SFPE (NZ) TECHNICAL PUBLICATION - TP 2004/1

CALCULATION METHODS FOR WATER FLOWS USED FOR FIRE FIGHTING PURPOSES

(Refer to TP 2005/2 for “Calculation Methods for Water Storage for Fire Fighting Purposes”.)
(Refer to TP 2005/3 for "Comparison of Methods used for Fire Fighting Water Supplies".)

1. INTRODUCTION

Despite the many new techniques that have come to the assistance of firemen, the properties of water enable it to be the most efficient, cheapest and readily available medium for extinguishing the majority of fires [1]. Water has the highest heat-absorbing capacity of any of the common substances. Water's ability to absorb great quantities of heat makes it a very important fire-fighting tool. Most fires are extinguished with water. Exposed structures near the fire can also be protected by cooling them with water spray. The two most important physical properties of water are its ability to expand into steam when heated above 100°C and its ability to absorb heat both as water and vapour. These properties need to be examined in detail to explain the importance of water as a fire fighting resource in the fire extinguishing process [2]. Fires also fall into two basic types being either (a) three dimensional gaseous ventilation controlled (VC) fires or (b) two dimensional fuel surface controlled (FC) fires [3]. The point where VC fires change to FC fires has been termed the “*FC/VC Changeover Point*”.

2. PROPERTIES OF WATER

The unique properties of water that are useful in fighting fires are:-

(a) Volumetric Expansion.
(b) Heat Absorption Capacity which can be sub-divided into three categories:-
  (i) Specific Heat as water;
  (ii) Latent Heat of Vaporisation;
  (iii) Specific Heat as water vapour.

3. VOLUMETRIC EXPANSION

Water can be used to smother fire by converting the water into steam. Once water has absorbed sufficient heat to convert it from a liquid to steam, it expands as a vapour. The volume of steam produced at 100°C is approximately 1,600 times the original liquid volume. The volume continues to increase as the temperature increases beyond 100°C. Table 1 lists expansion rates for water at selected temperatures of 100°C and above. Refer also to Figure 1.

Temperature °C	Volume of Vapour Produced litres	Volume of Vapour Produced m^3/ℓ of water
100	1,600	1.6
200	2,060	2.0
300	2,520	2.5
400	2,980	3.0
500	3,440	3.4
600	3,900	3.9

Table 1. Expansion rates for 1 litre of water to vapour

Fire fighters can use this high expansion property of water to fill a room with steam that replaces the air. In addition, the water itself absorbs heat. Thus at the same time a fire can be smothered and cooled by the combined process of steam production and heat absorption.

Steam generated from a fire fighters hose does more than simply fill the area immediately involved. If 1 m³ of steam is produced for each 1 m³ of air, the level of oxygen in the mixture becomes half that for normal air. The steam can follow the same path taken into the fire by the air itself and can then extinguish fire at locations well away from the original application site. Water, if applied appropriately, can save fire fighters unnecessary work on the fire ground. It can enable them to extinguish a fire from the perimeter of a danger area.

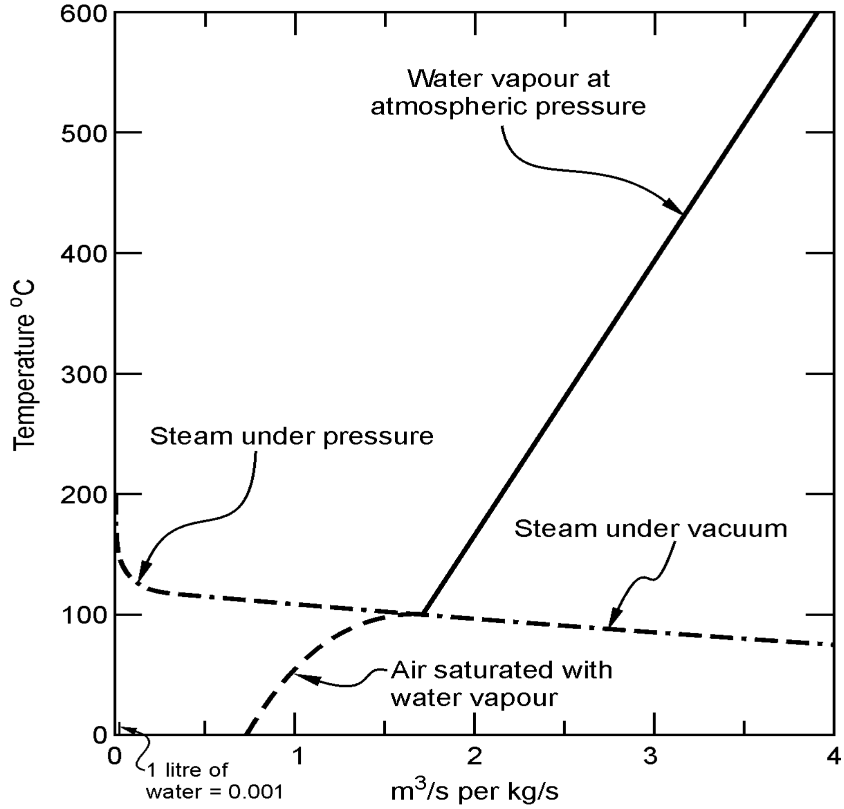

Figure 1: Volume of water after being applied to a fire at the rate of 1 ℓ/s and heated to vapour at fire temperature [4][5].

Example 3.1

Determine the time required for a 10 ℓ/s fog nozzle to fill a room 6 m by 6 m by 3 m if the water is converted to steam at 100°C. Assume that steam conversion is instantaneous and perfect. The conversion rate is conservatively taken 1.6 m³/ℓ (see Table 1).

Room volume	=	6 m x 6 m x 3 m	=	108 m³
Expansion rate	=	10 ℓ/s x 1.6 m³/ℓ	=	16 m³/s
Time to fill	=	108 m³/16 m³/s	=	6.7 seconds

Example 3.2

Determine the time required for a 10 ℓ/s fog nozzle to fill a room 6 m by 6 m by 3 m if the water is converted to water vapour at 300°C. Assume that vapour conversion is instantaneous and perfect. The conversion rate is 2.5 m³/ℓ (see Table 1).

Room volume	=	6 m x 6 m x 3 m	=	108 m³
Expansion rate	=	10 ℓ/s x 2.5 m³/ℓ	=	25 m³/s
Time to fill	=	108 m³/25 m³/s	=	4.3 seconds

4. SPECIFIC HEAT

Specific heat is the amount of heat required to raise 1 gram (g) of a substance by 1 degree Celsius (°C). Specific heat is expressed in Joules (J). The specific heat capacity of water varies slightly from 0°C to 100°C, but at 18°C it is 4.183 kJ/kg°C [2][6]. 18°C is selected because it is the typical temperature of water when it comes from an underground water main.

<u>Example 4.1</u>
Determine how much heat will be absorbed in raising 10 kg of water from 18°C to 100°C.

$$E_{ab} = 4.183 \text{ kJ/kg°C} \times 10 \text{ kg} \times (100°C - 18°C) = 3{,}430 \text{ kJ}$$

Specific heat capacity is expressed in J/kg.K or J/kg.C.

5. LATENT HEAT OF VAPORISATION

The latent heat of vaporisation is the amount of heat required to change a liquid into a vapour without a change in temperature. For water, this is 2,257 kJ/kg [6].

Water does not boil immediately upon reaching its boiling temperature (100°C at sea level). Once boiling point is reached, the water must absorb additional heat energy to convert the water into a vapour. This is the latent heat of vaporisation. Of the unique properties of water, this one is the most valuable as a fire protection tool.

<u>Example 5.1</u>
Determine how much heat will be absorbed if 1 kg of water at an initial temperature of 18°C is perfectly converted to steam at 100°C:-

$$\begin{aligned} E_{ab} &= 4.183 \text{ kJ/kg} \times (1 \text{ kg}) \times (100°C - 18°C) + 2{,}257 \text{ kJ/kg} \times (1 \text{ kg}) \\ &= 343 \text{ kJ} + 2{,}257 \text{ kJ} \\ &= 2{,}600 \text{ kJ} \\ &= \underline{2.6 \text{ MJ}} \end{aligned}$$

6. COMBINED SPECIFIC HEAT AND LATENT HEAT

The final effect of water upon a fire is a combination of specific heat and latent heat of vaporisation. We have to compute the total amount of heat absorbed by a unit of water when raised from its initial temperature in a water main to the temperature of the fire gas. The total heat absorbed occurs in three stages:-

(a) Specific heat multiplied by the mass of water and the increase in temperature to reach boiling temperature at 100°C;
(b) Plus, the product of latent heat of vaporisation at 100°C multiplied by the mass of water;
(c) Plus, the specific heat of steam multiplied by the mass of steam and the increase in temperature from 100°C to the temperature of the fire gas. The combined equation is:-

$$\underline{E_{ab} = c_1.W(T_2 - T_1) + L.W + c_2.W(T_3 - T_2)} \text{ ....kJ} \qquad \text{(Eq. 1)}$$

where
E_{ab} = total heat energy absorbed, in kJ
c_1 = average specific heat capacity of water between 18°C and 100°C = 4.183 kJ/kg°C
L = latent heat of vaporisation of water at 100°C = 2,257 kJ/kg
c_2 = average specific heat of vapour between 100 and 300°C = 4.090 kJ/kg°C
W = mass, in kilograms
T_1 = initial temperature, in °C
T_2 = boiling point of water, 100°C
T_3 = final temperature, in °C (for practical reasons use 300°C as a maximum).

Refer to Figure 2.

<u>Example 6.1</u>
Determine how much heat will be absorbed if 1 kg of water at 18°C is perfectly converted to water vapour at 300°C:-

$$
\begin{aligned}
E_{ab} &= 4.183 \text{ kJ/kg x (1 kg) x (100°C - 18°C)} + 2{,}257 \text{ kJ/kg x (1 kg)} \\
&\quad + 4.090 \text{ kJ/kg x (1 kg) x (300°C - 100°C)} \\
&= 343 \text{ kJ} + 2{,}257 \text{ kJ} + 818 \text{ kJ} \\
&= 3.418 \text{ kJ} \\
&= \underline{3.4 \text{ MJ}}
\end{aligned}
$$

This is illustrated graphically in Fig. 2.

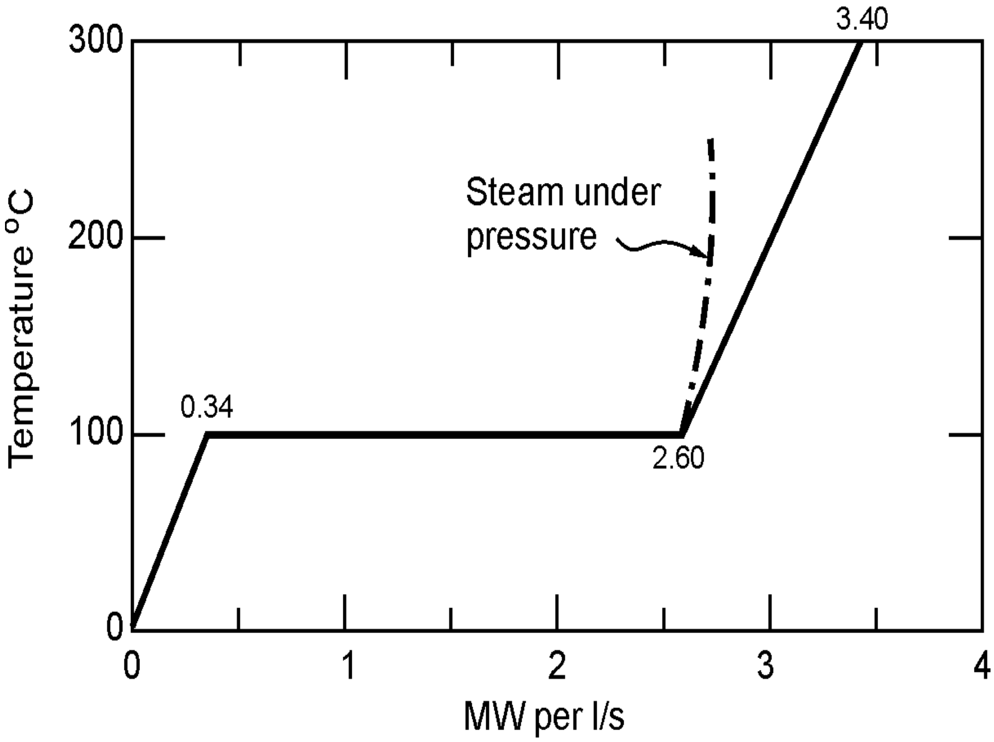

Figure 2: Cooling power of water at 18°C applied to a fire at the rate of 1 ℓ/s [4][5].

The information in Table 2 below indicates that 1 kg of water, converted to steam as in Example 6.1 above, would be an insufficient amount to absorb the heat released by 1 kg of any of the fuels listed. The result however is different when water is applied to a fire in typical fire fighting rates in kilograms of water per second, that is, litres per second.

Substance	MJ/kg
Wood	16
Polyurethane	23
Coal	29
Rubber Tyres	32
Gasoline	45

Table 2: Nett Heat of Combustion values for selected common fuels.

In example 6.1 above it was determined that 1 kg of water when boiled at 100°C from an initial temperature of 18°C can absorb 2.6 MJ. Put another way, for each MJ of fuel in the fire load a fire-fighter theoretically needs 1/2.6 or 0.38 kg of water as steam at 100°C to absorb the heat output of each MJ in the fuel.

As a further example, each ℓ/s (kg/s) of water vapour at 300°C fed into a fire is theoretically capable of absorbing 3.4 MW of fire intensity as shown in Fig. 2 above.

From this it will be apparent that 5 kg of water, as water vapour at 300°C, has the theoretical capacity to absorb 5 x 3.4 = 17 MJ. This is enough to absorb the heat generated by 1 kg of wood or 16 MJ when burnt in a fire. It will also be apparent that 14 kg of water has the capacity to absorb the heat generated by 1 kg of gasoline. (Table 2).

What has been expressed above can be shown diagrammatically as in Fig. 3 below. However this is a very simplistic view of the problem as it does not indicate the efficiencies of the cooling and heating process.

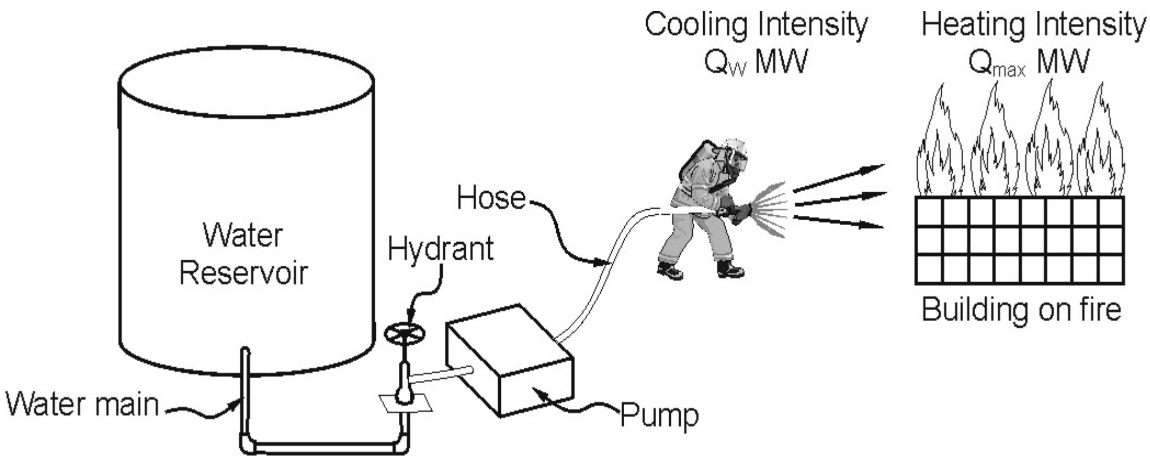

Figure 3: Simplified fire fighting diagram. A more realistic approach is shown in Fig. 5 where factors for inefficiencies have been introduced.

7. RULE-OF-THUMB FORMULA

[Kimball [7] refers to a conservative rule-of-thumb formula often used by fire fighters in the USA to overwhelm a fire in a totally involved space using a jet nozzle. This says that the cubic footage of the space divided by 100, then multiplied by 3 equals the flow required in US GPM.

Example 7.1 - US Fire Service System [2] [7]
Determine what flow in US GPM would be needed for a room 20 ft x 20 ft x 10 ft:-

F = (20 ft x 20 ft x 10 ft) / 100 x 3 = 120 US GPM

Example 7.2 - Metric System
There is an equivalent rule of thumb in the metric system. This says that the volume of the space in metres³, divided by 15, equals the flow required in ℓ/s. If we convert the feet measurements in Example 7.1, to metric values, then the flow needed for a room 6.1 m x 6.1 m x 3.1 m would be:-

F = (6.1 m x 6.1 m x 3.1 m) / 15 = 7.7 ℓ/s (= 122 US GPM)

8. EFFICIENCY IN FIRES

Water can never be applied at 100% efficiency for various reasons, and most building fires do not retain 100% of the heat energy in the room where the fire is occurring. The net result is that both the energy absorption of the water flow available and the energy production of the fire need to be modified by the following efficiency factors.

These can be expressed as:-

(a) heat absorption efficiency of a water main;
(b) heat production efficiency of a building fire.

9. HEAT ABSORPTION EFFICIENCY OF WATER FLOW FROM A FIRE MAIN

The heat absorption described thus far illustrates perfect conditions for the absorption of heat by the water. On the fire ground, the application of water from a fire main into a fire rarely approaches 100% efficiency in most cases. Unlike a laboratory test, there will always be inefficiencies in the application of water to a building fire, except in small fires. The area of the footprint of a hose jet fired through a window may often cover only a part of the burning area of a large fire inside the building but providing extra water will not solve this problem which is one of geometry. Water may also be used to cool down smoke gases and hot surfaces to enable a fireman to approach closer to the actual fire.

Parts of the fire may have to be extinguished first to enable the firemen to reposition to carry out the extinction of other parts of the fire. Water may also be used to wet down exposed combustible surfaces not yet involved in the fire, such as neighbouring buildings, etc. As little as 20% of the water flow may actually strike the burning fuel surface [8]. If k_w is taken as the cooling efficiency of a water flow, then a figure of 50% is recommended for jet nozzle use in TP 2004/1. Even if a fire fighting team does manage to use the water flow efficiently, for the design of water mains is recommended that 50% should be allowed for suppression plus 50% extra to cover exposures, leaks, strong wind, accessibility, etc.

This is shown In simplified terms in Fig. 5 and can be expressed as:-

$$Q_W = Q_S + Q_X \ldots\ldots\ldots\ldots \text{MW}$$

Where Q_W = Theoretical heat absorption capacity of the available water main flow

Q_S = Heat absorption in the water used directly on the fire for suppression

Q_X = Heat absorption in the extra water not used directly on the fire

Example 9.1

Find the total heat energy absorption capacity of a 12.5 ℓ/s water main if the water is initially at 18°C, assuming that perfect steam conversion is accomplished at 100°C:-

Q_S = 12.5 ℓ/s x 2.6 MJ/ℓ x 1.00 = 32.5 MW

Example 9.2

If the efficiency k_w of a 12.5 ℓ/s water main means only 75% is available for suppression via a fog nozzle find the total heat energy absorbed.

Q_S = 12.5 ℓ/s x 2.6 MJ/ℓ x 0.75 = 24.4 MW

Example 9.3

If the efficiency k_w of a 12.5 ℓ/s water main means only 50% is available for suppression via a hose nozzle, find the total heat energy absorbed.

Q_S = 12.5 ℓ/s x 2.6 MJ/ℓ x 0.50 = 16.3 MW

Example 9.4
An office type of fire burning at 100% efficiency would have an average release heat rate of approximately 0.25 MW for each square metre of area. Determining Q_{max}, the amount of heat released for this fire in a space measuring 100 m^2, we find:

$$Q_{max} = \quad 100\ m^2 \times 0.25\ MW/m^2 = 25.0\ \underline{MW}$$

If the foregoing is true, one hand line delivering 12.5 ℓ/s in a fog pattern at k_w = 75% efficiency could deliver just enough water flow to control and extinguish this fire burning at 100% efficiency. See Example 9.2 above. But Example 9.3 above shows that using the jet nozzle at k_w = 50% efficiency means that it will not be able to control the above fire. However if the fire burns at less than 100% efficiency, as will be explained later, then 12.5 ℓ/s from the water main may be more than sufficient water to control and extinguish this fire.

10 HEAT PRODUCTION EFFICIENCY OF A BUILDING FIRE

Combustion, or burning, causes chemical reactions between the oxygen (generally supplied as air) and the combustible material (generally hydrogen or carbon or hydro-carbon compounds of these elements), which reactions generate heat. Combustion of hydrocarbon fuel is brought about by the combustion of the hydrogen (H) and carbon (C) in the fuel with the oxygen (O) contained in the air (and/or in the fuel). The combination of hydrogen with oxygen forms water vapour (H_2O) that carries away with it some of the heat generated and causes some of the difference between the gross and nett "heat of combustion" value of a fuel. Combustion Engineers tend to work in "gross" values whereas Fire Engineers tend to work in "nett" values. Fig. 4 below is a typical Combustion Engineer's diagram based on "gross" values.

So far as combustion is concerned, only the oxygen is of value. The nitrogen being a dilutent plays no useful part in the combustion process and is merely a "passenger". Table 3 shows the properties of nitrogen and oxygen in air. Both the oxygen and the nitrogen have to be heated up to the temperature of the products of combustion and thus each gas absorbs and carries away some of the heat generated. The higher the exit temperature of the smoke, the greater will be the heat loss via these two components in the smoke.

	By Volume		By Weight	
	percent	ratio	percent	ratio
Nitrogen	79.0	3.76	76.8	3.31
Oxygen	21.0	1.00	23.2	1.00

Table 3: Approximate proportions of nitrogen and oxygen in air.

Fig. 4 illustrates the changes a building fire goes through as it grows in size. When a small fire first ignites in a building, the air supply will be in excess and the airflow ratio will be between 2 and 3, at say near point B. As the fire grows in size, the relative airflow ratio falls to the point where the air supply is controlled by the size of the available openings. The airflow ratio decreases with increasing fire size from B to C to D and finally finishes up somewhere between D and E. Only for a small part of the growth will the fire efficiency be close to the suggested conservative design value of k_F = 0.50. After growth is completed, the fuel efficiency factor could well lie between E and D, that is between 0.15 and 0.45 for the remainder of the fire duration.

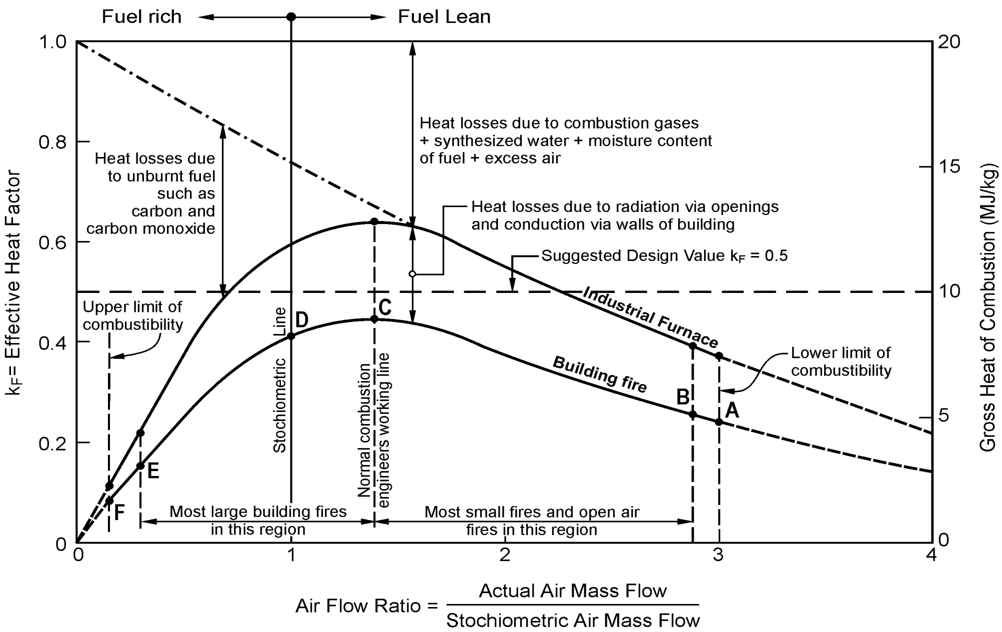

Figure 4: Combustion diagram for a typical air-dry wood fuel showing relationship between gross heat of combustion and air-flow. For a building fire the effective heat coefficient k_F rarely exceeds 0.45 thus a k_F value of 0.50 can be considered a conservative and upper limiting value for design purposes. [Modified from Fig 5 of Ref. [9]).

For example, if the burning rate of air-dry wood fuel is 1 kg/s and this requires say 5 kg/s of air for complete or stoichiometric combustion; this air will absorb 4.6 MW of heat flow, representing 26% of the gross heat of combustion value of the fuel. This is illustrated by the stoichiometric point D on Fig. 4 where the air flow ratio is 1. If the air supply is almost trebled to say point B on Fig. 4, the surplus air becomes a “passenger”, and if say the exit temperature of the smoke falls to 600°C, then the heat potential removed from the combustion zone by the "combusted" air plus the "passenger" air rises to 35% of the fuel's gross calorific value.

In an oxygen-rich (or fuel-lean) atmosphere, excess air is present. This air not only can carry away large quantities of heat, but the higher the temperature, the greater the heat loss. The exit temperature from a steam boiler furnace might be deliberately kept by the Combustion (Boiler) Engineer as low as possible, say 250°C, whereas in a fully developed building fire the temperature may range from 600 to 1200°C.

When carbon burns completely, such as in an oxygen-rich (or fuel lean) atmosphere, it results in the formation of a gas, namely carbon-dioxide (CO_2). As a hot gas this also carries away some of the potential heat energy in the fuel. When carbon burns incompletely, such as in an oxygen deficient (or fuel-rich) atmosphere, it may produce three outcomes:-

Firstly, it may form carbon dioxide (CO_2) in the oxygen rich areas of the fire, which subsequently combines with further carbon in the oxygen deficient areas of the fire and this downgrades into carbon monoxide. This second reaction results in the "absorption" of heat from the hot fuel bed and surroundings producing a temperature drop and a slowing down in the rate-of-burning.

Secondly, it may form carbon monoxide (CO). This compared with carbon dioxide contains only half the amount of oxygen per unit weight of carbon. If unburnt, the carbon monoxide carries away unused, some of the potential heat energy which was in the fuel.

Thirdly, in a fuel-rich atmosphere, carbon alone may be distilled from the fuel by the heat of the fire. The unburnt carbon particles can be referred to as “excess pyrolysate”. If it moves out through the openings as black smoke, which is typically the case, it will carry with it a considerable amount of potential heat energy in the fuel that will not be burnt within the building.

The dynamic viscosity of air at 20°C is 18 μPa.s. Air becomes more viscous as it is heated. At 800°C the viscosity rises to 44 μPa.s, which is 2.44 times the value at 20°C. While frequently not recognised as an important factor in fire engineering, the increased viscosity of heated air will enable it to hold in suspension and carry off more smoke and uncombusted fuel particles as excess pyrolysate than might otherwise be expected.

Wood contains about 50% carbon and 6% hydrogen. When wood is burning, each of these two fuels is competing for oxygen supply. Carbon, if converted to carbon dioxide, has a calorific value just under one quarter of that of hydrogen and one-sixteenth if only converted to carbon monoxide. Each is converted to a gas as the wood is burnt. Thus, if each square metre surface of solid wood is burning at the rate of 40 mm/hr = 23 kg/h.m^2, it would release 11.5 kg/h.m^2 of carbon and 14 kg/h.m^2 of hydrogen. In hourly gas production terms, these represent about 102 m^3 of carbon dioxide and 27 m^3 of hydrogen.

Wood also contains about 40% "in built" oxygen, whereas some fuels have none at all. For instance, gunpowder contains all the oxygen it requires for combustion within itself, but many liquid fuels and plastics contain none at all. The fresh-air demands can thus vary widely between fuels. Many fire engineering design methods based on rate-of-burning formulae derived from experiments on wood, are not always applicable to other fuels.

Most fires occur in fuels in their natural state. For example, timber in buildings has a natural moisture content in the region of 10 to 15% of its oven-dry weight. Not only is this water driven off during combustion taking away heat in the form of vaporisation energy and steam heat, but the potential heat energy of the fuel is downgraded by 10 to 15% depending on the moisture content.

In industry the Combustion Engineer controls combustion in such a manner that the process is efficient as possible. Not only is the maximum amount of useful heat obtained from the fuel, but also the maximum possible heat is absorbed into the industrial process and the minimum is allowed to be wasted by radiation through openings, or conduction through walls and ceilings, or up the chimney. This is shown as the upper curve in Fig. 4.

In a building fire there is no control over the efficiency of the combustion process. A large proportion of the energy released from the fuel may not be burnt within the building and will escape out the openings in the form of hot gas, hot unburned fuel, hot excess air, hot synthesized moisture, hot natural moisture, and radiation. From a fireman's point of view, the more energy that flows out via the openings, the less remaining energy there will be to affect the structure and the less will be the water required inside the building. There is little point in a fireman using a hose to put water on these external flames or smoke.

Heat energy can also flow through openings in the form of radiation. Industrial furnaces limit the amount of openings in the furnace for this reason and might keep the radiation loss as low as 1%. In building fires, the radiation which escapes via the openings or from the exterior surfaces of the hot walls and ceilings and can be as much as 10% to 20% of the heat potential in the fire load.

As stated above building fires rarely burn at 100% efficiency. According to Hamarthy [10], the heat production efficiency coefficient "k_F" for building fires can range from 0.50 down to 0.10, that is 50% to 10%. Wood at normal moisture content in buildings has a gross heat of combustion value of 20 MJ/kg, a nett heat of combustion value of about 17.5 MJ/kg and after allowing for some residual ash, the value drops to about 16.8 MJ/kg. A k_F factor of 0.50 represents a calorific contribution of 8.4 MJ/kg, or roughly 50% of that available in wood at normal moisture content. Thus normal wood burning in a building of average ventilation characteristics would contribute an effective heat flow into or via the structure of only 8.4 MJ/kg. The balance of the fuel energy (8.4 MJ/kg) would escape via the openings.

The fuel being released during the fire can be determined as mass loss rate R in kg/s. By multiplying R by the nett heat of combustion of the fuel H'n in MJ/kg, the mass loss rate R can then be converted into total energy loss Q in MW.

Complete combustion occurs as a chemical reaction and as such follows normal laws for molecular reaction, both for chemical change and rate-of-change. Perfect combustion depends on an optimum air mass M to fuel mass R ratio, termed the stoichiometric ratio "S". Thus S = M/R.

Incomplete combustion results when insufficient or excess air is available. Below or above certain limits of air termed the upper and lower limits of combustibility (refer to points F and A in Fig. 4), the fuel will not burn. Inside these limits the M/R ratio can vary below and above S. Assuming suffix $_B$ represents fuel burnt inside, suffix $_{UB}$ represents unburnt fuel exported outside, M = total air flow, M_B = stoichiometric air, M_{UB} = passenger air, R = total fuel pyrolysed, R_B = actual fuel combusted and R_{UB} = uncombusted but pyrolysed fuel, then:-

$$\frac{M}{R} = \frac{M_B + M_{UB}}{R_B + R_{UB}}$$

When M/R is less than S, the burning atmosphere is fuel-rich and $M_{UB} = 0$. When M/R is greater than S, the burning atmosphere is fuel-lean and $R_{UB} = 0$. In simplified terms:-

$R_{max} = R_B + R_{UB}$ .... kg/s

or $Q_{max} = Q_B + Q_{UB}$..MW

The fireman only needs to provide water equal to or greater than the heat energy Q_B being released in the fire inside the building. Even though Q_{UB} is being released by the pyrolisation process of the fire, it provides no heat energy within the building. The question is what are the proportions of Q_B and Q_{UB} in a typical building fire? Hamarthy [10] quotes values for Q_{UB} as high as 90%. Hamarthy states "***A striking feature of the heat balance data is that a very large portion of the energy contained in the fuel, normally from 50 to 90 percent, leaves the compartment in the form of chemical energy and/or sensible heat of gases***." In general terms Q_{UB} can be assumed to be high when a fire compartment is poorly ventilated.

Calculating building fire efficiencies is beyond the scope of this SFPE Technical Report, but in most fires and especially ventilation controlled fires, 50% can be taken as being conservative for the value of Q_{UB} in simple fire engineering design. That is Q_B and Q_{UB} would each have a value of 0.50 times the value of Q_{max}. For specific fire engineering design, a variable k_F factor ranging from say 0.15 to 0.50 could be calculated. See also points E and C on the lower curve in Fig. 4.

11 COMBINING EFFICIENCIES OF WATER MAINS AND BUILDING FIRES

Combining the efficiencies of both water mains and fires can be done as follows:

Example 11.1

If the efficient use of a water main at 12.5 ℓ/s is only 50%, as in Example 9.3, and the combustion efficiency of the fire is only 50%, find the total energy that can be absorbed from the water main:-

$$Q_S = 12.5\ \ell/s \times (0.50 \times 2.6\ MJ/kg) / 0.50 = 32.5\ \underline{MW}$$

Or by re-arranging the equation the amount of water required will be:-

$$F = (0.50 \times 32.5\ MW) / (0.50 \times 2.6\ MJ/kg) = 12.5\ \underline{\ell/s}$$

As a general equation, the required flow will be as follows:-

$$F = \frac{k_F \times Q_{max}}{k_W \times Q_W} \text{ .... l/s} \qquad \text{(Eq. 2)}$$

where F = fire fighting water flow in ℓ/s
k_F = heating efficiency of fire (conservatively 0.50)
k_W = cooling efficiency of available water (conservatively 0.50 for a water main)
Q_{max} = maximum heat output of fire in MW
Q_W = absorptive capacity of water at 100°C = 2.6 MW/ℓ/s.

In simple terms this means that for each MW of Q_{max} in a fire, the fire fighting water flow, will need to be 0.50 / (0.50 x 2.6 MJ/kg) = 0.385 ℓ/s/MW of Q_{max}.

As an equation this becomes:-

$$F = 0.385 \ \ell\text{/s/MW of } Q_{max} \text{ .... } \qquad \text{(Eq. 3)}$$

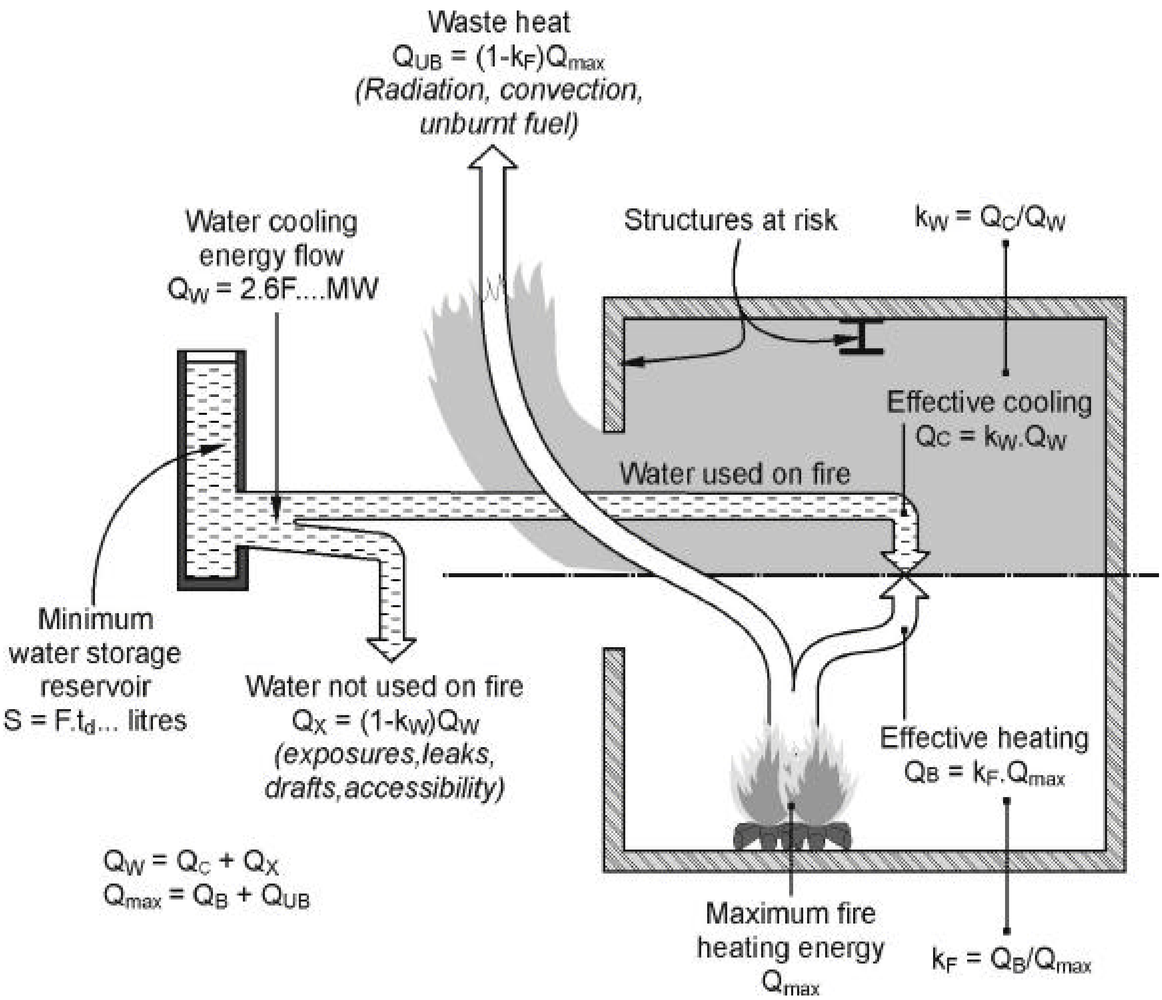

Figure 5: Diagram illustrating thermal balance between effective heating Q_B and effective cooling Q_C after other heat and water losses are considered. [11]

12. ANALYSIS

Using Eq.3, an extensive study of various floor areas, ventilation opening ratios and fire load energy densities (FLED's) was carried out resulting in over 700 pages of calculations and graphs. The floor areas ranged from 100 to 5000 m². FLED's selected were 400, 800 and 1200 MJ/m^2. Ventilation openings ranged from 2 to 20% of floor area. Stud heights ranged from 2.4 to 6.0 m using the former for small buildings and the latter for large. Growth and decay coefficients were selected as 225 and 900 s/MW respectively (that is between moderate and fast). Nett heat of combustion was selected as 18 MJ/kg to cover a mix of wood and plastic. It was noted that the fires were ventilation controlled (VC) at the low end of percentage openings but, as the ventilation increased a point was reached within the 2 to 20% range where the fires changed over to fuel surface controlled (FC) burning. For convenience this point has been given the name "***FC/VC changeover point***". The fire intensity did not increase from that point onward regardless of any further increase in ventilation openings. It was therefore found that the greatest fire intensity Q_{max} occurred at the FC/VC changeover point. This was then taken as the most conservative answer for that particular floor area and the corresponding design fire fighting water flow was calculated. By using Equations (4) and (5) from Ref. [11], Q_{max} can be eliminated from Eq. (3) above resulting in the more useful formula as shown in Eq. (4) below. It is more useful because it only involves E the total fire load in MJ where E = FLED x Floor Area:-

$F = 0.00741 \times E^{0.666}$ .... l/s (Eq. 4)

This was then used to produce Appendix A attached.

As a further useful guide, Appendix B from Ref. [1] gives flows through typical pipe sizes used as water mains in streets. This in turn can be used to determine the maximum FLED a given water main size can protect.

13. SUMMARY

Water is a very important tool in fire suppression. The ability of fire fighters to deliver water into a fire in sufficient volumes, safely and at maximum efficiency, is a prime consideration.

Water has the greatest heat-absorbing capacity of the common substances. 1 kg of water at an initial temperature of 18°C converted to steam at 100°C will absorb 2.6 MJ of heat energy. Based on this property alone, it can be calculated that using a water main at a conservative 50% efficiency to control a fire burning at a conservative 50% efficiency, a fire fighting water flow of $F = 0.385\ \ell/s/MW$ of Q_{max} will be needed.

Alternatively and depending on the growth and decay coefficients selected for the design fire, a fire fighting water flow of $F = 0.00741\ E^{0.666}\ \ell/s$ will be needed.

Further useful properties of water which are not included in the above fire fighting water flow calculation and therefore become extra bonuses are:-

(a) an extra 1.0 MJ of heat absorption per kg of water will be available if the steam temperature rises from 100°C to 300°C as it would normally do in a fire,
(b) if the more modern fog nozzle is used instead of a jet nozzle, the water available from a water main will result in more effective suppression, and
(c) because of water's ability to expand when it becomes steam, thereby displacing oxygen and starving the fire, 1 litre of water will create a steam volume of 1.6 m³ when heated to 100°C, and 3.9 m³ when heated to 600°C.

Cliff Barnett
FSFPE, Dist FIPENZ
Past Pres SFPE NZ Chapt

REFERENCES:

[1] Barnett, C R – "Water Supply for Fire Fighting Purposes", Proceedings of 50th Jubilee Year Conference, Institution of Fire Engineers, New Zealand Branch (1979);

[2] Cozad F Dale – "Water Supply for Fire Protection", Prentice-Hall Inc., Englewood, Cliffs, NJ (1981);

[3] Grimwood, P – "Changing Tactics", FEJ and FP Journal, May (2004).

[4] Barnett, C R – "Fire Compartment Sizing Design Method", International Symposium on Fire Engineering for Building Structures and Safety, The Institution of Engineers, Australia, Melbourne (1989);

[5] Barnett, et al – "Fire Safety in Tall Buildings", McGraw Hill Inc, New York, Chapter 10 (1992).

[6] Rose, J W and Cooper, JR – "Technical Data on Fuel", published by The British National Committee, World Energy Conference, Scottish Academic Press, 7th Edition (1977);

[7] Kimball, W Y – "Fire Attack 1", National Fire Protection Association, USA (1966);

[8] Sardquist, S and Holmstedt, G – "Water for Manual Fire Suppression", Journal of Fire Protection Engineering, Vol 11, Nov (2001).

[9] Foxwell, G E, Editor – "Efficient Use of Fuel", Ministry of Power, UK, HMSO 2nd Ed, (1958).

[10] Hamarthy, T Z – "Fire Technology" 8, Pages 196 and 326 (1972).

[11] Barnett, C R – "BFD Curve" – Fire Safety Journal 37 (2002) 437-463.

Appendix A

Water Flow in l/s

Floor Area m^2	400 MJ/m^2	800 MJ/m^2	1200 MJ/m^2
0	0	0	0
100	9	14	18
200	14	22	28
300	18	28	37
400	22	34	45
500	25	40	52
600	28	45	59
800	34	55	71
1000	40	63	83
1200	45	71	94
1400	50	79	104
1600	55	87	113
1800	59	94	123
2000	63	100	132
2200	67	107	140
2400	71	113	149
2600	75	120	157
2800	79	126	165
3000	83	132	172

Flow = 0.007411 * E $^{0.666}$ ………………litres/sec……Eq. (4)

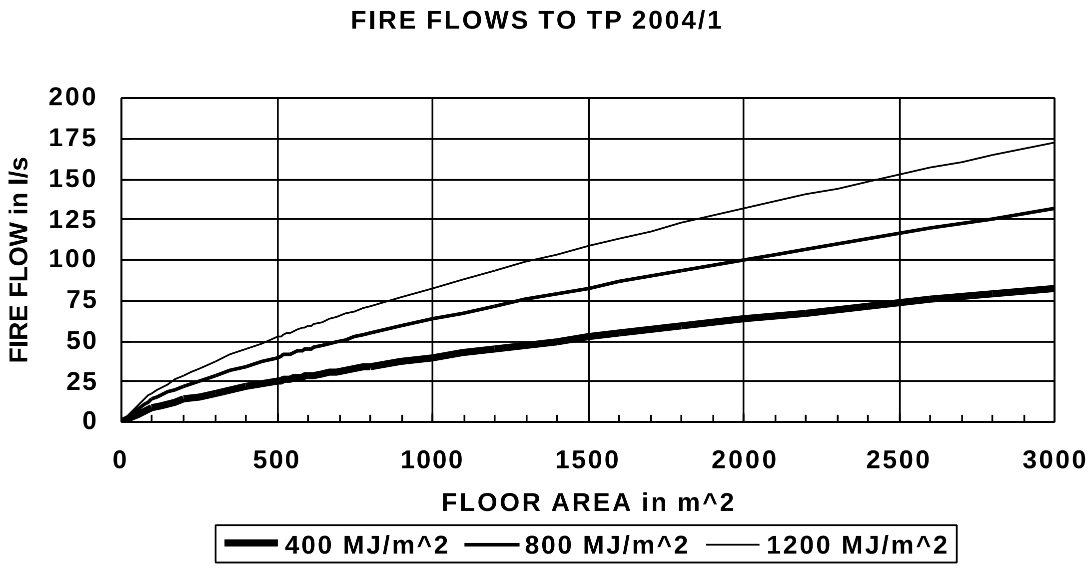

Fig. 6 Fire fighting water flows calculated as per Eq. 4. (Heating Efficiency 0.50, Cooling Efficiency 0.50, Heat of Combustion taken as 18 MJ/kg).

Appendix B

Pipe Diam	Typical Flow Looped Main	Typical Flow Single Main
mm	l/s	l/s
100	25	12.5
150	56	28
200	100	50
225	122	61
250	148	74
300	206	103
375	312	156
450	440	220

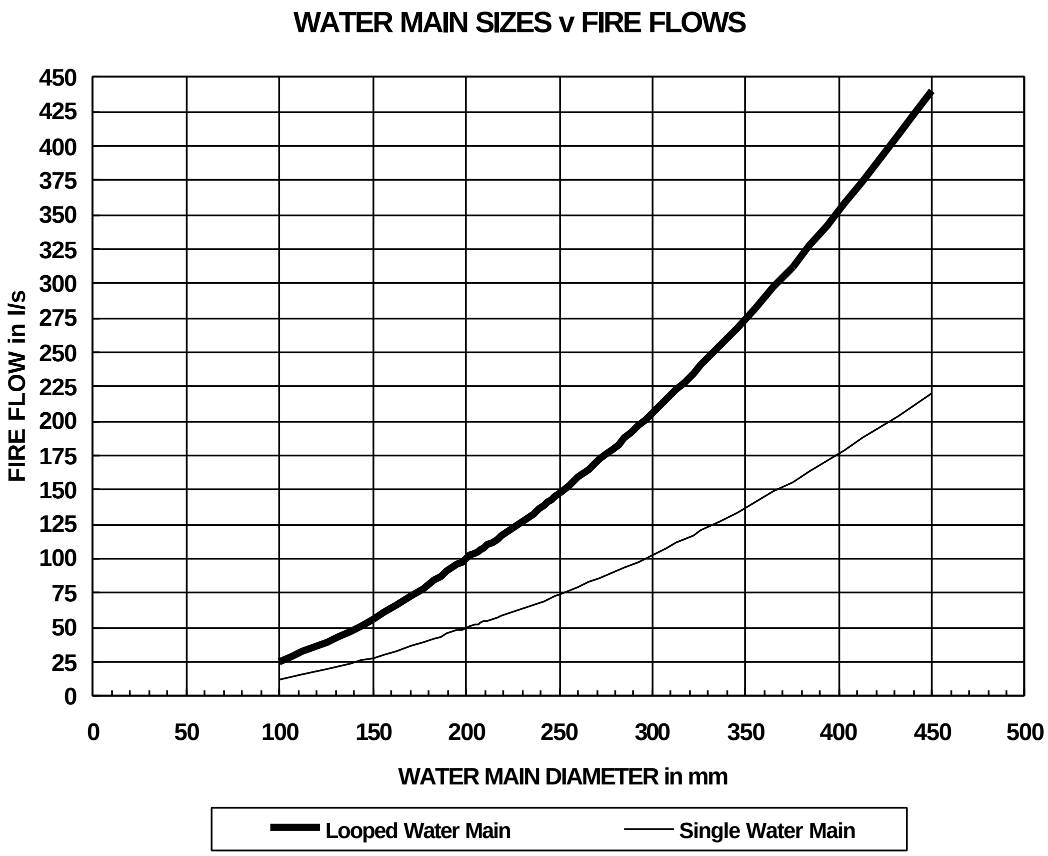

Fig. 7 **Typical flow capacities of street water mains using a nominal pipe velocity of 1.5 m/s [1]. For fire mains, Waterworks Engineers generally install looped water mains (two way flow) where possible.**