Experiments and Theory in the Extinction of a Wood Crib

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ABSTRACT

Small scale extinction experiments and a theoretical analysis on the critical water application rate were performed using a wood crib fire and a water stream. Water was manually applied from the top layer to the lower layer or in reverse, and also with top layer variations of the initial degree of combustion to eluciate the effects of heat input to the wet surface. On the supposition that the extinction of the whole body follows fluctuation between local extinction and reignition, a dynamic equation was composed. The experimental results seemed to be in reasonable agreement.

INTRODUCTION

In order to extinguish a wood crib fire, it is necessary for water to be applied above the critical water application rate. Many precise investigations have been carried out on this subject, including those by Kung [1], Tamanini [2], Tyner [3], et al. [4,5]. A review of this past work is presented by Heskestad [6]. In his paper critical rates ranging from 1.3 to 3.0 $g/m^2 \cdot s$ are presented depending on the wood species, geometry and percent preburn. Magee and Reitz's work [7] on the extinction of plastics fires under the influence of radiation seems to suggest a similar effect as on wood fires. Fuchs and Seeger's theoretical work [8] seems to indicate that the heat falling onto the fuel surface is constant throughout the whole extinction period. Also in reviewing the previous research and Usui's [9,10] experimental data on the relationships between reignition time and the water content in the char layer of the wood ember, the author obtained a simple theoretical formula [11] which following further experiments was revised to fit a wide range of heating temperatures [12,13].

The primary aim of this paper is to try to give a more fundamental and universal principle for extinction based on the dynamism between reignition and local extinction. As may be seen in big scale fires or in small water application rates relative to fire objects, extinction seems to take place under a dynamic balance between local extinction in front of the nozzle and reignition after drying when the nozzle has moved on. No doubt the heat input onto the local extinguished area decreases as the remaining fire area decreases, and the longer the time it takes to suppress fire of the whole body, the more heat it receives. The time necessary for igniting the wet ember is dependent on the amount of the soaked water, and it is this time tolerance which makes the whole object capable of being extinguished.

The reignition time of the wet ember, τ, is correlated as a function of the heating temperature, T, the amount of water soaked, x, and the unique ignition time, τ_0, of the non wet charred wood as follows [12,13],

$$\tau \simeq \frac{L}{G\sigma T^4} X + \tau_0 \qquad (1)$$

Where, L is the heat required for vaporizing water from ambient temperature (620 Kcal/Kg), G is the overall heat absorption coefficient, σ the Stefan-Boltzmann constant.

Then the above said condition for total extinction can be expressed as,

Reignition time $\geqq$ Time required for sweeping the whole object. (2)

Because τ_0 is a complex function of the degree of carbonization and the heating condition etc., and since it is relatively short if the heating temperature is high [13], we eliminate it as a first step and approximate as,

Drying time $(Lx/G\sigma T^4) \geqq$ Time required for sweeping the whole object. (3)

The author has already applied this dynamism for the extinction of a room fire and compared it successfully with the past data [14]. They will be presented elsewhere with other mechanisms of extinction.

EXPERIMENTAL APPARATUS AND PROCEDURE

Wood cribs were made of Japanese cedar (density, 0.4 ~ 0.5 g/cm^3) with a moisture content of 9 ~ 13 percent. The stick size was 3 cm. square × 21 cm long and the cribs were arranged in four sticks per layer, and there were eight tiers. The crib was placed on a netted steel frame with four legs and put on a platform type load cell. The whole experimental assembly is shown in Fig. 1. The weight change during the burning and extinction process was also recorded.

The water was manually applied from a glass-capillary. The stream was a thin cylindrical jet of moderate speed. It was directed towards the inside surfaces from grid-window openings. It could easily reach deep into inside surfaces. This jet was moved as smoothly as possible from one window from the same level to another, and then to the upper or lower level, depending on the method used. The water flow rate was adjusted by keeping the height from the water surface in a tank to the capillary tip nearly constant. The fluctuation of the flow rate by changing the tip height in the range of the crib height was measured, and was very small. The application of the water was started when the crib weight diminished to a pre-determined weight.

Extinction was judged to have been reached when all the glowing of the charcoal disappeared. And it was considered inextinguishable once the enlargement of the wet area seemed to stop. At this stage, the balance between the extinguished and the burning area was kept for a short time, although water was continually applied. After a time, the balance was destroyed and glowing material was scattered into the extinguished area and the recession of the extinguished area advanced and fell uncontrollably.

Reignition takes place after the drying by radiation from flames and from glowing hot char surfaces. Because flames move only upward, the type of
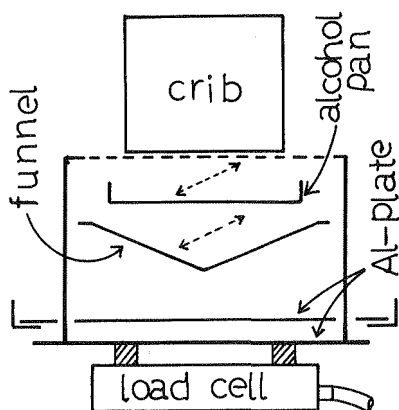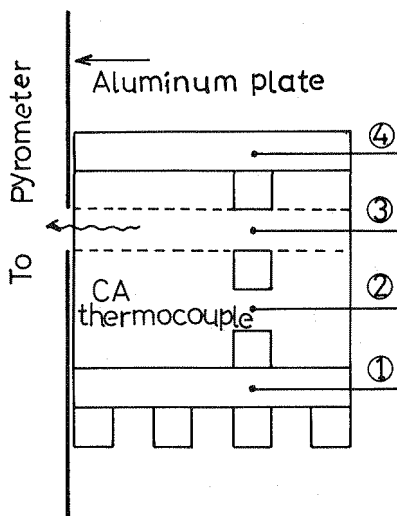
Fig. 1 Experimental assembly.

Fig. 2 Set up for measuring heat flux from window and temperature in the crib.

radiation must differ depending on whether the water is applied from the bottom towards the top or from the top towards the bottom. To make this mechanism clear is another objective.

We have to apply much water to the surfaces extinguished at an earlier stage. At present, this is done empirically, and thus reignition occurred sometimes. In that case, the jet was quickly directed to extinguish and to cover the shortage of the water. The jet was then restored to its former position.

For the purpose of providing a basis for the theoretical analysis, the radiation intensity from the horizontal grid-window and the temperature in it were also measured. An aluminum plate of the size 0.1 × 50 × 50 cm with a 3 cm square window was pressed closely onto one side of a crib. An outline of the set up is shown in Fig. 2. The plate was arranged so as to shield excessive radiation to the pyrometer from flame and crib surface, but not from the window. A pyrometer was placed on the axis of the window at a suitable distance. The crib was placed on a load cell, as shown in Fig. 1. The weight and temperature change in the grid were correlated with heat flux.

RESULTS AND DISCUSSION

Thermal Radiation from the Crib

In this theory, the author assumes black body radiation from the wall and from the flame, irrespective of thickness. In the case of a wood fire where the hot flame heats up the char surface and makes it glow, these will not separated.
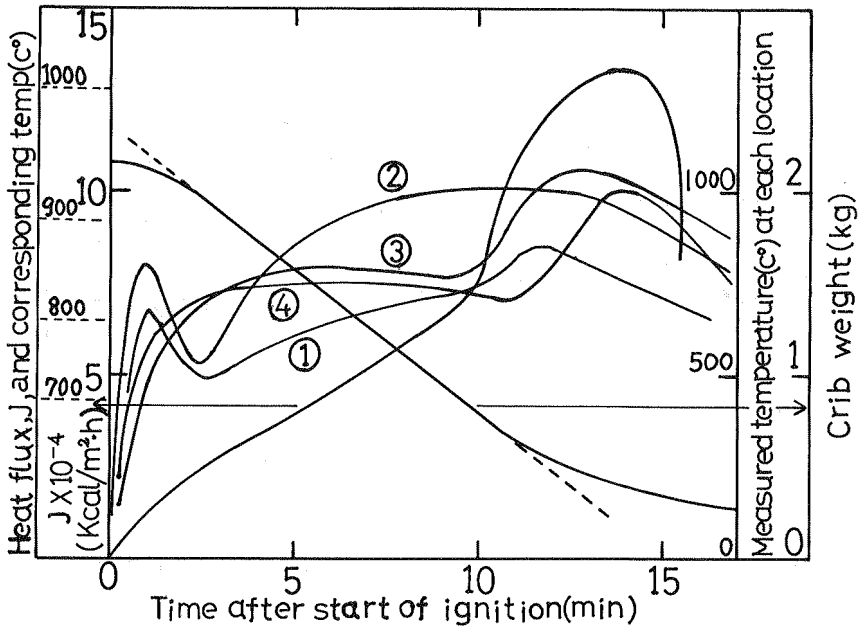
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Fig. 3 Heat flux, temperature and weight change versus ignition time.

While it is not the aim of this paper to discuss this, it does try to define the overall intensity of radiation from the horizontal shaft window in order to contribute to the analysis of the following Case-1 and Case-2. As seen in Fig. 3, the temperature and the radiated energy from the third window coincide well if we assume black body radiation in this window space. In fact, the intensity is a function of shaft depth, although the maximum depth must be very short as seen in the experiment in Fig. 3. The threshold depth for giving black body radiation must be somewhat shorter than 21 cm for this geometry. As seen in Fig. 3, the radiation intensity increases as the burning time continues, and shortly before the end of pyrolysis, the intensity and temperature increase sharply. This indicates the shifting from flaming gas combustion to glowing surface combustion. It is not difficult to imagine that the critical water application rate should also vary in accordance with the burning degree.

Table-1 Observed critical water application
          rate, W, (g/min)

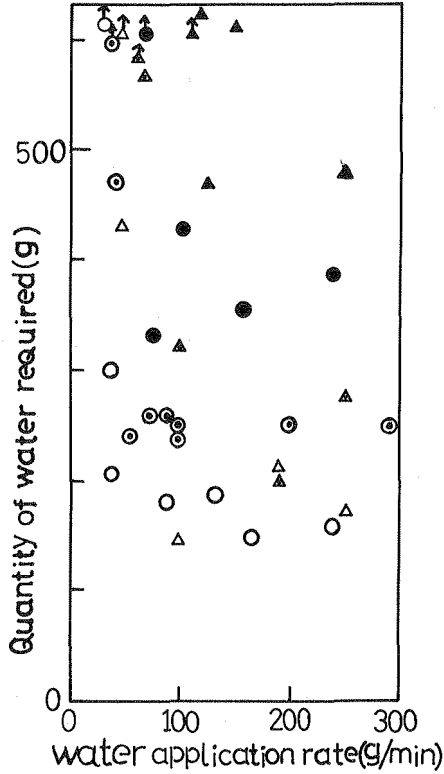| Application method	Initial mass loss ratio $\phi = (M_0-M)/M_0$		
	0.2	0.4	0.6
Bottom to Top	35	40	72
Top to Bottom	47	65	114

Fig. 4 Necessary amount of water
versus application rate for extinction

Arrow mark indicate inextinguishable.

ϕ	0.2	0.4	0.6
Bottom to top	○	◉	●
Top to bottom	△	⬬	▲

Experimental Results and Theory on the Critical Water Application Rate

The quantity of water (or the time) necessary for extinction versus the application rate as a function of the application method and the initial combustion rate, ϕ, is illustrated in Fig. 4. The burning degree, ϕ, is defined as $\phi = (M_0 - M)/M_0$, where M_0 is the initial crib weight and M is the weight at the beginning of water application. The critical application rate, W, was extrapolated from Fig. 4 and listed in Table-1. The critical rate is quite distinct. Above this point, as seen in Fig. 4, the necessary quantity for extinction is relatively constant depending on the method, but it sharply increases as it nears the critical rate almost vertically, so as to enable its definition within a very narrow range of accuracy. The constancy of the necessary quantity of water above the critical rate depends on, ϕ, and the application method. This

type of constancy is described in another paper by the author [15] and can also be seen in Tyner's experiment [3].

As seen in Fig. 4 and Table-1, more difficulty was observed (1) when the water was applied from the top downwards than from the bottom up, and (2) when the combustion degree increased.

The inner surface area (neglecting the vertical side wall) of this crib is about 0.5 m^2. So the critical rate may be converted, if like Heskestadt, we adopt the conventional expression by dividing the value in Table-1 by 0.5 m^2, to obtain 1.2 ~ 3.8 g/m^2·s. This value agrees with the previous works cited by him (1.3 ~ 3.0 g/m^2·s). Here again, the noteworthy facts are that this value depends on the application method and burning degree.

Theoretically, this critical rate can be derived as follows. Figure 5-(a) is a sectional plan of a crib with an enlarged vertical shaft. For the ease of computing heat transfer, let us assume that the vertical shaft is close to the cylinder, as shown in Fig. 5-(b). First we consider step by step the case when the water stream is applied horizontally from the bottom upwards. Because the flame moves from the burning area upwards, the wet shaft wall receives heat from the upward flame and from the glowing surfaces, as shown in Fig. 5-(b), through radiation only.

Deciding upon the proportion of heat from the flame and from the wall is very difficult, but at an early stage, the proportion from the flame must be bigger than at the final stage where the charcoal begins to glow. Fortunately according to computations, these discrepancies seem relatively small. In this paper two simplified cases, one where a flame does not exist and two where a flame exists and is dominant, are assumed and calculation of heat transfer was made as follows.

Case-1; Radiation from Hot Wall Only

The heat, H, input to the wet wall-1 was assumed irradiated from the hot wall-2, then,

$$H = JA_2F_{21} \tag{4}$$

where J is the heat flux from wall-2, A_2 is the surface area of the hot glowing wall-2, F_{21} is the configuration factor from wall-2 to wall-1. And because,

$$A_2F_{21} = \frac{A_0}{2r^2}\left[s\sqrt{s^2 + 4r^2} + h\sqrt{h^2 + 4r^2} + 2Sh - \ell\sqrt{\ell^2 + 4r^2}\right] \tag{5}$$

Then the maximum quantity of heat input to wall-1 is when the wet area occupied one half of the total.

$$(A_2F_{21})_{max} = \frac{\ell}{4r^2} A_0\left[\ell + \sqrt{\ell^2 + 16r^2} - 2\sqrt{\ell^2 + 4r^2}\right] \tag{6}$$

Then,
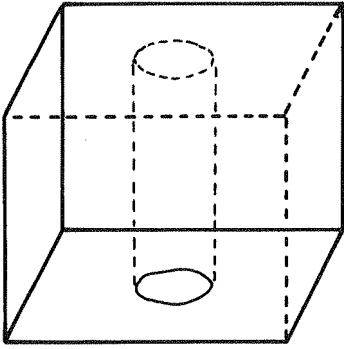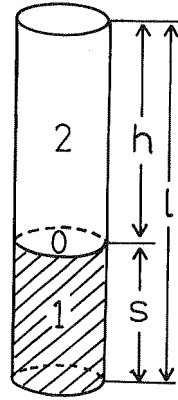
Fig. 5-(a) Crib with vertical shafts.

Fig. 5-(b) Cylindrical shaft model.

$$H_{max} = J(A_2 F_{21})_{max} \tag{7}$$

Here from Eq. (3), we have obtained the suggestion that the primary condition for extinguishing the whole object is to sweep the whole body before drying. This idea may be expressed as an energy relationship. Then the critical water application rate, w, is obtained as the rate which can remove the maximum heat from the wetted surface by evaporating. When $(r/1)^2$ is small enough,

$$w = \frac{H_{max}}{L} \approx \frac{J}{L} A_0 \tag{8}$$

Where A_0 is the horizontal sectional area of the shaft and 1, s, h, are the crib, the wet-wall, the burning-wall height respectively.

Let's suppose for the heat flux, J, a value at 750°C ($\phi = 0.2 \sim 0.6$), which corresponds 891 Kcal/m^2·min, and putting the value, $A_0 = 9 \times 10^{-4}$ m^2, the critical application rate, w, per vertical shaft is then calculated from Eq. (8) as,

w = 1.29 (g/min per shaft)

In reality, the vertical shaft is not solely composed of wall, but there are also horizontal shaft spaces. All these inner wall surface areas were converted into that of a vertical shaft, and the equivalent number of vertical shafts was obtained. The total required critical rate, W, was obtained by multiplying A_0 by the equivalent shaft number (19.7) as,

W = 1.29 × 19.7 = 25.4 (g/min)

Referring this value to Table-1, the theoretical W is somewhat smaller than observed. Actually, some water must penetrate into the chink between layers and remain on the surface without contributing to extinction; it was applied in

vain. Besides, the combustion degree, or the heat intensity, increases as time goes on, especially as critical conditions are approached. There is no steady state burning, thus elevating the experimental value. Moreover, the temperature near the bottom of the crib is generally higher than the temperature near the top which makes it difficult to obtain an average. The heat flux in Fig. 3 seems to be a better index for predicting the critical application rate.

Case-2; Radiation from the Hot Wall and the Flame

In Fig. 5-(b), because the upward cylinder is filled with burning flames, the radiation from the vertical shaft space must be taken into account together with that from the wall. Then, we can assume the heat is radiated from the round ceiling surface-0.

Then we obtain in the same manner,

$$H = JA_0F_{01}$$

$$A_0F_{01} = A_0\left[1 - \frac{1}{2}\left\{2 + (\frac{\ell}{r})^2 - \sqrt{\left\{2 + (\frac{\ell}{r})^2\right\}^2 - 4}\right\}\right]$$

$$- \frac{1}{2} A_0 (\frac{\ell}{r})^2 \left[\sqrt{1 + (\frac{2r}{\ell})^2} - 1\right] + \frac{1}{2} A_0 (\frac{S}{r})^2 \left[\sqrt{1 + (\frac{2r}{S})^2} - 1\right]$$

And,

$$(A_0F_{01})_{max} = \frac{1}{2} A_0 \left[\sqrt{\left\{2 + (\frac{\ell}{r})^2\right\}^2 - 4} - (\frac{\ell}{r})^2\right]$$

So,

$$w = \frac{H_{max}}{L} \approx \frac{J}{L} A_0 \quad \text{(Per shaft)} \tag{9}$$

The required quantity, W, is the same as in Case-1. This H_{max} is attained when the extinguished wall-1 advances to the top of the crib.

As a matter of fact, the difficulty of extinguishing appeared when about one half of the height was suppressed; if it could pass this point, the total extinction seemed relatively easy. If it did not pass, the glowing combustion spots began to scatter around the lower portions and to fall uncontrollably. So case-1, where the radiation from the hot wall was assumed, seems more practical.

In the reverse situation when the water is applied from the top layer downwards, the wetted area is exposed to adjacent flame radiation as well as to the lower glowing surface throughout the extinguishing period, and receives more heat. Thus W must become somewhat larger than in the aforesaid case. This is obvious in Table-1. Exact computation for this case seems rather difficult, but the principle for extinction by the dynamism seems applicable.

If we want to obtain the critical rate, e, in the conventional form "weight per area per time" we merely need to divide Eq. (8) by the shaft wall area $2\pi r\ell$.

$$e = \frac{w}{2\pi r \ell} = \frac{Jr}{2L\ell} \tag{10}$$

When $r = \sqrt{9/\pi}$ (cm), $J = 891$ (750°C) - 1540 (900°C) (Kcal/m^2·min), we obtain from Eq. (10) as,

$$e = 0.85 - 1.5 \ (g/m^2 \cdot s)$$

Critical application rate per unit area is again a function of the inner heat flux, J. Referring to Fig. 4, Eq. (10) also seems to explain Table-1 well.

CONCLUSIONS

The critical water application rate was derived experimentally as well as theoretically for wood crib fire extinction. In order to make clear the mechanism of heat transfer from glowing wall and from flame, the water stream was applied horizontally from bottom layer to top layer and the reverse. The rate was precisely obtained empirically and it was found that it varied much depending on the burning degree and the method of applying the water. The rate increased as the burning degree increased and the bottom to top method required a smaller rate than the reverse case.

A theoretical analysis was also performed. When the application rate is sufficiently small and critical, the reignition speed competes with the suppression speed. Then the fundamemental condition for the total extinction can be defined as,

Reignition time $\geqq$ Time required for sweeping the whole object.

According to this definition, a dynamic formula for heat transfer was established, and the results seemed to agree reasonably well with the experiment and with past data. But this critical rate is theoretically a complex function of heat flux in the crib and the geometry and it is expressed by the dimension [MASS/TIME]. If we want to transform it into the conventional expression [MASS/AREA/TIME], we can obtain this by merely dividing it by the surface area in the crib.

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