. AFFF Spread Over Liquid Surface with Different Foam Expansion. *Materials Science and Engineering*, 10, 9789813226517\_0160.
- [6] Dahlberg M., "Foam Spread Experiments on a Liquid Surface", SP Report 1994: 16, 1994