Extinguishment Behaviour of Simple Burning Wood Cribs under the Action of Sprinkler Spray

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ABSTRACT

Extinguishment tests on simple vertically orientated burning wood cribs have been performed using varying quantities of water and varying water application rates. Extinguishment effectiveness has been measured by net sample consumption, and by measuring sample consumption rates during extinguishment using calorimetry of the CO_2 product gases. It has been shown that for a given quantity of water, the optimum fire fighting strategy is a fast release of water at a high flow rate, rather than a continuous release of water at a low flow rate. Extinguishment effectiveness has been correlated against the ratio of water application rate and mass burning rate, and the results are compared with findings of other investigators.

INTRODUCTION

In many cases, water damage caused by sprinkler application can prove more costly than the damage caused if the fire were left to burn to extinction. Therefore, methods are needed to determine the minimum amount of water required to extinguish a fire, as well as optimum strategy of water release.

Empirical work to date has centred on the important, but subtly different, study of determining the effect of water application rate on extinguishment. Kung and Hill [1] burnt wooden cribs composed of 17.5 mm thick spars, of three different heights. They were able to measure the rate of water application during each burn, and a ratio for its effectiveness in extinguishing the fire was defined. Tamanini [2] also conducted a study of crib fire extinguishment. He found that there was a minimum water flowrate required to save any combustible mass during extinguishment, at 0.15 mg/cm^2/s for openly packed cribs, and 0.3 mg/cm^2/s for densely packed cribs. Similar experiments have also been conducted by Unoki [3].

Tamanini [4], in a study on the extinguishment of small (191x279 mm) vertical slabs of wood, found the minimum impacting water flowrate to effect extinguishment was approximately 0.22 mg/cm^2/s. Takahashi [5] investigated the extinguishment of wooden cribs using a moving water source and concluded that extinguishment will occur only if the reignition time for the spars is greater than the time required by the water spray to sweep the whole crib. Lee [6] used calorimetry techniques [7] on large scale rack storage fires to determine burning rates during extinguishment under different water application rates. A similar power-law relationship between extinguishment effectiveness, burning rate, and water application rate was found to that of [1].

The purpose of the present work is to study the effect on extinguishment of varying the quantity of water and its application rate. To accomplish this, the amount of sample consumed during extinguishment of a simple wood crib fire is measured, for a range of water application amounts and rates. Also, by measuring carbon dioxide within the product gases, using a simple calorimeter technique, the burning rate during extinguishment is found.

This paper is an extension of an earlier study, which considered the extinguishment effec of varying the quantity of water on extinguishment at a specific flowrate. For completeness we include the experimental procedure and findings from that work, but more details can be found in [10].

EXPERIMENTAL METHOD

Layout and equipment

The experiments were conducted in a large fire gallery, measuring 5.4m wide and 2.4m high. The tunnel had a total length of 130 m with the tests being conducted 30 m from the entrance. Air flow through the gallery was controlled by an exhaust fan, and was measured using a fan type anemometer to be approximately 0.9 m/s. A screen installed upstream of the testing area reduced the air velocity in the vicinity of the sample to 0.6 m/s. Figure 1 shows the position of the sprinkler and sample within the gallery.

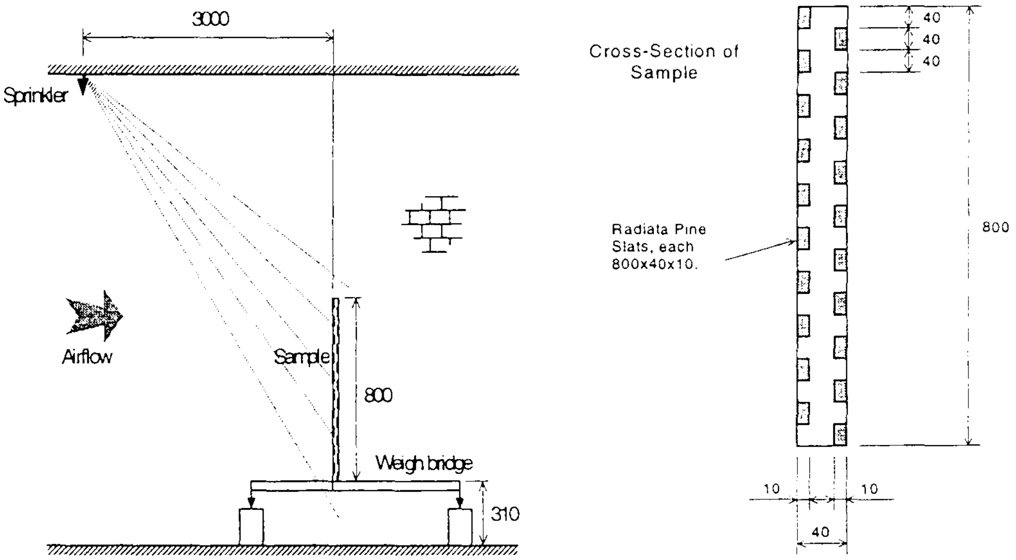

Figure 1. Side view of tunnel showing sprinkler and sample location; cross-section of sample.

The fuel sample was composed of 20 radiata pine slats, each measuring 12x40x800 mm. Simpler geometries, including large vertical slabs, were tried, but in those cases steady state burning could not be achieved reliably. Depending on the source of the wood and weather conditions, the moisture content of the wood after dressing could vary from 10% to as much as 50%. To achieve consistency, the samples were dried in a 60°C convective airstream for two days prior to burning, bringing their moisture content down to approximately 2%. In the short periods between drying and burning, the samples were stored in sealed bags containing anhydrous crystals.

Prior to testing, the samples were placed on a metal supporting frame, which in turn rested on three load cells. The frame included a porous tray resting under the wood, which caught any fragments of char falling from the sample during the final stages of the burn. The mass of the total system, sample, frame, tray and char was recorded by a datalogger at least once per second.

Extinguishment was accomplished by a ceiling mounted standard commercial fire sprinkler, namely a 'Wormald type A 15mm diameter spray pendant'. Water was fed from an external tank via a pump, and was controlled using an electronic timer connected to a solenoid. The flow was measured using a flow driven pulse generator, and the supply pressure was maintained at 350k Pa.

Different water flow rates were achieved by chopping the flow coming out of the nozzle. The chopper consisted of one or two thin metallic disks, each with two open sectors, which allowed flowrates ranging from full amount of water to one-quarter of the spray. The frequency at which the chopping device operated was sufficiently high to yield an effect on the burning surface equivalent to that due to a continuous water application. Full flow rate experiments were performed without a restrictor.

When the sprinkler was activated during the burn, water collected on surfaces of both the wood and the frame. Therefore, to determine the consumption rate of the sample during this period, CO_2 measurements were made and scaled against the mass consumption rate. The air flow through the gallery was channelled through two orifices 20 m downstream of the testing area, and from these well mixed flows, a continuous sample of product gas was analysed by an infrared gas analyser.

Thermocouples placed behind the sample recorded the air temperature, and a total heat flux meter fitted with a sapphire window, located two metres in front of the sample, recorded the radiative heat flux. The process was also captured on video.

Experimental procedure

Due to the geometry of the sample and direction of the water droplets, no water could pass between the wood slats without impacting the crib. Thus, the flowrate of water reaching the burning surface was measured by placing a collecting 'window' at the location of the sample, capable of catching any water that would normally impact the surface of the wood. This window was placed on the load cells, the sprinkler was run, and the rate of water collection found, enabling the impaction flow rate to be determined.

To enable consistent and uniform ignition, the samples were first heated by a radiative L.P.G. burner. This had the effect of bringing the temperature of the wood close to the pyrolysis point, and also of drying out any remaining moisture. No significant mass loss was found during this period, and heating ceased at the slightest visible sign of charring. Provided this condition was met, the time of 'warm up' had no effect on subsequent combustion. Ignition was achieved using a hand held, large diameter blow torch swept across the surface of the wood. After several minutes of warming, ignition by the blow torch was achieved in around one minute. A further 15s later, quasi-steady burning of the sample was accomplished.

Three different types of tests are considered in this paper. For the first type, no extinguishment was allowed, and the samples burnt to extinction. For the second, the sprinkler was activated at different restrictor opening ratios, and left on until sample extinguishment occurred. In the third series of tests, both restriction of the spray and the time of sprinkler activation were varied. In all cases, the time taken for extinguishment of flaming combustion was recorded.

After burning, the samples and any char were again dried over a two day period to establish the final sample mass.

A numerical transformation was developed to calculate the CO_2 production rate from the concentration of CO_2 as measured at the analysis point. Further, it was assumed that the level of CO_2 production was proportional to the mass loss rate of the sample, thus enabling the sample consumption rate to be determined during the extinguishment process. A complete explanation can be found in [10].

RESULTS AND DISCUSSION

Burning rate

Figure 2 shows the normalised sample consumption rates for six tests at a fixed water application rate but for varying quantities of water. The rates are normalised with respect to their initial burning rates,

$$\dot{m} = \frac{\dot{m}_s}{\dot{m}_{s,\max}} \times \dot{m}_{s,\max,av}$$

where, $\dot{m}$ is the normalised sample consumption rate,

$\dot{m}_s$ is the actual sample consumption rate during extinguishment,

$\dot{m}_{s,\max}$ is the actual sample consumption rate just prior to water application, and

$\dot{m}_{s,\max,av}$ is the average actual sample consumption rate over all tests just prior to water application.

In this figure, time zero marks the removal of the blow torch and the onset of self sustained burning. Until 20s, some tests show a higher level of consumption rate, a result of the action of the blowtorch during the ignition period. In the case of the extinguishment tests, water is applied at 60s for periods as indicated.

As shown in Fig 2., and from previous work [11], samples not acted upon by water burn at a steady rate of approximately 14 g/s for 100 s. From this point onwards, the rate decreases until extinguishment is achieved at roughly 450 s.

Following water application, all samples experienced a consistent fall in mass consumption rate while the water was acting, but if the sprinkler ceased, as in the part extinguishment cases, the fall relaxed noticeably. From there onwards, the rate approached zero in an almost asymptotic fashion.

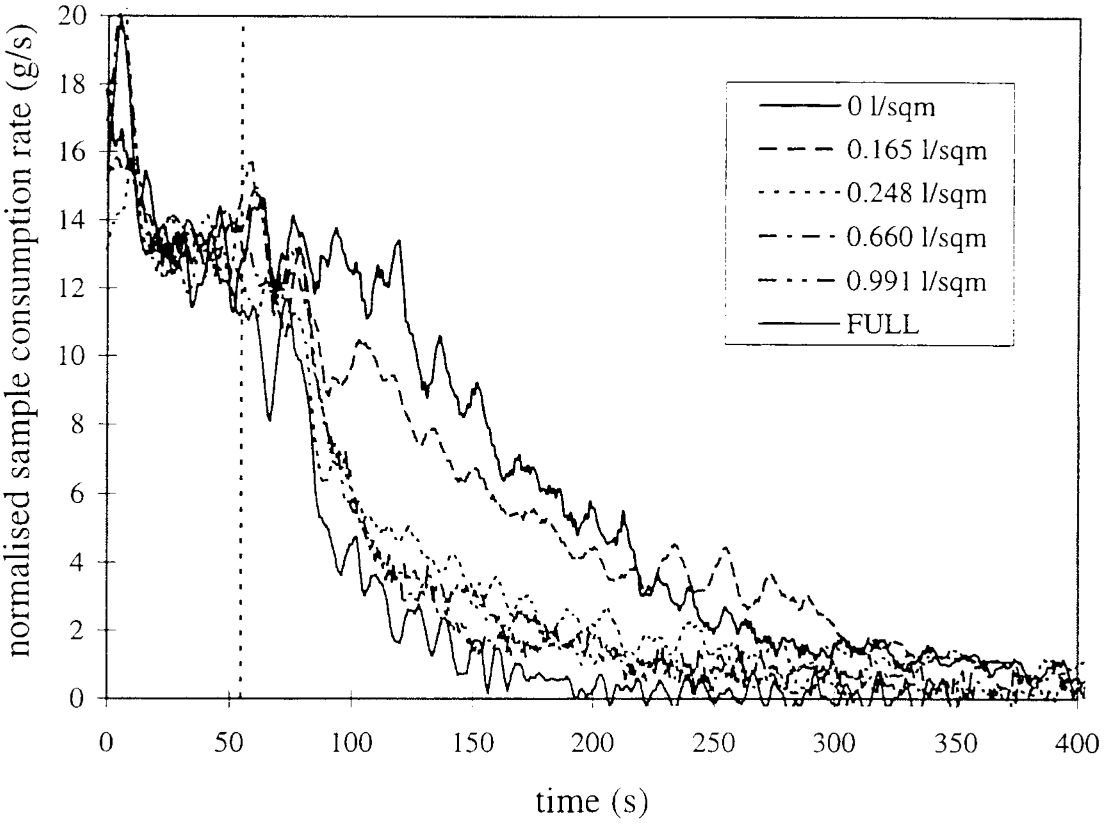

Figure 2. Sample consumption rates during extinguishment from carbon dioxide calorimetry for varying quantities of water application at a fixed application rate.

It was noticeable during the tests that combustion did not decrease immediately followin the application of the water spray. This phenomenon is supported by Fig. 2, which shows th the burning rate does not fall until approximately 15 s after sprinkler activation. This probably due to extra airflow created around the sample by the water spray, encouragin combustion by providing more oxygen to the surface of the wood. In addition, the water m take a significant amount of time to cool the pyrolysing portion of slats, as postulated previous work [11], because the slats are surrounded by a char layer of a few millimetres dep

It is interesting to compare the consumption rate of 10 s application (0.165 l/sqm, Fig. with the non-application test. While the rate in the 'dry' test is higher at first, after 250s th sprinkler test consumption rate is greater, suggesting that any remaining water has bee evaporated and the sample now has a greater proportion of wood left to burn.

Effectiveness ratio for full spray extinguishment tests

A comparison of the wood mass consumed during sprinkler operation versus the mass available for combustion at the onset of extinguishment is useful in that it indicates how effective the water is in extinguishing combustion. The following ratio has been adopted for this purpose from the work on crib and pallet fires [1],

$$R = \frac{m_i - m_f}{m_i - m_0 P_r}$$

where m_i is the sample mass just prior to sprinkler operation, or in the cases where no sprinkler is used, one minute after uniform ignition, m_f is the final sample mass after drying, m_0 is the initial sample mass at the onset of self sustained burning, and P_r is the mass fraction of non-combustible material in the wood.

The non-combustible mass fraction used was 0.226, determined by averaging the proportion of sample mass remaining in the three dry (non-extinguishment) tests. The amount of water used in each test was calculated from the product of the sprinkler activation time and the measured flow rate.

R is plotted against water application in Fig 3. For the tests with no spray restrictor (series 1, Fig. 3), R is approximately constant at unity between no water application and 0.25 $\mathrm{l/m^2}$. Thus, the water is totally ineffective at preserving any sample mass. Above this amount of water application, R decreases to approximately 0.2 under full extinguishment conditions. Thus, 0.25 $\mathrm{l/m^2}$ is a critical amount of water, under which the fire is capable of evaporating all impacted spray without altering the final proportion of mass burnt.

For a water application rate of 1.0 $\mathrm{l/m^2}$, the value of R is approximately equal to the value for full extinguishment tests. Thus, the extra 2-4 $\mathrm{l/m^2}$ of water applied in some tests does little to preserve the sample's mass. In a commercial fire situation, this excess water may cause significant fire damage, or if limited water supplies were available, reduce the effectiveness of the fire fighting operation.

The results have been fitted to the following exponential function [10], as shown in Fig. 3,

$$R = \begin{cases} 1 & \ldots\ldots \text{if } m \le 0.25 \\ 1.12 \exp\left(\dfrac{0.094}{m - 0.087}\right) - 1 & \ldots\ldots \text{if } m > 0.25 \end{cases}$$

where, m is the amount of water applied ($\mathrm{l/m^2}$).

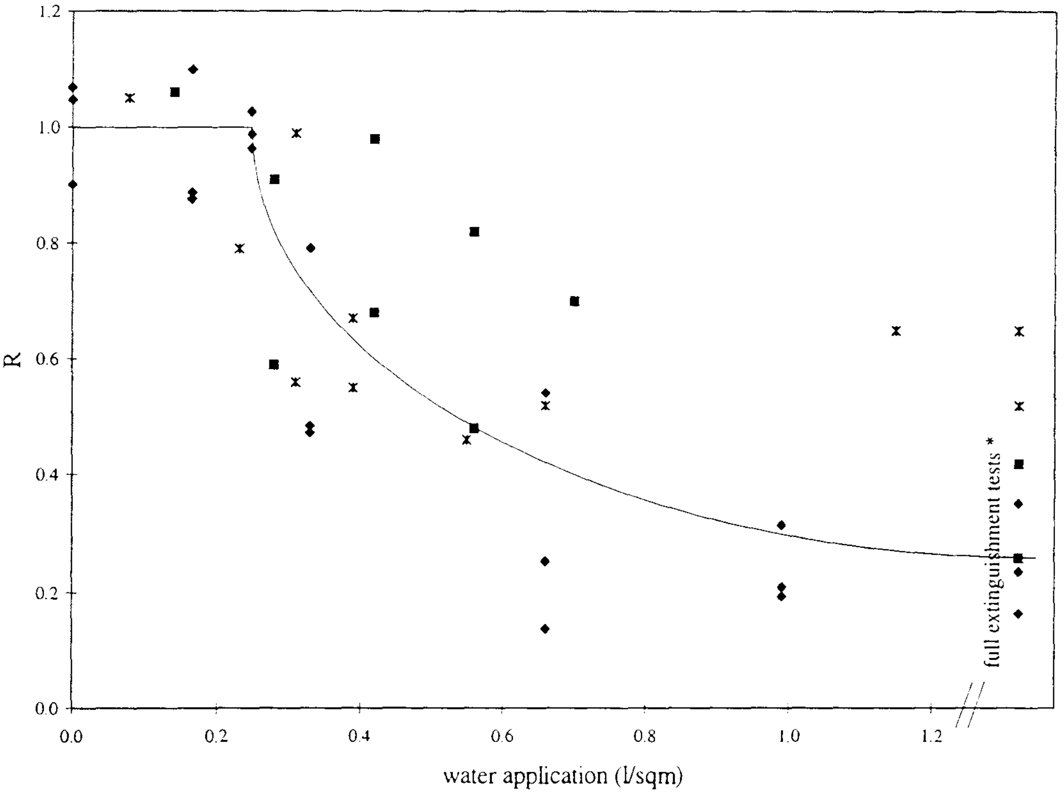

Figure 3. Effectiveness of extinguishment for varying quantities of water application.

* - the total water application amounts for the full extinguishment tests;

◆ and solid line - series 1; water application rate of 14.9 g/m^{2}s;

■ - series 2; water application rate of 7.0 g/m^{2}s;

⁎ - series 3; water application rate of 3.9 g/m^{2}s.

There is some scatter in the effectiveness ratio (Fig. 3). Small scale burning of the sample may be partly the cause. It was found that after most of the flames had extinguished during water application, small sections of the sample could continue to burn, slowly evaporating moisture from surrounding wood, and gradually progressing along the spars. Below the critical application amount and at full extinguishment however, the results are more consistent.

Effect of water application rate

The effect of water application rate on extinguishment may be interpreted in terms of an optimisation problem. If a fixed amount of water is available, then different strategies may be applied for fire extinguishment: a quick release of water at high flow rate or a slower release with decreased flow rate.

To describe this effect quantitatively, it is convenient to analyse the data for different restrictor opening ratios in the same (Fig. 3) coordinate system. Two additional series of tests are presented in Fig. 3 with water flow rates ranging from 3.9 g/m^{2}s to 7.0 g/m^{2}s.

Figure 3 shows that the effect of water application rate is not significant for the total amount of released water below ~ 0.6 l/sqm. The apparent maximum difference of extinguishment ratio of ~ 0.2 lies in the range of experimental scattering.

For higher rates, however, the difference is more significant, especially for the lowest rate of 3.9 g/m^{2}s. For the full amount of water around 1.0 l/sqm, the effectiveness ratio for this case is almost three times lower than that for a water application rate of 14.9 g/m^{2}s. There is a similar difference for the full extinguishment case. For the flow rate in the middle of the experimental range (7.0 g/m^{2}s) the difference in the effectiveness ratio compared with series 1 is significantly smaller (~ 30 %).

These results show that the higher rate of release is more effective for a given amount of water. However, this is only true for the total water application above 0.6 l/sqm, and for the effect to be noticeable, the difference in water application rate has to be several times higher.

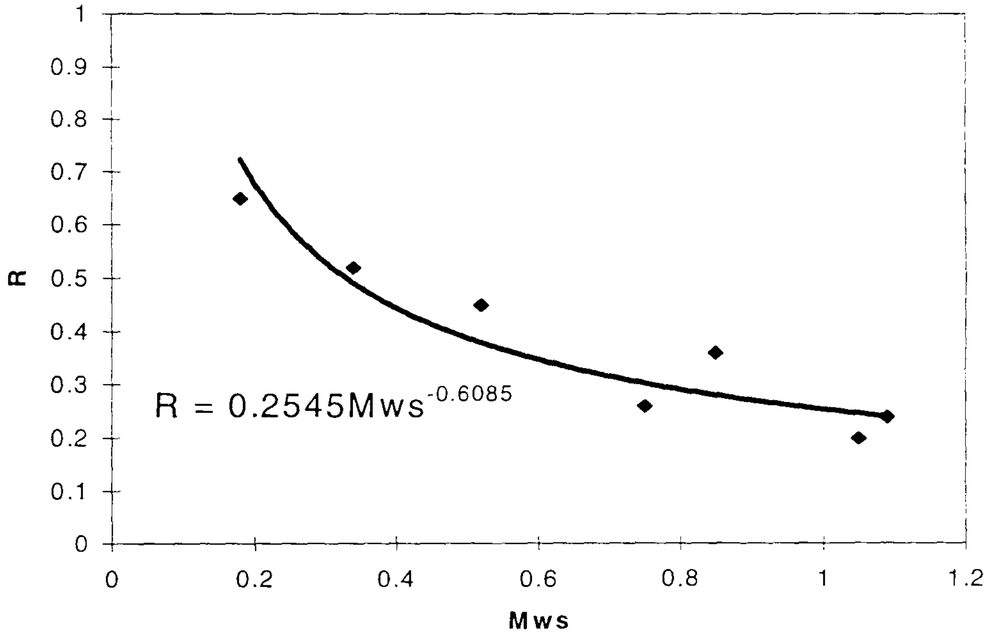

Figure 4. Correlation of the extinguishment effectiveness with the ratio of water application rate and the sample burning rate.

It is interesting to plot the effectiveness ratio as a function of water application rate for unlimited water capacity (full extinguishment test). This is done in Fig. 4.

This figure also shows higher extinguishment capability for high water release rates. The dependence may be approximated as

$$R = 0.25\,(M_{w\,s})^{-0.6085}$$

where $M_{w\,s} = m_w\ /\ m_s$ is the ratio of the water application rate and the crib burning rate just prior to sprinkler operation.

This correlation is different from the one obtained by Kung and Hill [1] in their study of extinction of wood cribs. Kung and Hill used 6-, 11- and 16-layer cribs. They found that the extinguishment ratio varies as $(m_w/m_s)^{-1.55}$ for all three types of cribs.

The samples employed in the present study correspond to 2-layer crib with vertical orientation. The apparent difference in the above results means that the correlation of Kung and Hill loses universality for cribs with fewer layers. For this type of crib, orientation is also likely to have significant effect and should be investigated in a separate study.

Another reason for the discrepancy may lie in the different characteristics of the water sprays hitting the sample. The most important characteristic is the droplet size distribution in the spray. In Kung and Hill's study water was supplied via a number of perforated tubes. In contrast, the advantage of the present study is that it employs of a commercial sprinkler which is actually used in fire fighting. Although an accurate comparison of droplet distributions is not possible for both studies, droplets of various diameters are well known to behave significantly differently when hitting a hot surface [9]. Therefore, the effect of droplet size distribution should also be given attention in future studies.

CONCLUSIONS

Wooden samples of a 'simple' geometry and vertical orientation have been uniformly ignited, prior to extinguishment by varying quantities of water at different application rates. Water was applied from a ceiling mounted commercial fire sprinkler.

For unrestricted sprinkler spray, a critical water application amount of 0.25 l/m^2 was found, for which the sample burnt completely, nullifying the effect of the water. Around this critical application amount, the extinguishment times were found to be at a maximum.

At 1 l/m^2 of water application, a similar proportion of the sample was saved compared with the full water application tests (sprinkler left on until extinguishment). This amount of water was 3-5 times less than that used during the full application tests, and could represent a significant reduction in commercial fire damage costs through reduced water damage. However, tests indicated that while the mass of sample consumed was minimised at 1 l/m^2 of water application, small-scale fires could continue to burn for significant periods. These small-scale fires were not capable of large-scale reignition.

The effect of water application rate has also been analysed. It has been shown that a fast release of water at higher flow rates is generally more effective for extinguishment than a more prolonged release at lower flow rate. This effect is noticeable at total water application amounts higher than 0.6 l/m^2, and especially for full sprinkler operation tests, which are most important for fire technology at present. The extinguishment effectiveness has been correlated with the ratio of the water application rate to the sample burning rate. For the 2-layer cribs used in the present study, the correlation was found to be different from that obtained in the previous studies of wood cribs with more layers. This suggests that the universality of correlations in respect to the number of layers is limited to the cases with relatively high numbers.

The rate of sample consumption during extinguishment was also found using carbon dioxide analysis of the product gases. Sample consumption rates fell steeply during water application, but for application amounts below the critical value, subsequently rose to the non-extinguishment rate.

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