Engineering Relations for Water Mist Fire Suppression Systems

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1. Introduction

The characteristics of water mist as a fire suppressant is that it is no inert gas until it has been evaporated, which mainly occurs when the droplets are in contact with flames and hot gases. When small droplets however entrain flames, the combined action of cooling and inerting makes the water mist a very efficient fire suppressant.

The problem of designing and engineering a water mist system is mostly a mist transport problem, and the challenge for manufacturers is to design nozzles which produce water mist with optimum droplet size distribution, throw length and coverage (often denoted water application density). The design of supply lines, valves, automatic operations and water supply is more or less similar to other fire suppression systems.

This paper covers some engineering relations and important features of the fire suppression mechanisms of water mist systems, based on experimental experience.

The two main approaches to engineering the system are:

Local application, relevant for well ventilated fires, like fires in the open or small fires relative to the enclosure volume. The dimensioning parameter of this type of system is a water mist **flow rate** per unit **volume of flame** or "fire environment", i.e. a part of an enclosure.(Litres per second and cubic meter). A fraction of water per fuel release rate may also be applied for this approach (kg/s water per kg/s fuel).

Total flooding of an enclosure, relevant when air supply may be restricted. **A** specific **water fraction** based on **enclosure volume** is the dimensioning parameter (Litres of water per cubic meter enclosure volume).

2. Fire suppression mechanisms

The three main fire suppression mechanisms which are dominant in water based systems are cooling, reduction of fuel evaporation and inerting. The conditions where a flaming fire may exist is limited by temperature and fuel/oxygen concentration. In Figure 1 a correlation of reaction rate of a certain species of a reaction chain is presented as a function of temperature. The reaction rate (mass of fuel burnt per time unit) is very temperature dependent, and below a certain temperature, the reaction is slowing down. When the reaction rate decreases beyond a rate of mixing fuel and air, the reaction stops, i.e. the flaming combustion seizes.

Figure **2** shows the limits of fuel concentration in an atmosphere containing oxygen. Fuel vapour pressure along the vertical axis is equivalent to volume concentration. The lower and upper flammable limit is varying with mixture temperature. One can see that with higher temperature combustion is possible within a wider range of fuel concentration.

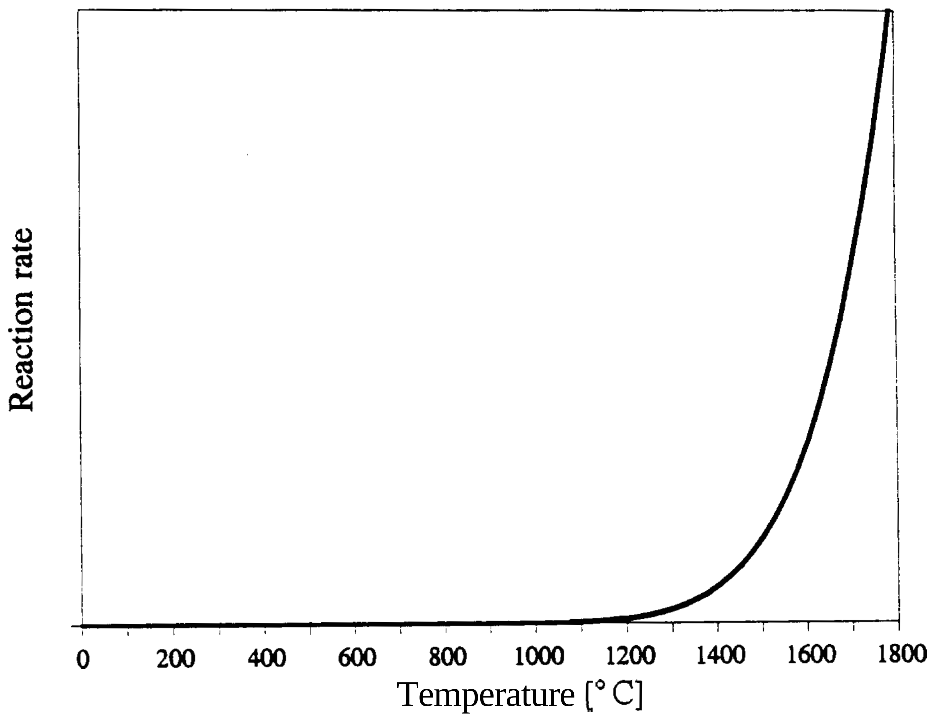

Fig. 1 Typical temperature dependence of reaction rate.

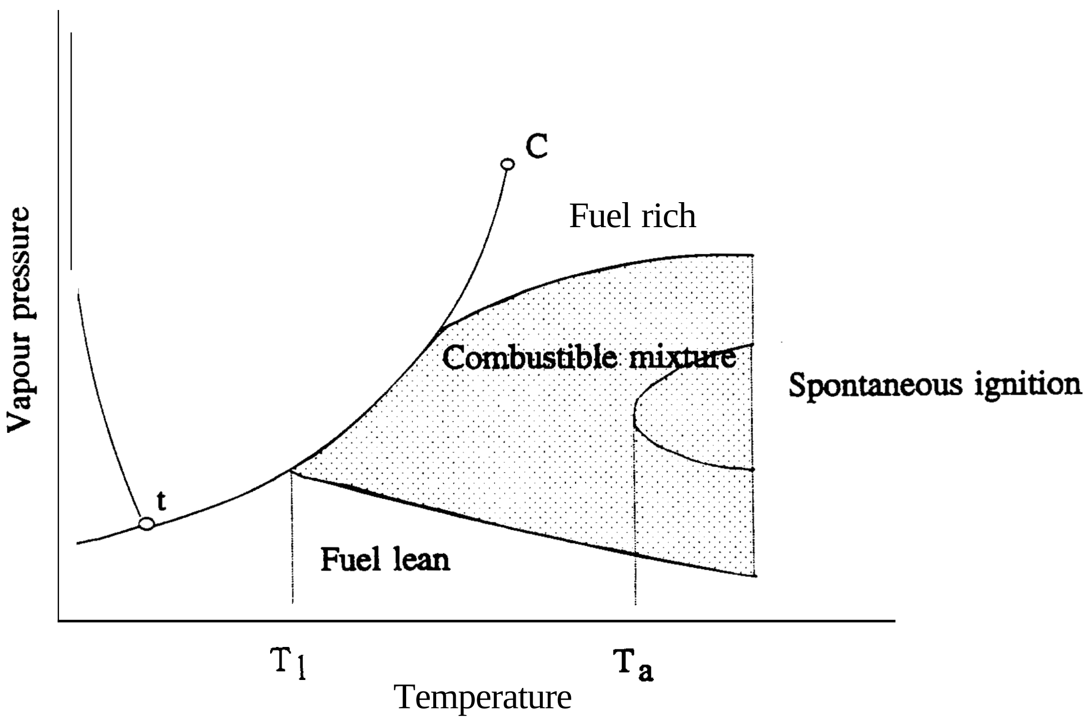

Fig. 2 Limits of fuel concentration in an oxygen containing atmosphere.

To suppress a fire which is burning with a continuous supply of fuel and oxygen, the suppression agent must limit either the fuel or the oxygen supply or reduce the temperature of the flame zone. To optimize the effect of a fire suppressant system, a combination of the effects (both cooling and inerting) is favourable. Such a combined effect is representative for a water mist suppression system.

Figure 3 illustrates schematically the two mechanisms in one chart. The example is: A fire of a certain size (constant fuel supply rate) is burning within a control volume. The oxygen concentration is shown along the vertical axis and the control volume temperature along the horizontal axis. To suppress the fire, a combination of oxygen concentration and temperature must be achieved. This limit is indicated in the chart with a line. The cooling effect of the fire suppressant brings the conditions towards lower temperature, to the left in the chart, as the inerting effect brings the conditions towards lower oxygen concentration, downwards in the chart.

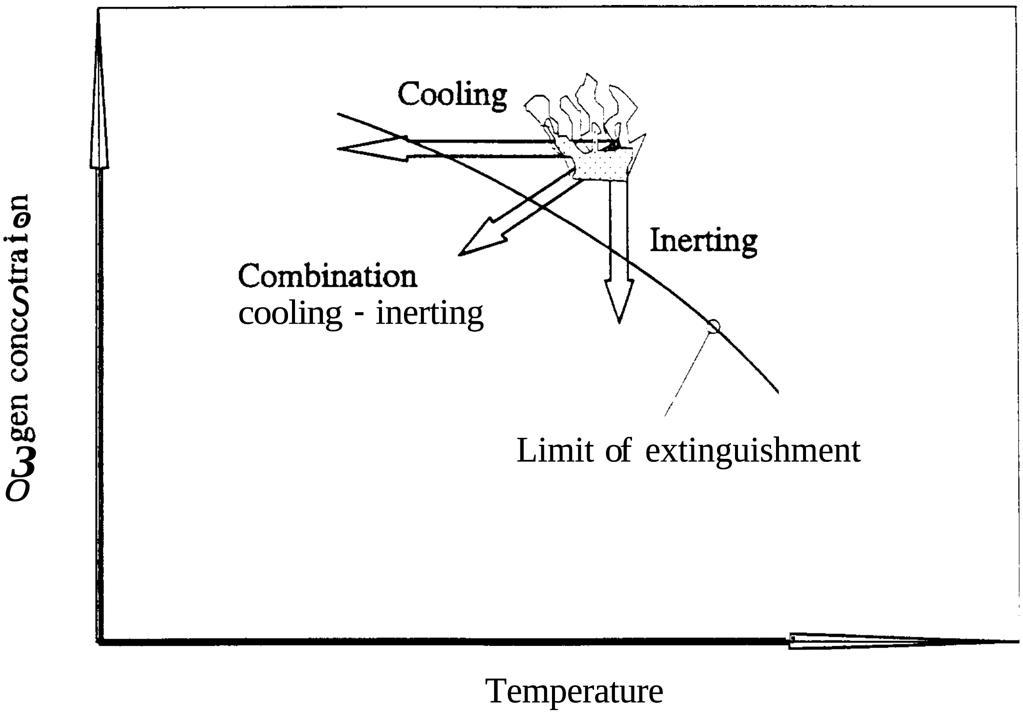

Fig. 3 The mechanisms of cooling and inerting (schematic).

Figure 4 shows the equilibrium conditions of some fire suppression agents. The different behaviour at ambient pressure explains the reason why water mist may utilize both cooling and inerting when it penetrates into a fire plume, whilst CO, and Halons immediately will evaporate at the nozzle when the pressure is reduced to ambient (1 bar). Water mist, consisting of small liquid water droplets, will not be an inert gas before it is evaporated.

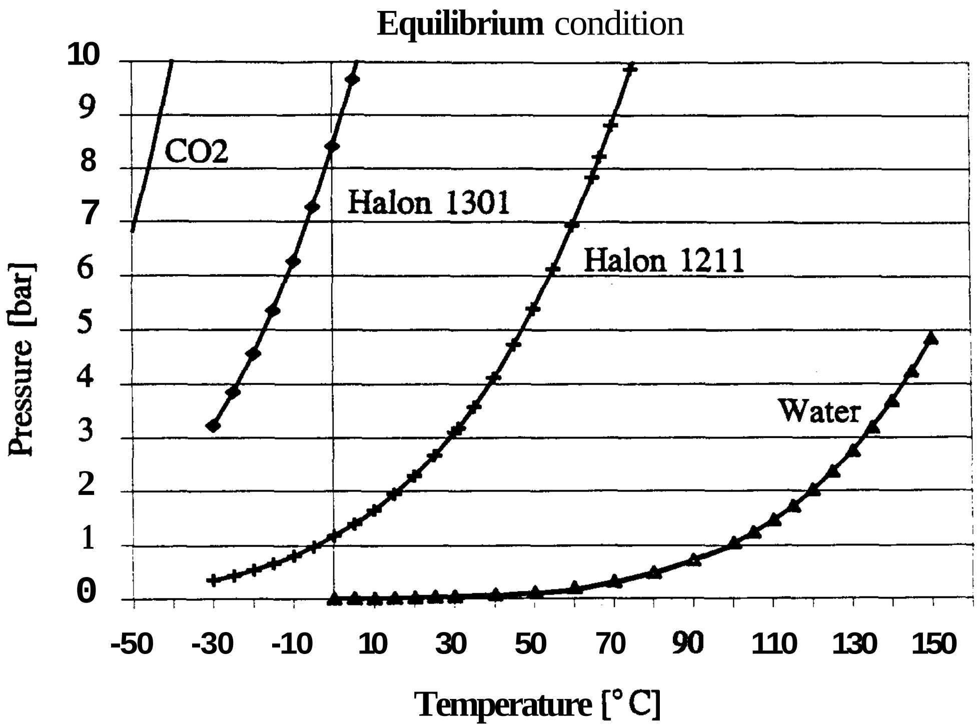

Fig. 4 Equilibrium conditions for different fire suppression agents.

3. Real fire scenarios

In idealized fire models, the conditions are considered to be more or less uniform in one control volume. This is not true, except for small volumes. **A** useful model to illustrate what happens in a fire is to suppose an air tight enclosure with a fire source inside. **As** the fire bums, the temperature increases and the oxygen concentration decreases until a critical limit for flaming fire is reached. This condition is denoted self extinguishment, and will be achieved in an air tight enclosure. Realistic enclosures are seldom totally air tight, and some supply of air is normal. The reason for self extinguishment is that the fire itself consumes oxygen and produces inert gases, mainly CO, and water vapour. The rate of oxygen consumption is decided by the fire size.

To classify real fire scenarios with regards to how complicated extinguishing is, the main parameters to consider are fire size, enclosure size, air supply options and how the fire suppressant may reach the fire.

Figure 5 illustrates four different situations of fire suppression. In all situations a liquid pool fire is used as an example, concentrating on flame extinguishing rather than reduction of fuel evaporation rate. The sketch denoted a) represents an open fire, with air supply from all sides. The only possible way to extinguish this fire with a gaseous suppressant agent is to feed the suppressant into the flaming zone at a sufficiently high rate and application density. The engineering factors of this type of system will be an application rate and the penetration ability of the spray. The position of the spray nozzles will be of great importance, since the fire may survive if any "black spots" in the spray occur. Wind influence may also be of great importance in this situation.

In the sketch denoted b) the open fire is seen in an enclosure. It is still possible to design a fire suppression system to hit a fire directly and achieve instantaneous suppression. This is a typical option if the fire sources in an enclosure are well defined by position and fire type. An example may be a fire in an engine with its fuel supply system in a large engine room. The engineering basis may then be local application with sufficient application density and penetration ability. The dimensioning factors may be similar to an outdoor fire, except for wind influence.

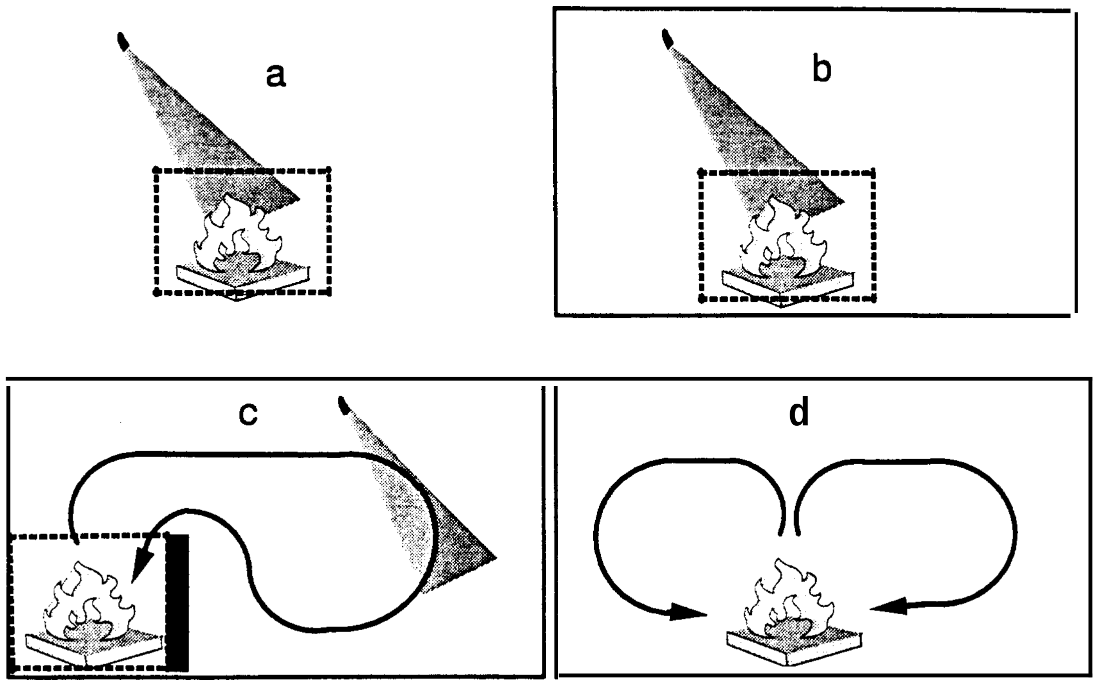

Fig. 5 Four different situations of fire suppression. a) open unconfined fire, b) enclosed "open" fire, c) enclosed "hidden" fire, d) enclosed self extinguishing fire.

The sketch denoted c) illustrates an enclosure with fire sources in different, unpredictable positions. Some of the fire sources may be hidden from direct hit of any spray. This situation calls for so called total flooding systems. The challenge of engineering this type of system is to cover all possible fire sources and to fill the enclosure with water mist. The water mist should then follow the flow patterns inside the enclosure so that any occurring fire must entrain water mist with the air used for combustion. If the enclosure is relatively air tight, with closed doors and ventilation system shut down by dampers, the fires may be extinguished by a combination of oxygen depletion due to combustion and cooling/inerting of flames due to evaporation of water droplets. Water droplets will, if they are small enough, follow the air, entrain flames and the hot smoke plume, evaporate and form inert *water vapour*. Recirculation of fire products and water vapour will eventually lead to fire suppression.

The dimensioning factor for total flooding systems is a total amount of water rather than an application rate. The design factors additional to this are choice of type and position of nozzles. The design should ensure to fill the whole enclosure with water mist, to avoid "black spots" and water droplet deposition onto surfaces.

If the enclosure has openings which can not be closed or have a ventilation system which must be kept running, special solutions may be chosen which fulfil the "total flooding " concept.

In some cases total flooding systems may be designed by a sequence of "shots" of water mist rather than a continuous spray. The duration of all "shots" should then be sufficient to obtain the needed ***specific waterfraction*** , ***(litresper cubic meter),*** in the enclosure. The possible air supply routes should then be "contaminated" by water mist, such as door openings and ventilation inlets.

The last sketch, denoted d) illustrates what happens in an enclosed fire without any fire suppressant. The recirculation of fire products into the flames and the smoke plume leads to self extinguishing due to lack of oxygen.

4. Local application - open fire: Minimum application rate.

To extinguish an open fire, the application rate of water must be sufficient to obtain a critical combination of oxygen concentration and temperature in all parts of the flames simultaneously. Experiment series performed by SINTEF in 1989/1/ and a subsequent test series in 1992 /2/, showed that an application rate of 8 litres/min was sufficient to extinguish a well ventilated 1 MW propane gas fire. The time to achieve extinguishment was then in the order of 10 seconds. From those experiments, a Spray Heat Absorption Ratio (SHAR) was defined, representing the ratio of the heat absorbed by the water spray to the heat produced by the fire.

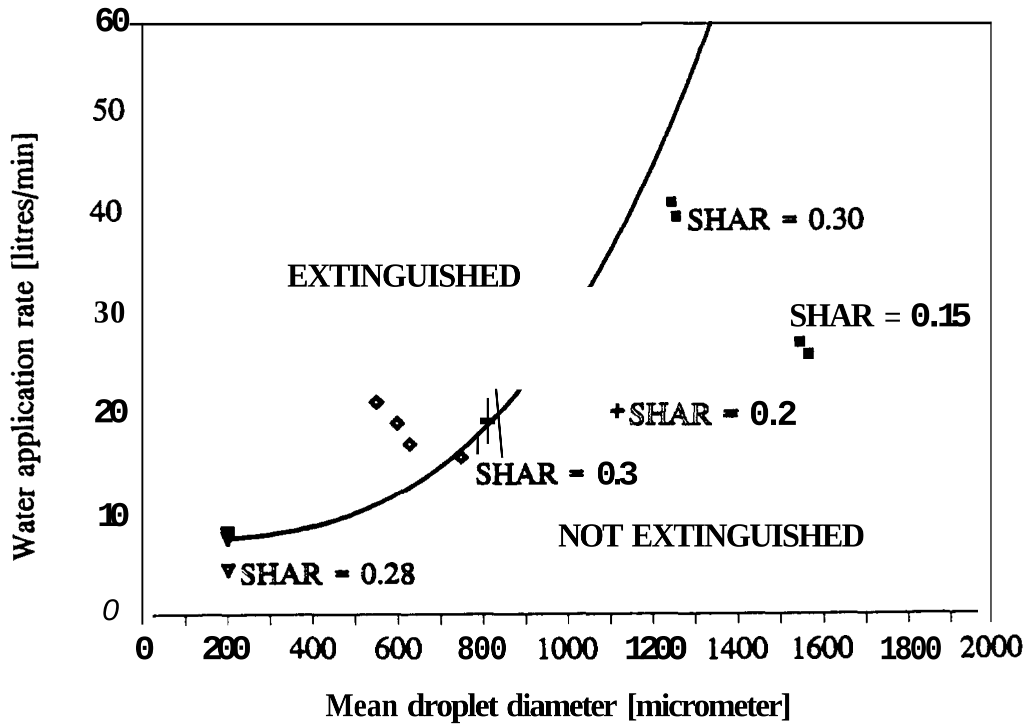

Fig. 6 Water application rate in experiments with 1 MW propane gas fire in 30 m^3 well ventilated enclosure.

The experiments with a water spray vertically downwards directly hitting the fire source gave the results that if the SHAR value exceeded 0.3, the fire was extinguished. The experimental results are shown in Figure 6. This means as a rule of thumb, if about 1/3 of the heat produced by the fire may be removed by a water spray, extinguishment of well ventilated fires is possible. This is **an** important finding, since rough estimates formerly have been based on the suggestion that the water spray must remove a similar amount of heat which is produced by the fire.

A concept of using flame volume instead of heat release rate of the fire may also be introduced. **A** rough estimate has been carried out, and this shows that the critical water application rate per volume of flame becomes approximately 0.5 litres per m^3 and second. The flame volume of the 1 MW gas fire is then estimated by traditional flame height correlations /3/, (Heskestad) giving a flame height of 3.1 m, and a concept of a conical flame shape.

Another engineering correlation for local application of water mist is to consider the ratio of water-to-fuel necessary to achieve extinguishment. In the SINTEF experiments a ratio of approximately 5-6 was found for extinguishment of gaseous propane fires, which is corresponding to other references, for instance McCaffrey, /4/ who refers that extinguishment occurs with a water spray into diffusion jet methane flames at a water-to-fuel ratio less than 10.

The spraying time to obtain extinguishment by local application is short, in the order of seconds, but if objects inside the flame have been heated during the fire before activating the water spray, a longer spraying time may be necessary to prevent re-ignition when the spray is turned off.

5. Closed spaces - total flooding: Minimum amount of water

A totally different approach to suppression system engineering is possible in scenarios where fire products may be recirculated into the fire plume. The dimensioning factor may then be a total amount of water per enclosure volume unit, ***specific water fraction,(litres per cubic meter).*** The application mode (time and rate) may vary as long as every part of the enclosure is covered by the spray nozzles. In principle, such a system may utilize very low application rates, as long as the product of spraying time and application rate exceeds a minimum amount of water. Nozzle types with different flow rate, droplet size distribution, nozzle number and position may be varied as long as the minimum specific water fraction can be obtained in the enclosure. The difference of systems will be the time to extinguishment and the ability to extinguish small and hidden fires. An illustration of the different factors affecting time to extinguishment is shown in Figure 7. The time to extinguishment will be influenced by water application rate and mode, and by the size of the fire relative to the volume of the enclosure.

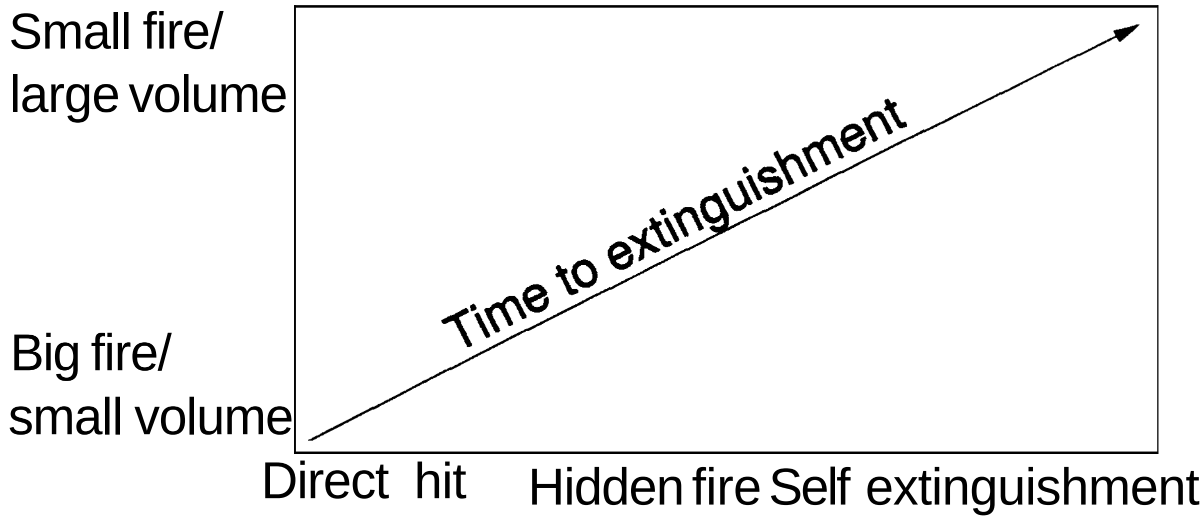

Fig. 7 Factors affecting time to extinguishment.

A large fire in a small enclosure will rapidly reach conditions where extinguishment is relatively easy. If the fire plume is hit directly by the water mist, a very short time to extinguishment is achieved. This is a factor to be well aware of, both in evaluating a suppression system test and in design of systems. Some very spectacular demonstrations of suppression systems may be given when a large fire has been allowed to develop, with pre-heating of the inventory of the enclosure and reduction of the oxygen concentration before system activation. The real difference of system's efficiency will appear by the ability to suppress small, hidden fires in large enclosures.

A well designed system based on total flooding of water mist was tested in three different scales at SINTEF in 1992-93, /5,6/. The first test series was performed in a 30 m^3 test enclosure, the next series in a 70 m^3 turbine enclosure and the third in a 130 m^3 enclosure representing an engine room.

A variety of fire sizes, fire types and locations were tested. The fire types were gaseous propane jet fires, diesel oil and lubrication oil spray fires, diesel oil pool fires and lagging fires (diesel oil soaked into insulation mats).

In the turbine enclosure (70 m^3) and in the engine room (130m^3) a typical small fire was a 1 m^2 liquid pool fire. A large fire was 4 pool fires of 1 m^2 simultaneously with a spray fire of about 1 MW. The fires were located at different positions, directly exposed to the water spray or hidden behind obstacles. The enclosures were tested with natural ventilation through openings, with mechanical ventilation and with air supply limited to leakages. A realistic mockup of a gas turbine was placed in the 70 m^3 enclosure, and in some of the tests the steel surfaces were heated to 3-400 °C in order to represent a running turbine and the possibility of re-ignition of diesel oil sprayed onto hot areas. In the third test series in the 135 m^3 enclosure, with the same ceiling height as in the 70 m^3 enclosure, the mockup representing an engine was not heated. A principal sketch of the engine room enclosure is shown in Figure 8.

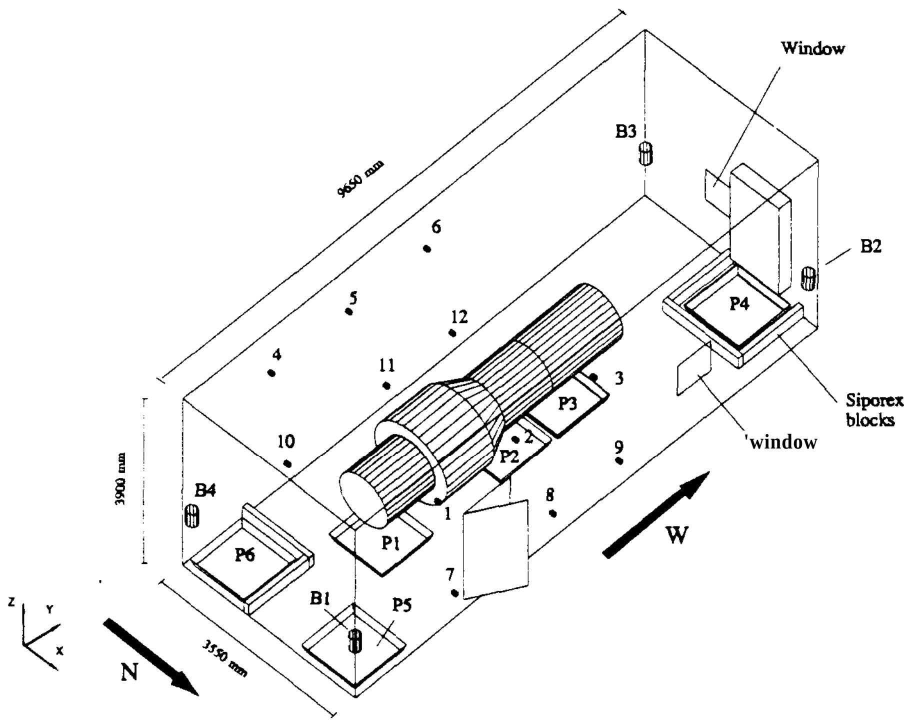

Fig. 8 Principal sketch of 130 m^3 enclosure (engine room).

Measurements of temperatures, differential pressure between enclosure and the ambient, flow rates of fuel spray leakage and ventilation, characteristics of water mist system and concentration of oxygen, CO_2 and CO were logged continuously.

The water mist system was based on a twin-fluid nozzle, the Fine Water Spray system of Securiplex/Ginge Kerr.

The minimum amount of water needed for extinguishing a fire in the turbine enclosure was calculated for two different fire scenarios. One scenario is a relatively large fire in the 70 m^3 enclosure, and the specific water fraction necessary for extinguishment was 0.06 - 0.07 litres/m^3. In this scenario a great deal of the extinguishing effect is due to inert gas "production" and oxygen consumption by the fire itself, and recirculation of fire products, water vapour and droplets into the fire plume. In the similar fire scenario in the 130 m^3 enclosure, the specific water fraction necessary for extinguishment was 0.05 - 0.10 litres/m^3.

Another, more challenging scenario is with a small fire in the enclosure, typically a 1 m^2 diesel pool fire in the 70 m^3 enclosure. The minimum specific water fraction was then 0.4 - 0.6 litres/m^3. In the similar fire scenario in the 130 m^3 enclosure, the specific water fraction necessary for extinguishment was **0.42** - 0.66 litres/m^3.

Even if these numbers are valid only for the tested system it indicates the engineering numbers to be used.

6. Limits for fire suppression.

Figure **3** showed the principle of a limit for fire suppression, with a combination of cooling and inerting. Figure 9 shows results from practical tests in the 130 m^3 enclosure, where the inert condition is represented by the average oxygen concentration at the time of extinguishment, and the maximum of some measured hot gas layer temperatures of the enclosure is representing a temperature along the horizontal axis.

The resulting pairs of oxygen concentration and maximum temperature indicate the existence of the limit shown in Figure **2.** The absolute value of the limit, or a correlation of the two variables shown in Figure 9 will be valid for a certain fire scenario and a water mist system, and is not universally applicable. **A** more universal limit may be found by more idealized experiments, and may be used in fire suppression modelling.

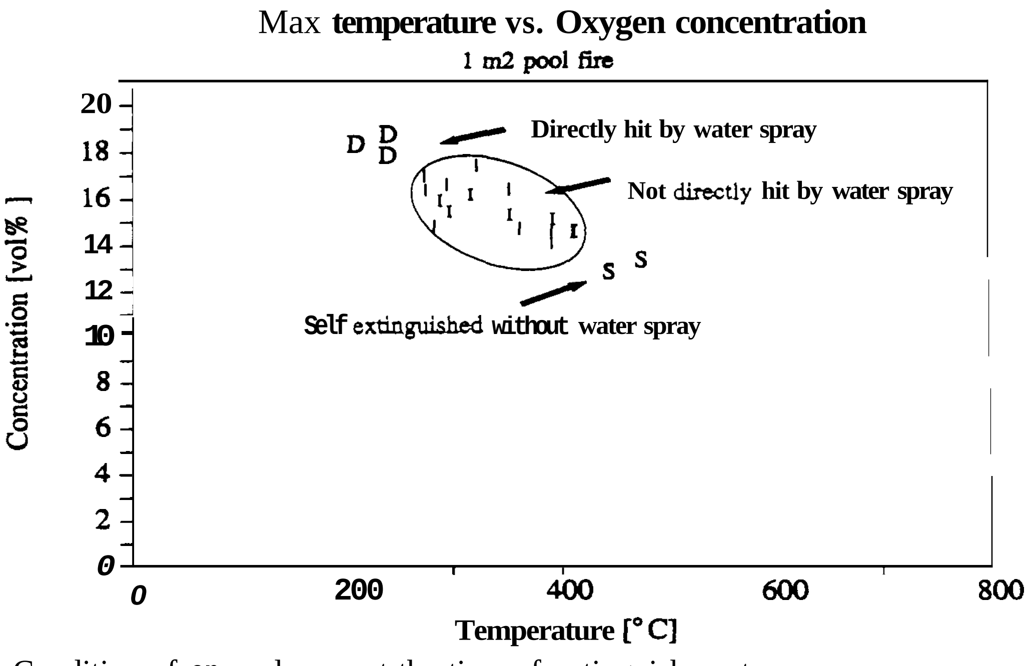

Fig. 9 Condition of an enclosure at the time of extinguishment.

7. Spraying sequence.

In the turbine enclosure experiments there were restrictions on the duration of a "shot" of water, due to a risk of damage of the turbine shell by thermal stresses due to rapid cooling. **A** maximum spraying time was originally set to 10 seconds, based on calculations of the material performance due to a water spray directed onto the metal surface.

This restriction led to a need to optimize the location and type of nozzles. The experience from this optimization procedure was that a sequence of shots of water mist was more favourable with respect to effective use of water than a continuous spray. Some of the explanation may be that the fire itself (a liquid pool fire) is reduced to a very small fire by the first shot of 10 seconds, producing inert fire products and water vapour at a low rate, and then grows bigger when the water spray is shut off. When the next "shot" is activated, the time to reach critical conditions for extinguishment is short. Additional to this explanation it is possible that the circulation of water mist in the enclosure is slowed down when the fire size is reduced, subsequently leading to less vaporization. **A** certain fire size must exist to maintain an effective mixing process inside the enclosure.

One 10 seconds spray was sufficient to extinguish all tested diesel pool fires of 1 m^2 or bigger in the 70 m^3 enclosure, when the number of activated nozzles was sufficiently high. To optimize the number of nozzles, a spraying sequence of 10 seconds spray at 60 seconds interval was tested. This spraying sequence was also tested in the 130 m^3 enclosure, and in addition 20 seconds sprays at intervals were tested. The most efficient way of utilizing a certain amount of water was 20 seconds sprays at intervals.

8. Pressure inside enclosure.

The pressure inside an enclosure during a fire follows a certain pattern, dependent on the tightness of the construction. In a relatively air-tight enclosure with closed door and ventilation shut by dampers, the pressure will first be increasing by thermal expansion of air and combustion products. Smoke will be pressed out of the enclosure. When the amount of oxygen available for combustion is limited, the heat production of the fire is decreasing, and the enclosed gases are cooled by the inventory and the inner surfaces of the enclosure. **A** decreasing pressure is following, leaving the enclosure at lower pressure than the ambient, due to the loss of mass during the expansion period. In this situation, air from the ambient is entering the enclosure, and the fire is increasing due to the oxygen supply. This fluctuating pressure is seen until the fire is extinguished.

When water mist is introduced to the enclosure after a certain burning time, two processes start. The first process is the cooling of the air and combustion gases , leading to thermal contraction. The next process is thermal expansion of water at evaporation, when water is expanding about 1600 times at the phase transition from liquid to gas. The two processes will take place very rapid, and without any experimental evidence, it is difficult to predict the added effect of the two processes.

Figure 10 shows two typical pressure transients measured in a 130 m^3 enclosure, with relatively big fires. The second graph represents a fire which is self extinguished, with the characteristic pressure fluctuations. The first graph shows the same fire extinguished by a water mist. Only one pressure drop below ambient is observed. The magnitude of the pressure above and below ambient is the same, in the order of 500 Pa. These pressure fluctuations does not make any possibility of structural damage of normal constructions.

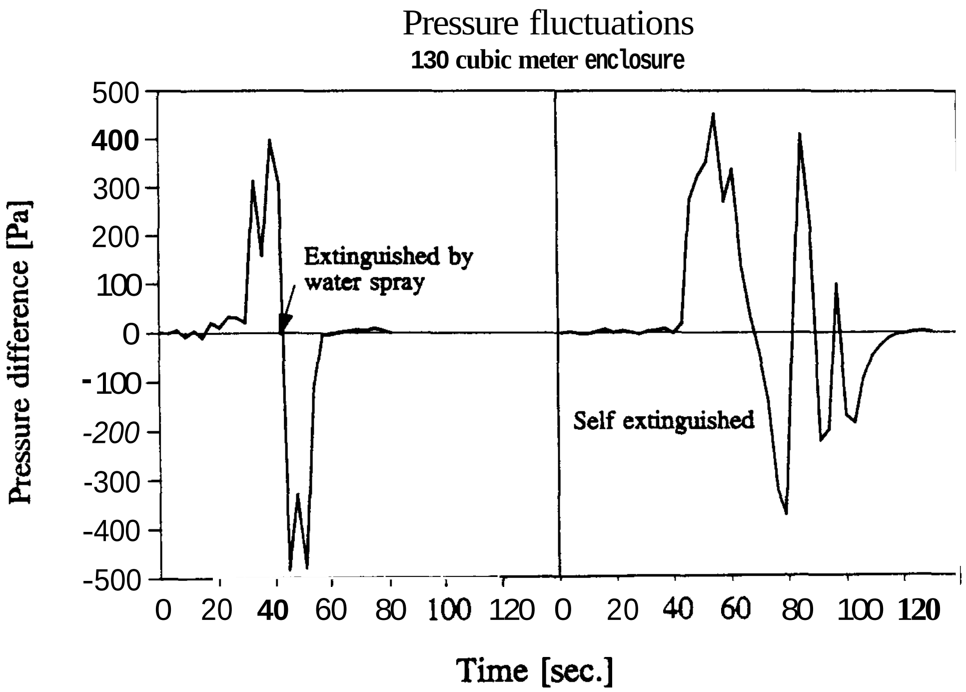

Fig. 10 Typical pressure transients in 130 m^3 enclosure for relatively big fires.

9. Conclusions

The engineering relations described in this paper has been applied to installation of a water mist system in the turbine hoods of the offshore platforms of British Petroleum in the North Sea, as alternative to Halon systems. Several releases of the water mist system have been experienced in fires, with successful extinguishment. The numbers presented in the engineering relations are valid for the tested system, but may indicate the range in which typical application rates and water fractions will be.

References:

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