MS Excel Workbook for Calculation of the Temperature of Protected Steel Elements in a Fire Exposure according to Nominal Curves

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Abstract **– This article presents a procedure for evaluation of the temperature of the steel element in a fire situation. The gas temperature in the fire compartment is given by the three nominal curves: ISO834, Hydrocarbon and Outer curve. The simple calculation model described in 4.2 of EN 1993-1-2 [1] is used. The proposed solution is based on the tables containing data for the temperature of the steel elements which are calculated with the VBA macros in MS Excel [2],[3].**

Keywords **– *F*ire situation, Protected steel elements, Nominal curves.**

1. Introduction

According the system of Eurocodes [1],[4] the fire situation is an integral part of the structural design. The detailed information is given in [5] and [6] for a fire design of buildings.

Data in a tabular form is presented in [2] for the temperature of the steel element exposed to fire expressed by the ISO 834 nominal curve. The number of tables is 9. Each of them has 9 columns and 7 rows. They use parameters k_l , F and time t which are described below. The number of tables must be triple of all the nominal curves to be covered. The large amount of the numbers (1701) makes it difficult for their direct utilization. In this study the time periods are reduced from 7 to 5 – 30, 60, 90, 120 and 180 minutes. In general case the temperature of the element is extracted from the tables with interpolation. An interpolation procedure is proposed for this purpose.

The range that is covered is from 300 to 800 ^{0}C. This covers the needs of the design for the fire situation.

2. Calculation of the temperature of a steel element in fire

According to the section 4.2.5.2 of [1] the temperature of a steel element increases during a time interval Dt (which is recommended to be 20 seconds) by the following value :

$$\Delta\theta_{a,t}=\frac{\lambda_p/d_p}{c_a\rho_a}\frac{A_p}{V}\frac{1}{1+\frac{\phi}{3}}\left(\theta_{g,t}-\theta_{a,t}\right)\Delta t-\left(e^{\phi/10}-1\right)\Delta\theta_{g,t}$$

$$(\text{but } \Delta\theta_{a,t}\geq 0,\ \text{if } \Delta\theta_{g,t}>0) \qquad (1)$$

where:

c_a	is the temperature dependant specific heat of steel, [J/kgK];
c_p	is the temperature independant specific heat of the fire protection material, [J/kgK];
ρ_a , ρ_p	is the unit mass of the steel and protection material, [kg/m^3];
A_p/V	is the section factor , [m^{-1}];
d_p	is the thickness of the fire protection material, [m];
Δt	is the time interval , [sec];
λ_p	is the thermal conductivity of the fire protection system , [W/mK];
$\theta_{a,t}$,$\theta_{g,t}$	is the steel and the ambient temperature at time , [^{0}C];
$\Delta\theta_{g,t}$	is the increase of the ambient temperature during the time interval Dt , [K];

$\Delta\theta_{a,t}$ is the increase of the steel element temperature during the time interval Dt, [K];

The section factor Ap/V is evaluated according to the recommendations given in Table 4.3 from [1]. In equation (1) **F** is :

$$\phi = \frac{c_p \rho_p}{c_a \rho_a} d_p \frac{A_p}{V} \quad (2)$$

The number of independent variables in (1) can be reduced from 7 to 2 (k_λ and **F**) as given bellow:

$$\Delta\theta_{a,t} = \frac{k_\lambda}{10000} \frac{\phi}{1+\frac{\phi}{3}} \left(\theta_{g,t} - \theta_{a,t}\right) \Delta t - \left(e^{f/10} - 1\right) \Delta\theta_{g,t}$$

$$(\text{but } \Delta\theta_{a,t} \geq 0, \text{ if } \Delta\theta_{g,t} > 0) \quad (3)$$

where:

$$k_\lambda = \frac{\lambda_p .10000}{d_p^2 c_p \rho_p} \quad (4)$$

If we introduce the parameter k_m :

$$k_m = \frac{k_\lambda \phi}{1+\frac{\phi}{3}} \quad (5)$$

the equation (3) can be written as:

$$\Delta\theta_{a.t} = \frac{k_m}{10000} \left(\theta_{g,t} - \theta_{a,t}\right) \Delta t - \left(e^{\phi/10} - 1\right) \Delta\theta_{g,t} \quad (6)$$

$$(\text{but } \Delta\theta_{a,t} \geq 0, \text{ if } \Delta\theta_{g,t} > 0)$$

The temperature of the element $\mathbf{Q}_{a,t}$ can be calculated with a VBA macros on MS Excel as a sum of increasing given by equation(6). Another approach to calculate the temperature of the element is to find out an appropriate approximation relationship – see the next equations (7), (8) and (9).

$$\theta_1 = \theta_{km} . k_1 \quad (7)$$

where

$$\theta_{km} = (a k_m^2 + b k_m + c) \quad (8)$$

$$k_1 = d(\phi / k_m)^2 + e.\phi / k_m + f \quad (9)$$

The coefficients of equations (8) and (9) are determined for each of the three nominal curves for the time t = 30, 60, 90, 120 and 180 min.

The coefficients of equation (8) are obtained by regression analysis from 81 values of the temperature of the steel elements - see Figure 1.

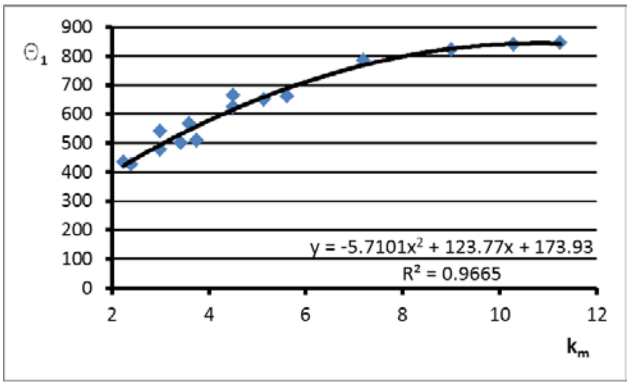

Fig.1 Interpolation relationship between k_m and $\mathbf{Q}_1$ for t= 60 minutes and nominal curve ISO 834

It can be seen from Fig.1 that the calculationed with VBA macros values differs from the trend line in some cases up to 5 percents. The relative error k_1 is defined as function of the ratio F/k_m by regression analysis.

The function insert trendline of MS Excel is used for a regression analisys.

3. Description of the MS Excel Workbook for the computation of temperature of the steel elements.

The proposed workbook consists of two worksheets. The first one (see Table 1) describes input data and export of the results. The calculations are realized on the second sheet. This worksheet can be hidden from the user to avoid an intentional damage. On the first worksheet the input data comprises the properties of the steel section and the fire protection. The results are presented in a tabular and a graphical form. The temperature is calculated for three nominal curves – ISO834,Hydrocarbon (HC) and Outer curve. The table consists of 15 cells. In each of them are given values of the temperature of the steel element as a function of time and type of the nominal curves.

The relation time vs. temperature of the steel elements exposed to fire are presented in the graphic (for t = 30, 60, 90, 120, 180 min).

The worksheet for the calculations of the temperature of the steel element according to equation(7) is given in Table 2.

The parameters k_m and F/k_m are calculated at the beginning of this worksheet. These cells are named as km and fikm for convenience. In the further expressions these names are used instead of their absolute addresses.

The user inputs only the ones the coefficients of the polynoms Q_{km} and k_1 into region of cells bordered by bold line. In the column at the right of this region temperature $\mathbf{Q}_1$ is calculated according to the equation(7).

In the next column $\mathbf{Q}_a$ is calculated.

When $\mathbf{Q}_1<300\ ^0C$ "<300" for the all nominal curves is displayed.
For the ISO834 and HC curves ">800" is displayed when $\mathbf{Q}_1>800\ ^0C$ or $k_m > -b/2a$.

When $k_m = -b/2a$ the polynomial curve k_m reaches its maximum. The descending part of this polynomial curve is not a solution of the problem.
These conditions are realized with a logical function if().

$Q_{a,i}$ = *IF(OR((*$Q_{1,i}$ *>800);(km>-b*$_i$*/(2a*$_i$*)));">800";IF(*$Q_{1,i}$ *<300;"<300";* $Q_{1,i}$*))*

For the outer nominal curve the upper limit of the gas temperature is 680 ^0C. In this case the logical function is:

$Q_{a,i}$ = *IF(OR((*$Q_{1,i}$ *>679);(km>-b*$_i$*/(2a*$_i$*)));"=679";IF(*$Q_{1,i}$ *<300;"<300";* $Q_{1,i}$*))*

Table 1. Excel worksheet with input data and results .Interpolation relationship between k_m and Q_1 for t = 60 min . for the nominal curves.

Input data:

A section factor	A_p/V=	300	m^{-1}
A thermal conductivity	λ_p =	0.2	W/mK
Atemperature independent specific heat	C_p =	1700	J/kgK
A unit mass of the fire protection material	ρ_p =	800	kg/m3
A thickness of fire protection	d_p =	0.02	m

Results

Temperature $\Theta_{a,t}$ =

Time, min	Nominal curves		
	ISO 834	HC	Outer curve
30	305.8	501.7	314.5
60	595.0	>800	492.7
90	>800	>800	574.6
120	>800	>800	640.0
180	>800	>800	>679

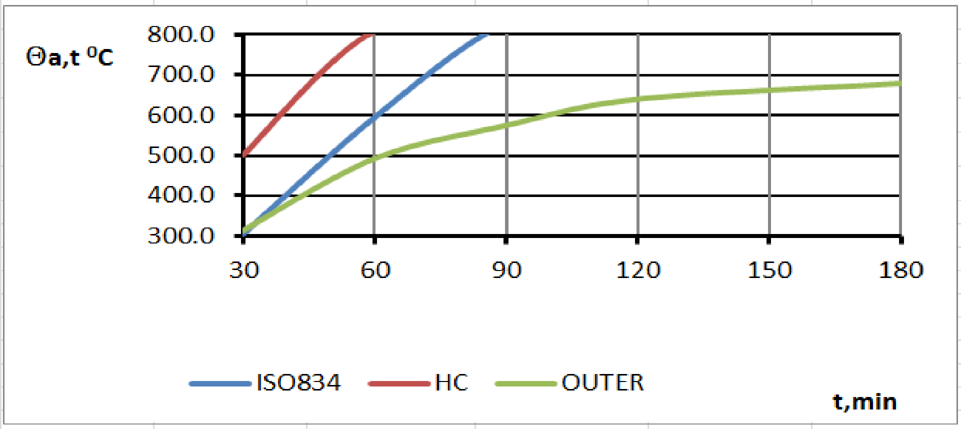

Table 2. Worksheet for the calculation of the temperature of the steel element.

k_{ι}=	3.6765	F=	1.7325

k_m	4.0377
F/k_m=	0.4291

	min.	a	b	c	d	e	f	Q_1	Qa	ISO834	HC	Outer
ISO 834	30	-3.2792	89.709	-9.7403	0	-0.3138	1.1575	305.85	305.8	305.8		
	60	-5.7101	123.72	173.93	0	-0.1204	1.0769	595.03	595.0	595.0		
	90	-21.916	252.54	111.29	-0.019	-0.0489	1.0985	830.94	>800	830.9		
	120	-40.916	348.96	134.65	0	-0.0617	1.0692	914.04	>800	914.0		
	180	-195.1	796.13	12.293	0	-0.0429	1.0982	49.80	>800	810.0		
HC	30	-4.806	122.8	77.013	0	-0.154	1.0807	501.72	501.7		501.7	
	60	-30.161	310.55	31.163	0	-0.05	1.041	808.86	>800		808.9	
	90	-65.765	468.44	31.771	-0.0024	-0.0325	1.0338	867.54	>800		810.0	
	120	-135.14	659.08	23.903	-0.0013	-0.0207	1.04	496.77	>800		810.0	
	180	-235.81	884.63	65.498	0	-0.008	1.0174	-209.9	>800		810.0	
Outer	30	-1.7131	58.939	100.2	0	-0.1225	1.0664	314.54	314.5			314.5
	60	-6.3406	111.82	144.57	0	0	1	492.69	492.7			492.7
	90	-9.2364	133.54	197.75	0	0	0.98	574.64	574.6			574.6
	120	-15.861	170.95	218.05	0	0	0.985	639.97	640.0			640.0
	180	-28.124	228.23	235.4	0	-0.0146	1	694.04	>679			679.0

The values in the last 3 columns are used for the graphical representation of the results. The values are calculated according the following expressions:

- for the curve ISO834 :

$Q_{I,i}$=if(km>-b_i/2/a_i;810;$Q_{1,i}$)

- for the Hydrocarbon curve (HC) :

$Q_{H,i}$=if(km>-b_{i+5}/2/a_{i+5};810;$Q_{1,i+5}$)

- for the Outer curve :

$Q_{O,i}$=if(km>-b_{i+10}/2/a_{i+10};679;$Q_{1,i+10}$)

4. A numerical example

A steel element with a section factor 300 m^{-1} is protected by 20 mm gypsum board with the following properties:

c_p=1700 J/kgK; ρ_p=800 kg/m^3; λ_p=0.2 W/mK;

d_p= 0.02 m .

k_{ι} = 3.676 ; Ø= 3.745

The following results are obtained (table 3):

Table 3. The results.

curve	t,[min]	MS Excel Worksheet	VBA macros	Error,%
ISO 834	30	306.8	323.2	5.35
	60	595	614.3	3.24
	90	>800	799.9	-
	120	>800	951.1	-
	180	>800	1204	-
HC	30	501.7	500.2	-0.30
	60	>800	826.6	-
	90	>800	1014.7	-
	120	>800	1142	-
	180	>800	1319.6	-
Outer	30	314.5	297.6	-5.37
	60	492.7	468.8	-4.85
	90	574.6	580.7	1.06
	120	640	636.4	-0.56
	180	>679	670.1	-

5. Conclusions

The use of interpolation relationships provides a convenient way to calculate the temperature of protected steel element in fire. The obtained accuracy is about 3 -5 %. This level of accuracy is for a range of temperature from 300 to 800 ^{0}C, which represents a practical interest / see section 4.2.5 of [1].

The proposed solution is easy for implementation.

It is described in details in this article. This MS Excel Workbook is especially useful for the early stages of the structural design.

References

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