WATMIST- A ONE-ZONE MODEL FOR WATER MIST FIRE SUPPRESSION

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ABSTRACT

A one-zone model for simulating the effect of fire suppression and extinguishing using water mist is developed. The model solves a set of equations with the iteration by an EXCEL spreadsheet. The basic simulation is that pressure is constant, letting air and combustion products enter or leave the compartment without any restrictions. Heat produced by the fire is transferred to the ambient by the conduction of energy through the boundaries, limited by the convective heat transfer to the inner surfaces of the compartment. The energy balance of the gases in entering or leaving the compartment is also taken into account. Heat transferred to the water mist is calculated by separate procedures, including an efficiency factor valid for a set of system parameters, flow rate of water into the compartment, and the possibility of the atmosphere to receive water vapour. When the temperature inside the compartment is below 100 °C, the saturation pressure of water vapour at the actual temperature limits this. When the temperature is above 100 "C, water evaporates at a rate proportional to the water supply rate and the mentioned efficiency factor, limited by convective heat transfer between droplets and gases. Oxygen concentration is calculated from the oxygen consumed by the fire and the dilution caused by evaporation of water inside the compartment. The oxygen balance also considers additional oxygen brought in by additional air through leakage and doorway flow. The heat release rate from the fire is treated as growing fire approaching the theoretical maximum after a time of development. When the oxygen concentration approaches a calculated extinguishing concentration dependent on temperature, the heat release rate is reduced proportionally to the quotient between the actual oxygen concentration and the limit, by a linear approach. The extinguishing limit is the empirical correlation published by Wighus [I].

The model is based on the concept of a well-stirred reactor, and all processes are considered to take place simultaneously throughout the space. The physical properties of cornbustion products are considered to be that of air. The model is used to simulate large-scale extinguishing tests in an IMO Machinery test enclosure, and the results of the simulation are compared to the experimental results.

DESCRIPTION OF THE WATMIST MODEL

INPUT VALUES

Enclosure data:		
Dimensions:	Length, width and ceiling height	[m]
	Wall thickness	[m]
Thermal properties:	Specific heat capacity of wall material	[kJ/kg K]
	Convective heat transfer coefficient to walls	[kW/m² K]
Fire data:		
Dimensions:	Pool side	[m]
Combustion properties:	Specific fuel burning rate	[kg/m² s]
	Theoretical net heat of combustion	[kJ/kg]
	Theoretical net heat of combustion of Oxygen	[kJ/kg]
	Constant combustion efficiency	[-]
Initial atmospheric conditions:		
	Air temperature	[°C]
	Initial Oxygen concentration	[vol%]
Water mist characteristics:		
	Water supply temperature	[°C]
	Water supply rate per nozzle	[litres/min]
	Number of nozzles	[-]
	Preburn time without water supply	[s]
	Median droplet diameter	[m]
	System efficiency factor	[-]

Heat transfer coefficient water droplets/atmosphere [kW/m² K]
Optional: Intermittent spray sequence.

CALCULATIONS

The calculation model calculates the energy and mass balance of the compartment with the effect of a fire and a water spray.

Fire model:
The fire source is calculated as a pool fire equivalent with a user-specified fuel evaporation rate [kg/m² s]. To simulate realistic fire development and to avoid too steep gradients in heat release rate, the fuel burning rate is gradually increased by a time-dependent scheme up to the maximum theoretical value, described by Eq. (1).

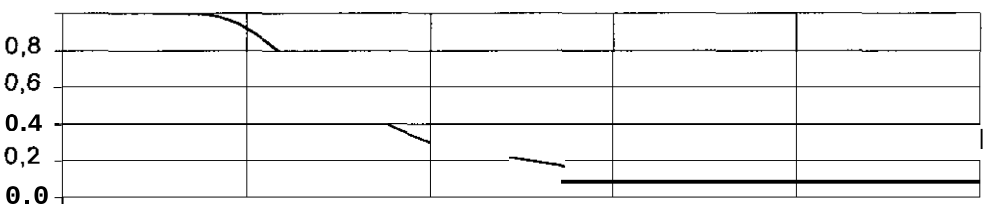
$$\dot{m}_{fuel} = \dot{m}_{fuel\max}\cdot(1-\frac{f_t}{t}) \qquad (1)$$

The theoretical maximum heat release rate is calculated based on constant combustion efficiency, ε_c and the net heat of combustion of the fuel, described by Eq. (2).

$$\dot{Q} = \dot{m}_{\max}\cdot\varepsilon_c\cdot\Delta H_c \qquad (2)$$

This heat release rate is optionally reduced by two mechanisms, both based on oxygen depletion. First, the heat release rate may be reduced by Eq. (3), based on the equivalence ratio of the fire atmosphere [2]. The equivalence ratio ϕ is here calculated as the initial oxygen concentration divided by the actual concentration. This correlation is also shown in Figure i.

$$\dot{Q}_{redstoich} = \dot{Q}\cdot(1-1/\exp(2,5\cdot\phi^{-2,8})) \qquad (3)$$



$$\dot{Q}_{ext\lim it} = \dot{Q}_{redstoich}\cdot\left(\frac{C_{O_2}-C_{O_{2\lim it}}}{C_{O_{2init}}-C_{O_{2\lim it}}}\right) \qquad (4)$$

The oxygen concentration at extinction limit is dependent of the temperature of the entrained gases, as described by Eq. (5) [1]. (T is the temperature in Kelvin.)

$$C_{O_{2ext\lim it}} = 20,9 - 0,000045.T^2 \qquad (5)$$

HEAT BALANCE

The heat balance of the compartment is based on the heat produced by the fire, and it is immediately, without any time delay left for mixing, transferred to the compartment. This is the concept of a one-zone, well-stirred reactor. The properties of the gases inside the compartment are considered to be those of air. irrespective of changes in composition. Heat is transferred to the walls by convective heat flux; radiation is not considered. The heat transferred to the **walls** accumulates there and **is** further transferred to the ambient by convective heat transfer. The equations for heat release are shown above (Fire Model). The temperature of the walls is calculated by Eq. (6).

$$T_{wall(t+1)} = T_{wall(t)} + (T_{gas} - T_{wall})_{(t)} \cdot hc_{wall} \cdot A_{wall} / cp_{wall} \cdot m_{wall} \qquad (6)$$

The heat stored in the walls is then calculated by Eq. (7).

$$Q_{wall} = \Delta T_{wall} \cdot cp_{wall} \cdot m_{wall} / \Delta t \qquad (7)$$

The heat transferred to the ambient by convection from the outside surface of the compartment is calculated by **Eq. *(8).***

$$Q_{wall/ambient} = (T_{wall} - T_{ambient}) \cdot hc_{wall} \; . A_{wall} \qquad [\text{kW}] \qquad (8)$$

The **gas** temperature inside the enclosure is calculated from a heat balance. The balance, based upon heat release of the fire, heat transferred to the compartment boundaries, and heat transferred to the water mist, is calculated by Eq. (9).

$$\Delta T_{gas} = \Delta t \cdot (\dot{Q}_{ext\,\lim it} - \dot{Q}_{wall} - \dot{Q}_{wall/ambient} - \dot{Q}_{water}) / (M_{gas} \cdot cp_{gas}) \qquad [°\text{C}] \qquad (9)$$

The mass conservation is calculated by the change of density of gases inside the enclosure as a function of temperature, by the ideal gas law. It is calculated by Eq. (10) (T in Kelvin).

$$M_{gas} = V \cdot \rho_{ref} \cdot (T_{ref} / (T_{gas} + 273{,}15)) \qquad [\text{kg}] \qquad (10)$$

The change of internal temperature induces a change of mass in the compartment, and this change is also taken into account in the oxygen concentration calculations.

HEAT TRANSFER TO WATER

The heat transferred from the hot gases inside the enclosure to the water is dependent of several factors. The basic concept is the supply of water with a certain droplet size distribution. The size distribution is characterised by the median droplet diameter. The first simplification is that the supply of water droplets is considered to be equal to the loss of water by run-off, which implies that the heat transfer at each time step is proportional to the water supply rate. The active droplet surface is also considered to be the **sur**face of the water distributed into droplets of diameter similar to the median droplet diameter. The heat transfer is calculated by Eq. (11).

$$\dot{Q}_{water} = \dot{m}_{water} \cdot (6 / D_m \cdot \rho_{water}) \cdot hc_{droplet} \cdot (T_{gas} - T_{water}) \cdot \varepsilon_{water} \qquad [\text{kW}] \qquad (11)$$

Eq. (11) contains a water efficiency factor ε_{water} that is a system adjustment factor. It counts mainly for differences in the distribution of droplets in different mists, and is a factor that can be adjusted to fit experimental data.

The maximum rate of evaporation of water based on heat transfer between hot gases and droplets is calculated by Eq. (12).

$$m_{evapconv} = Q_{water} / ((100 - T_{water}) \; . cp_{liquidwater} + \Delta H_{evap}) \qquad [\text{kg/s}] \qquad (12)$$

A very important feature of the **WATMIST** model is, however, how the evaporation of water takes place. Three possible tracks can then be followed. If the average gas temperature inside the enclosure is lower than the boiling point of water (100 "C), the maximum fraction of vapour that can exist is limited by the saturation temperature. The correlation of water vapour saturation pressure and temperature is shown in Figure 2.

The correlation is described by Eq. (13) and (14) [4].

$$p_{ws} = A \cdot 10^{(m \cdot T/T_n)} \qquad \text{[mbar]} \qquad (13)$$

-40<T<50 °C: A= 6,1078, m= 7,5, T_m= 237,3

50<T<100 "C: A= 5,9987, m= 7,33, T_m= 229,1

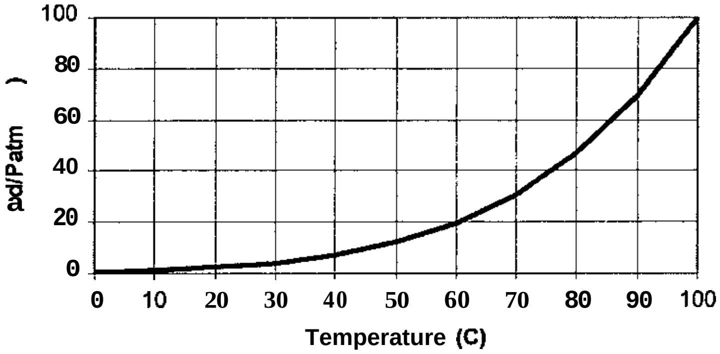


Figure 2. Saturation pressure of water in air at atmospheric pressure.

Absolute humidity (water vapour in the atmosphere):

$$a = 216{,}68 \cdot RH \cdot P_{WS} / (1000 \cdot (100 \cdot (T + 273{,}2))) \qquad [\text{kg/m}^3] \qquad (14)$$

In this temperature region, the maximum amount of water that can exist as vapour is limited by the absolute humidity with relative humidity 100%. It means that if water is vaporised in the hotter zones of the compartment, it will condense and form liquid droplets when the temperature is lowered. The maximum average vapour content is then as calculated by Eq. **(13)** and (14).

The maximum rate of evaporation in this temperature regime is then calculated by Eq. (15).

$$m_{evapsat} = \Delta a \cdot V / At \qquad \text{[kg/s]} \qquad (15)$$

If the average temperature rises above 100 "C, there is no longer any limit of how much water vapour that can exist. The limiting factor is the heat available for evaporation and the heat transfer process between droplets and hot gases, given by droplet size distribution and water supply rate, and flow characteristics of the water mist. **A** third limitation to the rate of evaporation also exists. The maximum evaporation rate is limited by the heat supply to the compartment, which is taken care of by the energy conservation, reflected by the gas temperature.

The heat absorbed by water evaporation is subsequently calculated by

$$Q_{evap} = m_{evap} \cdot ((100 - T_{water}) \cdot cp_{liquidwater} + \Delta H_{evap}) \qquad [\text{kW}] \qquad (16)$$

m_{evap} is the lowest value calculated by Eq. (12) or (15).

OXYGEN CONSERVATION

Oxygen is consumed by the fire and is subsequently a strong function of the heat release rate of the fire. In this model, a concept often used in fire calorimetry is used. Ideally, the consumption of oxygen is less for underventilated fires, hut this is disregarded in this model. The consumption of oxygen is simply taken as the specific heat of combustion based on the consumption of oxygen instead of that of fuel.

$$m_{Oxygen-fire} = Q_{ext\,limit} / \Delta Hc_{Oxygen} \qquad \text{[kg/s]} \qquad (17)$$

Furthermore, gas in- or out-flow changes the oxygen concentration. The model calculates the loss of oxygen by outflowing gas as the average oxygen concentration inside the compartment multiplied by the flow rate. For the inflowing gas, the ambient oxygen concentration is used.

SOLVING THE EQUATIONS

The equations above and certain internal "household" of parameters are programmed into an Excel 97 spreadsheet, and a time axis is introduced. Many of the calculated values are interdependent, and the built-in solving scheme of the spreadsheet is used. **A** time step of about 0.05 sec is necessary to obtain convergence and approximately 50–100 iterations are needed to get a final solution. On a Pentium III 600 MHz 130 Mh **RAM** computer, one calculation of 32000 time steps takes about 2-3 min.

DISCUSSION

MASS BALANCE

The mass conservation scheme of the model includes the gas phase only. The in- and out-flows of gases are actually simulated by keeping a constant pressure inside the compartment and then calculating the mass inside based on the ideal gas law. The temperature ofthe gases actually controls the mass. By increasing the temperature some of the mass is lost through expansion, while the contraction of gases by decreasing temperature leads to in-flow of ambient air. Water that evaporates is included in the gas mass balance. The volume ***of*** liquid water is ignored. One relaxation of accuracy is by considering the gases inside the compartment always to have the properties of air.

HEAT BALANCE

Heat production and **losses** simulate the heat balance of the compartment. Heat production by the fire is time dependent and varies with the concentration of oxygen. Heat losses to the walls include stored heat and heat transferred to the ambient, depending of the wall temperature and the average gas temperature inside. The model disregards the floor area as a heat sink, assuming the water at the floor will rapidly cool the floor to a temperature well below the gas temperature inside the enclosure and closer to the water supply temperature. The model also adds the area of the ceiling to the wall area and **uses** the same convective heat transfer coefficient. This is a simplification with insignificant impact for the results,

Heat transferred to the water heats it up from the supply temperature to the boiling point. When the average gas temperature inside passes 100 °C, the water evaporates and takes up the heat of evaporation. Conversely, this heat will be given to the compartment by condensation. Heat transfer from hot walls to the gases inside will occur in a similar way if the inside temperature is reduced. The heat balance is used **to** calculate the average gas temperature, which is a primary parameter of the model.

OXYGEN CONCENTRATION

The oxygen concentration inside the compartment is controlled by the consumption of oxygen by the fire, by the supply of ambient air with normal oxygen concentration, and by the loss of oxygen through outflow of gases from the compartment.

FIRE DEVELOPMENT

One key feature of the WATMIST model is how the fire development is modelled. The growth is modelled by an empirical model, simulated by a time-dependent stepping up of fire output toward its theoretical maximum. The choice of empirical factors is adjusted to fit a typical pool fire development, which reaches its maximum fire size after **1-3** minutes. This factor may be reduced to simulate a spray fire.

The reduction of fire output is simulated by two mechanisms. First, the fire heat release rate is made dependent on the absolute ratio of fuel and air, represented by the stoichiometric fraction. This is calculated by oxygen concentration, supposing that fuel always is in excess in the volume. This is the situation in most practical applications of the model. Second, the heat output is made dependent of the proximity to an extinction limit, by a linear correlation. This is not documented by any theoretical or experimental verification, but is introduced to count for the temperature dependency of the extinction limit. These two correlations are made optional in the model. Experience with calculations shows that the use of the proximity to an extinction limit performs better seen from a equation solving point of view, since the fire size is gradually reduced. Using the stoichiometric fraction method combined with an extinction criterion gives an abrupt fire development, with more challenges to the solving procedure as a consequence.

EXTINCTION CRITERION

The model also contains an extinction criterion depending of the proximity to the extinction limit. This criterion can be seen as a compensation for the lack of dynamic accuracy due to the assumption that all reactions and mixing happen simultaneously in the compartment. In real life, local differences of temperature and oxygen concentration occur, and the recirculation of fire products in the compartment will in some cases lead to extinguishment of a localised fire, even if the average oxygen concentration is above the extinction limit. The only transient compensating for this in the present model is the energy stored in the walls that can lead to further evaporation of water when the fire is close to extinguishment. When the fire load is above a certain level, this leads to an average oxygen concentration at or below the extinction limit, but with smaller fires the oxygen level never reaches the critical concentration. The extinction criterion can be adjusted to match real occurring phenomena, such as extinguishment of a fire of a certain size in an enclosure volume (maximum non-extinguishable fire).

PARADOX OF WATER MIST

Small obstructedfires are more difficult to extinguish than larger.
Too much water makes it difficult to extinguishsmallfires.

These effects have been observed in experiments from the first introduction of water mist. For instance, conclusions from the project Halon Replacement by Fine Water Spray Technology–Turbine Hood application, carried out by SINTEF in 1992 [5], say:

- Small fires are difficult to extinguish with the Fine Water Spray system, except when the spray directly hits the fire base.
- The Fine Water Spray system operates as a total flooding fire suppression system when the fire size is big related to the room.
- When a small number of nozzles is installed in an enclosure, a sequence of 120 [s] water spray, intermission 120 [s] and then a second 120 [s] water spray is an efficient way of extinguishing small fires. This sequence is more efficient than one single water spray of longer duration.

Recent research carried out by the US Coast Guard, reported in March 2000 [6], concludes similarly:

> Small fires must be extinguished by direct flame interaction with the mist, while the obstructed fires are extinguished primarily by oxygen depletion (indirect effects). Fires that are extin-

guished by direct flame interaction are typically extinguished in less than one minute and are relatively unaffected by compartment volume or ventilation conditions. Fires that require some degree of oxygen depletion to aid in extinguishment (obstructed fires) have longer extinguishment times, which have been shown to be a function of fire size to compartment volume ratio (assuming constant ventilation condition). The extinguishment times for these fires approach infinity as the fire is reduced to the critical value. The critical value/size is primarily a function of ventilation condition in the space.

Possible Explanation

When the temperature of the gases of the compartment is below about 70 °C, the maximum concentration of water vapour that can exist is limited to less than 30%. This makes the added effect of water vapour as an inert gas less pronounced. The high flow rate of water effectively cools down the gases in the compartment, which also reduces the possibility of inert gas to exist. The water that has evaporated in the hot zone of the fire condenses and will reoccur as (liquid) droplets. Larger fires heat the compartment to higher temperatures, and hence more water exists as vapour (inert gas).

This effect explains partly why there is a "largest non-extinguishable fire" connected to a certain fire scenario, based on compartment size and ventilation conditions. Water mist is transferred into inert gas (water vapour) at a rate decided by the fire size, and the leakage of the inert gas is determined by the ventilation conditions. In addition, the temperature development of the gases inside the enclosure also determines the production or reduction of inert gas. It then becomes possible to cool the compartment gases to a temperature below the point where free inert gas can exist in the atmosphere at the desired concentration. By reducing the flow of water, either by lower flow rate or by intermittent spray, the smaller fires may be extinguished.

Based upon the experiments, there is evidence that a fire was extinguished after the water mist system was shut down, but it was impossible to obtain extinguishment as long as the system was running. The increased temperature allowing higher water vapour concentration of the recirculating gases when the cooling effect of water droplets stops, explains this. However, there is still a certain quantity of droplets floating in the air, entraining the hot zones or evaporating on hot surfaces after shutdown of the system.

Sequencing of the water spray is also seen to be more efficient than continuous spray. This is explained by the increasing temperature of the compartment when the spray is off, allowing more water to exist as vapour due to the higher saturation pressure.

EXAMPLES OF CALCULATION

Some examples of trends calculated by WATMIST are shown in Figures 3 - 9. The input values of the compartment are as follows: Floor - 10 x 33 m, ceiling height 9.1 m; walls and ceiling - 0.2 mm thick steel plates; specific heat capacity - 0.5 kJ/kg K. The convective heat transfer coefficient to the walls and ceiling is set to 0.03 kW/m² K. Initial gas temperature in the compartment is 25 °C, water supply temperature is 10 °C. Specific fuel burning rate of the pool is set to 0.05 kg/m² s. Preburn time of the pool before water is introduced is 15 s. Net heat of combustion of the fuel is 44600 kJ/kg. The factor in the time-dependent step-up function is 4. The reduction of heat release rate is calculated by the proximity to extinction limit (Eq. 4). The extinction criterion is 0.01. The water supply is set to 200 litres/min, and the mean droplet diameter 100 µm. The water mist system efficiency factor is set to 1. Convective heat transfer between droplets and gas is set to 0.03 kW/m² K.

The calculations give a maximum heat release rate of 2897 kW, reached after about 60 s (Figure 3). The maximum theoretical heat release rate is 3346 kW. Then the oxygen concentration limits the combustion, and the heat release rate gradually decreases until extinguishment occurs in about 33 min. Figure 3 shows the heat stored in the walls in the first phase of the fire, and given back to the internal gases when the gas temperature decreases sufficiently. The heat transfer to the water is gradually reduced after a rapid growth period. Very little heat is taken up by water evaporation, since the maximum average temperature never exceeds 100 °C.

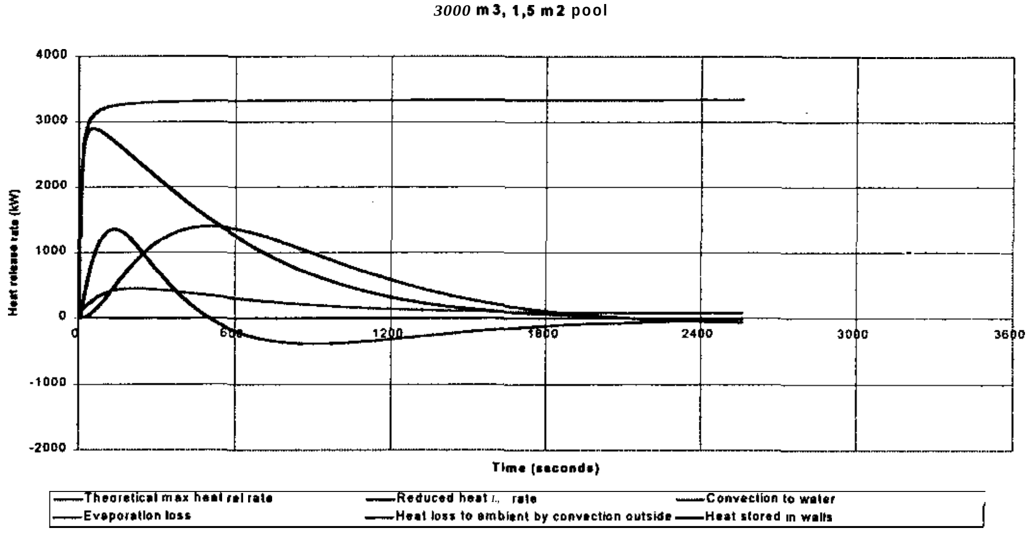


Figure **3.** Heat balance of compartment and heat release rate of fire, in a **3000** m^3 enclosure, **1.5** m^2 pool fire.

Figure **4** shows the temperatures of the gas and the walls. A rapid increase of average temperature to a maximum of **84 °C** after about **3** min is followed by a decreasing temperature until the fire is extinguished.

The oxygen concentration inside the compartment is shown in Figure 5. The oxygen concentration starts at ambient air concentration, 20.9%, and decreases to a minimum of 17%. The extinguishment limit starts at about 17% when the temperature is **25 °C,** but decreases to about **15.3%** when the temperature reaches its maximum of **82 °C**. The extinguishment limit then gradually increases until the difference between the actual oxygen concentration and the limit is 1%. The heat release is zero. The transients are slow after the first growth phase, and small changes of input parameters will highly influence the time to extinguishment.

Figure **6** shows the heat release rate of a pool twice the size of the one in Figure 3. Maximum theoretical heat release of the **3** m^2 pool fire is **6690** kW; however, in the calculation, it reaches only 5517 kW before the reduction due to limited oxygen appears. The minimum oxygen concentration is **16.6%** and the maximum average gas temperature is **132** "C (Figures **7** and 8). This leads to shorter time to extinguishment, about 13 min.

From the tests carried out by the US Coast Guard **[6],** one conclusion is that a maximum non-extinguishable fire may be scaled by a factor about **1-2** kW/m^3 enclosure volume. Using this factor for the **3000** m' enclosure as in the calculations above, a maximum non-extinguishable fire in this enclosure would be 3000–6000 kW. The calculations show a time to extinguishment of **33.3** min for the **3346** kW fire, which is outside the requirement for the IMO **668** (15 min) **[7].** The **6690** kW fire is extinguished within **12.6** min, which is within the IMO **668** requirements. With the chosen values of the calculation, the results correspond with the findings in large-scale tests. However, more work should he carried out and further comparison with test results is necessary to fully validate the WATMIST model.

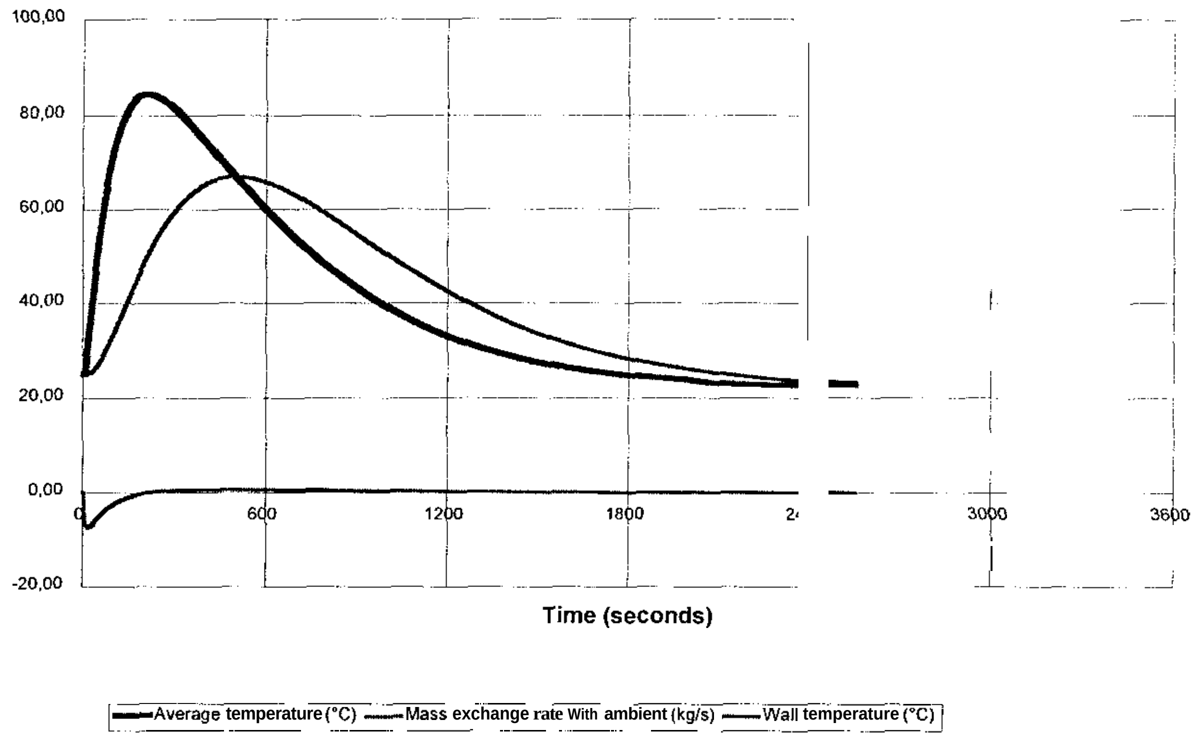


Figure 4. Temperatures and mass exchange rate in a 3000 in' enclosure, 1.5 m^2 pool fire

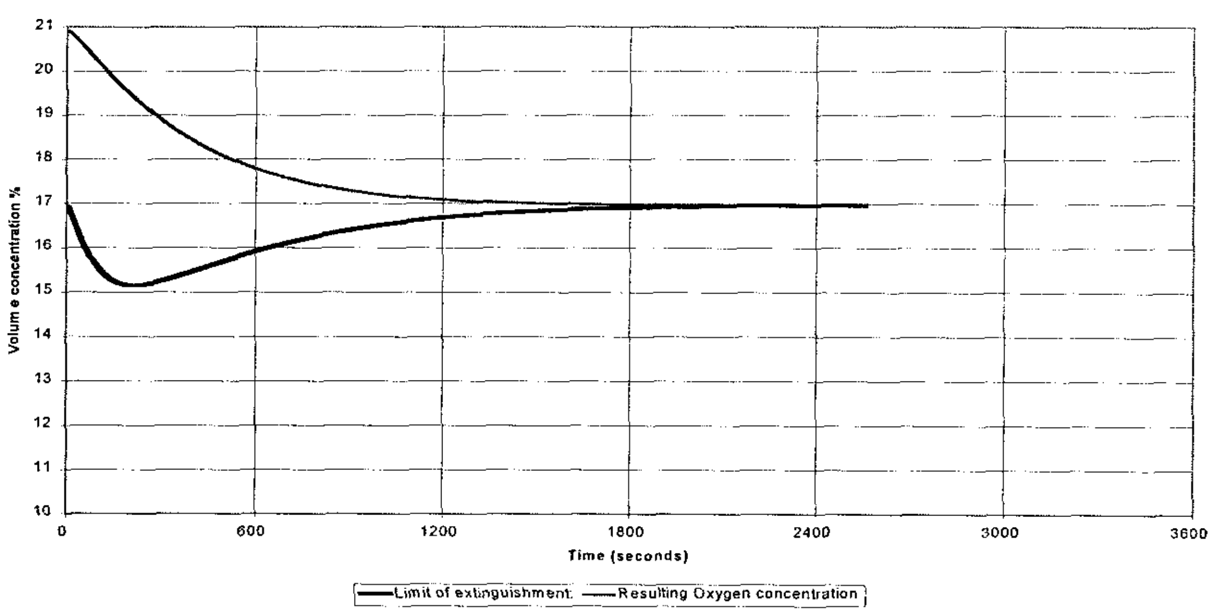


Figure 5. Oxygen concentration and extinguishment limit in a 3000 m^3 enclosure, 1.5 m^2 pool fire.

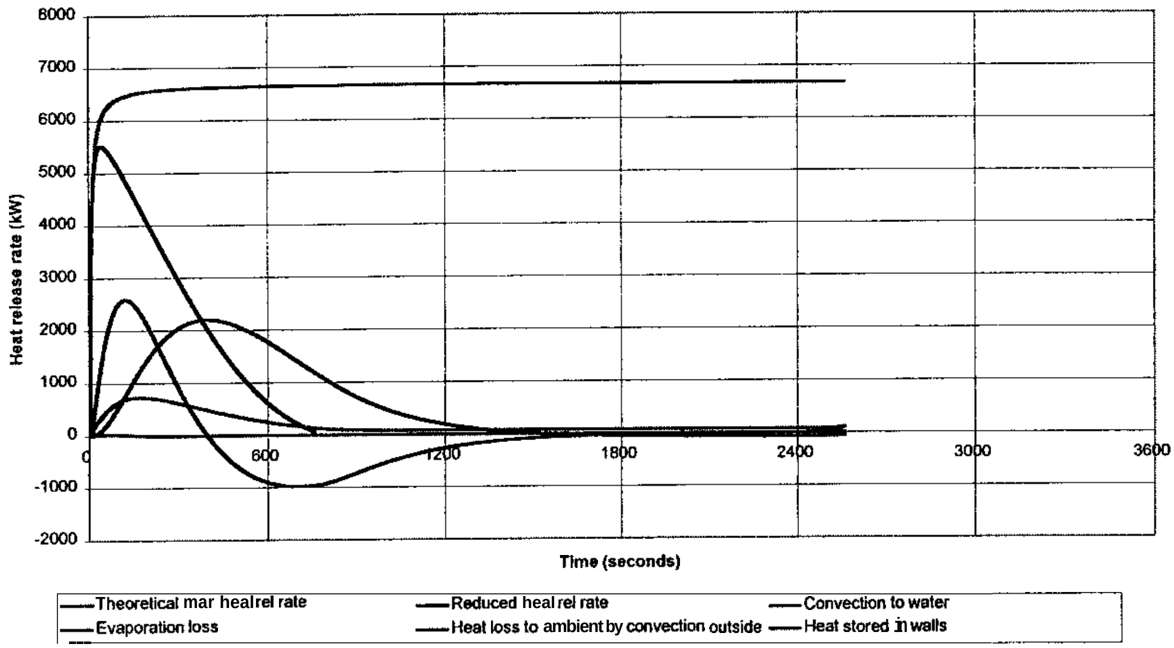


Figure 6. Heat balance of **compartment and heat release rate** of **fire, in a 3000** m^3 enclosure, 3 m^2 pool fire.

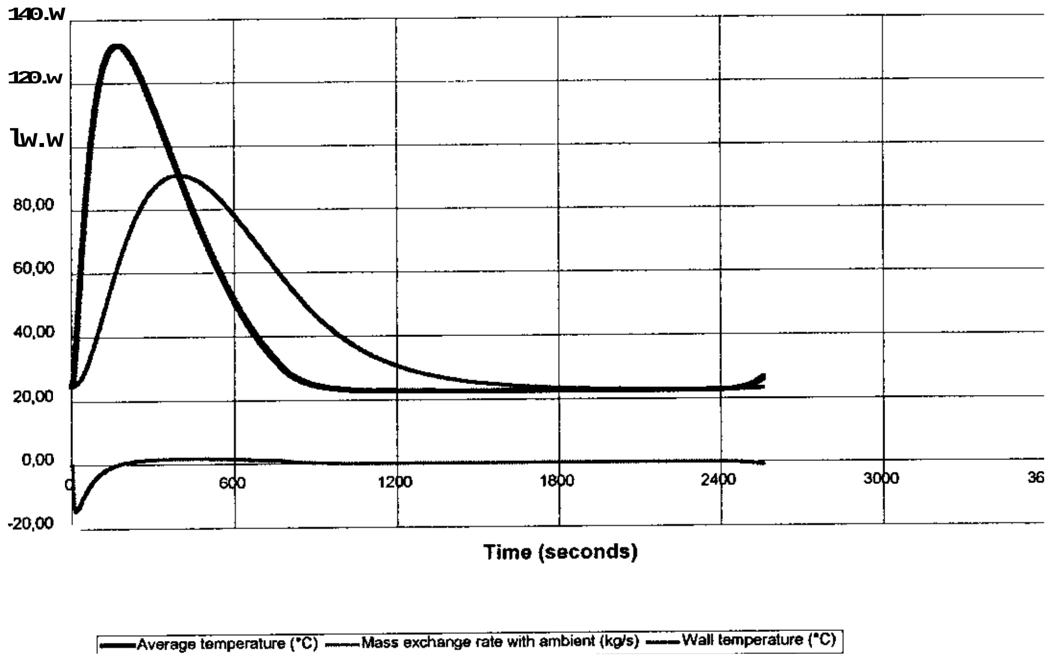


Figure 7. **Temperatures and mass exchange rate in a 3000** m^3 **enclosure,** 3 m^2 **pool fire.**

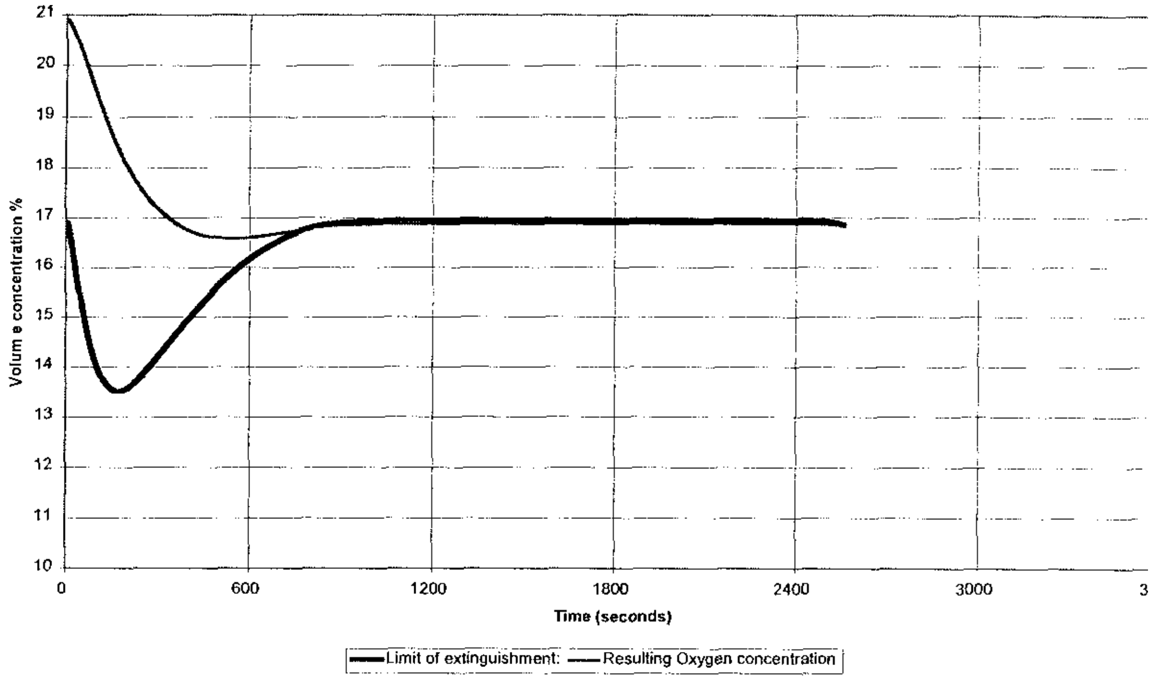


Figure 8. Oxygen concentration and extinguishment limit in a 3000 m^3 enclosure, 3 m^2 pool fire.

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