AN EMPIRICAL MODEL FOR EXTINGUISHMENT OF ENCLOSED FIRES WITH WATER MIST

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SUMMARY

The combustion mechanisms of fires are complex. To predict the conditions for extinguishment, the combustion chemistry combined with thermodynamics and fluid dynamics should be described in detail. Several concepts have been proposed for prediction of extinguishment. The critical concentration of a fire suppressant has been widely used, and in some practical applications a minimum concentration of oxygen in the fire atmosphere has been applied.

However, these methods have limitations in their applicability to practical life, and in many cases large safety factors have been adopted to cover uncertainties. SINTEF has a long record of experiments with water-based fire suppression systems, including water mist. Based on these experiments, an empirical model based on the concentration of oxygen and the temperature in the fire atmosphere has been developed. The paper proposes a correlation between these parameters, leading to a limit for sustained flaming fire. The correlation is based on experiments in a 30-m^3 compartment, with gaseous, liquid, and solid material fire sources.

1.0 THEORETICAL BASIS

Temperature and concentration limit the reaction rate of combustion of reactants. Inert condition is defined as the limiting concentration of a suppression agent where no reaction will take place. This limiting concentration is normally defined at normal atmospheric temperature and pressure, and is often linked to an experiment apparatus like the "cup-burner test."

In a real situation, the fire suppression agent is normally supplied after the fire has been initiated, based on detection of some kind. The two modes **of** supplying the suppression agent are the so-called Local application (direct hit) and Total flooding (room inerting). In both cases, the suppression and finally extinguishing of a fire is dependent of the transport of agent into the combustion zone of the fire, either as a direct stream or as a recirculating flow of combustion products seeded with suppression agent. Most frequently used fire suppression agents, such as CO_2 and formerly Halon **121**1 and 1301, are gases at normal atmospheric conditions. These gases will mix with other gases in the enclosure, and by diffusion (turbulent or molecular) tend to occupy all available space. The dynamics of the diffusion process is then the critical success factor. In practice, the supplied gaseous suppression agents are mixed within the total available volume of the enclosure within some minutes, and the leakage from the room is the only loss term limiting the effective time of inerting.

Water vapour may only exist as a fraction of the atmosphere at temperatures below its boiling point, 100 °C at atmospheric pressure. This fraction is denoted the maximum humidity, or saturation pressure of water. Figure 1 shows the saturation pressure of water vapour.

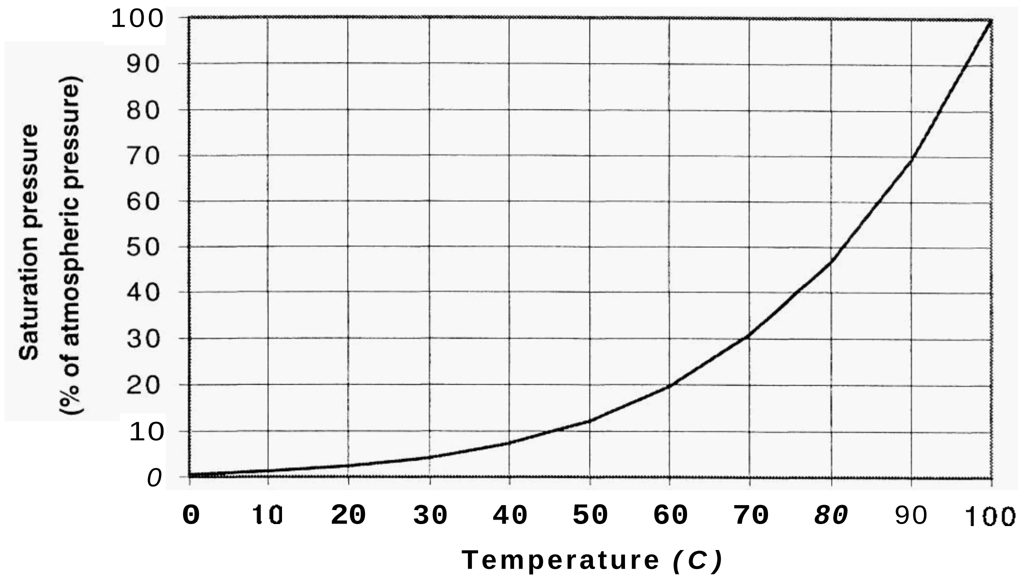

Figure 1. Saturation pressure of water vapour in air below the boiling point at atmospheric pressure.

In case of water mist fire suppression systems, the limiting success factor is to which extent water may evaporate and form an inert gas (water vapour) that may deplete oxygen from the combustion zone, and cool the reactants to a level below a critical temperature. If the temperature of the mixture of air, combustion products and water vapour drops below 100°C, it is possible for water to condense and form water droplets. These droplets may settle onto surfaces, or fall out in zones with low air velocity. The concentration of water vapour will gradually be reduced as the temperature is lowered. If the fire is small compared to the total volume of the room, the heat produced by the fire may be insufficient to keep the re-circulating gases above the critical temperature where it may contain a water vapour fraction above the inerting limit.

From literature, a critical inerting limit of water vapour in air is 25-30 vol% [1]. The corresponding lower temperature where air can keep this concentration of vaporised water is about 65–70 "C.

2.0 EXPERIMENT SETUP

In 1996 SINTEF carried out **a** series of experiments in a 31-m^3 steel compartment. The tests are part of a project (FIREDASS –Fire Detection and Suppression Simulation) sponsored by the European Commission under the BRITE/EURAM Programme, carried out by a consortium of industry and university partners in Europe [2]. The compartment dimensions are 2.3 m wide, 2.3 m high, and 5.9 m long. It was air tight, equipped with an air supply system, a water mist fire suppression system, various fire sources and instrumentation to measure the flow of air, water and fuel, temperatures, velocities, pressures, heat fluxes, and gas concentrations. The volume and dimensions, **as** well as the air supply system simulated a cargo bay of an aeroplane.

The fire sources were a propane gas burner with a surface area of 0.09 m^2, diesel oil pools with surface area 0.09 m^2 and 0.25 m^2 and cardboard boxes filled with shredded paper. Water spray application was varied, with no water as a minimum and water from 4 nozzles as a maximum. The relative position of fires source and nozzles was varied, as well as obstructions between the fire source and the spray. Thirty-five (35) tests were carried out. The main purpose of the tests was to produce basis for computer model validation, including the basis for the modelling of conditions for extinguishment of fires influenced by water vapour.

3.0 INSTRUMENTATION

Temperatures were measured by 1.5-mm metal sheathed bare-bead chromel-alumel thermocouples mounted in **6** racks inside the compartment, with **8** thermocouples in each rack. In addition, wall and ceiling steel temperatures were measured.

The gas species were measured at two positions, one inside the compartment, about ¼ of the length from the rear wall, centrally and 0.53 m above the floor, and in the exhaust channel, centrally at the top of the rear wall. **A** concentration of oxygen, carbon dioxide, and carbon monoxide was measured by two sets of analysers. The gas samples were dried by passing a reservoir of blue gel before entering the analysers.

Humidity was measured at the same two positions by a specially designed apparatus, consisting of an insulated, heated sampling tube keeping the temperature above the boiling point of water, and a commercially available **HUMICAP** ® probe [3]. This equipment makes it possible to measure the real water vapour concentration **of** the gas sample, which normally is ignored in fire testing.

The additional instrumentation is not described here.

4.0 RESULTS

In a former presentation at the 1995 HOTWC a correlation between temperature and oxygen concen-tration was sketched [4]. The correlation had **an** average of all measured thermocouples in a 130-m^3 enclosure as the representative temperature. The oxygen concentration was a "dry" concentration. To make the correlation more universal, an attempt is made to use the conditions of the gases entraining the fire zone. These conditions are represented by the real oxygen concentration, compensated for the actual water vapour concentration, and the average temperature in the compartment at the same level above the floor as the gas sample was taken. Flame temperatures are disregarded when the 600-mm level temperatures are averaged.

Pairs of oxygen concentration, representing the minimum measured oxygen concentration and maximum average temperature at the 600-mm level, are presented in Table 1, which includes some characteristics of the fire scenario. The second column shows the number of water mist nozzles that were activated. The third column gives the relative position between the fire source and the nozzles. The fourth column indicates if there was any obstruction between the spray nozzle and the fire source, and the fifth column shows whether the initial fire source was bigger or smaller than about 80 kW. The results from Table **1** are shown graphically in Figure ***2.***

Table 1. Results from the SINTEF FIREDASS tests.[a]

	Number of nozzles	Direct hit: D Indirect hit: I	Obstructions: 1,1a, or 2 No obstruction: 0	Large: L (>80 kW) Small: S (<80 kW)	Min O_2 vol%	T 600 °C
02HS	0		0	L	10,8	119
03HS	0		0	L	10,8	120
04PS	0		0	S	15,0	61
05PM	0		0	L	16,6	96
06BX	0		0	L	17,8	66
06BXb	0		0	L	11,7	169
07PS	4	D	0	S	16,5	34
08BX	4	D	0	L	14,3	48
09HS	4	D	0	L	14,7	50
10PS	1	D	0	S	16,1	48
11HS	1	I	0	L	13,1	79
12PS	1	I	0	S	16,1	36
13PM	1	I	0	L	16,0	60
14BX	1	I	0	L	15,2	77
15HS	1	D	0	L	14,3	85
16PS	1	D	0	S	16,0	45
17BX	1	I	0	L	15,7	98
18HS	2	D	0	L	14,7	97
19PS	2	D	0	S	16,2	43
20HS	2	D	0	L	14,6	70
21PS	2	D	0	S	17,1	39
22PS	2	I	1	S	16,4	31
23PS	1	I	1	S	16,3	33
24PS	1	D	1	S	16,0	35
25BX	2	D	1	L	15,5	38
26PS	2	D	1a	S	18,1	34
27BX	2	D	1a	S	15,4	45
28PS	2	D	2	S	16,5	30
29PS	1	I	2	S	15,5	33
30PS	1	D	2	S	15,8	31
31BX	2	D	2	L	15,1	37
32PS	2	D	1a	S	18,6	34
33PS	0		0	S	14,7	53
34BX	0		0	L	15,0	151
35PS	2	D	0	S	15,9	43

[a] Reference 2

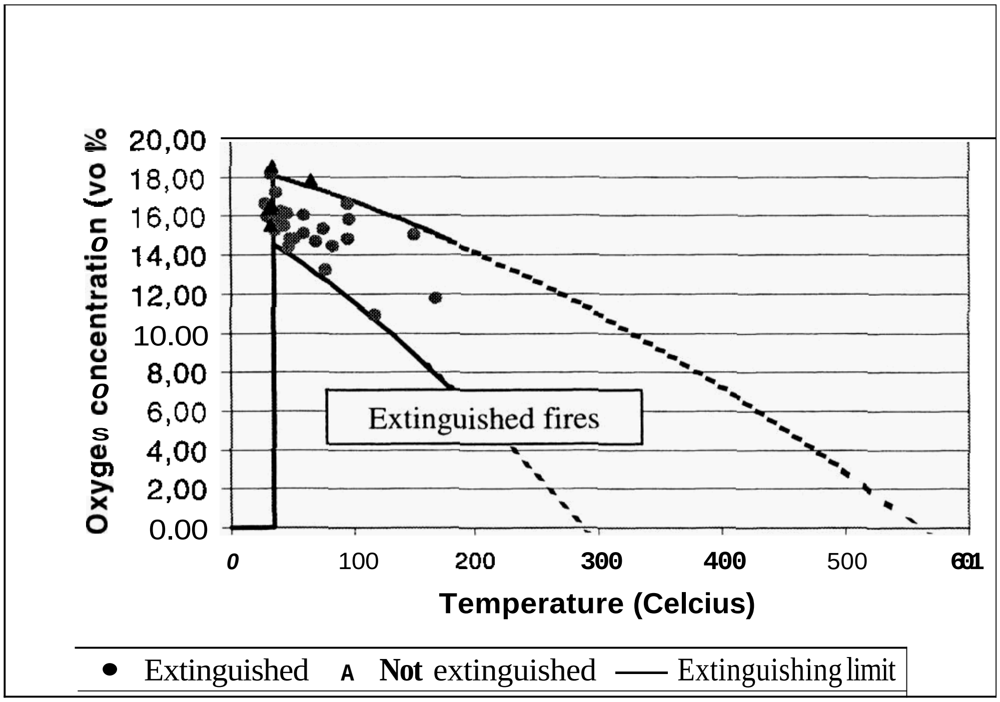

Figure 2. Upper and lower limit for the correlation **of** extinguishment.

Extinguishing limit refers to an upper and a lower limit for measured pairs of temperature and oxygen concentration. The lines are described by the equations, giving the limiting oxygen concentration for extinction:

$O_{2\text{ext limit}} = 20.9 - k \cdot T^{n}$
$k = 0.00003$ (upper limit)
$k = 0.000067$ (lower limit)
$n = 2$
T = representative temperature of the gases entering the fire zone [K]

and

$T > 35\,^{\circ}\mathrm{C}$

The constants in the equation are chosen by an empirical approach, with the normal atmospheric oxygen concentration as an upper value, and the values decreasing with increasing temperature. The equations are not justified for temperatures above 170°C, which is show by dotted lines in the graph.

The lower temperature limit of 35 °C is chosen, since almost all test fires that were not extinguished had an air supply temperature below this level. Two tests had lower temperature, but were extinguished as well. Both these fires were partly obstructed from the rest of the compartment, and local condition had a significant influence on the fire behaviour. The limit of 35 °C is well below the theoretical minimum inerting level of water vapour in air, which indicates that some water droplets follow the airflow into the fire zone.

5.0 DISCUSSION

The upper limit shown in Figure 2 includes some tests where local conditions may have influenced the conditions at extinguishment, rather than the measured pair of temperature and oxygen concentration. If this limit is used in modelling, one may expect a too optimistic prediction of extinguishing fires. If the lower limit is used, a quite conservative prediction will be the result.

A suggested limit of extinguishment matching most of the small pool fires, being more conservative than one larger pool fire and some cardboard box fires, is shown in Figure **3.** This limit is described by the equation:

$$O_{2ext\ limit} = 20.9 - k \cdot T^{n}$$

$$k = 0.000045$$

$$n = 2$$

and:

$$T > 35^{\circ}C$$

This formulation of a temperature dependent limiting oxygen concentration for the extinguishment of fires has great potential in mathematical modelling, as well as in general understanding of the behaviour of water mist systems.

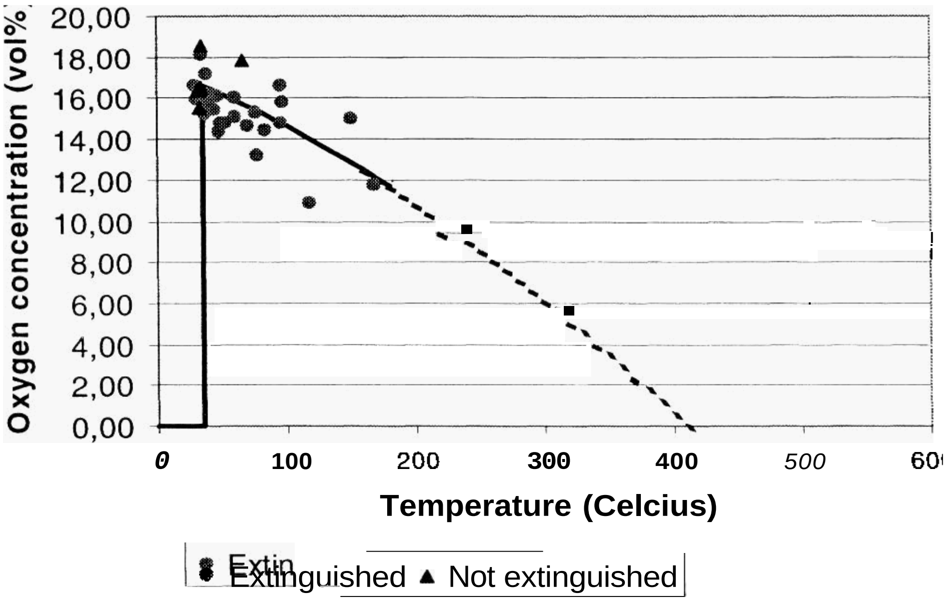

Figure 3. Suggested limit for the correlation of extinguishment, $n = 2$, $k = 0.000045$.

The relatively large span of results can be explained by the big variation of fire sources, relative location of nozzles versus fire sources, and the obstruction of the fire from direct hit from the mist. The minimum measured values of oxygen may also be somewhat dependent on the dynamics of the fire. If a relatively large fire heats the enclosure, the oxygen concentration may continue to decrease after the fire is extinguished. This occurs due to the evaporation of water in contact with high temperature zones, either in the combustion products or in heated parts of the enclosure. The fact that only one spot measurement of oxygen concentration is used also means that the minimum concentration may deviate from the condition just at extinguishment.

A more systematic variation of the conditions where extinguishment occurs, including measurement of the conditions at more than one position, will make the constants used in the equation even more reliable.

The most reliable data for the conditions just at the time of extinguishment are considered to be the results from tests with small fires that slowly approached extinguishment. Small pool fires were typical for this performance, as shown in Figure **4.** The case that is simulated is a 0.6-m^2 diesel pool fire in a 1000-m^3 enclosure. In this case there is a supply of air through openings, but the supply is governed by the pressure difference between the enclosure and the ambient. The real oxygen concentration approaches the limit of extinguishment, but the limit is changing due to different temperature. If this gradient is slow, the two lines will never cross, indicating that a minor fire will remain.

It is also possible for the water mist to cool the fire products and the entraining air to a temperature below which the water vapour can sustain vaporised at a sufficient concentration. The only way to ensure extinguishment in this case is to apply water droplets into the fire zone directly, either through the momentum from the nozzles or by very small droplets following the general air flow pattern.

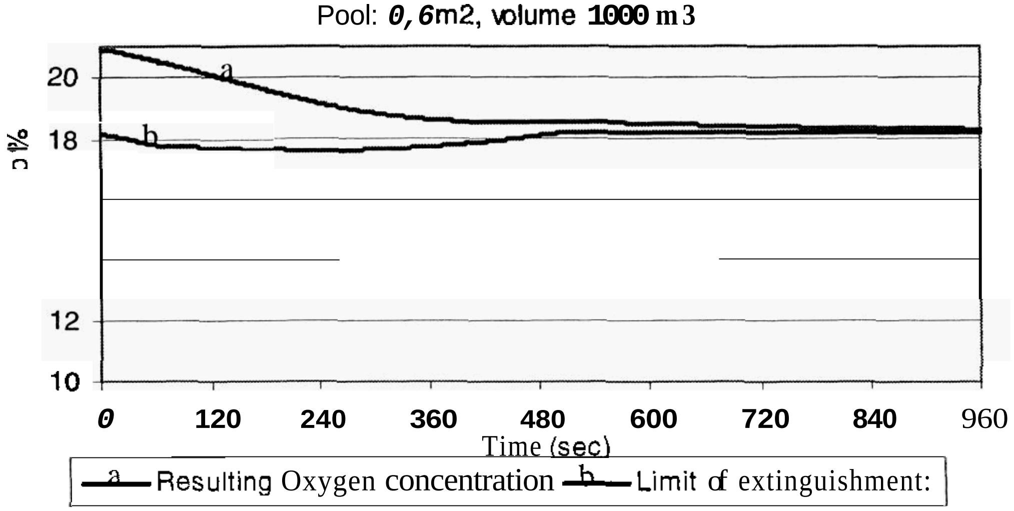

Figure 4. The time history of oxygen concentration compared with the limit of extinguishment for a small (0.6-m^2) pool fire.

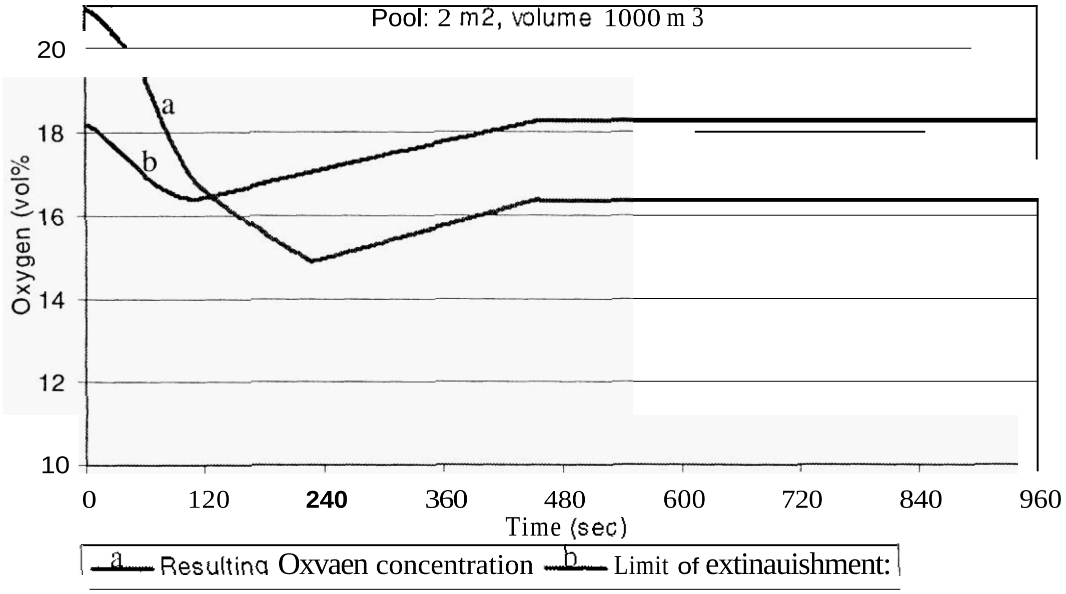

Figure 5. The time history of oxygen concentration compared with the limit of extinguishment for a larger (2-m^2) pool fire.

Figure 5 shows a slightly different situation, with a larger pool fire (2 m$^{2)}$. The gradient of the decreasing oxygen concentration is steeper, leading to a situation where the concentration passes the limit of extinguishment, and the fire is extinguished. In this case, a considerable amount of water is evaporated, even after fire extinguishment. This explains the continuing decrease of oxygen concentration after the crossing of the extinguishing limit. The increase of oxygen concentration stops when the gases inside the enclosure are cooled to the water application temperature.

6.0 ACKNOWLEDGMENTS

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7.0 REFERENCES

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