The Design Fire Tool OZone V2.0 - Theoretical Description and Validation On Experimental Fire Tests

1rst DRAFT
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List of symbols and notations

$1ZM$:		One zone model
$2ZM$:		Two zone model
A_f :	[m²]	Floor area of a compartment
A_{fi} :	[m²]	horizontal burning area of fuel
$A_{fi,max}$:	[m²]	maximum horizontal burning area of fuel
$H_{c,net}$:	[J/kg]	complete combustion heat of fuel (obtained in bomb calorimeter)
$H_{c,eff}$:	[J/kg]	effective combustion heat of fuel (in real fire)
m :	[]	combustion efficiency factor
$\dot{m}_{fi}$:	[kg/s]	pyrolisis rate
m_{fi} :	[kg]	total mass of fuel
$M_{fi,c}$:	[kg]	total mass of fuel in the compartment
m_{ox}:	[kg]	mass of oxygen in the compartment
$m_{ox,ini}$:	[kg]	mass of oxygen in the compartment at initial time
$m_{ox,in}$:	[kg]	mass of oxygen coming in the compartment through vents
$m_{ox,out}$:	[kg]	mass of oxygen going out of the compartment through vents
$q_{f,k}$:	[J/m²]	characteristic fire load density per unit floor area of compartment
$q_{f,d}$:	[J/m²]	design fire load density per unit floor area of compartment
RHR :	[W]	Rate of Heat Release
RHR_f :	[W/m²]	Rate of Heat Release per unit floor area of compartment
t_s :	[s]	Time of switch from the 2ZM to the 1ZM
m_U & m_L,	[kg]	mass of the gas of, respectively, the upper and lower layer (2ZM)
T_U & T_L,	[K]	temperatures of the gas of, respectively, the upper and lower layer (2ZM)
V_U & V_L,	[m³]	volumes of, respectively, the upper and lower layer (2ZM)
E_U & E_L,	[J]	internal energies of, respectively, the upper and lower layer (2ZM);
r_U & r_L,	[kg/m³]	gas densities of, respectively, the upper (*U*) and lower (*L*) layer (2ZM)
$c_v(T)$,		the specific heat of the gas in the compartment at constant volume
$c_p(T)$,		the specific heat of the gas in the compartment at constant pressure
R,	[]	the universal gas constant
γ	[]	the ratio of specific heat
i,	[]	indicia equal to *U* for upper layer, to *L* for lower layer and *g* for 1ZM
m_g,	[kg]	mass of the gas in the compartment (1ZM)
T_g,	[K]	temperature of the gas (1ZM)
E_g,	[J]	internal energy (1ZM)
r_g,	[kg/m³]	gas density (1ZM)
V,	[m³]	volume of the compartment (constant)
p,	[Pa]	absolute pressure in the compartment considered as a whole.
$\dot{m}_{VV,in}$:	[kg]	mass of gas coming in the compartment through vertical vents
$\dot{m}_{VV,out}$:	[kg]	mass of gas going out of the compartment through vertical vents
$\dot{m}_{VV,U,in}$:	[kg]	mass of gas coming in the upper layer through vertical vents
$\dot{m}_{VV,U,out}$:	[kg]	mass of gas going out of the upper layer through vertical vents
$\dot{m}_{VV,L,in}$:	[kg]	mass of gas coming in the lower layer through vertical vents
$\dot{m}_{VV,L,out}$:	[kg]	mass of gas going out of the lower layer through vertical vents

$\dot{m}_{FV,in}$:	[kg]	mass of gas coming in the compartment through forced vents
$\dot{m}_{FV,out}$:	[kg]	mass of gas going out of the compartment through forced vents
$\dot{m}_{FV,U,in}$:	[kg]	mass of gas coming in the upper layer through forced vents
$\dot{m}_{FV,U,out}$:	[kg]	mass of gas going out of the upper layer through forced vents
$\dot{m}_{FV,L,in}$:	[kg]	mass of gas coming in the lower layer through forced vents
$\dot{m}_{FV,L,out}$:	[kg]	mass of gas going out of the lower layer through forced vents
$\dot{m}_{HV,in}$:	[kg]	mass of gas coming in the compartment through horizontal vents
$\dot{m}_{HV,out}$:	[kg]	mass of gas going out of the compartment through horizontal vents
$\dot{m}_{HV,U,in}$:	[kg]	mass of gas coming in the upper layer through horizontal vents
$\dot{m}_{HV,U,out}$:	[kg]	mass of gas going out of the upper layer through horizontal vents
$\dot{m}_{HV,L,in}$:	[kg]	mass of gas coming in the lower layer through horizontal vents
$\dot{m}_{HV,L,out}$:	[kg]	mass of gas going out of the lower layer through horizontal vents

$\dot{q}_{VV,in}$:	[kg]	energy coming in the compartment through vertical vents
$\dot{q}_{VV,out}$:	[kg]	energy going out of the compartment through vertical vents
$\dot{q}_{VV,U,in}$:	[kg]	energy coming in the upper layer through vertical vents
$\dot{q}_{VV,U,out}$:	[kg]	energy going out of the upper layer through vertical vents
$\dot{q}_{VV,L,in}$:	[kg]	energy coming in the lower layer through vertical vents
$\dot{q}_{VV,L,out}$:	[kg]	energy going out of the lower layer through vertical vents
$\dot{q}_{FV,in}$:	[kg]	energy coming in the compartment through forced vents
$\dot{q}_{FV,out}$:	[kg]	energy going out of the compartment through forced vents
$\dot{q}_{FV,U,in}$:	[kg]	energy coming in the upper layer through forced vents
$\dot{q}_{FV,U,out}$:	[kg]	energy going out of the upper layer through forced vents
$\dot{q}_{FV,L,in}$:	[kg]	energy coming in the lower layer through forced vents
$\dot{q}_{FV,L,out}$:	[kg]	energy going out of the lower layer through forced vents
$\dot{q}_{HV,in}$:	[kg]	energy coming in the compartment through horizontal vents
$\dot{q}_{HV,out}$:	[kg]	energy going out of the compartment through horizontal vents
$\dot{q}_{HV,U,in}$:	[kg]	energy coming in the upper layer through horizontal vents
$\dot{q}_{HV,U,out}$:	[kg]	energy going out of the upper layer through horizontal vents
$\dot{q}_{HV,L,in}$:	[kg]	energy coming in the lower layer through horizontal vents
$\dot{q}_{HV,L,out}$:	[kg]	energy going out of the lower layer through horizontal vents

1 Introduction

In the previous ECSC Research "Competitive Steel Buildings through Natural fire Safety Concept" [], t

Zone models are numerical tools commonly used for the evaluation of the temperature development of the gases within a compartment during the course of a fire. Based on a limited number of hypotheses, they are easy to use and provide a good evaluation of the situation provided they are used within their real field of application. Since the first numerical one zone models have been made by Petersson, major developments of the numerical fire modelling have been done. Among other things, multi-zones, multi-compartment and computational field dynamics models have been developed. Although zone models are the less sophisticated numerical fire model, they have their own field of application and thus are essential tool in fire safety engineering applications.

The main hypothesis in zone models is that the compartments is divided in zones in which the temperature distribution is uniform at any time. In one zone models, the temperature is considered to be uniform within the whole compartment. This type of model is thus valid in case of fully developed fires, contrary to two zones models which are valid in case of localised fires. In this last type of model there are a hotter layer which is close to the ceiling and a cooler layer which is close to the floor.

The aim of this paper is to present on one hand a new compartment fire model called "OZone" and on the other hand its validation on full scale fire tests. This zone model has been developed in the scoop of the ECCS researches *"Natural Fire Safety Concept"* (NFSC1) and *"Natural Fire Safety Concept - Full Scale Tests, Implementation in the Eurocodes and Development of an User Friendly design tool"* (NFSC2). The probabilistic approach to define the action of fire developed in the scoop of NFSC 1 have been included in the code.

OZone V2 is a code which includes a two zones and a one zone models with a possible switch from two to one zone if some criteria are encountered. It thus deals with localised and fully engulfed fires. OZone V2 is an improvement of OZone V1 which was a one zone model developed in the NFSC1 research.

In OZone several improvements on existing zone models have been made. The wall model is made by the finite element method and is implicit. And finally different combustion models have been developed to cover different situations of use of the code.

Within the same researches a database of natural fire tests has been created (see NFSC 1998) and full scale fire tests have been carried on. The code has been validated on XX tests of these tests and a comparison of the one zone model of OZone and another one zone model NAT has been made.

A Graphic User Interface has been developed to define the input data.

2 Zone model formulation

The fundamentals of the two and one zone models of OZone are presented in this section. Figure 1 and Figure 2 show schematic views of the two models.

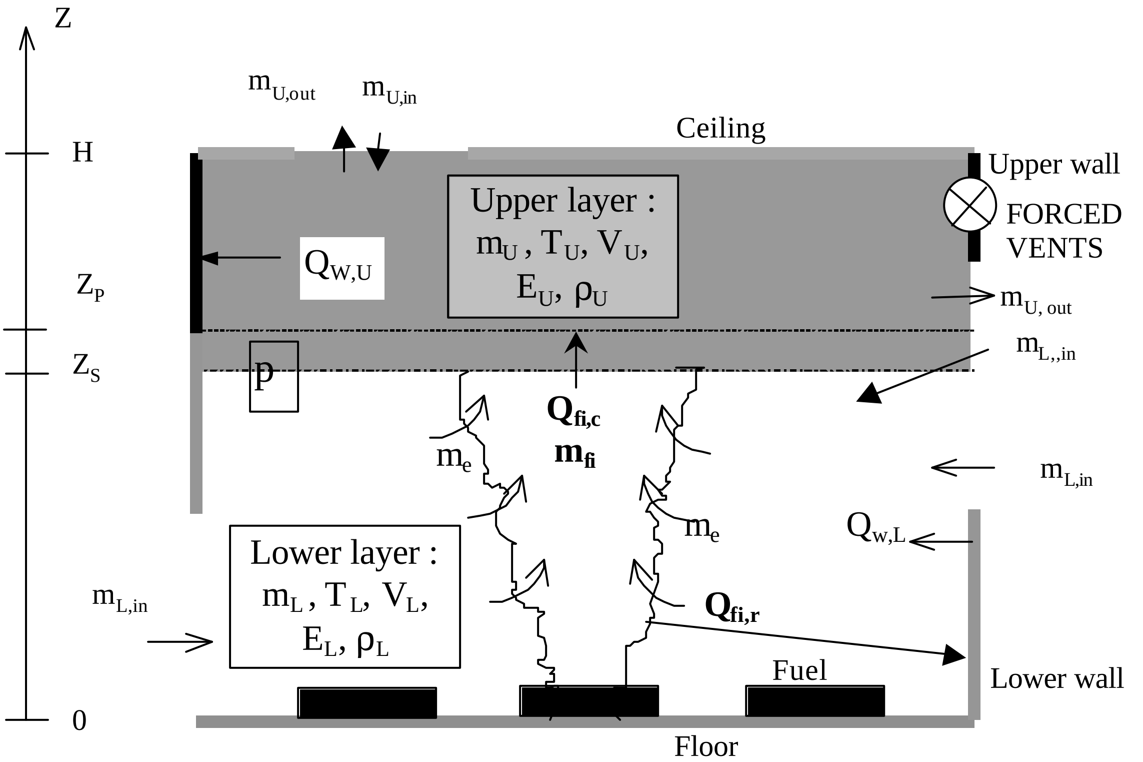


Figure 1 Schematic view of two zone model and associated submodels

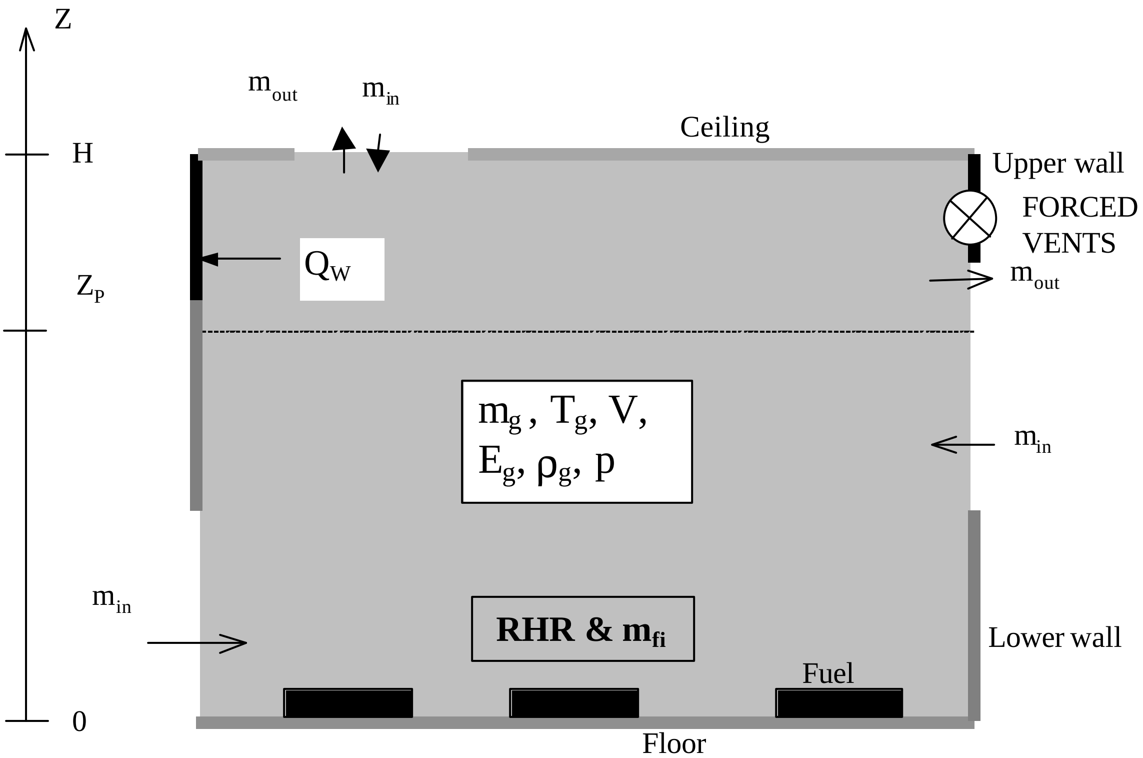


Figure 2 Schematic view of one zone model and associated submodels

2.1 Two zones model

Numerical two zone models are normally based on eleven physical variables. These variables are linked by seven constraints and four differential equations describing the mass and the energy balances in each zones. The time integration of these differential equations allows to calculate the evolution of the variables describing the gas in each zones. The mass balance equation expresses the fact that, at any moment, the variation of the mass of the gas of a zone is equal to the mass of combustion gases created by the fire, plus the mass coming into the compartment through the vents minus the mass going out of the compartment through the vents. The energy balance equation expresses the fact that, at any moment, there is a balance between, on one hand, the energy which is produced in the compartment by the combustion and, on the other hand, the way in which this energy is consumed: by the heating of the gases in the compartment, by the mass loss of hot air through the openings (including a negative term accounting for the energy of incoming air), by the radiation loss through the openings and, finally, by the heating of the partitions. It has to be mentioned that the term "partition" is used here to represent all the solid surfaces of the enclosure of the compartment, namely the vertical walls, the floor and the ceiling.

The eleven variables which are considered to describe the gas in the compartment are: m_U and m_L, the mass of the gas of respectively the upper and lower layer; T_U and T_L, the temperatures of the gas; V_U and V_L, the volumes; E_U and E_L, the internal energies; r_U and r_L, the gas densities of respectively the upper (*U*) and lower (*L*) layer and finally *p*, the absolute pressure in the compartment considered as a whole.

The seven constraints are:

$$\begin{aligned} & r_i = \frac{m_i}{V_i} \\ & E_i = c_V(T) m_i T_i \\ & p = r_i R T_i \\ & V = V_U + V_L \\ & i = U, \quad L \end{aligned} \tag{1}$$

with $c_V(T)$, the specific heat of the gas in the compartment;
R, the universal gas constant
i, equal *U* for upper layer & *L* for lower layer

The specific heat of the gas at constant volume and at constant pressure, the universal gas constant R and the ratio of specific heat are related by :

$$\begin{aligned} & R = c_p(T_i) - c_v(T_i) \\ & g(T_i) = \frac{c_p(T_i)}{c_v(T_i)} \end{aligned} \tag{2}$$

The variation of the specific heat of the gas with the temperature is taken into account by the following relation :

$$c_P(T) = 0.187\, T + 952 \; [J/(kg\, K)] \tag{3}$$

This law is obtained by a linear regression on the point by point law given in the NFPE Handbook of Fire Protection Engineering.

The mass balance equations have the general form of equations (4) and (5) in which a doted variable $\dot{x}$ means the derivative of x with respect to time. Equations (4) et (5) states that the variation of gaseous mass in each zones is made of the mass exchanges of one zone with the fire, with the other zone, and with the external world trough the different vent types (see §5).

$$\dot{m}_U = \dot{m}_{U,VV,out} + \dot{m}_{U,HV,in} + \dot{m}_{U,HV,out} + \dot{m}_{U,FV,in} + \dot{m}_{U,FV,out} + \dot{m}_e + \dot{m}_{fi} \tag{4}$$

$$\dot{m}_L = \dot{m}_{U,VV,in} + \dot{m}_{L,VV,in} + \dot{m}_{L,VV,out} + \dot{m}_{L,HV,in} + \dot{m}_{L,HV,out} + \dot{m}_{L,FV,in} + \dot{m}_{L,FV,out} - \dot{m}_e \tag{5}$$

The energy balance equations have the general form of equations (6) and (7) stating that the variation of energy in each zones is made of the energy exchanges of one zone with the fire, with the other zone, with the surrounding partitions and with the external world trough vents.

$$\begin{aligned} \dot{q}_U = {} & \dot{q}_{U,rad} + \dot{q}_{U,wall} + \dot{q}_{U,VV,out} + \dot{q}_{U,HV,in} + \dot{q}_{U,HV,out} \\ & + \dot{q}_{U,FV,in} + \dot{q}_{U,FV,out} + c_p(T_L)\dot{m}_{ent}T_L + 0.7RHR \end{aligned} \tag{6}$$

$$\begin{aligned} \dot{q}_L = {} & \dot{q}_{L,rad} + \dot{q}_{L,wall} + \dot{q}_{U,VV,in} + \dot{q}_{L,VV,in} + \dot{q}_{L,VV,out} \\ & + \dot{q}_{L,HV,in} + \dot{q}_{L,HV,out} + \dot{q}_{L,FV,in} + \dot{q}_{L,FV,out} - \dot{q}_{ent} \end{aligned} \tag{7}$$

In these balances, mass or energy rate corresponding to a decrease of mass or energy in the compartment are negatives.

Four basic variables have to be chosen to describe the system. Provided that the zones temperatures T_U and T_L, the altitude of separation of zones Z_S and the difference of pressure from the initial time Dp are chosen, equations (4) to (7) can be transformed in the system of ordinary differential equations (ODE) formed by equations (8) to (11). [FORNEY 1994]

$$\dot{\Delta p} = \frac{(g-1)\dot{q}}{V} \tag{8}$$

$$\dot{T}_U = \frac{1}{c_p(T_U)\, r_U\, V_U}\left(\dot{q}_U - c_p(T_U)\,\dot{m}_U\, T_U + V_U\, \dot{\Delta p} \right) \tag{9}$$

$$\dot{T}_L = \frac{1}{c_p(T_L)\, r_L\, V_L}\left(\dot{q}_L - c_p(T_L)\,\dot{m}_L\, T_L + V_L\, \dot{\Delta p} \right) \tag{10)}$$

$$\dot{Z}_S = \frac{1}{g(T_L)PA_f}\left(\left(g(T_L) - 1\right)\dot{q} - V_L\, \dot{\Delta p} \right) \tag{11}$$

2.2 One zones model

In case of a one zone model, the number of variables which is reduce to six, describing the gas in the compartment as a whole. i.e. m_g, the mass of the gas; T_g, the temperature of the gas; V, the volume of the compartment (constant); E_g, the internal energy; p, the pressure in the compartment; r_g, the gas density.

The number of constraints is reduce to 4:

$$\begin{aligned} r_g &= \frac{m_g}{V} \\ E_g &= c_V(T_g)m_g T_g \\ p &= r_g R T_g \\ V &= cst \end{aligned} \tag{12}$$

The mass balance is expressed now by equation (13):

$$\dot{m}_g = \dot{m}_{in} + \dot{m}_{out} + \dot{m}_{fi} \tag{13}$$

And the energy balance is expressed by equation (14):

$$\dot{q}_U = \dot{q}_{rad} + \dot{q}_{wall} + c_p(T_g)\dot{m}_{out}T_g + c_p(T_{out})\dot{m}_{in}T_{out} + RHR \tag{14}$$

In these balances, mass or energy rate corresponding to a decrease of mass or energy in the compartment are negatives.

Four basic variables have to be chosen to describe the system. Provided that the zone temperature *T* and the difference of pressure from the initial time *Dp* are chosen, equations (13) and (14)can be transformed in the system of ordinary differential equations formed by equations (15) and (16).

$$\Delta \dot{p} = \frac{(g-1)\dot{q}}{V} \tag{15}$$

$$\dot{T}_g = \frac{1}{c_p(T_g)\; r_g\; V}\left(\dot{q} - c_p(T_g)\,\dot{m}_g\,T_g + V\,\Delta\dot{p}\right) \tag{16}$$

2.3 Time integration

As said before, the systems of equations (8) to (11) (2ZM) and of equations (15) and (16) (1ZM) are to be solved to know the gas characteristics of zones at each time. These systems of ODE are stiff. A physical, although not rigorous from a mathematical point of view, interpretation of stiffness is that the time constant relative to the pressure variation is much shorter than the time constant of the temperature variation. It is therefore usual to rely on a specialised library solver specifically written for this kind of problem. In the code OZone, the solver DEBDF is used.

3 Partition model

During the development of the OZone V1 (one zone) code in Liege, it was decided that the partition model should be such that the energy balance is fully respected which was not the case in existing zone model. That is only possible if the wall temperatures are solved implicitly.

Usually the partition models of zone model are based on finite difference. This method does not allow to solve the equation implicitly and therefor to fully coupled the zone and the partition models. This problem can be solved model by using the finite element method and by modifying the usual finite element formulation. To fully respect the energy balance in case of one zone model, partitions have to be modelled by one dimensional finite elements and in case of two zone model have to be modelled by two dimensional finite elements because vertical fluxes exist in vertical partitions.

Even if OZone V2 includes a two zone and a one zone, a one dimension partition model have been included in it. Some preliminary work on two zone model with a two dimensional partition model have been made and has shown that partition model based on one dimension finite elements is a good approximation of the one based on two dimension. In most cases, the two dimensional phenomenon are negligible. The increases of the computing time and of the difficulties to define the compartment are quite big and are useless in most cases.

Partitions can be divided in three types: The upper horizontal partition, the ceiling; the lower horizontal partition, the floor; and finally the vertical partitions, the walls. The basic finite element formulation is the same for the three types of partitions but the boundary conditions are different.

3.1 Partition model formulation

First of all, a partition is discretised by a single dimension finite element model as depicted in Figure 3. With this discretisation, the temperature is computed at the interface between the different layers, or elements, and the hypothesis is made of a linear temperature variation on the thickness of each layer.

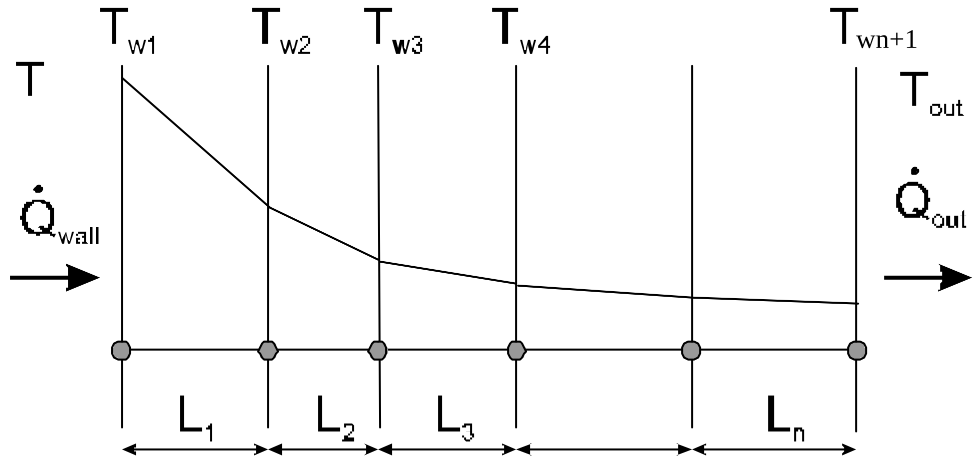


Figure 3 one dimensional finite elements discretisation of partitions

With this discretisation and this hypothesis on the field of temperature, well known developments show that the equilibrium of each finite element **i** is described by the following equation:

$$\mathbf{K}_{el,i}\ \mathbf{T}_{el,i} + \mathbf{C}_{el,i}\ \dot{\mathbf{T}}_{el,i} = \mathbf{g}_{el,i} \tag{17}$$

with

$$\mathbf{T}_{el,i} = \begin{Bmatrix} T_{w,i} \\ T_{w,i+1} \end{Bmatrix} \tag{18}$$

$$\mathbf{K}_{el,i} = \frac{k_i}{L_i}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{19}$$

$$\mathbf{C}_{el,i} = c_i\ \rho_i\ L_i \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix} \tag{20}$$

and $$\mathbf{g}_{el,1} = \begin{Bmatrix} \dot{q}_{wall} \\ 0 \end{Bmatrix} ;\ \mathbf{g}_{el,2} \ \ to \ \ \mathbf{g}_{el,n-1} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} ;\ \mathbf{g}_{el,n} = \begin{Bmatrix} 0 \\ \dot{q}_{out} \end{Bmatrix} \tag{21}$$

Equations 12 and 13 are in fact simplified expressions because the material properties have been considered as constant in each element, allowing to take them as constant multipliers out of the matrix. The temperature dependency in the element could also be taken into account, owing to the well known numerical integration techniques of Gauss. Equation (20) is furthermore the diagonalised version of the complete matrix, having a value of 1/3 for the diagonal terms and 1/6 for the off diagonal terms. The advantage of the diagonal form is first that it smooth the spatial oscillations which could arise in the solution if too thick elements are used in the discretisation. Another advantage is related to the computing strategy, as will be explained in the formulation of equation XX.

The assembly of the N equations of type (17) which can be written for each of the N finite element making the partition produce the system of equations (22) in which the size of the vectors is N+1 and (N+1) x (N+1) for the matrices.

$$\mathbf{K}\ \mathbf{T}_w + \mathbf{C}\ \dot{\mathbf{T}}_w = \mathbf{g} \tag{22}$$

with $$\mathbf{g} = \begin{Bmatrix} \dot{q}_{wall} \\ 0 \\ \\ 0 \\ \dot{q}_{out} \end{Bmatrix} \tag{23}$$

The energy transmitted at the partition interface results from heat transfer by convection and radiation between zones and the partition and between the fire and the partition. The energy transmitted at the interface between the outside world and the partition is due to heat transfer by convection and radiation. The evaluation of these terms is explained in §3.2.

We note T_{w1} the inside partition surface temperature and $T_{w,n+1}$ the outside partition surface temperature. T_z is the gas temperature of the zone in contact with the partition inside surface, i.e. $T_z = T_U$ or T_L in case of 2ZM or $T_z = T_g$ in case of 1ZM.

From the system of equations (22), it is very easy to obtain the system of equations (24), efficiently computed owing to the diagonal nature of $\mathbf{C}$.

$$\dot{\mathbf{T}}_w = \mathbf{C}^{-1} \left(\mathbf{g} - \mathbf{K}\ \mathbf{T}_w \right) \tag{24}$$

This system of equations is a set of N differential equations for the N temperatures of the partition. The temperature of the compartment is only present in the first term of the load vector, see equations XX and XX. It has a similar form as the system of equations (8) to (11) (2ZM) and of equations (15) and (16) (1ZM) established for the variables of the gas zones and could be written in the following way.

$$\begin{aligned}
\dot{T}_{w,1} &= g_1(T, T_{w,1}, T_{w,2}) \\
\dot{T}_{w,2} &= g_2(T_{w,1}, T_{w,2}, T_{w,3}) \\
&. \\
\dot{T}_{w,i} &= g_i(T_{w,i-1}, T_{w,i}, T_{w,i+1}) \\
&. \\
\dot{T}_{w,N+1} &= g_N(T_{w,N}, T_{w,N+1}, T_{out})
\end{aligned} \tag{25}$$

3.2 Connection of the zone and the partition models

3.2.1 Two zone model

In 2ZM, the ceiling is always connected to the upper layer and the floor to the fire and to the lower layer. Vertical partitions are divided in two part, an upper one, connected to the upper layer and a lower one connected to the fire and to the lower layer (Figure 4). The area of each part are calculated by multiplying the length of the wall by its height which is varying with time and is function of the altitude of separation of the zones, Z_S. The area of openings included in each partition are of course subtracted. The finite element discretisations of the two parts are identical, only the boundary conditions are different.

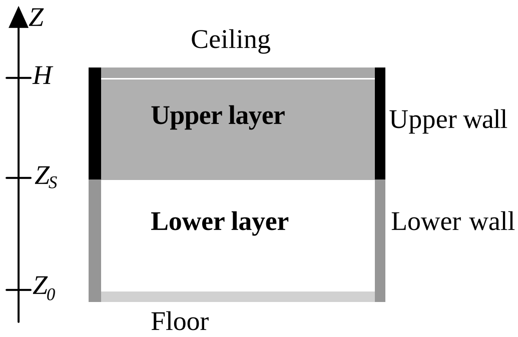


Figure 4

The system of equations (24) has to be build once for the ceiling and once for the for the floor. If the enclosure has M different types of walls, it has to be build 2M times. If $N_{eq,c}$ and $N_{eq,f}$ the number of node of the ceiling and of the floor, and $N_{eq,i}$ the number of node of the wall n°i, the total set of partition equations contains $N_{eq,w}$ differential equations, given by equation (26).

$$N_{eq,w} = N_{eq,f} + N_{eq,c} + \sum_{i=1}^{M} 2N_{eq,i} \tag{26}$$

Equations (8) to (11) and equations (24) form a set of $N_{eq,w}$+4 differential equations which can be passed on to the numerical solver. This one will integrate the equations taking into account the coupling between the compartment and the partition and solving the $N_{eq,w}$+4 variables which are the pressure variation, the temperature in the upper zone, the temperature in the upper zone and the altitude of the zone interface, plus the temperatures at each node of the partitions.

It has been said in the introduction of this chapter that the effect of vertical fluxes is weak.

Using one dimension partition model in two zone model lead to artificially create or suppress some energy in the wall. Considering an increasing upper layer thickness (Figure 5), if the height separation between the zones is Z_S at time t and Z_S+DZ_S at time $t+Dt$, a wall of height DZ_S is transformed from lower wall to upper wall. As the temperature of lower wall are generally lower then the ones of upper wall, some energy is created (XX). On the contrary if the upper layer thickness is decreasing, some energy are lost. The only way to be rigorous when modelling walls in 2ZM, is to make a single two dimensional partition model which would take into account vertical fluxes. The variation of Z_S has to be taken into account in the boundary condition of the two dimensional elements.

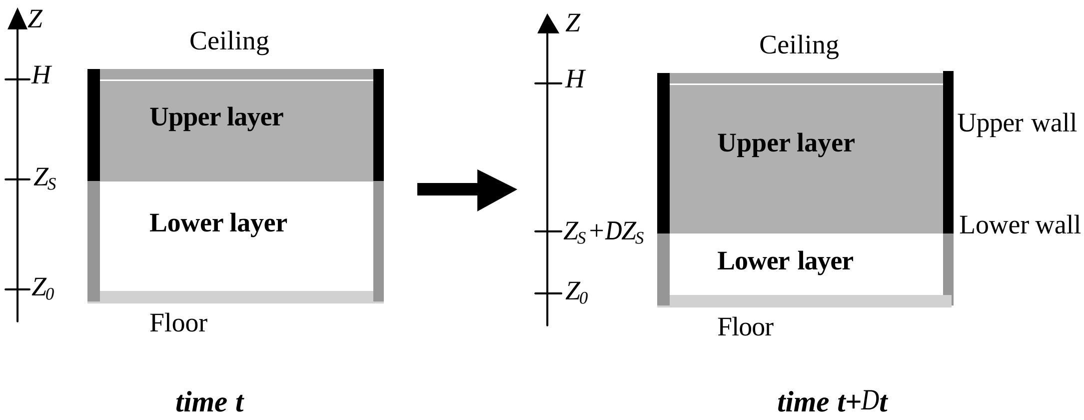


Figure 5

Boundary conditions

For all type of partitions, the energy transmitted at the interface between the outside world and the partition is due to heat transfer by convection and radiation and is given by equation (27).

$$\dot{q}_{pout} = h\left(T_{out} - T_{wN+1}\right) + e * s\left(T_{out}{}^4 - T_{wN+1}{}^4\right) \tag{27}$$

The upper layer is composed of a mixture of combustion products and fresh air entrained by the plume from the lower layer. It is considered to be opaque and radiation between partitions connected to it are neglected. The energy transmitted between the inside surfaces of upper partition and the upper layer results from heat transfer by convection and radiation.

$$\dot{q}_{wall,U} = h\left(T_U - T_{w1}\right) + e * s\left(T_U{}^4 - T_{w1}{}^4\right) \tag{28}$$

The lower layer is composed essentially of fresh air with only few combustion products, so its relative emissivity is considered to be nil. The energy transmitted between the inside surfaces of lower partitions and the lower layer results only from heat transfer by convection. The radiation from the fire is represented by the $q_{fi,w}$ term.

$$q_{wall,L} = h\left(T_L - T_{w1}\right) + q_{fi,w} \tag{29}$$

$q_{fi,w}$ [W/m²] is obtained by dividing 30% of the rate of heat release by the total area of lower partition, including the opening area (see also §XX).

3.2.2 One zone model

When considering a one zone model during a whole simulation, a vertical partition is divided two parts connected to the single zone (Figure 6). The finite element discretisations of the two parts and the boundary conditions are identical. Therefor the temperatures distribution in the partitions and the flux densities on the bounders are the same in the two parts. Indeed in a one zone model a vertical wall would normally not be divided into two. The results obtained with two partition models for a single wall are identical then those which would be obtained with only one partition model for the same single wall. The consequence of this procedure is only to increase the number of equation to be solved and therefor the computing time. Anyway this have been done in order to enable the combination of 2ZM and 1ZM as explained in detail in §4.1.2.

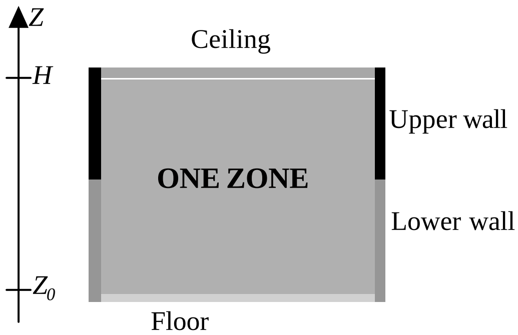


Figure 6

Again, in one zone model, the system of equations (24) has to be build one time for the ceiling and one time for the for the floor. If the enclosure has M different types of walls, it has to be build 2M times If $N_{eq,c}$ and $N_{eq,f}$ the number of node of the ceiling and of the floor, and $N_{eq,i}$ the number of node of the wall n°i, the total set of partition equations contains $N_{eq,w}$ differential equations, also given by equation (26).

Equations (15), (16) and equations (24) build $N_{eq,w}$ times form a set of $N_{eq,w}$+2 differential equations which can be passed on to the numerical solver. This one will integrate the equations taking into account the coupling between the compartment and the partitions and will solve the $N_{eq,w}$+2 variables which are the pressure variation and the temperature in the compartment, plus the temperatures at every node of the partitions.

For 1ZM, if one considers that the usual procedure sets the limits of the compartment on the inside surface of the wall and adds a wall sub-model on top of it, the proposed procedure amounts in fact to set the limit of the compartment on the outside surface of the wall. Because all the equations are solved simultaneously with an implicit procedure, the energy balance between the gas and the wall is totally respected.

Boundary conditions

For the three types of partitions, the energy transmitted at the interface between the outside world and the partition is due to heat transfer by convection and radiation and is given by equation (30).

$$\dot{q}_{p\rho ut} = h\left(T_{out} - T_{wN+1}\right) + e * s\left(T_{out}{}^{4} - T_{wN+1}{}^{4}\right) \tag{30}$$

The energy transmitted at the inside partition interfaces results from heat transfer by convection and radiation between the zone and the partitions.

$$\dot{q}_{wall} = h\left(T_g - T_{w1}\right) + e * s\left(T_g^{\ 4} - T_{w1}^{\ 4}\right) \qquad (31)$$

4 Switch from two zones to one zone model

If some criteria are encountered during a two zone simulation, the code will automatically switch to a one zone simulation, which suits better to the situation inside the compartment at this moment. The simulation will continue to the end of the fire considering a one zone model. The criteria of switch will be explained in §8. The aim of this paragraph is to set how OZone deals with the basic variables of the zone models, how it sets the one zone initial conditions and how it deals with partitions models.

4.1.1 Zone models formulation

t_s is the time at which the switch from the 2ZM to the 1ZM happens. The values of the eleven basic variables describing the gas in the two zones are known until t_s thanks to the time integration of equations (8) to (11) and considering the constraints (1). To continue the simulation with a one zone model, it is possible to begin to solve the equations (15) and (16) associated to initial conditions representing the situation at that time. The point is to set the 1ZM initial values (at time t_s).

In one zone model there are six variables describing the gas in the compartment as a whole, linked by four constraints. We then need 2 new constraints to fix the new initial conditions.

One obtain these two additional condition by setting that during the transition from 2 zones to 1 zone, the total mass of gas and the total energy in the compartment are conserved.

$$m_g(t_s) = m_U(t_s) + m_L(t_s) \qquad (32)$$

$$E_g(t_s) = E_U(t_s) + E_L(t_s) \qquad (33)$$

The initial (at time t_s) one zone temperature $T_g(t_s)$ and one zone pressure $p(t_s)$ can be deduce from equations (32), (33) and (12).

Afterward the one zone model runs with its associated sub-models for calculating exchanges of energy and mass through the vents. The partition models formulation and their initial values are explained at §4.1.2.

Comments - **temperatures diminuent** +autres options possibles

4.1.2 Wall model formulation

The partition temperatures at time t_s are obtained by integrating the set of equations (24) coupled to the 2 zone basic equations (8) to (11). At this time, the height of the lower and upper walls (vertical partitions) are respectively $Z_S(t_s)$ and $H\text{-}Z_S(t_s)$. From the time of transition t_s to the end of the calculation the one zone model is linked to the lower and upper walls which keep the dimension they had at time t_s, i.e. $Zs(t_s)$ and $H\text{-}Z_S(t_s)$. During the transition no modification of partition temperatures of wall dimension is made, only the boundary conditions are modified. This way to proceed enables to fully respect the conservation of energy during the transition from the two zones to the one zone model.

If a one zone model simulation is set from the beginning of the calculation, the dimension of the lower and upper walls are the initial dimensions, deduced from the initial altitude of separation of zones, until the end of the calculations.

It means that during a one zone simulation (one zone as well as combination strategy) a wall is represented by two identical partitions which see the same boundary conditions at each time.

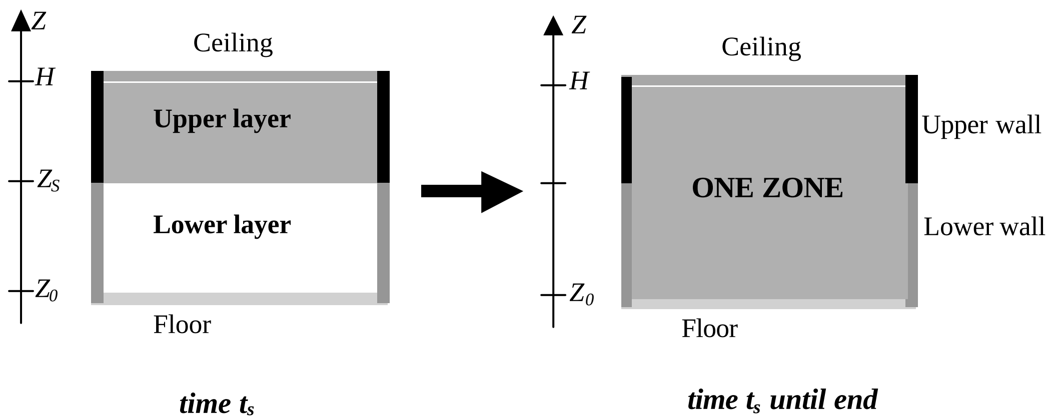


Figure 7

With a two zone model, lower walls are heated directly by radiation from the fire, and they give back energy to the lower layer by convection. If the switch encountered, they exchange energy by radiation and convection with the single zone.

5 Exchanges through the vents

Three types of vent models have been introduced in OZone V2.0: vertical vents; horizontal vents and forced vents.

5.1 Pressure

Although the pressure is uniform in the compartment when solving the basic equations of the problem, the pressure is not uniform in the compartment when calculating the mass flow trough the openings. In this case, the variation is exponential with the altitude (Z), equation (34).

$$p(Z) = p_0 \, e^{-\frac{g(Z-Z_0)}{RT}} \quad (34)$$

Z_0 : floor level

5.2 Vertical vents (vv indicia)

5.2.1 Convective exchanges

The mass flow through vents is calculated by integrating the Bernoulli's law on each openings.

$$\Delta p = \frac{1}{2} r v^2 \qquad (35)$$

$$\dot{m}_{a,VV,b} \quad = \quad K\, b(T \text{ or } t) \int_{Z'}^{Z''} \frac{P_A(z)}{R\,T_A} \sqrt{2\,R\,T_A \left(1 - \frac{P_B(z)}{P_A(z)}\right)}\, dz \qquad (36)$$

With *A indicia*: variable at origin of the flux
B indicia: variable at destination of the flux
Z' & Z'': bounds of integration on altitude Z
b : width of vertical vent
a : U if the integration is made in the upper layer, L if the integration is made in the lower layer and g in case of one zone model.
b : *in* if gas goes in the compartment, *out* if gas goes out of the compartment

If the altitude where the pressure inside the compartment is equal to the pressure outside of the compartment is in a vertical vent, the vertical vents is divided in two parts, one where the mass flow goes inside the compartment and another one where the mass flow goes outside. This altitude is called the neutral plane altitude. Moreover in a two zone model, if the altitude of separation between the zone is in the opening, another subdivision in two encountered. In 1ZM, three possibilities exist following the neutral level position. In 2ZM, 10 possibilities exist following the neutral level and the zone separation altitude positions. For each vertical vent, equation (36) is the solved 1 or 3 times with the appropriate bounds of integration on the altitude (Z' & Z'' can be the sill of the vent, the soffit of the vent, the neutral plane altitude or the separation between the zone altitude). Figure 8 shows in case of 2ZM and 1ZM one possible situation of relative position of Z_{sill}, Z_P, Z_S and Z_{soffit}.

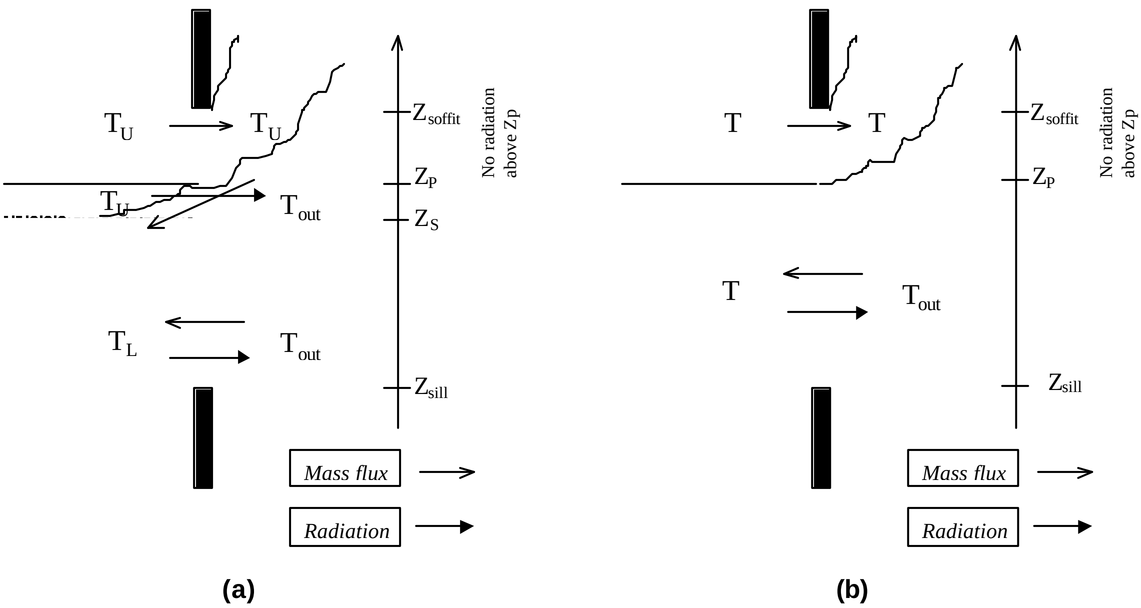


Figure 8 Exchanges through vertical vents in (a) 2ZM and (b) 1ZM

The energies of this mass fluxes are calculated by equation (37) in case of 2ZM and by equation (38) in case of 1ZM.

$$\begin{aligned} \dot{q}_{U,VV,out} &= c_p(T_U)\,\dot{m}_{U,VV,out}T_U \\ \dot{q}_{U,VV,in} &= c_p(T_{out})\dot{m}_{U,VV,in}T_{out} \\ \dot{q}_{L,VV,out} &= c_p(T_L)\dot{m}_{L,VV,out}T_L \\ \dot{q}_{L,VV,in} &= c_p(T_{out})\dot{m}_{L,VV,out}T_{out} \end{aligned} \tag{37}$$

$$\begin{aligned} \dot{q}_{VV,out} &= c_p(T_g)\dot{m}_{VV,out}T_g \\ \dot{q}_{VV,in} &= c_p(T_{out})\,\dot{m}_{VV,in}T_{out} \end{aligned} \tag{38}$$

5.2.2 Radiative exchanges

The radiation through the windows is taken into account by the Stefan-Boltzmann law. One consider that the radiation exists only bellow the altitude where the pressure inside the compartment is equal to the pressure outside the compartment. Above this level the gases goes out of the compartment and the temperature outside (in the plume) is assumed to be equal to the temperature in the compartment and thus it is considered that the net radiation flux is equal to zero (Figure 8).

If the windows is closed no mass exchange exists through it. The glazing can be assumed to be adiabatic and thus no radiation through it is considered. If radiation is considered through the glazing, it is evaluated by the stephan-boltzman law.

$$\dot{q}_{gl,rad} = e_{gl}^{*}\ s\ \left(T_Z^{\,4} - T_{OUT}^{4}\right) \tag{39}$$

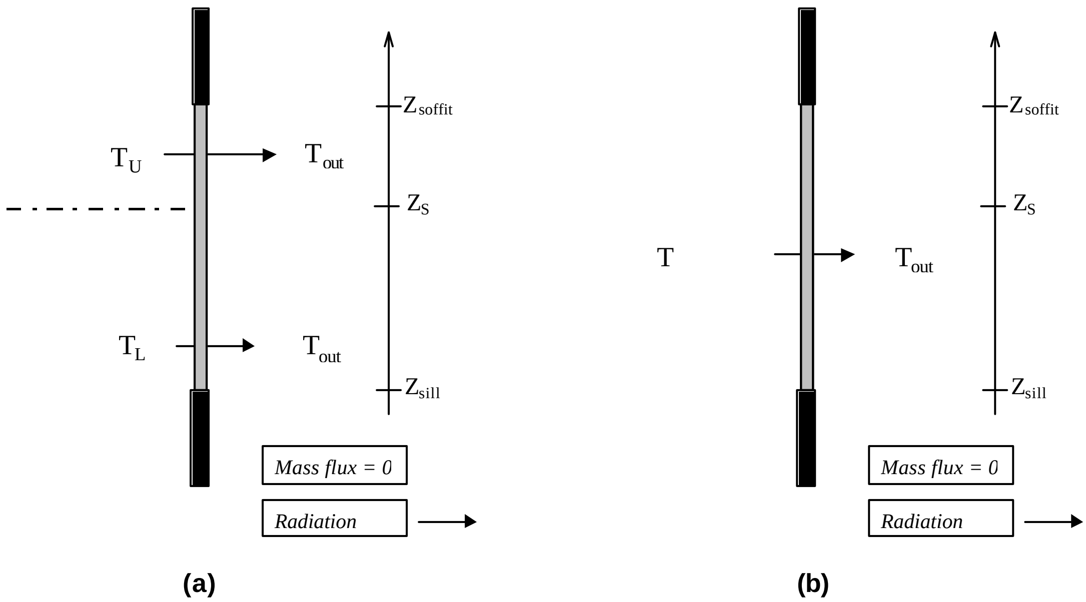


Figure 9 Radiative exchanges through closed vertical vents in (a) 2ZM and (b) 1ZM

e_{gl}^{*} is a parameter which include the relative emissivities of the gazes and include also the part of energy which is reflected on the interfaces between gas and glass and absorbed by the glazing material. It is highly dependent on the nature of the glazing material.

5.3 Horizontal vents (hv indicia)

Gas flow through an horizontal ceiling vent is not always driven by the single pressure difference, buoyancy can also have a significant effect. These forces may lead to bi-directional exchange flow through the vent. Therefor it is not appropriate to unconditionally use Bernoulli's equation to model flow through horizontal vent.

Cooper has established a model for calculating flows through circular, shallow (i.e. small depth to diameter ratio), horizontal vents. This model calculated the flow considering the pressure driven forces and when appropriated the combined pressure and buoyancy effects. The Cooper model is described in COOPER 95, COOPER 97

5.4 Forced vents (fv indicia)

Forced vent model is build to represent the effect of mechanical ventilation. The forced vents are defined by the volume rate flow that they induced, $\dot{V}_{FV}$, their height Z_{FV} and their diameter D_{FV}

When the zone interface is above the forced vent elevation + 1.5 D_{FV}, the exhausted gas is lower-layer air only. When the zone interface is below the forced vent elevation - 1.5 D_{FV}, the exhausted gas is upper-layer air only. When the zone interface is between Z_S + 1.5 D_{FV} and Z_S - 1.5 D_{FV}, the mass of extracted air from each layer is proportional to the distance between Z_S and Z_{FV} and $3D_{FV}$. (Figure 10).

If the forced vent is in the ceiling the interpolation is made as shown in Figure 11. When the zone interface is above the forced vent elevation - D_{FV}, the exhausted gas is lower-layer air only. When the zone interface is below the forced vent elevation - 2 D_{FV}, the exhausted gas is upper-layer air only. When the zone interface is between Z_S-D_{FV} and Z_S-2D_{FV}, the mass of extracted air from each layer is proportional to the distance between Z_S and Z_{FV}-D_{FV} and $2D_{FV}$.

$$\dot{m}_{FV} = r_{gas}\dot{V}_{FV} \tag{40}$$

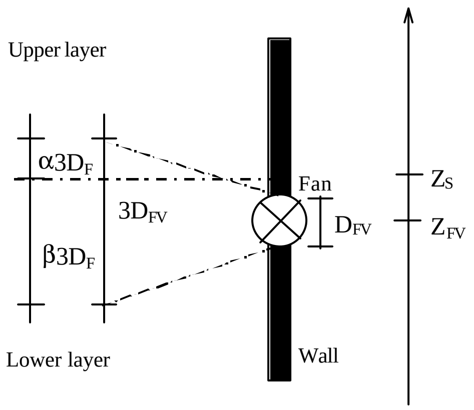


Figure 10

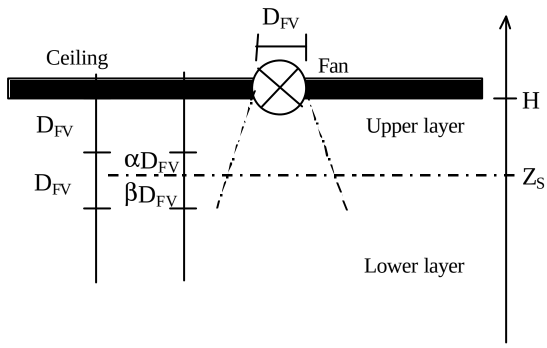


Figure 11

5.5 Opening size variation (glazing breakage)

During the course of a fire the number of vent which are opened can vary. Their size can also be modified. This can be the result of glazing breakage, automatic opening or firemen arrival… In OZone, the opened vent size can be defined to be a function of the temperature of the zone in contact with the glass (T_Z) or to be a function of time. Criteria function of zone temperature can represent breakage due to thermal action. Criteria function of time can represent the firemen arrival. Four variation types exist : a one step variation with temperature, a stepwise variation with zone temperature, a linear variation with zone temperature and a variation with time.

A broken glazing can not be closed afterward. So the percentage of broken glass is either increasing, either constant but never decreasing.

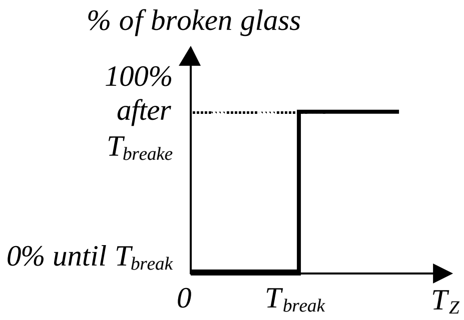


Figure 12 Temperature dependent

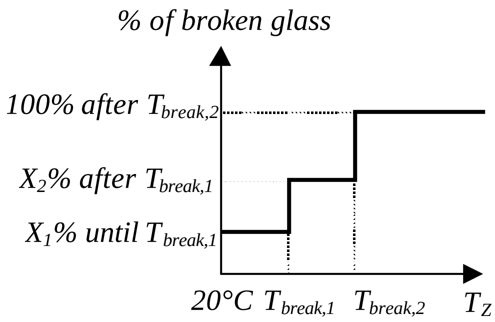


Figure 13 Temperature dependent Stepwise variation

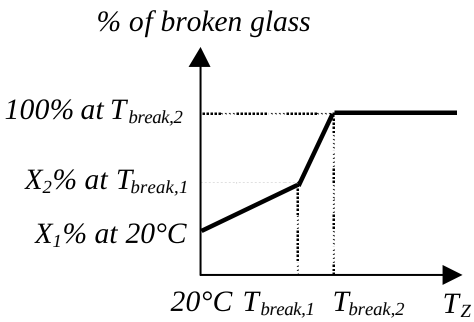


Figure 14 Temperature dependent Linear variation

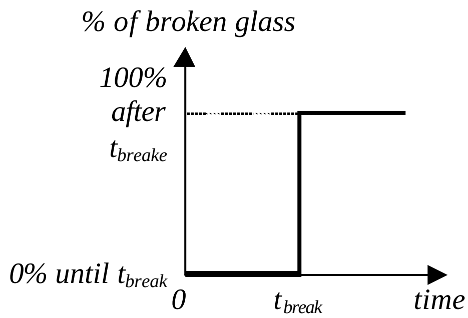


Figure 15 Time dependent

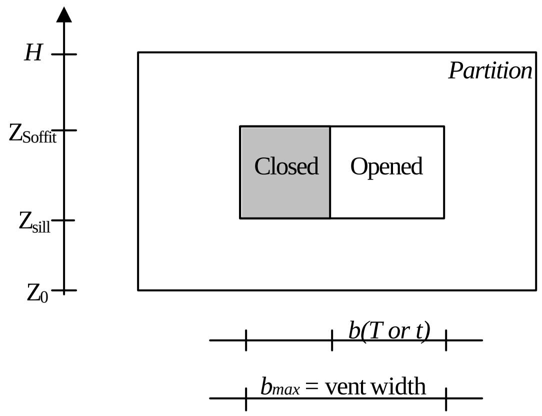


Figure 16 Elevation view of vertical vent

The size variation of a vertical vent is modelled by a variation of its width *b*. The size variation of an horizontal vent is modelled by a variation of its area A_{HV}.

6 Fire source model - Input of heat and of combustion products in the compartment

To represent the fire, the basic inputs zone models need are the heat release rate *RHR(t)* [W], the pyrolisis rate $\dot{m}_{fi}(t)$ [kg/s] and the fire area $A_{fi}(t)$ function of time. The pyrolisis rate is taken into account in mass balances and the heat release rate in energy balances. This chapter explains the physical parameters used to define the fire source, how they are related and how OZone deals with them in function of the oxygen available in the compartment. The strategy of calculations may also influence these inputs as explained in §8.

6.1 Basic parameters

Rate of Heat Release - RHR

The rate of heat release is the quantity of energy which is released by the fire per second. The *RHR* depends on the type and quantity of fuel present in the compartment, on the quantity of oxygen available in the compartment, on phase of the fire (rising, stationary, decreasing)…

Pyrolisis Rate - $\dot{m}_{fi}$

The pyrolisis rate $\dot{m}_{fi}$ is the quantity of mass of solid fuel which is transformed into combustible gases per second. It is indeed the mass loss rate of fuel.

Combustion Heat of Fuel - H_c

The energy released by the combustion of one unit of mass of fuel in an oxygen bomb calorimeter under high pressure and in pure oxygen is $H_{c,net}$, the complete (or net) combustion heat of the fuel. Under these conditions nearly all the fuel is burnt, leaving no residue and releasing all its potential energy. In real fires the energy that the same unity of mass is able to release is lower then $H_{c,net}$. Usually about 80% of the complete combustion heat is released. A part of the combustible is not pyrolised leaving some soot and not all of the volatile produced by pyrolisis is converted in heat. The effective combustion heat of fuel is defined as the ratio between the rate of heat release during a real fire and the rate of mass of fuel loss during this real fire.

$$H_{ceff}(t) = \frac{RHR(t)}{\dot{m}_{fi}(t)} \tag{41}$$

The efficiency of the combustion is represented by the combustion efficiency factor *m*, ratio between the effective and the complete combustion heat of the fuel:

$$m(t) = \frac{H_{ceff}(t)}{H_{c,netf}} \tag{42}$$

The values of the effective combustion heat and therefor of the combustion efficiency factor depend on many parameters, the temperature in the compartment, the way of storage of fuel… and are actually varying with time. Nevertheless, in most cases it is assumed to be constant.

Fire Area - $A_f(t)$

The fire area is the burning area of fuel. In real fires, it is usually varying with time. In some cases (ex. pool fire tests), the fire area can be constant. The maximum fire area in a compartment is the floor area on which combustible is present. In most case the maximum fire area is equal to the floor area. The pyrolisis rate and the heat release rate are of course linked to the fire area (see next paragraphs). Moreover, some air entrained models (§7) depend on the fire diameter and therefor on the fire area.

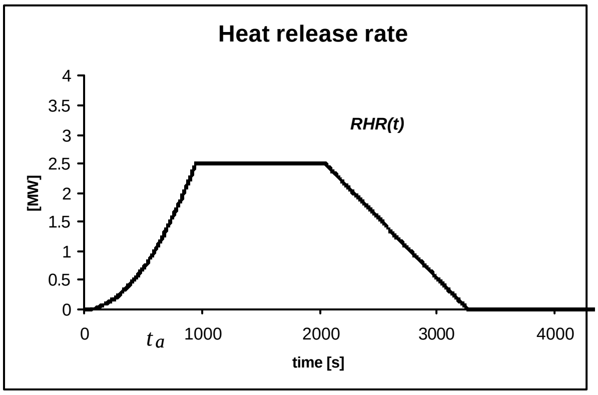


Figure 17 Input Rate of Heat Release Curve

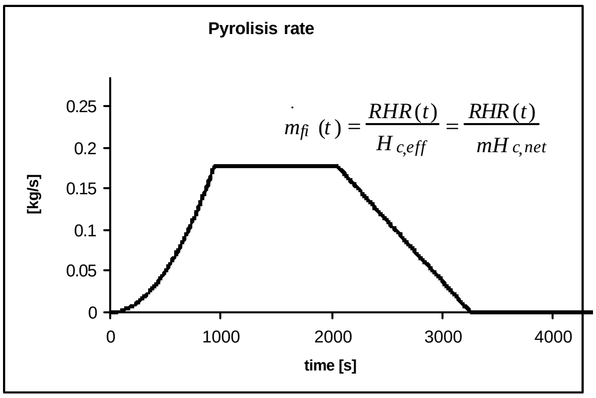


Figure 18 Input Pyrolisis Rate Curve

In OZone, the fire source is defined by three parameters, the pyrolisis rate, the heat release rate and the fire area. They can be linked (as shown on Figure 17 and Figure 18) or defined independently ones of the others. This will be discussed in the following paragraphs.

6.2 Combustion chemistry

The following chemical reaction is considered :

$$1\,kg\ of\ fuel\ +\ 1.27\ kg\ of\ 0_2\ =\ 2.27\ kg\ of\ combustion\ products\ +H_{f,eff}\,MJ \tag{43}$$

6.3 Oxygen balance

The mass of oxygen in the compartment is calculated at each time by integrating the oxygen balance:

$$\dot{m}_{ox} = \dot{m}_{ox,in} + \dot{m}_{ox,out} - 1.27\dot{m}_{fi} \tag{44}$$

The initial mass of oxygen in the compartment is considered to be 23% of the initial mass of gas, supposed to be fresh air. The mass of oxygen coming in the compartment is considered to be 23% of the mass of gas coming in the compartment through vents, supposed to be fresh air. The mass of oxygen going out of the compartment is considered to be ξ_{ox} % of the mass of gas going out of the compartment. ξ_{ox} is the concentration of oxygen in the gas inside the compartment and is calculated by equations (45).

$$\begin{aligned} x_{ox} &= \frac{m_{ox}}{m_U + m_L} \qquad (2ZM) \\ x_{ox} &= \frac{m_{ox}}{m_g} \qquad (1ZM) \end{aligned} \tag{45}$$

The concentration of oxygen in the compartment is supposed to be uniform in the compartment. Even if this assumption is only obvious in case of 1ZM, it has been extended to 2ZM.

6.4 Combustion models

Users of OZone have to choose between the three different combustion models. Each of them has been designed to represent a different situation of utilisation of the code. With "no combustion model", the presence of oxygen in the compartment does not influence the rate of heat release. When no more oxygen is available inside the compartment, the "external flaming" combustion model limit the amount of energy release inside the compartment and the "extended fire duration" combustion model limit the amount energy release inside the compartment and extend the initial fire duration.

6.4.1 No combustion model

Choosing this model, the user consider that the pyrolisis rate and the rate of heat release set in the data have to be considered in the mass and energy balances. No control by the ventilation will encountered. At each time, the following equations will be satisfied:

$$\begin{aligned} \dot{m}_f(t) &= \dot{m}_{f,data}(t) \\ RHR(t) &= RHR_{data}(t) \end{aligned} \tag{46}$$

This case corresponds to the simulation of tests where the mass loss and the rate of heat release have been measured. It suits also to situations where the pyrolisis rate is known and where the fire is assumed to be fuel controlled.

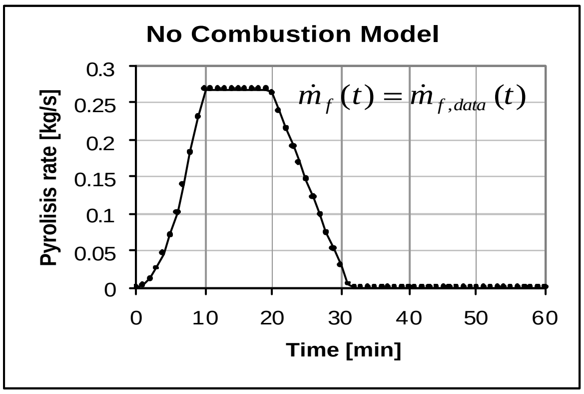


Figure 19 Rate of Heat Release Curve

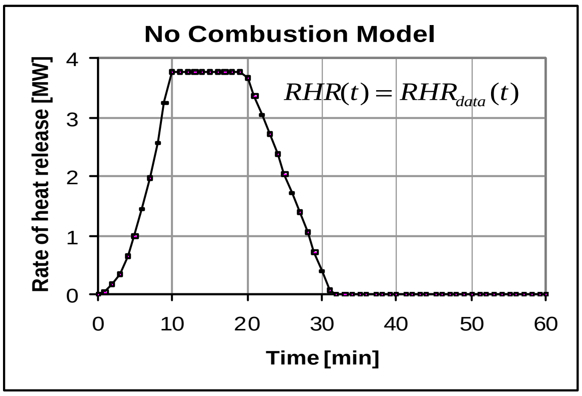


Figure 20 Pyrolisis Rate Curve

6.4.2 External flaming Combustion model

In this model external combustion is assumed, all the fire load is transformed into gases in the compartment but only a part of it delivers energy in the compartment. The rate of heat released by the fire may be limited by the quantity of oxygen available in the compartment, the pyrolisis rate remaining unchanged.

When the mass of oxygen in the compartment is higher than 0kg, the fire is fuel controlled and all the mass loss of fuel delivers energy into the compartment.

$$\begin{aligned} &\dot{m}_f(t) = \dot{m}_{f,data}(t) \\ &RHR(t) = RHR_{data}(t) = \dot{m}_f(t) H_{f,eff} \end{aligned} \tag{47}$$

If all the oxygen in the compartment is consumed, the fire is ventilation controlled and the combustion is not complete. The energy released is governed by the mass of oxygen coming in the compartment through vents:

$$\begin{aligned} &\dot{m}_f(t) = \dot{m}_{f,data}(t) \\ &RHR(t) = \frac{\dot{m}_{ox,in}(t)}{1.27} H_{f,eff} \end{aligned} \tag{48}$$

When oxygen is again available in the compartment, the fire is coming back to fuel controlled regime and equation 41 governs the pyrolisis and the heat release rates.

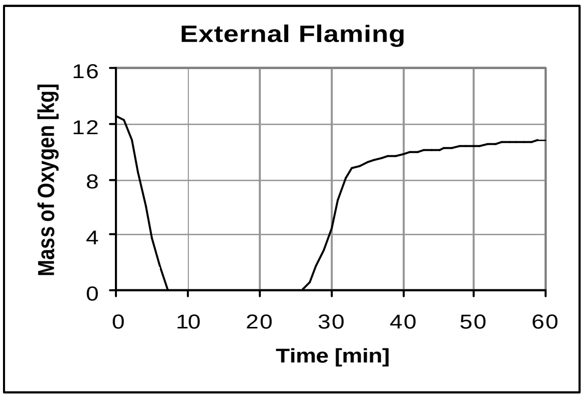


Figure 21 Oxygen mass curve

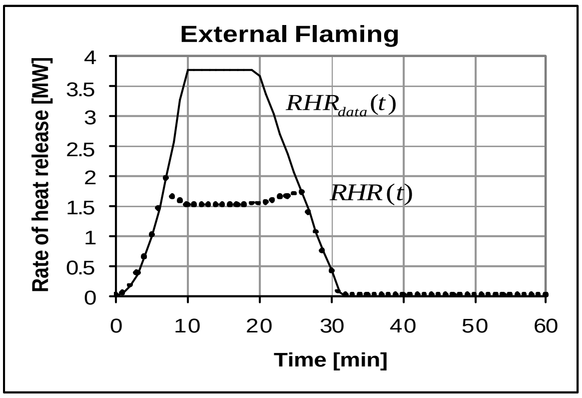


Figure 22 Rate of Heat Release Curve

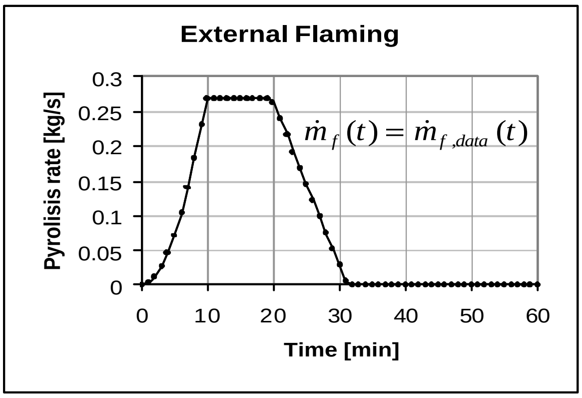


Figure 23 Pyrolisis Rate Curve

6.4.3 Extended fire duration combustion model

This model supposes that the release of mass may be limited by the quantity of oxygen available in the compartment. The total mass of fuel is burnt inside the compartment (safe procedure) then the fire duration is increased compared to the input one.

When the mass of oxygen in the compartment is higher than 0kg, the fire is fuel controlled and all the mass loss of fuel delivers energy into the compartment.

$$\begin{aligned} &\dot{m}_f(t) = \dot{m}_{f,data}(t) \\ &RHR(t) = RHR_{data}(t) = \dot{m}_f(t) H_{f,eff} \end{aligned} \tag{49}$$

If the mass of oxygen in the compartment is 0kg, the fire is ventilation controlled. In this case, the mass lost by the fire is governed by the mass of oxygen coming in the compartment and all the pyrolised mass is transformed into energy:

$$\begin{aligned} &\dot{m}_f(t) = \frac{\dot{m}_{ox,in}(t)}{1.27} \\ &RHR(t) = \dot{m}_f(t) H_{f,eff} = \frac{\dot{m}_{ox,in}(t)}{1.27} H_{f,eff} \end{aligned} \tag{50}$$

The linear decreasing phase begins when 70% of the total fire load is consumed.

In this model no external combustion is assumed, all the fire load delivers its energy into the compartment. If the fire is ventilation controlled, the pyrolysis rate is proportional to the oxygen coming in the compartment. This model is not a physical model because pyrolise is not directly dependant on oxygen concentration. It has been established for design procedures, in order to avoid uncertainties on the maximum pyrolisis rate per unit floor area and therefor to be on the safe side concerning the fire duration.

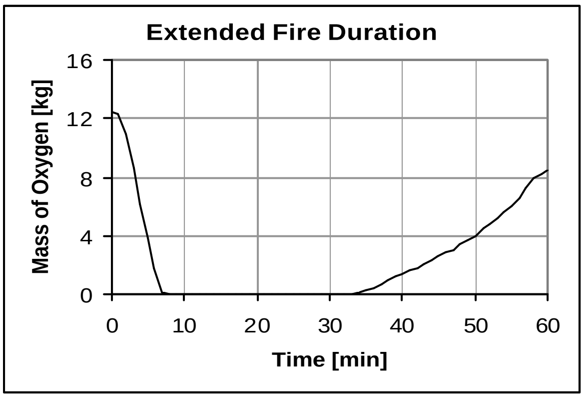


Figure 24 Oxygen mass curve

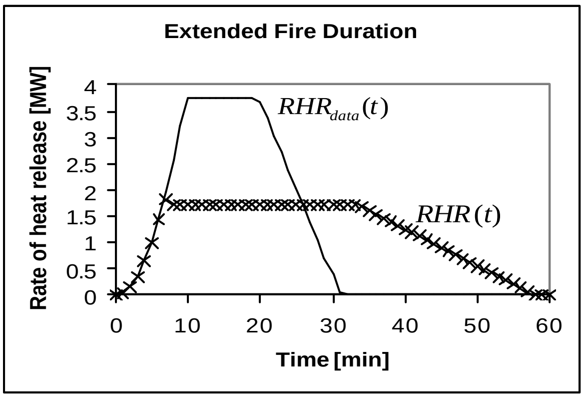


Figure 25 Rate of Heat Release Curve

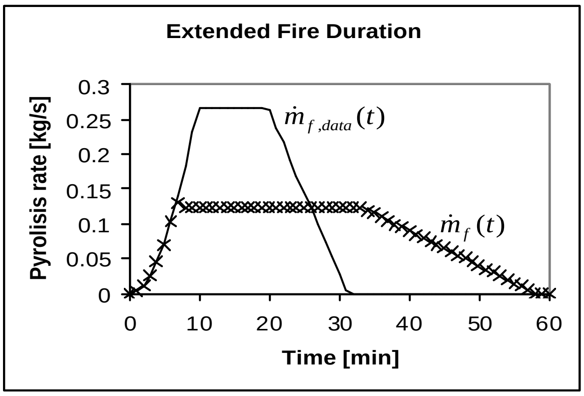


Figure 26 Pyrolisis Rate Curve

6.5 Natural Fire Safety Concept Design Fire

6.5.1 Definitions

Fire Load Density - q_f

The characteristic fire load density q_{fk} considered in the NFSC Design Fire is the 80% fractile of the fire load distribution obtained by survey in real compartments. Data are available for different types of occupancies of compartments. In order to obtain these data's, the mass of combustible present in compartments has been measured and then multiplied by the combustion heat of the fuel and divided by the floor area of the compartment. The complete combustion heat has been considered in these evaluations. (51)

$$q_{f,k} = H_{c,net} \frac{m_{fi}}{A_f} \tag{51}$$

The design fire load density is given by :

$$q_{f,d} = g_{q1} g_{q2} \prod_i g_{n,i} \; m \; q_{f,k} \tag{52}$$

Maximum Fire Area - $A_{fi,max}$

The maximum fire area is the maximum burning area of fuel, i.e. the maximum area of floor on which combustible is present. In most case the maximum fire area is equal to the floor area.

Maximum Rate of Heat Release per Unit Area of Fire - RHR_f

RHR_f is the maximum quantity of energy which can be released by unit area of fire in steady state situation with no ventilation controlled. This quantity, RHR_f, is given in the literature for different type of compartment occupancies. The values of RHR_f are for real fires and take into account the incomplete combustion. The mass loss per unit area corresponding to this energy release is then obtained from :

$$RHR_f = \dot{m}_{fi,f} \; H_{c,eff} = m H_{c,net} \dot{m}_{fi,f} \tag{53}$$

Fire Growth Rate - t_a

The rising phase of fire is characterised by fire growth rate t_a. It is the time at which the fire area A_f has grown to a value leading to an effective rate of heat release of 1MW.

$$RHR(t) = 10^6 \left(\frac{t}{t_a} \right)^2 = A_{fi}(t) \; RHR_f \tag{54}$$

$$\dot{m}_{fi}(t) = \frac{RHR(t)}{H_{c,eff}} = \frac{RHR(t)}{mH_{c,net}} = \frac{10^6 \left(\frac{t}{t_a} \right)^2}{mH_{c,net}} \tag{55}$$

Decreasing phase

The decreasing phase of the fire begins when 70% of the design fire load is consumed. This phase is considered to be linear.

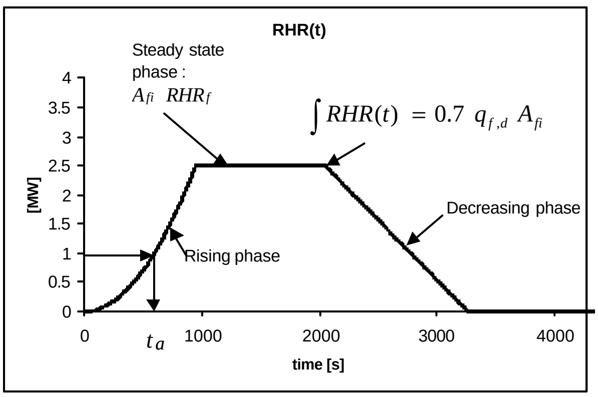


Figure 27 NFSC Rate of Heat Release Curve

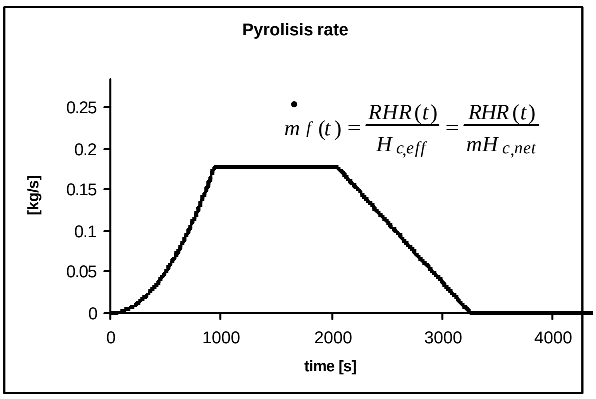


Figure 28 NFSC Pyrolisis Rate Curve

6.5.2 Parameters values

In the research NFSC1 1998, the design fires are given function of the parameters defined in §6.5.1. The tables hereafter shows the values of these parameters included in OZone V2.

The fire growth rate, the maximum rate of heat release per unit area of fire and the fire load density are given in table 1 in function of the type of building occupancy.

Table 1 : t_a, RHR_f , $q_{f,k}$

Occupancy	t_a []	RHR_f [kW/m²]	$q_{f,k}$ [MJ/m²]
Dwelling	Medium	250	948
Hospital	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping Centre	Fast	250	730
Theatre (movie/cinema)	Fast	500	365
Transport (public space)	Slow	250	122

The influence of active measure is taken into account by $g_{n,i}$ factors given in table 2.

Table 2: $g_{n,i}$

Active measures	$g_{n,i}$
Automatic Water Extinguishing System	0.61
Independent Water Supplies 1	0.87
Independent Water Supplies 2	0.7
Automatic Fire Detection by Heat	0.87
Automatic Fire Detection by Smoke	0.73
Automatic Alarm Transmission to Fire Brigade	0.87
Work Fire Brigade	0.61
Off Site Fire Brigade	0.78

The influence of the compartment area is taken into account by the factor $g_{q,1}$ factor. The values of $g_{q,1}$ are approximated by the formula of equation (56). This law has been obtain by a fit on tabulated value.

$$g_{q,1} = 0.1688 \ln(Af) + 0.5752 \qquad (56)$$

The influence of the danger of fire activation is taken into account by $g_{q,2}$ factors given in table 2.

Table 3: $g_{q,2}$

Danger of fire activation	$g_{q,2}$
Low	0.85
Medium	1
High	1.2
Very high	1.4
Ultra high	1.6

6.6 User defined fire

It is possible to define any fire curve by using the option user defined fire. The rate of heat release (*RHR(t)*), the pyrolisis rate ($\dot{m}_{fi}(t)$) and the fire area ($A_{fi}(t)$) can be defined function of time.

If *RHR(t)* or $\dot{m}_{fi}(t)$ is not known, the combustion heat $H_{c,net}$ and the combustion efficiency factor m have to be provided by the user. *RHR(t)* and $\dot{m}_{fi}(t)$ are related at each time by equation (57)

$$RHR(t) = mH_{cnet}\dot{m}_{fi}(t) \tag{57}$$

If $A_{fi}(t)$ is not known, the maximum fire area $A_{fi,max}$ have to be defined. $A_{fi}(t)$ is then deduced from equation (58). The hypothesis is made that the maximum value of the fire area arrives when the rate of heat release is maximum. If the fire is defined by the pyrolisis rate, the RHR is first deduced by equation (57).

$$A_{fi}(t) = A_{fi,\max}\frac{RHR(t)}{RHR_{\max}} \tag{58}$$

The combined model (see §8) can be used if the fire is defined point by point. In this case only a switch to the one zone model is done without modification of the rate of heat release.

6.6.1 *RHR(t)* and $\dot{m}_{fi}(t)$ and $A_{fi}(t)$ are given

When the fire is completely known, the user can define the three parameters *RHR(t),* $\dot{m}_{fi}(t)$ and $A_{fi}(t)$ point by point function of time. This case correspond to tests where the mass lost and the rate of heat release inside the compartment have been measured. The fire area is also known at each time. For example, this situation could arrive when modelling a full scale pool fire test with two zone phenomena with mass loss measurement and RHR measurement by oxygen depletion in the upper layer gases extraction device (Figure A FAIRE). In this situation it is not possible to use any combustion model, cf. §6.6.5.

6.6.2 *RHR(t)* and $\dot{m}_{fi}(t)$ and $A_{fi,max}$ are given

This case correspond to tests where the mass lost and the rate of heat release inside the compartment have been measured. The fire area is not known and is assumed to be proportional to the heat release rate and evaluated by equation (58). In this situation it is not possible to use any combustion model, cf. §6.6.5.

6.6.3 *RHR(t)* or $\dot{m}_{fi}(t)$ and $H_{c,net}$ and m and $A_{fi}(t)$ are given

This case correspond to tests where the mass lost or the rate of heat release inside the compartment have been measured. The unknown quantity is deduced from equation (36). The fire area is known at each time.

6.6.4 *RHR(t)* or $\dot{m}_{fi}(t)$ and $H_{c,net}$ and m and $A_{fi,max}$ are given

This case correspond to tests where the mass lost or the rate of heat release inside the compartment have been measured. The fire area is not known and is assumed to be proportional to the heat release rate. The unknown quantity of *RHR(t)* or $\dot{m}_{fi}(t)$ is deduced from equation (36) and the fire area is evaluated by equation (58).

Other design fires then NFSC ones can also be defined by this procedure. The combustion models can be used or not.

6.6.5 Comments on the use of combustion models

It has been stated in §0 & §6.6.2 that combustion model n°2 can not be used if *RHR(t)* and $\dot{m}_{fi}(t)$ are both given. This is due to the fact that combustion model are based on the assumption that the effective combustion heat is constant which, a priori, is not the case if these to variables are given. If they are both known and combustion model have to be used, a value of the effective combustion heat has to be fixed and only one variable must be given as data. The effective combustion heat is normally different at each time so the mean value or the maximum value (or any other reasonable value) has to be considered. This choice has, of course, a direct impact on the results.

7 Entrained air and plume model

When a mass of hot gases is surrounded by colder gases, the hotter and less dense, mass will rise upward due to the density difference, or rather, due to buoyancy. This phenomenon happens above a burning fuel source. The buoyant flow is referred to as a fire plume. Cold air is entrained by the rising hot gases, causing a hot layer of hot gases to be formed below the ceiling. Different analytical expressions of the properties of fire plume have been proposed by several authors. Four of them have been implemented in OZone.

It should be mentioned that some of these empirical formulas have been obtained by fit on the total energy release rate Q and others on the convective part of it Q_c. In OZone, it is assumed that Q_c is equal to 0.7 Q.

7.1 Heskestad

The model of Heskestad is the default plume model in OZone. It is the model with the less assumption. It has been shown in "Development of design rules for steel structures subjected to natural fires in Closed Car Parks. February 97." that it is the model which best fit to CFD plume simulations.

The virtual origin of the plume is at the altitude z_0 :

$$z_0 = 0.083\dot{Q}^{2/5} - 1.02D \tag{59}$$

The flame height L_{fl} is given by :

$$L_{fl} = 0.235\,\dot{Q}^{2/5} - 1.02D \tag{60}$$

The plume mass flow rate above the flame height ($z > L_{fl}$,) is given by :

$$m_p = 0.071\dot{Q}_c^{1/3}\,(z - z_0)^{5/3} + 1.92\ 10^{-3}\dot{Q}_c \tag{61}$$

The plume mass flow rate below or at the flame height ($z < L_{fl}$,) is given by :

$$m_p = 0.0056\,\dot{Q}_c\,\frac{z}{L_{fl}} \tag{62}$$

7.2 Zukoski

$$m_p = 0.21\left(\frac{r_\infty^2 g}{c_p T_\infty}\right)^{1/3} Q_c^{1/3}\ z^{5/3} \tag{63}$$

7.3 Mac Caffrey

$$m_p = 0.011\,Q\left(\frac{z}{Q^{0.4}}\right)^{0.566} \qquad for\ \ 0 < \frac{z}{Q^{0.4}} < 0.08 \tag{64}$$

$$m_p = 0.026\,Q\left(\frac{z}{Q^{0.4}}\right)^{0.909} \qquad for\ \ 0.08 < \frac{z}{Q^{0.4}} < 0.20 \tag{65}$$

$$m_p = 0.124\,Q\left(\frac{z}{Q^{0.4}}\right)^{1.895} \qquad for\ \ 0.20 < \frac{z}{Q^{0.4}} \tag{66}$$

7.4 Thomas

The Thomas plume model is intended for entrainment in the near field or flame region, when the mean flame height is considerably smaller then the fire diameter. In this region, the entrained air is less influenced by the heat release rate then by the fire perimeter, and therefor the fire diameter.

$$m_p = 0.59\,D\,z^{3/2} \tag{67}$$

8 Combination strategy

Two zone and one zone models are based on different hypothesis and one can not say that there is a better model then the other. Indeed they correspond to different types of fires or different stages of the same fire. They simply have different application domain and in fact they are complementary. When modelling a fire in a given compartment, it is important to know whether a two zone model or a one zone model is appropriated.

The fire load can be considered to be uniformly distributed if the real combustible material is present more or less on the whole floor surface of the fire compartment and when the real fire load density (quantity of fuel per floor area) is more or less uniform. By opposition, the fire load is localised if the combustible material is concentrated on quite small surface compared to the floor area, the rest of the floor area being free of fuel.

Fires ignitions are in most cases localised and therefor a fire remains localised during a certain amount of time. If temperatures are sufficiently high to provoke spontaneous ignition of all the combustible present in the compartment, a flashover occurs. Generally two zone models are valid in case of localised fires or pre-flashover fires and one zone models are valid in case of fully engulfed fires or post-flashover fires. Also if the thickness of the lower layer is weak compared to the height of the compartment, the two zone assumption is not applicable anymore and a one zone model is more appropriated. Moreover if the fire area is big compared to the floor area, the one zone model assumption is better then the two zone one.

These considerations implies that to model fires in a compartment with uniformly distributed fire load, a two zone model is well adapted for the first stages of the fire and then a one zone model can be a better assumption if some conditions on temperatures, fire area and smoke layer thickness encountered. In many cases, it is difficult to know a priori if a fire will remain localised during its entire course, if flashover will happen etc. and in general to known whether a two or a one zone(s) model is appropriated.

One can imagine to make a manual combination strategy. It implies to make first a two zone model simulation, to check until when it is valid (i.e. to find the time of transition from two to one zone) and then to restart a one zone model simulation with new initial condition obtained from the results of the first two zone simulation at transition time. The last step is particularly difficult, especially concerning the initial partition temperatures, and not permitted by existing one zone models.

That's why an automatic combination strategy is proposed. With this strategy, the simulation always begin with the two zone model assumption and if one of the above described condition encountered, the simulation will leave two zones model to go to one zone model and/or will modify the mass and energy released by the fire. One of these two modifications can arrive alone along the fire duration or they can arrive successively or simultaneously.

The modification of the main variables and of the basic equations when the one zone model switch occurs has been presented in §0. The criteria of the transition from two to one zone and the consequences on the fire source model are discussed in §8.2.

In case of localised fire load, when the upper layer temperature is sufficiently high to ignite the fuel by radiation; the complete fire area start to burn and the rate of heat release is modified. In this case the fire stay localised and a two zone phenomenon is continuing and so a two zone model is still appropriated. A one zone model can be more appropriated then a two zone one if the upper layer thickness is big compared to the compartment height.

It is also still possible to choose to follow a two zones or a one zone strategy for the entire duration of a fire. With these strategies, the whole simulation is made considering two or one zones, from the initial time to the end of the calculation. No modification of the rate of heat release is made by the code, except from combustion models (see §6.3).

8.1 Fully developed fire

If a fire is modelled by the plain curve of the Figure 29. The growing phase, represented here by a t^2 curve, is reaching a maximum at the time at which all the fuel has been ignited. If the fuel ignition happens only by flame spread the maximum is reached without modification of the initial t^2 curve. If the temperatures of hot gases of the upper layer of a fire reach a sufficiently high temperature (about 500°C to 600°C), the radiative flux between the hot gas and the non burning combustible materials can be as high as to ignite the fuel. At this moment there is a very fast increased of the energy release rate. This phenomenon is called flashover. This modification is made by modifying the initial heat release rate curve as indicated by the doted line in Figure 29. At the flashover time, the RHR curve is left and goes to its maximum value equal to the maximum fire area multiplied by the heat release rate density RHR_f.

If the gases in contact with the fuel reach a temperature of about 300°C, the fuel also ignites and the rate of heat release increases as stated for the flashover phenomena.

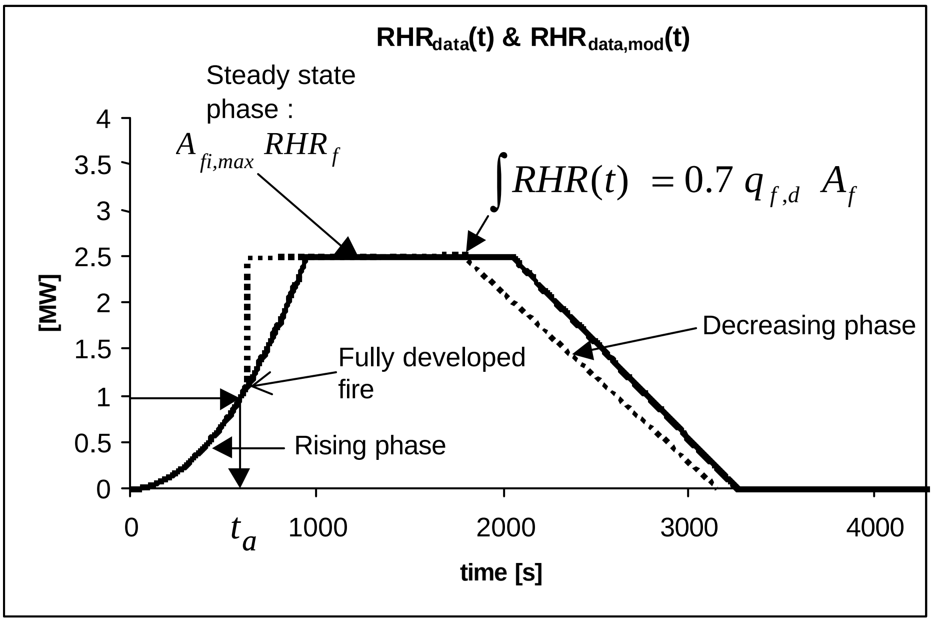


Figure 29 Modification of RHR(t) in case of flashover.

8.2 Criteria of transition from two to one zone model and/or of modification of the input of energy

The aim of this chapter is to describe the criteria of the transition from two to one zone and/or of modification of the fire source model.

- Criterion 1 (C1) : $T_U > T_{FL}$

  High temperature of the upper layer gases, composed of combustion products and entrained air, leads to a flashover. All the fuel in the compartment is ignited by radiative flux from the upper layer. The flashover temperature (T_{FL}) is set to 500°C.

- Criterion 2 (C2) : $Z_s < Z_q$ and $T_Z > T_{ignition}$

  If the gases in contact with the fuel have a higher temperature than the ignition temperature of fuel ($T_{ignition}$), the propagation of fire to all the combustible of the compartment will occur by convective ignition. The gases in contact (at temperature T_Z) can either belong to the lower layer of a two zone, the upper layer (if the decrease of the interface height (Z_S) leads to put combustible in the smoke layer - Z_q is the maximum height of the combustible material) or the unique zone of one zone models. $T_{ignition}$ is assumed to be 300°C.

- Criterion 3 (C3) : $Z_S < 0.2\ H$

  The interface height goes down and leads to a very small lower layer thickness, which is not representative of two zone phenomenon.

- Criterion 4 (C4) : $A_{fi} > 0.25\ A_f$

  The fire area is too high compared to the floor surface of the compartment to consider a localised fire.

Criteria 1 or 2 lead necessarily to a modification of the rate of heat release as specified in §8.1. If the fire load is localised the simulation will continue using a 2ZM and if the fire load is uniformly distributed, a 1ZM will be considered. If one of the criteria C3 or C4 is fulfilled, the code will switch to a one zone model but the RHR will not be modified, except if criterion C1 or C2 happens simultaneously. The Table 4 and Figure 31 summarise the four criteria.

Table 4

CRITERIA :	**EFFECT**	
	LOCALISED q_f	**DISTRIBUTED q_f**
C1 : $T_U > 500°C$	$A_{fi} = A_{fi,max}$	1ZM + $A_{fi} = A_{fi,max}$
C2 : $Z_s < H_q$ and $T_U > T_{ignition}$ (2ZM) or $Z_s > H_q$ and $T_L > T_{ignition}$ (2ZM) or $T > T_{ignition}$ (1ZM)	$A_{fi} = A_{fi,max}$	1ZM + $A_{fi} = A_{fi,max}$
C3 : $Z_s < H$	1ZM	1ZM
C4 : $A_{fi} > 0.25\%\ A_f$	-	1ZM

If the fire load is localised, five different paths are possible :

- PATH 1 - None criterion are encountered then the model will remain with two zones and the RHR curve will not be modified until the end of the fire.
- PATH 2 - Criterion C1 or C2 is first encountered, leading to a RHR modification. Criterion C3 is not encountered, the model remains a two zones one.
- PATH 3 - Criterion C1 or C2 is first encountered, leading to a RHR modification. Criterion C3 is encountered, the model switch from a two zones to a one zone.
- PATH 4 - Criterion C3 is first encountered, the model switch from a two zones to a one zone. The criteria C1 and C2 are not encountered, leading to no RHR modification.
- PATH 5 - Criterion C3 is first encountered, the model switch from a two zones to a one zone. The criterion C1 or C2 is then encountered, leading to a RHR modification.

If the fire load is uniformly distributed, three different paths are possible :

- PATH 6 - Criterion C1 or C2 is encountered, leading to a RHR modification and a simultaneous switch from a two zones to a one zone model.

- PATH 7 - Criterion C3 or C4 is first encountered, the model switch from a two zones to a one zone. The criterion C1 and C2 are not encountered, leading to no RHR modification.
- PATH 8 - Criterion C3 or C4 is first encountered, the model switch from a two zones to a one zone. Criterion C1 or C2 is then encountered, leading to a RHR modification.

As the definition of the limit between uniformly and localised fire load is base on the criterion C4, it is obvious that criterion C4 never arrives in case of localised fire load. For the same reason, in case of uniformly distributed fire load, criteria C4 will always be fulfilled and therefor a simulation with uniformly distributed fire load will always switch to one zone model.

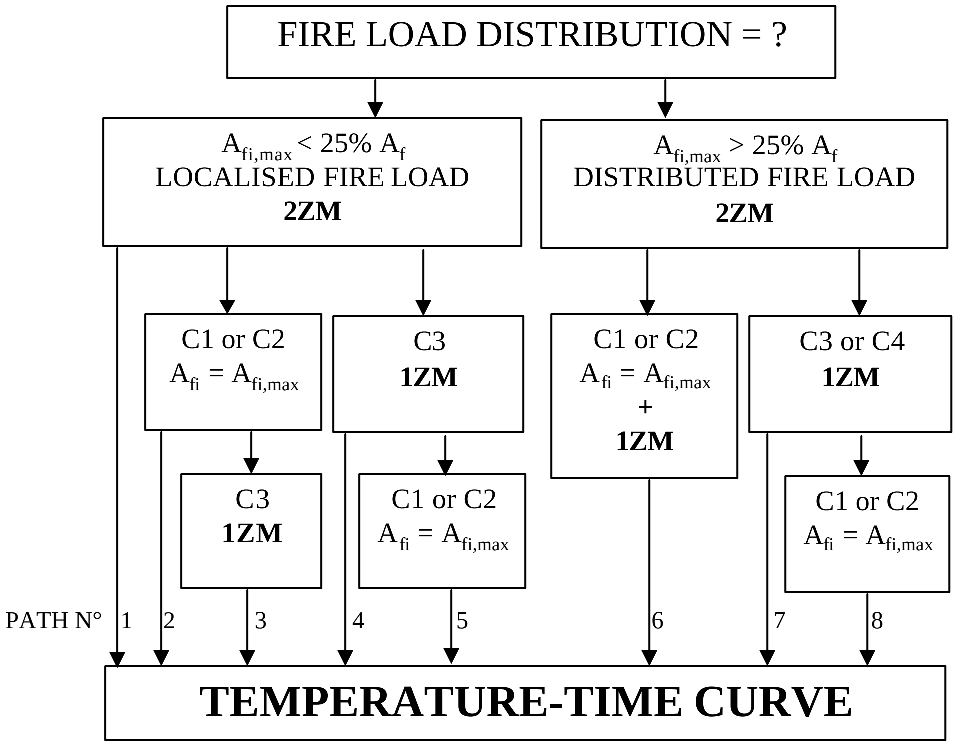


Figure 30 Organisation chart of the combination strategy

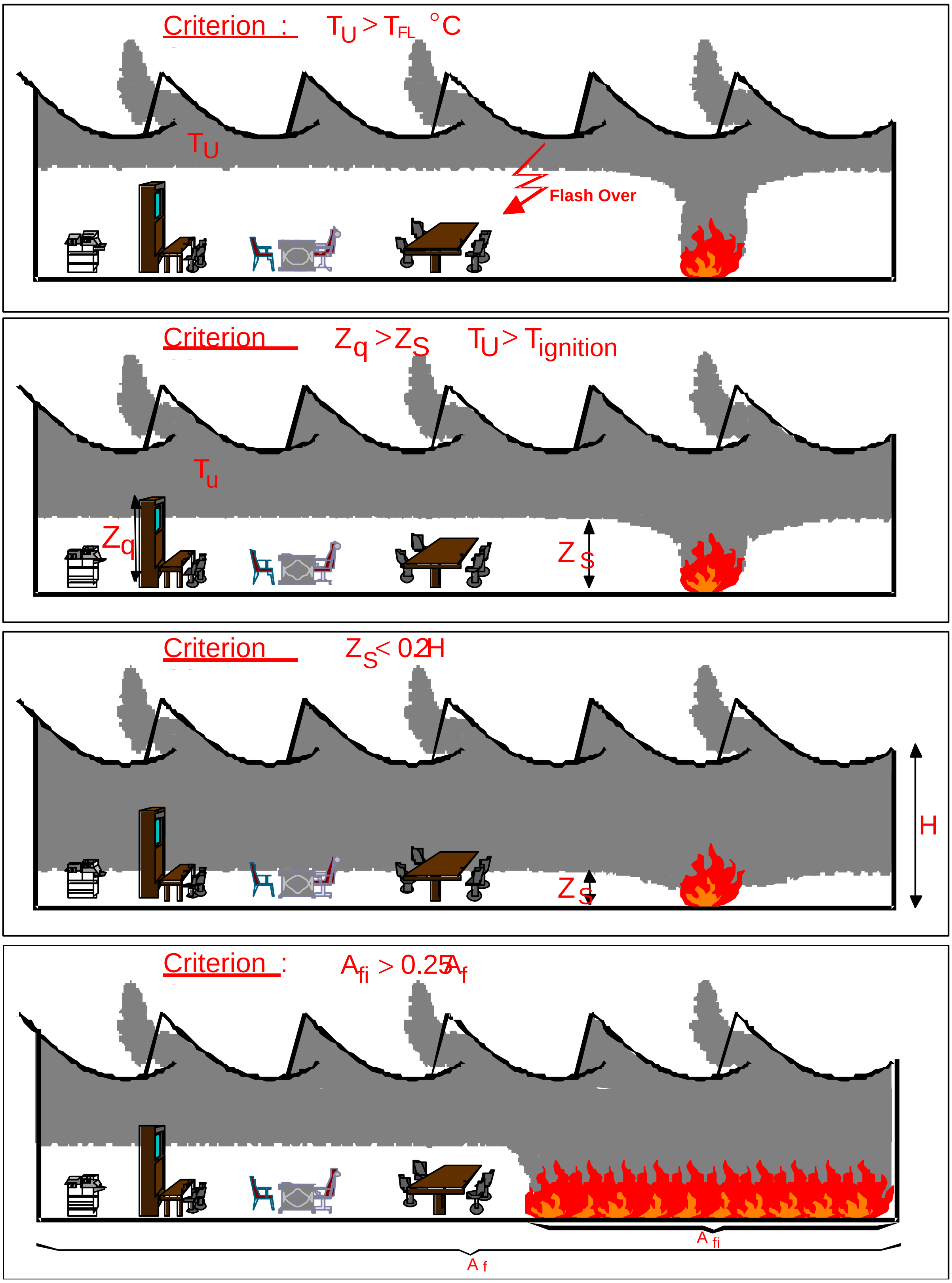


Figure 31 Four criteria to switch from two zone to one zone model and/or modify the heat release rate

9 Heating of steel profile.

The temperature which is calculated for the hot zone in a two zone fire situation can be considered as the average value of the temperature field in the air. In fact, the thermal impact of a localised fire can be much more severe on structural elements located in the vicinity of the flames than the impact coming from the air at the average temperature. For example, if the failure of the structural elements located close to a fire may be critical for the stability of the whole structure, then the average temperature is no more sufficient and the localised effect of the fire must be taken into account. The Hazemi model represents this local effect (Figure 32).

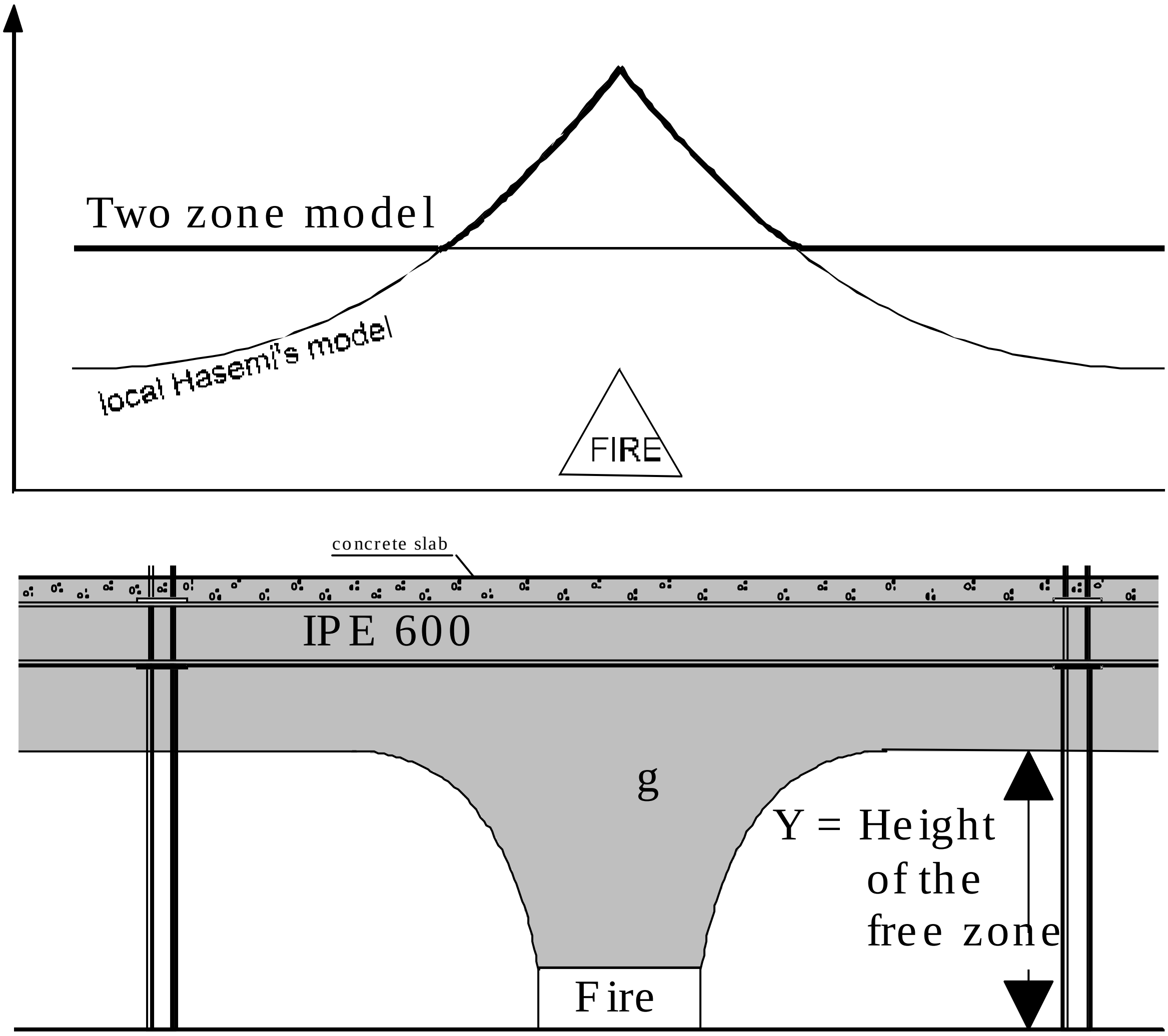


Figure 32

9.1 Non dimensional model of Hazemi for localised fires

The model is based on non dimensional coefficients. Hasemi uses the Froude number, given by equation (68).

$$Q^* = \frac{Q}{\rho_\infty\, C_p\, T_\infty\, g^{1/2}\, D^{5/2}} \tag{68}$$

Introducing in equation (68) the appropriate values for the specific mass, specific heat and room temperature of air as well as the acceleration of the gravity leads to the more convenient form of equation (69).

$$Q^* = \frac{Q}{1.11 \text{ x } 10^6 \ D^{5/2}} \tag{69}$$

with Q Rate of Heat Release of the burner,
D diameter or characteristic length of the burner.

This variable is used to estimate the vertical position of the virtual source with respect to the surface of the burner. This position is the one where a virtual point source would produce the same effects as the real burner. The position of the virtual source *z'* is calculated according to equation (70).

$$\begin{aligned} \frac{z'}{D} &= 2.4 \ \left(Q^{*2/5} - Q^{*2/3}\right) \qquad for \quad Q^* \le 1 \\ \frac{z'}{D} &= 2.4 \ \left(1 - Q^{*2/5}\right) \qquad for \quad Q^* > 1 \end{aligned} \tag{70}$$

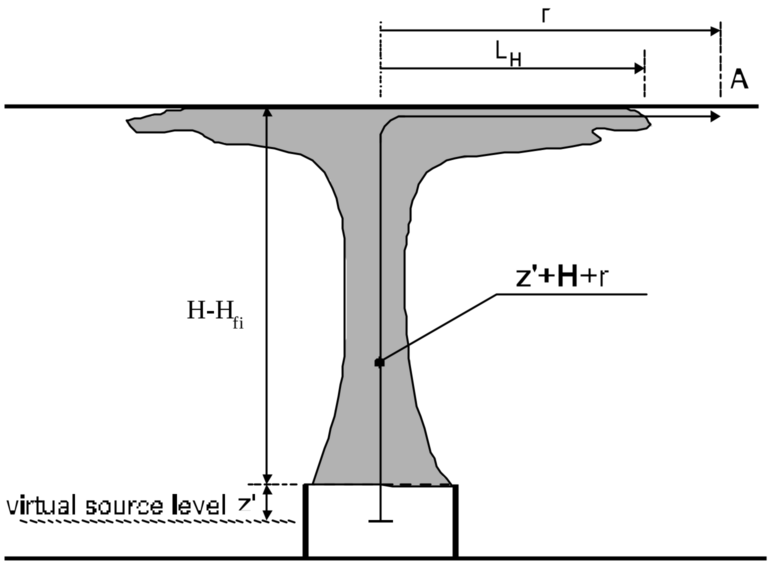


Figure 33 Horizontal flame length

When the flame impinges on the ceiling, it is deviated and develops horizontally on a distance L_H, see Figure 33. Whereas the position of the heat virtual source has to do with the dimension of the burner, " D " in equation (69), the relative length of the flame with respect to the compartment is linked to the vertical distance between the burner and the ceiling, " H " on Fig. 2. The Froude number that gives indications on the length of the flame is therefore calculated according to equation (71), very similar to equation (69).

$$Q_H^* = \frac{Q}{1.11 \ \text{x} \ 10^6 \ H^{5/2}} \tag{71}$$

with $H-H_{fi}$ Vertical distance between the burner and the ceiling.

It is observed during the tests that the ratio of the length of the flame from the burner, $H + L_H$, and the burner to ceiling distance H is proportional to the Froude number with the exponent 1/3. This fact is reflected in equation (72).

$$\frac{L_H + H}{H} = 2.90 \quad Q_H^{*1/3} \tag{72}$$

y is the non dimensional ratio between the distance from the virtual source, z' + H + r, and the total length of the flame, z' + H + L_H .

$$q'' = 100 \qquad \text{for} \quad y \leq 0.30$$
$$q'' = 136.3 - 121y \qquad \text{for} \quad 0.30 < y \leq 1.00 \qquad (73)$$
$$q'' = 15 \; y^{-3.7} \qquad \text{for} \quad 1.00 < y$$

The net heat flux at the boundaries of a steel profile q_{net}, taking into account the flux lost due to the temperature of the section, is given by equation (74).

$$q_{net} = q'' - h\left(T_s - 293\right) - s \; e^*\left(T_s^4 - 293^4\right) \qquad (74)$$

with h Coefficient of convection (25 W/mK),
T_s Temperature of the section (in K),
σ Constant of Stefan-Boltzman (5.67 10^{-8}),
ε^* Relative emissivity (0.50).

It is possible to deduce a fictive local temperature which has the same effect then the net heat flux calculated with this method. It is indeed the temperature of steel profile with a very high massivity. This steel profile has a temperature which is very closed to the gas temperature, thus we have : $T_{loc} = T_s$. T_{locs} is then obtained by solving equation (75)

$$q'' - h\left(T_{loc} - 293\right) - s \; e^*\left(T_{loc}^4 - 293^4\right) = 0 \qquad (75)$$

9.2 Heating

The heating of unprotected or protected steel profile is then calculated by considering the ENV 1993-1-2 methods. The gas temperature is either the upper zone temperature, the fictive local temperature obtained by Hasemi's method or the maximum of these two temperature.

The evolution of steel temperature is computed using equation (4.21) for an unprotected steel cross-section:

$$\Delta q_{a,t} = \frac{A_m / V}{c_a \rho_a} \dot{h}_{net,d} \Delta t \qquad (4.21)$$

or, equation (4.22) for a protected steel cross-section

$$\Delta q_{a,t} = \frac{\lambda_p A_p / V}{d_p c_a \rho_a} \frac{(\theta_{g,t} - \theta_{a,t})}{(1 + \phi/3)} \Delta t - (e^{\phi/10} - 1)\Delta q_{g,t} \quad \text{but } \Delta q_{a,t} \geq 0 \qquad (4.22)$$

with:

$$f = \frac{c_p \, r_p}{c_a \, r_a} d_p A_p / V$$

where $q_{g,t}$ – the ambient gas temperature is either the hot zone temperature, the localised fire temperature, or the maximum between the two previous values.

10 Fire Resistance

The fire resistance of members is determined based on the assumptions stated in ENV 1993-1-2, § 2.4.4 - Member analysis using the equation (2.2) :

$$E_{fi,d} \leq R_{fi,d,t} \tag{2.2}$$

where:

$E_{fi,d}$ is the design effect of actions for the fire situation, determined in accordance with ENV1991-2-2;

$R_{fi,d,t}$ is the corresponding design resistance at elevated temperatures.

OZone implements the calculation of fire resistance for:

Tension members (4.2.3.1)

Compression members with Class 1, Class 2 or Class 3 cross-section (4.2.3.2)

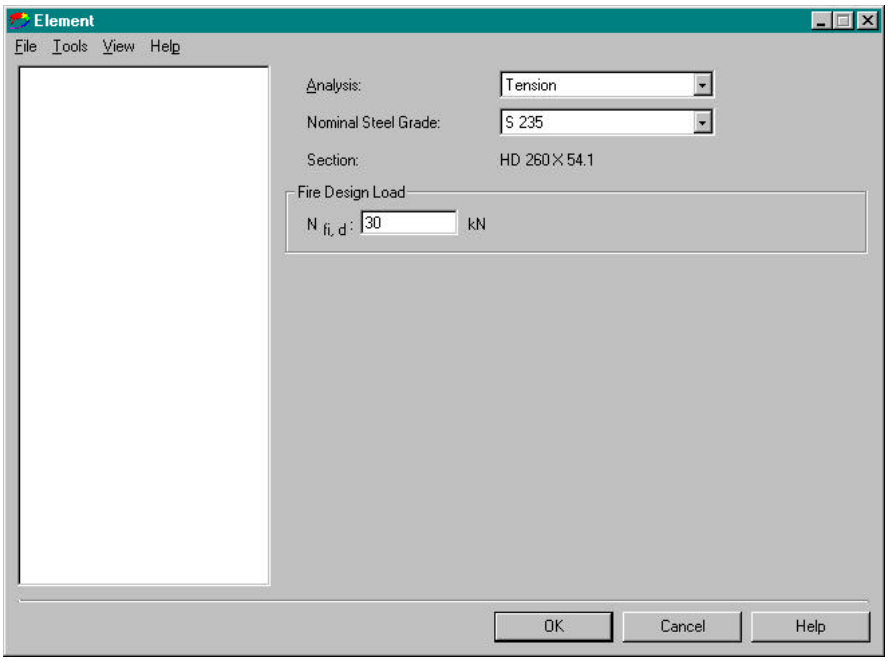
Beams with Class 1, Class 2 or Class 3 cross-section (4.2.3.3 and 4.2.3.4)

10.1 Tension Members (4.2.3.1)

For tension members the user must input the design axial load for the fire situation $N_{fi,d}$ and the steel grade. The steel profile is described in a previous step of the simulation (Steel Profile window).

OZone will then incrementaly compute the design resistance of the tension member $N_{fi,\theta,Rd}$ at the uniform temperature q_a ; $q_a + \Delta q_a$ and check this resistance against the design axial load $N_{fi,d}$. The design resistace of the tension member is computed using equation 4.4 :

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{Rd} [g_{M,1} / g_{M,fi}] \tag{4.4}$$



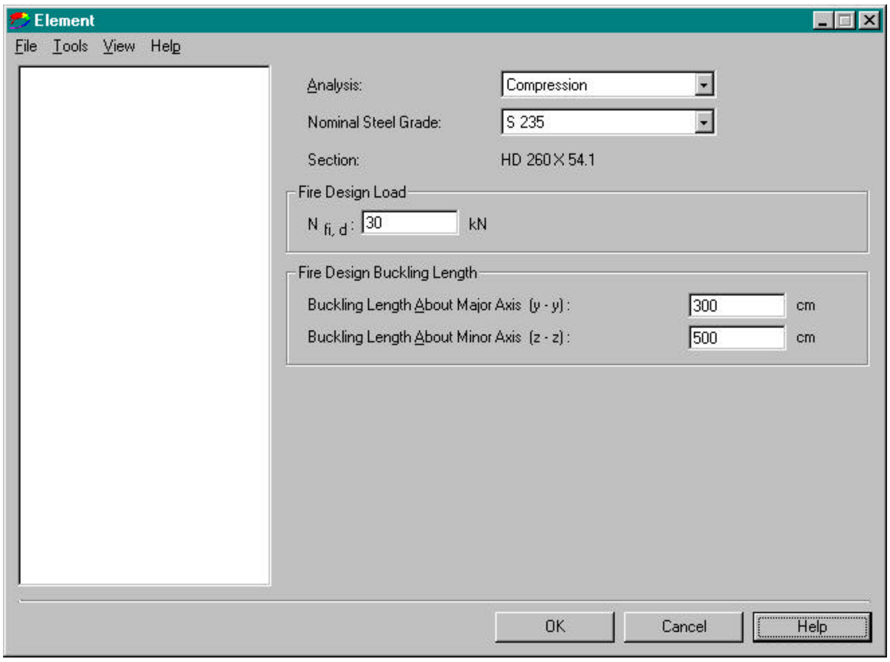
10.2 Compression members with Class 1, Class 2 or Class 3 cross-section (4.2.3.2)

For compression members the user must input the design axial load for the fire situation $N_{fi,d}$, the steel grade and the buckling lengths about the major and minor axis (for the fire design situation). The steel profile is described in a previous step of the simulation (Steel Profile window).

OZone will then incrementaly compute the design buckling resistance of the compression member $N_{b,fi,\theta,Rd}$ at the maximum temperature $q_{a,max}$; $q_{a,max} + \Delta q_{a,max}$ and check this resistance against the design axial load $N_{fi,d}$. The design buckling resistace of the compression member is computed using equation 4.5 :

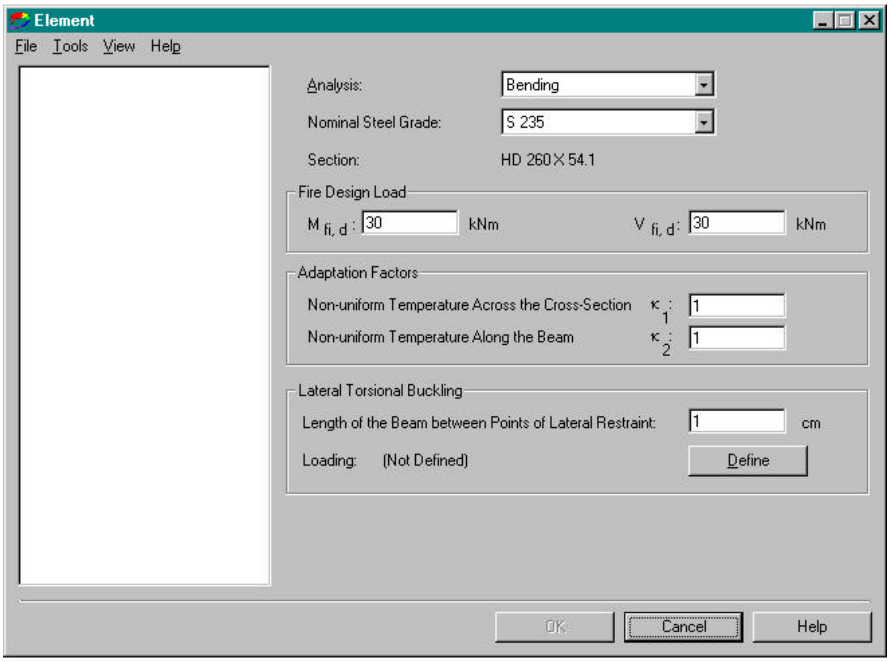
$$N_{b,fi,t,Rd} = [c_{fi}/1,2] A \; k_{y,\theta,max} f_y / g_{M,fi} \qquad (4.5)$$

The value of c_{fi} is taken as the lesser of the values $c_{y,fi}$ and $c_{z,fi}$ determined as stated in 4.2.3.2(2).

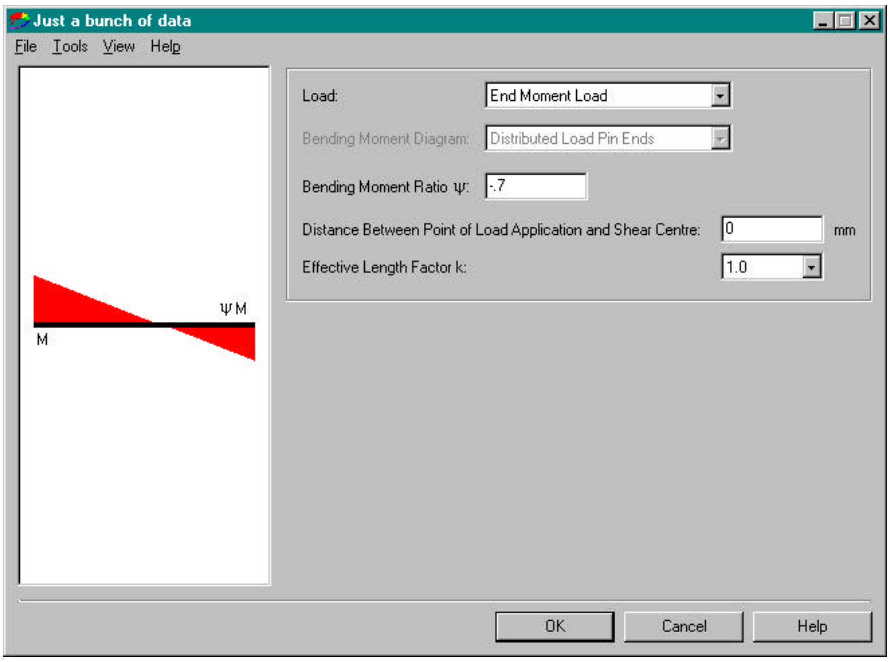


10.3 Beams with Class 1, Class 2 or Class 3 cross-section (4.2.3.3 and 4.2.3.4)

For beams the user must input the design bending moment for the fire situation $M_{fi,d}$, the design shear force $V_{fi,d}$, the steel grade, the adaptation factors for non-uniform temperature distribution κ_1 and κ_2.



The length of beam between points of lateral restraint as well as the shape of the bending moment diagram must be given. The steel profile is described in a previous step of the simulation (Steel Profile window).



OZone will then incrementaly compute the design moment resistance of the beam $M_{fi,\theta,Rd}$ at the maximum temperature $q_{a,max}$; $q_{a,max} + \Delta q_{a,max}$ and the design buckling resistance moment $M_{b,fi,\theta,Rd}$.

The design moment resistance of a Class 1 or Class 2 cross-section member is computed using equation (4.9) :

$$M_{fi,t,Rd} = M_{fi,\theta,Rd} / k_1 \, k_2 \qquad (4.9)$$

or, equation (4.14) for a Class 3 cross-section :

$$M_{\mathrm{fi,t,Rd}} = k_{\mathrm{y},\theta,\mathrm{max}} M_{\mathrm{Rd}} [g_{\mathrm{M},1} / g_{\mathrm{M,fi}}] / k_1 k_2 \tag{4.14}$$

The design buckling moment resistance of a Class 1 or Class 2 cross-section member is computed using equation (4.11) :

$$M_{\mathrm{b,fi,t,Rd}} = [c_{\mathrm{LT,fi}} / 1{,}2] W_{\mathrm{pl,y}} k_{\mathrm{y},\theta,\mathrm{com}} f_{\mathrm{y}} \ / \ g_{\mathrm{M,fi}} \tag{4.11}$$

or, equation (4.15) for a Class 3 cross-section :

$$M_{\mathrm{b,fi,t,Rd}} = [c_{\mathrm{LT,fi}} / 1{,}2] W_{\mathrm{el,y}} k_{\mathrm{y},\theta,\mathrm{com}} f_{\mathrm{y}} / g_{\mathrm{M,fi}} \tag{4.15}$$

Ozone will check the design moment resistance, or the design buckling moment resistance (if $\bar{l}_{LT,q,com}$ > 0.4) against the design bending moment $M_{\mathrm{fi,d}}$.

11 Validation

11.1 Comparison of the one zone model with an existing code (NAT)

In this section, an academic example of application of the OZone code is presented and the results are compared with those of the one zone model NAT [XX]. This code was made at the CSTB in France and the calculations presented here were made by Daniel Joyeux from the CTICM, France.

The compartment has the following dimension: length, 5m; width, 5m; height, 2.5m. There is one opening of 1.4m large and 1.9m height, the sill is 0.4m height. The wall (ceiling and floor included) are 20cm thick and made of normal weight concrete. The rate of heat release is given at the figure n°4 and has a maximum of 4MJ/s.

The temperature and the pressure of the gas in the compartment are given in Figure 34 & Figure 35. The different terms of the energy balance are shown on Figure 36.

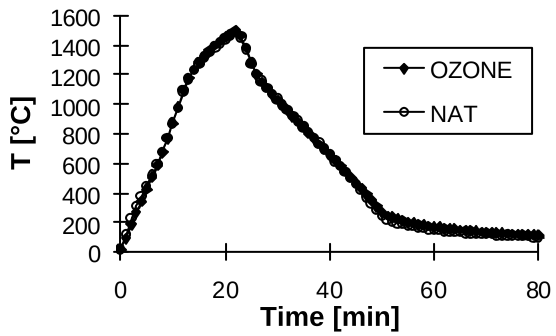


Figure 34 Temperature of gas

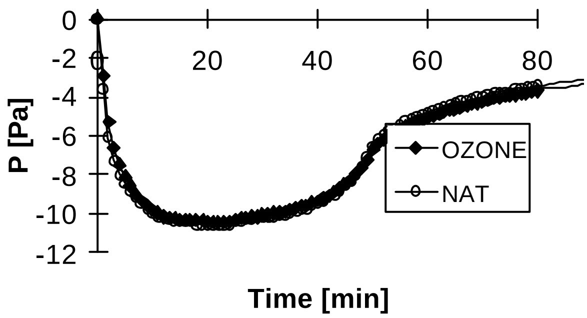


Figure 35 Pressure in the Compartment

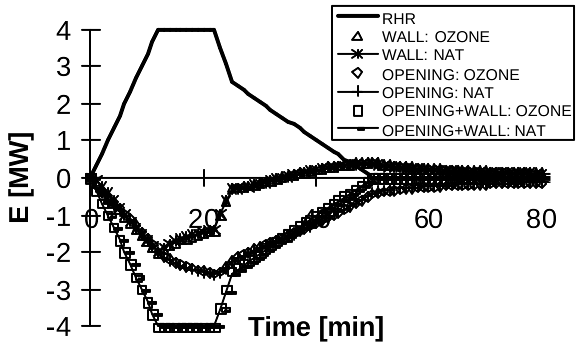


Figure 36 Energy Balance

A very good agreement is found between the two codes.

11.2 Comparison with Experimental Tests

The data base of experimental fire tests comprises more than 80 test results, 54 of them having been analysed up to now. In these tests, the fire load per total area of the enclosure varied between 37 and 151 MJ/m² whereas the opening factor varied between 0.015 and 0.157 $m^{0.5}$. Observation of the results showed that some tests lead to a fuel bed control regime whereas others were clearly ventilation controlled. When the pyrolisis rate or the Rate of Heat Release – RHR - had been measured during the test, it was introduced in the simulation and combustion model number 1 was activated ; lack of oxygen leads to a reduction of the RHR but the duration of the fire is not increased, which amount to assume external flaming. When only the fire load was known, a RHR curve was introduced, based on a t² growing phase, a constant release phase and a linear descending branch starting when 70 % of the fire load has been consumed. In the later case, the combustion model number 2 of OZone was activated ; a lack of oxygen leads to a reduction of the RHR leading to a duration of the fire longer than the one assumed in the data.

Figure 37 gives a comparison of the maximum gas temperature as measured in the test and computed by the model. Each point is representative of a test and the oblique line is the location of the point giving a perfect fit. The doted line is the linear regression among all the points.

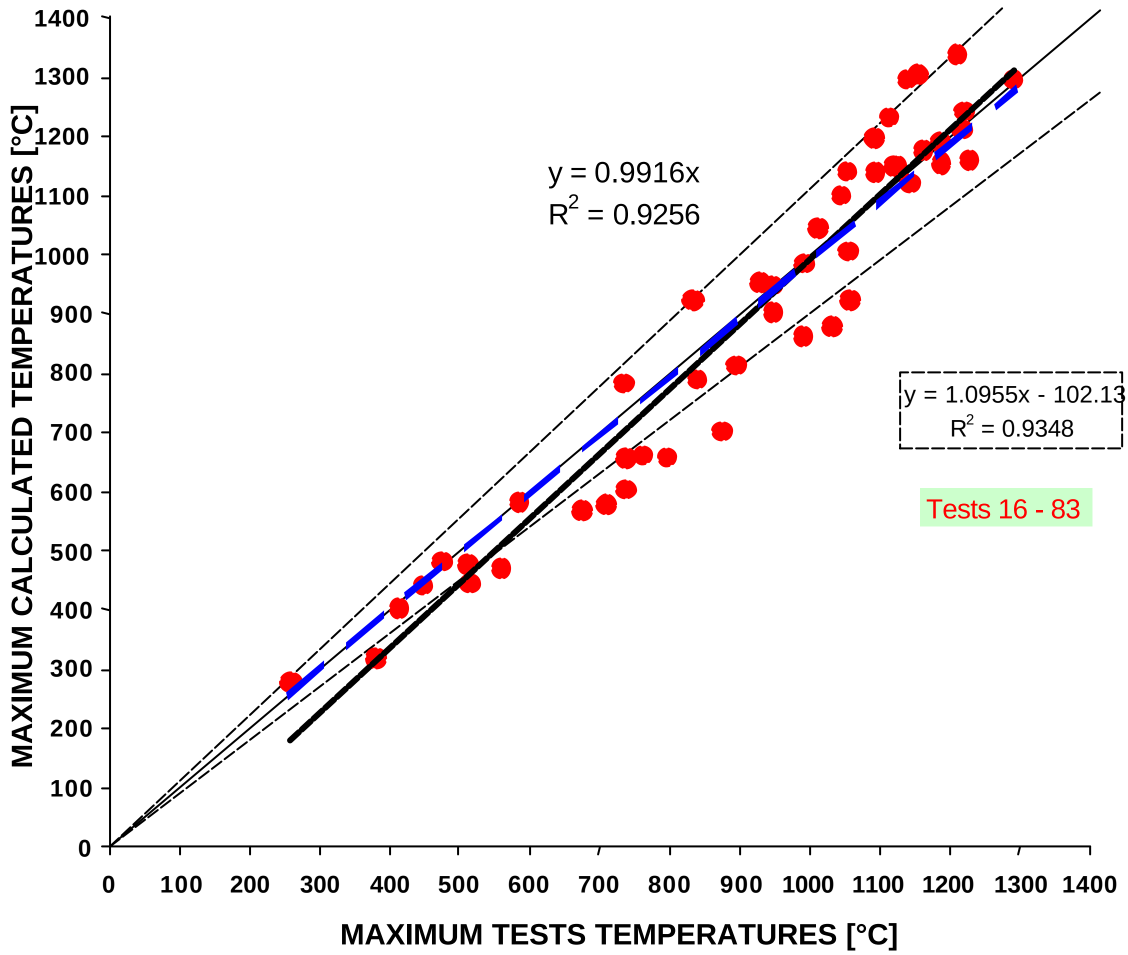


Figure 37 maximum temperature in the compartment

The maximum gas temperature is yet only a scalar and may not be a sufficiently good indicator of the good fit between two curves. For each test, the temperature evolution was computed in a typical unprotected steel section – HEB200, U/F = 147 m^{-1} – first submitted to the recorded gas temperature, then submitted to the computed gas temperature. This allowed to draw figure 4 where each test is represented by the maximum temperature in the unprotected steel section and where the agreement is also rather good.

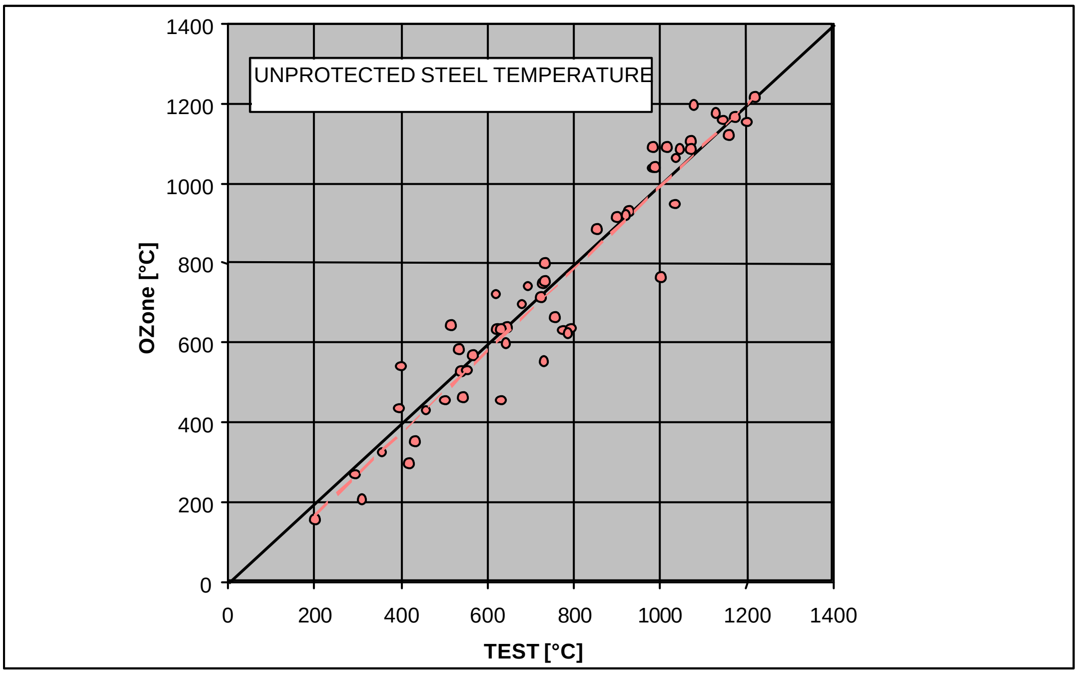


Figure 38 maximum temperature in the unprotected steel section

The temperature in an unprotected steel section tends to follow the evolution of the gas temperature with a rather limited delay. The maximum steel temperature is therefore sensitive to the severity of the fire, much more than to the duration of the fire. With this in mind, another comparison was made, based on the maximum temperature computed in a *protected* steel section. The same section was chosen but supposed to be protected by 20 mm of a dry material having a specific heat of 1850 J/kgK, a specific mass of 300 kg/m³ and a thermal conductivity of 0.20 W/mK. Figure 5 has been drawn with these values.

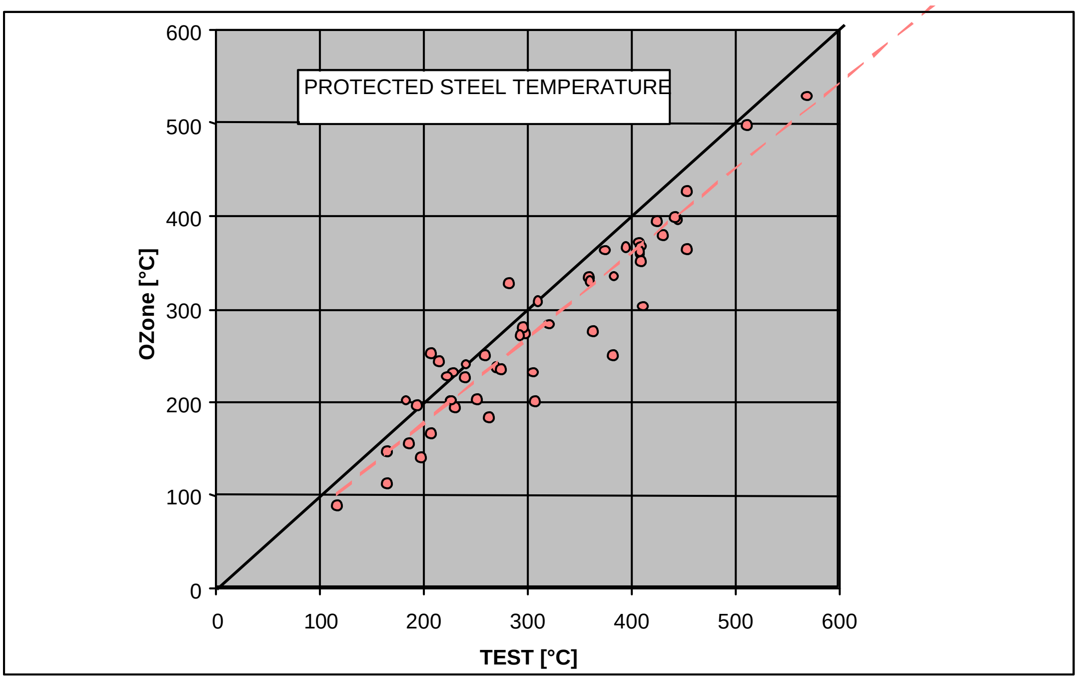


Figure 39 : maximum temperature in the protected steel section

Although the correlation is still very good, there seems to be a systematic trends for OZone to underpredict the protected steel temperatures by a factor of approximately 10 %. This was clearly traced to the fact that the temperature of the gas decrease somewhat faster in the OZone simulation than in the experimental test. Although this should be confirmed experimentally, this could be due to the fact that the recorded experimental temperature is in fact the temperature of thermocouples placed in the compartment and that these thermocouples are influenced not only by the gas temperature but also by the radiation flux that they receive from the walls and the burning combustibles. The walls and the burning materials, cooling down slower than the gas, would then to some extend delay the cooling down of the thermocouples.

12 Conclusions

In the new zone model OZone, the variation of the specific heat of the gas in the compartment is taken into account.

The discretisation of the walls by a traditional finite element approach allows to formulate the differential equations which govern the heat transfer by conduction within the material. These equations can be added to the usual set of two differential equations describing the evolution of situation within the compartment. These two sets of equations can be solved simultaneously by the numerical solver. Because the two sets of equations are coupled by the temperature of the inside surface of the wall, the energy balance between the compartment and the wall is strictly respected.

This proposed procedure provides an elegant and robust way to account for the heat transfer to the walls that does not require the introduction of hypotheses on the time evolution of the interface temperature.

Three different combustion models have been introduced to allow the user to run the code for different purposes. The combustion models 0 and 1 are designed to model full scale fire tests. The CM1 can also be used in a design procedure if the duration of the fire is known or imposed by the user. The combustion model 2 has to be used in fire safety design procedures.

A combination of a two and a one zone model is included. The criteria of transition offers to the user an automatic decision procedure to know whether a two or a one zone model is appropriated to the fire stage which is model.

The comparison between OZone and NAT is very good. The agreement between experimental test results and results computed by a numerical code based on this procedure appears as quite satisfactory.

A Graphic User Interface has been developed to define the input data.

The code is available for free at the University of Liège for general public (contact: JF Cadorin, jf.cadorin@ulg.ac.be or JM Franssen, jm.franssen@ulg.ac.be).

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