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Defining the fire decay and the cooling phase of post-flashover compartment fires

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ABSTRACT

The current research study discusses and characterises the fire decay and cooling phase of post-flashover compartment fires, as they are often mixed up despite their important heat transfer differences. The two phases are defined according to the fire heat release rate time-history. The fire decay represents the phase in which the fire heat release rate decreases from the ventilation- or fuel-limited steady-state value of the fully-developed phase to fire extinguishment. This phase is highly influenced by the fuel characteristics, ranging from fast decays for hydrocarbon and liquid fuels to slow decays for charring cellulosic fuels (wood). Once the fuel is consumed, the compartment volume enters the cooling phase, where the cooling in the gas-phase and solid-phase happens with significantly different modes and characteristic times. The thermal boundary conditions at the structural elements are then defined according to physical characteristics and dynamics within the compartment. The research study also underlines how the existing performance-based methodologies lack explicit definitions of the decay and cooling phases and the corresponding thermal boundary conditions for the design of fire-safe structural elements under realistic fire conditions.

1. Introduction

During the last two decades, the fire research community has continuously highlighted the limitations of the current design methodologies based on standard fire furnace testing [1]. The standard fire curve is characterised by a monotonically increasing temperature-time curve and it is deemed to represent a worst-case scenario for traditional structural elements exposed to post-flashover fully-developed compartment fires. However, many researchers and practitioners have emphasised the importance and advantages of performing performance-based designs based on more realistic fire conditions [2]. Indeed, adopting holistic performance-based methodologies enables a more comprehensive understanding and quantification of the integrity and stability of structural elements and systems. These approaches also allow for optimisation processes and studies on structural reliability [3].

One of the main discussion points around standard fire furnace testing is that this methodology does not consider the fire decay phase and it does not assess the behaviour of structural elements and construction components during cooling [4]. As the combustible content gets consumed during a fully-developed fire, the heat release rate decreases, and a decay phase commences. This decay phase changes the nature of the temperature, heat flux and soot volume fraction fields within a compartment. Eventually, burn-out is achieved when all combustible materials are consumed, or at least until significant burning ceases. This is the onset of the cooling phase.

Indeed, it has been evidenced how the effects of the fire decay phase and the subsequent cooling are relevant for all main construction materials because they may produce critical conditions, possibly completely different to those observed during heating in a post-flashover fully-developed fire. First, construction materials may experience further reduction in the mechanical properties (strength and stiffness) during cooling. This is the case for concrete structures [5]. In the case of steel, mechanical properties are generally considered fully reversible (below a certain maximum temperature), nevertheless, redistribution of temperatures across the section can result in complex deformations and stress generation [6]. This is because the material's thermal inertia can delay the thermal penetration within construction materials. For instance, the temperatures inside concrete members (i.e. tensile

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reinforcement) or protected steel sections may continue to rise after the period of maximum gas temperature [5]. Moreover, fire-induced large deformations in steel structures due to thermal expansion can produce new forces redistributions and member contractions during cooling: this can become the critical condition for steel connections [6]. Finally, these phases can also seriously challenge timber structures because wood loses its mechanical properties in an irreversible manner at relatively low temperatures [7]. As a result, the fire decay phase and the subsequent cooling occurring after burn-out of all combustible furnishings can create completely different and challenging conditions for the integrity and stability of structures.

However, the research and engineering efforts have been traditionally focused on the thermal effects of the fire fully-developed phase (i.e. heating phase), which is commonly considered the most challenging situation for load-bearing structures, given the high temperatures and heat fluxes [8]. Little attention has been paid to the fire dynamics and heat transfer after the fully-developed phase of a fire. In many large-scale compartment fire tests, this information is not even collected and/or reported or the fire is manually extinguished before the fire reaches the cooling phase [9]. On the other hand, the majority of engineering tools aimed at estimating the thermal exposure to load-bearing systems for post-flashover compartment fires focus on the maximum temperature and the duration of the fully-developed phase, with little interest and very simple approaches devoted to the fire decay and cooling phases (e.g. Eurocode parametric fire curves [10]).

Nowadays, the understanding of structural behaviour during heating has matured enough to raise some key questions regarding the decay and cooling phases. As more studies related to this topic are being published, little effort is placed in clarifying the differences between the fire decay phase and the cooling phase and their treatment remains highly inconsistent. The two phases are often mixed up [2,5,7,11,12] despite their very different heat transfer characteristics and relevance. As a result, the available literature does not offer conclusive data and/or definition that separates the fire decay from the cooling periods of compartment elements and that allows for a quantitative characterisation of the thermal exchange.

The current study underlines the characteristics and the differences between the fire decay and cooling phase of post-flashover compartment fires. The different phases of a natural fire are compared, and the corresponding thermal boundary conditions are defined. In addition, experimental research is scrutinised and analysed to provide evidence of the differences between the fire decay and cooling phase, highlighting the importance of the fuel load (wood cribs vs. pool fire).

2. Phases of post-flashover compartment fires and thermal boundary conditions

Depending on the compartment and fuel characteristics, in particular the compartment ventilation and the fuel type and distribution, the heat generated by the fire within an enclosure can depend on the air (oxygen) or fuel supply. Accordingly, the evolution of a compartment fire is typically considered to follow two distinctive regimes, namely ventilation-controlled (regime I) or fuel-controlled (regime II) [13,14]. *Ventilation-controlled fire* are generally characterised by a limited oxygen availability due to the relatively-small openings, which allow for the compartment to fill up with high soot volume fraction smoke and attain flashover. In contrast, in the case of a *fuel-controlled fire*, the oxygen is abundant due to large opening and/or compartment size, smoke is free to move or leave the compartment, the fire grows according to the fuel characteristics (distribution and type) and soot volume fractions are lower. The differences between ventilation-controlled or fuel-controlled fires have been largely discussed in the literature and the greater severity of ventilation-controlled fires for load-bearing structural elements has been highlighted by several researchers [13,14].

This research study focuses on post-flashover compartment fires, assuming the attainment of flashover [8,15]. Figs. 1 and 2 underline the main characteristics of the various phases of a post-flashover compartment fires exploring different physical quantities. As an example, and for simplicity, Fig. 1 only presents a case where the structure has a higher thermal inertia than the compartment linings. Fig. 2 graphically presents the physical characteristics of all different phases of the fire, emphasizing the evolution of the smoke layer.

2.1. Growth phase

After fire ignition, the fire grows according to the intrinsic fuel characteristics: physical and chemical properties, geometry, and distribution. This causes a gradual increment of the fire heat release rate, which is typically approximated by a αt^2 relationship, where α [W/s^2] is a generally considered as only fuel-specific fire growth rate, even though the fire growth is typically also affected by other aspects (e.g. ignition, fuel geometry, compartment characteristics). The compartment temperature gradually increases, where the gas-phase closely follows the fire heat release rate [8]. A smoke layer usually descends within the

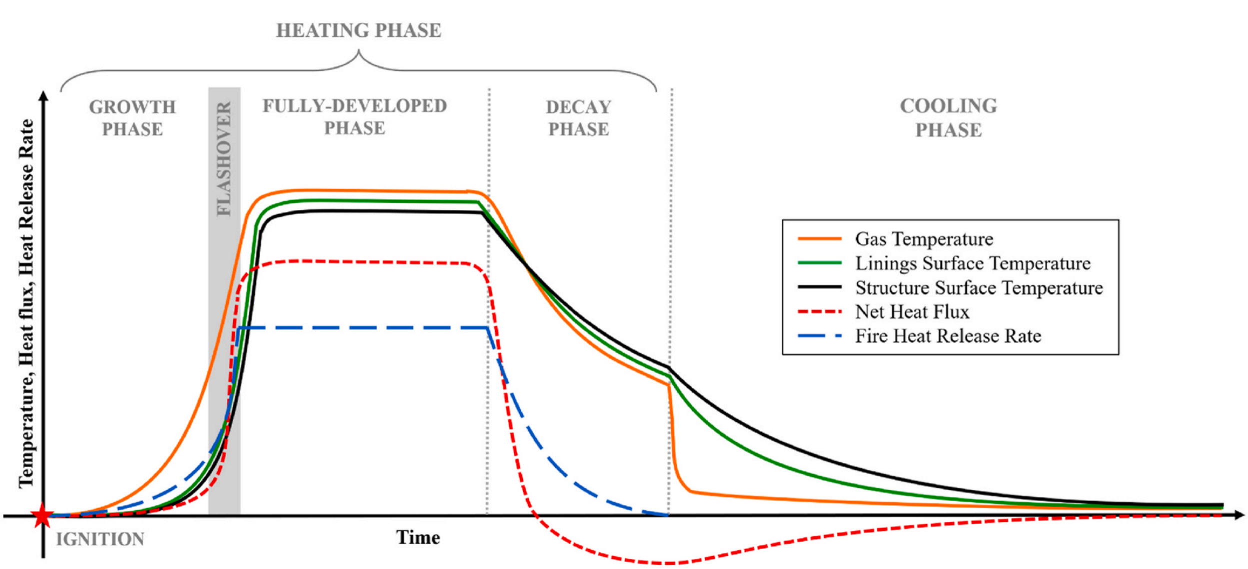

Fig. 1. Comparison between gas, compartment linings surface temperatures, structural element surface temperature, net heat flux, and fire heat release rate during the various phases of a post-flashover compartment fire.

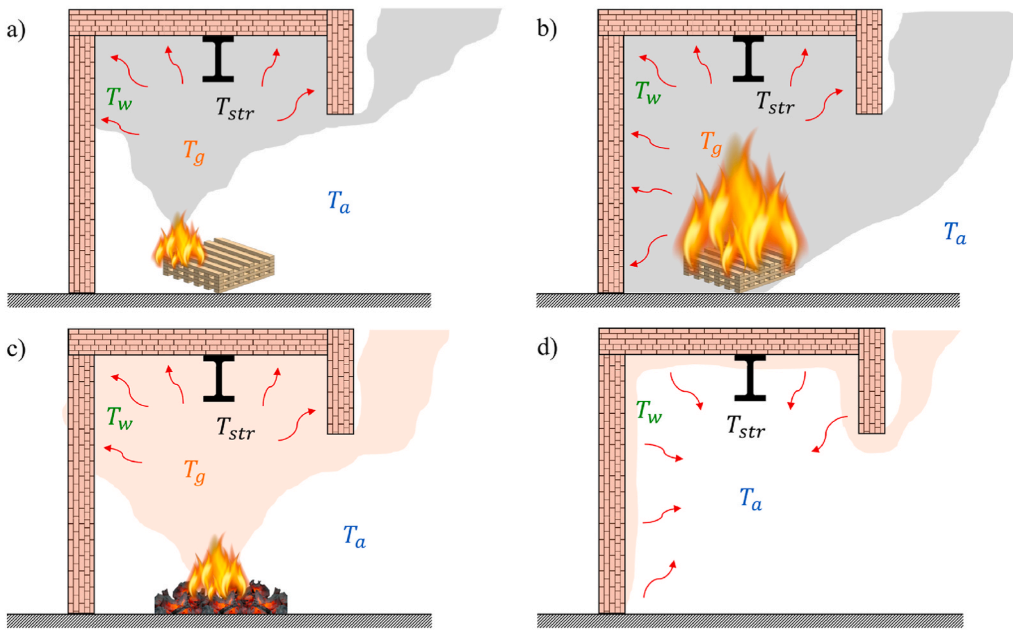

Fig. 2. Side view schematisation of the various phases of a post-flashover compartment fire:a) growth phase; b) fully-developed phase; c) decay phase; d) cooling phase.

enclosure, causing a decrease in the supply of oxygen, increased soot production and the consequent decrease of the optical depth. The compartment elements slowly heat up, but the heat fluxes imposed on the compartment are still relatively low.

2.2. Fully-developed phase

If the conditions are met, at flashover all combustible items in the compartment ignite simultaneously and flames appear to essentially fill the entire volume [8,15]. There is a rapid increase in the fire heat release rate, which generally tends to a steady-state value. For ventilation-controlled conditions, this value directly depends on the oxygen supply at the opening (i.e. opening factor), which is in turn controlled by the static pressure difference between the enclosure (hot) and the surrounding environment (ambient temperature). Since the flow fields are dominated by thermal expansion of the gases, low velocities and negligible momentum are usually observed within the enclosure. The fire heat release rate is closely followed by the compartment gas temperature, which, for relatively small compartments, can be assumed as homogenous over the enclosure volume. This assumption is no longer valid for large compartments, particularly if the aspect ratio deviates far from cubic compartments [16]. Similarly, the compartment elements increase their temperature due to the significantly higher heat fluxes, following their thermal inertia. Combustion is rich, soot concentrations are high, and the whole enclosure is filled with dense smoke, which further decrease the optical depth (practically null).

2.3. Decay phase

The fully-developed phase lasts while the fuel pyrolysis gases are able to sustain the high heat release rate. When the fire heat release rate starts to diminish due to fuel depletion, charring, etc., the conditions within the compartment evolve towards fuel burnout. During this phase combustion gradually becomes lean again (sufficient availability of oxygen) and the fire returns to be fuel-controlled. As in the pre-flashover stages, the fire heat release rate is directly dependent on the fuel (e.g. charring vs. non-charring), characterising its temporal evolution. Similarly to the growth phase, the compartment gas temperature follows the fire heat release rate, while the compartment linings decrease their temperature depending on their thermo-physical properties (primarily thermal inertia). The reduced soot production and increased intake of cold air through the opening results in a decrease in smoke density (increase optical depth). The heat fluxes to the compartment elements significantly decrease while heat losses from the hot compartment surfaces start to increase. Eventually, heat transfer to the compartment elements becomes negative, commencing the cooling process.

It is important to highlight that this study focuses on traditional compartment fires, therefore it assumes a defined “movable” fuel load and an onset of fire decay. Thus, it does not consider combustible structural elements and/or compartment linings that can impact the fire decay. For instance, for a mass timber building, the problem would fundamentally change because flame extinction and smouldering processes of the combustible compartment elements would have a key role in the fire decay phase. This problem is extremely relevant, but it falls outside the scope of the current study, and it will be the objective of future studies.

2.4. Cooling phase

When the main flaming combustion processes cease and the heat release becomes negligible, the compartment volume enters a pure cooling phase. This phase is characterised by the two significantly different modes of cooling: gas-phase and the solid-phase cooling [17]. After a rapid transition period, the smoke inside the compartment is fully evacuated and cold air flows continuously into the enclosure through openings. Consequently, the gases inside the compartment quickly become optically thin and tend to ambient temperature. If the opening is sufficiently large, this phenomenon is typically fast, with a characteristic time in the order of a few minutes. In contrast, the compartment linings, surrounded by gases at ambient temperature, slowly cool down through surface convective and radiative cooling. The temperature decay of the structure/linings is naturally slower, with a characteristic time in the order of hours. The various compartment elements exchange heat through radiation and cool down following their thermo-physical properties (e.g. thermal inertia).

3. Thermal boundary conditions

To perform an accurate assessment of the performance of structures exposed to post-flashover fires, it is important to understand the various phases that occur during a fire event and, more importantly, properly define the thermal conditions at the boundaries of the structural element under analysis [18]. A general definition of the thermal boundary conditions to an exposed element j within a compartment composed of various elements j can be written as:

$$\dot{q}''_{net,j} = h_c(T_g - T_{s,j}) + \sum_{i=1}^{n} F_{i-j}\bar{\varepsilon}\sigma\left(T_i^4 - T_{s,j}^4\right) \tag{1}$$

where $\dot{q}''_{net,j}$ [W/m^2] is the net heat flux received at the exposed surface of the compartment element j under analysis, which has a surface emissivity ε_j [−] and a surface temperature $T_{s,j}$ [K]; h_c [W/m^{2}K] is the convective heat transfer coefficient, T_g [K] is the temperature of the surrounding gases, σ is the Stefan–Boltzmann constant (5.67 × 10^{-8} W/m^{2}K^4), F_{i-j} [−] is the view factor between the element j and another compartment element i, which has a surface emissivity ε_i [−] and a surface temperature T_i [K]. The effective emissivity $\bar{\varepsilon}$ can be calculated combining the emissivities of the emitting and receiving body (ε_j and ε_i) [34]. Eq. (1) can be applied to correctly describe the heat transfer at the element surface during the various phases during and after a fire, with the aim of correctly reproducing the heat fluxes to the compartment elements under analysis.

3.1. Growth phase

The growth phase is usually disregarded for structural fire engineering purposes because of its short duration, large optical depth, and low temperatures [4]. Thus, this phase is not further considered within the scope of this study.

3.2. Fully-developed phase

Since after flashover all compartment elements are assumed to be surrounded by optically-thick and high-density smoke, structural elements primarily exchange heat with the smoke layer. The compartment linings are "invisible" to the other elements, the view factor (F_{i-j}) and the smoke emissivity (ε_i) tends to unity. Both radiative and convective heat transfer take place between the smoke (T_g) and exposed surfaces of structural elements ($T_{s,j}$). Nevertheless, due to the high gas temperatures and the low gas velocities, the heat transfer is primarily dominated by radiation and the heat fluxes are significant (up to 150–200 kW/m^2). As a result, the thermal boundary conditions during the fire fully-developed phase can be written as:

$$\dot{q}''_{net,j} = h_c(T_g - T_{s,j}) + \varepsilon_j\sigma\left(T_g^4 - T_{s,j}^4\right) \tag{2}$$

Similar expressions and assumptions can be also found in most engineering applications, like Eurocode 1 [10]. In these applications, simple assumptions are made in regard to the convective heat transfer coefficient (h_c). These assumptions are appropriate because the low velocities make the convective heat transfer coefficient insensitive to the compartment and fire characteristics.

3.3. Decay phase

The compartment conditions during the decay phase lead to an important decrease in the smoke optical density, therefore the compartment gases gradually become again transparent for exposed structural elements. Consequently, depending on the geometry and thermo-physical properties, the exposed surfaces of structural elements ($T_{s,j}$) exchange heat through radiation with the fire flames, the hot compartment linings, the openings and possibly with the remaining smoke. The radiative heat transfer becomes more complicated because it requires the estimation of the contributions of each single element j within the compartment, based on the view factor (F_{i-j}), effective emissivity ($\bar{\varepsilon}$) and surface temperature (T_i). A challenging calculation could be the quantification of the radiative heat flux from the fire flames, which can be considered separately ($\dot{q}''_f$). Indeed, the fire heat release still ensures radiative heat transfer, as well as hot compartment gases (T_g). The gas temperatures are lower when compared to the fully-developed phase, but nevertheless still significant. Velocities tend to increase (order of magnitude of a few m/s) within the compartment resulting in higher convective heat transfer coefficients (h_c). Therefore, the convective heat transfer from the hot gases becomes potentially more important. Given the influence of many factors into the fire decay phase, heat fluxes to compartment elements can be positive or negative. According, the thermal boundary conditions during the decay phase can be written as:

$$\dot{q}''_{net,j} = h_c(T_g - T_{s,j}) + \sum_{i=1}^{n} F_{i-j}\bar{\varepsilon}\sigma\left(T_i^4 - T_{s,j}^4\right) + \dot{q}''_f \tag{3}$$

3.4. Cooling phase

In this phase, the fire extinguishes and accordingly the heat flux from the flame vanishes ($\dot{q}''_f$). The compartment gases tend to ambient temperature (T_a) and the structural elements ($T_{s,j}$) and compartment linings undergo surface convective cooling according to their thermo-physical properties (e.g. thermal inertia). The absence of smoke makes the compartment gases fully transparent, thus the exposed surfaces of structural elements ($T_{s,j}$) exchange heat through radiation with the compartment linings ($T_{w,i}$). As in the case for the decay phase, the estimation of the radiation contribution requires a more detailed calculation based on the contributions of all the "visible" compartment elements. Depending on the geometry and thermo-physical properties, the various compartment elements can still exchange a positive or negative heat flux with the surrounding environment. Following these considerations, the thermal boundary conditions during the cooling phase can be written as:

$$\dot{q}''_{net,j} = h_c(T_a - T_{s,j}) + \sum_{i=1}^{n} F_{i-j}\bar{\varepsilon}\sigma\left(T_{w,i}^4 - T_{s,j}^4\right) \tag{4}$$

4. Considerations on the fire decay and cooling phase

4.1. Heating phase and cooling phase

It is challenging to clearly characterise what "heating phase" and "cooling phase" mean within a compartment fire. The heating phase can be defined as the period in which the net heat flux into an exposed surface of the structural element is positive, therefore the structural element is increasing its thermal energy. Similarly, the cooling phase can be defined as the period when the net heat flux is negative, hence the structural element is decreasing its thermal energy. However, in this way, the characterization of the two phases would be different for different components of the compartment. The net heat flux would depend on the evolution of the compartment gases and linings, as well as heat transfer coefficients (e.g. convective heat transfer coefficient and surfaces emissivity), geometry (e.g. view factors), and the thermo-physical properties of the structural element (e.g. thermal inertia). The cooling phase can be univocally defined by a negative heat flux, therefore all the instants when the compartment gases and linings have a temperature lower than the exposed surface of the structural element under analysis. Nevertheless, during the fire decay phase, it is not possible to simplistically define heating or cooling. While the overall energy within the compartment is still increasing (fire heat release rate greater than zero), depending on the compartment and elements characteristics, some materials can cool, others can heat up.

From what was discussed in Section 2 and shown in Fig. 1, the authors have decided to focus on the compartment enclosure and relate the two phases to the fire heat release rate. Accordingly, the *heating phase* is considered as the period after fire ignition that provides a heat gain to compartment enclosure. In contrast, the *cooling phase* concerns all the instants after fuel burnout, when the fire heat release rate is null or negligible. In this way, the heating phase, composed of the growth, the fully-developed and the decay phase, can be univocally differentiated.

4.2. Duration of the fire phases and time to burnout

Based on the above definition, the duration of the various fire phases can be estimated according to various assumptions and methodologies. In particular, the *time to burnout*, defined as the time for which the total compartment fuel has combusted and/or extinguished (negligible fire heat release rate), becomes a fundamental parameter because it distinguishes the heating phase from the cooling phase. It is important to state that, the estimation of the duration of the various fire phases is directly linked to the definition of the fire heat release rate time-history.

As regards to the growth phase, assuming a αt^2 relationship, its duration can be simply calculated based on the fire growth rate (α) [8]. However, the duration of the growth phase is typically fast compared to the other phases (order of minutes), in particular for high fire growth rates. Often, due to the low heat fluxes, immediate flashover is assumed for structural fire engineering calculations, disregarding the growth phase (e.g. standard fire curve [10]).

The fully-developed phase of the fire is related to its regime, either ventilation-controlled (regime I) or fuel-controlled (regime II) [13,14]. For ventilation-controlled fires, the duration of the fully-developed phase (t_{max} [h]) is typically estimated according to Kawagoe's correlation to estimate the fuel burning rate and heat release rate ($\dot{Q}_{max}$ [MW]) based on the compartment ventilation conditions (i.e. opening factor) [19]:

$$\dot{Q}_{max} \cong 1.5\, A_v \sqrt{h_{eq}} \tag{5}$$

$$t_{max} = \frac{q_f'' A_f}{\dot{Q}_{max}} \cong 0.0002\, \frac{q_f'' A_f}{A_v \sqrt{h_{eq}}} \tag{6}$$

where A_v [m^2] and h_{eq} [m] are the area and equivalent height of the compartment opening, q_f'' [MJ/m^2] is the fuel load density, which is assumed evenly distributed over the fuel area A_f [m^2]. It is important to note that Eq. (5) and Eq. (6) are only valid for ventilation-controlled fires (regime I), thus are not truly representative of the decay phase.

The time-history (evolution and duration) of a fuel-controlled fire (regime II) is directly related to the fuel itself, which depends on a series of fuel characteristics, such as distribution and type. However, this is typically simplified in a maximum characteristic heat release rate for a specific fuel ($\dot{Q}_{max}$ [MW]). Accepting that $\dot{Q}_{max}$ [MW] can be computed, the duration of the fully-developed phase (t_{max} [h]) can be calculated in a similar manner as shown in Eq. (6).

In general, these expressions assume that the growth phase and the decay phase have negligible energy contribution and the heating phase is principally constituted by the fully-developed fire. Indeed, these expressions assume that the total fuel load is consumed during the fully-developed fire at a steady-state heat release rate (ventilation or fuel-controlled). Therefore, the end of fully-developed phase is defined as the point when fuel burnout is attained, hence the beginning of cooling phase. This is generally adopted in performance-based structural fire engineering because it represents a conservative approach: it is a more critical case for load-bearing structures as it is assumed that the higher temperatures of the fully-developed phase dominate over the potentially longer, but cooler, decay phase. The main limitation of this approach is that it cannot provide the time evolution of the heat flux, which is essential for a correct structural analysis.

If a contribution to the fire heat release rate is introduced for the decay phase as part of the heating phase, the fully-developed phase has to be shortened to maintain the same total fire heat release. In order to implement this, it becomes fundamental to know the moment in which the fire decay phase commences and the evolution of the heat release rate during the decay phase. Indeed, the duration of the fire decay phase is closely linked to the definition/assumption related to the heat release rate.

4.3. Heat release rate during the fire decay phase

The available literature rarely offers information regarding the fire decay and cooling phase of a post-flashover compartment fire. It is frequently assumed that the fire decay phase starts when 70–80% of the total fuel has consumed [14] and then the gas temperature (or heat release rate) decreases linearly from the maximum to zero [8]. However, in general, no theoretical or experimental effort has been made to characterise the decay phase, in particular the evolution of the heat release rate. From the experimental point of view, the heat release rate of compartment fires is rarely explicitly estimated, nevertheless it is essential to establish the manner in which the compartment is being affected and the optical depth of the smoke. In contrast, theoretical studies have been based on strong undemonstrated assumptions. The Swedish fire curves represent an interesting case, where the fire heat release rate curves were obtained by trial and error based on an energy balance and uncorrected experimental thermocouple measurements [20].

In general, as discussed in Section 2, when the fire starts decaying at the end of the fully-developed phase, it becomes again fuel-limited, as is the case for the growth phase. In the case of a ventilation-controlled fire, there is a transition from a ventilation-controlled phase to fuel-controlled. Accordingly, during the decay phase, the characteristic burning rate of the remaining fuel controls the fire dynamics within the compartment. This can be significantly different depending on the fuel characteristics. In particular, charring cellulosic fuels like wood would slowly decay, while hydrocarbon and liquid/molten fuels would quickly quench after the fuel has been fully consumed.

This is evident when calorimetry experiments in open laboratory conditions on different fuels are analysed. Fig. 3 compares the heat release rates estimated for a number (1, 2, 4, 8) of wood cribs (56 × 56cm, 46 cm tall) arranged in arrays to the heat release rates estimated for a small pool fire (19 × 13cm, 3 cm tall) with 300 mL of heptane [21]. Apart from the absolute values, it is important to qualitatively compare the evolution of the heat release rate for the two different fuels. Fig. 3 highlights how wood cribs have a relatively-fast fire growth, typically affected only by moisture and configuration of the crib. The steady-state burning is typically short in open conditions, but in a ventilation-controlled compartment fires this can be directly affected by the ventilation conditions. However, in general, after an important drop, the wood cribs are characterised by a slow fire decay: the duration of the decay phase is in the same order of magnitude to the growth and full burning phases [22]. Often, the decay phase is also influenced by smouldering phenomena occurring in charred wood.

In contrast, pool fires are typically characterised by relatively-slow fire growth (see Fig. 3). This phase is characterised by a clear transient growth of pool fire intensity generated by the evolving heat losses into the liquid, edge heating effects, tray heating, and lip effects [23]. As in the case of wood cribs, the steady-state burning is typically short in open conditions, but it also depends on the pool size and fuel quantity, as well as ventilation conditions in a ventilation-controlled compartment fire. However, differently to wood cribs, the pool fire is characterised by a fast decay: the burning rate decreases because fuel layer gets thinner, and heat losses to the tray become more important before the fire quickly extinguishes due to fuel depletion.

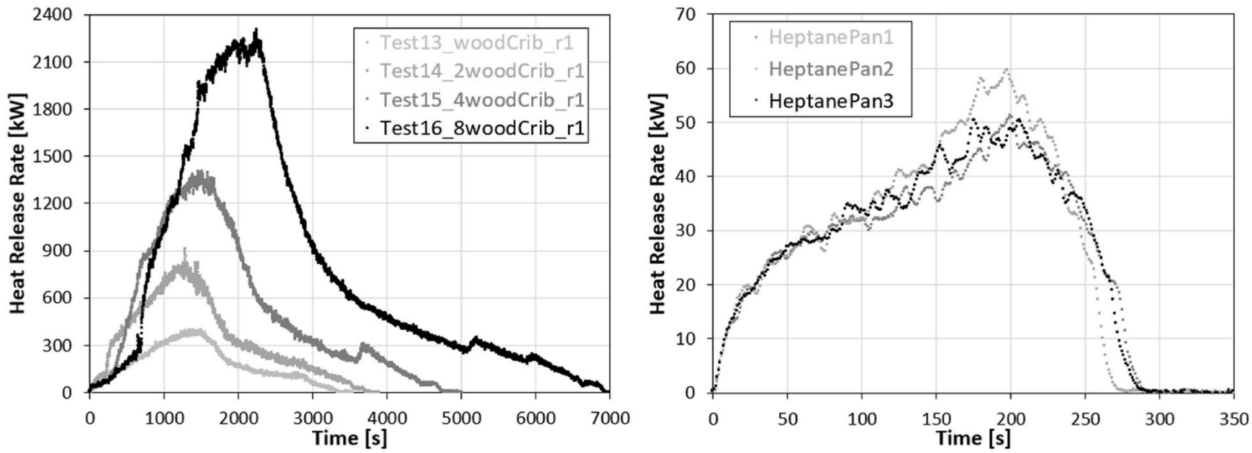

Fig. 3. HRR comparison between wood cribs (left) and pool fires (right) [21].

5. Full-scale compartment fire tests

The discussed fundamental difference in the evolution of the fire heat release rate for wood cribs and pool fires has important consequences in the fire decay phase of post-flashover compartment fires. This can be discussed by analysing two examples of full-scale compartment fire tests.

5.1. *Full-scale compartment fire test with wood crib*

The first analysed full-scale compartment fire test is extracted from the series of full-scale fire tests carried out in 1999–2000 at the BRE Cardington facilities within the scope of the "Natural Fire Safety Concept 2 (NFSC2)" series [24,25]. The experimental campaign represents one of the most well-documented experimental campaigns on post-flashover compartment fires. The series was conducted on a compartment measuring 12 × 12 m in plan, 3.4 m in height, and involved a total of eight scenarios, which differed for ventilation conditions, fuel load composition and compartment boundaries. Similarly to many other full-scale compartment fire tests, the chosen fuel was primarily wood cribs, evenly distributed throughout the compartment floor area. Test 8 is chosen for analysis, an exemplar case which has been largely used for various past analyses and modelling studies [26,27]. This scenario is characterised by an opening factor of 0.10 $m^{0.5}$ (unique opening, 7.2 m wide and 3.4 m high), a fuel load density of 680 MJ/m^2 (80% wood cribs and 20% plastic, by calorific value), and insulating compartment linings with an approximated thermal inertia of 1600 $J/m^2s^{0.5}K$ [24,25].

Fig. 4 shows the main results as regards to Cardington test 8 in terms of compartment temperatures and heat release rate during the various fire phases. The fire heat release rate could not be easily determined from the evolution of the fuel mass and mass loss rate (shown in Fig. 5) because the compartment fuel was also composed by 20% of plastic (by calorific value). This calculation requires a crucial assumption related to the definition of the burning time for the wooden and plastic fuel. Indeed, given the significantly different effective heat of combustion of the two fuels (polypropylene 43 MJ/kg, wood 17 MJ/kg), this assumption can have important consequences on the estimation of the fire heat release rate. Fig. 4 reports the fire heat release rate estimated by Kumar et al., who assumed that the early part of the heat release curve was dominated by the plastic contribution [27]. The shaded area aims at estimating the overall heat release rate for the compartment fire, following the typical behaviour of wood cribs.

Observing the results presented in Figs. 4 and 5, it can be noticed that the compartment fire quickly grew, leading to a short growth phase and achieving temperatures above 1100 °C and the maximum heat release rate in less than 10 min. A ventilation-controlled fully-developed fire followed for about 20 min. Following the fire heat release rate, it can be observed that the fire decay began around 30 min. Thus, the decay phase started relatively early, when about 50–60% of the fuel load was combusted (refer to Fig. 5). The decay phase had a long duration

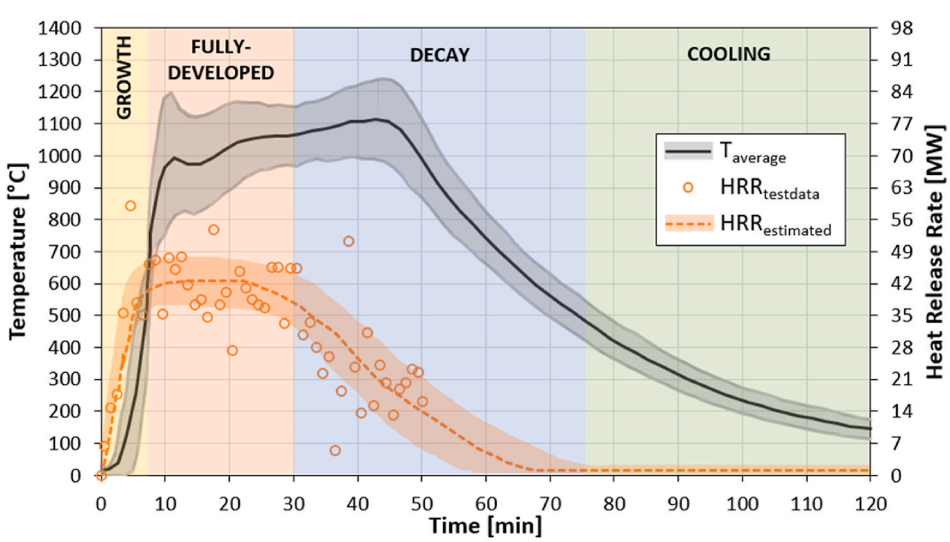

Fig. 4. Cardington fire test 8: compartment average, maximum and minimum temperatures, and heat release rate (experimental and estimated).

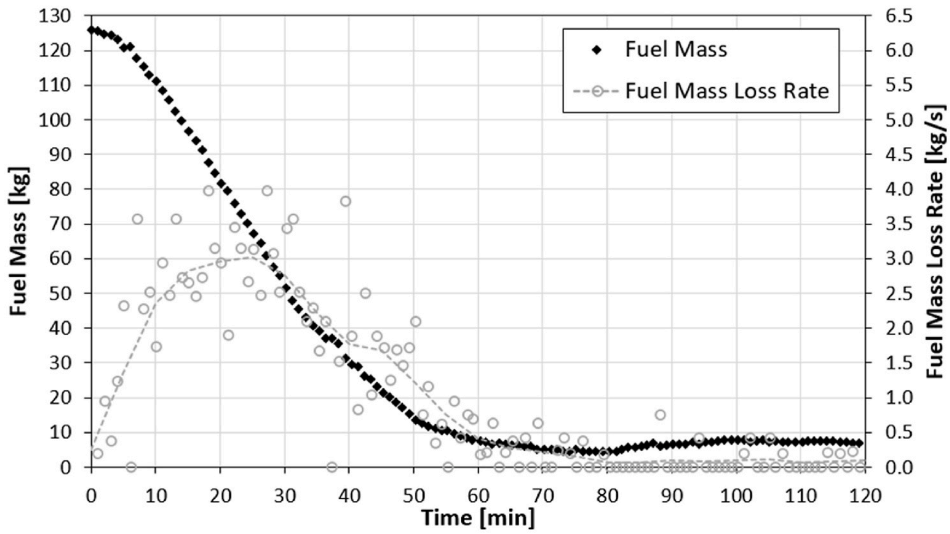

Fig. 5. Cardington fire test 8: fuel mass and fuel mass loss rate.

(approximately 45 min) mainly due to the slowly burning and extinguishment of wood cribs, which is in line with what observed in Fig. 3. Fig. 5 shows that the mass continued to significantly decrease, with a decaying burning rate, up to approximately minute 70, and only then the cooling phase started.

Fig. 4 shows a transition occurring at minute 45, where the temperature within the compartment starts decaying. This discontinuity cannot be clearly identified in the heat release rate (Fig. 4) or in the mass loss (Fig. 5), nevertheless, it is consistent with a plateau in the burning rate (Fig. 5). While the data provided by the authors [26] does not allow to conclusively establish what is the reason for this transition, it is most likely due to a change in the burning mode from ventilation to fuel-limited conditions.

During the decay and cooling phase, it is important to highlight that the temperature measurements tend to have less scattering. This related to the fact that, given the higher optical thickness during these phases, all exposed surfaces tend to thermal equilibrium. This fact has an important effect on the thermocouple measurements, which are strongly influenced by the radiation from the hot compartment linings. Indeed, they provide an estimation of the combined effects of the gas phase temperature and the radiative heat being transferred from the surface of the compartment linings [19,26].

5.2. Full-scale compartment fire test with pool fire

Differently from wood cribs, it is rarer to find full-scale compartment tests that involves pool fires and liquid fuels. An interesting example is offered by Kamath et al. [28], who performed a full-scale compartment fire test to investigate the behaviour of an earthquake-damaged reinformed concrete frame. The experimental campaign was conducted on a compartment measuring 3 × 3 m in plan and 3 m in height. The compartment had a single 3 × 1 m opening, resulting in an opening factor equal to 0.056 $m^{0.5}$. The compartment walls were constituted of steel angles and sheets combined with glass wool insulation, creating high-insulating walls. A 1 × 1 × 0.05 m mild steel tray burner was placed in the middle of the compartment and fed with kerosene for 1 h (peak flow rate of 1.43×10^{-4} m^3/s).

Fig. 6 shows the main results as regards to the compartment pool fire test in terms of compartment temperatures, obtained through three gas-phase thermocouple trees, each composed of five thermocouples (15 in total, 2 malfunctioning and not reported) [28]. In addition, Fig. 6 offers an estimation of the fire heat release rate during the various phases. This curve and its shaded area aim at qualitatively estimating the heat release rate of the pool fire (normalised with regards to the maximum steady-state value), following its typical behaviour discussed in Section

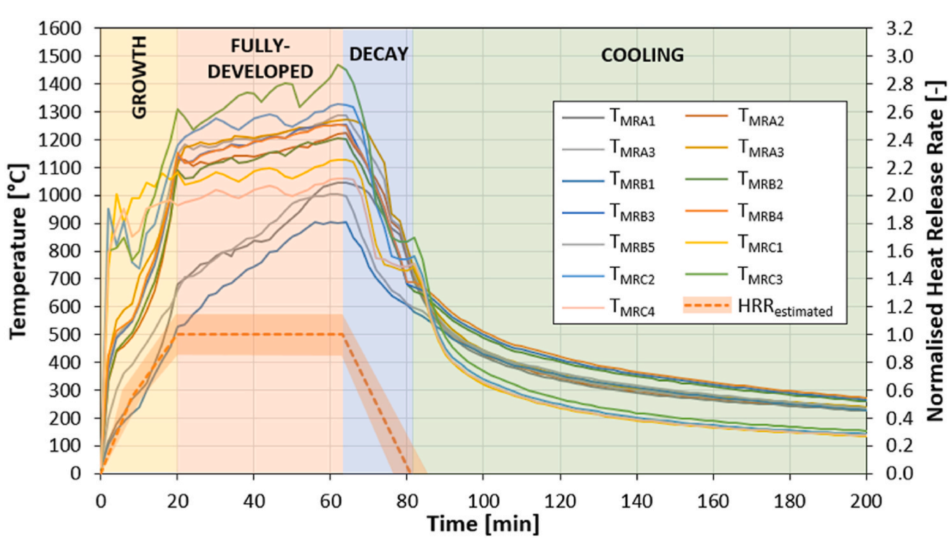

Fig. 6. Pool fire compartment fire test: compartment average, maximum and minimum temperatures, and heat release rate (estimated and normalised) [28].

4.3 and shown in Fig. 3.

Fig. 6 highlights how the pool fire had a relatively slow fire growth, leading to a long growth phase (about 20 min). The transient growth of the pool fire is also evident in the full-scale compartment fire test, as underlined in Fig. 3 and in Section 4.3 [23]. Afterwards, due to the continuous fuel supply to the pool fire and the compartment ventilation conditions, the fire underwent the fully-developed phase, which was typically ventilation-controlled and lasted for about 40 min. The authors stated that the supply of fuel to the pool was terminated after 60 min, but fuel burnout was observed after approximately 80 min from ignition [28]. Indeed, when the fuel supply was cut, the burning rate of the pool fire first increased for a short period because, as the fuel thickness decreased, heating through the tray lip was enhanced and the convective currents got suppressed. The end of the full-developed phase and the beginning of the decay phase around minute 63 are also confirmed by the temperature measurements. In this case, the decrease in burning rate is very fast so the regime change coincides with the onset of the decay phase. The end of the decay phase and the beginning of the cooling phase can be observed around minute 80 where a clear discontinuity points to the pool fire extinction. This can also be seen in the temperature measurements. Once the cooling phase starts, similarly to the wood cribs case, the temperature measurements suddenly had less scattering.

6. Discussion on existing methods

The previous sections have defined and discussed the main characteristics of the fire decay and cooling phases. In particular, the analysis has highlighted the close relationship of these two phases with the evolution of the fire heat release rate. In particular, the fire decay phase is highly fuel-dependent, and its characteristics may largely vary depending on the fuel type and distribution. The main question that arises is related to how the most adopted engineering methods for structural fire calculations deal with the decay and cooling phases of post-flashover compartment fires.

Empirical methods (e.g., BFD curves [29]) do not usually include any energy consideration, as they are obtained through empirical formula and regression techniques from experimental data.

Energy considerations come to play when the fire is defined as input, for example in terms of heat release rate time-history. This is generally the case for one-, two- or multiple zone models (e.g., OZone [30] and B-RISK [31]), as well as for applications in computational fluid dynamics (CFD) (e.g. FDS [32]). The fire can be also defined as a specific fuel with intrinsic characteristics, like ignition, pyrolysis temperature and/or flame spread rate. However, for engineering applications, the fire heat release rate is often defined as input.

For example, this is the case for the “natural fire models” defined according to Eurocode 1 [10]. This is the most commonly adopted methodology throughout Europe for performed-based structural fire engineering calculations. Fuel load densities, effective heat of combustion, fire growth rates, and maximum values of fuel-controlled fire heat release rates are prescribed, and engineers can estimate the ventilation-controlled (based on opening factor) or fuel-controlled (based on building occupancy) maximum fire heat release rate for each specific case. This value is assumed constant throughout the entire fully-developed fire phase. The decay phase is assumed to be a linear decrease starting when 70% of the total fuel load has been burnt and completed when the fuel load has been completely burnt. Analogous equations as the ones discussed in Section 4.2 can be used to calculate the duration of the various fire phases, with the fully-developed fire phase above all. In general, even if it contains strong assumptions, the methodology is robust and provides a clear definition of the fire decay phase.

In contrast, the Eurocode parametric fire curves [10] do not have this rigorous definition of the energy contribution and the fire decay phase, as for the natural fire models. The Eurocode parametric fire curves represent the most adopted methodology to parametrically simulate post-flashover compartment fires as a function of a few input parameters related to the fuel load and compartment characteristics. It is common belief that Eurocode parametric fire curves methodology is based on the same principle as natural fire models [10]. However, the duration of the fire fully-developed phase (t_{max} [h]) is calculated assuming that the total fuel load is consumed during the fully-developed phase at a steady-state heat release rate (ventilation or fuel-controlled). For instance, for ventilation-controlled fires, this is calculated as:

$$t_{max} = 0.0002\,\frac{q_t''}{O} = 0.0002\,\frac{q_f''A_f}{A_t}\,\frac{A_t}{A_v\sqrt{h_{eq}}} = 0.0002\,\frac{q_f''A_f}{A_v\sqrt{h_{eq}}} \tag{7}$$

where q_f'' [MJ/m^2] is the fuel load density related to the surface floor area A_f [m^2] and q_t'' [MJ/m^2] is the fuel load density related to the total surface area of the enclosure A_t [m^2] ($q_t'' = q_f''A_f/A_t$), and O [m$^{0.5}$] is the opening factor ($O = A_v\sqrt{h_{eq}}/A_t$).

This expression is analogous to Eq. (6), which follows Kawagoe’s theory [19]. Therefore, the Eurocode parametric fire curves assume that the total fire heat is released during the fully-developed phase, therefore the end of this phase should correspond to the beginning of the cooling phase, without any decay phase. However, the methodology proposes thermal exposures based linear temperature decrease after the completion of the fully-developed fire. Apart from the unphysical nature of these constant cooling rates, it is misleading what the Eurocode parametric fire curves are trying to represent with the suggested “cooling phase” [12,17,33]. This could be the product of several levels of overestimation to generate redundancy and safety margins, nevertheless it is hard to find a comprehensive explanation and a scientific basis to justify this choice.

In addition, Eurocode 1 [10] does not offer any guideline related to the definition of the thermal boundary conditions during the fire decay and cooling phases. The thermal boundary conditions of structural elements exposed to post-flashover fires are usually only defined for the fully-developed fire phase, when a smoke layer characterised by high temperatures and low optical thickness completely surrounds all compartment elements and exchanges heat through radiation and convection. Consequently, for simplicity, these thermal boundary conditions are usually adopted also in other fire phases, without any critical thinking. For instance, this is the case for the “cooling phase” of the Eurocode parametric fire curves methodology, where thermal boundary conditions identical to the heating phase are applied.

7. Application example

Given the lack of comprehensive studies and guidelines aimed at carefully defining appropriate thermal boundary conditions during the fire decay and cooling phases of post-flashover compartment fires, an application example is included, starting from the thermal boundary conditions described in Section 3. The presented example provides a quantitative assessment of the temperatures experienced by various compartment elements during the fire decay and cooling phases of post-flashover compartment fires, considering the influence of fuel nature (wood crib vs. liquid pool) and the optical thickness of the compartment gases (e.g. smoke).

The example examines the thermal conditions experienced by a steel column (section factor A/V 100 m^{-1}), place in the middle of a compartment. In order to highlight the influence of the compartment linings and provide a simple solution, the compartment boundaries are assumed as a steel box, 20 mm thick (high thermal inertia and lumped capacitance method for temperature calculations [34]). In total, four cases are analysed, considering different gas optical thicknesses and fire decay and cooling within the compartment.

Based on the outcomes presented in Section 5, two different temperature-time curves were defined for the compartment gas phase. The first case represents a wood crib fire, and the growth, the fully-developed, and the decay phases were defined according to the Cardington fire test 8 (shown in Fig. 4). In contrast, the second case represents a pool fire. To simply the comparison, the fire growth and fully-developed phases were kept identical, while the fire decay phase was defined combining the full-scale test presented in Section 5.2 and the typical HRR curves for pool fires shown in Fig. 3 (15 min day, from maximum to negligible HRR, therefore from maximum to ambient temperature). The defined temperature-time curves for the wood crib and pool fires are displayed in Fig. 7.

As regards to the fire growth and fully-developed phases, the thermal boundaries conditions at the structural element ($\dot{q}''_{net,str}$) and compartment linings ($\dot{q}''_{net,w}$) were defined in accordance with Section 3.2. Assuming an optically-thick environment in the compartment (i.e. dense smoke), the structural element and compartment linings primarily exchange heat through radiation and convection with compartment gas phase, hence smoke (T_g). The view factor between the smoke layer and the compartment elements (F_{sm-str} and F_{sm-w}) tend to 1, as well as the smoke emissivity (ε_{sm}). Since the compartment linings are assumed to be exposed to ambient conditions (T_a) on the unexposed side, radiation and convective losses at the unexposed side are considered. Accordingly, the thermal boundary conditions can be defined and simplified as:

$$\begin{aligned}\dot{q}''_{net,w} &= h_{c,in}(T_g - T_w) + F_{sm-w}\bar{\varepsilon}\sigma\left(T_g^4 - T_w^4\right) - h_{c,out}(T_w - T_a) - \varepsilon_w\sigma\left(T_w^4 - T_a^4\right) \\ &= h_{c,in}(T_g - T_w) + \varepsilon_w\sigma\left(T_g^4 - 2T_w^4 + T_a^4\right) - h_{c,out}(T_w - T_a)\end{aligned} \tag{8}$$

$$\begin{aligned}\dot{q}''_{net,str} &= h_{c,in}(T_g - T_{str}) + F_{sm-str}\bar{\varepsilon}\sigma\left(T_g^4 - T_{str}^4\right) \\ &= h_{c,in}(T_g - T_{str}) + \varepsilon_{str}\sigma\left(T_g^4 - T_{str}^4\right)\end{aligned} \tag{9}$$

To carry out the calculations, the steel emissivity (ε_w and ε_{str}) was set as 0.70, ambient temperature (T_a) 20 °C, and the steel density and specific heat capacity 7850 kg/m^3 and 600 J/kgK [35]. The convective heat transfer coefficient within the compartment ($h_{c,in}$) was set as 25 W/m^{2}K, while the convective heat transfer coefficient at the unexposed side of the compartment linings ($h_{c,out}$) was set as 4 W/m^{2}K [10].

To define the thermal boundary conditions during the fire decay and cooling phases, the presence of a smoke layer and the optical thickness of the compartment gases have a key role in the problem, so two opposite (extreme) cases were considered. The first case assumed the presence of an optically-thick smoke layer also during the fire decay phase and, similarly to the growth and fully-developed phases, analogous thermal boundary conditions are defined, as presented in Eq. (8) and Eq. (9). Also, in this case, the structural element and compartment linings primarily exchange heat through radiation and convection with the smoke (T_g), and the view factors (F_{sm-str} and F_{sm-w}) and smoke emissivity (ε_{sm}) tend to unity.

In contrast, if the optical thickness of the compartment gases is assumed drastically reduce at the beginning of the fire decay phase, the radiation heat transfer significantly changes, while convective heat transfer is not affected (assuming the same temperature-time curve for compartment gases). Indeed, the view factor between the structural element and the compartment boundaries (F_{str-w}) tend to zero, while the view factor between the compartment boundaries and the structural elements (F_{w-str}) tends to unity. In other words, this means that the steel column is assumed much smaller than the compartment linings surface, therefore the steel column "sees" and is affected by the compartment linings, while the compartment linings are not affected by the steel column. Accordingly, the thermal boundary conditions can be defined and simplified as:

$$\begin{aligned}\dot{q}''_{net,w} &= h_{c,in}(T_g - T_w) + F_{str-w}\bar{\varepsilon}\sigma\left(T_{str}^4 - T_w^4\right) - h_{c,out}(T_w - T_a) - \varepsilon_w\sigma\left(T_w^4 - T_a^4\right) \\ &= h_{c,in}(T_g - T_w) - h_{c,out}(T_w - T_a) - \varepsilon_w\sigma\left(T_w^4 - T_a^4\right)\end{aligned} \tag{10}$$

$$\begin{aligned}\dot{q}''_{net,str} &= h_{c,in}(T_g - T_{str}) + F_{w-str}\bar{\varepsilon}\sigma\left(T_w^4 - T_{str}^4\right) \\ &= h_{c,in}(T_g - T_{str}) + \bar{\varepsilon}\sigma\left(T_w^4 - T_{str}^4\right)\end{aligned} \tag{11}$$

Starting from the defined temperature-time curves of the compartment gases (wood crib vs. pool), the temperature evolutions of the compartment linings and the steel column can be calculated, as shown in Fig. 7. Results evidence how, for both cases, the optical thickness of the compartment gases (i.e. smoke presence and density) has a minor effect on temperature evolutions of the compartment linings and steel column. The quantification of the temperature-time curve of the compartment gases is much more important because it mainly controls the thermal boundary conditions, both during heating and cooling. This emphasises the effect of having a short fire decay phase as for pool fires, rather than having a slow fire decay phase as for wood cribs. In the case of wood cribs, the slow decay phase directly affects the temperature evolution of structural elements, in which the compartment linings have a minor influence. In contrast, the short decay phase of pool fires underlines the key role played by compartment linings during the cooling phase and in general for conditions that tend to pure cooling with semi-transparent compartment gases.

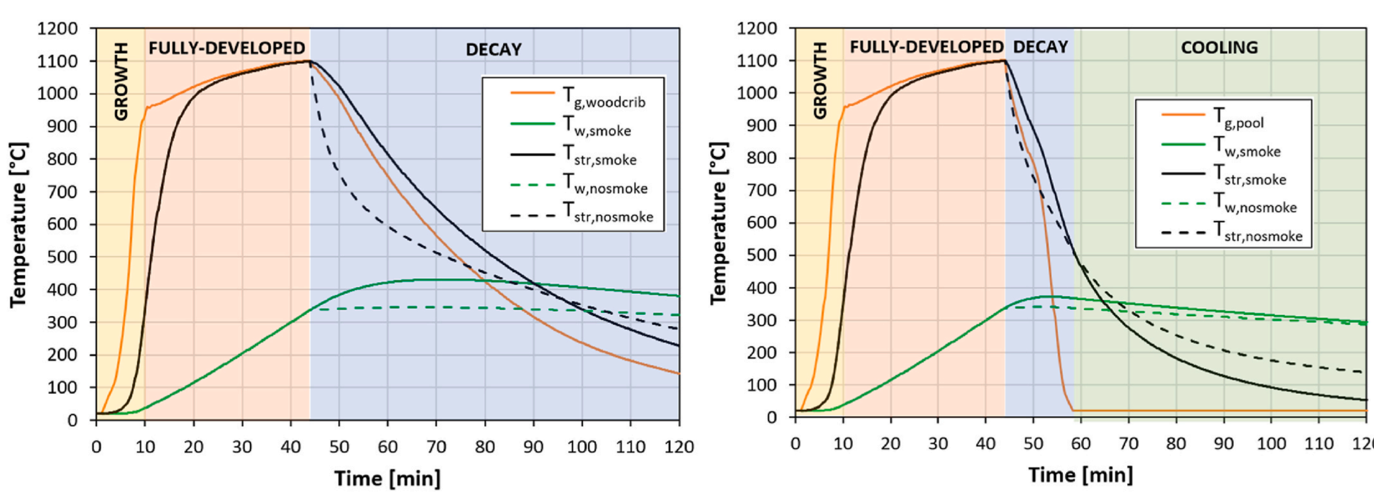

Fig. 7. Influence of compartment gas optical-thickness (smoke or no smoke) on the temperature evolution of compartment linings and structural element for a wood crib fire (left) and liquid pool fire (right).

8. Conclusions

The current research study focuses on characterising the fire decay and cooling phase of post-flashover compartment fires, which are often mixed up despite their very different heat transfer characteristics, but have key roles in ensuring the structural integrity and stability of fire/safe structures. The research study emphasises the main characteristics, especially as regards to the evolution of the solids and gases temperatures, smoke layer and gases optical thickness. After the fire has reached flashover and sustained the fully-developed phase, the fire heat release rate starts to diminish, evolving towards fuel burnout. This instant represents the beginning of the fire decay phase and the fire returns to be fuel-controlled. In particular, experiments have shown how charring cellulosic fuels like wood typically have slow decay, while hydrocarbon and liquid fuels quickly quench after the fuel has been fully consumed, resulting in a fast decay. Once the fire extinguishes and the heat release becomes negligible, the compartment enters the cooling phase, which is characterised by different modes of cooling for the gas-phase and the solid-phase. While after flames quenching the compartment gases quickly become optically thin and return to ambient temperature, the compartment solids (e.g. linings) slowly cool down through surface convective and radiative cooling following their thermo-physical properties.

The study evidenced how the fuel-dependent heat release rate governs the transition between the decay and cooling phases, which in turn are characterised by different thermal boundary conditions. Based on the described fire phases, the corresponding thermal boundary conditions at the structural elements are then defined and the various phases are directly associated with the fire heat release rate, so they can be univocally differentiated. The heating phase is considered as the period after fire ignition that provides a heat gain to compartment enclosure. In contrast, the cooling phase concerns all the instants after fuel burnout, when the fire heat release rate is null or negligible.

The existing methodologies for performance-based design of structural elements exposed to fire offer various approaches to treat this problem, but they are typically not explicit in the definition of the various phases. For instance, it is often unclear if the total fuel load is assumed to be consumed during the fully-developed fire phase, or significant heat release rate is expected during the fire decay phase. In addition, guidelines related to the definition of the thermal boundary conditions for the fire decay and cooling phases are rarely presented. Consequently, for simplicity, the thermal boundary conditions for fully-developed fires are usually adopted also in other fire phases, with limited physical justification.

Given the aim to reproduce more realistic fire conditions for modern performance-based methodologies for the design of fire-safe structural elements, there is a need to better define and treat all the various phases of compartment fires and the corresponding thermal boundary conditions. The continuous publication of research studies focused on the performance of load-bearing structures exposed to the "fire decay phase" or "cooling phase" require consistency in the definition of the thermal boundary conditions and the compartment conditions that they are aiming at reproducing. Only in this way, performance-based design methodologies for fire-safe structures until complete fuel burnout can be truly ensured.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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