A Zone Model for Fast Verification of Release of Ultrafine Water Mist for Fire Extinction in Compartments

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1 Introduction

Ultra Fine Water Mist (UFWM) fire extinction is a promising technology to achieve fire suppression with reduced quantities of water [1]. Its use can also limit properties losses by limiting the damage to structures and objects consequent to large water release. However the mechanisms of extinguishment are very complex because of the strong interaction of the aerosol particles with the fluid dynamics and fire structures. These effect poses several issues for a proper dimensioning of the system. Indeed it is difficult to predict the quantity of water able to reach the flame, because the convective motion in the compartment, caused by the fire itself, strongly affects the path of the released droplets already at few tens of centimetre from the injection point. Particles so small as those produced by UFWM injectors, with initial size of 50 micron or less, rapidly dissipate their initially high inertia (high injection pressure of about 100 bar) and, even if injected close to the fire, they very rapidly evaporate becoming immediately very light and small and therefore effectively dragged by the flow field. Mechanisms of extinction of the fire by UFWM are them self very complex. Several mechanisms can play a role: cooling by the evaporating water and oxygen depletion by the high volume expansion of evaporating water are only the main mechanisms. Also other mechanisms are important in a real fire, like the attenuation of radiative heat transfer by the curtain formed by the water mist, or chemical effects of the vapour water with the combustion reactions, as well as fluid dynamics effects due to the interaction of the jets of water spray released in proximity of the fire, causing an increase of turbulence in the region of the flame.

The main problem is therefore the difficulty to predict which mechanisms predominate and if they act on a global scale or on a local scale. To provide an engineering model for the proper dimensioning of UFWM systems is equally difficult. In this work, a simple zone model [2] is derived to assess some of the minimum requirements that a proper dimensioning of the system has to satisfy. Based on simplifying assumptions valid for UFWM, i.e. when water droplets have a diameter less than 50 microns, balance equations of energy, air, water vapor and liquid water particles are derived for the volumes formed by the partitioning of a confined ambient interested by a fire into three zones: fire column (zone 1), ceiling zone (zone 2) and the remaining of the ambient (zone 3). Being the aim to verify that a proper amount of UFWM release is determined (in compartments where the ignition source cn be located anywhere), the logic is to assign the expected fire and the desired extinction rate and then estimate if the assumed water release is commensurate. This assessment is obtained by verifying several indicators during the

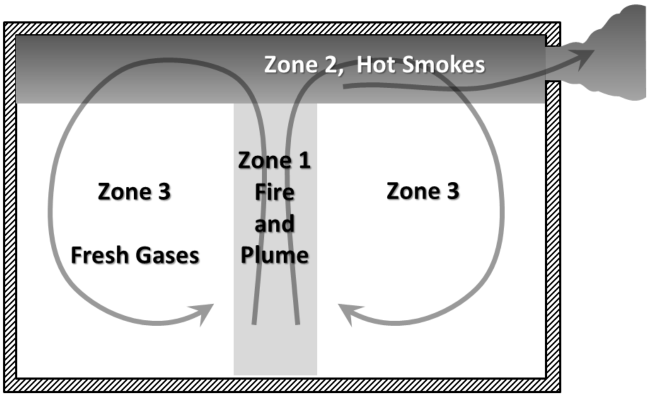

Figure 1: Division of the compartment into 3 different zones. Also indicated is the assumed flow pattern with grey arrows.

model evolution: temperature reached in the fire zone, depth of the hot smokes ceiling layer, amount of liquid water mist in zone 3, amount of air (oxygen) in the fire zone.

Validation and limits of the model are derived comparing results with a full scale fire test data of a workstation (tables, books, paper files, chair and computer) completed by a CDF numerical simulation with the FDS software by NIST. The fire test proved the effectiveness of the UFWM system. It will be shown that the zone model is able to reproduce a coherent evolution of the variables by adopting the UFWM flow rate used in the successful extinction test.

2 Model Equations

The compartment is divided into 3 zones, as shown in Fig. 1:

- Zone 1, is the flame zone, where highest temperatures develops. Because of the high temperature, and being the evaporation time of UFWM at high temperature of the order of ms, we can assume that all particle entering this zone immediately vaporize. The imprint on the floor of this zone is kept constant, while its height reduces with the increase of the thickness of the smoke layer. The heat and gases produced by the fire are released in this zone.
- Zone 2, is the hot layer of smokes, kept at a constant temperature above 100 Celsius, but its depth vary. We can assume that all UFWM droplets entering this zone immediately vaporize. Hot gases enter this zone at the temperature of Zone 1 and leave this zone at its fixed temperature. Part of the gas is released to the atmosphere to avoid the pressurization of the compartment.
- Zone 3 is a buffer, at the fixed temperature of fresh gases, between zone 2 and zone 1. Droplets entering this zone does not vaporize and so they can accumulate or be transferred to the flame zone.

The prescribed amount of UFWM total release is distributed among the 3 zones. In this paper it is assumed that the total flow rate is partitioned following the instantaneous volume fraction of each zone with respect to the whole volume. Different partitioning could be assigned in order to study the effect of different release strategies.

For each zone the following balance equations are enforced.

2.1 Zone 1

Air mass balance

$$\frac{dm_{w1}}{dt} = -F_{w12} + F_{w31} + F_{WM31} + \frac{V_1}{V_{tot}} \dot{m}_{WM} \tag{1}$$

Water vapour mass balance

$$\frac{dm_{a1}}{dt} = -F_{a12} + F_{a31} + \dot{m}_{fire} \tag{2}$$

where:

- F_{12} e F_{31} are the mass fluxes of gas leaving and entering zone 1, respectively, $[kg/s]$;
- F_{WM31} is the mass flux of liquid vapour coming from zone 3 by the total volumetric flux, [kg/s]
- $\dot{m}_{WM}$ is the total flow rate of UFWM released per unit time, [kg/s];
- V_1e V_{tot} are the volume of zone 1 and the total volume of the compartment, respectively, $[m^3]$;
- $\rho_{a,w}$ are the density of air and water vapour, the numeric subscript referring to the zone o origin, $[kg/m^3]$;
- $\dot{m}_{fire}$ is the mass of gases released by the fire, [kg/s].

Each mass flux carry on an amount of energy that, when computed at the temperature of the zone of origin, can be expressed as:

$$\dot{Q}_{12} = (c_{w1} F_{w12} + c_{a1} F_{a12})\, T_1 \tag{3}$$

$$\dot{Q}_{31} = (c_{w3} F_{w31} + c_{a3} F_{a31} + c_{wl3} F_{WM31})\, T_3 \tag{4}$$

Energy balance. This balance include the production term deriving by the Heat Release Rate of the fire, $HRR(t)$, and the cooling effect of the evaporating water droplets, H_{LHV1}, computed as:

$$H_{LHV1} = \left(\frac{V_1}{V_{tot}} \dot{m}_{WM} + F_{WM31} \right) \left(c_{wl} \left(373 - T_w \right) + LHV_1 + c_w \left(T_1 - 373 \right) \right) \tag{5}$$

where:

- C_{WM3} is the mass concentration of liquid UFWM in the zone 3, $[kg/m^3]$;
- LHV_1 is the latent heat of vaporization of all droplets in zone 1, [J/kg];
- T_w is the temperature of the UFWM entering the domain, [K].

Collecting all terms, the energy balance takes the form:

$$\frac{d\left(c_{w1} m_{w1} + c_{a1} m_{a1}\right) T_1}{dt} = -\dot{Q}_{12} + \dot{Q}_{31} + HRR(t) - HLV_1 \tag{6}$$

2 Zone 2

Air mass balance

$$\frac{dm_{w2}}{dt} = -F_{w23} + F_{w12} + \frac{V_2}{V_{tot}} \dot{m}_{WM} - F_{w,out} \tag{7}$$

Water vapour mass balance

$$\frac{dm_{a2}}{dt} = -F_{a23} + F_{a12} - F_{a,out} \tag{8}$$

where:

- $F_{a,w,out}$ is the mass flux of air or water leaving the domain trough the vent, $[m^3/s]$;
- F_{23} is the flux from zone 2 to zone 3, $[m^3/s]$;
- V_2e V_{tot} are the volume of zone 2 and the total volume, respectively, $[m^3]$;

Energy balance. The balance of energy takes into account the contributes due to convective fluxes, entering ($\dot{Q}_{12}$) and leaving ($\dot{Q}_{23}$ e $\dot{Q}_{out}$) the zone, and the energy subtracted by the evaporation of the UFWM in zone 2 (HLV_2):

$$\dot{Q}_{12} = (c_{w1}F_{w12} + c_{a1}F_{a12})\,T_1 \tag{9}$$

$$\dot{Q}_{23} = (c_{w2}F_{w23} + c_{a2}F_{a23})\,T_2 \tag{10}$$

$$\dot{Q}_{out} = (c_{w2}F_{w,out} + c_{a2}F_{a,out})\,T_2 \tag{11}$$

$$H_{LHV2} = \left(\frac{V_2}{V_{tot}}\dot{m}_{WM}\right)LHV \tag{12}$$

Collecting all terms, the energy balance of zone 2 takes the form:

$$\frac{d\,(c_{w2}m_{w2} + c_{a2}m_{a2})\,T_2}{dt} = \dot{Q}_{12} - \dot{Q}_{23} - HLV_2 - \dot{Q}_{out} \tag{13}$$

The last term is the energy leaving the domain with the vented gases. This balance, in which the temperature T_2 is kept constant, acts as an evolution equation for the depth h_2 of the layer of hot gases at the ceiling, when the argument of the time derivative is expressed as $(c_{w2}m_{w2} + c_{a2}m_{a2})\,T_2 = T_2\,(c_w\rho_{w2}A_2h_2 + c_a\rho_{a2}A_2h_2)$.

2 Zona 3

Adopting the same convention for the definition of the quantities relevant to zone 3, the balance equations are easily described, acting this zone as a buffer for exchange of mass and energy from zone 2 to zone 1. *Air mass balance*

$$\frac{dm_{w3}}{dt} = F_{w23} - F_{w31} + \frac{V_1}{V_{tot}}\dot{m}_{WM} \tag{14}$$

Water vapour mass balance

$$\frac{dm_{a3}}{dt} = F_{a23} - F_{a31} \tag{15}$$

Energy balance. The conservation of energy, where T_3 is kept constant, has to be equally enforced as a constraint to obtain the correct heat fluxes from zone 2 and zone 3.

$$\frac{d\,(c_{w3}m_{w3} + c_{a3}m_{a3})\,T_3}{dt} = Q_{23} - Q_{31} \tag{16}$$

Liquid phase water mist mass balance. In this zone, the liquid water mist is allowed to accumulate. The time evolution of this quantity is expressed by the equation:

$$\frac{d\rho_{WM}V_3}{dt} = -\rho_{WM}\frac{F_{31}}{\rho_3} + \frac{V_3}{V_{tot}}\dot{m}_{WM} \tag{17}$$

The momentum balances for the 3 zones are not explicitly derived. It is assumed that the only driving force of the flow is the fire. In this case, empirical correlations exists that give the entrainment of gases in the fire and plume zone $F_{31} = F_{a31} + F_{w31}$. Here the correlation of McCaffrey [3] is adopted. This correlation gives F_{31} as a function of the ratio between the height of the flame, Z [m], and the energy released by the fire Q_f, that in our case is a prescribed function of time.

The solution of the system of equations is obtained adopting an explicit iterative procedure, implemented in Matlab. The resulting time step to maintain stability is of the order of 0.1 s, therefore compatible with the assumed hypothesis of instantaneous vaporization of UFWM droplets in zone 1 and 2.

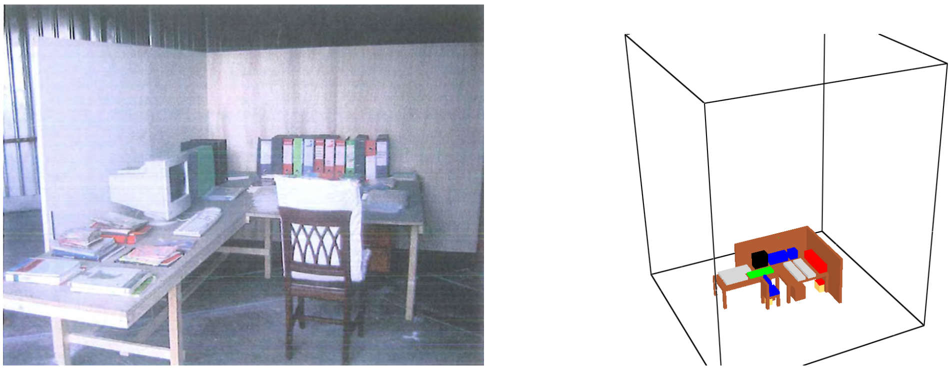

Figure 2: The fire test scenario adopted for the model validation. Left: a photograph of the disposal of materials before the test. Right: the representation of the same scenario with the FDS software.

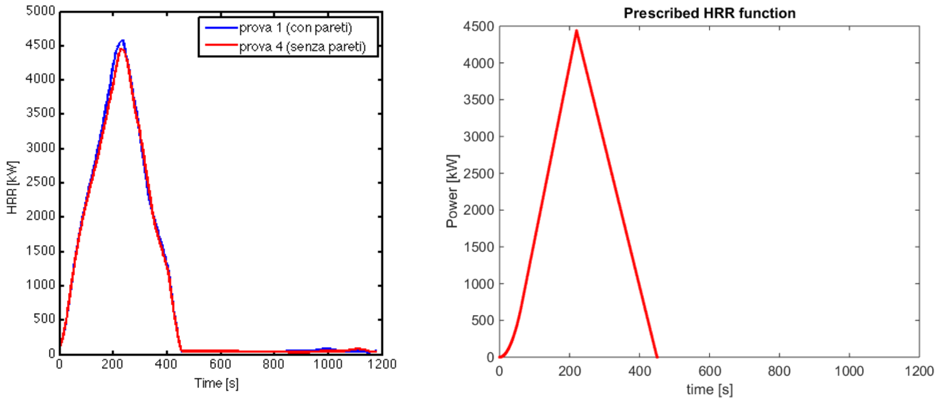

Figure 3: The HRR curve computed with the FDS software reproducing the experimental fire (left) and the assigned parametric curve in the simulation.

3 Results

The model has been applied to verify the ability to predict the amount of water mist tht was required during a full scale fire test of a standard workstation. The layout of this experimental setup is shown in Fig. 2. Because during the fire tests the HRR curves was not recorded, the FDS software [4] has been adopted to reproduce the same fire test and obtain the function $HRR(t)$ that is the main input, together with the release rate of UFWM for the developed procedure. Figure 3 compare the HRR function computed with the help of FDS reproducing the experimental fire and the assigned parametric HRR function. To extinguish this fire, 10.72 l/min were released, starting 60 seconds after the ignition. The same amount of UFWM has been assigned for the simulation.

Several parameters could be adopted to verify that the released amount of water is sufficient to determine the extinction of the fire. Fig. 4, left, shows the computed profiles of the average temperature in the plume zone and the computed height of the layer of smokes. They show that the prescribed amount of water release is adequate to limit the temperature increase in the flame zone and to avoid the smoke layer to growth up to the occupation of the entire volume of the compartment. It is noticed, however, that the prediction does not appear satisfactory. The layer of smokes increase too much, leaving out only a small layer of fresh gases at the end of the simulation. The included assumption are indeed too conservative to obtain an accurate quantitative prediction. A second indication of the effectiveness of the

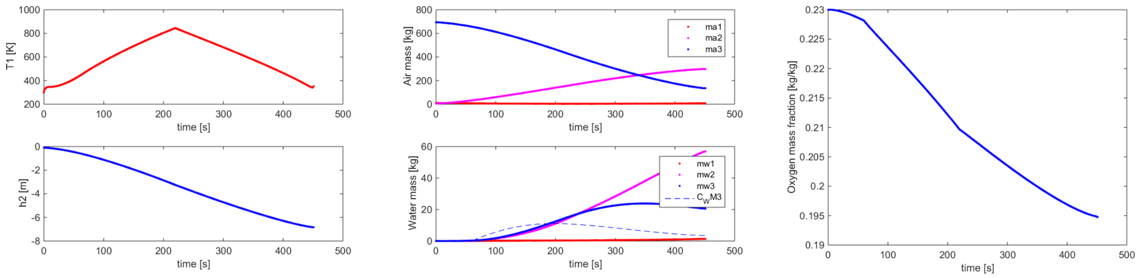

Figure 4: From left to right: time evolution of the temperature T_1 in the zone of the plume and of the depth of the layer of hot smokes (bottom); time evolution of mass of air and water; oxygen concentration versus time in the plume zone.

UFWM release is reported in Fig. 4, left. It results that liquid water starts to accumulate in the fresh gas region, thus allowing Water Mist to be transported by the flow motion into the plume zone, adding this contribute to the effect of Water Mist released directly into the plume zone. The oxygen concentration in zone 1 is reported in Fig. 4, right. Oxygen depletion is significant, even if its reduction does not appear sufficient to smother the flame.

3 Conclusions

The illustrated results are very preliminary and cannot be considered, at the present stage of development of the model, as fully validated. However they are sufficient to illustrate the potentiality of the approach in obtaining several indication about a proper dimensioning of a UFWM system. Despite its simplicity, the model appear useful for a first estimate of the UFWM flow rate required to extinguish a given fire, taking into account the interaction between the different zones of the compartment and the possibility for the WM to reach the fire zone in proper amount. Furthermore, several extinction mechanisms can be estimated: fire cooling by UFWM evaporation, oxygen depletion by water vapor substitution, effectiveness of the thermal radiation shield provided by the UFWM. The work is at an early stage and the validity of results needs to be confirmed with respect to several parameters ranging from the dimensions of the compartment, to the fire power.

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