BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 66 (70), Numărul 1, 2020
Secţia
CONSTRUCŢII DE MAŞINI

BENCHMARK ANALYSIS BETWEEN DIFFERENT FIRE MODELS

BY

ZENO-COSMIN GRIGORAŞ*

"Gheorghe Asachi" Tehnical University of Iaşi,
Faculty of Civil Engineering and Building Services

Received: January 22, 2020
Accepted for publication: March 16, 2020

Abstract. The purpose of this paper is to analyze, for the same input data, the temperature-time curve calculated for different fire models and to compare the obtained results.

The case study takes into account the same input data for all fire models: an enclosed space (an office type room), with openings for ventilations (one window) - ventilation controlled fire, the same thermal properties for the enclosure elements (walls, ceiling and floor) and the same fire load density.

Different fire models are used: standard temperature-time curve, parametric temperature-time curve, zone model (OZone software is used) and CFD model (FDS software is used).

The standard temperature-time curve (the most used fire model) uses a simple equation to describe the temperature-time variation. This fire model does not consider any particularities of the analyzed space and has the tendency to generate higher temperature compared to the other fire models specified above, which considers the particularities of the analyzed space.

Keywords: standard temperature-time curve; parametric temperature-time curve; zone fire model; CFD fire model.

*Corresponding author; *e-mail*: zeno.grigoras@gmail.com

1. Introduction

This case study analyzes the temperature-time curves for different fire models defined by EN 1991-1-2 Eurocode 1: Actions on structures. Part 1-2: General actions – Actions on structures exposed to fire (EC 1-1-2) as following: nominal temperature-time curve and natural fire models.

Nominal temperature-time curves are the most basic fire models, developed in the mid ‘70s. These models do not take into account any particularities of the analyzed space (like the geometry of the room or the type and quantity of combustible materials) and they generate the same results for any type of space.

From this category of fire models, the standard temperature-time curve (also named “standard fire” or “ISO 834 standard fire”) is used.

Natural fire models consider the geometry of the analyzed space, the thermal proprieties of the enclosure elements, different ventilation condition, the type and quantity of the combustible materials. This category of fire models may by divided in: simplified fire models and advanced fire models.

From the category of simplified fire models, the parametric temperature-time curve is used for this case study. It is a two-stage fire model: only growth (or heating) phase and the decay (or cooling) phase is modelled. The variation of temperature has an exponential definition for the growth stage and a linear decrease for the decay stage (both detailed in chapter 3). This fire model assumes the uniform distribution of temperature in the analyzed space and it is intended for hand calculation.

From the category of advanced fire models, the zone fire model and the CFD (Computational Fluid Dynamics) fire model are used for this case study. Both fire models are a three-stage fire models: growth phase, fully developed phase and decay phase are modelled.

These fire models use, as main input data, the Rate of Heat Release to describe the fire development.

Zone models assume a uniform temperature distribution inside each layer. CFD models can compute different temperatures in each point of the computational domain.

Both fires models are intended for computer software.

The standard temperature-time curve and the parametric temperature-time curve use the effects of the fire to compute the temperatures.

Zone models and CFD models use the causes of the fire to compute the temperatures.

2. The Analyzed Space

The analyzed space for this case study is represented by a typical office room with a floor area of 6 m x 6 m and a floor to ceiling height of 3.4 m. There is a single window opening in the front elevation 3.6 m wide x 2 m high. The walls are made of brick masonry - 20 cm thickness and the ceiling and roof are made of reinforced concreate - 20 cm thickness. The thermal proprieties of the enclosing elements are presented in Table 1.

No information about the thermal properties of commonly used construction materials is provided in the Eurocode. Common values from literature are used (www.materconstrucc.revistas.csic.es; www.infrared-thermography.com).

For simplification purpose, the construction elements are one single layer (no plaster is modelled). Parametric, zone and CFD fire models can model construction elements made of different layers of materials.

Table 1
Thermal Proprieties of the Enclosing Elements

Thermal property	Material	
	Concreate	Brick
Density [kg/m^3]	2500	2000
Specific heat [kJ/(kg·K)]	0.75	0.90
Thermal conductivity [W/(m·K)]	1.70	1.00
Emissivity [-]	0.95	0.94

3. Research Methods

For this case study the research methods are the fire models defined by the European Legislation (EC1-1-2):
– standard temperature-time curve;
– parametric temperature-time curve;
– zone fire model using OZone software;
– CFD fire model using FDS software.

3.1. Standard Temperature-Time Curve

From the category of nominal temperature-time curves, the standard temperature-time curve (also named “standard fire” or “ISO 834 standard fire”) is used. It is a one-stage fire model: only the heating phase is modelled. The variation of temperature has a logarithmic definition. This fire model assumes the uniform distribution of temperature in the analyzed space, being conceived for hand calculation.

The standard temperature-time curve is given by Eq. (1) (EC1-1-2):

$$\Theta_g = 20 + 345 \cdot \log_{10}(8 \cdot t + 1) \tag{1}$$

where: Θ_g is the gas temperature in the fire compartment [°C]; t is the time [min].

For the current case study, the standard temperature-time curve is represented in Fig. 1

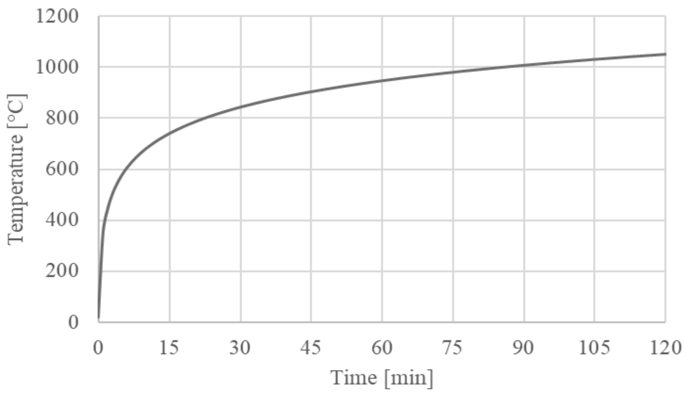

Fig. 1 – Standard temperature-time curve.

3.2. Parametric Temperature-Time Curve

From the category of simplified fire models, the parametric temperature-time curve is used for this case study. It is a two-stage fire model: only growth (or heating) phase and the decay (or cooling) phase. The variation of temperature has an exponential definition for the growth stage and a linear decrease for the decay stage. This fire model assumes the uniform distribution of temperature in the analyzed space. This fire model is intended for hand calculation.

This fire model is valid for fire compartments up to 500 m^2 of floor area, without openings in the roof and for a maximum compartment height of 4 m. It is assumed that the fire load of the compartment is completely burnt out (EC1-1-2).

It is a two-stage fire model: only growth (or heating) phase and the decay (or cooling) phase is modelled, each stage with its own equation.

The temperature-time curve in the heating phase is given by Eq. (2) (EC1-1-2):

$$\Theta_g = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.240e^{-1.7t^*} - 0.472e^{19t^*}) \qquad (2)$$

where: Θ_g is the gas temperature in the fire compartment [°C]

$$t^* = t \cdot \Gamma \qquad (3)$$

t is the time [h]

$$\Gamma = [O / b^2] / (0.04 / 1160)^2 \tag{4}$$

O is a factor taking into account openings into walls (windows or doors); *b* is a factor considers the density, specific heat and thermal conductivity of the boundary of enclosure (wall, roof and ceiling).

The maximum temperature Θ_{max} [°C] in the heating phase happens for $t^* = t^*_{max}$; where this maximum time t^*_{max} [h] is given by Eq. (5) and t_{max} [h] is given by Eq. (6) (EC1-1-2):

$$t^*_{max} = t_{max} \cdot \Gamma \tag{5}$$

$$t_{max} = \max[(0.2 \cdot 10^{-3} \cdot q_{t,d} / O);\ t_{lim}] \tag{6}$$

where $q_{t,d}$ is the design value of the fire load density related to the total surface area of the enclosure [MJ/m^2]; t_{lim} is the time limit on the fire growth rate [min].

For the cooling phase, three different definitions are given by Eq. (7) considering different values for t^*_{max} (EC1-1-2):

$$\begin{aligned} \Theta_g &= \Theta_{max} - 625 \cdot (t^* - t^*_{max} \cdot x) && \text{for} \quad t^*_{max} \le 0.5 \\ \Theta_g &= \Theta_{max} - 250 \cdot (3 - t^*_{max}) \cdot (t^* - t^*_{max} \cdot x) && \text{for } 0.5 < t^*_{max} < 2 \\ \Theta_g &= \Theta_{max} - 250 \cdot (t^* - t^*_{max} \cdot x) && \text{for} \quad t^*_{max} \ge 0.5 \end{aligned} \tag{7}$$

where: *x* is a factor regarding t_{max} and t_{lim} [-].

For calculating the parametric temperature-time curve it is necessary to:
– use Eq. (2) for the heating phase (exponential growth);
– use Eq. (5) to calculate the time where the maximum temperature occurs;
– use Eq. (7) for the cooling phase (linear decrease).

For the current case study, the parametric temperature-time curve is represented in Fig. 2. The maximum temperature of 846°C is achieved at the 1227 s or 20.46 min.

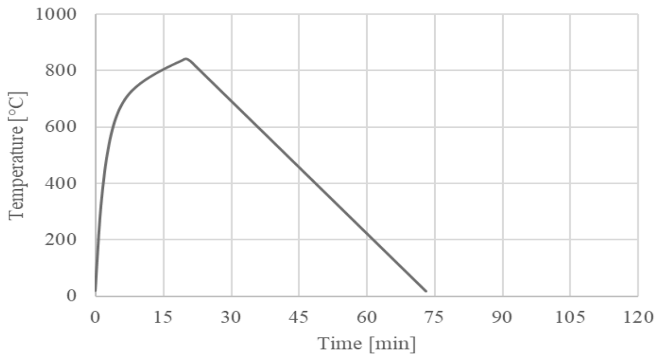

Fig. 2 – Parametric temperature-time curve.

3.3. Zone Fire Model – OZone Software (Version 3.0.4)

From the category of advanced fire models, the zone fire model is used for this case study, being a three-stage fire model: growth phase, fully developed phase and decay phase. This fire model uses, as input data, the Rate of Heat Release to describe the fire development.

The zone fire model may be defined as (EC1-1-2):

– two zone model (intended for pre-flashover conditions): assumes the existence two layers (a hotter upper layer and a cooler lower layer). In each layer the temperatures are uniform.

– one zone model (intended for post-flashover conditions): assumes the existence of one layer with an uniform temperature distribution. This type of model is suitable for post-flashover fires.

Zone fire models are intended for computer software. For this case-study, the Ozone software is used (it has been implemented a combination between the two zone model and one zone model, but it offers the possibility to use for analysis only a two zone model or only an one zone model).

Two zone models (Fig. 3) are normally based on eleven physical variables (for upper and lower layer: mass of the gas, temperature of the gas, volume, internal energy, gas densities; and finally, the absolute pressure in the compartment considered as a whole) linked by seven constraints and four differential equations describing the mass and the energy balances in each zone. The time integration of these differential equations allows to calculate the evolution of the variables describing the gas in each zone (Cadorin *et al.*, 2001).

In the two zone model, 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 (Cadorin *et al.*, 2001).

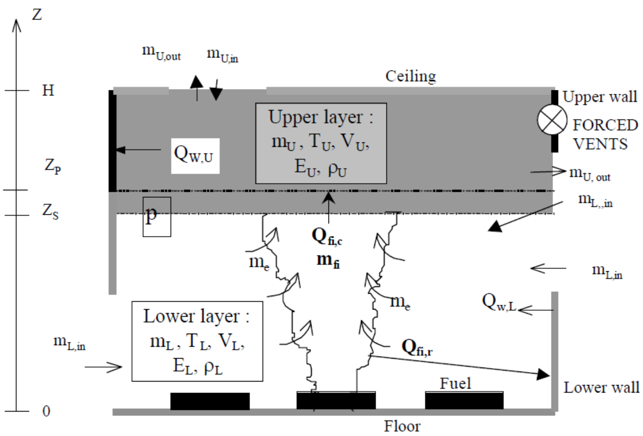

Fig. 3 – Schematic view of two zone model and associated submodels in OZone (Cadorin *et al.*, 2001).

The one zone model (Fig. 4) uses a reduced number of variables – six (mass of the gas, temperature of the gas, internal energy, volume of the compartment - constant, pressure in the compartment and gas density) and a reduced number of constraints – four (Cadorin *et al.*, 2001).

In the one zone model, a vertical partition is divided into two parts connected to the single zone (Cadorin *et al.*, 2001).

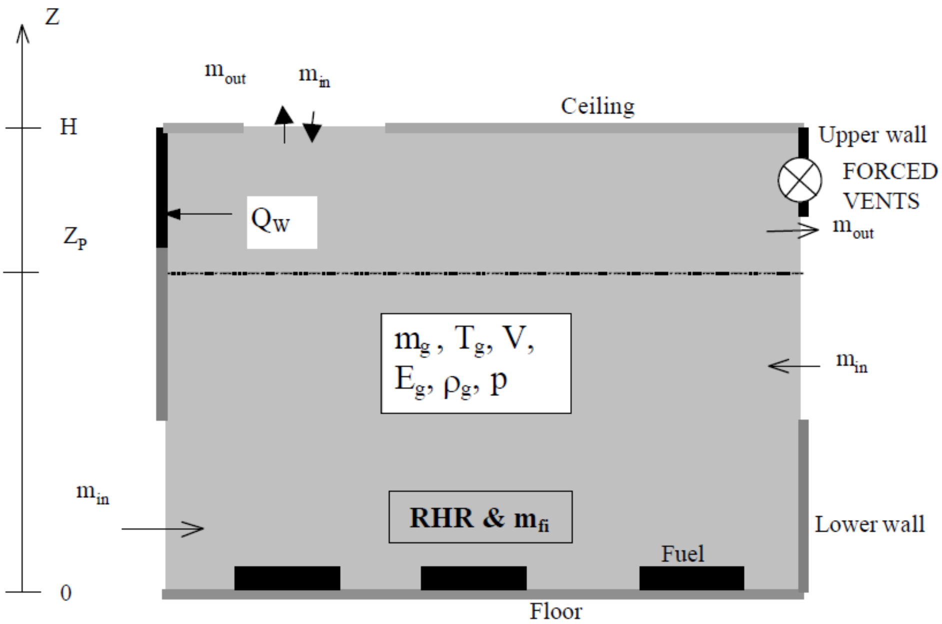

Fig. 4 – Schematic view of one zone model and associated submodels in OZone (Cadorin *et al.*, 2001).

OZone software has the possibility to switch automatically from two zones to one zone model if some criteria are encountered (Cadorin *et al*, 2001). This situation can better approximate the real fires when flashover occurs.

The software uses RHR (Rate of Heat Release) to describe the energy released, as heat, by fire per second.

For this case study, the RHR is modelled using the procedure described in the European Legislation (EC1-1-2) and specific literature (Grigoraş and Diaconu-Şotropa, 2013; Grigoraş & Diaconu-Şotropa, 2014).

The procedure is based on the ideal fire development (Fig. 5), considering a three-stage fire: growth, fully developed and decay (Grigoraş and Diaconu-Şotropa, 2013).

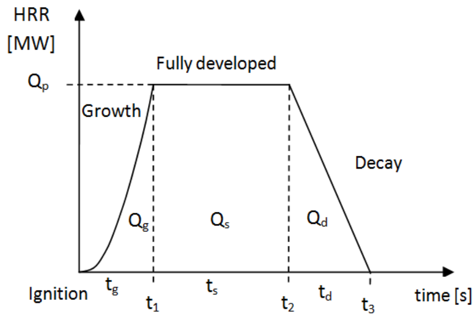

Fig. 5 – Development of an ideal fire model (obtained by simplification) used for calculation (Grigoraş and Diaconu-Şotropa, 2013).

First, the characteristic value for the fire load density is established using the European Legislation (EC1-1-2): 511 MJ/m^2 for an office type space considering the 80% fractile value.

Taking into account different factors (combustion factor, activation risk due to the type and size of compartment and different active firefighting measures) the design fire load density is 482.4 MJ/m^2.

The total energy released by fire as heat is calculated multiplying the floor area of the space with the design fire load density resulting 17370 MJ (Grigoraş and Diaconu-Şotropa, 2013; Grigoraş and Diaconu-Şotropa, 2014). The maximum Heat Release Rate is established at 14.255 MW in accordance to European Legislation (EC1-1-2).

For each fire stage the energy and duration of each stage is calculated (Grigoraş and Diaconu-Şotropa, 2013; Grigoraş and Diaconu-Şotropa, 2014).

The end time for each stage are presented in Table: growth stage – 1133 s or 18.88 min, fully developed stage – 1510 s or 25.16 min and decay stage – 2241 s or 37.35 min.

For this case study the RHR (Rate of Heat Release) variation is shown in Fig. 6.

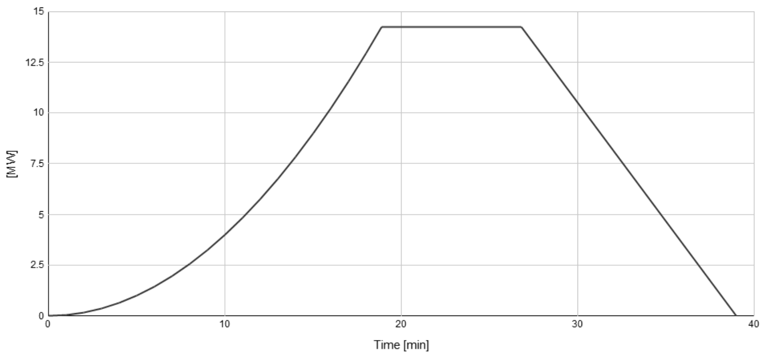

Fig. 6 – Input data for RHR [MW] in Ozone software.

The analysis type selected for calculations was the combination of two zone and one zone model for better results, considering that flashover occurs for the current case study. For the input RHR, the maximum temperature for the hot layer computed by Ozone was 974°C at 26 min. Results are shown in Fig. 7.

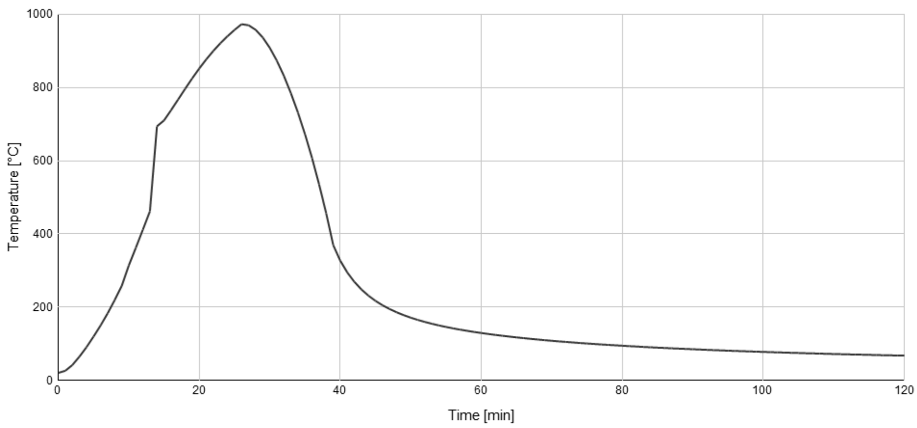

Fig. 7 – Temperature-time curve for the hot layer calculated by Ozone.

3.4. CFD Fire Model – FDS Software (Version 6.7.5)

The CFD (Computational Fluid Dynamics) fire models solve numerically the partial differential equations giving, in all points of the compartment, the thermo-dynamic and aero-dynamic variables, by using the mathematical statements of the conservation laws of physics (conservation of mass, conservation of momentum and conservation of energy).

CFD fire models are intended for computer software. For this case-study, the FDS (Fire Dynamics Simulator) software is used. The software solves numerically a form of the Navier-Stokes equations, appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires.

The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally driven flow, with an emphasis on smoke and heat transport from fires (McGrattan *et al.*, 2020).

FDS uses a three-dimensional rectilinear grid for the computational domain, in which it simulates the flow of hot gasses and smoke in case of fires. The software is based on technique similar to the finite volume method for radiation problems (McGrattan *et al.*, 2020).

The major features of the model are (McGrattan *et al.*, 2020):

– low Mach, large-eddy simulations (LES);
– explicit, second-order, kinetic-energy-conserving numerics;
– structured, uniform, staggered gird;
– simple immersed boundary method for treatment of flow obstructions;

– generalized “lumped species” method (simplified chemistry using a reaction progress variable);

– Deardorff eddy viscosity sub-grid closure;

– constant turbulent Schmid and Prandtl numbers;

– eddy dissipation concept (fast chemistry) for single-step reaction between fuel and oxidizer;

– grey gas radiation with finite volume solution to the radiation transport equation.

Like Ozone, FDS uses RHR (Rate of Heat Release) to describe the energy released, as heat, by fire.

The same RHR-time curve used in chapter 3.3 was inputted for FDS.

FDS can calculate different parameters (like temperature, pressure, velocity, visibility, gas toxicity, etc.) in any point of the computational domain. For monitoring the results, a device that records gas temperature was modelled in the center of the ceiling, at 1 cm underneath. The mesh uses cells with a size of 0.20x0.20x0.20 m, for better describing the geometry of the analyzed space.

For the input data, the maximum gas temperature computed by FDS has two peak values: 882°C at 18 min and 870°C at 30 min. The results are shown in Fig. 8.

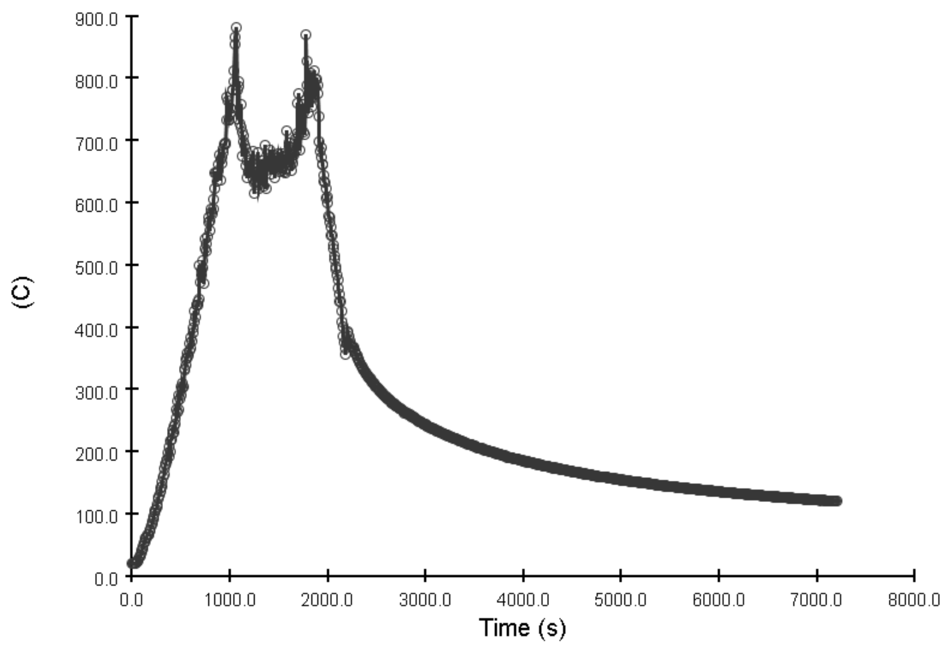

Fig. 7 – Temperature-time curve calculated by FDS.

4. Conclusions

Four different fire models have been used to calculate the temperature-time curve for the analyzed space (an office type room with common geometry and common building materials).

The maximum gas temperatures and the time when they are reached are shown in Table 2. For all models the total time of the analysis was considered of 120 min.

Table 2
Maximum Temperature and the Corresponding Time

Fire model	Maximum temperature [°C]	Corresponding time for maximum temperature [min]
Standard temperature-time curve	1049	120
Parametric temperature-time	846	20.46
Two zone and one zone (Ozone software)	974	26
CFD (FDS software)	882 870	18 30

A comparations between the complexity of each fire model is shown below in Table 3:

Table 3
Comparations Between Used Fire Models

Fire model	Model complexity	Fire stages	Intended for	Analyzed space particularities considered
Standard temperature-time curve	verry low	only growth (heating)	hand calculations	none particularities
Parametric temperature-time	low	growth, decay (heating, cooling)	hand calculations	some particularities
Two zone and one zone (Ozone software)	high	growth, fully developed, decay	computer software	main particularities
CFD (FDS software)	verry high	growth, fully developed, decay	computer software	all

Note: Computer running time for: OZone - 3 s and for FDS – 2 h and 45 min

A comparations between the computed temperatures for each fire models used in this case study is shown in Fig. 8

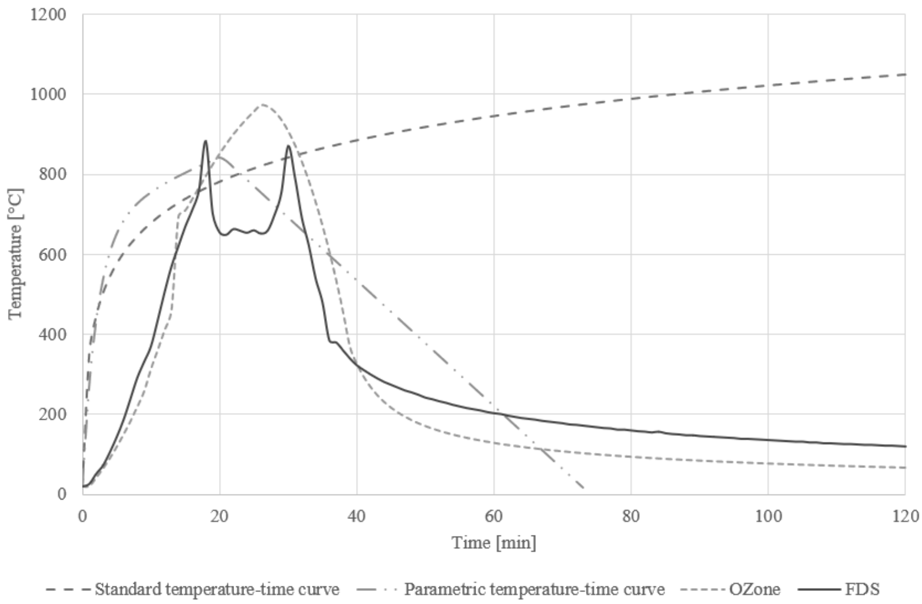

Fig. 8 – Temperature-time curve for the used fire models.

The standard temperature-time curve gives the maximum temperature only at the end of analysis. This fire model is outdated and can generate results that are not corresponding to the real fires. For particular cases, this model must be used with caution. This model is intended to be used only for general situations *e.g.* fire testing for construction products.

The parametric temperature-time curve can generate a maximum temperature close to the average maximum temperature between OZone and FDS. This fire model can be used for quick calculations, when a computer software is not available.

OZone and FDS generate very close results, about 10% differences (which are in engineering acceptable limits).

OZone estimates a maximum temperature higher than that from FDS, but for the decay stage, the temperatures are lower than those from FDS.

Due to the advanced user knowledge and increased simulation time required by FDS, it is recommended to use OZone for common situations, were only the maximum temperature is analyzed, like design projects.

FDS may be used when the temperature needs to be monitored in different points of the computational domain or, when different parameters are necessary to be analyzed. An FDS analysis is suitable for particular situations, like research projects.

REFERENCES

Cardorin J.F., Pintea D., Franssen J.M., *The Design Fire Tool Ozone V2.0 – Theoretical Description and Validation on Experimental Fire Tests*, University of Liege, Belgium, 2001.

Grigoraş Z.-C., Diaconu-Şotropa D., *Establishing the Design Fire Parameters for Buildings*, Bul. Inst. Polit. Iaşi, **LIX(LXIII)**, 5, s. Constructions. Arhitecture, 133-141 (2013).

Grigoraş Z.-C., Diaconu-Şotropa D., *Establishing the Design Fire According to SR EN 1991-1-2 Annex E* (transl. from Romanian), AICPS Review, 1-2/2014, 150-155 (2014).

McGrattan K., McDermott R., Vanella M., Hostikka S., Floyd J., *Fire Dynamics Simulator – Technical Reference Guide, Volume 1: Mathematical Model*, National Institute of Standards and Technology Special Publication 1018-1 Sixth Edition, United States of America, 2020.

*** www.infrared-thermography.com/material-1.htm.

*** www.materconstrucc.revistas.csic.es/index.php/materconstrucc/article/view/2293/3054.

*** *Eurocode 1: Actions on Structures – Part 1-2: General Actions – Actions on Structures Exposed to Fire.*

ANALIZA COMPARATIVĂ ÎNTRE DIVERSE MODELE DE INCENDIU

(Rezumat)

Scopul lucrării îl reprezintă analiza, pentru aceleaşi date de intrare, a curbei temperatură-timp calculată pentru diverse modele de incendiu şi compararea rezultatelor obţinute.

Acest studiu de caz utilizează aceleaşi date de intrare pentru toate modelele de incendiu: un spaţiu închis (de tip birou), având deschideri pentru ventilare (o fereastră) – incendiu controlat de ventilaţie, aceleaşi proprietăţi termice pentru elementele de închidere (pereţi şi planşee) şi aceaşi densitate de sarcină termică.

Sunt utilizate diverse modele de incendiu: curba standard temperatură-timp, curbă parametrică temperatură timp, modele zonale (programul de calcul OZone) şi modele CFD (programul de calcul FDS).

Curba standard temperatură-timp (cel mai utilizat model de incendiu) utilizează o simplă ecuaţie pentru a descrie variaţia temperaturii în raport cu timpul. Acest model de incendiu nu ia în considerare diversele particularităţi ale spaţiului analizat şi are tendinţa să genereze temperaturi mai mari comparativ cu celelate modele de incendiu precizate anterior care iau în considerare particularităţile spaţiului analizat.