# A Theoretical and Experimental Study of Extinguishing Compressed Air Foam upon n-heptane Storage Tank Fire with Variable Fuel Thickness

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## Abstract

Compressed air foam (CAF) was widely used as a cleaner fire extinguishing technique since the banning of halogen-based agents for environmental reasons. In this work, its extinguishing behavior upon a radiation-controlled storage tank fire was firstly investigated based on the controlling mechanism of burning rate. A formula of burning rate after foam discharge is deduced. It was found that the oleophobic effect of fluorocarbon surfactants, the increased foam layer thickness and less diffusion coefficient had coupled chemical and physical effects on extinguishing. Due to the properties of CAF, a special phenomenon of the sudden increase of the flame temperature and radiation after foam discharge was observed and analyzed. A concept of effective and total extinguishing time was suggested, both of which decreased with the increased foam flow rate, but the decrease rate reduces at higher flow rate. For the case of lower fuel thickness, its burning rate was lower and the extinguishing time was longer. The foam dosage with flow rate at total extinction had a 'U' type map. Thus, there is an optimum point, where the foam dosage is the lowest with a moderate less total extinguishing time, which has an important implication for firefighting applications.

**Keywords:** Compressed air foam, Foam spreading, Stagnant layer modelling, Effective and total extinguishing

## Introduction

Foam extinguishing is a problem of particular interest since the banning of halogen-based agents for environmental reasons. Halon fire extinguishing agents are halogenated alkanes compounds which can destroy the ozonosphere [1]. Therefore, the study of high efficiency and environment-friendly fire extinguishing technology is important in the field of environmental protection. The traditional foam system using aspirating-type nozzles have several potential limitations, such as poor foam quality and low discharge momentum. But for the CAF, with the advantages of high efficiency, stability, less water consuming and environmental friendliness, it was widely used for the extinguishing of fires as a cleaner extinguishing technique. A large number of studies have been performed on the characteristics of the foam extinguish the liquid pool fires [2-4]. Previous studies have focused on the foam characterization and the extinguishing efficiency under different foam flow rate, but underlying causes were rarely analyzed. In this work, the extinguishing behavior of CAF-AFFF upon a radiation-controlled storage tank fire with varied foam flow rate and different fuel thickness was firstly investigated based on the controlling mechanism of burning rate. The temperature and radiation variation, extinguishing time and mass loss rate were studied through these well-designed tests, in which the burning characteristics after foam discharge were studied. The research results are vital to the optimization design of environment-friendly fire extinguishing technique, and are helpful to understand the foam extinguishing mechanism and efficiency upon the storage fires.

## Theoretical modelling

Here, we try to derive a simple model of burning rate, in a qualitative way, to investigate the individual effect of the foam thickness, fuel diffusion, heat transfer and oxygen concentration upon the inhibiting ability of the foam based on a stagnant layer model [5].

$$\dot{m}_f''L = \frac{\rho D}{\delta}\left[\frac{Y_{O_2,\infty}\Delta h_c}{r}(1 - X_r - X_F) - c_p\left(T_v - T_\infty\right)\right] + \dot{q}_r'' + \dot{q}_e'' - \sigma\left(T_v^4 - T_\infty^4\right) - \dot{m}_{F,dis.}''(1 - X_{resid.} - X_{drain.})L_F \qquad \text{(Eq. 1)}$$

where, $\dot{m}_f''$ is the fuel mass loss rate, $L$ is the fuel's heat of gasification, $\rho$ is the density, $D$ is the diffusion coefficient, $\delta$ is the fluid-dynamical boundary layer, $\Delta h_c$ is the heat of combustion, $r$ is the stoichiometric mass ratio of oxygen to fuel reacted, $X_r$ is the radiation fraction, $X_F$ is the foam heat loss in the flame as a fraction of flame energy, $T_V$ is the vaporization temperature, $T_\infty$ is the ambient temperature, $\dot{m}_{F,dis.}''$ is the foam discharge rate, $X_{resid.}$ is the residual foam fraction, $X_{drain.}$ is the foam drainage fraction, $L_F$ is the heat of gasification of the liquid phase of the foam. $\dot{q}_e''$ is the external radiant heat flux from the wall, $\dot{q}_r''$ is the flame radiant flux. Thus, the AFFF impedes the fuel transportation and inhibits the burning rate by the coupled chemical and physical effects. Larger boundary layer thickness, less diffusion coefficient, greater oxygen displacement via foam vapor formation, causing decrease in burning rate in joint efforts.

## Experimental setup and methodology

Experiments were performed with n-heptane tank fires under an exhaust smoke collecting hood. N-heptane was contained in a circular steel tank, 40 cm deep, with a diameter of 50 cm. The foam was discharged vertically at the edge of the tank from a nozzle with an inner diameter of 3 cm. Then the fuel in the tank was filled up to 30 cm or 15 cm in fuel height (containing the water thickness of 3 cm). As shown in figure 1, thermocouples were used to measure the temperatures at different locations. Heat flux sensor was placed outside the oil tank to measure the heat flux during the experiments. Cameras were used to record the flame and foam.

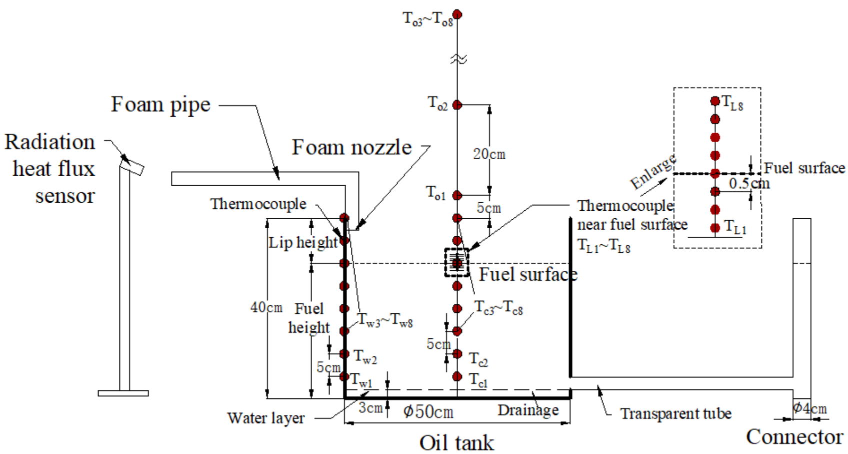


Fig. 1. Schematic illustration of the experimental setup.

## Temperature and radiation

As shown in Fig. 2, the initial decline in the flame temperature results from the discharged foam covering part of the fuel surface. The bursting of bubbles created by foam tends to increase the oxygen concentration, which has a promotional effect on combustion efficiency. The increase in the flame temperature can be explained by the relationship between the pool fire temperature and oxygen concentration as follows

$$c_p\left(T_{flame}-T_\infty\right)=\frac{Y_{f,0}\left(1-X_r-X_F\right)\Delta h_c-L_m+c_p\left(T_v-T_\infty\right)}{1+rY_{f,0}/Y_{O_2,\infty}} \quad \text{(Eq. 2)}$$

Where the temperature is proportional to the oxygen concentration. On the other hand, the application of foam increased the air entrainment and flame oscillation frequency, so the chemical reaction increased.

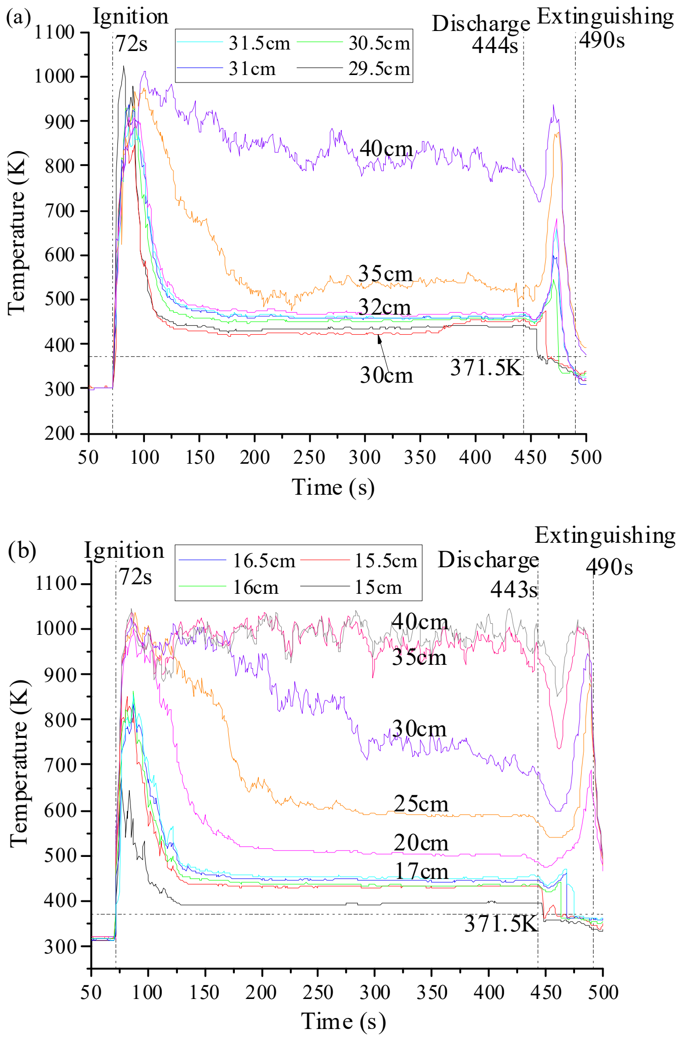


Fig. 2. Variations of the axial temperature (K) with foam flow rate at 10 L/min at different fuel thickness: (a) flame temperature above the fuel surface with fuel thickness at 27 cm; (b) fuel thickness at 12 cm; (where the labeled height is the vertical distance of the thermocouple from the tank bottom).

In the Fig. 3, there is a significant increase of the flame radiation. It is mainly attributed to the expansion of flame volume and increased gas-vapor mixture concentration based on $\dot{q}_r'' = k_{ext} f_v l_m \sigma T^4$. Where, $f_v$ is the gaseous mixture concentration, and $l_m$ is the optical extinction length [6-8]. With continuous foam discharge, an increase in the boundary layer thickness and decrease in the diffusion coefficient reduce the burning rate as shown in Eq.1. A decrease in the burning rate reduces the feedback of heat to the foam and fuel surface and the promotion effect of the bubble burst decreases, and the burning rate thus decreases drastically and all temperatures and the radiation levels decrease rapidly.

Thus, in the process of firefighting, we should pay attention to the increase in temperature and radiation, and correctly assess the thermal damage during fire extinguishing. It is important for protecting the safety of personnel and equipment.

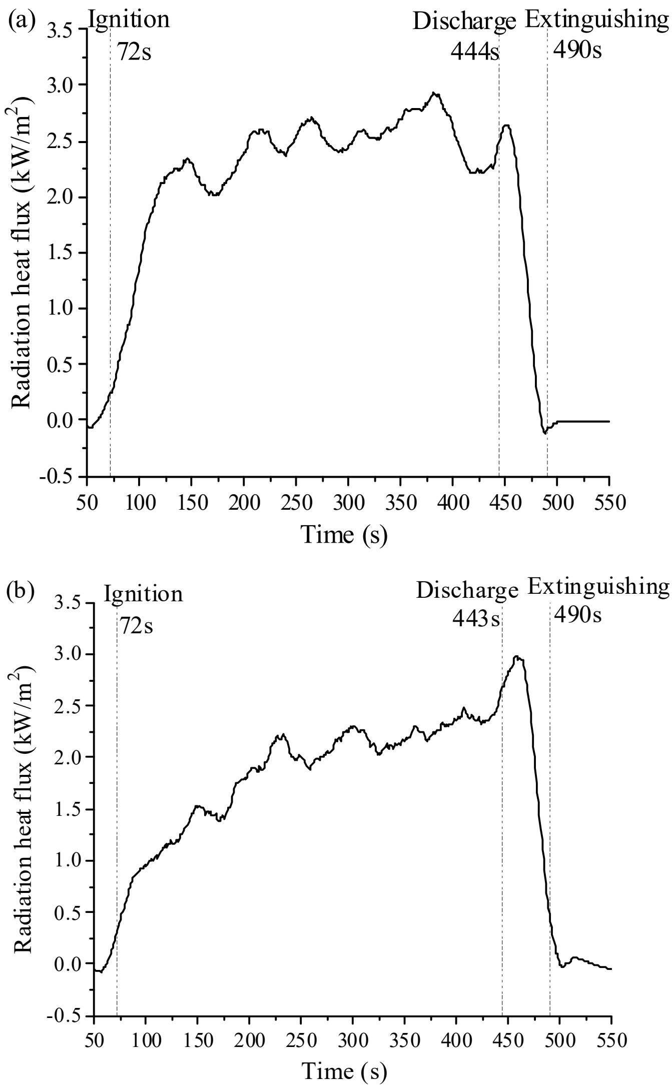


Fig. 3. Variations in the radiation heat flux (kW/m$^2$) recorded by the target receiver for a foam flow rate of 10 L/min: (a) fuel thickness of 27 cm and (b) fuel thickness of 12 cm.

**Mass loss rate and extinguishing time**

A point model was employed, that the flame was approximated by a point usually located at the centroid of the flame while the radiation from the point source was assumed to be isotropic. This is reasonable in our experiments owing to the distance between the radiometer and flame center being five times the pool radius [9]. The mass flow rate is therefore calculated according to

$$\dot{m}_f = \frac{\dot{q}''_R \cdot 4\pi R^2}{X_r \Delta h_c \cos\phi} \qquad \text{(Eq. 3)}$$

Where $\dot{q}''_R$ is the heat flux measured by a radiometer at a distance $R$ from the point source, $\phi$ is the angle formed by the normal to the gage surface and the line of sight to the point source, and $X_r$ is the radiation fraction, assumed to be a constant of 0.3 [10].

Figure 4 shows variations in the mass loss rate of fuel after the discharge of foam. It is seen from the figure that the burning rate first increases briefly and then decreases. And it decreases more rapidly for a higher foam flow rate. This is because, according to Eq.1, an increase in the discharge of foam strengthens the oleophobic effect of fluorocarbon surfactants, increases the boundary layer thickness, and decreases the diffusion coefficient. The burning rate thus decreases rapidly, corresponding to shorter effective and total extinguishing times as shown in Fig. 5.

The effective extinction limit is defined as the lowest burning rate sustaining a small flame, which is about 10% of the initial value of the constant burning [11]. The effective extinction limit is about 0.40 g/s for fuel thickness of 27 cm and about 0.37 g/s for fuel thickness of 12 cm. The total extinction time is defined as the flammability limit, which is a constant value for a fuel; e.g., it is 0.2 g/s for n-heptane. As Fig. 5 (a) shows, the effective and total extinguishing time reduce with the rising foam flow rate, but the decrease rate descends at higher flow rate. The reason is that, for a higher foam flow rate, more bubbles break and there is more entrained air that raises the oxygen concentration. As shown in Eq.1, the combustion efficiency increases and the burning rate increases, which diminishes the inhibiting effect of the foam to a greater extent

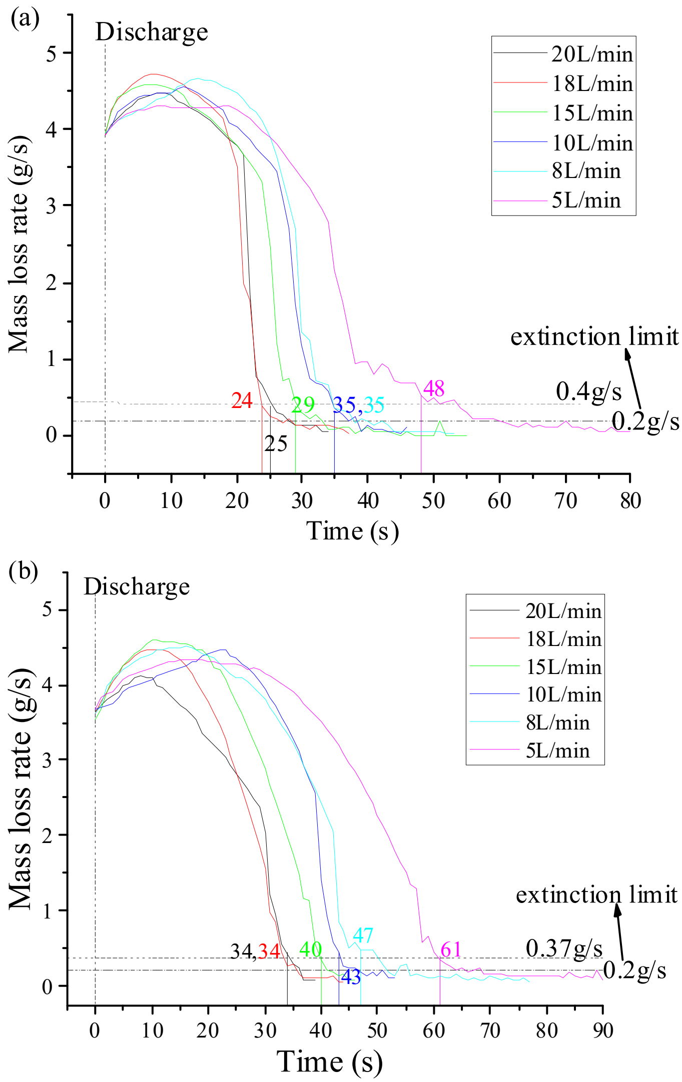


Fig. 4. Variations in the fuel mass loss rate (g/s) after foam discharge for various foam flow rates (L/min): (a) fuel thickness of 27 cm and (b) fuel thickness of 12 cm.

Fig. 5 (b) shows the effective and total foam dosage with foam flow rate, the foam dosage is the foam flow rate multiplied by the needed extinguishing time. It can be seen that, for the foam dosage of total extinction, there is a 'U' type curve. Thus, there is an optimum point, where the foam dosage is the lowest with a moderate less total extinguishing time, which has an important implication for firefighting applications.

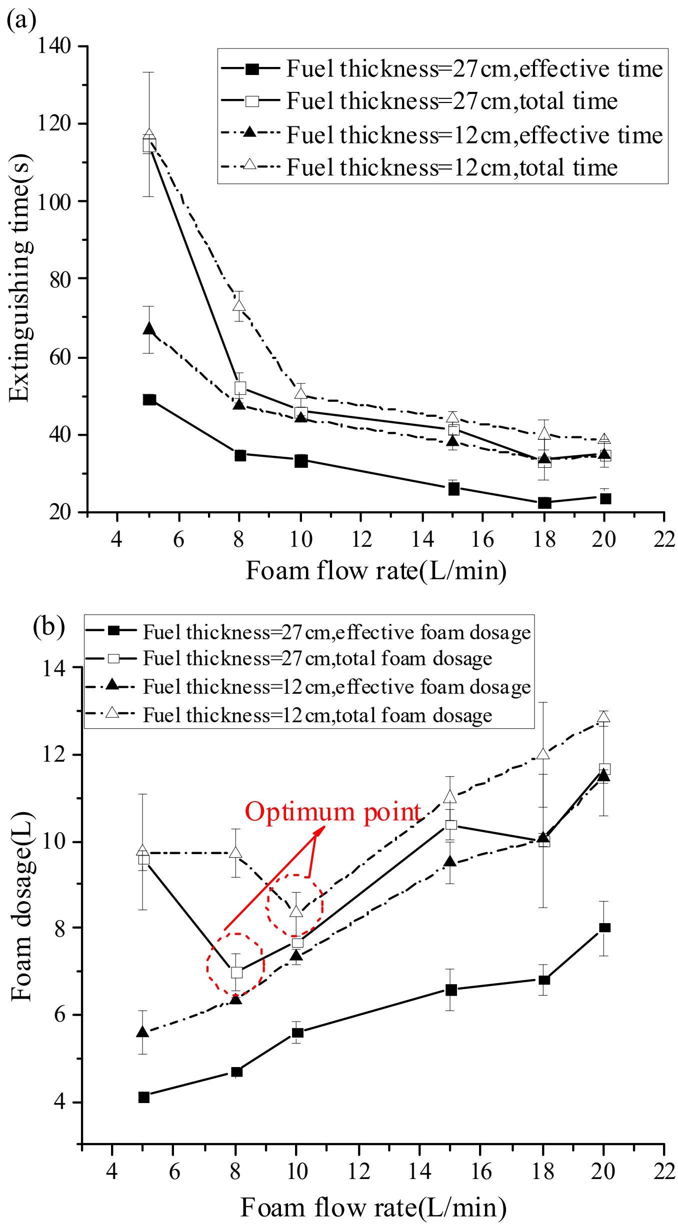


Fig. 5. Effective and total extinguishing times versus the flow rate (L/min) (a) and effective and total foam dosages (L) versus the foam flow rate (L/min) (b) with standard deviations.

For the case of lower fuel thickness, its extinguishing time was longer and foam dosage is bigger. For a lower fuel thickness, as there is more heat feedback from the flame and the tank wall, there is a higher evaporation rate of the foam and larger reduction of the foam layer thickness. As the promotion effect of the reduction of the foam layer thickness outweighs the inhibition effect of foam cooling on the fuel burning rate, it takes longer for the flame to extinguish. Thus, it also takes more foam dosage to put out fires.

## Conclusion

Equipment for the production of CAF-AFFF was proposed. The production was characterized and the extinguishing of a fire in an n-heptane storage tank was investigated. The research results are vital to the engineering application of CAF, and are helpful to determine the optimal engineering application parameters.

A deduced theoretical formula of the inhibited burning rate can be used for the analysis of the foam extinguishing mechanism qualitatively. The formula incorporates the fuel diffusion coefficient, boundary layer thickness, oxygen concentration, heat feedback, and foam evaporation rate. Experiments showed that, owing to the oleophobic effect of fluorocarbon surfactants, the greater thickness of the foam layer and lower diffusion coefficient have coupled chemical and physical effects, which have an important impact on fire fighting.

After the discharge of foam, there is initially a sudden increase in the flame radiation and then an increase in the flame temperature. The former is mainly attributed to the expansion of the flame volume and the increased gas–vapor mixture concentration, while the latter is due to the promotion of the combustion efficiency, induced by the large release of oxygen from broken bubbles of the CAF exposed to stronger flame radiation. The discovery of this phenomenon is of great significance to guide the safety of firefighting.

Both the effective and total extinguishing times decrease with the foam flow rate. However, the rate of decrease is slower at a higher flow rate owing to the bursting of bubbles and upholds combustion efficiency. The variation in the foam dosage with the flow rate at total extinction has a U-shaped curve, which is mainly due to the longer total extinguishing time at a lower flow rate. There is an optimum point having the lowest dosage and a moderate total extinguishing time. It is instructive for extinguishing fires.

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