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Rapid Estimation of the Heat Release Rate of Combustible Items

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Heat release rate (HRR) from a fire is the most important parameter to describe the potential hazards posed from a fire. Indeed, the environmental consequences of a fire in a confined space depend in large measure on the HRR. Typically, the HRR curves of combustible items are determined in laboratory experiments. For the aim of a rapid hazard assessment, it is infeasible to perform fire experiments on every combustible item inside a given building due to the costs and the time required. Therefore, approximations should be adopted.
In this work, we propose a simple method to estimate the HRR curve of a generic combustible item or group of items, through a conventional HRR curve (t-squared growth, peak HRR and linear decay).
The conventional curve is drawn considering two main elements: the exposed surface and geometry of the combustible items and a categorization of the constituent materials of the combustible items.
Indeed material type and geometry of the combustibles influence the fire growth, while exposed surface and material type are of importance when considering peak HRR.
Results are compared with full-scale experiments available in the literature, showing the validity of the approach.
The method can be usefully adopted to estimate HRR curves of single as well as multiple combustible items especially in existing activities, where data can be collected from an inspection of the premises aimed at a rapid fire hazard assessment.

1. Introduction

Fire safety management in existing buildings requires the pro-active prediction of the potential fire scenarios, which may induce fatalities, injuries, and structural damages, loss of functionality and economical losses for the exposed assets.
It is worth noticing that the evolution of a fire within a building or enclosed space is addressed by the interaction between the enclosure and the combustion process. Such interaction is very complex; nevertheless, it is important to predict the resulting conditions in order to manage fire safety both in ordinary and emergency conditions. Grimaz and Tosolini (2013) and Grimaz et al. (2014) proposed respectively an approach to assess the egress system safety and fire safety in existing premises to support the decision making of the stakeholders. In both the methods, the assessment process is based on the inspection of the workplace and the recognition of a limited number of important indicators, than the fire hazard is described through emergency scenarios. This approach has been further developed in Dusso et al. (2015) to assess the explosion hazard in small premises and in Dusso et al. (2016) to assess fire hazard. In the latter work, the potential adverse situations that characterize the analysed system are identified through the rapid, visual recognition and characterization of the fuel packages. A fuel package is a group of combustible items whose characteristics and arrangement are such that the ignition of one item can be expected to cause the spread of fire to the remaining items in the group, mainly due to radiation from fire. The potential fire-induced adverse situations are then described through two indicators: the first is a qualitative description of the potential fire pattern, and the second is a quantitative evaluation of the thermal load on sensible targets, based on Hot Gas Layer Temperature (HGLT).

However, it is worth noting that any quantitative evaluation of the fire consequences requires the evaluation of the heat release rate of combustible items in fire. Indeed, the heat release rate is the most important parameter to describe the fire hazard in buildings (Babrauskas and Peacock, 1992). The fire consequences such as the hot gas layer temperature and rate of descent of the smoke layer, the likelihood of flashover and the ignition of other items placed near to the burning one can be calculated based on heat release rate from the fire. A major problem remains the evaluation of the heat release rate associated with the combustibles in the building. Therefore, in this framework, a method to rapidly evaluate the heat release rate of single combustible items or group of items is needed to perform a quick fire hazard assessment.Typically, heat release rates of combustible items are determined in laboratory experiments: full-scale HRR can be directly measured through two types of techniques: open-burning HRR calorimeters and room fire tests. On the other hand, the Cone Calorimeter is frequently used to measure the small-scale HRR. Further details about these technics can be find in Babrauskas (2016). Nowadays, there are many measurements of the fire behavior of different combustibles, as an example upholstered furniture and mattresses have been studied in the CBUF project (CBUF, 1995) and in Krasny et al. (2001); fire tests on electrical household appliances are presented in Hietaniemi et al. (2001); tests concerning household materials (Vincent et al. 2015) and surface and lining materials have been presented among others by Wickstrom and Goransson (1987), Sundstorm (2007) and Collier (2007). Results of different fire experiments on various objects are collected e.g. in Sardqvist (1993), Kim and Lilley (2000) and Babrauskas (2016). Notice that although data may be available from laboratory experiments in the literature, such data may not apply directly to the specific, real-world fire situations (Kim and Lilley, 2000). Indeed, the laboratory data does not usually take into account the enhancement of burning rates because of radiation feedback, or the effect of low oxygen concentrations. On the other hand, there may be significant size and mass as well as material differences between the experimental items and the objects of interest. However, since it is infeasible due to costs and time required to obtain and perform fire experiments on duplicates of every combustible item or group of items inside a given building, it is necessary to rely on some approximations. Babrauskas (2016) proposed to use the HRR curve of the closest matching object from available literature to approximate the burning behavior of a given item, introducing corrections for size and mass differences between the experimental items and the object of interest. On the other hand, various prediction models have been proposed for the estimation of the heat release rate of specific categories of combustible items, e.g. Babrauskas and Krasny (1985) for upholstered furniture; Wickstrom and Goransson (1987) for lining materials.However, such methods were primarily intended for the estimation of the burning behavior of a specific range of combustible items and they would not be effective for different combustible items. On the other hand, the methods give insights on the most important characteristics to look for in order to evaluate the HRR of an object. An alternative approach for quantifying the heat release rate, often used in design situations is to estimate the fire characteristics based only on use and occupancy. This is a rather simple method and suggested values can be found in various literatures such as ISO 16738-2 (2009) or EN 1991-1-2 (2002). However, this approach is not suitable if the aim is the assessment and evaluation of the actual characteristics of a building.This work discusses a rapid method that allows a first evaluation of the heat release rate of single combustible items or group of items based on the elements that can be collected during an inspection of the building.

2. Methodology

2.1 The conventional HRR curve

From a theoretical point of view, the heat release rate is the product of the fuel weight loss and the heating value of a unit mass of fuel, however from a more practical perspective, in fire engineering it is usually approximated through the conventional curve shown in Figure 1. Generally, the evolution of the fire is divided into four phases: pre-growth, initial growth, steady or maximum burning and decay. Therefore, to describe characteristics of HRR curves, one has to determine the time to start initial growth, the time to grow to maximum burning (t_{max}), the time to end of maximum burning and start the decay phase (t_{decay}) and the time to decay to burnout of principal part (t_{tot}) and the maximum HRR (HRR_{max}). Among these periods, the initial growth, maximum burning and decay phases are the main parts. Indeed, the pre-growth period is affected by many uncertain factors and it is generally neglected (Karlsson and Quintiere, 2000) although it can play an important role when considering ASET (Available Safe Egress Time) for people. In such a way, the HRR curve is shifted to the left by the length of pre-growth period, and the HRR curve is approximated by three components: time squared-growth, steady burning and decay. The most common way to describe the heat release rate during the growth stage is with the t^2-fire and the following relation gives the heat release rate:

$$HRR(t) = \alpha \cdot t^2 \tag{1}$$

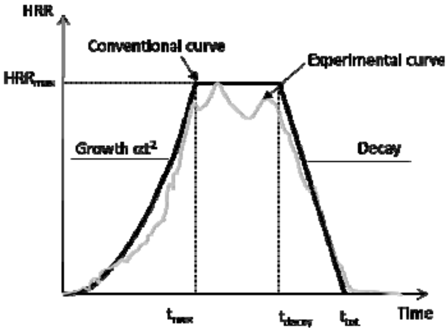


Figure 1: Sketch of a general HRR experimental and conventional curve.

Where α is the fire growth coefficient (kW/s²) and t is the time (s). Values for α are associated with specific growth rates and times to reach a conventional reference HRR of 1055 kW (0.003 for Slow; 0.012 for Medium; 0.047 for Fast; 0.188 for Ultra-fast fire). It is worth noting that the growth rate of the fire has a significant impact on the ASET, as showed in Tosolini et al. (2012 and 2013) through numerical simulations. The growth phase lasts until the maximum HRR is reached at t_{max}, this interval of time can be assessed introducing the value of HRR_{max} in equation (1) and solving for t. The HRR_{max} depends on both the characteristics of the object (materials, thickness, shape, burnable surface) and on the ventilation, which can cause the transition from a fuel-controlled fire to a ventilation-controlled fire. In general terms the maximum heat release rate is

$$HRR_{\max} = \min\left(HRR_{peak}; HRR_{flashover}\right) \quad (2)$$

Where HRR_{peak} is the peak HRR of the object or group of objects, while $HRR_{flashover}$ is the heat release rate corresponding to the establishment of flashover. However, in the present work, we focus on HRR_{peak}, therefore assuming free-burning conditions (no ventilation-controlled combustion). Assuming this simplified HRR curve, there is a need for a method that allows a first evaluation of the growth rate and maximum heat release rate of single combustible items or group of items starting from the elements that can be collected during an inspection of the building.

2.2 Growth rate

The analysis of literature on fire experiments shows that it is possible to identify the following relation between the growth rate α and the characteristics of the combustibles:

$$\alpha = f\left(\text{GEOM; FUEL; VENT}\right) \quad (3)$$

Where GEOM represents the geometrical factors of the combustible materials (thickness, shape), FUEL represents the type of combustible materials and VENT represent the effect of ventilation. However, assuming free burning conditions (and hence fuel-controlled combustion) it has been derived the following Table 1. In Table 1, combustible items have been categorized according the material type and thickness, in such a way it can give guidance in the definition of the growth rate of a fire involving a combustible item or group of items.

2.3 Peak heat release rate

It seems reasonable that peak HRR depends on the burnable exposed area (A) and material type (FUEL) of combustibles, as well as on the ventilation conditions (VENT):

$$HRR_{peak} = f\left(\text{A; FUEL; VENT}\right) \quad (4)$$

Assuming free burning conditions, the peak heat release rate for the fuel-controlled fire can be estimated by looking for values of the heat release rates per unit area, HRRPUA (kW/m^2), for the item or group of items and by estimating the burnable area (A_b). Therefore, the peak heat release rate HRR_{peak} is given by:

$$HRR_{peak} = HRRPUA \cdot A_b \quad (5)$$

Hietaniemi and Mikkola (2010), based on the results of small-scale experiments on both wood and plastic materials, proposed the values for HRRPUA summarized in Table 2, which have been adopted as a reference in the present method.

Table 1: Potential growth rate α associated with different categories of combustible solids.

Item characteristics (FUEL, GEOM)	Typical items	Growth rate	Reference
Wood-based, thick materials (thickness > 20 mm)	Wood furniture, timber, books	S	Babrauskas (2016); Gann et al. (2001)
Wood-based, thin materials (thickness ≤ 20 mm)	Paper, interior finish and lining materials, cardboard boxes, fabrics, wood furniture, wood pallets	F ÷ UF	Babrauskas (2016); Gann et al. (2001); Sardqvist (1993); Lawson et al. (1983)
Electronic devices and electrical household appliances	Computer, printer, power panel, TV set, dishwasher, washing machine, refrigerator	S ÷ M	Bundy and Ohlemiller (2004), Hietaniemi et al. (2001)
Plastic materials	Upholstered furniture (chair, sofa, mattress)	M ÷ F	Gann et al. (2001)
Plastic materials, thin	Linear furnishings (curtains, displays, stands)	F ÷ UF	Hoglander and Sundstrom (1997); Ahonen et al. (1984)
	Thin plastic furniture (stackable PP chairs) and other thin plastic objects (bin, boxes, packaging material)	F ÷ UF	Babrauskas (2016); Hoglander and Sundstrom (1997)
Cooking materials	Oil, food snacks (potato chips and cheese nibbles)	F ÷ UF	Babrauskas (2016); Gann et al. (2001)

3. Application of the method to a case study: office workstation

To assess the capability of the proposed method to identify the growth rate and peak HRR of combustible objects, a case study has been selected from literature. Madrzykowski and Walton (2004) performed fire experiments on a single office workstation (figure 2). A single workstation included several combustible items: a workstation, a computer with monitor and keyboard, an office task chair and a sled base chair. In addition, papers, letter trays, notebooks, a telephone and a phone book were placed on and in the desk. A wastebasket and two recycling bins were placed under the desk. The workstation can be assumed as a fuel package; indeed, due to the characteristics of the objects and distribution of the items they can involve each other in the fire and burn as a single item. Since the workstation geometry and the constituent items and materials are described in detail in the original work, it has been possible to estimate both the growth rate and the peak HRR following the method presented in the previous section. The workstation fuel package is characterized by thin plastic materials (letter trays, bins, lining material of the workstation), which can be characterized by a F or UF growth rate according to Table 1. Other materials such as the electronic materials and the desk can be classified with a Slow to Medium growth rate (Table 1); however, in order to be on the safe side, a growth rate ranging from F to UF has been selected. The single workstation fuel package covered a floor area of approximately 1.93 m by 1.63 m. The workstation panels, which formed two complete sides of the workstation and two partial sides, were 1.04 m high and 0.054 m thick. Both sides of the panels are exposed to the fire. Therefore, the burnable area A_b is approximately 13.2 m^2.

The workstation fuel package is made of cellulosic materials as the main constituent (paper, books and the hardboard constituting the desk and workstation side panels) as well as plastic materials (office chair, letter tray, wastebasket, electronic devices and lining material of the workstation panels). Therefore, the HRRPUA is assessed to be 300 kW/m^2. According to eq. (4) the peak HRR is 3960 kW.

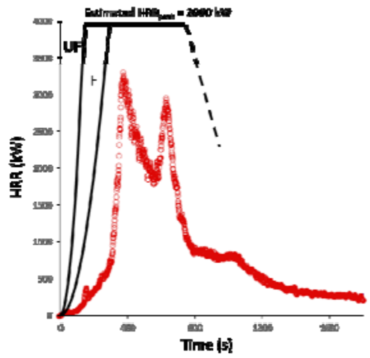
The fire experiment with the workstation was conducted under “free burn” conditions, which means there were no compartmentation effects and no ventilation limits. Comparison of the estimations with the results of the free-burning experiments is reported in figure 2. The experimental HRR curve resembles a Medium growth rate in the first 200 s followed by a UF growth. The measured peak HRR is about 3300 kW.

It is worth noting that despite the simplifications introduced in the method, it allows to obtain reasonable estimations of the growth rate and the magnitude of the peak HRR (20% overestimation) for the considered fuel package.

Table 2: Heat release rate per unit area for different materials (derived from Hietaniemi and Mikkola, 2010). ΔHc: heat of combustion.

HRRPUA (kW/m^2)	Description of the fuel package
150 ÷ 250	Cellulosic materials such as wood and paper products. Plastics with ΔHc < 10 MJ/kg may fall into this category. E.g. PFTE (teflon), heavily halogenated plastics.
300	Cellulosic materials and some plastics that are fire retarded or plastics with 10 MJ/kg ≤ ΔHc < 20 MJ/kg fall into this category. E.g., different PVCs, fire retarded plastics. Furniture fire load may fall to this or the next category.
500	Mixtures of cellulosic materials (major ingredient) and highly combustible plastics such as ABS, PE, PP and PS, or fire loads with plastics such as PET, POM, and PMMA as the principal component. Plastics with 20 MJ/kg ≤ $ΔH_C$ < 30 MJ/kg: e.g., PMMA (plexiglass), polycarbonate, PU, EPDM (rubber) may fall in this category. Furniture fire load may fall also into this category.
1000 ÷ 1500	Notable amounts of non-fire retarded plastics materials with ΔHc ≥ 30 MJ/kg may fall in this category. E.g. nylon, ABS, PE, PP. such ABS, PE, PP and PS. The other materials may be, e.g., cardboard boxes, wood, etc.

a)



b)

Figure 2: a) Single workstation fuel package (Madrzykowski and Walton (2004)). b) Comparison of the experimental HRR (dotted curve) and the estimated HRR for the single workstation.

4. Conclusions

The heat release rate (HRR) is the most important parameter to describe the fire hazard in buildings, since the environmental consequences of a fire depends largely on it. The HRR of an object depends on both intrinsic properties of the items as well as on boundary conditions, i.e. ventilation, compartment effects, ignition source. In this work we assumed as a reference a conventional HRR curve with a t-squared growth phase and a peak, steady state phase and we developed a simple method that allows a first, rapid estimation of the growth rate and peak HRR of a single combustible item or a group of combustible items. The method is based on a categorization of material type and of the geometry of the items (shape and burnable surface). The method adopts simplifications of the actual, complex behavior of the fire and relies essentially on the results of free-burning experiments in the literature. We applied the method to a case study. We noticed that despite the simplifications introduced in the method, it allows to obtain reasonable estimations of the growth rate and the magnitude of the peak HRR (20% overestimation).Quite clearly, several sample test cases should be analyzed to extend the validity of the method. However, it can be useful to perform a preliminary fire hazard assessment and to create hazard maps covering the building based on the different categories of growth rate (Table 1) and HRRPUA (Table 2).

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