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Quick Assessment of the Hot Gas Layer Temperature and Potential Fire Spread between Combustible Items in a Confined Space

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The effective management of fire safety requires understanding in advance the resulting conditions of a fire in a confined space. This task is usually achieved by considering several quantitative indicators, establishing threshold limits for each one corresponding to specific hazardous situations and then calculating if such threshold limits are reached. In such a way, it is possible to assess whether or not management conditions are satisfactory.
In this work, two main indicators are considered: the hot gas layer temperature and the thermal radiation from the fire. Indeed, the hot gas layer temperature is related with the occurrence of hazardous conditions for people, the spread of the fire to combustible items far from the fire source and hence with the occurrence of flashover and critical conditions for stability of structural elements. On the other hand, thermal radiation from a fire source can be considered as the primary cause of fire spread in pre-flashover conditions, when there is not direct flame impingement and outside the plume, where convective heat transfer is not a principal factor in fire heat transfer. Therefore, in order to estimate if a remote object from the fire will ignite; one must be able to quantify the radiative heat flux received by the target.
Both the hot gas layer temperature and the thermal radiation to a target can be assessed by using either analytical equations or fire simulation models. Due to their simplicity and quick use, analytical equations could be suitable for preliminary, rapid hazard assessment. In this work, a comparison between two simple analytical equations and the results obtained using CFD simulations (FDS) for a set of scenarios are presented with the aim of assessing capabilities of the analytical models in foreseen hot gas layer temperature and the thermal radiation from the fire.

1. Introduction

Fires in confined spaces are complex phenomenon; nevertheless, the effective management of fire safety requires understanding in advance the resulting conditions of a fire. This task is usually achieved by considering several quantitative indicators, establishing threshold limits corresponding to specific hazardous situations and then calculating if such threshold limits are reached. In such a way, it is possible to assess whether or not management conditions are satisfactory.
To this aim, in the last decades, simulation models such as two-zone models and computational fluid dynamics (CFD) have been developed to predict fire dynamics in single-room as well as multi-room geometries. On the other hand, there is a range of correlations available in the literature derived from experiments and empirical data, which allows describing different fire phenomena (e.g. flame length, hot gas temperature, etc.). These correlations are generally less accurate compared with computer simulations, but they have the benefit of being simple and cost-effective, and still giving a good description of the physical problem (Johansson and van Hees, 2014). Therefore, they can be usefully applied for rapid assessment of the fire hazard. As an example, Tosolini et al. (2012) and Grimaz and Tosolini (2013) adopt an analytical equation proposed by Karlsson and Quintiere (2000) to assess ASET (available safe egress time).

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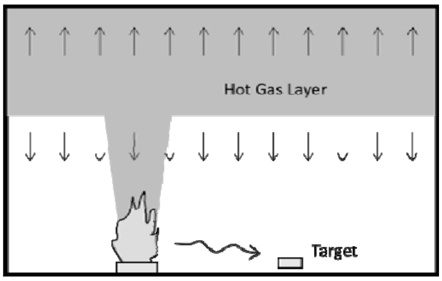


Figure 1: Sketch of two-layer model and radiation from flames for a compartment fire.

The equation has been compared with the results of CFD simulations (FDS) and results show that trends obtained with the analytical correlation are comparable with the CFD simulations (Tosolini et al., 2013).
Recently, Dusso et al. (2016) proposed a methodology aimed at the quick assessment of fire hazard in confined spaces, further developing the methodology outlined by Grimaz et al. (2014). The assessment process is divided in two phases. The first is the inspection of the workplace and the rapid, visual recognition and characterization of the fuel packages, i.e. 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. In the second phase it is assessed the impact of the fire on sensible targets (people, property, and structures) based on the Hot Gas Layer Temperature (HGLT).
In this framework, there is a need for simple correlations that can be used for hand calculations to get a first estimate of both the HGLT and the radiation from the fire. Indeed, the HGLT determines the onset of hazardous conditions for people and property; on the other hand, radiation from fire determines the potential propagation of the fire between objects (Figure 1).
In this work, a comparison between two simple analytical equations and the results obtained using CFD simulations (FDS) for a set of scenarios are presented with the aim of assessing capabilities of the analytical models in foreseen HGLT and the thermal radiation from the fire.

2. Hot Gas Layer Temperature

The Hot Gas Layer Temperature (HGLT) generated from a fire in a confined space can be adopted as the main indicator in order to assess the onset of hazardous conditions for people, property (ignition hazards) and structural damage (Karlsson and Quintiere, 2000). From a literature survey, Dusso et al. (2016) identified three temperatures corresponding to different impacts on targets and adopted the simple correlation proposed by McCaffrey, Quintiere, and Harkleroad (1981) to rapidly estimate the hot gas layer temperature in an enclosure.

2.1 The MQH correlation

McCaffrey, Quintiere, and Harkleroad (1981) have developed a simple method (in the following called MQH) that allows calculating directly the hot gas layer temperature in a naturally ventilated enclosure as a function of the heat release rate (HRR) from the fire, the ventilation conditions, the enclosure geometry and the thermal properties of the enclosure in a pre-flashover fire. 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 1 can be derived:

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

Where ΔT is the temperature rise (°C), HRR is the heat release rate of the fire (kW), A0 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.

Table 1: Summary of enclosures considered in the simulations with t-squared fires (S, M, F, UF growth factors).

Enclosure ID	Enclosure geometry (m)	Ventilation factor ($m^{5/2}$)	Fuel
A1	6.0 x 6.0 x 3.0	2.8	Ethylene
B1	12.0 x 12.0 x 3.0	2.8	Ethylene
C1	20.0 x 20.0 x 3.0	2.8	Ethylene
A3	6.0 x 6.0 x 6.0	2.8	Ethylene
B3	12.0 x 12.0 x 6.0	2.8	Ethylene
C3	20.0 x 20.0 x 6.0	2.8	Ethylene

It is worth noting that the data on which the MQH method is based were taken from experiments in conventional-sized rooms, 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 fuel-controlled. Bukowski (2001) 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 eq. 1 it is possible to rapidly assess the HGLT starting from the HRR of the fuel package and the room characteristics (geometry, ventilation and boundary conditions). In order to study the capability of eq. 1 to predict the HGLT in enclosures larger than those from which the correlation was derived, we have performed a series of numerical experiments with the CFD model Fire Dynamics Simulator (FDS) (McGrattan et al., 2014) and we have compared the previsions of the MQH correlation with the model output.

2.2 Numerical experiments and comparison of the results

Data from CFD simulations with the Fire Dynamics Simulator (FDS 6) (McGrattan et al., 2014) were used as an alternative to experimental data and 24 scenarios have been modelled: we have defined a set of six simple enclosures whose characteristics are summarized in Table 1. We have considered a ventilation factor $A_0(H_0)^{0.5}$ of 2.8 $m^{5/2}$, which corresponds to an opening 1 m wide, and 2 m high. We have assumed that 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). In this work, we present the results concerning t-squared fires burning inside the confined spaces in Table 1, while results concerning steady state fires was reported in a previous work (Dusso et al., 2016).

In t-squared fires, the heat release rate (HRR) grows according the following equation:

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

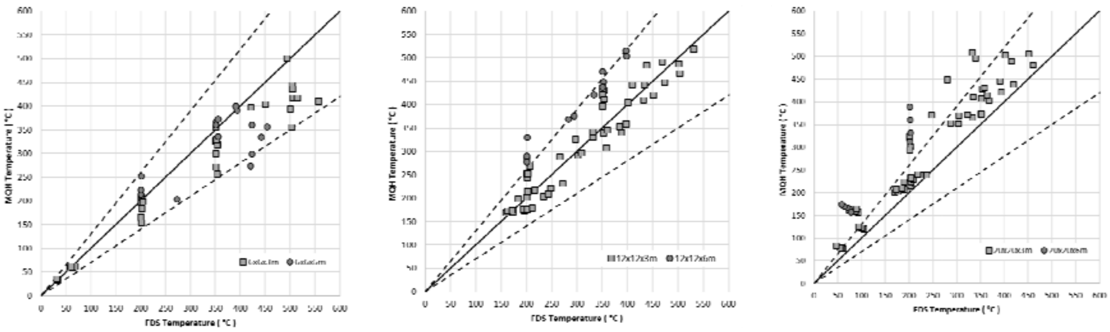
Where α is the fire growth coefficient (kW/s^2) and t is the time (s). Conventional values for α are: 0.003 for “Slow” fires; 0.012 for “Medium”; 0.047 for “Fast” and “0.188” for Ultra-fast fires. These values were defined with reference to the time it takes for the fire to reach the conventional reference HRR of 1055 kW (Karlsson and Quintiere, 2000).

As a starting point, a mesh refinement analysis was carried out assuming as a reference the enclosure B1 in Table 1. The output used to check the results of mesh refinement is the HGLT. The grid sizes checked were 0.30, 0.20 and 0.10 m and following to this analysis a grid size of 0.10 m was selected for all the scenarios.

The HGLT has been measured through specific devices distributed according a 2.0 m x 2.0 m horizontal grid, then for each time considered the mean of all the devices has been calculated and compared with the output of the MQH correlation for the same scenario. Indeed, for a same scenario, the temperatures have been calculated for different times after ignition. Figure 2 reports the results obtained respectively by using Eq. 1 and FDS for the scenarios in Table 1. It has been assumed as a metric for the comparison between an FDS observation and the corresponding MQH prediction the relative difference calculated according to Eq. 3, where ΔX_{corr} and ΔX_{FDS} are respectively the value of the correlation and the FDS predictions:

$$\varepsilon = (\Delta X_{corr} - \Delta X_{FDS}) / \Delta X_{FDS} \tag{3}$$

It can be seen that for the enclosures A1, B1, A3 and B3, for all the growth rates the HGLT given by the MQH correlation varies between ±30 % with respect to the prediction of FDS. However, such a relative difference is about twice the uncertainty of the FDS predictions (McGrattan et al., 2015). On the other hand, when considering the enclosures C1, C3 the MQH correlation shows a tendency to overestimate the HGLT respect to the FDS predictions, irrespectively from the growth rate. The overestimation is larger in the enclosure with height of 6 m (C3 scenarios) and in some cases, it is larger than 60 %.



a) b) c)

Figure 2: Comparison of numerical experiments with FDS 6 and MQH correlation predictions: a) Enclosures A1, A3; b) enclosures B1, B3; c) Enclosures C1, C3. Solid lines represent the bisector (if the predictions of MQH and FDS are the same the point fall on this line). The slopes of the dashed lines are 1±30 %.

3. Radiation from the fire

While the first item ignited burns, one or more nearby items can ignite and increase the fire size, due to direct flame contact or convective heat transfer in the case the second item is sufficiently close to the flames, but more usually, due to radiant heat. The radiant flux ignition is a very complicated phenomenon, indeed it depends on many factors: the radiant energy from the flames on the first item, the hot gas layer and the room surfaces. Simplifying assumptions commonly introduced in fire engineering are that radiation from hot gases and other surfaces can be assumed negligible prior to flashover, i.e. radiation to second fuel packages comes only from the flame above the first burning item. This is a somewhat “strong” assumption; nevertheless considering only the radiation from the flames it allows assessing if nearby objects, which are neither in direct contact nor above the burning one inside the plume, where convection heat transfer may be predominant, may be ignited. Many fire standards adopt this assumption in order to define separation distances between objects and the size of potential fires, e.g. NFPA 92B (2009) and NFPA 555 (2009).
Beyler (2002) describes three major steps involved in estimating the thermal radiation from a fire. The first step is to determine the geometric characteristics of the fire (both burning rate and physical dimensions of the fire); the second is to characterise the radiative properties of the fire and the last is to calculate the incident radiant heat flux to the target. Empirical correlations in the literature include simple estimates of flame radiation from a point or cylindrical source adopting different approximations. One of the simplest correlations is the point source model proposed by Modak (1977). This model is adopted also in NFPA92B and due to its simplicity, it seems particularly useful when the aim is a rapid assessment of the potential involvement of nearby combustible items in the fire and therefore to identify and to define the fuel packages.

3.1 The point source model

The point source model (Modak, 1977) assumes that radiative energy is assumed to emanate isotropically from a single point source located at the centre of the flame (Figure 3). Here, the point source is located at mid-height of the flame. The mean flame height, H (m), can be calculated by the well-known Heskestad correlation. The radiative heat flux q_r'' (kW/m^2), at any distance R (m) from this point is given by:

$$q_r'' = \cos\vartheta\left(\chi_r \cdot HRR\right) \Big/ \left(4\pi R^2\right) \tag{4}$$

Here cos θ is the view factor and it accounts for a target that is at an angle θ from the source; χ_r is the radiative fraction (generally, the radiative fraction depends on the fuel type, flame size and flame configuration, however here a value of 0.35 was used); HRR is the heat release rate of the fire (kW).
The performance of the point source model is investigated in the following by comparing with the predictions of FDS 6 for a set of scenarios.

3.2 Numerical experiments and comparison of the results

Data from CFD simulations with the Fire Dynamics Simulator (FDS 6) (McGrattan et al., 2014a) were used as a reference. In FDS, the radiative heat transfer is included through the solution of the radiation transport equation (RTE) for a non-scattering grey gas as the default model, however in some limited cases it is

possible to use a wide band model. Soot is the combustion product that contributes the most to thermal radiation in large-scale fire scenarios.
FDS treats the combustion products as a grey medium because the radiation spectrum of soot is continuous. The spatial discretization of the RTE is achieved by dividing the unit sphere into roughly 100 solid angles by default. This is a user-controlled parameter. The model presents several limitations (NUREG-1824, 2014). First, the absorption coefficient for the smoke-laden gas is a complex function of its composition and temperature. Because of the simplified combustion model, the chemical composition of the smoky gases, especially the soot content, can affect both the absorption and emission of thermal radiation. Second, the radiation transport is discretized via approximately 100 solid angles. For targets far away from a localized source of radiation, this discretization can lead to a non-uniform distribution of the radiant energy. However it has been shown that FDS can predict heat fluxes to targets with an uncertainty of 25% with respect to experimental measurements (McGrattan et al., 2015). Since the emphasis has shifted from HGL temperature to heat transfer near the fire, the size of the numerical grid cells became more important. A mesh refinement analysis was carried out assuming as a reference the case P1 in Table 2. The output quantity used to check the results of mesh refinement is the radiative heat flux. The grid sizes checked were 0.10, 0.075 and 0.05 m and following to this analysis a grid size of 0.05 m was selected for all the scenarios. The radiative heat flux has been measured through specific devices placed at different distances from the center of the fire (0.4, 0.6, 0.8, 1.0, 1.2 and 1.4 m) and different heights from the base of the fire (0.0, 0.3 and 1.2 m). Figure 4 reports the results of the comparison between the radiative heat fluxes estimated with eq. 4 and those measured in the simulations with FDS for the scenarios in Table 2. From the comparison, it appears that the estimates of the heat fluxes for the given conditions do not show a clear trend of either over- or under-prediction. Other authors have obtained similar results comparing the point source model predictions with full-scale experiments involving small burners (e.g. Overholt, 2014). However, after a number of tests, it seems that assuming the point source at a height above the base of the fire of one quarter of the flame length it reduces the scatter of the previsions with respect to the classic assumption to consider the point source at mid-height of the flame.

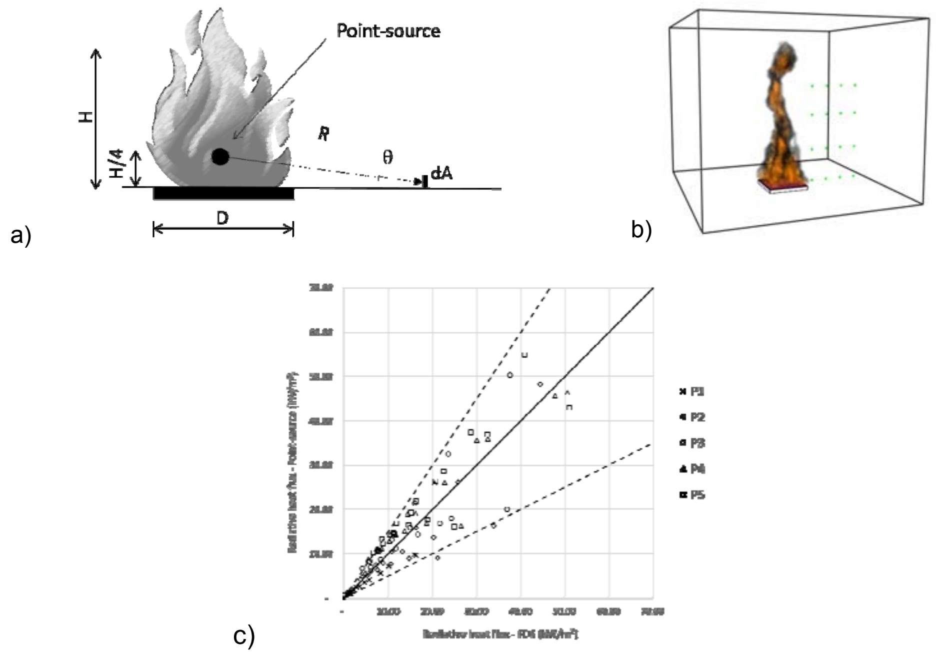


Figure 3: a) Sketch of the point source model for the radiation from a fire. The point source has been assumed to be at H/4. b) Geometry of the modelled scenarios. c) Comparison of the radiative heat fluxes estimated with eq. 4 and measured in the simulations with FDS. The slopes of the dashed lines are 1±50 % (they represent two times the FDS uncertainty).

Table 2: Summary of enclosures considered in the simulations with t-squared fires (S, M, F, UF growth factors).

Case ID	HRR (kW)	Soot yield (g/g)	Fire diameter (m)	Mesh (m)	Boundaries
P1; P2	100; 400	0.23	0.45	3 x 3 x 3	open
P3; P4; P5	600; 800; 1000	0.1	0.56	3 x 3 x 4	open

4. Conclusions

The work presents the comparison of two simple analytical equations with the results obtained with the Fire Dynamics Simulator (FDS 6) for a set of scenarios and it extends the analysis performed in a previous work. The analytical equations considered here are the MQH correlation to calculate the pre-flashover hot gas layer temperature in a confined space and the point source model to evaluate radiation from a burning item. In the present work, the correlation proposed by McCaffrey, Quintiere, and Harkleroad (MQH) has been adopted to assess the hot gas layer temperature in a confined space where a t-squared fire is burning. Considering the simplicity and ease of use of the correlation, the results obtained compare well with the results obtained for the corresponding scenarios with FDS. The results presented allows drawing the application range of the MQH analytical correlation, however more experiments should be performed before a general conclusion can be derived. Nevertheless, the MQH correlation can be adopted as a decision support tool for a preliminary assessment of fire hazard in confined spaces. Radiation from flames is a rather complex phenomenon, however, in order to assess if an object in fire can ignite adjacent combustible items, one has to estimate the radiation from the flames. Here a very simple model has been compared with the FDS predictions. The comparison does not show a clear trend; therefore, one should take caution when using the point source model.

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