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Semi-empirical model for estimating the Heat Release Rate required for flashover in compartments with thermally-thin boundaries and ultra-fast fires

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Abstract

More than 1 billion people are living in informal settlements and refugee camps where houses are commonly built from thermally-thin materials (e.g. steel/asbestos sheets). In fire safety literature there is insufficient attention describing the required conditions for flashover (e.g. Heat Release Rate needed for flashover, $\dot{Q}_{FO}$) in such compartments. In this work, $\dot{Q}_{FO}$ and heat fluxes to the surroundings for compartments with thermally-thin boundaries were investigated using eight compartment fire tests built with 0.5 mm steel sheets and four fuel loads. Numerical simulations were conducted to validate FDS for this application, using the heat release rate inside and outside the compartment, the gas layer temperature and the heat fluxes to the surroundings. The validated model was employed to conduct demonstrative sensitivity and parametric studies to understand the heat balance for thermally-thin under-ventilated compartments. It was found that the heat transfer on/from the walls of the compartment is dominated by radiation, in contrast to the compartments with thermally thick boundaries where the wall conduction dominates. The radiative heat transfer coefficient h_{rad} was then resolved numerically and correlated against the gas layer temperature, wall temperatures and the $\dot{Q}_{FO}$ to create a semi empirical correlation for estimating the $\dot{Q}_{FO}$.

Keywords: compartment fires; heat transfer; CFD; modelling; flash-over, thermally thin

1 Introduction

Over 95% of the 180,000 global annual fire deaths occurred [1] in low- and middle- income countries (LMICs) with a considerable portion of these fires occurred within informal settlements (ISs). ISs are at high risk of fires that cause trauma, injury or death. ISs' numbers and sizes globally have increased dramatically in recent years. Affordable and accessible urban housing has not kept pace with rising population growth and as a result, people have been forced to live in low quality informal settlement dwellings (ISDs). The absolute number of IS residents has grown by 213 million since 1990 and this number is still increasing due to rapid urbanization.

To be able to understand the fire risk in these settlements and ultimately to increase their resilience to fires, we need to model the fire spread and to do so, we need to first try to understand how the fire initiates in each dwelling and radiates to the surroundings. Therefore, there is a need to study the fire dynamics and spread within these settlements [2]. In these settlements, dwellings are usually made out of cheap, easily sourced, local materials, which commonly result in combustible (e.g. Timber) or non-combustible thermally-thin construction materials (e.g. Steel sheets) [2]. It is important to note that thermally thin in this paper is defined as materials that have a Biot number of 10^{-1} or less, where the temperature gradient within the solid may be ignored [3].

The term "compartment fires" refers to those which are confined within an enclosure that can be described as a building. The specifications of the enclosure can highly affect the fire progress/growth within the compartment, i.e. the compartment dimensions, the size of the openings (ventilations), the lining materials and the wall (boundaries) properties. In the past few decades, there has been a lot of research on compartment fires and how these specifications affect different fire stages (growth, fully developed and decay) [3]. The fully-developed fire stage is also usually referred to as the 'post-flashover' stage, where flashover was first defined and studied quantitatively by Waterman in 1968[4], who defined it as conditional on a heat flux of 20 kW/m^2 on the floor. The occurrence of flashover in a certain compartment generally means that the room is well filled with flaming combustion and that the heat fluxes to all the fuel packages are high enough to cause auto-ignition [5], at this moment the occupant life safety vanishes.

Based on that, the ability to predict the heat release rate needed for flashover ($\dot{Q}_{FO}$) has attracted extensive attention within the fire safety community, especially in mid 1970s and early 1980s. Hägglundet and Persson (1976) [6] defined a flashover criteria as 600 °C just below the ceiling when flames were observed outside of the door. However, more detailed understanding and definitions of flashover emanated from Babrauskas 1979-1980 [7] and Thomas 1981 [8] who defined the flashover criteria as an upper gas layer temperature of 600 °C or as radiation on the floor level of 20 kW/m^2, and created simple empirical correlations based on the heat balance for the gas layer within tens of compartment fire tests (with concrete walls) to estimate the room flashover potential. Thomas [8] included the three heat transfer/exchange mechanisms from the gas layer to the walls, namely conduction, convection and radiation. This was followed by the work done in 1981 by McCaffrey et al. (MQH) [9] who analysed more than 100 experimental compartment fires from different tests series using different fuel loads, fuel types, compartment sizes, ventilation factors and wall materials. The flashover criteria was taken as 525 °C beneath the ceiling and a heat balance was done on the upper gas layer. A heat transfer coefficient was developed depending on the duration of the fire, the thermal characteristics of the compartment's boundary (namely conductivity, diffusivity, density and thickness) with mostly inert thermally-thick walls. MQH then suggested an empirical correlation (Eq.1):

$$\dot{Q}_{FO} = 610(h_k A_T A_o H^{\frac{1}{2}})^{1/2} \tag{1}$$

where h_k is the effective heat transfer coefficient, A_T is the total wall area, A_o is the opening's area and H is the opening height. One of the main limitations of the MQH is that it doesn't consider the growing heat release rate or when the walls of the compartment (boundaries) are thermally thin (lumped).

In 1994, Peatross and Beyler [10] used fifteen natural ventilation and twelve forced ventilation compartment fire experiments in a steel ship compartment (with 12.7 mm steel boundaries) to modify the MQH correlation for predicting temperatures in compartments with conductive boundaries. However, Peatross and Beyler's correlation was mostly empirical and did not consider cases with thinner wall thickness (e.g. 0.5 mm steel sheets as those found in ISs), fast growing fires or different walls' emissivity which is common to be different in ISs (e.g. clean steel sheets compared to asbestos sheets).

In 2015, Evegren and Wickström [11] developed a simple model to predict the upper layer temperature-time curve in compartments with lumped boundaries for a given heat release curve. This model requires inputs like the volume of the compartment, the ventilation factor, the boundaries' properties, the fuel/fuel pan details and the HRR-time curve.

In the current study the Heat Release Rate needed to reach flashover ($\dot{Q}_{FO}$) is being evaluated for extremely thermally-thin (Biot number of the order of 10^{-2} or lower) bounded compartments with boundaries made of steel, aluminium, and asbestos sheets with thickness ranging from 0.5-4 mm with an ultra-fast fire. The study is based on conducting eight small scale compartment fire tests to validate the Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS) [12] using the experimental data from quarter scale ISO 9705 room [13] fire tests built with carbon steel sheets and using four fuel loads of Polypropylene (PP) beads in a pan in the middle of the compartment. The validated model is then used to further understanding of the effect of changing the wall thermal properties and the ventilation factor value on the $\dot{Q}_{FO}$, and the generated data is used to propose a data-based semi-empirical correlation for estimating the $\dot{Q}_{FO}$ for these extremely thermally-thin compartments.

2 Methodology

2.1 Experimental setup

As presented in Fig. 1, a quarter scale ISO-9705 compartment used in the experimental work was made out of 0.5 mm corrugated steel sheets, with the dimensions of 0.6 m × 0.9 m × 0.6 m (L × W × H) and one opening of 0.2 m × 0.5 m (W × H) on the short wall. The compartment was placed under a large-scale calorimetry hood with a fan to capture the gas products during the fire test for the HRR calculations. The HRR measurement was based on the oxygen consumption calorimetry principle and used measurements of exhaust flow velocity and gas volume fractions (Oxygen consumption) along with the formulation derived by Janssens[14], the suggested error for this method is ±10% for complete combustion and this error increases with larger amounts of CO or soot produced.

2.2 Experimental conditions

In total, eight experiments were conducted, where the ventilation factor, and amount of accelerant were kept constant (at 0.0707 $m^{5/2}$, and 200 ml of Heptane, respectively). The ventilation factors (Vf) are defined as [15] $Vf = A_w H^{1/2}$, where A_w is the area of the opening and H is the height of the opening.

Four different fuel loads used to capture the load needed to reach flashover in this compartment (80, 40, 32, 24 MJ/m^2, respectively) were then used in two experiments each. The naming convention for the experiments is thus 80_1 for the first experiment using a fuel load of 80 MJ/m^2, and 80_2 for the second, and so forth for the remaining fuel loads. The fuel used was the Polypropylene (PP), adopted in order to mimic the burning of solid fuel loads which mainly consist of hydrocarbons, the fuel pan was 0.4 m × 0.4 m and placed in the middle of the compartment. For more information, reference [16] gives detailed information about the thermal degradation of the PP.

2.3 Measurement Locations and instrumentation

Thermocouples: temperatures were recorded at the four corners of the compartment using four thermocouple tress, each made out of five 1.5 mm Type-K thermocouples (to measure the gas temperature within the compartment). Each tree was placed at 5 cm from each wall, with the first thermocouple 10 cm from the floor and the top thermocouple 10 cm from the ceiling and 10 cm separation distance between the thermocouples in between. The locations are presented in Fig. 2. **Heat fluxes:** The incident radiative heat fluxes to the surroundings were calculated using the measured temperatures via the Thin Skin Calorimeters (TSCs) [17] at 20, 40 and 60 cm from the top of the door and 15, 30 and 45 cm from the top of the left wall. **Flow velocity:** The flow velocity was measured at three vertical locations in the middle of the door

0.1 m, 0.25 m and 0.4 m from the floor via three bi-directional flow probes. The flow probes were designed based on the bi-directional probes proposed by McCaffrey and Heskestad [18] and the measured velocities were then corrected by the method proposed by Gupta et al. [19].

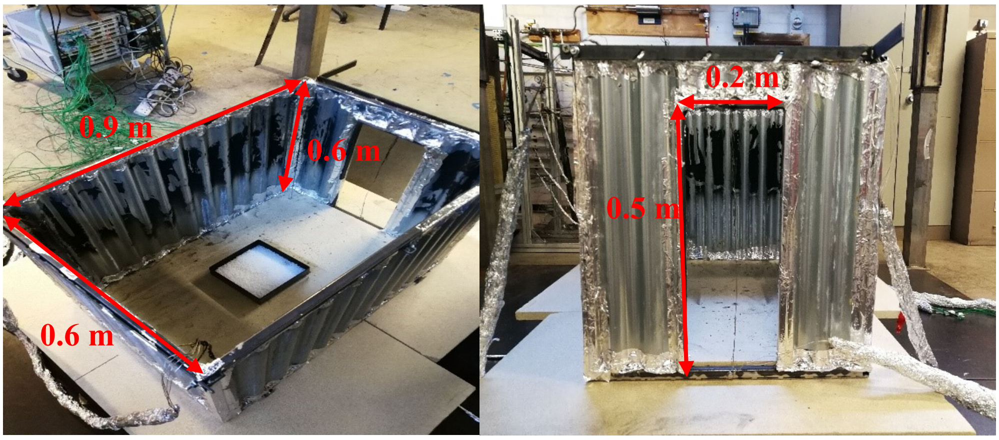

Fig. 1. Quarter scale ISO-9705 compartment (open ceiling for demonstration)

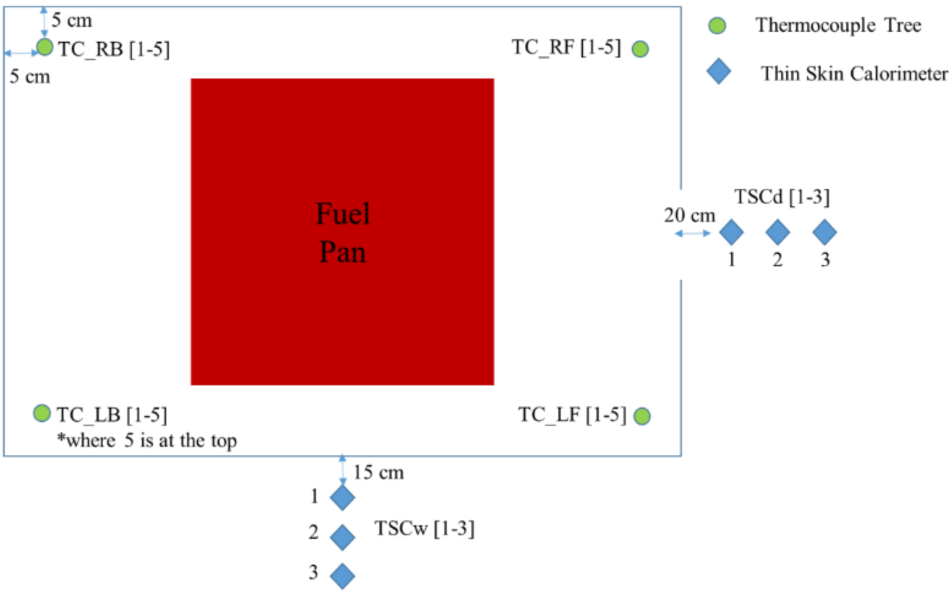

Fig. 2. Measurements' locations (Not to scale)

2.4 Numerical setup (Model description and simulations details)

In this study, the Fire Dynamics Simulator (version 6.6.0) [12] was used to model the experiments and to do any further parametric studies. The set-up in the model corresponds to the experimental set-up reported above, the temperatures were computed by modelling a K-type thermocouple of 1.5 mm and the heat fluxes were calculated by using the radiative heat flux measuring device in FDS. The fire was represented on a surface with the same location and dimensions as the tray used in the experiments and the edges of the tray were modelled with the same thickness and material (0.5 cm thickness, 10 cm lip and carbon steel as a material), the fire was modelled using the simple pyrolysis model in FDS, where the fire is represented by a Heat Release Per Unit Area (HRRPUA) curve corresponding to the experimental HRR measured via the Oxygen consumption method. The computational domain has been set to X= 1.10 m, Y= 1.5 m and Z= 0.9 m, the cell size used in the simulations was

Δ= 5 cm and a cell size sensitivity analysis was conducted as presented in Fig. 3 – three cell sizes were tested, namely 10 cm, 5 cm and 2.5 cm. The gas layer temperature was compared for each and it was found that the 10 cm cell size case underestimated the temperature in the steady state by around 30 % and overestimated the Heat flux at 60 cm from the door by around 160% compared to the 2.5 cm cell size. However, the 5 cm cell size underestimated the gas layer temperature at the steady state by around 10% and overestimated the heat flux at 60 cm from the door by around 13% compared to the 2.5 cm cell. Therefore, it was decided to use a cell size of 5 cm in this study throughout the whole domain based on a 'precision × computational time' evaluation.

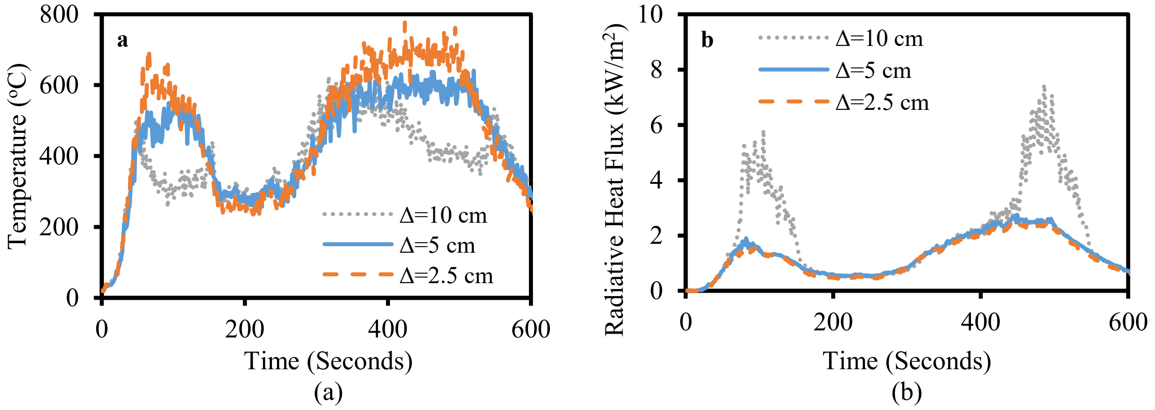

Fig. 3. (a) Cell size (Δ = 10, 5, and 2.5 cm) sensitivity analysis simulations of test 40_11 for gas layer temperature at TC_LF_5, and (b) for radiative heat flux at 60 cm from the door

For more details regarding the FDS inputs, the PP [20] was used with a Heat of Combustion of 43.3 MJ/kg, soot yield of 0.058, CO yield of 0.024 and radiative fraction of 37%. The heat transfer parameters for carbon steel and the insulation on the floor were: density of 7850 and 208 kg/m^3; emissivity of 0.6 and 1.0; specific heat of 0.6 and 0.8 kJ/kg.K; and conductivity of 48 and 0.1 W/mK, respectively.

3 Results and discussion

3.1 Repeatability in experimental work

As mentioned before, each test was done twice to explore repeatability and as presented in Fig. 4 the total HRR curves were duplicated with good accuracy for all fuel loads. It was noticed that flashover was reached for all fuel loads apart from 24 MJ/m^2. It was also noticed that there are consistently two peaks in the HRR curves, the first peak at around 80 and 500 seconds, for the fuel loads 40/32/24 and 80 MJ/m^2, respectively, as the Heptane accelerant burns away, with the other peak occurring when the compartment reached flashover due to the burning of the PP at around 300 and 700 seconds, for the 40/32 and 80 MJ/m^2, respectively. It was also found that for lower fuel loads, the HRR spikes related to the Heptane burning were much higher, as there is much more space on the tray for the Heptane to burn and for air to be entrained, that also could be due to the fewer heat losses with less PP in the tray and eventually a lower endo-thermicity. It is also important to note that the Flashover Criteria in this work was taken as that of the MQH of 525 °C, where the gas layer temperature for the four fuel loads cases is presented in Fig. 5.

It should also be noted that in Tests 32_1&2 flashover was achieved however flames were rarely observed outside of the compartment. This gives a borderline of fuel load needed to reach flashover, defined as the fuel where the flashover criteria is reached (525 °C at the steady burning of the PP) and most of the burning is happening inside of the compartment. It is assumed that if any lower fuel load was used in this compartment then flashover would not occur.

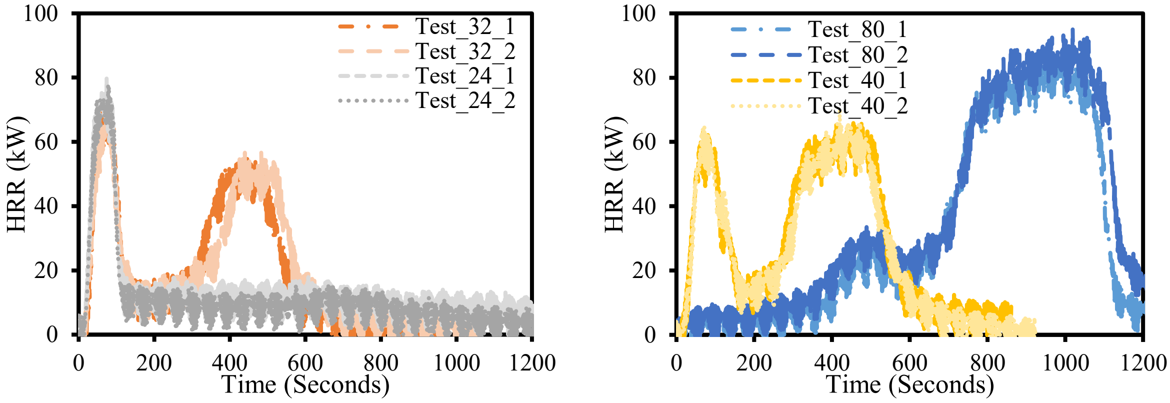

Fig. 4. HRR-time curves evaluation in all tests

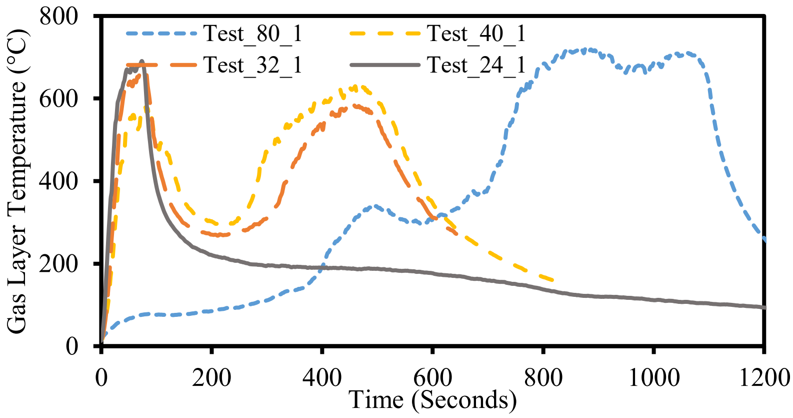

Fig. 5. Gas layer temperatures for all tests at the top of the left front thermocouple tree (TC_L_F_5)

3.2 Validation

To validate the FDS model using these experiments, the HRR-time curves found in Tests [80_1, 40_1, 32_1 and 24_1] were used as a ramped input for the FDS (HRRPUA) to model one test of each fuel load. The measurements of gas layer temperatures in the four corners using the top thermocouple in each tree were then compared to the corresponding location in the FDS model, the radiative heat fluxes were calculated using the TSCs and compared to the results calculated by the 'Radiative Heat Flux Gas' device in FDS.

One of the main challenges for FDS is modelling under-ventilated compartment fires due to the complexity when it comes to the combustion (due to the large uncertainties in the combustion chemistry) and turbulence modelling needed to mimic the real situation. **Combustion modelling:** FDS's default combustion model is based on the mixing-limited, infinitely fast reaction of lumped species and a simple extinction model which is developed based on one criteria 'The critical flame temperature value'. In cells with temperature below this critical value combustion does not occur, as the energy release will not raise the temperature above the critical value needed for combustion. Therefore, it is important when using the simple pyrolysis model for combustion in FDS to make sure that the burning is occurring at the correct locations compared to the experiments. **Turbulence modelling:** FDS is solving turbulence based on the Large Eddy Simulation (LES) technique with the turbulent viscosity model, Deardorf's[21], as a default.

In this work, the HRR peak in test 32_1 (the borderline case) is assumed to correspond to the maximum burning that could occur in this compartment; therefore the first validation case was test 32_1. This case was used to investigate the ability of FDS to compute all the burning inside the compartment, before moving to more complex conditions (burning occurring inside and outside of the compartment), as for tests 40_1 and 80_1. In order to compute how much heat was released at the opening compared to inside of the compartment, in FDS, a device (volume based) was set outside of the compartment to capture any burning occurring externally.

As it is shown in Fig. 6(a) the model presents almost no burning happening outside of the compartment for test_32_1, meaning that FDS managed to compute all the combustion needed inside of the compartment as observed in the experiments. It is also good to note that when the Heptane was burning at the beginning of the experiment only around 5 kW were captured by FDS outside of the compartment. By subtracting this from the total HRR (inside + outside) at the same time, it could be concluded that the maximum heat release that this compartment under this configuration can handle inside is around 55-60 kW. To challenge the ability of FDS to model a longer Post-Flashover fire, the more complex scenario of test 40_1 with 40 MJ/m^2 fuel load was simulated. Test 40_1 had a sustained external plume post-flashover as shown in Fig. 6 (b). Fig. 6 (a) presents the HRR-time curves for both total and outside the compartment when modelling test 40_1 via FDS. It is observed that FDS successfully reproduced the maximum HRR (burning) inside the compartment for Heptane and PP steady burning, where the peak HRR inside the compartment was around 55-60 kW. One could then infer that FDS computed the external plume with an HRR close to that found in the experiments.

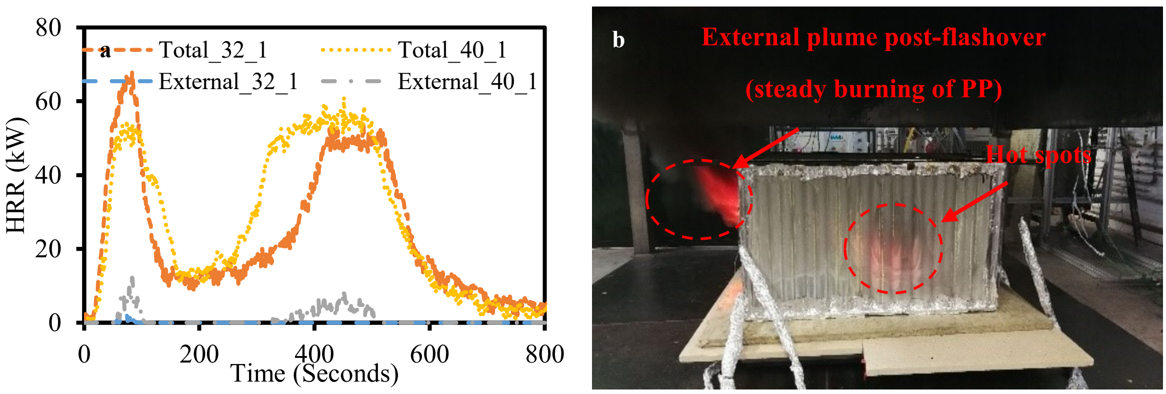

Fig. 6. (a) total and external HRR-time curves for Test 32_1 and Test 40_1 (FDS)

(b) External Plume and heated walls (Test 40_1)

It is also important to investigate the ability of the FDS to compute the combustion in the correct locations inside the compartment. As presented in Fig. 7 for both tests 32_1 (a) and 40_1 (b), FDS managed to capture the same temperature- time curve for the gas layer with overestimation of around +10% and underestimation of around -15 % compared to the experiments for tests 32_1 and 40_1 respectively, which could give an indication for the accuracy of the combustion modelling within the compartment (distribution of combustion inside the compartment). For the sake of completeness, Fig. 8 presents a comparison between the experimental and numerical results for the thermocouples 1 to 4 of the left front thermocouple tree for test 40_1. It was found that the same underestimation occurred along the height of the thermocouple tree with around -15%, while the very bottom thermocouple's temperature was overestimated by around +40%.

To capture the velocities at the door in FDS the total velocity was computed at the same three locations as the flow bi-directional probes in the experiments. As presented in Fig. 9 FDS captured well the flow through the door at both 0.4 and 0.25 m (also at 0.1 m but not presented here) which means that the expected location of the neutral plane for both cases is almost the same.

As presented in Fig. 10, FDS captured the radiative heat flux trends and values at 60 cm from the door and 45 cm from the wall. FDS also computed quantitatively well the radiative heat fluxes at 15 cm and 30 cm from the wall, not presented here. However, the TSCs located at 20 cm and 40 cm from the door were excluded from the analysis due the flame impingement on both, which is beyond the current calibration limits for these TSCs. It is also good to note that the radiative heat flux from the walls was almost the same value as from the door, which shows the effect of the hot thermally-thin walls in radiating to the surroundings (and probably re-radiating to the inside of the compartment). All in all, FDS replicated (to a good extent) the main measurements, namely heat release rate locations, gas layer temperatures, the radiative heat fluxes to the surroundings, and the flow field through the door. Test 80_1 was also used to validate FDS and ended up with very close agreement.

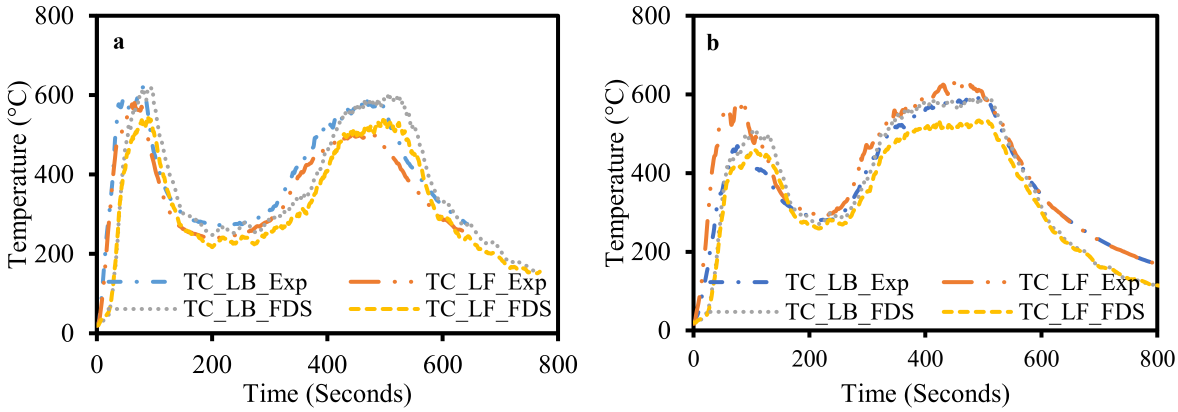

Fig. 7. (a) Comparison between the experimental and numerical gas layer temperature-time curves Test 32_1 and (b) Comparison between the experimental and numerical gas layer temperature-time curves for Test 40_1 (Top thermocouples [TC_5] at two corners)

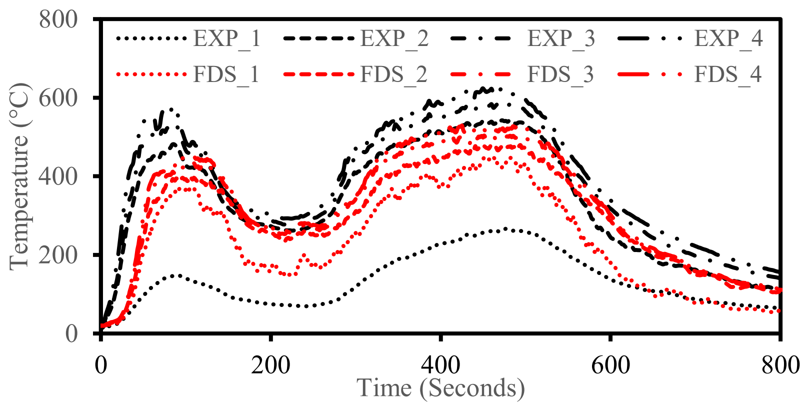

Fig. 8. Comparison between the experimntal and numerical results for the thermocouples 1→4 of the left front thermocouple tree for Test 40_1

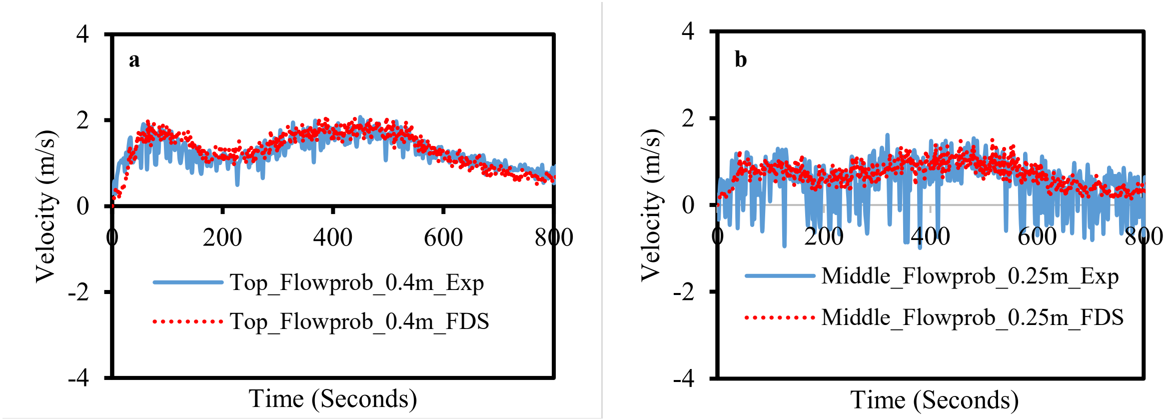

Fig. 9. Comparison between the experimental and numerical velocity-time curves at (a)the top and (b) the middle flow probes locations

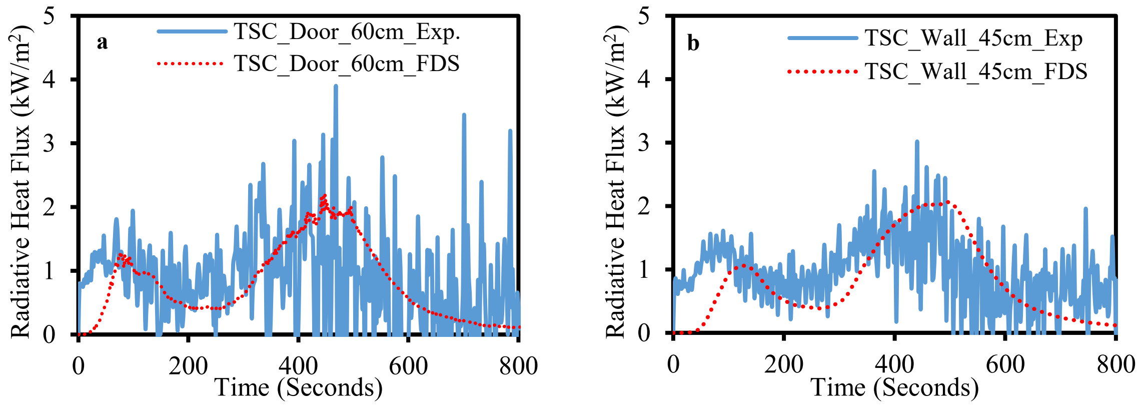

Fig. 10. Comparison between the experimental and numerical Heat Flux-time curves at 60 cm and 45 cm from the (a) door and (b) the side wall

4 Boundary material and ventilation factor parametric study

To understand the effects of changing the wall properties and ventilation on the $\dot{Q}_{FO}$, a parametric study was conducted using six different thermally-thin materials (Table 1) and four different ventilation factors (Table 2). Under-ventilated compartment fires are considered as one of the main challenges to FDS, therefore as our model has been validated with a certain ventilation factor, this parametric study will only focus on this and larger opening sizes.

ISDs are usually packed with very flammable materials [22] within a very limited space, ventilation is always available for the early stages of the fire with the presence of accelerants (e.g. methane cylinders for cooking) [23], and therefore, it is assumed to be an ultra-fast growing fire. To simulate such conditions, the PP tray (Ramped HRRPUA curve) was replaced by a constant HRRPUA burner in FDS, with the same simple pyrolysis model inputs, so it is easier to control the HRR within the compartment and also to be able to define the exact $\dot{Q}_{FO}$ in each case, where the Flashover criteria was set to be 525 °C at the four corners of the gas layer. To define the $\dot{Q}_{FO}$, in each case the burner intensity was increased/decreased by 2.5 kW till the flashover criteria was reached. Based on the previous experimental analysis the gas layer reached 525 °C when the HRR inside of the compartment was around 45 kW, therefore 45 kW was assumed to be the first guess for this ventilation case. As presented in Table 2, the $\dot{Q}_{FO}$was increased with the ventilation factor and it was generally increased with the boundaries' emissivity too.

The model developed by Evegren and Wickström [11] captured the temperature-time curve for the gas layer in the experiments very well, which means that the model is validated also for small scale compartment fires with solid fuels. However, as presented in Table 2 for fast growing fires (using a burner) the model did not manage (in most cases) to capture the correct $\dot{Q}_{FO}$ with under-predictions between 7 to 24%. Additionally, to use this model a software is needed to do the calculations (e.g. Excel) even with no computational time, this model is not as simple as an empirical correlation for $\dot{Q}_{FO}$ (e.g. Eq.1). Therefore, it was deemed important to examine a heat transfer model/analysis using the results from this study to create a simple empirical correlation to estimate the $\dot{Q}_{FO}$ for compartments with thermally thin boundaries.

Table 1. Parametric study materials properties

Material	**Thickness δ (mm)**	**Emissivity ε**	**Conductivity k (W/mK)**	**Specific Heat C_p (kJ/kg.K)**	**Density ρ (kg/m^3)**
Carbon steel	0.5	0.6	48	0.6	7850
Stainless-Steel 304[24]	0.5	0.54	14	0.5	8030
Stainless-Steel clean[24]	0.5	0.26	14	0.5	8030
Stainless Steel lightly polished[24]	0.5	0.19	14	0.5	8030
Aluminium anodized[24]	0.5	0.76	186	1.042	2770
Asbestos[25]	4	0.94	0.58	0.873	1920

Table 2. Parametric study results when varying the materials listed in Table 1 and the ventilation factor of the single opening

	$\dot{Q}_{FO}$ (kW)					
Ventilation Factor (m$^{5/2}$)	Carbon Steel FDS/[11]	Stainless-Steel 304 FDS/[11]	Stainless-Steel Clean FDS/[11]	Stainless-Steel lightly polished FDS/[11]	Aluminium anodized FDS/[11]	Asbestos FDS/[11]
0.0707	45/45	45/45	40/37.5	40/35	50/45	47.5/45
0.1060	52.5/52.5	55/52.5	50/45	45/42.5	57.5/50	55/52.5
0.1414	72.5/60	70/60	57.5/50	55/47.5	65/57.5	65/57.5
0.1767	85/65	80/65	67.5/55	60/52.5	72.5/62.5	70/62.5

5 Heat Transfer model explanation

This section presents, a heat transfer analysis for the compartment, conducted to create a semi-empirical correlation to estimate the $\dot{Q}_{FO}$ with two simple step calculations.

As discussed earlier, the rate of heat release at the onset of flashover can be obtained from several correlations from the literature (e.g.[5];[8]), while the most popular correlation is the

MQH empirical correlation ([9]). Computing the $\dot{Q}_{FO}$ for the current small-scale compartment numerical and experimental work resulted in $\dot{Q}_{FO}$ values much higher than those observed in the experiment/simulations, being 10^3 times higher or more. This behaviour can be attributed to h_k, since the materials considered in the present work are in general highly conductive, leading to very high values for h_k, and therefore $\dot{Q}_{FO}$ from Eq.1. Based on these findings, an alternative methodology must be developed to describe the relationship between $\dot{Q}_{FO}$ and the heat transfer through the walls and ceiling of the compartment. The heat fluxes (both convective and radiative) on the internal walls and ceiling will eventually be transferred to the external ambient environment through conduction, convection and radiation. Taking into account the thermal resistances by conduction through the boundary, convection on/from the internal/external surface of the boundary, and radiation on/from the internal/external surface of the boundary, an overall heat transfer coefficient (U) can be defined as:

$$U = (R_{cond} + R_{EQ\ In} + R_{EQ\ Out})^{-1} = (\frac{\delta}{k} + (\frac{1}{h_{conv}+h_{rad}})_{In} + (\frac{1}{h_{conv}+h_{rad}})_{Out})^{-1} \qquad (2)$$

where *In* refers to the internal surface, *Out* refers to the external surface, h_{conv} is the convective heat transfer coefficient, computed using correlations for free convection [24], and h_{rad} is the radiative heat transfer coefficient, computed as: $h_{rad} = \epsilon\sigma(T_B^2 + T_S^2)(T_B + T_S)$, where ε is the surface emissivity, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/(m².K^4), T_B is the temperature of the boundary/wall and T_S is the temperature of the surroundings. In this study, it was considered that T_B is uniform on the walls (taken as an averaged value for nine points on the wall, three points on the left corner, three on the right corner and three on the middle. The points were equally distributed vertically bottom, middle and top of each section) and on the ceiling (this is a reasonable consideration, since the walls have low Biot number and the thermal gradient could be ignored), and T_S was considered as the hot gas temperature when analysing the internal heat transfer resistance ($R_{EQ\ In}$) and as the ambient temperature when analysing the external heat transfer resistance ($R_{EQ,Out}$). Eq.2 must be computed separately for walls and ceiling, obtaining U_{Wall} and U_C, respectively. Then, the overall heat transfer coefficient taking into account all boundaries is obtained from Eq.3, where, A_{Wall} is the wall area, A_C is the ceiling area and A_T is the total wall and ceiling area

$$U_{Wall+C} = \frac{A_{Wall}}{A_T}U_{Wall} + \frac{A_C}{A_T}U_C \qquad (3)$$

Fig.11 presents the rate of heat release at the onset of flashover ($\dot{Q}_{FO}$) as a function of the overall heat transfer coefficient (U_{Wall+C}) for the boundary materials (asbestos board, stainless steel, aluminium, carbon steel) and for the different ventilation conditions considered in this study. This figure clearly shows that $\dot{Q}_{FO}$ can be related to U_{Wall+C}, A_T and V_F. As a first attempt for improving the predictions of $\dot{Q}_{FO}$, h_k was replaced by U_{Wall+C} in Eq.1, which led to significantly better predictions, but still 10 times higher than the experimental values.

This first approach suggests that the consideration of a heat transfer coefficient that takes into account conduction, convection and radiation would be better for describing the relationship between $\dot{Q}_{FO}$ and the heat transfer mechanisms for thermally thin bounded compartments. This is despite the fact that the correlation in Eq.1 is apparently not adequate to this scenario (ultra-fast fires and thermally thin boundaries). Since the thermal resistance by conduction (R_{cond}) is very small, its influence on U is negligible.

For all fires scenarios considered, the convective heat transfer coefficient (h_{conv}) for the walls and the ceiling, both internal and external, are in the range 1.0-6.0 W/(m².K), so, despite the convective thermal resistance not being negligible, there is not a broad variation on this parameter that would explain the variation of $\dot{Q}_{FO}$ for the different fire scenarios. The same can be stated when comparing the radiative heat transfer coefficient (h_{rad}) for the walls and the ceiling, both internal and external. Those coefficients varied from 15 to 100 (W/m².K) for the fire scenarios considered, but for each fire scenario, they did not present a significant difference when comparing the values obtained for the walls and for the ceiling. Fig. 12 shows the rate of heat release at the onset of flashover $\dot{Q}_{FO}$ as a function of the radiative heat transfer coefficient of the internal walls ($h_{rad,walls,IN}$), for several boundary materials and ventilation conditions. This figure is very similar to Fig.11, so the replacement of U_{Wall+C} by h_{rad} (for the internal wall) is a good choice, since this parameter is simpler to obtain than U_{Wall+C}, and the behavior of $\dot{Q}_{FO}$ for both parameters U_{Wall+C} and $h_{rad,walls,IN}$ is essentially the same. Finally, a new correlation was fit to predict $\dot{Q}_{FO}$ as an alternative to Eq.1. The linear regression was performed using a IBM-SPSS software [26], and the input data were those from Table 1 (materials properties) Table 2 ($\dot{Q}_{FO}$ data from FDS).

$$\theta_{rad} = 10^{7.542}(\varepsilon\sigma A_T A_W H_W^{\frac{1}{2}})^{-0.117} \quad (4)$$

$$\dot{Q}_{FO} = 10^{19.606}\theta_{rad}^{-2.099} \quad (5)$$

where θ_{rad} is defined as $(T_B^2 + T_S^2)(T_B + T_S)$. Equations 4 and 5 are used together to predict the rate of heat release at the onset of flashover ($\dot{Q}_{FO}$) using as inputs only the wall emissivity (ε), the total area (A_T), and the ventilation factor (Vf). Fig. 13 shows a comparison of the rate of heat release at the onset of flashover ($\dot{Q}_{FO}$) obtained from the new correlation, Eq.5, and results from FDS (input data for the regression process). Blue markers denote data conditions used to fit Eq.5. It is noted that all blue markers present a maximum of ±25% agreement, demonstrating that the new correlation properly represents the considered fire scenarios. The proposed correlation was then tested for eight additional computational fire scenarios, considering two different materials (stainless steel, ε = 0.68 and ε = 0.33) and four ventilation conditions. The red markers on Fig. 13 denote such external validation, using data from these eight additional fire scenarios. It is observed that all red markers are within the ±25% boundaries with accuracy around ±15%, so the validity of the proposed correlations for fire scenarios other than those used to fit them are adequately shown.

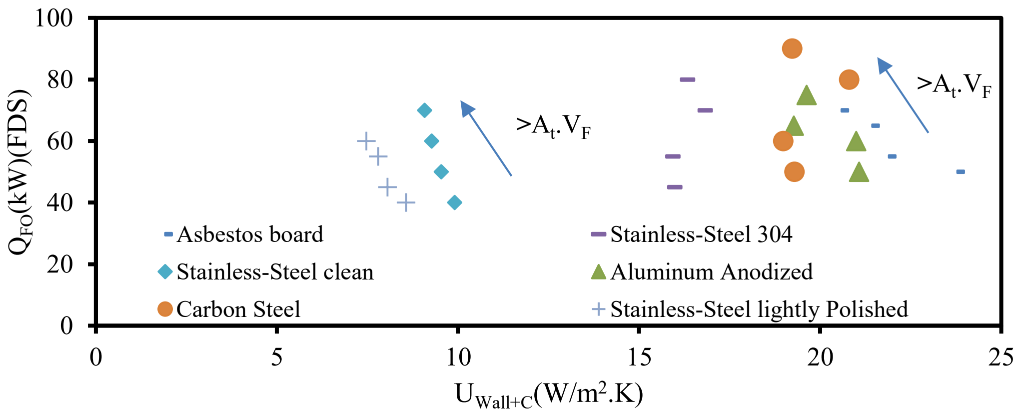

Fig.11. Rate of heat release at the onset of flashover ($\dot{Q}_{FO}$) as a function of the overall heat transfer coefficient (U_{Wall+C}) for several boundary materials and ventilation conditions

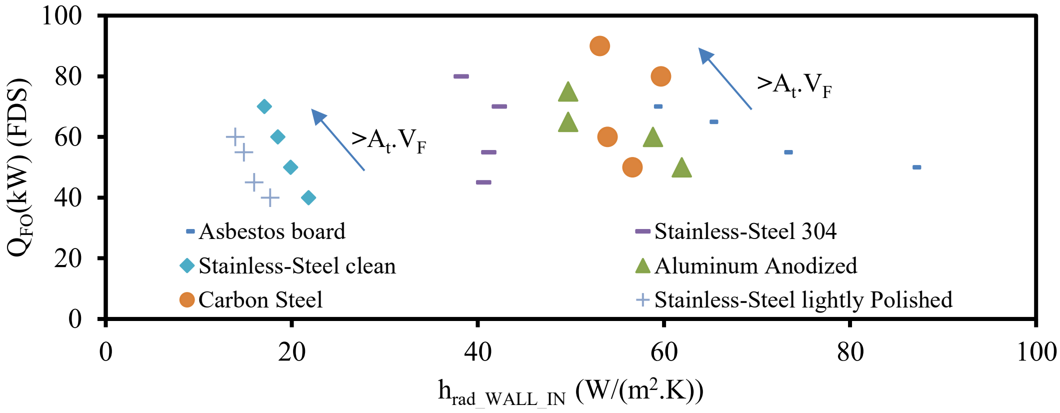

Fig. 12. Rate of heat release at the onset of flashover ($\dot{Q}_{FO}$) as a function of the radiative heat transfer coefficient (h_{rad}) of the internal walls, for several boundary materials and ventilation conditions

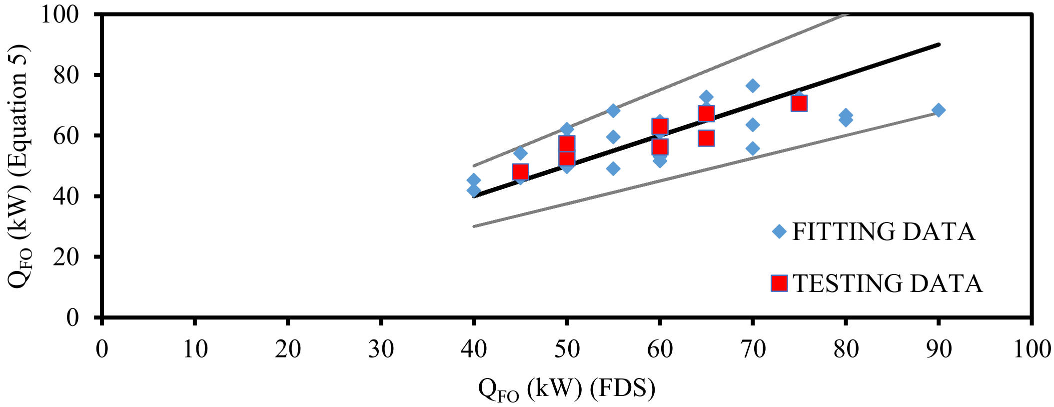

Fig. 13. Rate of heat release at the onset of flashover ($\dot{Q}_{FO}$): comparison of Eq. (5) outputs and results from FDS used as inputs to fit Eq. (5). Blue markers denote data conditions used to fit Eq. (5). Red markers denote external computational validation data used to test the new correlation

6 Sensitivity analysis

To prove the findings in the previous analysis, it was essential to conduct a sensitivity analysis for two compartments: one is thermally thin (Carbon steel case) and the other is thermally thick with a 13 mm Cement Asbestos wall (with its properties taken from [9] and was used to produce the MQH equation). The sensitivity analysis is undertaken for the compartment with the first ventilation factor of 0.0707 $m^{5/2}$ for both cases. The burner intensity used for the thermally thin case was 45 kW and the fire duration was set to 1300 seconds. The compartment with thermally thick boundaries was found to reach flashover with 30 kW for the same ventilation factor, so the 30 kW burner and 1300 seconds fire was used for the compartment with thermally thick boundaries. The sensitivity analysis of the thermal parameters is presented in Table 3 where the bold number is the value used in the base case to compare the effect of decreasing ↓ or increasing ↑ the value of each parameter on the gas layer for TC_LF_5 and the Radiative Heat flux on the front right corner on the floor. Firstly, it was found that the compartment did not reach flashover in the thermally-thin case when the emissivity was increased to 0.95 and did not reach flashover when the conductivity of 14 W/m.K was used for the thermally-thick case. Based on the pervious heat transfer analysis, the main heat transfer mechanism in the compartments with thermally-thin boundaries was radiation, and based on the MQH equation's analysis, the conductivity is the main mechanism in the thermally-thick compartments. The sensitivity analysis presented in Table 3 validates both assumptions especially for the thermally thin case, where it was found that conductivity has almost no effect on the fire dynamics. Conductivity was found to be dominating for the thermally thick, as expected, however, the sensitivity analysis shows that emissivity could also have some significant effect on the amount of radiation from the walls to the fuel packages within the compartment; this needs more investigation to be fully evaluated.

Table 3. Senstivity analysis for the effect of the conductivity and emissivity on the gas layer tempetature and heat flux on the floor for thermally thin and thermally thick compartments

Thermally Thin				
	Gas Layer Temperature (LF_5)		**Heat Flux on the floor**	
Conductivity, k (W/m.K) (0.48↓ **-4.8-** 48↑)	**0.48↓**	**48↑**	**0.48↓**	**48↑**
	0.9%	-0.2%	3.1%	-0.48%
Emissivity, ε (0.1↓ **-0.6-** 0.95↑)	**0.1↓**	**0.95↑**	**0.1↓**	**0.95↑**
	22.7%	No Flashover	178.4%	No Flashover
Thermally Thick				
	Gas Layer Temperature (LF_5)		**Heat Flux on the floor**	
Conductivity, k (W/m.K) (0.48↓ **-4.8-** 48↑)	**0.48↓**	**48↑**	**0.48↓**	**48↑**
	18.2%	No Flashover	89.8%	No Flashover
Emissivity, ε (0.1↓ **-0.6-** 0.95↑)	**0.1↓**	**0.95↑**	**0.1↓**	**0.95↑**
	0.9%	-0.9%	38.7%	-8.6%

7 Conclusions and future work

An experimental and numerical study was undertaken to understand the heat transfer mechanisms within compartments with thermally-thin boundaries + fast growing fires, and an empirical correlation was developed that describes the Heat Release Rate (HRR) needed for flashover $\dot{Q}_{FO}$. These findings were compared to observations for similar conditions in thermally-thick compartments in order to understand the main differences in the heat transfer mechanisms.

The following points were concluded:

- FDS was validated using eight under ventilated compartment fires with thermally-thin boundaries, where the gas layer temperature, flow through the openings, the heat fluxes to the surroundings and the HRR inside/outside of the compartment were matching the experimental results with around 10-15% variation.
- An extensive parametric study showed that the wall emissivity was the main heat transfer parameter for the $\dot{Q}_{FO}$ calculations for the walls of the thermally-thin compartments.
- An empirical correlation was conducted to estimate the $\dot{Q}_{FO}$ for thermally-thin compartments with ultra-fast growing fires (burners) based on the emissivity of the walls, the total walls area and the ventilation factor.

- The empirical correlation was tested numerically and showed very good accuracy, with less than 15% variation.
- A sensitivity analysis for the main heat transfer parameters was done on thermally-thin and thermally-thick compartments, where it was confirmed that the main parameters for heat transfer for the walls in the former is emissivity and for the latter are conductivity and emissivity.
- Some limitations of the model: The $\dot{Q}_{FO}$ correlation is based on $0.19 \leq \varepsilon \leq 0.94$, small scale compartment with ultra-fast fires and thermally thin boundaries.

For future work:

This work is the first of a series of thermally thin small- and large-scale compartment fires to further understanding the heat transfer mechanism and the fire dynamics in these compartments and future work will focus on:

- The effect of leakage (to better simulate the ISDs into more details)
- A wider range of ventilation factors.
- Different fire scenarios (e.g. fast/medium/slow fires).

8 Acknowledgments

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HIGHLIGHTS:

- Thermally thin small scale compartment tests conducted with 4 different fuel loads.
- FDS model validated for small scale under ventilated compartment fire.
- Numerical parametric study: ventilation effect and wall's thermal properties.
- An empirical correlation for $\dot{Q}_{FO}$ for thermally thin compartments was generated.
- Sensitivity analysis: main heat transfer parameters for thermally thick/thin walls.

LIST OF FIGURES