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Review

Forty years of material flammability: An appraisal of its role, its experimental determination and its modelling

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ABSTRACT

Material flammability is a fundamental aspect of fire as it corresponds to the root of a fire. Its characterisation through the identification of "fire properties" is essential. The concept of material flammability has evolved in the past forty years and its experimental and numerical development has followed the evolution of its role in the Fire Safety Engineering strategy. Two main approaches coexist: ranking-based and comprehensive. While the ranking-based approach is still mainly used in a prescriptive strategy, comprehensive approaches, more fundamental, expand with the growing use of the Performance-Based strategy.

There are weaknesses associated with both approaches. The origin of these weaknesses can be understood by investigating the difficulties associated with the measurement and the modelling of material flammability.

It ends up that despite the significant improvement in the past forty years, material flammability still represent a weak point in the global assessment of the fire safety level. Indeed, while the Heat Release Rate (HRR) is considered as the most important parameter in Fire Safety Engineering studies, it is also probably the "fire property" with the highest uncertainty.

However, material flammability should not and cannot prevent innovation and building construction. This implies that the fire safety level should be thought of as a societal risk.

1. Concept of material flammability

Material flammability is one of the predominant domains of Fire Safety Engineering (FSE) since it embodies the root of a fire and it governs its evolution. Indeed, the flammability of a material is characterized by its ease of ignition, the rapidity of the fire growth over its surface (*i.e.* continuous flame spread) and the production rates of heat, smoke and toxic components resulting from its combustion.

Fig. 1a is an ideal representation of the different phases that constitutes a fire whereas Fig. 1b and c show experimental data, respectively from bench-scale and full scale tests. Fig. 1a should be considered only for illustration purposes since it is common for real solid material that the steady burning phase is either significantly reduced or not reached before the decay starts (Fig. 1b). Alternatively, for some materials such as liquids, flame spread over the surface can be very fast, so that steady burning is reached almost instantaneously (according to the material surface area). Detailed reviews of these fire phases (with their embedded complexity) are available in the literature [1,2].

Material flammability cannot be expressed by a single quantifiable property since it is composed of different phases. However, a set of "fire properties" can help to define the processes of each phases [2,3]. "Fire properties" are not true material properties. This term shall be kept general. The set of "fire properties" suggested by Lautenberger et al. [3] to characterize solid material flammability is listed in Table 1. While this set is focused on solid material, material flammability is not constrained to a specific material state. Indeed, fire properties exist also for liquid and gas materials (*e.g.* flashpoint and firepoint for liquids or Lower Flammability Limit (LFL) and Minimum Ignition Energy (MIE) for gases and vapours). Nevertheless, a specific attention will be paid to the condensed phases in this paper.

The relevant "fire properties" to characterize material flammability are based on the mathematical representation of the fire phases from Fig. 1a. The definition and the number of "fire properties" evolve therefore with the sophistication level of the mathematical model (*i.e.* the physical and chemical mechanisms embedded in the model).

The "fire properties" can be divided into two groups: microscopic and macroscopic properties. The former, called internal factors by Atreya [6], are material properties. In theory, they are not dependent of the fire environment. They incorporate in particular the thermo-physical properties (*i.e.* density, specific heat and thermal conductivity), the radiative properties (*e.g.* absorption coefficient) and the kinetic parameters (*i.e.* parameters defining the reaction rate).

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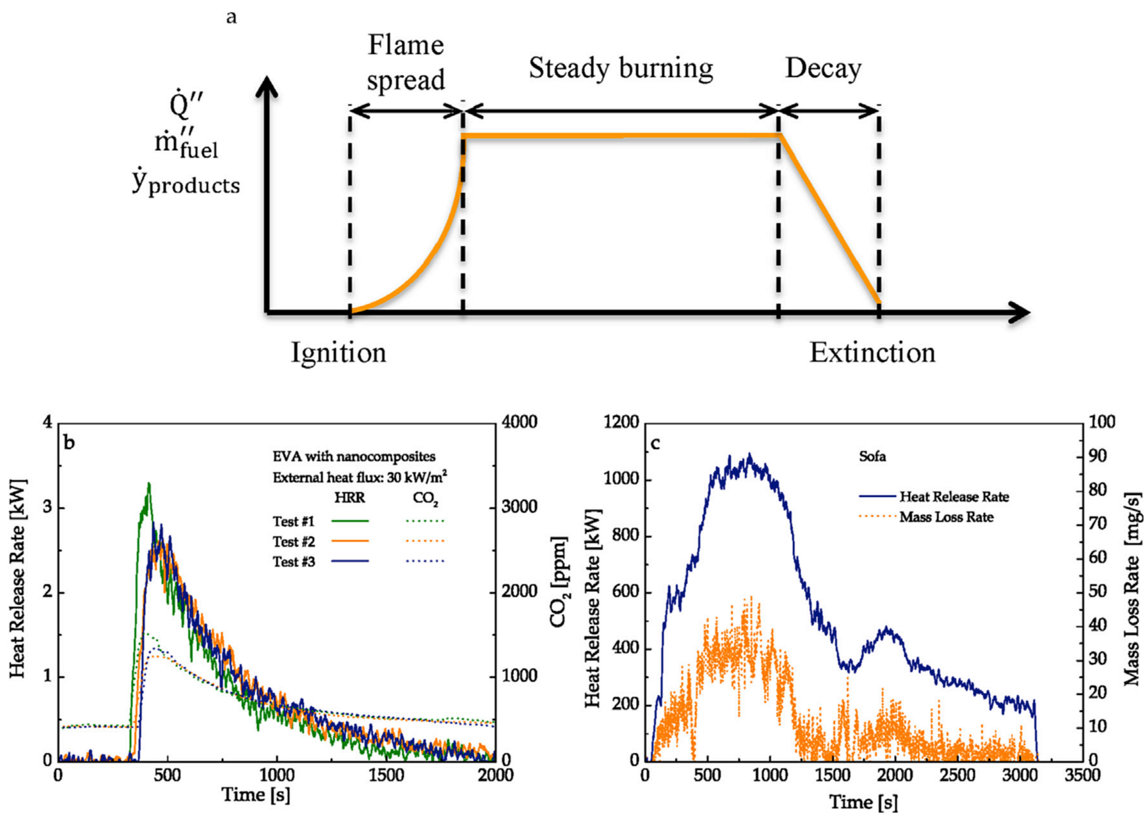

Fig. 1. a) Theoretical and b-c) experimental evolutions of the fire phases characterizing material flammability. Experimental data: b) Ethylene vinyl acetate (EVA) with nanocomposites (bench-scale using Fire Propagation Apparatus) [4] and c) Sofa (real scale using Oxygen consumption calorimetry) [5] ($\dot{Q}''$ and $\dot{m}''_{fuel}$ represent respectively the heat and the mass release rate per unit area while $\dot{y}_{products}$ is the production rate of species such as Carbon dioxide).

Table 1
"Fire properties" suggested by Lautenberger et al. [3] to characterize solid material flammability.

Ignition	
T_{ign}	Surface temperature at ignition
$k\rho c$	Apparent thermal inertia
$\dot{q}''_{critical}$	Critical heat flux for ignition
Flame spread	
T_{ign}	Surface temperature at ignition
$k\rho c$	Apparent thermal inertia
ω	Flame spread parameter.
Burning and heat release rates	
$\Delta H_c/\Delta H_g$	Heat release rate parameter or combustibility ratio
Smoke and toxic component production rate	
y_i	Species yield

The macroscopic "fire properties", which correspond to global properties, are affected experimentally by:

- the environmental conditions such as the flow field and the atmosphere composition;
- the general scenario configuration such as the mode of external heating and the material orientation.

Both fire environment and general scenario configuration form what Atreya called the external factors [6]. The flame spread parameter [1], the heat of combustion and the ignition criterion are macroscopic "fire properties".

Although the microscopic "fire properties" are in theory fundamental material properties, in practice they generally cannot be measured directly. Their extraction requires the use of a model that encompasses simplifications. These "fire properties" cannot therefore be considered as true material properties since their value will be affected by the model used and its associated assumptions. This can be the case for the thermal inertia which, by definition, is based on the product of three thermo-physical properties but that becomes a global property when estimated from measurements of piloted delay time to ignition [7]. This global property is, in that case, apparatus dependent.

Finally, the "fire properties" are not necessarily constant over time (*e.g.* upward flame spread parameter).

2. Material flammability in FSE strategy

2.1. Evolution of the role of material flammability in the FSE strategy

The requirements in terms of material flammability depend on its place in the FSE strategy. The latter has evolved over four decades. Prof. Edwin Smith [8], who was one the pioneers in the early 70s, suggested that material flammability can be defined in terms of ignitability, heat release rate (HRR) and total heat release with the ultimate objective of affirming the importance of material flammability in the FSE strategy: "*Combustibility of building materials, furnishings, and occupancy must be known before a rational evaluation of a structure's resistance to the development of a catastrophic fire can be made*" [8].

Historically, the goal was not to quantify material flammability to predict fire development and its consequences, but only to minimize both of them. The materials were ranked according to their contribution in the different fire phases from Fig. 1. This strategy, based only on a qualitative evaluation of the material flammability, is called the ranking-based approach.

Innovations such as the development of fire retardants and the

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