Water for Manual Fire Suppression

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ABSTRACT: Water demand for manual fire suppression is analyzed. The Fire Point Theory is validated concerning fuel surface cooling effects and the critical water flow rate is determined and compared with previous investigations. It is shown that the critical flow rate is not the best use of resources. Therefore, the water flow giving the minimum total volume is determined. Data from real fires was compared with this experimentally-determined flow. There is a difference between experiments and real fires in terms of the water flow rate used, the control time and the total volume of water used. The reasons behind these differences are explained.

KEY WORDS: water, fire suppression, fire fighting, critical flow rate, experiments.

INTRODUCTION

THERE HAVE BEEN some attempts to describe the need for resources when water is used as an extinguishing agent in order to assist in determining the fire brigade resource requirements [1–3]. Most previous work was aimed at explaining the phenomenon behind water as an extinguishing medium or to summarize the research in the area [4–6].

The computer code *Fire Demand Model* [7] is one of a very limited number of models for estimating the effect on fires of manual fire suppression. In this model, the user sets the extinction criterion by defining minimum gas and wall temperatures. It is likely that this model will predict fire suppression better if a control criterion based on the energy balance at the fuel surface is applied, as described in this paper.

Models are available for estimating the demand of resources, for instance, with dry powder as an extinguishing agent for pool fires [8], and for attacks

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using foam as the extinguishing agent. The hypothesis of this paper is that it is possible to make a similar estimate of the demand of resources in the case of manual suppression of fires in wooden fuels using water as the extinguishing medium. The main difference between the focus of this paper and previous work is that here, the minimum total use of extinguishing agent is the main concern, rather than the minimum flow rate.

This work does not concern active fire suppression systems, i.e., sprinkler systems. The reason for this is the way the water is applied. In manual firefighting, the water is applied from the side of the fire, in most cases through the lower layer of a relatively cold atmosphere. In sprinkler suppression, on the other hand, water is applied onto the fire plume, and has to overcome the buoyancy of the fire. In sprinkler suppression, the water droplets have to be large enough or have a sufficient momentum to penetrate the flames, while in manual suppression, the optimum size of droplets is smaller. This paper concerns manual fire suppression, and does not take into consideration the process of search and rescue preceding the actual attack on the fire. Another limitation is the presence of diffusion flames, rather than pre-mixed flames.

TECHNIQUES OF WATER APPLICATION

Water as an extinguishing agent can be used for many purposes, both offensively and defensively. It can be used to hit the flames, the hot gases produced, the heated surfaces of the room, the fuel surface and the fuel not yet involved in the fire. Cooling of the fuel and stopping fuel gasification is the main mechanism when applying the water at the fuel surface [9,10], and cooling of the flames below the adiabatic flame temperature is the main mechanism when applying water droplets into the flames [11]. There are also other effects, e.g., the stirring of fire gases due to the water flow and to the generation of steam. The different ways may be more or less isolated and the aim and the result are different. In some of these cases, the conditions for firefighters in a fire room deteriorate and, in some cases, the conditions improve. What is worst for the fire is not necessarily best for the firefighters. The water may be applied in one of five ways, giving different effects on the fire itself and on the possibility to approach it:

- Droplets into the flames. Flames are extinguished by cooling below the adiabatic flame temperature at the extinction limit. The flames go out, but the pyrolysis rate is unaffected in the short term, especially in the case of fires of materials for which the fuel surface is covered with an insulating layer of char. This gives an almost immediate re-ignition of the fire. In the long term, the radiation from the flames decreases, giving a lower pyrolysis rate. By cooling the flames, the smoke temperature falls, the smoke volume decreases and the environment for the firefighters in a room on fire is ameliorated. Even though the fire may not be extinguished, this way of applying the water may enable firefighters to approach the fire.

- Droplets into the hot smoke. This way of applying water has many similarities to the previous method, with the exception that the flames or the fire itself are unaffected. The smoke gases are, however, cooled and contract, giving an improved environment for firefighters approaching the fire. The increase in volume due to evaporating water is less than the contraction due to the cooling of the gases. Even though the fire itself is not affected, the application of water facilitates approach to the fire. The overall decrease in temperature in the room also reduces the heating of fuel surfaces and pyrolysis of fuel surfaces not yet involved is limited.
- Droplets onto hot, non-burning surfaces. The water is heated and a portion is evaporated, and this steam may make the room inert. The proportion of water that evaporates is modest in general, depending on the application rate and the surface temperature. This approach requires an enclosed space, which cannot be reached from outside. On the one hand, the space must be closed to contain the steam, and on the other hand, openings must be available to give the firefighters access to the hot surfaces. At the same time, the expanding gases make conditions worse for the firefighters; turn-out gear, in general, provides better protection from hot but dry fire gases than from steam.
- Drops or droplets on the burning fuel surface. The fuel itself is cooled, reducing the pyrolysis rate and quenching the flames. On their way to the fuel surface, the water droplets can also block heat radiation affecting the fuel. At the same time, the smoke is filled with steam, to some extent, thus making the room inert. For the firefighters, the worsening conditions due to the high content of steam in the smoke gases may be such a hindrance as to stop the attack. Apart from this, the method is effective in fire fighting, as the pyrolysis rate and thereby the heat release rate is directly reduced. This way of applying water is the most common one.
- Drops or droplets on fuel surfaces not yet involved in the fire. This method prevents fuel from starting to pyrolyze and the fire is extinguished after some time due to lack of fuel. Status quo is reached by limiting the fuel. The method has basically no effect directly on the fire and is a time-consuming, defensive strategy.

EXPERIMENTAL AND THEORETICAL ESTIMATION OF THE CRITICAL WATER FLOW RATE

The critical flow rate of water is the lowest rate of water application necessary to achieve extinction, but with an infinite amount of time available. An estimate of this critical flow rate based on four different test series, seen in Table 1, has been made by Heskestad [4]. The values are estimated from small-scale tests on wood, a few on wood cribs of approximately one cubic meter. The technique used to apply the water for extinction is the fourth on the list above, namely, using the water as drops or droplets on the burning fuel surface.

In the comprehensive survey by Rasbach [5], critical water flow rates for some different fuels were compared. He also draws attention to the fact that this flow rate increases with increasing external radiation and explains how this is balanced with the heat capacity of water. The energy needed to heat water from 10°C to steam at 100°C is 2640 kJ/kg. Using the density of water, this means that 1.0 kg/m^{2}s of water impinging on the fuel surface and evaporating, will absorb an external heat flux of 2640 kW/m^2. If only this heat balance at the surface is taken into account, a heat flux of 10 kW/m^2 requires a water density 0.0038 kg/m^{2}s higher than without external heat to control a fire.

Another investigation [6] also concerns the critical flow rate. Here, the relation between critical mass loss rate and critical water application rate is discussed theoretically and investigated in small-scale experiments.

The Fire Point Theory developed by Rasbach [9] and extended by Beyler [10] explains how the critical water flow rate can be derived theoretically. The theory applied here takes only the extinction due to the effect of surface cooling into consideration. The effect of the evaporated water and other gas phase effects are neglected. The theory is based on conditions that are not

Table 1. Some experimentally determined critical water flow rates [4].

Referred Tests	Critical Water Flow Rate [kg/m^{2}s]
Crib test by Bryan and Smith	0.0017
Crib test by Kida	0.0025
Small crib test by Kung and Hill	0.0019–0.0024
Pallet test by Kung and Hill	0.0025
Small slab test by Tamanini	0.0013
Small crib test by Tamanini, loosely packed–densely packed	0.0015–0.0030

time-dependent but are approximately in a steady state. The energy balance at the fuel surface can be expressed, as

$$L_V\dot{m}'' + \dot{q}''_L + \dot{q}''_W = f\Delta H_c\dot{m}'' + \dot{q}''_E$$

which can be rearranged to give

$$(f\Delta H_c - L_V)\dot{m}'' + \dot{q}''_E - \dot{q}''_L - \dot{q}''_W = 0$$

where f is that fraction of heat released which is transferred back to the fuel surface by convection and radiation, ΔH_c is the effective heat of combustion of the volatile fuel, L_V is the heat of gasification of the fuel and $\dot{m}''$ is the burning rate per unit area of the fuel. $\dot{q}''_L$, $\dot{q}''_W$ and $\dot{q}''_E$ represent heat losses from the surface, heat lost by evaporating water and externally applied heat, respectively. The burning rate at the critical point, $\dot{m}''_{cr}$, can be substituted by using Spalding's B-number theory [6]:

$$m''_{cr} = \frac{h}{c_p}\ln(1 + B_{cr})$$

where h is the convective heat transfer coefficient, c_p is the specific heat of air at constant pressure and

$$B_{cr} = \frac{Y_{O2}\Delta H_{R,O2} - c_p(T_s - T_a)}{\Delta H_{g,conv}}$$

Y_{O2} is the oxygen mass fraction and $\Delta H_{R,O2}$ the heat of combustion per unit mass of oxygen consumed. T_s is the surface temperature and T_a is the ambient temperature. $\Delta H_{g,conv}$ is the flame convective energy transfer to the fuel per unit mass of fuel gasified. In this case, $Y_{O2}\Delta H_{R,O2} >> c_p(T_s - T_a)$. At extinction, i.e., at the critical fuel mass loss rate, $f = \phi$, where ϕ is the fraction of heat generated which must be lost for the flame to be quenched. At this point, the convective heat transfer dominates, giving

$$\Delta H_{g,conv} = \phi\Delta H_c$$

This makes the fire point equation:

$$(\phi\Delta H_c - L_V)\left[\frac{h}{c_p}\ln\left(1 + \frac{Y_{O2}\Delta H_{R,O2}}{\phi\Delta H_c}\right)\right] + \dot{q}''_E - \dot{q}''_L - \dot{q}''_W = 0$$

We are interested in the critical water flow rate to achieve extinction and continue with

$$\dot{q}''_W = c_w \dot{m}''_{w;cr} h_{V,W}$$

where c_w is the efficiency of water application, i.e., the fraction of water actually reaching its target, $\dot{m}''_{w;cr}$ is the critical water application rate and $h_{V,W}$ is the change in enthalpy between water at storage temperature and steam at 100°C, i.e., the energy required to heat the water and to evaporate it. Combined with the fire point equation this gives:

$$\dot{m}''_{w;cr} = \dot{m}''_{w;cr,0} + \frac{\dot{q}''_E}{c_w h_{V,W}}$$

The second term on the right-hand-side of the equation determines the additional flow rate of water demanded by external heat. The first term, $\dot{m}''_{w;cr,0}$, is the critical water application rate with no external heat flux. It is the intercept of the straight line between the applied radiant flux and the required water application rate:

$$\dot{m}''_{w;cr,0} = \frac{(\phi \Delta H_c - L_V)\left[(h/c_p)\ln\left(1 + Y_{O2}\Delta H_{R,O2}/\phi \Delta H_c\right)\right] - \dot{q}''_L}{c_w h_{V,W}}$$

By substituting representative values for the symbols, $\dot{m}''_{w;cr,0}$ and thereby $\dot{m}''_{w;cr}$, can be quantified.

Assuming that wood is the fuel, burning under normal conditions, most parameters can be estimated. ΔH_c and L_V are the heats of combustion and gasification of the fuel, 13.0 and 1.8 MJ/kg, respectively [6]. With an ignition temperature of 385°C [12], the convective heat coefficient h is in the order of 10 W/m^{2}K [13] and c_p is approximately 1.06 kJ/kgK [14]. This estimate is possible, as the parameters have only a minor temperature dependence. Assuming well ventilated conditions, the oxygen mass fraction of air, Y_{O2}, is 0.233. This mass fraction must, however, be reduced due to the evaporating water. The relation between fuel and water can be calculated. In a small-scale study using a flammability apparatus, the mass loss rate of particleboard at extinction was experimentally determined to be 0.0055 kg/m^{2}s [15]. Regarding the elemental composition, the molecular formula of wood is $CH_{1.7}O_{0.83}$ [6], with a molecular weight of 0.027 kg/mol. Under stoichiometric conditions, one mole of wood requires 1.02 mol of oxygen. The critical rate of water application can be determined by interpolation. Thereby, the stoichiometric reaction formula can be balanced by adding water, and the mass fraction of oxygen can be corrected, assuming well ventilated conditions:

$$Y_{O2} = \frac{(0.0055/0.027)1.02 \cdot 0.032}{\dot{m}''_{w,cr} + 0.0055 + (0.0055/0.027)1.02(0.032 + (0.79/0.21)0.028)}$$

This gives a reduction of Y_{O2}, the oxygen concentration, of about 5%. The heat of combustion per unit mass of oxygen consumed, $\Delta H_{R,O2}$, is 12.4 MJ/kg for wood [6]. If radiation in connection with heat losses from the surface is neglected, $\dot{q}''_L$ can be estimated as the conductive heat transfer in the material using

$$\dot{q}''_L = \lambda \frac{dT}{dx}$$

where the conductivity, λ, is temperature dependent for wood at the ignition temperature 0.2 W/mK [16, p. 164]. dT/dx is determined to be about 330 K/0.010 m [16, p. 195], giving an estimate of $\dot{q}''_L$ in the order of 6.5 kW/m. This estimate was confirmed by using the calculation method described in [17]. A one-dimensional calculation was made on particleboard, 0.030 m thick and with its surface exposed to the ignition temperature. The calculated conductivity at the time 5–10 min proved to be equal to the previous estimate. No data is available to estimate the efficiency of the water distribution, c_w, but to get the lowest estimate of the water demand, this factor is assumed to be unity. $h_{V,W}$, the energy needed to heat water from 10 to 100°C and to evaporation, is 2640 MJ/kg.

With these assumptions, the relation between the critical mass flow of water, $\dot{m}''_{w;cr}$, and ϕ, the portion of heat necessary to be removed for the flame to be quenched, becomes

$$\dot{m}''_{w;cr,0} = \frac{(\phi \cdot 13.0 - 1.3)[(10/1)\ln(1 + ((Y_{O2} \cdot 12.4)/(\phi \cdot 13.0)))] - 6.5}{1 \cdot 2640}\,\mathrm{kg/m^2s}$$

Normally, ϕ is in the order of 0.1–0.4 [10]. The solid lower line in Figure 1 illustrates the equation. The term within square brackets in the equation is the critical mass loss rate of the fuel, obviously also correlated to ϕ. The value of the critical mass loss rate previously used, 0.0055 kg/m^{2}s [15], is included in the figure, together with a 0.001 kg/m^{2}s span. This mass loss rate gives, with the assumptions above, a water demand of 0.0014 kg/m^{2}s.

The estimate is in accordance with the previously reported experimental values of water application, 0.0013–0.0030 kg/m^{2}s, the difference probably being explained by the lack of more accurate data and in inefficiencies in the

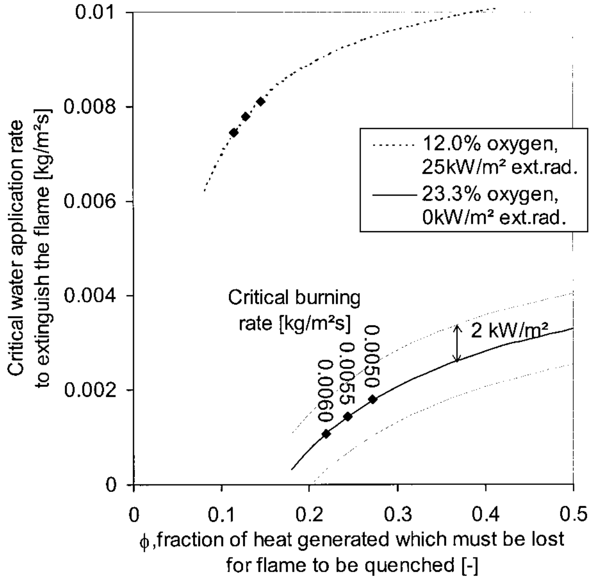

Figure 1. *Relation between the critical water application rate and the fraction of heat which must be lost for the flame to be quenched. The solid line represents well-ventilated conditions and the surrounding lines represent 2 kW/m^2 heat added or removed. The dotted line represents under-ventilated conditions with high external radiation due to a flashover fire.*

water application at experiments. Some of the estimates in the calculation are rough, e.g. the estimate of $\dot{q}''_L$. In the figure, the effects of a change in heat losses of 2 kW/m^2 are indicated. One can also note that the heat loss into the fuel is dependent on the thermal properties of the fuel.

The diagram includes also a line describing the critical flow rate for a ventilation-controlled, flashover fire. The oxygen mass concentration is reduced to 12% due to smoke re-circulation, before the reduction due to evaporating water, and an external heat flux of 25 kW/m^2 is employed.

In Figure 2, the external heat is plotted against the critical water application rate for two oxygen concentrations. External heat leads to an increase in water demand, to a minor extent reduced by a decrease due to the reduction in oxygen concentration. The lines are not parallel, due to the fact that the evaporating water alters the oxygen concentration. It is clear that an increase in external heat, e.g., in a flashover, leads to a much larger water demand than in the absence of external heat. It may, in fact, increase the demand 2–3 fold. A negative critical water application rate has no other physical meaning than that extinction will occur without the application of water.

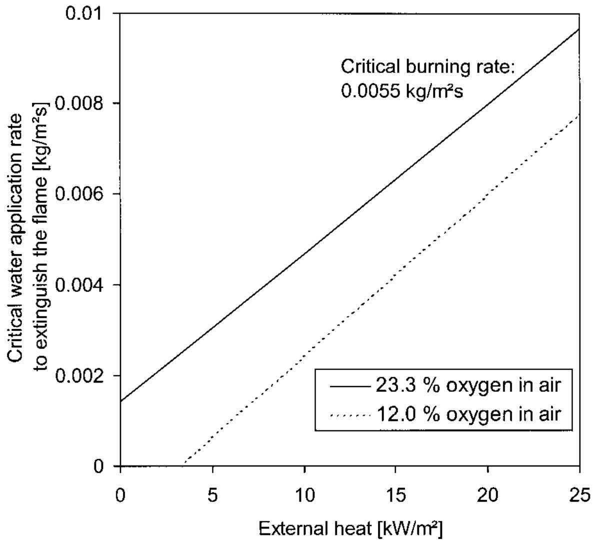

Figure 2. *External heat versus the critical water application rate.*

PROBLEMS USING CRITICAL WATER FLOW RATE FOR DIMENSIONING

Two main problems are involved in the use of the critical water flow rate for dimensioning manual fire suppression resources. The first problem is the action time of firefighters. A firefighter wearing a breathing apparatus will normally run out of air within half an hour. Some time always elapses from when the firefighter puts his mask on, to when he actually enters the building. Commonly, he is to search the area and rescue victims and, not until then, attack the fire with the aim of extinguishing it. There may be multiple seats of fire and concealed seats of fire may have to be freed. After that, the firefighter must have air left to enable a safe retreat and perhaps to start ventilating the area. The point is that to succeed, the action time does not allow a flow rate demanding a long time to control the fire. The action time requires a flow rate that controls the fire in not more than a few minutes or, preferably, a few seconds.

The other problem is that the critical flow rate does not give the best use of resources. The minimum water flow to control a fire implies an extremely long time, and thus, the total volume of water increases. The interesting flow rate would be the one requiring the smallest total volume of water. This flow rate can be called the optimum flow rate, since it indicates an optimum use of resources.

The control time for the small-scale tests varies to a large extent, from about half a minute to about half an hour. In large-scale experiments, on the other hand, the control time is commonly less than a minute and only occasionally exceeds five minutes. At longer times, i.e., approaching the critical flow rate, the tests were in general halted and the flow rate was regarded as insufficient. This means that critical flow rates are rarely achieved among tests on a large scale.

The control time declines with an increasing flow of extinguishing medium, as shown in Figure 3. The curve is asymptotic at both ends. This is logical, since a very small water application rate will not cool the flames enough for extinction or cool the fuel surface enough to reduce the pyrolysis rate to below the critical mass flow of fuel. This gives a minimum flow rate for extinction, the critical flow rate. It is also logical that it will take some time for the water to travel from the nozzle to the fuel surface and for the nozzle to cover the whole surface. This gives a minimum control time. The minimum control time is not governed by the extinction capacity, but rather by the time needed to cover the whole fuel area by the agent flowing from the nozzle. This time does not differ very much whether the flow rate is large or very large.

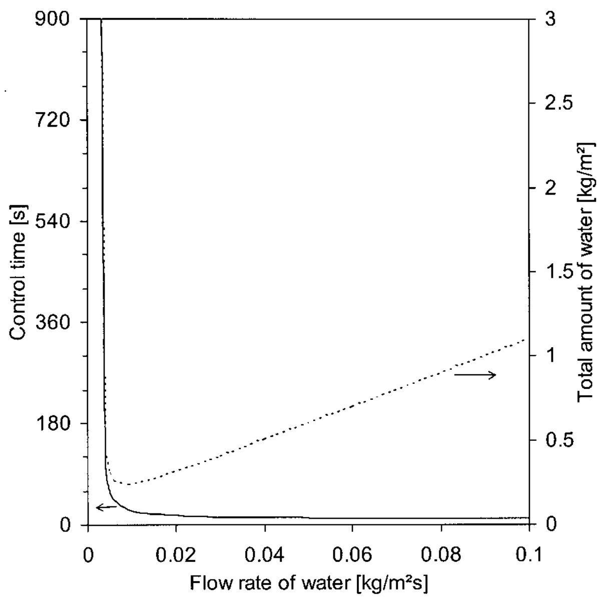

Figure 3. *The control time (solid) and the total amount of water (dotted) as a function of the water flow rate.*

This type of diagram can be plotted for all situations, but to be able to compare different scenarios, the flow rate and the total volume have to be normalized using some parameter describing the fire. Here, the fuel surface area is used, which is convenient, at least where wood fuels are concerned. The rate of heat release could also serve, but fewer results of extinction tests, in which the heat release rate was measured, are available.

The total amount of water is basically the flow rate times the control time. Plotted against the water flow rate, it gives the shape of a fishhook. Increasing the flow rate from the minimum flow rate for extinction, the total volume decreases. The curve has a low point, indicating a minimum total volume, corresponding to the most efficient use of resources. Increasing the flow further, the attack will not gain efficiency, as the extinction is not governed by lack of extinction medium, but rather by the technique used in applying it. Increasing the flow rate may give a faster extinction, but not sufficiently faster to counterbalance the increase in total volume.

To summarize, four points can be identified in the figures of total volume of extinction medium and control time plotted against the flow rate.

- There is a critical flow rate, a minimum flow rate of extinction medium to control the fire, albeit with an extremely long control time.
- There is a minimum total volume.
- The minimum total volume corresponds to an optimum flow rate, i.e., a flow rate giving the lowest total volume of extinction medium
- The optimum flow rate corresponds to an optimum control time, a control time that gives the lowest total demand for resources.

There is a problem involved in this model of describing fires in solid fuels and in real fires, which is the problem of steady state. The model assumes that the fire has reached a steady state and is constant in terms of mass loss rate or energy release. The assumption is good for pool fires in liquids of a reasonable depth, for example. A wood crib fire or a fire in furniture has a more dynamic development and it is not self-evident that it has a specific period in which it is in a steady state. Therefore, when estimating the flow rate of extinction medium experimentally, one has to make sure that the medium is applied when the fire has reached a steady state and that the measured time is shorter than the time lapse before the fire starts to decline. One has also to note that a different pre-burn time gives different char depth and thereby differences in the demand for water. This is also a relevant question in the case of real fires. When the duration of water application starts to increase, it is not certain that the operative strategic aims were reached. The fire may simply have started to run out of fuel.

EXPERIMENTAL ESTIMATE OF OPTIMUM WATER FLOW RATE

The critical water flow rate needed to control fires was determined theoretically and validated experimentally. There is, unfortunately, no theory describing the water demand giving the minimum total volume of water. Therefore, this has to be determined experimentally.

A number of different test series were studied, focussing on three parameters: the control time, the total amount and the mean flow rate of water used. To handle the different sizes of fire, the total amount and the flow rate were normalized using the surface area of the fuel, which is a measure of the area of the fuel that is exposed and participates in the fire. The control time is defined as the time when the derivative of the mass loss curve is zero, i.e., the time when the fuel starts to gain weight. Most fire tests are performed without measuring the weight of the fuel and, in the course of the survey, many fire tests were found for which the mass loss was not recorded. These are not included, as an identical extinction criterion must be used for all tests compared. Oxygen depletion calorimetry also gives a good measure of the reduction in burning rate, but the number of fire tests found is small. Another disadvantage of calorimetry is that the response time of the experimental equipment is longer than that of equipment used for mass loss measurements. Using calorimetry, all smoke has to be exhausted by fans, which may create problems in large fire scenarios.

Four test series with wood materials are included in this comparison. The first is a study of free burning wood cribs, made by Kung and Hill [18]. The tests were performed first on square cribs with a side of 0.185 m, having an exposed fuel surface area of 0.27, 0.50 and 0.72 m^2, on which 13, 11 and 16 tests were carried out, respectively. Five similar tests were performed on wood pallets with a side of 1.22 m and a fuel surface of 34 m^2. The application of water was from the top, using perforated pipes.

The second test series, by Bryan and Smith [19] simulates fire fighting using a stirrup pump. A free-burning wood crib, 0.78 m in diameter with exposed fuel surface of 7.0 m^2, was used and 15 tests are presented. The crib was rotated and the nozzle oscillated to cover the whole crib with the jet.

The two remaining test series have not yet been published in English. Ingasson of the Swedish National Testing and Research Institute performed the first one in 1999 [20]. The test set up was two piles of wood pallets interspersed with some polyurethane foam, and with a total exposed fuel surface of 35 m^2. The fire was extinguished manually by a firefighter attacking the fire with a standard nozzle but at different flow rates. He was allowed to attack the fire as efficiently as he could. The scene was a hall, $10.0 \times 10.0\,m^2$, with a ceiling height of 6.0 m, i.e., a room large in comparison with the fire. The temperature of the room was in the order of 300°C.

The last series was performed by Lundström et al. [21]. Six piles of wood pallets with 170–200 m^2 of exposed fuel surface, located in a fire hall, $14.0 \times 7.7\,m^2$, with a ceiling height of 6.3 m, were used. The pallets were arranged in two rows with three piles of pallets in each. The fire was attacked by a firefighter with restricted movement and nozzle operation. He used a standard nozzle with different flow rates but was not allowed to attack the fire from more than one point on the long side of the pallet arrangement. Five tests were used here. This test series produced temperatures in the upper part of the room of close to 600°C. This corresponds to an external heat flux of 30 kW/m^2. This heat flux concerns only about one quarter of the fuel surfaces, since the view factor from the fuel surfaces to the smoke layer has to be considered. If roughly 1.0 kg/m^2s of water that strikes the fuel surface and evaporates absorbs an external heat flux of 2640 kW/m^2, the extra water required would then be $1.0 \times (30/2640) \times 1/4 = 0.003\,kg/m^2s$.

The tests covered a range of fires, from small-sized wood cribs to large piles of wood pallets, with a heat release rate of up to about 17 MW. The tests were similar in the choice of fuel. In all tests wood materials were used, either as standardized wood cribs or as wood pallets. In the Ingasson test series, they were supplemented by some polyurethane foam. The fire conditions did not vary greatly, the fuel was either free burning or placed in a large hall. In the Lundström tests, the temperature of the room was high, demanding an extra flow of water.

In Figure 4, the total volume of water used to reach the control criterion is compared to the flow rate. Both are normalized using the exposed fuel surface area. As shown, the total volume of water decreases from the critical flow rate, about 0.002 kg/m^2s. The flow rate giving the smallest total volume is about ten times higher, 0.01–0.03 kg/m^2s. At this flow rate, the total volume has a minimum of 0.15–0.35 kg/m^2. Increasing the flow rate beyond this, the total volume of water increases.

The critical flow rate leads to an extremely long control time, as shown in Figure 5. Of more interest is the control time giving the minimum total volume of extinction medium. This optimum control time is short, in the range of 5–15 s, possibly the time it takes to cover the whole fuel surface with water and for the water to soak into the pyrolyzing material. The optimum time is so short that the distribution of water over the whole fuel surface, together with the heat transfer through the fuel, becomes more important than the actual flow rate of the water.

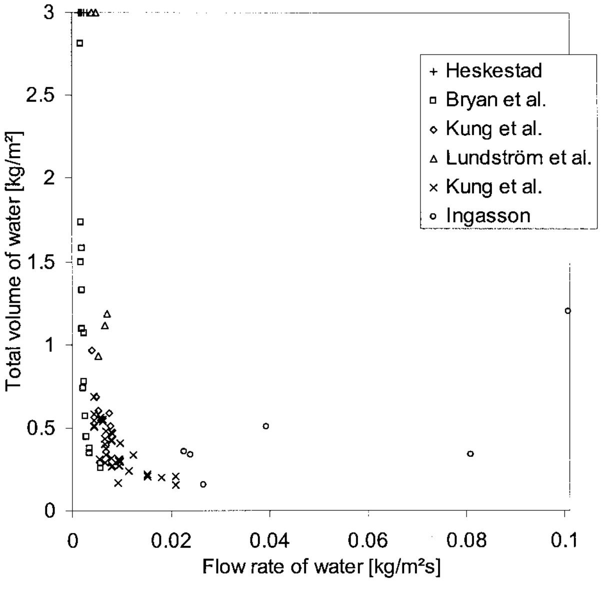

Figure 4. *The total amount of water used as a function of the flow rate. Note that the high room temperature in the Lundström tests increased the water demand.*

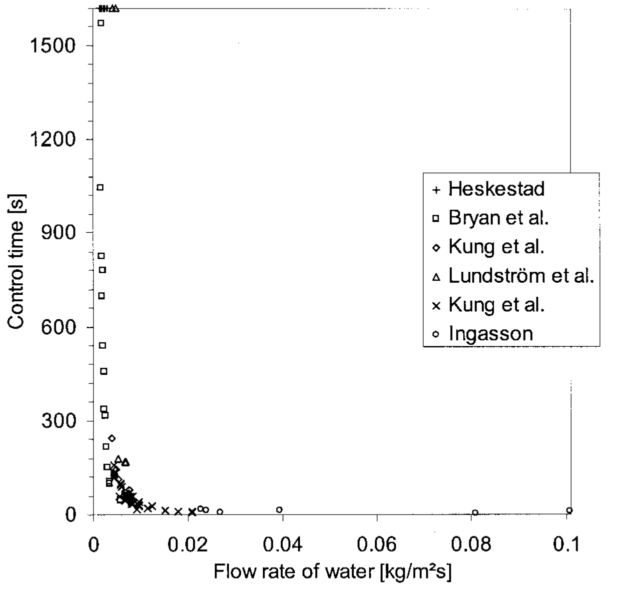

Figure 5. *The control time as a function of the flow rate. Note that the Lundström tests were performed with near-flashover room temperatures.*

The marks on the line at the top of both diagrams indicate critical flows reported previously by Heskestad [4] or tests that did not succeed in reaching the control criterion.

WATER FLOW RATES USED IN REAL FIRES

So far, in the study, the main concern has been the surface cooling effect of water, treated both theoretically and experimentally. If studies of real fires fall into the same pattern and the quantification of variables proves to be in the same range, this is an indication that the surface cooling effect is the dominating extinction mechanism in real firefighting operations. As shown in this chapter, this is the case, thus indicating that the surface cooling effect is dominant over other mechanisms, e.g., the cooling and dilution of flames in the gas phase.

In a study of 307 real fires in non-residential premises in London in the late 1990s, data was collected regarding extinguishing duration, water flow rate and fire area [22]. Although the horizontal fire area ranged from 0.1 to 1000 m^2, only fires with a horizontal fire area larger than 5 m^2 are included here. This is because the flow of normal firefighting nozzles is commonly so large that the control time becomes so short that it may be obscured by other events on the fire scene, e.g., the movements of the firefighters. Another limitation in the data is that attacks made using fire extinguishers are not included. This is because the amount of water is limited in such an attack, the variables thus not being independent. Having a water fire extinguisher, the control time normally equals the action time of the extinguisher whether the fire is actually under control or not and the total volume of water is fixed, normally at about 10 kg.

In Figure 6, the extinguishing duration is plotted against the flow rate used in these fires. There is a critical flow rate, approximately 0.13 kg/m^2s, below which the scatter among the data increases. The scatter could be explained by the fact that below the critical flow rate, there are two types of fires: the fires actually extinguished by the fire brigade, giving long times and high total volumes; and the fires that were fought in a defensive way, i.e., where the fire brigade prevents the fire from spreading until it runs out of fuel.

The extinguishing duration decreases with the flow rates to about 0.3 kg/m^2s, after which it begins to increase. This can probably be explained by the observation that these data points concern fires in which a high water flow was used, i.e., several nozzles or nozzles with a high volume flow. The nozzle flow rate is high when large nozzles are used, giving a lower efficiency. The larger the equipment, the longer the time required to set it up and also the longer to shut it down. A small branch nozzle operated hands-on by

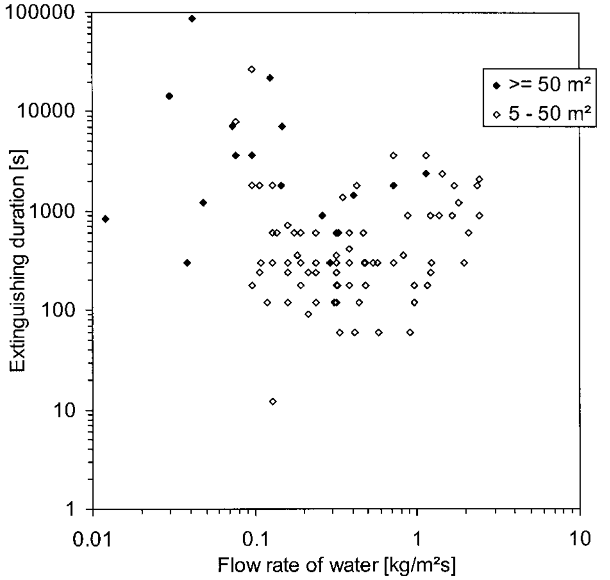

Figure 6. *The duration of the attack as a function of the flow rate. Filled marks represent fires with a horizontal fire area larger than 50 m^2.*

a firefighter involves only the firefighter who can see what to aim at and can determine to shut the nozzle when appropriate. A monitor on the other hand, is commonly set up by someone who is then designated to other duties. It takes more time to make a decision to shut it off and it takes longer to do it when the officer in charge makes the decision.

The scaling effect in fire operations can also be seen in the figures. Fires with a horizontal surface area of 50 m^2 or more (filled marks) have an extinguishing duration which is a factor of 4 longer than fires with a horizontal surface area of 5–50 m^2 (unfilled marks). This may be due to difficulties in reaching the whole fire area. Parts of the fire may have to be extinguished to enable the extinction of other parts and the firefighters may have to reposition during the attack.

There may be a desire on the part of fire brigades for over-kill, for example for safety reasons, and this would affect the flow rate, a desire to be on the conservative side, making sure the nozzle can handle the fire. It may be so, but would not primarily affect the relation between real fires and experiments and in the diagrams presented here. When changing the flow, it is mainly the control time that is changed. However, the scaling effect described above, increasing the duration of the operation when the size of the equipment is increased may be present, at least to some extent.

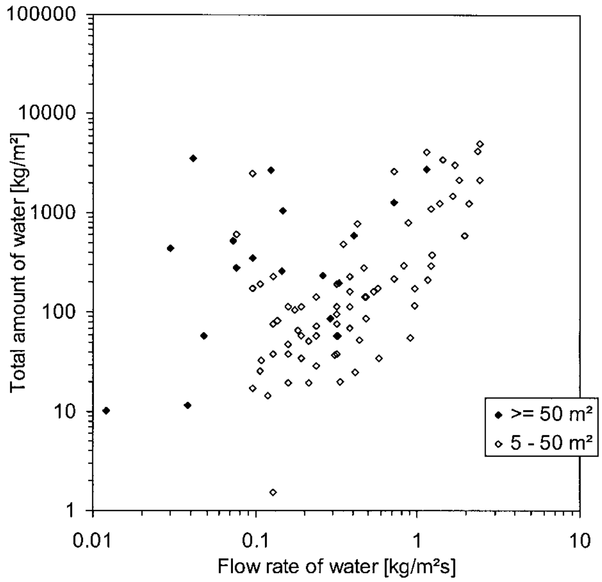

Figure 7. *The total volume of water versus the flow rate, in real fires.*

Figure 7 shows the relation between the total volume of water used in fighting the fires and the flow rate. The shape of the correlation between total volume and flow rate has the same pattern as previously described for the experiments. For real fires, the flow giving the lowest total volume of water is 0.2 kg/m^2s (ranging between 0.15–0.25 kg/m^2s). The corresponding flow for the experiments is 0.02 kg/m^2s, giving a difference of a factor 10.

There are several explanations for the differences in flow rate and extinguishing duration between experiments and real fires. Some of these factors are:

- the definition of fire area,
- the control criterion used,
- the repeating of fire tests,
- the determination of flow rate in real fires, and
- time estimates in real fires.

The first factor is likely to affect the flow rate and, the following factors, the duration of water application.

The flow rate for the real fires is normalized using the horizontal fire area, and for the experiments using the fuel surface area. The relation between the fuel surface and the floor area can be determined. The surface area factor Φ

is the fuel surface area divided by the mass of the fuel. The relation

$$\Phi = 0.54 \cdot q^{-0.64}$$

was found for office buildings [23], where q is the fire load density, defined as the mass of the fuel divided by the floor area of the room. In the study, the mass of the fuel was weighted to give a corresponding mass of wood with the same energy content as the actual fuel. Defining an area factor Θ as the relation between the fuel surface area and the floor area gives

$$\Theta = \Phi \cdot q = 0.54 \cdot q^{-0.64} \cdot q = 0.54 \cdot q^{0.36}$$

The fire load density varies [23] and, in the study cited, is of the order of $5\,\text{kg/m}^2$ for a reception and dining room. This gives the area factor 0.96 m^2/m^2. An office room has a fire load density of $30\,\text{kg/m}^2$, giving $1.8\,\text{m}^2/\text{m}^2$ and a library with a fire load density of $200\,\text{kg/m}^2$, has an area factor 3.6 m^2/m^2. An area factor of $2\,\text{m}^2/\text{m}^2$ would then be normal, thus explaining a part of the difference in optimum flow rate. It also explains some of the spread in the material, since the area factor varies. In spite of this quantification, there is still an uncertainty due to the difference between the horizontal fuel area and the floor area. The equation above gives the average fuel area per floor area, but fuel is not in general evenly distributed over the floor area.

Thus, a factor of not more than 5 between the optimum flow rate in real fires and in the experiments remains to be explained. The efficiency of application may be the explanation of this factor, indicating that about 20% of the water is actually used to strike the fuel surface. The remaining part may be either inefficiencies in application or water used in any of the other ways described in the first section of this paper. For instance, the water may have been used to cool the smoke gases to enable the approach of firefighters, or to wet fuel surfaces not yet involved in the fire.

From the previous diagram we get an extinguishing duration of 300 s (ranging from 90–600 s), which can be compared to the control time for the experiments, 10 s. The difference is a factor of 30.

One reason why time differs between experiments and real fires is the control criterion used. Firefighters are not satisfied just by controlling the fire but want to reach the stages of *flames out* and *fire dead*. In the experiments, on the other hand, control was defined as the time when the mass loss rate is less than the water application rate. A vigorous fire may, however, still be going on after the control criterion is reached. In one of the test series, in which professional firefighters performed the extinction [20], one can determine both the amount of water used to reach the control criterion and the amount of water used to extinguish the fire totally. For three of the experiments (No. 2, 6 and 7), the relation between the total amount of water and the total amount to reach the criterion, both in kg, was 68/17.6, 67/12.4 and 70/11.7 giving the factors 3.9, 5.4 and 6.0, respectively. The actual demand for water is thus a factor of at least 5 times higher than the amount needed for reaching the control criterion, due to an extinguishing duration at least 5 times longer. This is in an experimental situation. For real fires, the factor is likely to be higher rather than lower. Another aspect is that the control time is known to vary with the fire area, making the problem a matter of scaling. In large-scale firefighting, the water cannot be distributed simultaneously over the whole fuel surface. Thomas found the control time proportional to the square root of the fire area [2], which is also supported by data from modern firefighting [22].

The environment also affects the control time. It is known that firefighters in experimental set-ups perform better after a few similar tests than in the initial one, under identical conditions. This means an advantage in experiments that are repeated in a series of tests, over real fires that are each unique and unknown in advance. An estimation of this effect would be of the order of 50%, i.e. the initial fire would have a control time of 1.5 times that of the repeated and practiced fires.

For the experiments in one test series [20], the relation between the nominal (continuous) flow and the actual mean flow rate was 1.8, 1.6 and 1.8 for Experiments 2, 6 and 7, respectively. In another experimental series [21], the same relation was 3.7, 3.2, 2.3, 2.8 and 4.8 for Tests 2–6, respectively. The factor varies to a large extent depending on the technique used by the firefighters. The experiments indicate that because the firefighters open and close the nozzles of their hoses, it is likely that the time when the nozzle is open is a factor of 2–3 less than the total time. The time used for repositioning the nozzle, for instance, and mere walking time, may therefore conceal the time actually used for getting water onto the fire.

The optimum control time was found to be fractions of a minute for the experiments. The control time in the statistics over real fires is, however, commonly expressed in minutes. This means that if a firefighter opens the nozzle, say three times, and has it open for five seconds followed by ten seconds closed to reposition etc., it would give a total time of fifteen seconds, rounded to one minute. The actual time used is then only one quarter of the recorded time. Figure 8 shows the distribution of extinguishing duration times from the investigation of real fires [22]. As can be seen, 50% of the fires with an area larger than $5\,m^2$ have a control time of less than five minutes. Of all fires, 40% have a time less than a minute, which is the time unit used to collect the statistics. Another possible error in the statistics is due to the method of collecting data, the control time being recorded manually and after the fire. For fires with a control time of just

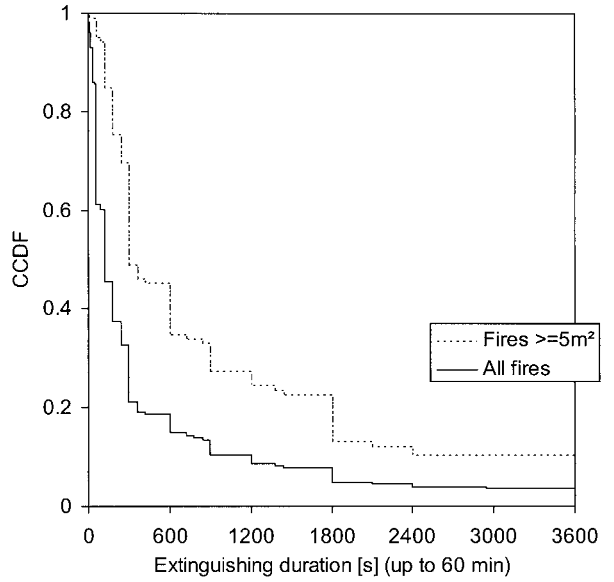

Figure 8. *The complementary cumulative distribution function of the extinction duration for all the real fires investigated and when fires larger than 5 m^2 were selected.*

a few minutes, this aspect may give a difference of a factor of 2. It is also noticeable how the time data cluster around multiples of five minutes. This factor and the previous one mean that the figures in the statistics are likely to be higher than is actually the case.

These factors, some measured and some estimated, may explain the whole difference between the control time in the experiments and extinguishing duration for the real fires.

The total volume of water used in the case of real fires is about 60 kg/m^2 (30–120 kg/m^2), compared to the experimental value of 0.2 kg/m^2. The difference is a factor of 300. This is explained by reasons discussed above, as 300 is the product of the flow rate factor 10 and the time factor 30.

CONCLUSIONS

In this paper, it was shown that *the Fire Point Theory* explains the demand for water to control fires. It proved possible to quantify the water demand by using the theory and reported experimental results to validate the theory.

To plan the dimensions of manual firefighting operations, the critical flow rate is not the best measure because it does not give the best use of resources and because the infinite time required is not available. The flow rate giving the minimum total use of water is a better measure. This flow rate was derived on the basis of both experiments and theory. Using statistics from real firefighting operations, it was possible to show that this flow rate gives the minimum use of water also in the case of real fires.

The flow rate using the minimum amount of water was determined experimentally to be $0.02\,kg/m^2s$ and statistically to be $0.2\,kg/m^2s$. The difference, a factor 10, can be explained by a factor of 2 by the definition of fire area, and the remaining factor of 5 is due to inefficiencies in the use of water.

The duration of the attack was determined to be 10 s in the experiments and 300 s using statistics. Having different control criteria explains at least a factor of 5. Learning by repetition in the test series accounts for a factor of 1.5. Short times to estimate in collecting statistics and the nozzle not being open during the entire extinguishing duration gives a factor of 2–3, and the method of measuring the extinguishing duration may give a factor of 2. Under these circumstances, the whole difference between extinguishing duration in real fires and control times in experiments is explained.

The total application of water was about $0.2\,kg/m^2$ in the experiments and about $60\,kg/m^2$ in the real fires. The difference is a factor of 300, explained by the factors discussed for the flow rate and the duration of the extinction.

One way to determine the total flow more accurately is to equip (some) fire engines with water flow meters. It is likely that the total volume used would prove to be smaller than currently estimated. If so, it would also be possible to quantify the demand for water during the different phases of fire extinction. Here, the focus is control of fires. There are indications that, by far, the greatest amount of water is not used during the control phase, but rather in the period after that, to extinguish all embers and to make sure that the fire does not re-kindle. This was estimated above to be at least a factor of 5.

The computer code *Fire Demand Model* [7] is one of a very limited number of models for estimating the effect on fires of manual fire suppression. In this model, the user sets the extinction criterion by defining minimum gas and wall temperatures. It is likely that this model will predict fire suppression better, by separating heating of surfaces in general and heating of fuel surfaces. By applying a control criterion based on the energy balance at the fuel surface as described in this paper, it is possible to improve the model.

ACKNOWLEDGEMENTS

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NOMENCLATURE

c_p	specific heat of air at constant pressure (kJ/kgK)
c_w	efficiency in water application (dimensionless)
f	fraction of heat released which is transferred back to the fuel (dimensionless)
h	convective heat transfer coefficient (W/m^2K)
$h_{V,W}$	change in enthalpy between water at storage temperature and steam at 100°C (MJ/kg)
ΔH_c	effective heat of combustion of volatile fuel (MJ/kg)
$\Delta H_{R,O2}$	heat of combustion per unit mass of oxygen consumed (MJ/kg)
L_V	heat of gasification of fuel (MJ/kg)
$\dot{m}''$	burning rate per unit area of fuel (kg/m^2s)
$\dot{m}''_{cr}$	burning rate at the critical point (kg/m^2s)
$\dot{m}''_{w;cr}$	critical water application rate (kg/m^2s)
$\dot{m}''_{w;cr,0}$	critical water application rate with no external heat flux (kg/m^2s)
dT/dx	temperature decrease per length (K/m)
q	fire load density; the relation between the fuel mass and the floor area (kg/m^2)
$\dot{q}''_E$	externally applied heat (kW/m^2)
$\dot{q}''_L$	heat losses from the fuel surface (kW/m^2)
$\dot{q}''_W$	heat lost by evaporating water (kW/m^2)
Y_{O2}	oxygen mass fraction (dimensionless)
ϕ	fraction of heat generated which must be lost for quenching the flames (dimensionless)
Φ	surface area factor; the relation between the fuel surface area and the fuel mass (m^2/kg)
λ	conductivity of fuel (W/Km)
Θ	area factor; the relation between the fuel surface area and the floor area (m^2/m^2)

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