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Jean-Marc Franssen was born in 1959. He graduated in 1982 as a Civil Engineer from the University of Liege where he started to make research on the subject of fire in buildings. His first works concerned the numerical modelling of structures submitted to fire, whereas he more recently started to have a look on the fire itself in the frame of different ECCS contracts linked with Natural Fire Safety Concept.

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NATURAL FIRES IN LARGE COMPARTMENTS

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EFFECTS CAUSED ON THE STRUCTURE BY LOCALISED FIRES IN LARGE COMPARTMENTS

A description is given of the small-scale steady-state tests made by Hasemi in Japan with the aim of measuring the heat flux transmitted by a localised fire to the ceiling or to a beam located above the fire. The parameters that influence the heat flux have been mentioned and an empirical model has been proposed, allowing the prediction of the heat flux. It is shown here how the model has been applied to full-scale transient fires. The model allows the calculation of the transient temperature in steel beams with a reasonable accuracy.
Keywords: heat flux, localised, model, steel, temperature, test.

1. Introduction

One of the hypotheses of the conventional time temperature curves, like the ISO 834 [1] or the ASTM E119 [2] curves, is that the same temperature holds within the whole compartment. This hypothesis is reasonable provided that the whole compartment is engulfed in flames, which could be the case in a small compartment like, say, a hotel room or even in larger compartments in a post flash over situation. This is why the hypothesis of uniform temperature is also considered in the numerical one-zone models.

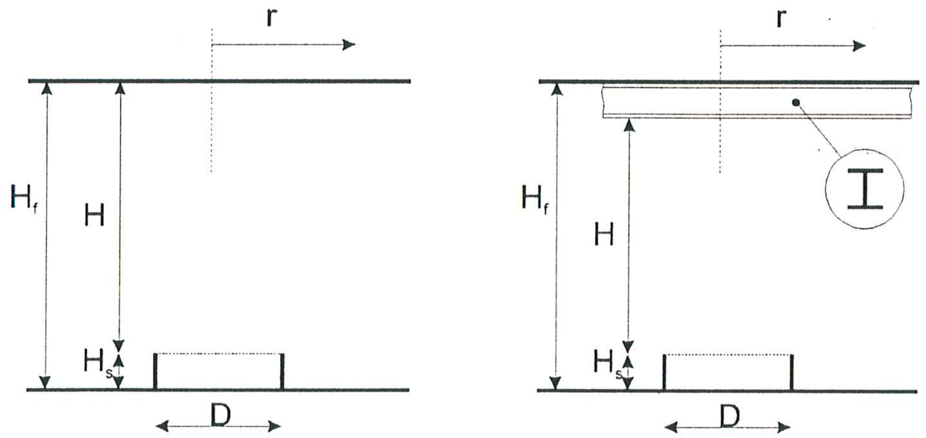
In a real fire, the temperature distribution in the compartment is yet highly non uniform, at least during the first instants, for any fire, and in some cases during the whole duration of the fire, when the size of the fire is small compared to the size of the compartment. For these cases, numerical two-zones model are usually applied, reflecting the observed fact that the gases in the compartment clearly form a two layers stratification, with the combustion gases located in the upper hot layer and the fresh air laying in the lower cold zone.

The temperature that is calculated for the hot zone in this hypothesis can be considered as the average value of the temperature field in the air. This value is general sufficient when the aim is, for example, to see whether the temperature may be as high as to lead to a flash over. The average value is also sufficient to make an assessment of the structural stability, provided that the global behaviour of the structure is the most critical, i.e., if the structure is not too sensitive to a local failure. It has to be recognised that, in fact, the thermal impact of a localised fire can be much more severe on the structural elements located in the vicinity of the flames than the impact coming from the air at the average temperature. 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.

A first solution to identify the relevant parameters can be found in the correlation formula proposed by Alpert [3] to calculate the maximum gas temperature in the ceiling jet flow which forms when a vertical buoyant fire plume impinges on a horizontal ceiling and the gases spread laterally. As indicated by the title of Alpert's publication, his work was done with the objective of predicting response times of detectors and not the structural behaviour of the structure. Whereas the air temperature is a good indication for the response time of a detector, the thermal solicitation of a structure is not only influenced by the temperature of the air flowing on its surface but also, via radiation, by the fire itself. It is therefore preferable to make direct measurements of the heat flux received by the surface if the temperature of a structure has to be calculated. This is the kind of measurements made by Hasemi in Japan and described in the next section.

2. Experimental Japanese tests

Hasemi et al. [4, 5] made the tests at the Building Research Institute in Tsukuba. Fig. 1 gives a sketch of the test set-up. The porous burner was either circular, with a diameter of 0.30, 0.50 or 0.60 meter, or square with sides of 1 meter. The energy was provided by propane and, depending on the gas flow rate and type of burning, the constant rate of heat release, " R.H.R. ", varied from 95 kW in some tests to a maximum of 200 kW in other tests. The plume is confined vertically by a horizontal plate but there is no lateral confinement; the air coming at the lower level and mixing with the propane to feed the combustion has not been mixed with already produced combustion gases because there is no lateral wall in the system. Several tests were made with different values for " Hf ", the distance between ground level and the horizontal plate representing the ceiling, from 0.40 to 1.20 meter. During the tests, the incident heat flux was measured at different positions " r " from the vertical axis of symmetry, either just under the ceiling (see Figure 1.a) or under the inferior flange of a steel profile fixed to the ceiling (see Figure 1.b). Additional tests were made by Wakamatsu et al [6] with energy release rates increased up to a maximum of 900 kW and floor to ceiling distances from 0.60 to 1.20 meter. The steel beams used had a depth of 450 mm.



a) flux on the ceiling   b) Flux on the beam

Fig. 1 Test set-up for the heat flux measurements

3. Non dimensional model

A practical way to generalise the results of the small-scale tests to other more general configurations is to build a model based on non dimensional coefficients. Hasemi uses the Froude number, given by Eq. 1.

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

Introducing in Eq. 1 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 Eq. 2.

$$Q^* = \frac{Q}{1.11 \times 10^6 \, D^{5/2}} \qquad (2)$$

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 Eq. 3, already proposed by Hasemi in earlier papers [7].

$$\frac{z'}{D} = 2.4\left(Q^{*2/5} - Q^{*2/3}\right) \qquad for \quad Q^* \leq 1$$

(3)

$$\frac{z'}{D} = 2.4\left(1 - Q^{*2/5}\right) \qquad for \quad Q^* > 1$$

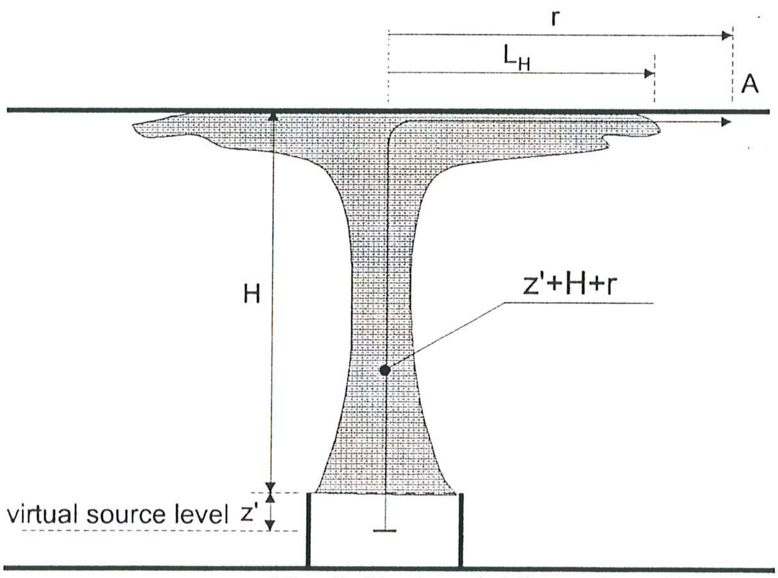


Fig. 2 Horizontal flame length

When the flame impinges on the ceiling, it is deviated and develops horizontally on a distance L_H, see Fig. 2. Whereas the position of the heat virtual source has to do with the dimension of the burner, " D " in Eq. 2, 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 Eq. 4, very similar to Eq. 2.

$$Q_H^* = \frac{Q}{1.11 \times 10^6 H^{5/2}} \qquad (4)$$

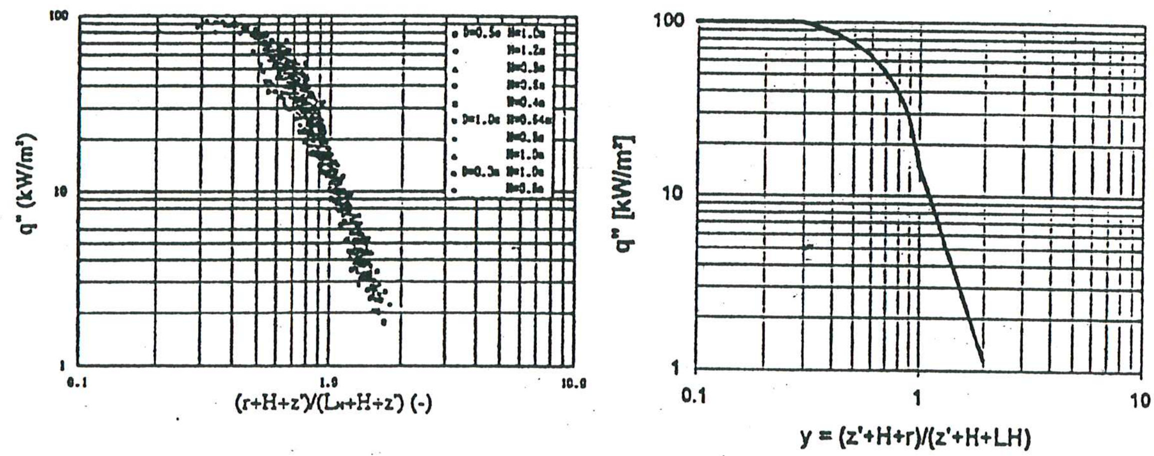
with H Vertical distance between the burner and the ceiling.

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 Eq. 5.

$$\frac{L_H + H}{H} = 2.90 \quad Q_H^{*\,1/3} \qquad (5)$$

Fig. 3.a, directly taken from [4], shows the correlation between the heat flux measured at any point A located at a distance r, see Fig. 2, and the non dimensional ratio between the distance from the virtual source, z' + H + r, and the total length of the flame, $z' + H + L_H$.

Eq. 6 is a good expression of this correlation and was used to draw Fig. 3.b.



a) Experimental correlation

b) Curve drawn with Eq. 6

Fig. 3 Relation between the position and the received heat flux

$$\begin{aligned} q'' &= 100 && \text{for } y \le 0.30 \\ q'' &= 136.3 - 121\,y && \text{for } 0.30 < y \le 1.00 \qquad (6) \\ q'' &= 15\,y^{-3.7} && \text{for } 1.00 < y \end{aligned}$$

In the case where a steel beam is present under the ceiling and the flux received by the lower face of the inferior flange has to be estimated, the value of H is then measured as indicated on Figure 1.b. The calculated flux is then the one that would be measured under a ceiling located at the lower level of the steel beam. In reality, there appears a geometrical distortion of the flame around the steel beam. The end of the flame is located under the ceiling and can thus not influence the lower face of the beam. The flux under the beam is therefore smaller than the flux that would be received by a ceiling located at the same level. The result must be reduced and observations of test results indicated that a multiplication factor of 0.85 leads to a good value for the flux received by the beam.

4. Applications to full-scale tests

4.1 Parc de la Villette

The model described in section 3 has been applied to the set of 4 full-scale tests made in Paris [8]. With a floor to ceiling distance of 10 m, surfaces of the fires as large as 150 m² and peak R.H.R. of some tens of MW, the scale is really different from the scale used in Japan to establish the model. Another interesting aspect of the French tests is their transient character, on the contrary to the steady state character of the Japanese tests.

For each test, the total released energy is estimated from the mass of burnt material [9]. From temperature measurements in the air, it is estimated that the evolution of the R.H.R. with time is bilinear, with a phase of increasing power followed by a phase of decreasing power. For test 4, which involved wood as well as polystyrene, it has been supposed that each material burnt with its own bilinear evolution of the R.H.R. The maximum R.H.R. of each test is calculated from the total released energy and duration of the test. The level of the fire source is taken as 0.40 m.

Table 1 gives the significant parameters of the 4 tests, as well as the measured flux measured bellow the inferior flange of a 500 m deep steel beam supporting the ceiling.

Test	1	2	3	4 Wood	4 Polyst.
Width of the fire (m)	5.8	5.8	11.6	5.8	5.8
Depth of the fire (m)	10.0	6.7	13.0	10.0	10.0
Characteristic length (m)	8.59	7.03	13.86	8.59	8.59
Released energy (GJ)	23.4	23.4	46.4	12.2	9.2
Duration of the fire (min.)	60	50	50	40	5
Time at max. R.H.R. (min.)	25	15	15	52	2
Max. R.H.R. (kW)	13.0	15.6	30.9	10.2	61.3
Max. heat flux; r = 0 (kW/m²)	17	21	34	24	24
Max. heat flux, r = 2.9 m (kW/m²)	7	8	17	9	9

Table 1 – Parameters of the tests in la Villette

Estimating that the flux received by the upper face of the inferior flange is only one half of the flux received by the lower face, the inferior flange of this IPE500 is submitted to an average heat flux q_{av} equal to 0.77 the flux q'' calculated by the model. The net heat flux at the boundaries " q_{net} ", taking into account the flux lost due to the temperature of the section, is given by Eq. 7.

$$q_{net} = q_{av} - h\left(T_s - 293\right) - \sigma\, \varepsilon^*\left(T_s^4 - 293^4\right) \qquad (7)$$

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).

The temperature evolution in the flange is calculated step by step using q_{net} and the simple equation given in Eurocode 3 [10] for the uniform temperature in unprotected profiles.

The calculated evolution of the temperature in the lower flange of the beam just above the fire is shown on fig. 4 and is compared to the corresponding measured values (fig. 11 of [8])

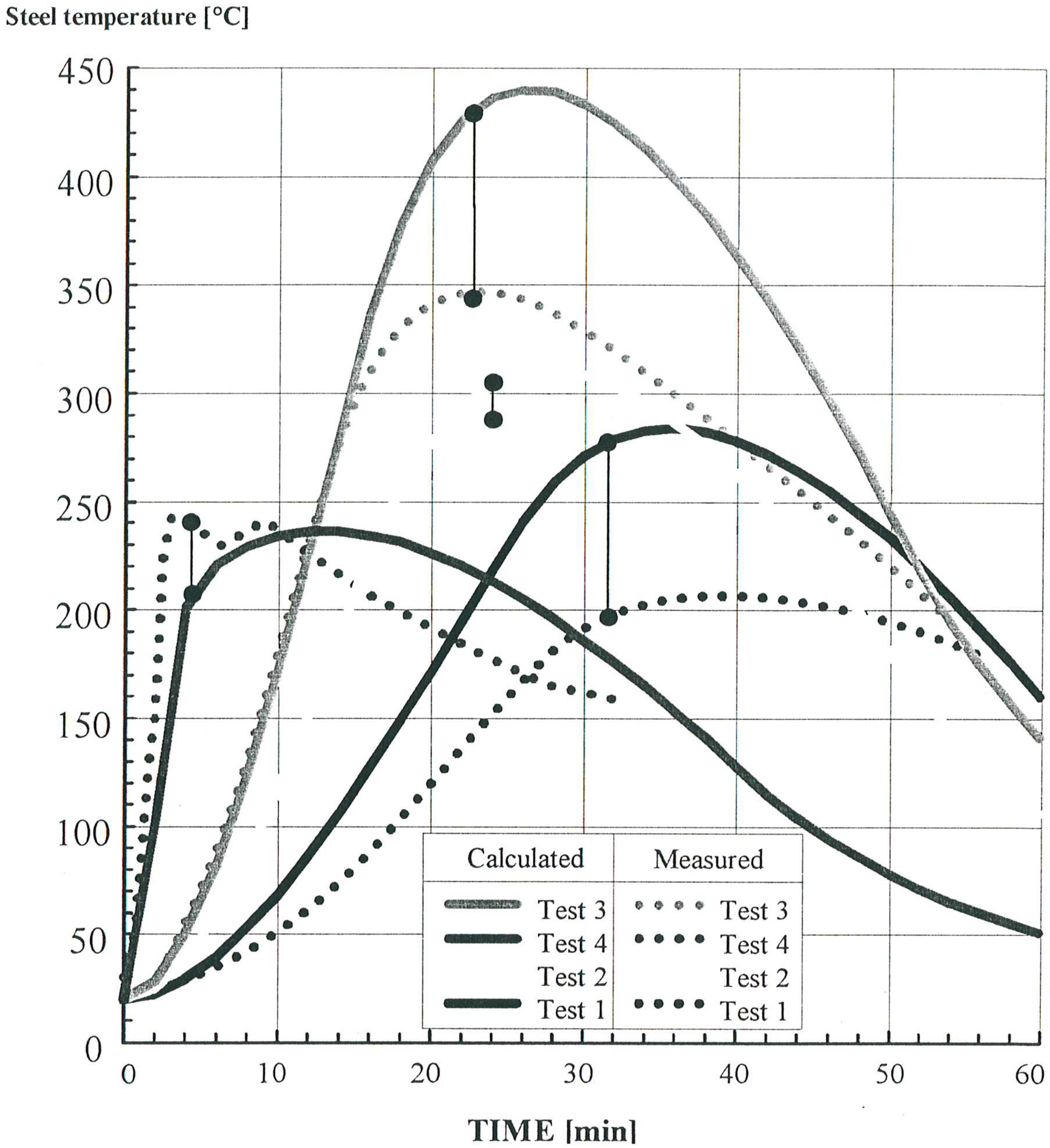


Fig. 4 : Temperature of the lower flange above the fire.

Fig. 4 shows a very good correspondence, in the shape of the different curves, in their relative positions, and in the value of the maximum steel temperature. It can be observed that the test 4 with its very high but very short R.H.R. peak due to the polystyrene is not very severe for steel, because of the transient effect.
For test 2 and 3, we have also calculated the evolution of the temperature in steel at different locations, from just above the fire up to a distance of 13 m from the fire. Fig. 5 shows how the maximum temperature experienced in the beam as a function of the distance from the fire. The calculated temperature is correctly predicted just above the fire, but the temperature predicted in sections far away from the fire are too low when compared with the measured temperatures. This is because Hasemi's model has been established in unconfined spaces whereas the tests in Paris have been made in a compartment in which a 2 layers stratification has been created with an accumulation of hot gases in the upper zone. That's why it is proposed to combine Hasemi's model with the calculation of the average

temperature in the upper zone and to adopt the maximum of the 2 models as shown on Fig. 6, the local Hasemi's model and the global zone model.

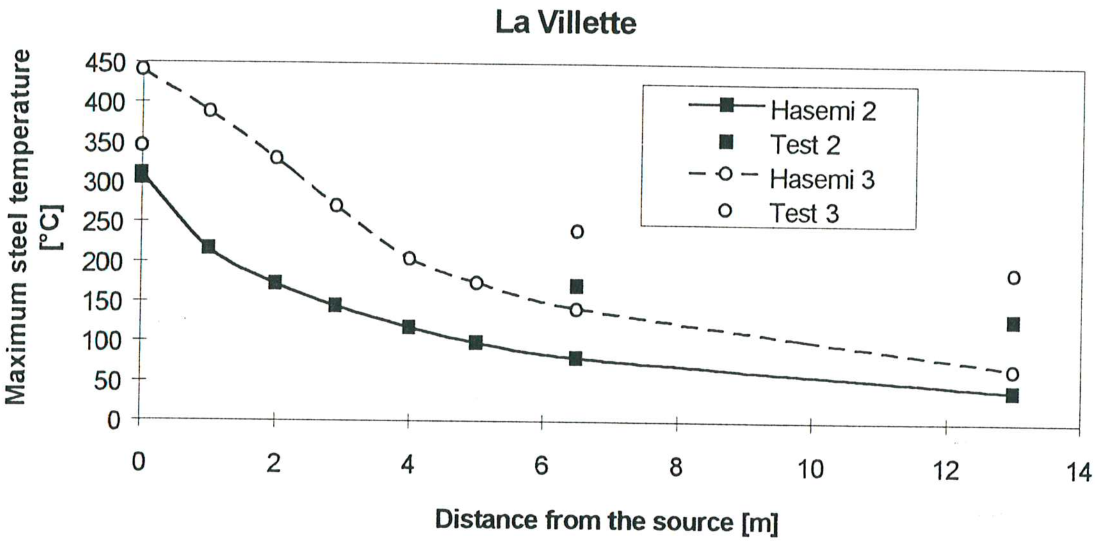


Fig. 5 : decrease of the temperature with the distance from the fire.

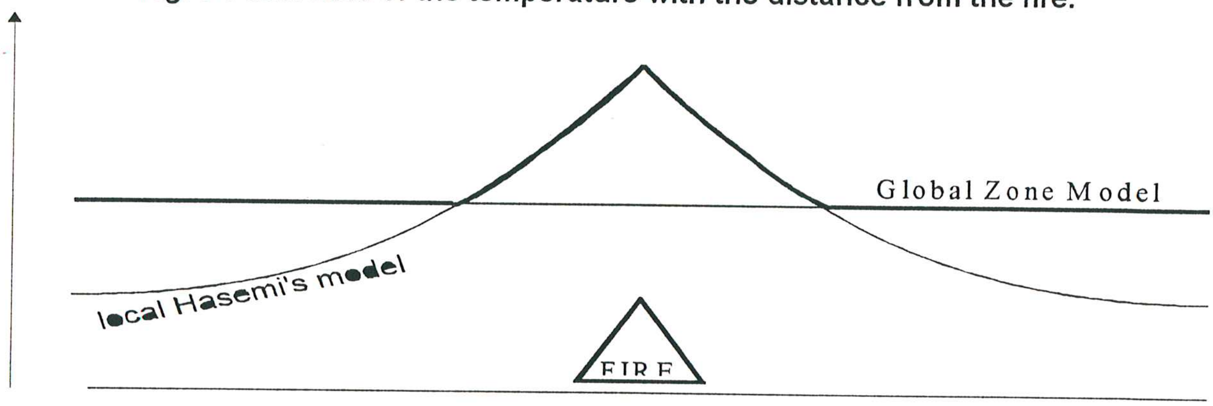


Fig. 6 : maximum of the 2 models.

This procedure defined in figure 6 has been applied to the tests of "Parc de la Villette" (figure 5). The mean temperature of the hot zone has been calculated by the simplified formula:

$$\theta = 20°C + (0,8\ Q) / M_{ent}\ [19]$$

with $M_{ent} = 0,188\ W_{fi}\ H^{3/2}$ according to Thoma's formula [11]

Test 2	$W_{fi} = \pi \times 7^2/4$ $= 38,48\ m^2$	Q_{max} = 15600 kW	Y = 2m [8] Y = 4m [8]	θ = 629,9 °C θ = 235,6 °C
Test 3	$W_{fi} = \pi \times 13,9^2/4$ $= 151,75\ m^2$	Q_{max} = 30900 kW	Y = 2m [8] Y = 4m [8]	θ = 326,4 °C θ = 128.3 °C

The above-mentioned data have been extracted from the table 1. Concerning the height Y of the free zone, the report [8] indicates a value between 2 and 4 m according to visual observations made during the tests. The fig. 7 shows how the fig 5 is changed if the procedure is applied.

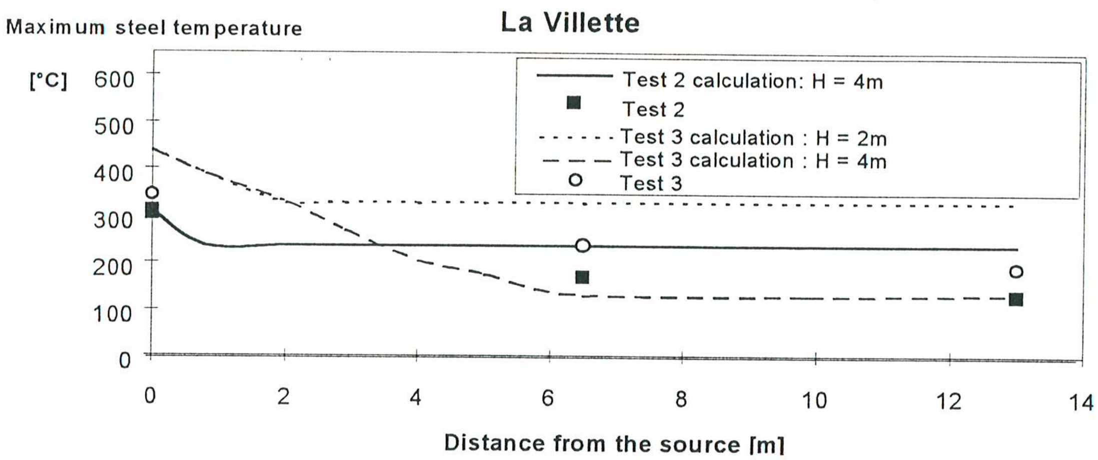


Fig. 7 : decrease of the temperature with the distance from the fire - final procedure combining global 2 Zone Model and Hasemi's model

4.2 Car fire tests

Nine tests have been made in Maizières-lez-Metz by CTICM on one or two burning cars in a small compartment [12,13]. In the fourth test, the car was a small car. A steel beam was placed above the car and the temperatures were measured during the fire in the steel flange. The Rate of Heat Release was also measured. The maximum value was more than 2 MW, but it occurred only during a short period of time as shown on Fig. 8 where the measured RHR curve has been schematised.

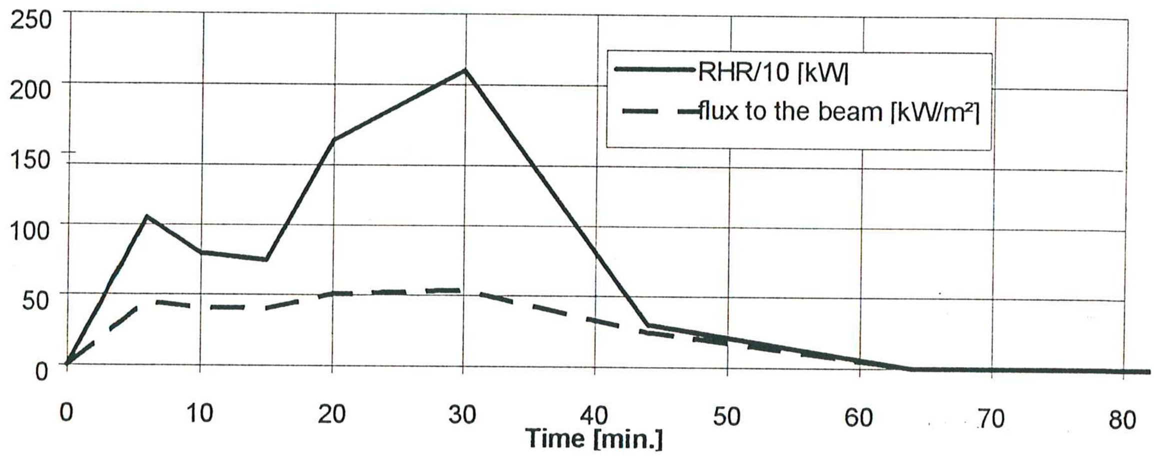


Fig. 8

Hasemi's method has been applied to this scenario and the temperatures in the lower flange of the HEB300 have been calculated. In order to apply the model, the following hypothesis have been made to represent the burning car:

- vertical position of the fire source Hs = 0.60 m
- characteristic length of the fire source D = 3.91 m (surface = 12 m²)

Fig. 8 shows the evolution of the flux received by the lower surface of the lower flange. It can be seen that it follows the evolution of the R.H.R. but that the relationship is not linear.
The evolution of the temperature in the lower flange of the steel beam is plotted on Fig. 9. The shape of the calculated curve is similar to the shape of the measured curve, but the calculated values are somewhat higher. This could be due to the presence of a dark layer of smoke in the upper zone of the compartment. This shows that, in some cases, the fact to

take the maximum of the 2 models, see Fig. 6, is on the safe side, at least in the vicinity of the fire.
Less severe results could also be obtained if the elevation of the fire source would be decreased. Additional comparisons for the other tests have be made and point out a same accuracy between calculated and measured steel temperature (see [12]).

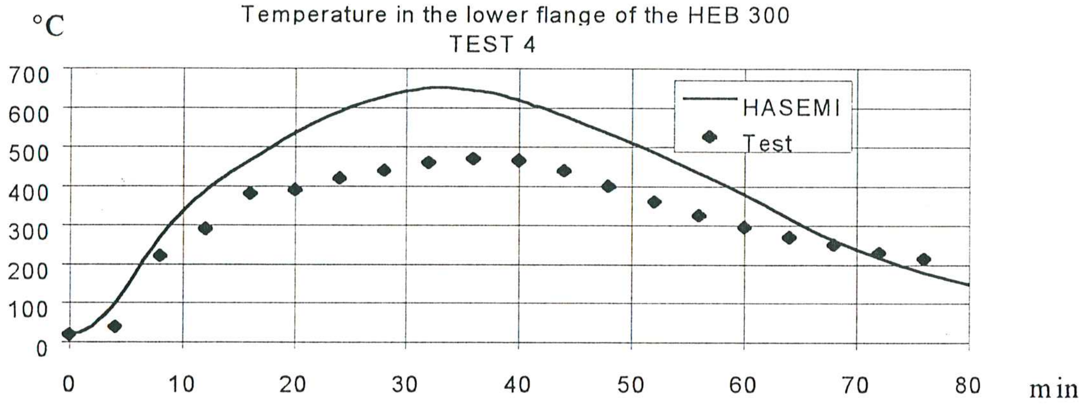


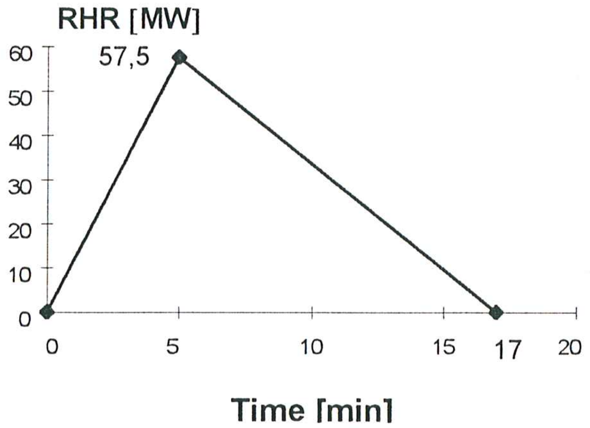
Fig. 9

4.3 Parc des Expositions, Paris [14,15]

A test has been realised in a exposition hall, the "Parc des Expositions" (Paris) the 20th of May 1994. The area of the central part of the hall is 144m x 65m and the height is 28 m. Horizontal openings have been foreseen in the roof for smoke evacuation. The burning load consisted of 120 wood pallets (3562 kg of wood).

This test has been analysed by using the Hasemi's modified method (see figure 6) with the following data :

- Rate of Heat Release deduced from the mass lost measurements.



- Diameter of the fire : D = 4 m
- Height of the fire : H_s = 0,84 m
- Height of the compartment H_f = 26 m

The air temperature of the following figure is in fact the steel temperature of a profile with a very small section factor. In that way, the Hasemi's method gives a good approximation of the air temperature.

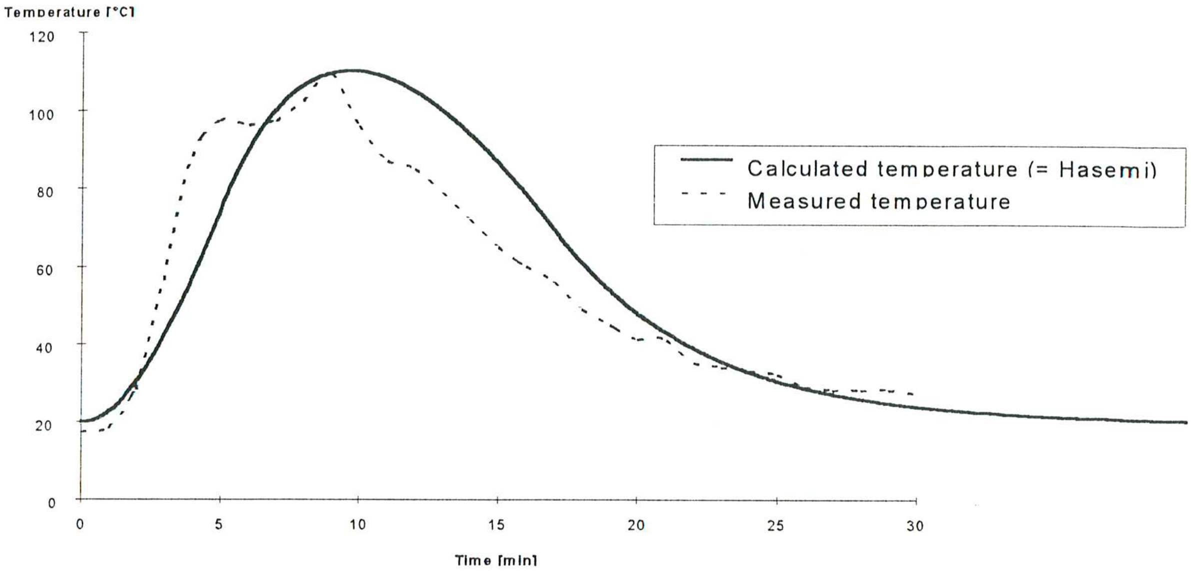


Fig. 10 : Calculated and measured air temperature at the ceiling just above the fire

At 24 m from the fire the mean temperature given by the 2 Zone model FIRST [16] is higher than the temperature given by Hasemi's method. The FIRST result is compared to the measured values in the following figure:

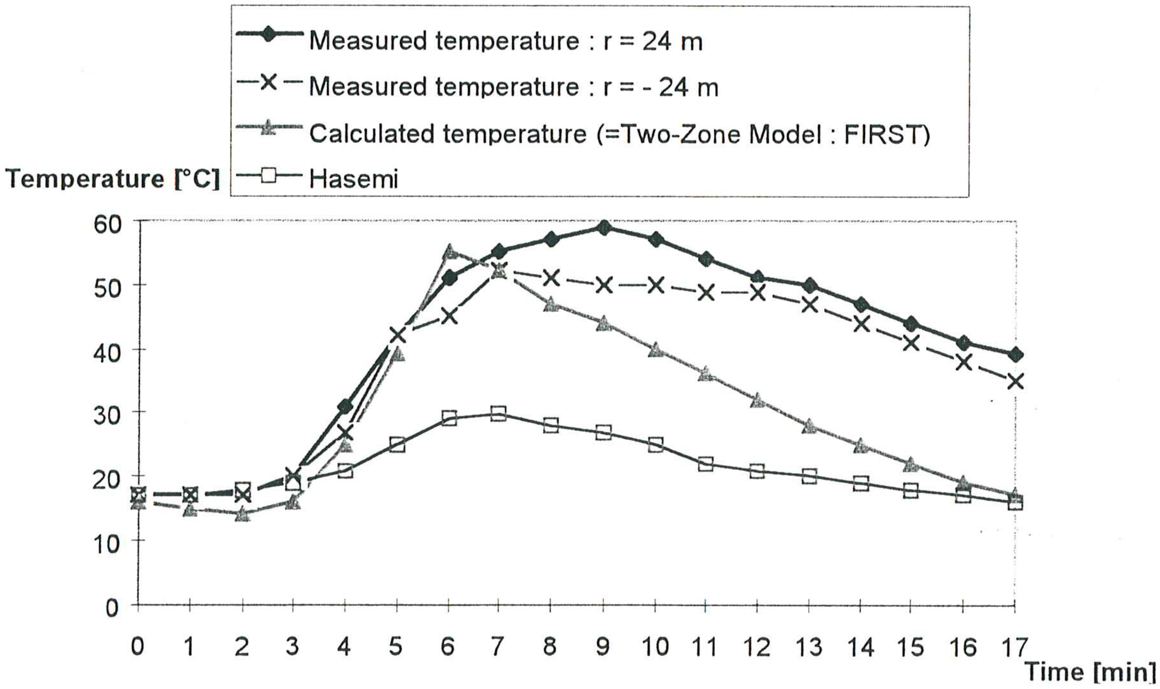


Fig. 11 : Calculated and measured temperature at the ceiling 24 m away from the fire

The figures 10 and 11 show again a good correspondence between measured and calculated values. Again the Hasemi's model provides the higher values and has to be chosen just above the fire while a two zone model approach is better far away from the fire. This justifies again the procedure of figure 6.

4.4 Comparison with CFD programs [18]

A benchmark [18] for the available air temperature calculation methods consisting of a localised heat source in the centre of a square compartment 30m x 30m with a height of 2,5 m and two small openings (100 cm x 20 cm) per wall has been performed by using two CFD programs:

- FLUENT: a commercial code used for this calculation by LABEIN in Spain
- VESTA: a code developed and used by TNO in the Netherlands

The following diagram shows the comparison at 1200 seconds between the CFD programs (FLUENT from LABEIN and VESTA from TNO) and Hasemi's method combined with the two Zone Model ARGOS [17] according to the figure 6.

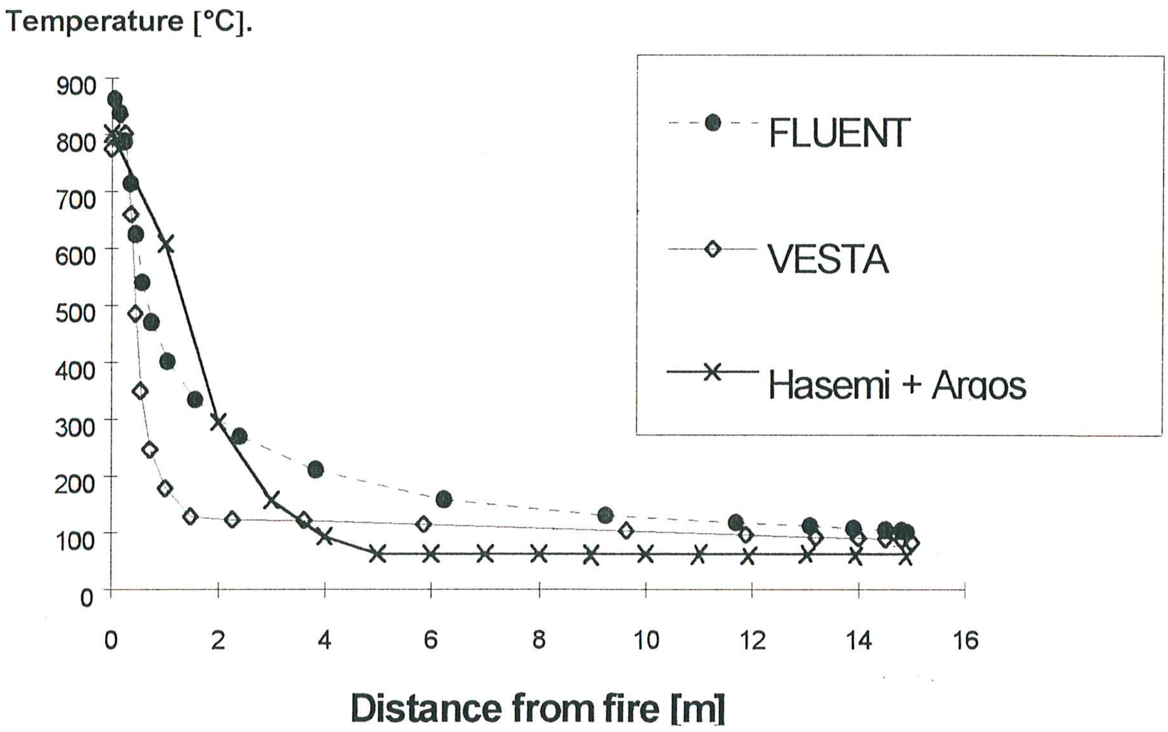


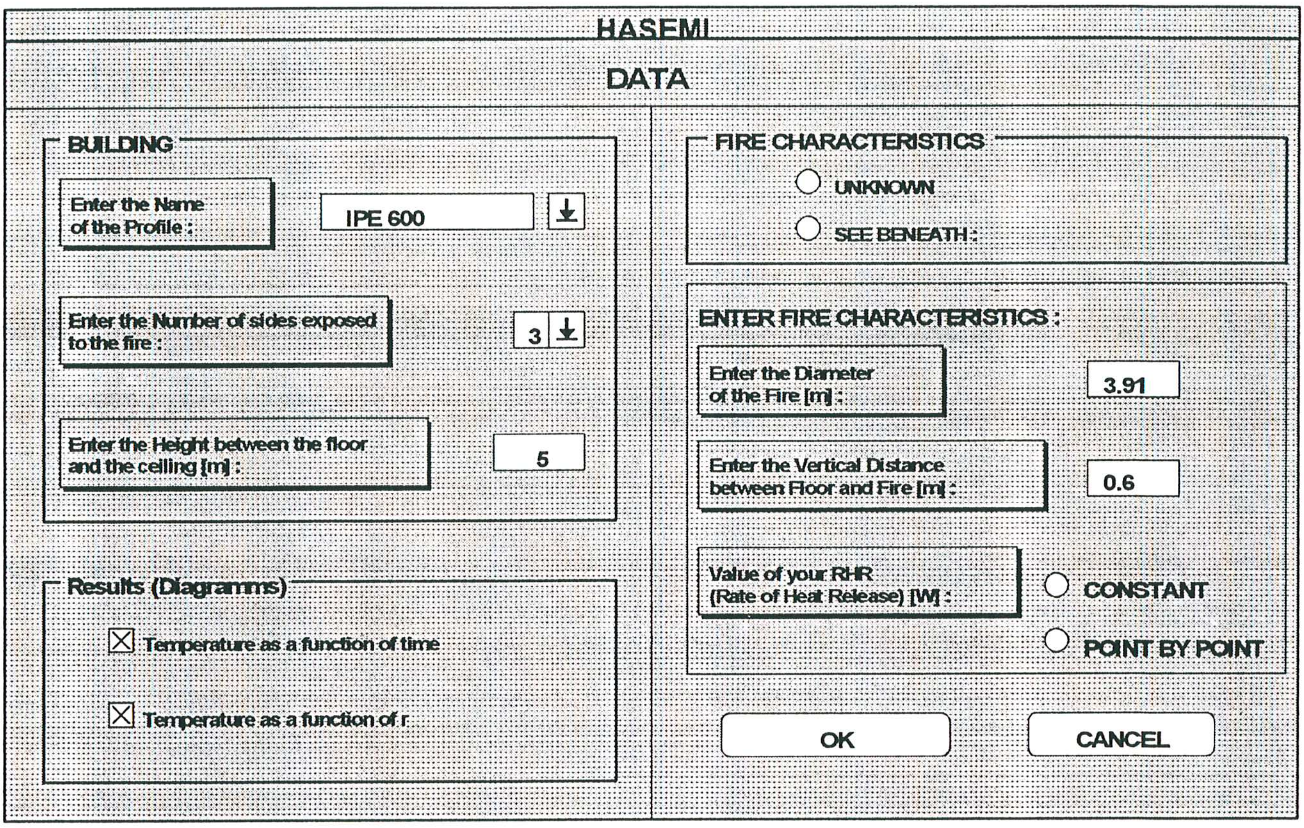
Fig. 12

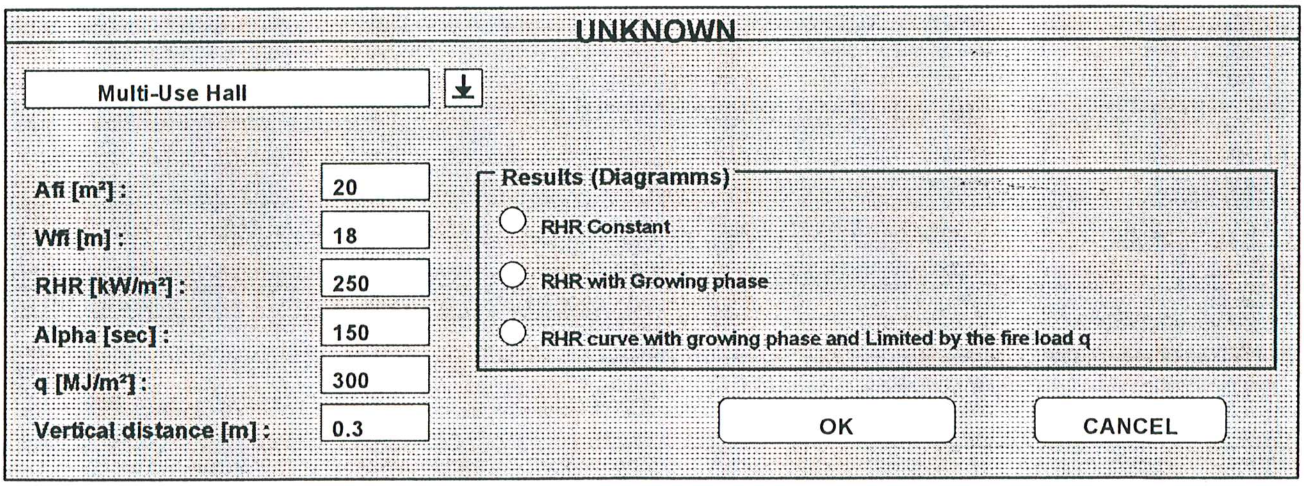
Again the procedure combining Hasemi's model and a Zone Model provides results closed to the reality that CFD results are supposed to represent. It has to be added that the Argos model gives very often rather low temperature compared to other Zone models [22].

5 DESIGN TOOL

Introduction

The whole method to determine the temperature field in the structure has been programmed on a spreadsheet (Excel 5.0) which has been called TEFINAF for TEmperature FIeld under NAtural Fire conditions. The data are introduced by the two following windows.





On the first window you can introduce the name of the profile and the number of sides exposed to the fire thanks to a “pull down menu”.

For the fire characteristics, you activate the option "see beneath" if your fire is well defined (Diameter, distance to the floor, RHR). If you are not able to give yourself the fire characteristics, you can choose the option "unknown" and then the second window appear. In this second window, a "pull down menu" enables to choose the building type for which the following data have already been stored:

A_{fi} : Fire Area in m²
W_{fi} : Fire Perimeter in m
RHR_{fi} : Rate of Heat Release per m² of fire
t_a : Time in sec needed to obtain a RHR of 1000kW during the growth phase.
q: the fire load per m²
and the vertical distance from the floor to the fire.

The library of these data can be easily updated. These data come from NBN S21-208-1 [19], BSI Standards [20], SIA 81[21] and from discussions with different experts [18] .

		A_{fi}	D	W_{fi}	RHR	t_α	q	vert.
		[m²]	[m]	[m]	[kW/m²]	[s]	[MJ/m²]	dist.
1	Aerogare Hall	9	3.4	12	250	300	200	0.4
2	Atrium in Office Building	9	3.4	12	250	300	200	0.3
3	Church	20	5.0	18	250	150	300	0.4
4	Exhibition Hall	36	6.8	24	500	150	400	0.6
5	"Do it yourself" centre	36	6.8	24	500	150	400	0.6
6	Hotel reception Hall	9	3.4	12	250	300	200	0.6
7	Multi-use hall	20	5.0	18	250	150	300	0.3
8	Offices (Large Area)	36	6.8	24	500	300	600	0.5
9	Picture gallery	9	3.4	12	250	600	300	0.7
10	Restaurant Room	20	5.0	18	250	150	300	0.4
11	Shopping Gallery	36	6.8	24	250	150	400	0.6
12	Sport Hall	9	3.4	12	250	300	200	0.3
13	Station Hall	9	3.4	12	250	300	200	0.4
14	Supermarket	36	6.8	24	250	150	400	0.7

Table 2

Thanks to these data, the RHR curve can be calculated.

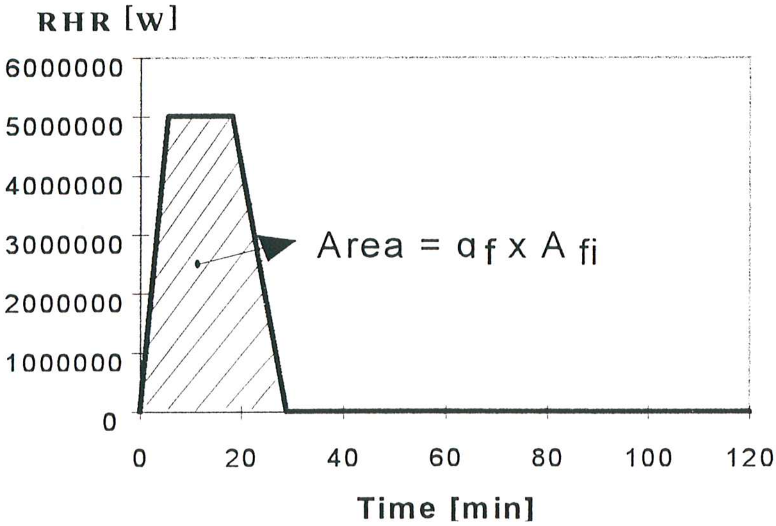


Figure 13 - RHR with growing phase and limitation with fire load. The decay phase starts when 70% of the fire has already burnt.

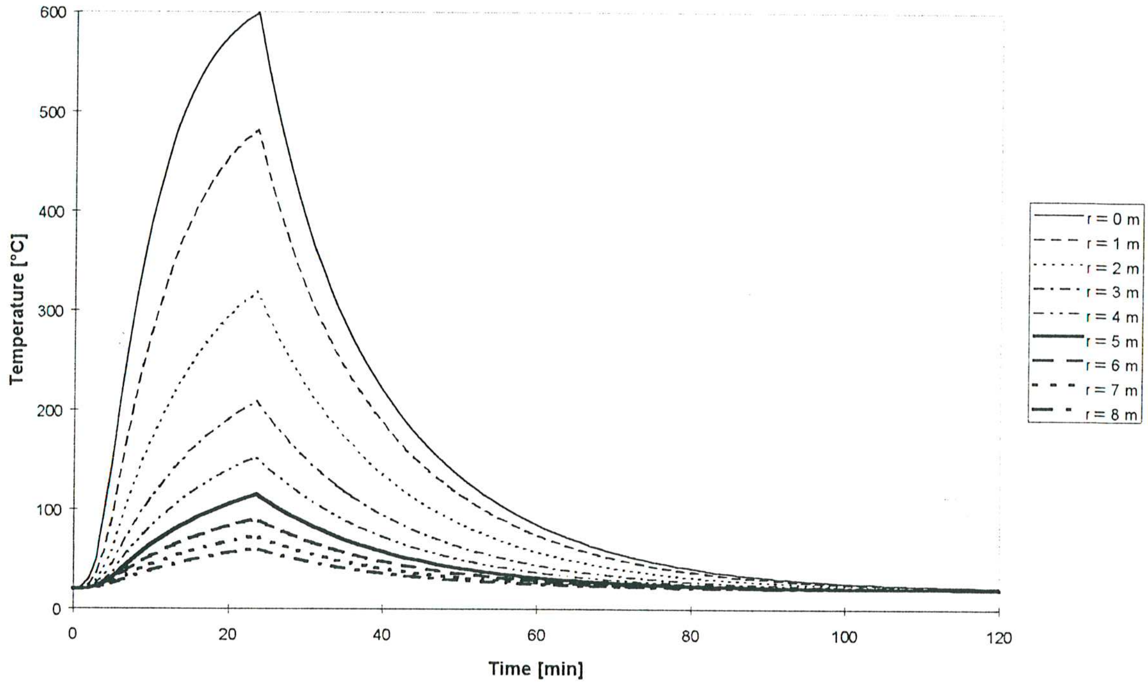


Figure 14 Steel Temperature of the Beam for different radial distance r

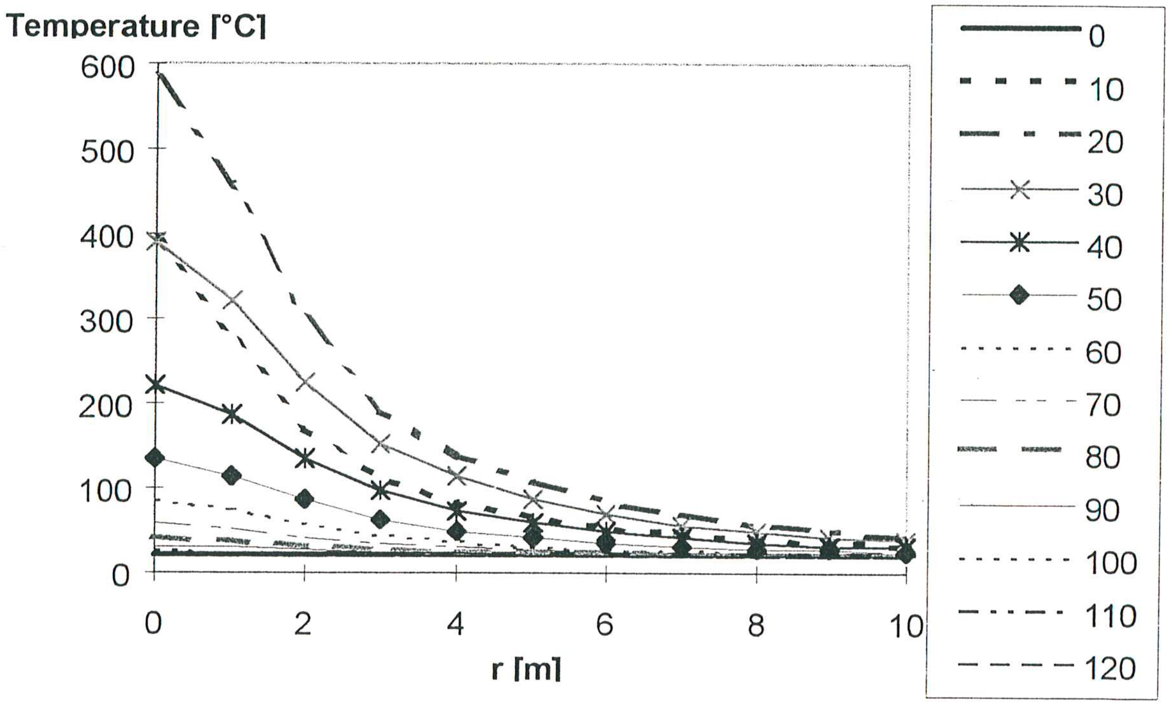


Figure 15: Steel Temperature of the Beam at different times as a function of the radial distance r

The final results are the temperature field in the beam at the ceiling depending on the time and on the radial distance r from the fire (see figures 14 and 15). Moreover a table provides the temperature and the thickness of the hot zone as a function of the forced ventilation or of the openings for the inlet and outlet in case of natural ventilation [19]. This table 3 enables to apply the procedure of the figure 6.

Height of the smoke layer d	Temperature of the hot zone	Forced ventilation	Natural ventilation, Openings area [m2] A_vC_v (Outlet), A_iC_i (Inlet)				
	[°C]	[m3/h]	$A_V*C_V/A_i*C_i=1$	**0,8**	**0,6**	**0,4**	**0,2**
1	162,75	124518,53	13,58	12,57	11,73	11,08	10,68
2	242,48	95182,50	5,76	5,38	5,06	4,82	4,67
3	432,91	70409,52	2,46	2,33	2,22	2,14	2,09
4	1197,03	51279,10	0,86	0,83	0,81	0,80	0,79

Table 3

In that way the temperature field in the compartment can be determined and can be used to perform the thermo-mechanical behaviour of the structure.

The temperature field depends upon the compartment size and the building type, which enables to define the fire characteristics (Fire loads, Rate of Heat Release, Fire Size). The heating of the beams is well determined (see the figure 6 and the following figure 16). This figure enables also to define the heating of the columns which depends upon their position. The top part has a uniform temperature whereas the remaining part is at ambient temperature. The buckling theory has been adapted for this case corresponding to a two zone heating [18].

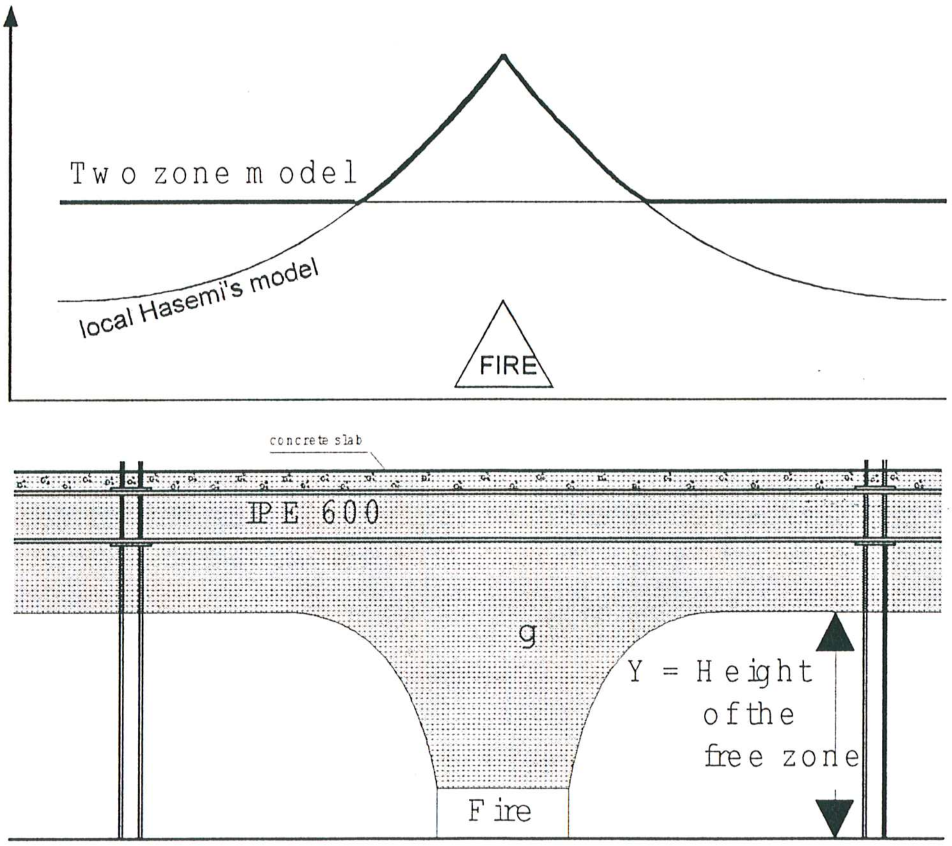


Fig. 7.1.4

Fig. 16

6 Conclusion

This method originally established by Hasemi takes into account the localised character of the fire and allows a simple evaluation of the flux received by an horizontal surface exposed to the fire.
In the present study, we have;

- slightly modified some equations of the model in order to have a best fit with the experimental results obtained by Hasemi,
- derived a practical way to apply the method and to obtain the average flux received by the lower flange of a beam,
- established the way how a burning car must be modelled in the method,
- described how the model must be combined with the results of a global 2 Zone model in order to take into account the heat accumulation in case of small openings in the compartment,
- verified the model when it is applied to a large compartment and in a transient situation,
- established an interactive spreadsheet (TEFINAF) which enables to use very quickly and easily the method

Hasemi's model has been combined with 3 different 2 Zone Model : Simplified formula [11,19] in chapter 4.1, FIRST [16] in chapter 4.3 and Argos [17] in chapter 4.4. Given the comparisons made up to now, this model seems particularly well appropriate to evaluate the localised effects of a fire on structure elements .

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