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On the Derivation of Temperature-Time Curves for Large Scale Compartment Fires

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Abstract: *Thermal environment prediction in compartment fires remains one of the main challenges for fire safety engineers. Indeed, the design of sprinklers, the egress sceneries, and the configurations of structures collapses, are closely related to the temporal evolution of the temperature within compartments. Despite several questionable assumptions, the Eurocode parametric fire curves (EPFC) are still the most adopted methodology to replicate natural fire exposure of structural elements. The present investigation examines, through a case study, the ability of the EPFC analytical formulation to recover the heating phase evolution on large-scale compartment fires. The analysis aims to tune the parameters of a non-uniform T-Time formulation, derived from a numerical experimentation. A focus is made on fire development key factors, namely, the opening factor, the fuel load density, and the walls effusivity, on which maximum temperature as well as heating phase duration are discussed. The investigation is completed by a nonstationary 3D-LES simulation, using the NIST-FDS® solver.*

Keywords: *fir engineering, temperature-time curve, numerical simulation, FDS*

1. Introduction

The ability to predict temperatures developed in compartments is of great significance for fire safety researchers and engineers. There are many uses of knowledge of temperature elevation history, including the prediction of hazardous conditions, thermal comfort of the occupants, as well as fire traveling scenarios [1]. In this direction, several attempts were conducted to provide temperature-time curves and the corresponding governing parameters. The investigations were based on various methodologies, including full-scale experimentations, physical-analytical models and numerical-correlative models [2]. In the model developed by Lie in 1988, an analytical expression for Temperature-Time curve was derived from an energy balance within a naturally ventilated compartment. 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 the national standards curves [3]. A correlative-analytical formulation for the T-Time curve in a ventilated enclosure was derived using a two-layer zone model [4]. 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. In [5] the authors proposed a unique function for T-Time evolution based on a "pulse phenomena", and featured three parameters that were linked to fuel and fresh air quantities. 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* [6] derived a simple temperature-time expression applicable to post-flashover ventilation-controlled fires.

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 EPFC curve. The backgrounds of the EPFC were recently revisited in [7]. 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 study.

2. Temperature-Time Formulations

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 [8]. The analytical expressions for T-time curves are considered as reliable tools, providing therefore instantaneous responses for engineers and fire professionals. The commonly used formulations are described in the following.

2.1. The ISO-834 Curve

The zero-parameter temperature-time curve was originally derived to mimic the heating conditions during testing. It was generalized as UK standards, in which excess temperature $\Delta T_g(t)$ was written as [5]:

$$\Delta T_g(t) = T_g(t) - T_0 = 345 Log_{10}(8t+1) \tag{1}$$

where t is the post-ignition time (in min) and T_0 is the ambient temperature (in °C). In the relation above, no physical nor geometrical parameter was introduced.

2.2. The EPFC Curves

The Eurocode parametric fire curves (EPFC) are the most widely used curves for replicating natural fire exposures on structures. It provides analytical expression that features one scaling parameter Γ, accounting for natural ventilation and walls thermal properties. The excess temperature is expressed as [7]:

$$\Delta T_g = T_{\max}\left(1 - 0.32e^{-0.2t^*} - 0.20e^{-1.7t^*} - 0.47e^{-19t^*}\right) \tag{2}$$

$T_{\max} = 1325°C$ and $t^* = t.\Gamma$ stands for the scaling time (in *hours*), which is implicitly related to the compartment opening factor (O) and the thermal inertia b of the boundary’s materials, as:

$$\Gamma = (O/b)^2 / (O_{ref}/b_{ref})^2 \;\; ; b = \sqrt{\rho.k.c} \; ; O = A_v\sqrt{H_v} / A_T \tag{3}$$

ρ, k, c denote density, thermal conductivity, and specific heat respectively, for the wall’s material, and A_v, H_v, A_t stand respectively for area and height of the opening and the total area of the enclosure.

2.3. The Swedish Curves

Two different expressions for the excess temperature were developed and incorporated into the Swedish standards, depending on whether the walls are categorized as thermally thin or thick:

For thermally thick boundaries [6]:

$$\Delta T_g(t) = T_{ulti}\left(1 - e^{-t/\tau_f}.Erfc\sqrt{t/\tau_f}\right)$$

(4)

For thermally thin boundaries [6]:

$$\Delta T_g(t) = T_{f,\max}\left(1 - R_{th}.e^{-t/\tau_{Core}}\right)$$

(5)

where τ_{Core}, τ_f are the time constants of the compartment, which are related to the natural ventilation and the thermal resistance (conduction, convection) of the solid boundaries. As combustion efficiency is empirically provided, the fuel load density allows for the calculation of T_{ulti} and $T_{f,max}$ [2, 6].

3. Results and Discussions

The case study focuses on a large naturally ventilated space discussed in the work of Du *et al* [8]. The compartment is quite spacious, with a height of 15 meters and a floor area of 32 meters by 32 meters. Each wall has an opening at the bottom, measuring 2 meters in height and 10 meters in width, which allows for the entry of air (see Figure 1).

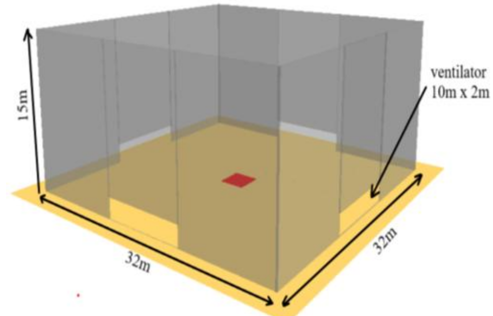

Fig. 1: Sketch of the compartment geometry.

In the centre of the space, a pool fire with a diameter of 3 meters and a heat release rate of 5 MW is positioned. The solid boundaries (walls) of the space are made of standard concrete and have consistent physical properties, as described in Table 1.

TABLE I: Walls physical properties

Material properties	Concrete
Density (kg.m^{-3})	2300
Thermal conductivity (W.m^{-1}.K^{-1})	1.70
Specific heat (J.Kg^{-1}.K^{-1})	900

The temporal evolution of the excess temperature according to ISO-834 calculation is sketched in Figure 2.

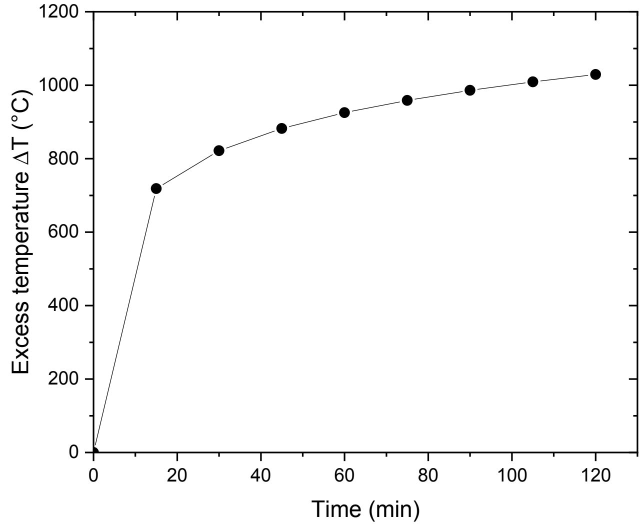

Fig.2 T-time curve according to ISO834

Since no specific parameters were introduced, the curve is believed 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 the EPFC calculations, the opening factor (O=0.028) and the scaling factor (β=0.187) were employed based on the geometric and physical data. It is worth noting that an initial calculation was carried out to adjust the EPFC fire load density to the transient heat release rate (HRR) provided in Du *et al*.'s study. Further details regarding this calculation can be found in [9].

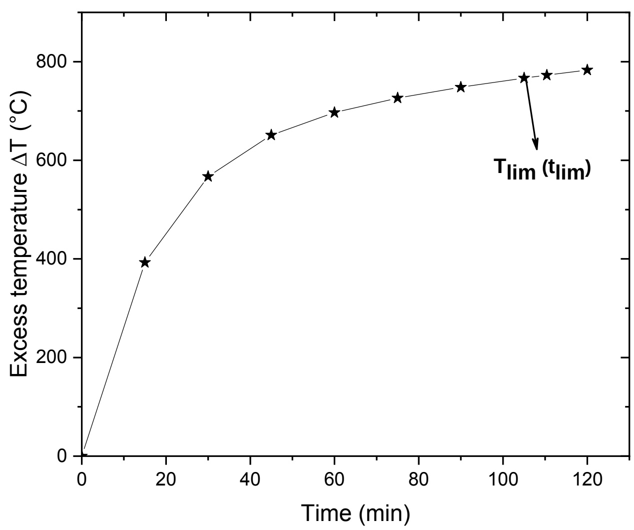

Fig.3 : The EPF curve of gas temperature.

Figure 3 illustrates the evolution of excess temperature as obtained through the use of EPF curve. The curve exhibits a less rapid heating rate compared to ISO-834, indicating the influence of natural ventilation on the fire progression. The maximum limiting temperature observed is approximately 769 °C, reached within a specific duration. The overall thermal level in this case study is approximately 24% less than that predicted by ISO-834. Moreover, the relative discrepancy between ISO-834 and EPFC during the heating period is 8%. This value indicates that the calibration of fuel and ventilation parameters in EPFC for this particular study was fairly accurate. Considering the heat resistance of solid boundaries under specific configurations, such as semi-infinite thick and thermally thin walls, the analytical expressions provided by Equations 4 and 5 can be applied.

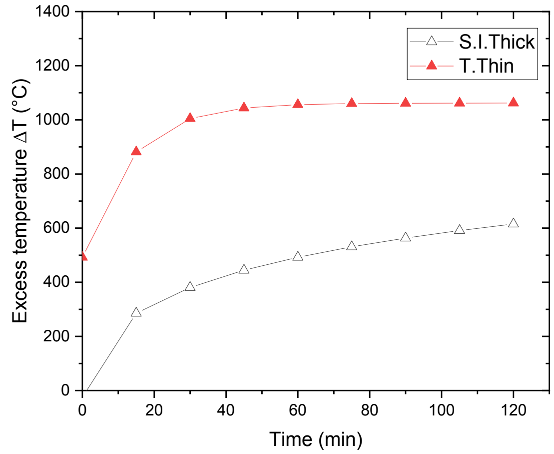

Fig.4: Temperature evolution (Swedish standard) for two lim iting assumptions.

Figure 4 depicts the temperature changes over time, considering the thermal resistance of solid boundaries. Assuming thin walls leads to a gradual approach to a stable gas temperature, reaching a maximum value of 1062 °C over a specific duration. However, when considering thick walls that are semi-infinite, the temperature cannot reach a maximum value due to the longer time constant involved. Instead, it remains around 470 °C for a 45-minute fire exposure. Using capacitance-based formulations for the boundaries helps approximate the temperature levels found in ISO curves, but with longer heating durations. In Figure 5.1, the EPF curve underestimates the heating duration by 8%, while the assumption of thermally thin walls causes a significant discrepancy of 62% for the Swedish curve. This difference is likely due to a flaw in calculating the overall thermal capacitance of the solid boundaries. The discrepancy is also noticeable for the maximum or limiting temperature (Figure 5.2). The EPF curve underestimates the ISO limiting temperature by 25%, while the Swedish curve, which considers semi-infinite thick boundaries, deviates by 40% compared to the ISO 834 standard.

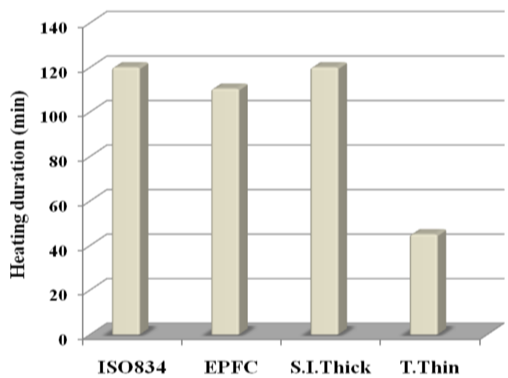

Fig.5.1: Heating phase duration (various formulations)

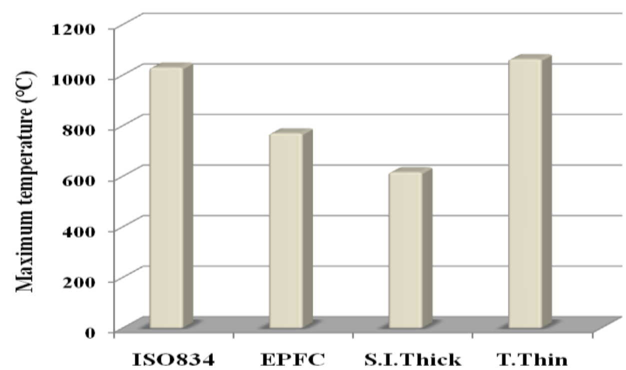

Fig.5.2: Maximum gas temperature (various formulations)

An additional numerical study was conducted to provide a detailed temperature-time profile within the compartment. The computational fluid dynamics (CFD) model employed in this study takes into account turbulent mixing and air entrainment, which enhances the realism of the results. However, due to the compartment's geometry, temperature distribution exhibits spatial non-homogeneity, particularly near the openings. Therefore, special attention was given to the buoyant zone of the fire plume, which is expected to be minimally influenced by fresh air inlets. Figure 6 illustrates temperature histories at a height of 6 meters above the floor. It is evident that both the ISO 834 and Swedish curves (based on the thin boundary assumption) capture the overall thermal trend during the exposure period, but there is still a significant overestimation. On the other hand, there is a satisfactory agreement between the filtered temperatures obtained from the large eddy simulation (LES) resolution and the EPF/Swedish curves. This can be attributed to the effective calibration of both the EPF and numerical methods, specifically considering the thermal properties of the solid boundaries in the compartment.

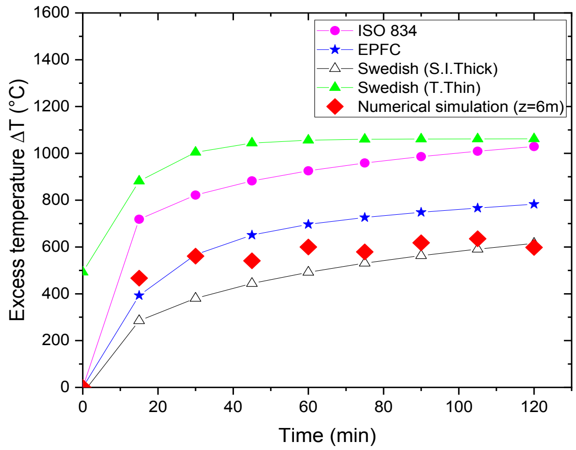

Fig.6: Time dependent temperature (All formulations)

4. Conclusions

The temporal evolution of gas and boundary temperature within a ventilated compartment is a crucial aspect of any fire safety project. Existing predictive calculations have been applied for specific purposes based on regional standards. In this study, the most commonly used analytical temperature-time formulations were provided, and the governing parameters were explicitly described. The investigation focused on a literature case study involving a naturally ventilated large compartment, with particular emphasis on the heating phase. The analysis revealed a minor discrepancy of no more than 8% in the predicted heating duration values when compared to ISO 834, EPF, and Swedish curves. This agreement was achieved through a calibration procedure conducted on the parameters related to solid boundary properties and the compartment opening factor. However, a relative deviation of up to 25% was observed in the maximum temperature predictions between ISO 834 and EPFC models. As the numerical simulations campaign is still in its early stages, no additional explanations can be provided at this time. Further research and subsequent physical explanations are expected to be presented in future works.

5. Acknowledgements

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