PART 5-1: Compartment fire

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1 TASK

The gas temperature of a fully engulfed fire in an office has to be determined. The room of the “Simulated Office” test of the Cardington building is chosen for this analysis. The measured temperatures during the fully engulfed fire are shown in Figure 3, so the calculation can be compared with these results.

A natural fire model is chosen for the calculation of the gas temperature. For fires with a flash-over, the method of the compartment fires can be used. A simple calculation method for a parametric temperature-time curve is given in Annex A of EN 1991-1-2.

Figure 1. Cardington building (left) and the office of the “Simulated Office” test (right)

Floor area: $A_f = 135$ m²
Total area of enclosures $A_t = 474$ m²
Total area of vertical openings: $A_v = 27$ m²
Vertical opening factor: $\alpha_v = 0.2$
Horizontal opening factor: $\alpha_h = 0.0$
Height: $H = 4.0$ m
Average window height: $h_{eq} = 1.8$ m (assumption)
Lightweight concrete: $\rho = 1900$ kg/m²
$c = 840$ J/kgK
$\lambda = 1.0$ W/mK
Fire growth rate medium

2 DETERMINATION OF FIRE LOAD DENSITY

EN 1991-1-2

For the determination of the fire load density the Annex E of EN 1991-1-2 offers a calculation model. The design value of the load density may either be given from a national fire load classification of occupancies and/or specific for an individual project by performing a fire load evaluation.

At this example, the second method is chosen.

Annex E.1

$$q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n$$

where:

m the combustion factor

δ_{q1} the factor considering the danger of fire activation by size of the compartment

δ_{q2} the factor considering the fire activation risk due to the type of occupancy

δ_n the factor considering the different active fire fighting measures

The fire load consisted of 20 % plastics, 11 % paper and 69 % wood, so it consisted mainly of cellulosic material. Therefore the combustion factor is:

$$m = 0.8$$

The factor δ_{q1} considers the danger of fire activation by size of the compartment, as given in Table 1.

Table 1. Fire activation risk due to the size of the compartment (see EN 1991-1-2, Table E.1)

	Compartment floor area A_f [m²]				
	≤ 25	≤ 250	≤ 2500	≤ 5000	≤ 10,000
Danger of fire activation δ_{q1}	1.10	1.50	1.90	2.00	2.13

$$\delta_{q1} = 1.5$$

A factor δ_{q2} considers the fire activation risk due to the type of occupancy, as given in Table 2.

Table 2. Fire activation risk due to the type of occupancy (see EN 1991-1-2, Table E.1)

Danger of fire activation δ_{q2}	Examples of occupancies
0.78	artgallery, museum, swimming pool
1.00	offices, residence, hotel, paper industry
1.22	manufactory for machinery & engines
1.44	chemical laboratory, painting workshop
1.66	manufactory for fireworks or paints

$$\delta_{q2} = 1.0$$

The factor taking the different active fire fighting measures into account is calculated to:

$$\delta_n = \prod_{i=1}^{10} \delta_{ni}$$

The factors δ_{ni} are given in Table 3.

Table 3. Factors δ_{ni} (see EN 1991-1-2, Table E.2)

δ_{ni} function of active fire fighting measures				
Automatic fire suppression	Automatic water extinguishing system	δ_{n1}		0.61
	Independent water supplies	δ_{n2}	0	1.0
			1	0.87
			2	0.7
Automatic fire detection	Automatic fire detection & alarm	δ_{n3}	By heat or	0.87
		δ_{n4}	by smoke	0.73
	Automatic alarm transmission to fire brigade	δ_{n5}		0.87
Manual fire suppression	Work Fire Brigade	δ_{n6}		0.61
	Off Site Fire Brigade	δ_{n7}		0.78
	Safe access routes	δ_{n8}		0.9 or 1.0 or 1.5
	Fire fighting devices	δ_{n9}		1.0 or 1.5
	Smoke exhaust system	δ_{n10}		1.0 or 1.5

$$\delta_n = 1.0 \cdot 0.73 \cdot 0.87 \cdot 0.78 \cdot 1.0 \cdot 1.0 \cdot 1.0 = 0.50$$

For calculating the characteristic fire load, the characteristic fire load has to be determined. It is defined as:

$$Q_{fi,k} = \sum M_{k,i} \cdot H_{ui} \cdot \psi_i$$

Annex E.2

where:

$M_{k,i}$ the amount of combustible material [kg]
H_{ui} the net calorific value [MJ/kg], see EN 1991-1-2, Table E.3
ψ_i the optional factor for assessing protected fire loads

The total fire loading was equivalent to 46 kg wood/m², so the characteristic fire load is:

$$Q_{fi,k} = (135 \cdot 46) \cdot 17.5 \cdot 1.0 = 108{,}675 \text{ MJ}$$

The characteristic fire load density is determined to:

$$q_{f,k} = Q_{fi,k} / A_f = 108{,}675/135 = 805 \text{ MJ/m}^2$$

The design value of the fire load density is calculated to:

$$\begin{aligned} q_{f,d} &= 805 \cdot 0.8 \cdot 1.5 \cdot 1.0 \cdot 0.5 \\ &= 483.0 \text{ MJ/m}^2 \end{aligned}$$

3 CALCULATION OF THE PARAMETRIC TEMPERATURE-TIME CURVE

Annex A

It has to be determined if the fully engulfed fire is fuel or ventilation controlled. For this, the opening factor and the design value of the fire load density related to the total surface are needed.

$$O = \sqrt{h_{eq}} \cdot A_v / A_t = \sqrt{1.8} \cdot 27/474 = 0.076 \text{ m}^{1/2} \begin{cases} \geq 0.02 \\ \leq 0.2 \end{cases}$$

and

$$q_{t,d} = q_{f,d} \cdot A_f / A_t = 483.0 \cdot 135/474 = 137.6\,\mathrm{MJ/m^2}$$

The determination, if the fire is fuel or ventilation controlled is:

$$0.2 \cdot 10^{-3} \cdot q_{t,d} / O = 0.2 \cdot 10^{-3} \cdot 137.6/0.076 = 0.362\ \mathrm{h} > t_{\mathrm{lim}} = 0.333\ \mathrm{h}$$

$\Rightarrow$ The fire is ventilation controlled

For calculation of the temperature-time curves for the heating and the cooling phase, the *b* factor is needed. This factor considers the thermal absorptivity for the boundary of enclosure. The density, the specific heat and the thermal conductivity of the boundary may be taken at ambient temperature. The floor, the slab and the walls are made of lightweight concrete

$$b = \sqrt{\rho \cdot c \cdot \lambda} = \sqrt{1900 \cdot 840 \cdot 1.0} = 1263.3 \frac{\mathrm{J}}{\mathrm{m^2 s^{1/2} K}} \quad \begin{cases} \geq 100 \\ \leq 2200 \end{cases}$$

The temperature-time curve in the heating phase is given by:

$$\theta_g = 20 + 1325 \cdot \left(1 - 0.324 \cdot \mathrm{e}^{-0.2 \cdot t^*} - 0.204 \cdot \mathrm{e}^{-1.7 \cdot t^*} - 0.472 \cdot \mathrm{e}^{-19 \cdot t^*}\right)$$

Because the fire is ventilation controlled, the time *t** is calculated to:

$$t^* = t \cdot \Gamma$$

where:

$$\Gamma = \frac{(O/b)^2}{(0.04/1160)^2} = \frac{(0.076/1263.3)^2}{(0.04/1160)^2} = 3.04$$

Now the heating phase can be calculated:

$$\theta_g = 20 + 1325 \cdot \left(1 - 0.324 \cdot \mathrm{e}^{-0.2 \cdot (3.04 \cdot t)} - 0.204 \cdot \mathrm{e}^{-1.7 \cdot (3.04 \cdot t)} - 0.472 \cdot \mathrm{e}^{-19 \cdot (3.04 \cdot t)}\right)$$

For calculation of the cooling phase, the maximum temperature is needed.

$$\theta_{\mathrm{max}} = 20 + 1325 \cdot \left(1 - 0.324 \cdot e^{-0.2 \cdot t^*_{\mathrm{max}}} - 0.204 \cdot e^{-1.7 \cdot t^*_{\mathrm{max}}} - 0.427 \cdot e^{-19 \cdot t^*_{\mathrm{max}}}\right)$$

where:

$$t^*_{\mathrm{max}} = t_{\mathrm{max}} \cdot \Gamma$$

The time t_{max} is determined as below, where t_{lim} is given in Table 4.

$$t_{\mathrm{max}} = \max \begin{cases} 0.2 \cdot 10^{-3} \cdot q_{t,d} / O = 0.2 \cdot 10^{-3} \cdot 137.6/0.076 = 0.363\ \mathrm{h} \\ t_{\mathrm{lim}} = 0.333\ \mathrm{h} \end{cases}$$

Table 4. Time t_{lim} for different fire growth rates

	Slow fire growth rate	Medium fire growth rate	Fast fire growth rate
t_{lim} [h]	0.417	0.333	0.250

So t^*_{max} is calculated to:

$$t^*_{\mathrm{max}} = 0.363 \cdot 3.04 = 1.10\ \mathrm{h}$$

The maximum temperature is calculated to:

$$\theta_{\max} = 20 + 1325 \cdot \left(1 - 0.324 \cdot e^{-0.2 \cdot 1.10} - 0.204 \cdot e^{-1.7 \cdot 1.10} - 0.427 \cdot e^{-19 \cdot 1.10}\right)$$
$$= 958.8\ °\mathrm{C}$$

During the cooling phase, t^* and $t^*_{\max}$ are calculated to:

$$t^* = t \cdot \Gamma = t \cdot 3.04 \quad [\mathrm{h}]$$

$$t^*_{\max} = \left(0.2 \cdot 10^{-3} \cdot q_{t,d} / O\right) \cdot \Gamma = 1.10\mathrm{h}$$

The temperature-time curve in the cooling phase for $0.5 \le t^*_{\max} \le 2.0$ is given by:

$$\theta_g = \theta_{\max} - 250 \cdot \left(3 - t^*_{\max}\right) \cdot \left(t^* - t^*_{\max} \cdot x\right)$$
$$= 958.8 - 250 \cdot (3 - 1.10) \cdot (t \cdot 3.04 - 1.10 \cdot 1.0)$$

where:

$t_{\max} > t_{\lim} \qquad x = 1.0$

Combination of the heating and cooling curves leads to the parametric temperature-time curve shown in Figure 2.

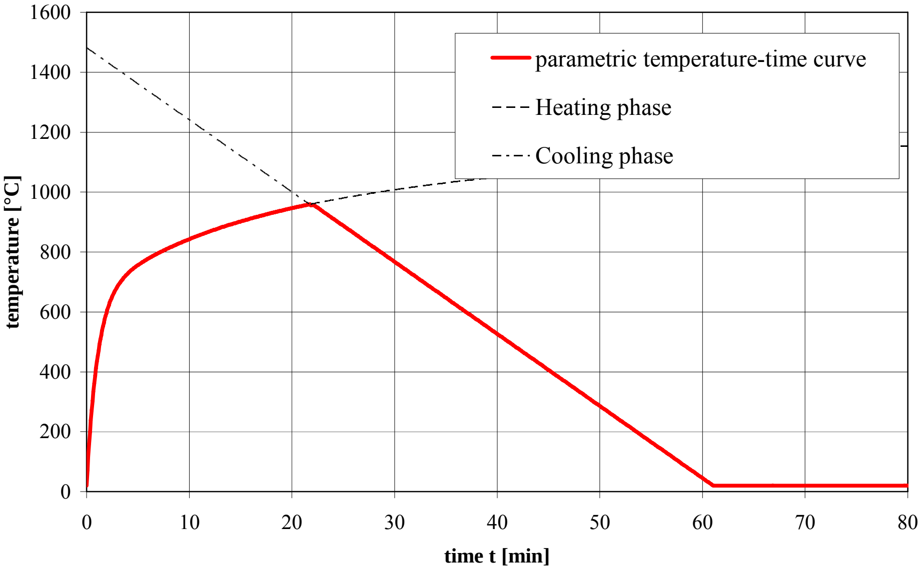

Figure 2. Gas temperature of the office calculated by using the parametric temperature-time curve of the office

4 COMPARISON BETWEEN CALCULATION AND FIRE TEST

To compare the calculation with the measured temperatures in the test, the factors δ_1, δ_2 and δ_{ni} for calculation of the fire load density have to be set to 1.0 (see Figure 3).

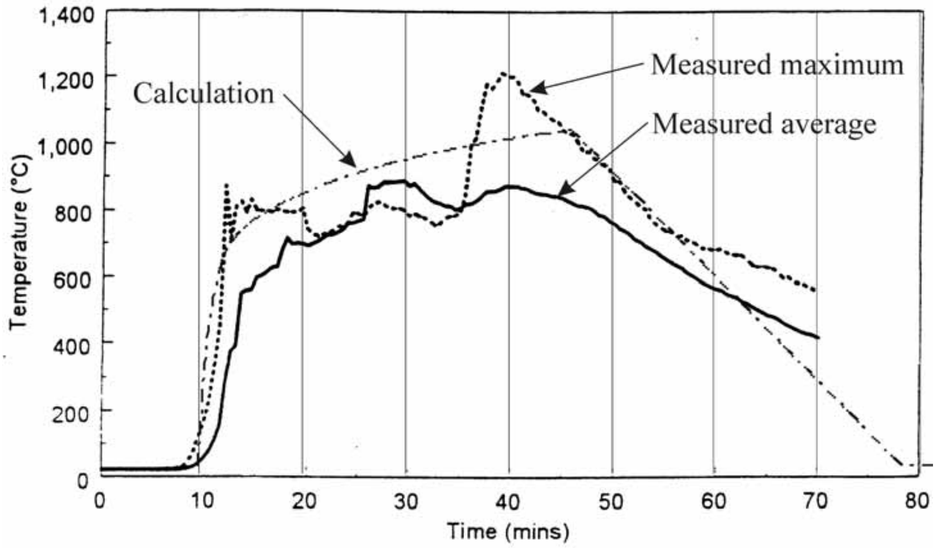

Figure 3. Comparison of measured and calculated temperature-time curves

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QUALITY RECORD	WP5		DIFISEK
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