An attempt to predict temperature-time histories for large scale compartment fires: A parametric analysis

ROMAISSA HACHANA[1], ABDALLAH BENAROUS[2], MOHAMED ROUDANE[1], PAULO PILOTO[3]

[1] LPEN, University of Blida1, Faculty of Technology, Department of Mechanics, Blida, Algeria
[2] LISICPE, University of Hassiba Benbouali of Chlef, Chlef, Algeria
[3] Polytechnic institute of Bragança (IPB), Bragança, Portugal
hachana_romaissa@univ-blida.dz

Abstract

The accurate prediction of thermal conditions within compartment fires poses a significant challenge for fire safety engineers. In fact, sprinkler design, exit sceneries, and collapse structure configurations are closely related to the temporal evolution of the temperature inside the compartments. Through a comprehensive review of existing methodologies and standards, this study attempts to contribute for advancing the state of the art in fire dynamics modelling.

The work deals with a comparative analysis of various temperature-time formulations proposed in the literature, providing insights into the discrepancies between theoretical models and real-world standards. It investigates the influence of key factors namely, the opening factor, the fuel load density, and the walls effusivity, on temperature histories. The natural fire curve, such as EPFC leads towards real world planning requirements, allows for a more tailored and pragmatic assessment for large-scale compartment fires, compared to the standard curves. The analysis aims, through a case study, to provide designers and architects with a practical way that facilitates early-stage planning and allows for effective fire prevention implementations.

Keywords: Fire engineering, Temperature-time curves, Compartment fire, Natural ventilation.

1. Introduction

The ability to predict temperatures developed in accidental fires is of great significance for research and engineering purposes. There are multi-domain uses of knowledge on temperature 5.6prediction of pressurized vessels explosions [2], protection of dwellings against wildland fires [3] and thermal characterization of firefighters clothing [4].

The investigations based on various methodologies, including full-scale test campaigns on buildings and numerical experimentations, evidenced the physical coupling between fire dynamics, ventilation and building boundaries heat transfer [5,6] Here, comparison analyses regarding existing formulations and standards, seem mandatory to calibrate the existing models and highlight the temperature-time governing parameters [7]. In the model developed by Lie, an analytical expression for temperature-time curve was derived from an energy balance within a naturally ventilated compartment [8]. The obtained formulation featured many parameters related to fuel load and opening factor. The numerical values of the significant parameters were not explicitly provided, and the author used a calibration approach to fit the proposed formulation with standard curves.

A correlative-analytical formulation for the t-time curve in a ventilated enclosure was derived using a two-layer zone model [9]. The quasi-steady expression for the temperature accounted for heat losses to the walls (enclosure boundaries), whose coefficients were implicitly linked to a "penetration" time, that was defined only for thermal conduction. Blagojevic *et al.* proposed a unified function for t-time evolution based on a "pulse phenomena", and featured three parameters that were related to fuel and fresh air quantities [10]. The so-called "idealized" curve has allowed reproducing the fire development phases, namely the growth (heating), the steady-burning and the decay, without considering the influence of the solid boundaries. The authors stated out clearly that the developed expression succeeded in recovering the global trend on a fire compartment, but the maximum temperature in the beneath of the ceiling was largely overestimated. On a basis of a one-zone model, Wickstrom *et al* derived a simple temperature-time expression applicable to post-flashover ventilation-controlled fires [11]. The parameter termed 'ultimate temperature" was introduced to account for hot gases-material boundaries heat transfers. For semi-infinite thick walls, the authors provided a t-time evolution in perfect accordance with the Eurocode parametric fire curves (EPFC). The backgrounds of the temperature-time standard curves and the need of complementary analyses were recently discussed and commented [7,12]. The authors highlighted the origins of the heating phase expression and discussed the noted discrepancies behind the calculations of its duration and maximum temperature. Fire load density, opening factor as well as walls properties were considered as the key parameters that evolve the temperature in both ventilation-controlled and fuel-controlled fires.

The present work is an attempt towards a global investigation on temperature-time prediction techniques, as done in regional standards. It is aimed to unify the analysis and highlight the governing parameters through a generic case.

2. Temperature time formulations

Before delving into the details of the thermal model, it is necessary to identify several critical factors that support the formulation. These parameters include the opening factor, fire load, and the characteristic parameter b associated with wall construction materials.

The opening factor, denoted as $\boldsymbol{O}$, is expressed by the formula: [13]

$$\boldsymbol{O} = \frac{A_v\sqrt{h_{eq}}}{A_t} \tag{1}$$

$$h_{eq} = \frac{\sum A_{vi}\times h_i}{A_v} \tag{2}$$

where A_v stands for total area of vertical openings on the walls, h_{eq} is the weighted average of opening heights, and A_t is the overall area of the enclosure.

The fire load q, is evaluated as: [13]

$$q = \frac{\sum_i g_i\times H_i}{A_f} \tag{3}$$

$$q_{t,d} = \frac{q_{f,d}\times A_f}{A_t} \tag{4}$$

$$q_{t,d} = q \times m \times \gamma_{q1} \times \gamma_{q2} \times \gamma_n \tag{5}$$

where $q_{t,d}$ is the design value of the fire load density related to the total surface area of the enclosure, $q_{f,d}$ is the design fire load density related to the floor area. m is a combustion efficiency factor, and γ_{qi} denote operating parameters that account for the fire risk.

The wall thermal inertia b, reflecting a material's ability to maintain the thermal energy, relates on density, conductivity, and specific heat, as: [13]

$$b = \sqrt{\rho \times c \times k} \qquad (6)$$

Temperature trends for naturally ventilated compartments are rarely tabulated for full-scale configurations. On the other hand, numerical experimentations (two-zone or field-based models) failed to provide general expressions for temperature evolution owing to strong dependencies on geometry, as well as on numerical parameters [6]. The analytical expressions for T-time curves are considered as reliable tools, providing therefore instantaneous responses for engineers and fire professionals.

2.1. Nominal temperature time curves

The ISO 834 curve is a standard fire test to evaluate the fire resistance of materials. It is expressed as [14]:

$$\boldsymbol{T = T_0 + 345\log(8t + 1)} \qquad (7)$$

where t [min]: the time, T the temperature in the compartment, T_0 the temperature in the compartment at the start of the fire.

The external fire curves are used in the testing of materials which are exposed to fire through the façade [14]:

$$\boldsymbol{T = T_0 + 660[1 - 0.686\exp(-0.32t) - 0.313\exp(-3.8t)]} \qquad (8)$$

In chemical processing sectors, the hydrocarbon curve is commonly used to describe how a fire involving liquid fuels develops [14]:

$$\boldsymbol{T = T_0 + 1080[1 - 0.325exp(-0.167t) - 0.675exp(-2.5t)]} \qquad (9)$$

As stated out in the literature [7,9], nominal curves fail in recovering heating scenarios in real compartment fires.

2.2. Natural temperature time curves

In order to better represent real fires, natural fire curves are considered. It provides a temperature-time relationship to be developed for a set of physical parameters, namely, fuel load, ventilation and thermal properties of compartment boundaries.

Curve A: It describes the maximum temperature, and the time elapsed to reach its value. The expression is related to the compartment construction material type, as [15]:

$$T_g(t) = T_{max} \times \left(\frac{t}{t_{max}}\right) \times e^{\left(1-\frac{t}{t_{max}}\right)} \qquad (10)$$

where $t_{max} = \frac{q}{(a \times O)}$ (11)

$$T_{max} = b + c \times (1 - e^{-d \times O}) \times q^{(m-n \times O)} \qquad (12)$$

The coefficients "a, b, c, d, m, n" are associated with wall materials properties [15].

Curve B: The European parametric fire curves (EPFC) are the most widely used curves for replicating natural fire exposures on structures. It provides analytical expressions that feature one scaling parameter, accounting for natural ventilation and walls thermal properties:[7]

The growth phase is described by the expression bellow:

$$T_g(t) = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \quad (13)$$

With $t^* = t.\Gamma$, and

$$\Gamma(O,b) = (O/b)^2/(0.04/1160)^2$$

During the decay phase equations (15) and (16) are employed:[13]

$$t^*_{max} \leq 0.5 \text{ , } T_g = T_{max} - 625(t^* - t^*_{max}.x) \quad (15)$$

$$0.5 < t^*_{max} \leq 2 \text{ , } T_g = T_{max} - 250(3 - t^*_{max})(t^* - t^*_{max}.x) \quad (16)$$

$x = 1$ if $t_{max} > t_{lim}$, and $x = t_{lim}.\Gamma/t^*_{max}$ if $t_{max} = t_{lim}$

where $t^*_{max} = \Gamma.\left(0.2 \times 10^{-3} \times \frac{q_{t,d}}{O}\right)$ (17)

3. Results and discussion

The dimensions of the compartment under consideration are 32 meters in length, 32 meters in width, and 15 meters in height as described in [6]. It can be noted that the bottom of every wall of the compartment geometry features an opening (ventilator), with 2 meters height and 10 meters width (Figure 1).

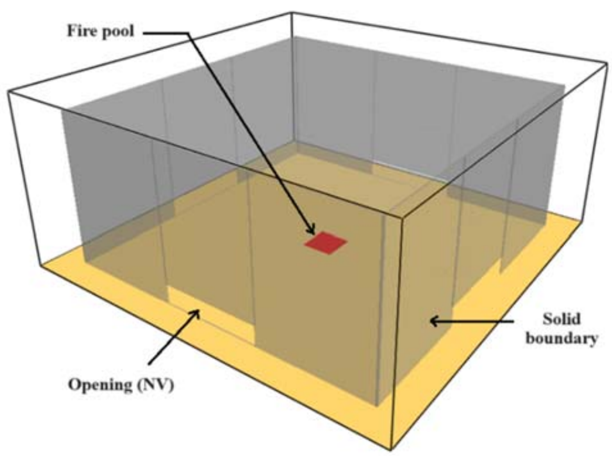

Figure 1. Sketch of the compartment geometry

The material of compartment boundaries was concrete. Assigned physical properties for two types (B and C) of commercial concrete, were considered in the calculations, see table1.

Table 1. Physical properties considered in the calculations [6]

Material properties	Normal concrete (B type-boundary)	lightweight concrete (C type-boundary)
Density ($Kg.m^{-3}$)	2300	1500
Specific heat ($J.kg^{-1}.K^{-1}$)	900	840
Thermal conductivity ($W.m^{-1}.K^{-1}$)	1.70	1.00

The temporal evolution of the excess temperature according to nominal calculations is sketched in Figure 2.

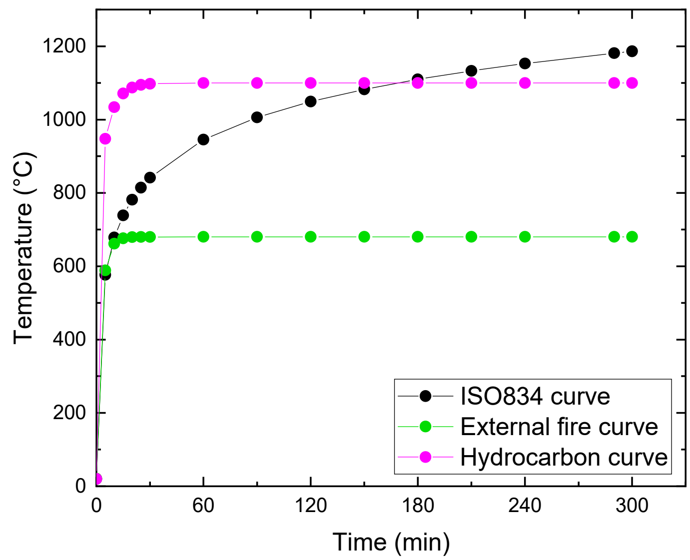

Figure 2. Nominal temperature- time curves

As presented, the hydrocarbon curve quickly rises to a constant temperature of 1100 ◦C after 30 minutes. The external fire curve stabilizes at 680 ◦C within 20 minutes. Since no specific parameters were introduced, the ISO834 curve is considered to be universal and applicable to all configurations. It is crucial to emphasize that it is not possible to predict the maximum gas temperature or time constant.

In figure 3, both curves A and B were plotted using similar parameters based on the geometric and physical data of the case study in comparison with the nominal standard curve. The calculated values for the parameters q, O as well as the scaling factor Γ are $q1 = 427.24\,MJ/m^2$, $O1 = 0.028\,m^{0.5}$ and $\Gamma 1 = 0.187$ respectively.

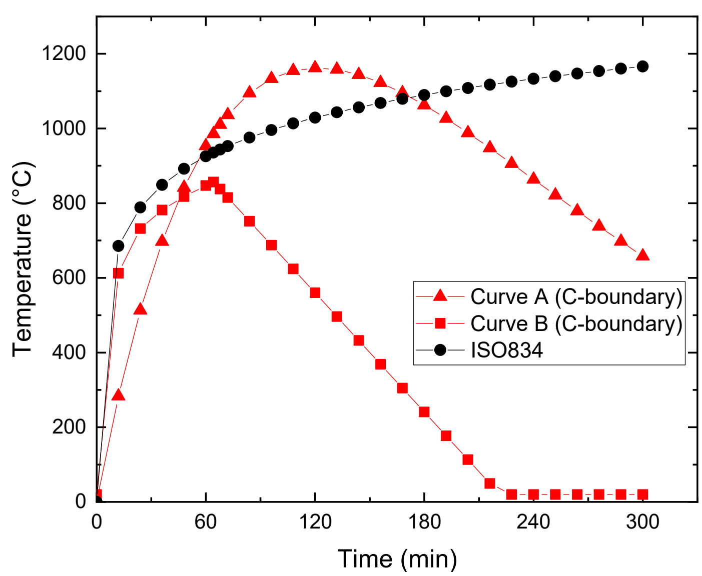

Figure 3. Temperature trends over time: comparison of curves A and B

During a duration of 64 min, maximum limiting temperature is approximately 856°C with a less rapid heating rate observed in curve B compared to ISO834. This highlights effect of natural ventilation. During this heating period, there is a relative discrepancy between curve B and ISO834 of about 9%. This implies that fuel and ventilation parameters calibration for this particular study was quite good. In turn, the trend of curve A not only intertwines with it but exceeds, revealing a highest temperature of 1162 °C. This threshold was obtained after 120 min of fire. It is worth mentioning that decay phases of two fire curves develop differently. Linear decay characterizes curve B whereas curve A follows an exponential decay pattern.

Figures 4 to 6 allow to face the temperature-time history for various fire scenarios.

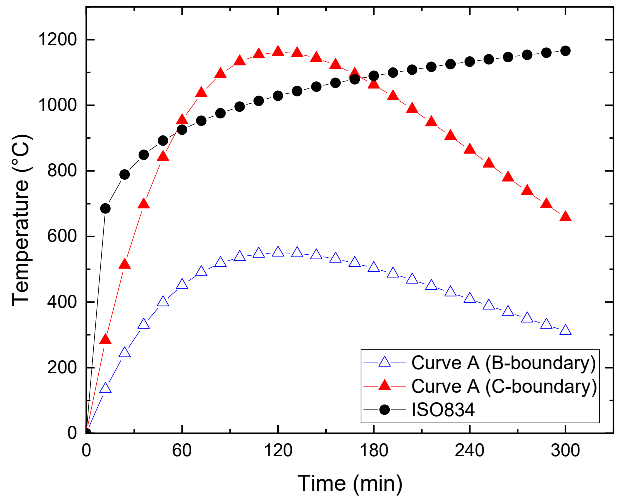

Figure 4. Temperature-time curves for two types of buildings

Figure 4 illustrates the temperature changes over time of curve A for various type of building (B and C), keeping the remaining parameters constant. It reveals a constant value for the necessary burning time to reach the highest temperature ($\boldsymbol{t_{max}}$=120 min). In this case, the predicted peak temperatures differ between the two building types, reaching 550°C with building B and 1162°C with C type boundary. This behaviour highlights a rise in temperature, owing to the thermal inertia of the buildings.

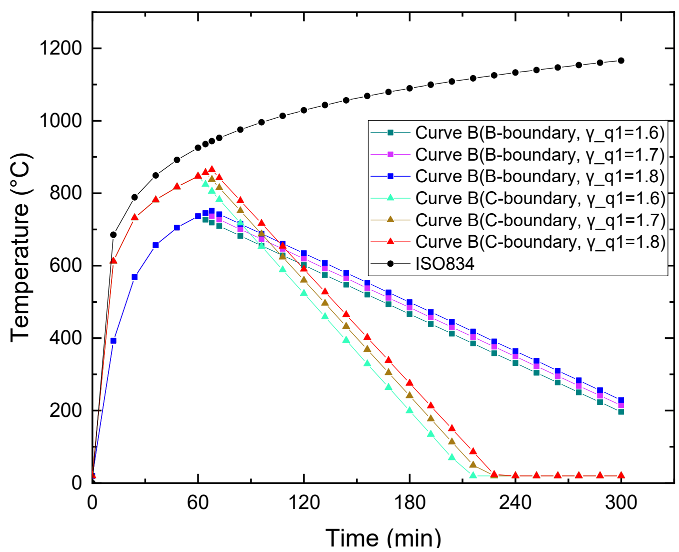

Figure 5. Temperature evolution (curve B) for several γ_{q1} values

Figure 5 displays the temperature–time trend of curve B with several values of $\boldsymbol{\gamma_{q1}}$ according to the floor area. The analysis suggests that the type of building has an effect on maximum temperatures for a conserved time required to reach this temperature. When $\boldsymbol{\gamma_{q1}}$ is changed from 1.6 to 1.8, the rise in temperature is the same until the maximum temperature is reached, while the curves overlap until the threshold $\boldsymbol{T_{max}}$ .After this period, clear patterns of the curves emerge, leading therefore to different maximum temperatures reached at various times. Moreover, γ_{q1} factor values of 1.6, 1.7, and 1.8, the maximum obtained temperatures are 736°C in 60 minutes, 744°C in 64 minutes, and 751°C in 68 minutes, respectively. The above analysis reveals how building type and γ_{q1} factor impact temperature histories thereby, providing a way for optimizing thermal performances.

Figures 6 and 7 illustrate the effect of varying the opening factor (0.028-0.056 $m^{0.5}$) and the fuel load (427-854 MJ/m^2) values respectively on the evolution of the T-time through the use of curves A and B.

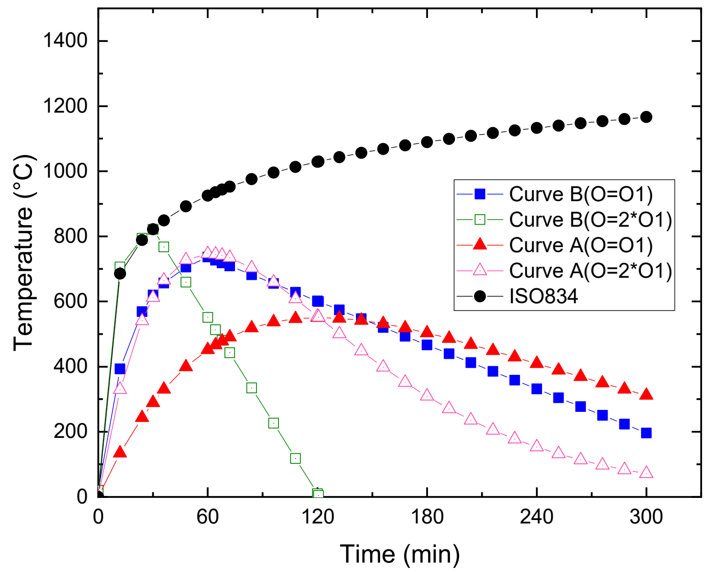

Figure 6. Temperature-time curve according to curves A and B: Influence of the opening factor

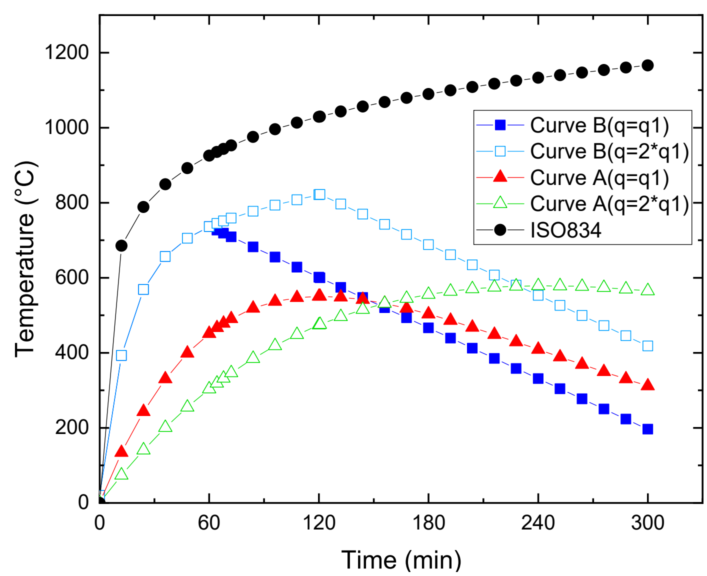

Figure 7. Temperature-time curve according to curves A and B: Influence of fire load

Significant differences in temperature profiles were observed in figure 5. Maximum temperatures obtained at various opening factors are 736°C with 0.028 $m^{0.5}$ and 861°C with 0.056 $m^{0.5}$, with a relative rise close to 17%. This increase in maximum temperature is associated with a notable reduction in the time taken to reach this peak. Such variations clearly indicate that there are drastic effects of variation in opening factor on the compartment thermal trend. Nevertheless, it is important to stress that as the fire progresses into the decay phase, the compartment gas temperature undergoes a fast decline. An antagonist trend is recovered in figure 6. Here, increasing fuel load density extends fire duration in the growth phase. Consequently, more energy is released into compartment fires leading to higher gases temperatures.

4. Conclusion

Recent research has underlined the importance of implementing holistic performance-based approaches that analyse structural performance in order to ensure the integrity and stability of structure in case of fire.

The present investigation was aimed at conducting a parameter analysis that could go into effect by using literature formulations to distinguish between standard and realistic building fires. It was found that parameters concerning the fuel and compartment have large influence because they mostly influence the maximum gas temperature, therefore the fire duration. Moreover, the paper allows through an in-depth case study to understand the challenges of making temperature predictions and emphasizes the controlling factors that can have an impact on building fire behaviour.

Acknowledgment

The authors are thankful to Prof. B. Lamri & Prof. A. Kada from the LISICPE Laboratory, Chlef, Algeria. This work is funded by a grant from the DGRSDT Algeria, project No. A01L02UN0201-20230003.

References

[1] Morys, M.; Habler, D.; Kruger, S.; Schartel, B.; Hothan S. 2020. Beyond the standard time-temperature curve: Assessment of intumescent coatings under standard and deviant temperature curves, Fire safety journal, 112: 102951

[2] Zhen Y, Wang Z, Wang J, Wang C, Cui Y. Experimental and numerical study on connecting pipe and vessel size effects on methane–air explosions in interconnected vessels. Journal of Fire Sciences. 2018;36(3):164-180.

[3] Cantor, P.; Arruda, M.R.T.; Fimo, J.; Branco, F. 2022. Proposal of standard wildfire curves for the design of protection of dwellings against wildland fire, Journal of Hazardous, toxic and radioactive waste, 26 (3).

[4] Mokoana VN, Asante JK, Okonkwo OJ. A review on volatilization of flame retarding compounds from polymeric textile materials used in firefighter protective garment. Journal of Fire Sciences. 2023;41(4):107-121.

[5] Xu, X.; Wang, Z.H.; Liu, X.L.; Ji, C.; Yu, N. H.; Zhu, H. Y.; Li, J.; Wang, P. F. 2018. Study on fire smoke control in super-high building Atrium, Procedia Engineering, 211: 844-852.

[6] Du, Y.; Li, G. Q. 2012. A new temperature-time curve for fire resistance analysis of structure, Fire Safety Journal, 54: 113-120.

[7] Lucherini, A. ; Jovanovic, B. ; Van Coile, R. ; Merci, B. 2021. Background and limitations of the Eurocode parametric fire curves, including the fire decay phase, In proceedings ASFE'21: Applications of structural fire engineering: 330-335. University of Ljubljana.

[8] Lie, T. T.- 1988. Fire temperature-time relations SFPE Handbook of fire protection engineering (1st ed), Chichester, UK, Wiley, Ch.6: 81-87.

[9] Walton, D.; Thomas, P. H. 2002. Estimating temperatures in compartment fires SFPE Handbook of Fire Protection Engineering. Ch.6: 996-1023.

[10] Blagojevic, M. D.; Pesic, D.J. 2011. A new temperature-time relationship in compartment fire, Thermal Science, 15 (2): 339-352.

[11] Wickstrom, U.; Bystrom, A. 2014. Compartment fire temperature: A new simple calculation method", In proceedings IAFSS: The international association for fire safety science: 289-301.

[12] Babrauskas, V. 2022. Comments on "the historical narrative of the standard temperature-time heating curve for structures", Fire technology, 58 (1): 15-20.

[13] CEN. EN 13501-2: 2016. Fire classification of construction products and building elements—Part 2: classification using data from fire resistance tests, excluding Ventilation services; CEN: Brussels, Belgium.

[14] Oli, T.; Ha, D.; Jang, T.; Park,C.; Kim, G.; Kim, S. 2024. Temperature distribution curve analysis on concrete through LS-DYNA, Fire 7 (1): 15.

[15] Santarpia, L., Bologna, S., Ciancio, V., Golasi, I. Salata, F. 2019. Fire temperature based on the time and resistance of buildings—Predicting the adoption of fire safety measures. Fire (2): 19.