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Quick Assessment of Fire Hazard in Chemical and Pharmaceutical Warehouses

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The evolution of fires in confined space such as chemical and pharmaceutical warehouses is characterized by the complex interaction between the combustion process, the enclosure and occupants, which has to be managed when coping with fire emergency and, more in general, for fire safety.
This paper proposes a quick, decision-making tool based on adversity scenarios and more specifically through the definition of four main elements: i) the potential fire spread categories, which describe the potential paths and extents of fire propagation; ii) the thermal load expressed as hot gas layer temperature; iii) the available safe egress time (ASET) for people to leave the enclosure, which is essential for organizing people evacuation; and iv) other specific hazards.
The proposed tool can be usefully adopted to improve the level of information to interested stakeholders (building owner, fire service, etc.) concerning both the fire hazard and the building fire performance.

1. Introduction

Fires constitute one of the most important hazards from chemical and pharmaceutical warehouses. They can give rise to serious damage to people as well as to the environment and they can cause extensive economical losses. For these reasons, in order to assist the management to identify the most suitable countermeasures (both organizational and technical), it is useful to have a tool that allows identifying in advance the potential adverse situations that could characterize the analysed system. In the present work, two indicators describe the potential fire-induced adverse situations, the first is a qualitative description of the potential fire, and the second is a quantitative evaluation of the thermal load on sensible targets, based on Hot Gas Layer Temperature (HGLT).
The assessment process is based on the inspection of the workplace (Dusso et al., 2015): the workplace is divided into cells, i.e. single rooms or enclosures, or in more in general, subsections of the same workplace separated from those adjacent by physical elements as walls or floors and - in the open - barriers or separation distances. Then, important information regarding the characteristics of the stored materials, the storage conditions and the features of the enclosure such as floor area, ceiling height, openings should be collected.

2. Qualitative description of the fire through potential fire scenarios

The qualitative evaluation aims at rapidly identify and communicate the fire-induced adverse situation. Indeed, it gives insights on the potential fire propagation paths and extent of the potential fire. These information are useful to point out evacuation impediment for occupants (e.g. due to fast horizontal propagation of the fire that can stop evacuation routes), to plan firefighting actions/tactics and to assist management in choosing between different countermeasures to improve the safety level of the premises and to protect the exposed assets.
We have defined the potential fire scenarios in Table 1, which describe the potential worst-case adverse situation that could characterize the analyzed cell. The definition of the scenarios is based on the concept of fuel package.

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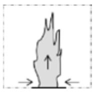
Table 1: Definition of conventional potential fire scenarios.

Potential Fire Scenario		Description of the fuel package
	Small, isolated fire	Combustibles are separated both in the horizontal and vertical plane. The fire remains confined to a single combustible item or near the area of origin because the heat released is not sufficient to spread the fire to other combustibles.
	Isolated fire with vertical propagation or torching effect	Combustibles are separated in the horizontal plane, while in the vertical plane there is a continuous distribution of fuels, so that the flames could propagate in vertical direction.
	Fire with horizontal propagation	Continuous fuels arrangement (in linear or planar configuration) in the horizontal plane. In the vertical plane, all materials rest on the surface or immediately above the floor or ground.
	Fire with vertical and horizontal propagation	Continuous fuel arrangement in both the horizontal and vertical plane, constituting a single large fuel package. The fire can propagate both horizontally and vertically and it can reach the full involvement of all the combustibles inside the enclosure.
	Wall/ceiling fire	Continuous fuel arrangement on walls and/or ceiling and/or floor (e.g. lining materials, insulation).

NFPA921 (2011) defines a fuel package as 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 strength of the fuel package concept is that it allows taking into account the predisposition, or susceptibility, of the storage conditions that lead to specific fire scenarios. The predisposition concept was defined in Grimaz and Pini (1999) and further developed in Grimaz et al. (2014). The predisposition concept is translated in practical terms in the following characteristics of the storage conditions: separation distances between combustible materials, as well as their ignitability and confinement and packaging conditions. These characteristics define whether the arrangement of the combustible materials is continuous rather than separated and therefore allows identifying the potential fire scenario. NFPA555 (2007) defines conventional separation distances beyond which the objects are not considered part of the same fuel package. The distances are 140 cm, 90 cm and 40 cm for easy-, normal-, and hard-to-ignite objects respectively. The confinement conditions and the surfaces of the combustibles potentially exposed to external heat play an important role on fire propagation as well and they are classified according to the approach adopted in Grimaz et al. (2012) for atmospheric emissions of hazardous substances (Table 2). Clearly, also the combustibles should be characterized in order to point out their intrinsic hazards. Therefore, during the inspection of each cell, important indicators should be collected through the analysis of the safety data sheets of the chemicals or other combustibles. This allows identifying the flammability, reactivity and health hazards posed by the substances. These hazards can be described quickly and synthetically through the flammability number (NF), reactivity number (NR) and health number (NH) as proposed in NFPA704 (2007). Furthermore, when considering fire hazard, the heat release rate (HRR) is essential. This parameter has to be considered when the question is 'How big is the fire?' (Babrauskas and Peacock, 1992). The growth rate of the potential fire is also an essential parameter to assess ASET (Available Safe Egress Time) for people to leave the building (Tosolini et al. 2012). Egress system vulnerabilities can be checked through PASS method (Grimaz and Tosolini, 2013).

The peak heat release rate ($HRR_{peak,E}$) is of importance in order to assess the effects of the fire. IF solid fuel packages are of concern, two approaches have been found suitable for the aims of the present rapid assessment tool, the Natori (2008) and Hietaniemi and Mikkola (2010) approaches. Both relate the peak HRR to the exposed surface of the combustible items ($A_{fuel\ package}$) and takes into account the effects of different materials considering two main categories: plastic-based materials and wood-based materials (Equation 1).

Table 2: Qualitative ranking of the confinement conditions.

Confinement conditions	Conventional contribution to the fire
In closed, non-combustible containers or cabinets.	No contribution to the fire.
In open non-combustible containers or cabinets.	90% of the combustible can contribute to the fire.
In combustible containers, or unconfined materials.	All the combustible can contribute to the fire.

$$HRR_{peak,E} = k_{material} \cdot A_{fuel\ package} \quad (1)$$

Here, $k_{material}$ is a constant depending from the material type. Natori (2008) determined $k_{material}$ from a correlation analysis of over one hundred full-scale experiments. For items commonly used in offices it takes the values of 238 kW/m^2 and 476 kW/m^2 for wood based and plastic based objects, respectively. The approach of Hietaniemi and Mikkola (2010) is similar, but the constant has been determined from small-scale experiments in cone calorimeter for different categories of materials. For liquids, equations to estimate the peak HRR can be find in many essential textbooks, e.g. Babrauskas (2002).
The results of the qualitative evaluation are presented for each analyzed cell through a pictogram (Figure 1), which is suitable for the creation of hazard maps covering the warehouse.

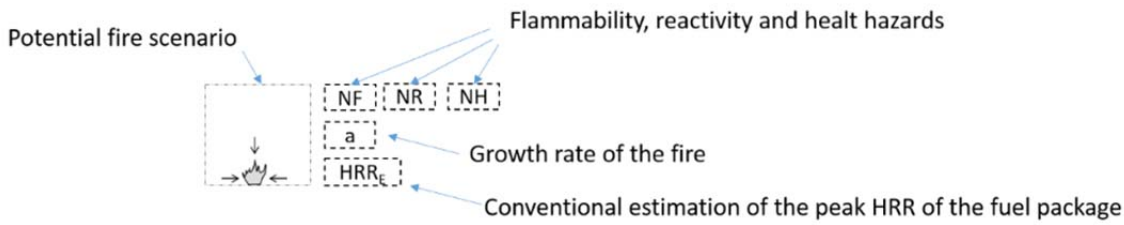


Figure 1: Sketch of the pictogram reassuming the results of the qualitative evaluation.

3. Quantitative assessment of the fire impact on sensible targets

Karlsson and Quintiere (2000) have suggested that the Hot Gas Layer Temperature (HGLT) generated from a fire in an enclosure can be adopted as the main indicator for the assessment of the onset of hazardous conditions for people, property and the prevision of structural damage, ignition hazards and the onset of flashover. We have identified three temperatures that correspond to different impacts on targets (Table 3).

Table 3: Impact of Hot Gas Layer Temperature (HGLT) on exposed targets.

HGLT	Impact on exposed targets
200°C	Tenability limit for people (ISO16738, 2009); temperature not sufficient to spread fire to other remote objects (Clarke, 1990), however, many plastic materials can melt (NFPA921, 2011); minor changes in building materials (Purkiss, 2007)
350°C	Fire can spread to other remote, easy-ignitable objects (Clarke, 1990); thermal and mechanical properties of most building materials (e.g. aluminium, steel and concrete) start to change substantially within this temperature (Purkiss, 2007)
500°C	The fire can reach flashover (Karlsson and Quintiere, 2000); Substantial degradation of mechanical properties of building materials (Purkiss, 2007).

A sensitivity study for the ASET performance criteria (Tosolini et al., 2012) highlighted that lower layer height and/or optical density determine the ASET in a fire origin room up to 4800 m^3. For larger volumes, the threshold limit for the upper layer temperature (200°C) is reached before the lower layer height equals the established threshold limit (2 m). The work of Tosolini et al. (2013) shows that an analytical equation proposed by Karlsson and Quintiere (2000) can be usefully adopted in order to rapidly assess ASET starting from growth rate of the fire, floor area of the enclosure and ceiling height of the enclosure. However, HGLT remains the main indicator to assess impacts on property and structures. Beside the specific characteristics of the fire, as the heat release rate, the HGLT is strongly affected by the geometrical and physical characteristics of the enclosure, and more specifically by the size of the enclosure (floor area and ceiling height), the openings, and the thermal characteristics of the boundary elements. Indeed, the larger the enclosure, the longer the time required to heat up the volume. Furthermore, the openings and both the thickness and the thermal conductivity of the boundaries determine the fraction of the heat generated by the fire that is lost through these elements. HGLT can be estimated by using either analytical equations or fire simulation models. Due to their simplicity and quick use, analytical equations can be useful for preliminary assessment of the fire hazard level. Conversely, fire simulation models are time-requiring tools, but they can be used for deterministic and design analyses, where much details are required.

3.1 The MQH methodology

McCaffrey, Quintiere, and Harkleroad (1981) have developed a simple method (MQH) for calculate directly the hot gas layer temperature in a naturally ventilated enclosure as a function of the heat release rate (HRR) from the fire, ventilation conditions, enclosure geometry and thermal properties of the enclosure in a pre-flashover fire. More recently, Bukowski (2001) suggests of using the MQH method in order to estimate the peak heat release rate (HRR) corresponding to a specific hot gas layer temperature. Hence, we have adopted this approach in order to define an objective criterion aimed at assessing the impact level of a fire on sensible targets, i.e. on people, properties and structural elements. The MQH equation is based on the enclosure energy and mass balance. The authors derived dimensionless variables upon which the temperature depends. Then, using results from more than a hundred experiments, through regression analysis they determined a number of constants, which allows correlating hot gas layer temperature to the dimensionless variables. These data included both steady state and transient fires in cellulosic and synthetic polymeric materials and gaseous hydrocarbon fuels. Compartment height ranged from 0.3 m to 2.7 m and floor areas from 0.14 m^2 to 12.0 m^2. The compartments contained a variety of window and door sizes. This approach allows developing a simple equation to calculate the hot gas layer temperature directly by hand. Details can be found in the original work.

Assuming as initial, standard conditions g = 9.81 m/s2, ρ_{air} = 1.2 kg/m^3, T_{air} = 293 K and c_p = 1.05 kJ/(kg K), the following Equation 2 can be derived:

$$\Delta T = 6.85\left(\frac{HRR^2}{A_0 \cdot \sqrt{H_0} \cdot h_k \cdot A_T}\right)^{\frac{1}{3}} \qquad (2)$$

Where ΔT is the temperature rise (°C), HRR is the heat release rate of the fire (kW), A_0 is the area of the openings (m^2), H_0 is the height of the openings (m) and $A_0(H_0)^{0.5}$ is called ventilation factor; A_T is the internal area of the enclosure (m^2). The term h_k is the effective heat transfer coefficient (kW/(m^2K)), refer to the original work for more details. It is worth noting that the data on which the MQH method is based were taken from experiments in conventional-sized rooms (in the order of 100 m^3), where the temperature differences varied from ΔT = 20°C to 600°C and the fire source was away from walls. The authors summarize the following limitations in applying the method: i) the rise in temperature must be at least 20°C and at most 600°C. ii) The method assumes that there is heat loss due to mass flowing out through openings. iii) The fire is assumed fuel-controlled. Bukowski suggests the method should work well for horizontal room dimensions up to 30 m and ceiling height of about 5 or 6 m or less. Therefore, starting from equation 2, it is possible to rapidly assess the HGLT simply comparing the HRR that will cause a given temperature increase with the $HRR_{peak,E}$ of the fuel package in the room. However, since the MQH equation stands only for fuel-controlled fires, the following procedure has been established. The first step is to calculate the the maximum HRR based on the airflow rate in through the openings for ventilation-controlled fire conditions ($HRR_{max,v}$), which can be estimated from Equation 3 (Karlsson and Quintiere, 2000):

$$HRR_{\max,v} = 1518 \cdot A_0 \cdot \sqrt{H_0} \qquad (3)$$

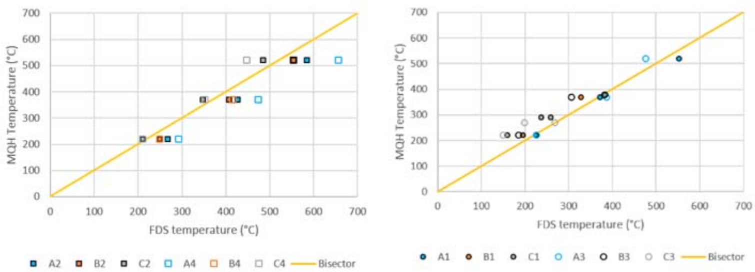
Then, if the peak HRR of the fuel package is smaller than $HRR_{max,v}$ it is possible to apply equation 2 to evaluate the temperature increase. Conversely, the combustion in the room is ventilation-controlled and equation 2 cannot be applied. In such a case, in order to assess HGLT it is possible to introduce $HRR_{max,v}$ in equation 2. In order to validate such a procedure, we have compared the MQH results with those obtained from the Fire Dynamic Simulation (FDS) (field model) (McGrattan et al., 2010), for a set of different enclosures and fires (steady-state). The results are presented in the following.

3.2 Results and Discussion

Aiming at evaluating the ability of the MQH equation to predict the hot gas layer temperature correlated to a given steady-state HRR, we have defined a set of twelve simple enclosures whose characteristics are summarized in Table 4. Here we have considered two ventilation factors, i.e. ($A_0(H_0)^{0.5}$): the first is 2.8 $m^{5/2}$, which corresponds to an opening 1 m wide, and 2 m high, the second is 13.1 $m^{5/2}$, which corresponds to two openings 1 m wide, and 2 m high and an opening 2 m wide and 2.4 m high. The heat transfer coefficient depends on the thermal properties of the boundary materials, we have assumed that all the boundary elements (walls, ceiling and floor) are made of concrete with the following properties: thickness 0.2 m, density 2300 kg/m^3, thermal conductivity 1.2 W/(m K) and specific heat 0.88 kJ/(kg K). For each enclosure, we have considered three fuel packages. Each fuel package is characterized by a steady-state HRR (Table 4), that according to the MQH equation will cause an increase in the HGLT of respectively 200 °C, 350°C and 500°C, after an exposure time of 900 s (15 minutes), which could be representative of firefighter's arrival time. It is worth noting that in some cases the fuel package HRR is larger than the $HRR_{max,v}$.

*Table 4: Summary of enclosures considered and results obtained from MQH equation. The symbol * identifies the cases where the HRR predicted from MQH equation is greater than $HRR_{max,v}$.*

Enclosure ID	Enclosure geometry (m)	Ventilation factor ($m^{5/2}$)	HRR (kW) of the fuel package for ΔT of: 200°C	350°C	500°C	$HRR_{max,v}$ (kW)
A1	6.0 x 6.0 x 3.0	2.8	686	1589	2714	4250
B1	12.0 x 12.0 x 3.0	2.8	1195	2765	4722*	4250
C1	20.0 x 20.0 x 3.0	2.8	1856	4297*	7336*	4250
A2	6.0 x 6.0 x 3.0	13.1	1442	3338	5700	19886
B2	12.0 x 12.0 x 3.0	13.1	2551	5906	10084	19886
C2	20.0 x 20.0 x 3.0	13.1	3982	9219	15741	19886
A3	6.0 x 6.0 x 6.0	2.8	843	1951	3331	4250
B3	12.0 x 12.0 x 6.0	2.8	1380	3195*	5495*	4250
C3	20.0 x 20.0 x 6.0	2.8	2059	4768*	8141*	4250
A4	6.0 x 6.0 x 6.0	13.1	1785	4132	7056	19886
B4	12.0 x 12.0 x 6.0	13.1	2953	6837	11674	19886
C4	20.0 x 20.0 x 6.0	13.1	4421	10236	17477	19886



a) Ventilation Factor 13.1 $m^{5/2}$ b) Ventilation Factor 2.8 $m^{5/2}$

Figure 2: Comparison between temperatures from MQH equation and mean temperatures from FDS simulations. a) Enclosures with ventilation factor 13.1 $m^{5/2}$. b) Enclosures with ventilation factor 2.8 $m^{5/2}$.

Each scenario has been modelled by using the Fire Dynamics Simulator (FDS-5, version 5.5.3) (McGrattan et al., 2010), which is a CFD simulation model. For each scenario, the HRR given in Table 4 has been introduced as input in FDS as a steady state HRR. The hot gas layer temperature has been measured through specific devices in several points distributed according a 2.0 m x 2.0 m horizontal grid. All simulations ran for 900 s. It is worth noting that the outputs of CFD models, and hence FDS, are strongly affected by the grid size. For this reason, a mesh refinement study has been performed. A simplified combustion model was used in FDS-5; this means that the simulations work best in cases where complete combustion (fuel-controlled) can be assumed (McGrattan et al., 2010). Whether a simulation was fuel-controlled or not was determined by studying the HRR: in the latter case, the HRR deviates from the one specified in the input file. In these cases, comparison of results shows that the MQH equation tends to a large over-prediction (in the order of 50 - 65%) of the temperatures reached in the enclosure with respect to those obtained from FDS simulations (Figure 2), due to the ventilation controlled conditions of the fire. Therefore, in the cases where the HRR of the fuel package is larger than $HRR_{max,v}$, we suggest to consider the following maximum HRR (Equation 4):

$$HRR_{max} = \alpha \cdot HRR_{max,v} \tag{4}$$

Where α = 0.7. This value has been determined from the analysis of the FDS simulations. Indeed, the analysis shows that for such a value of HRR the combustion starts a transition from fuel-controlled to ventilation-controlled conditions. Comparing the results of FDS simulations with the HGLT obtained from the MQH equation introducing as an input the value 0.7 $HRR_{max,v}$, it shows a better agreement (Figure 2) and the over prediction in the HGLT is reduced to 10-20 %. When considering the enclosures with larger ventilation factor (13.1 $m^{5/2}$), Figure 2 shows that the MQH equation tends to under-predict the temperatures reached in the enclosure with respect to those obtained from FDS simulations. The under prediction is higher (in the order of 20%) for the larger enclosures.

Conclusions

In the work, a methodology for the quick assessment of fire hazard is presented. The methodology allows a qualitative definition of the potential fire scenarios through the recognition of fuel packages. The fuel package concept allows pointing out not only intrinsic hazards of the combustible substances but also the predisposition of the storage conditions to lead to specific fire propagation paths. The methodology allows also a preliminary assessment of the impacts of the fire on sensible targets, i.e. people or structures. To this aim, a simple analytical equation, the MQH equation, has been adopted to estimate the hot gas layer temperature (HGLT) in enclosures with natural ventilation. Comparison with results of FDS simulations shows that MQH equation can be applied to assess the hot gas layer temperature generated by a fire of known HRR. However, in order to better estimate the effects of the fire, a procedure has been proposed to take into account the establishment of ventilation-controlled conditions. Both the potential fire scenario and the quick evaluation of HGLT can be useful to support the decision making process aimed at improving the level of safety of the workplace.

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