# A Computational Study on the Effect of Horizontal Openings on Fire Dynamics within Informal Dwellings

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## ABSTRACT

Fires in informal settlements are a major risk facing big cities within the developing countries, not only concerning life safety but also because they exert social and economic pressures on these communities. One of the cities most affected by informal settlement fires is Cape Town, Western Cape, South Africa. A research project, namely IRIS-Fire, was launched in order to develop a fundamental understanding of the technical issues regarding fire spread within the informal settlements of the Western Cape. In early investigations it was found that one of the main fire spread mechanisms between dwellings is external flaming and the heat flux from the vertical openings of the burning dwelling to its surroundings. In this paper a computational study is reported which seeks to quantify the effect of adding horizontal roof openings to the design of these informal dwellings. The main parameters in the design of the computational simulations were determined based on surveys done in the informal settlements in the Western Cape. Twenty different cases were investigated using different assumed fuel loads as 270, 410, 550 and 690 MJ/m$^2$ and horizontal opening sizes of 0.04, 0.16, 0.32 and 0.64 m$^2$. It was found that: adding horizontal openings with sizes larger than 0.16 m$^2$ can significantly increase the time for the dwelling to reach flashover, reduce the heat flux from external flaming to the surroundings, and reduce the size of the external flame plume.

**KEYWORDS:** Enclosure fire, external flaming, flashover, horizontal openings, informal settlements

## NOMENCLATURE

| | |
|---|---|
| $h$ | heat transfer coefficient (W/(m$^2$·K)) |
| $L$ | sample thickness (m) |
| $q''$ | heat flux (kW/m$^2$) |
| $\dot{Q}$ | heat release rate (kW) |
| $T$ | temperature (K) |
| $t$ | time (s) |
| $\Delta H_c$ | heat of combustion (kJ/kg) |
| $\dot{m}$ | mass loss rate (kg/sec) |

**Greek**

| | |
|---|---|
| $\varepsilon$ | emissivity (-) |
| $\sigma$ | Stefan Boltzmann constant (W/(m$^2$·K$^4$)) |

**Subscripts**

| | |
|---|---|
| $\infty$ | ambient |
| $cr$ | critical |
| $ig$ | ignition |

## INTRODUCTION

With the rapid increases in populations and urbanization within developing countries, there are now estimated to be more than one billion people living in Informal Settlements (IS) across the globe [1]. These IS are usually at risk of large and destructive fires because of dwellings' proximity to each other, the lack of fire safety measures, the presence of flammable construction materials and the

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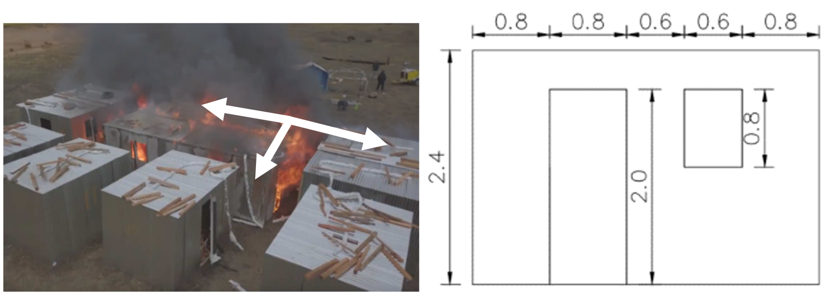
unsafe heating/cooking methods. Based on the World Health Organization analysis, in 2016 [1], 96% of the fire deaths around the world were determined to occur within the lower -and middle-income countries, where a considerable portion of the population is living in IS.

Around one third of the South African population is living in IS and the IS's population is increasing every year; for instance, it is estimated that the number of people living in informal settlements within Cape Town increased rapidly from 28,000 to 220,000 between 1993 and 2011 [1]. There are almost ten dwelling fires per day across South Africa and this is often leading to homelessness and sometimes death, where in some fires the number of people made homeless has reached 10,000, e.g. Imizamo Yethu fire in March 2017 [1]. Cape Town is called the "fire capital of South Africa" with the highest number of fire incidents in the country, where it is estimated that 47% of the fires occurred in informal settlements [2]. In the last few years there have been many notable large-scale fires within the informal settlements in Western Cape, such as [2]: 1) Khayelitsha, January 2013, 4,000 homeless and 2 dead, 2) Kayamandi, March 2013, 4,500 homeless and 2 dead, 3) Masiphumelele, November 2015, 4,000 homeless and 2 dead and 4) Imizamo Yethu, March 2017, 10,000 homeless and 4 dead.

Current research activities are investigating fire development within informal settlement dwellings as they currently are (e.g. [3]); however, there is a paucity of knowledge and data regarding design interventions to minimise the risk of fire spread (and thus help reduce the occurrence of large-scale fires). One of the main considerations when it comes to compartment fire dynamics is the importance of the ventilation factor and position as ventilation conditions are known to highly influence the fire growth within the compartment and the fire spread to adjacent compartments [4].

Experiments conducted within the international research project IRIS-Fire (Improving the Resilience of Informal Settlements to Fire), showed that fire spread between dwellings mainly occurs through direct flame impingement from the openings of the burning dwellings to adjacent structures, as shown in Fig. 1 (a). Wang *et al.* [5] estimated the critical distances between burnt and unburnt dwellings for the fire that occurred in Masiphumelele, South Africa, in 2015, as 3.5 m (where the flames did not spread when the distance between two dwellings is 3.5 m or more). This distance was calculated theoretically for the distance away from the centre of the window of a burning dwelling to the surroundings and then the results were achieved using high resolution aerial photography.




(a) (b)

**Fig. 1.** (a) Flame spread between dwellings (Taken from the IRIS-Fire large scale test, May 2018) (Photo credits: Rodney) and (b) Dwelling front wall design.

Therefore, it is hypothesised that finding a way to decrease the intensity of the flames impinging on adjacent structures from the burning dwelling post flashover, and increasing the time to flashover within the dwelling, could decrease fire spread within settlements.

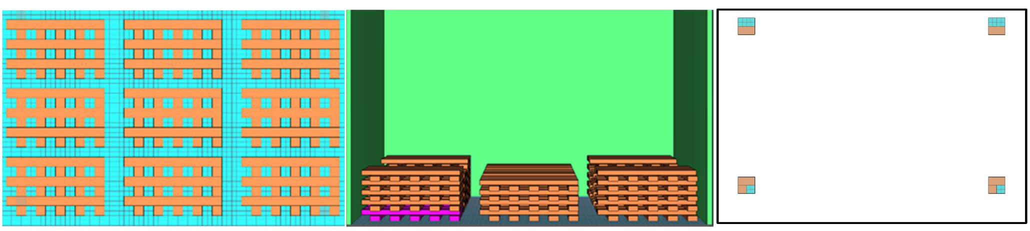
This paper, therefore, is proposing a new design intervention for the dwellings' ceilings by adding horizontal openings to relieve the smoke accumulation before flashover, thus prolonging the time to flashover and relieving some of the burning gases (flaming) from the ceiling openings after flashover. This is hypothesised to reduce the size and intensity of the flames from spreading between the dwellings and can in principle decrease the critical distance. This paper will explicitly examine: time to flashover; heat flux out of the openings; and the average flame length (and temperature) whilst varying the fuel load and size of the horizontal openings in the roof.

## MODELLING SET-UP

The study is done computationally using Computational Fluid Dynamics (CFD) software, namely the Fire Dynamics Simulator (FDS). FDS is a Large Eddy Simulation code solving a set of Navier-Stokes equations appropriate for the low Mach number/ buoyancy driven flows typical of fires [6, 7] (in this study version 6.6.0 FDS has been used).

Informal dwellings are usually small and, based on some site visits to the informal settlements in Western Cape [3], a typical informal dwelling will be approximately 2-5 m in length and width and with a height of around 2.5 m. Therefore, to facilitate the study and future comparisons with literature an ISO-9705 room [8] sized dwelling has been conceptualised, with one window and door on one of the long sides of the compartment. The dimensions of the compartment are follows: 3.6 m (L) x 2.4 m (W) x 2.4 (H) with a door of 0.8 m (L) x 2.0 m (H) and an arbitrarily sized window of 0.8 m (L) x 0.6 m (H), as shown in Fig. 1 (b). The typical material of the dwelling boundaries found in Western Cape is steel sheeting with cardboard or timber cladding on the interior for insulation [3]. Thus, the walls in these simulations were made of 0.05 m (i.e., the cell size within the model) thickness steel obstructions with a 1-D heat transfer thickness of 0.25 mm (to simulate the heat transfer through the thin steel sheets of 0.5 mm). To simulate the fires in the informal dwellings, four different fuels loads have been used, based on the surveys done in [3] where the average fuel load in an informal settlement in Stellenbosch, Western Cape, South Africa was found to be 410 MJ/m$^2$ with a standard deviation of 140 MJ/m$^2$. Based on that, in this computational work the fuel loads were as follows: 270, 410, 550 and 690 MJ/m$^2$. The fuel load was represented by wood cribs distributed on the floor area as shown in Fig. 2 (a). In addition to that, a flammable insulation material was added on the floor and the interior walls to simulate the insulation materials that are typically used in informal dwellings; this will also facilitate the fire propagation within the dwelling which will decrease the simulation time.

To simulate the burning within the dwelling, the FDS "simple pyrolysis model" was implemented, used with a domain of 4.0 m length, 4.0 m width and 3.0 m height and cell size of 0.05 m. In other words, the Heat Release Rates per Unit Area (HRRPUA) (kW/m$^2$) of the wood and the insulation material were used as an input. The HRRPUA of these materials were measured using Cone Calorimeter tests done on wood sticks and thin insulation material sourced from an IS in Stellenbosch, Western Cape. The critical heat fluxes for ignition of the wood and the insulation material were found to be 12 and 6 kW/m$^2$, respectively.



(a) (b) (c)

**Fig. 2.** (a) Wood cribs distribution on the dwelling's floor area plan section-view, (b) elevation section-view (middle), and (c) the horizontal openings positions.

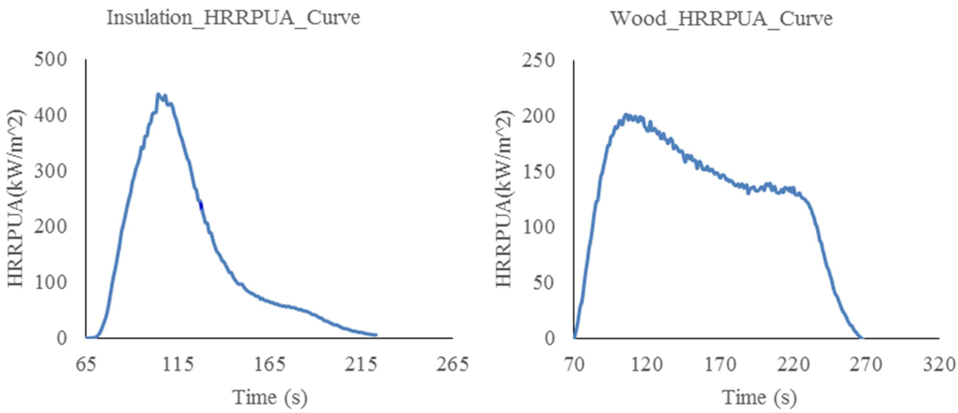



**Fig. 3.** HRRPUA curves used in the simulations.

The HRRPUA under a heat flux of 75 kW/m$^2$ was used in this study and determined from cone calorimetry experiments in the IRIS-Fire project (see Fig. 3). Using 75 kW/m$^2$ as the incident heat flux shortens the burning time of these materials and generates a higher HRRPUA peak thus producing a more intense fire to assess. To simulate the fire spread within the dwelling the critical ignition temperatures were used for both the wood and the insulation material, calculated as:

$$\varepsilon \dot{q}''_{cr} = h_c\left(T_{ig} - T_\infty\right) + \varepsilon\sigma\left(T_{ig}^4 - T_\infty^4\right), \tag{1}$$

where $\varepsilon$ is the emissivity factor, $\dot{q}''_{cr}$ is the critical heat flux (kW/m$^2$), $h_c$ is the heat transfer coefficient in the cone calorimeter around 12 W/(m$^2$·K) [9], $T_{ig}$ is the ignition temperature (K), $T_\infty$ is the ambient temperature (K) and $\sigma$ is the Stefan Boltzmann constant (5.67·10$^{-8}$ W/(m$^2$·K$^4$)). the value of $T_{ig}$ is estimated to be around 610 and 550 K for the wood and the insulation, respectively. In addition to that, the effective Heat of Combustion was calculated using the HRR curve obtained from the oxygen calorimetry and the Mass Loss Rate curve of specimens used in the cone, where it was found to be 14.7 and 50 MJ/kg for the wood and the insulation, respectively [10]:

$$\dot{Q} = \Delta H_c \dot{m}, \tag{2}$$

where $\dot{Q}$ is the heat release rate (HRR) (kW), $\Delta H_c$ is the effective heat of combustion (kJ/kg) and $\dot{m}$ is the mass loss rate (kg/s). It is important to note that it is difficult to precisely define the heat of combustion value especially for the wood as mentioned by Drysdale [10]. These values are not being presented as precise values and more material testing is planned. The first wood crib on the left (as shown in Fig. 2 (b)) was ignited at the beginning of the simulation with a HRRPUA double that which was found in the cone, simulating an assumed case where these sticks were soaked in a hydrocarbon liquid and ignited to start the fire development.

**Table 1. Materials thermal properties used in the simulations**

| Material | Density, kg/m$^3$ | Specific heat, J/(kg·K) | Conductivity, W/(m·K) |
|---|---|---|---|
| Wood [11] | 548 | 1600 | 0.13 |
| Insulation material* | 100 | 1500 | 0.4 |

*Where the insulation material properties were estimated by the authors to enhance the ignition and skip the long incipient stage of the fire.

The adopted Pre-Flashover soot yield was 0.015 (kg soot)/(kg fuel) as recommended by [12, 13], where Post-Flashover is expected to be higher, 0.03 (kg soot)/(kg fuel), due to the reduction in the combustion efficiency. However, since the main focus in this paper is on the time to flashover and the heat flux of the flames impinging just after flashover, the Pre-Flashover value was used throughout the simulations, thus assuming that the burning efficiency will not reduce significantly immediately Post-Flashover.

Five different horizontal ventilation cases were investigated in this paper. The vertical ventilation openings were identical in all cases (the window and the door), but the horizontal opening sizes were varied keeping the same origin point as shown in Fig. 2 (c). In total, 20 cases were examined under different ventilation conditions and fuel loads, as shown in Table 3.

The design of the celling's openings is small square-shaped areas in the four corners, made of materials that easily burn, melt or break away at temperatures between 250 and 350°C. The critical temperature for the holes (250 °C) was chosen based on two reasons. First, the hot layer temperature needed for flashover is approximately 500-600°C [10, 14], thus a lower temperature is required. Second, the piloted ignition temperatures and critical heat fluxes of common materials in IS (shown in Table 2) are within this range, and these materials could be used as covers for the openings, or make a supporting structure for a steel sheet cover. Another potential material for the opening would be glass as it may break and fall out in the range of 200-300°C in some fire situations [15]. Ideally, the chosen materials for this purpose should be thermally-thin materials so they can reach thermal equilibrium with the gas layer in as short a time as possible and justify the assumption that the material and the gas layer are at the same temperature.

**Table 2. Common materials in IS and their piloted ignition temperatures and critical het fluxes determined from cone calorimeter experiments**

| Material | Ignition Temperature (°C) | Critical Heat Flux (kW/m$^2$) |
|---|---|---|
| Wood | 330 | 11-12 |
| Plastic sheets | 310 | 10-11 |
| Tyres (rubber) | 270 | 7-8 |

## RESULTS AND DISCUSSION

### Cell size sensitivity analysis

The dimensions of the wood sticks were 0.1 m (W) x 0.05 m (H) x 0.6 m (L) or 0.9 m (L), therefore a maximum cell size for the simulations was 0.05 m, in order to capture the wood sticks. A cell size sensitivity analysis, using 0.04 and 0.025 m, was also undertaken to ascertain if the results are cell size independent. The criteria set here is an average of 15 % difference between the default cell size and the refined mesh. As shown in Fig. 4, the difference in the heat flux for case 690_0.0 at one metre away from the window is generally around or less than 15 %. Although not a scientific consideration, the computational time of the simulations was weighed against the general purpose of the study and it was decided that the 0.05 m cell size would provide sufficient accuracy.

### The time-temperature curve for the fire development (growth phase)

The process of the fire development within a compartment with no fire suppression or any means of firefighting proceeds via four different stages as mentioned in Buchanan and Abu [16]. The first stage is the incipient stage, where the fuel is still being heated. In this paper, the incipient stage was bypassed by incorporating the burning wood cribs from the very start of the simulations, in order to save computational time on phenomena not related to the focus of this study.

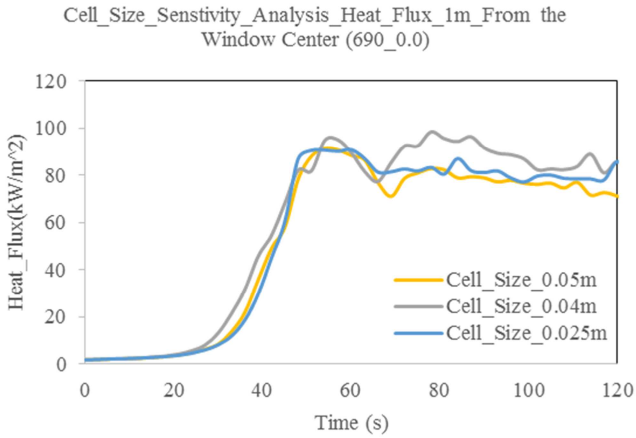
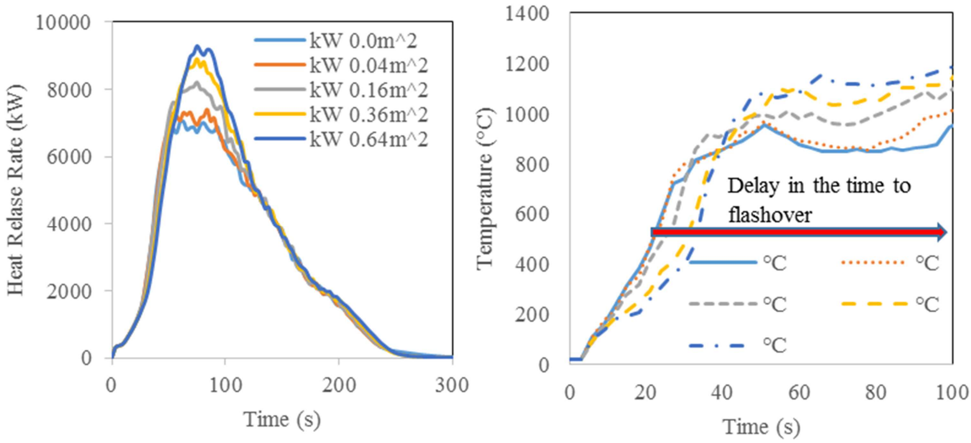



**Fig. 4.** Cell size sensitivity analysis.

The second stage is the growth phase, which is the period in which all the fuel packages approach full burning and thus it can be argued that flashover occurs at the end of the growth stage [16]. The growth stage development was compared between the different cases to quantify the effect of adding horizontal openings on the time to reach flashover. As shown in Fig. 5, the growth phase ending time (time to reach the peak temperature) increases with the increase of the horizontal opening's size. To be able to quantify this increase in time it was crucial to define the starting time for the full burning period (i.e., all the fuel packages are burning simultaneously). In compartment fires, it is often challenging to define the ending/starting time to each phase, especially the burning phase. Here, to be able to quantify the differences between different cases, the end of the growth phase was assumed to be the time when the slope of the ascending growth phase has decayed and the slope of the temperature time curve becomes +/- 10 K/sec. Taking case 410_0.0 as an example presented in Fig. 6, the gas layer temperature (just below the ceiling) increased with a steep slope of 30 – 50 K/s until it reached 820°C at 33 seconds, then the slope dramatically decreased to less than 10 K/s in most of the period between 33 and 215 seconds. Therefore, for case 410_0.0 the burning phase is deemed to prevail from 33 to 215 seconds, with the flashover happening around 33 seconds. Table 3 presents the burning time period for each case with a comparison between the time to flashover for each case and its default case (where there are no horizontal openings). It was found that the relative time to flashover significantly increases in most cases, with cases 410_10, 550_10 and 550_20 as exceptions where the time to flashover was similar to that of the the default case. It was also found that larger horizontal openings (total areas of 0.32 and 0.64 $m^2$) performed better with higher fuel loads, and smaller horizontal openings (total areas of 0.04 and 0.16 $m^2$) performed better with lower fuel loads.

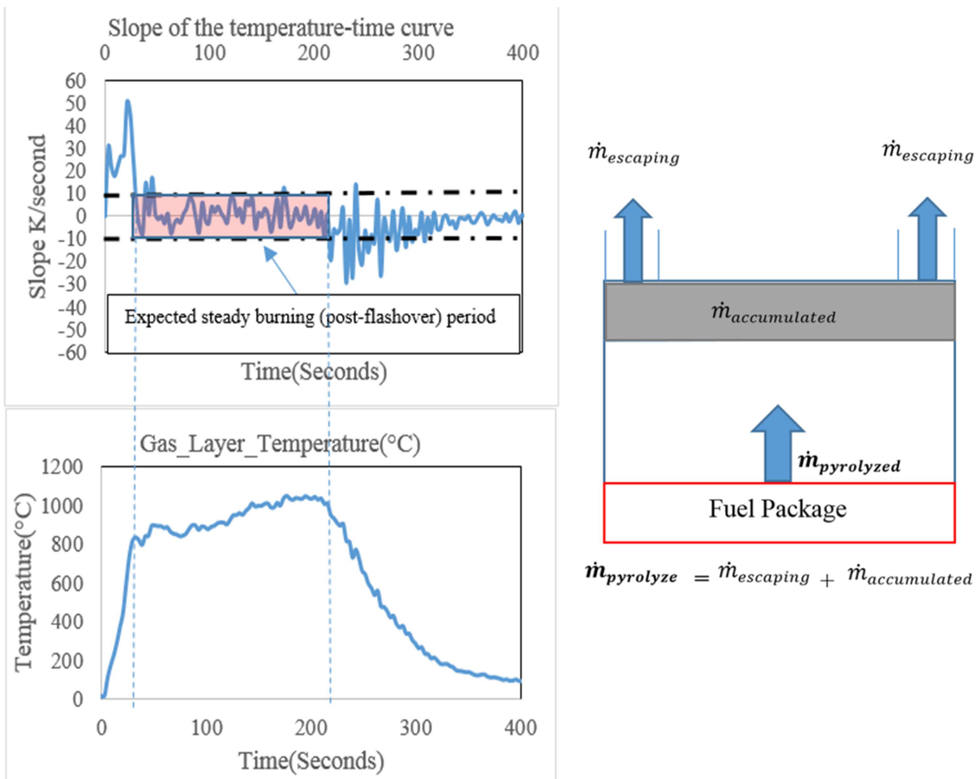
This result is expected to be due to the mass balance within the compartment and the amount of the pyrolyzed gases/smoke produced against the amount of the same escaping through the horizontal openings in each case, as shown in Fig. 6 (b), where $\dot{m}_{pyrolyzed}$ is the pyrolyzed gases production rate (kg/s), $\dot{m}_{escaping}$ is the rate of gases/smoke escaping through the ceiling's openings (kg/s) and $\dot{m}_{accumulated}$ is the rate of increase in the amount of the pyrolyzed gases (the smoke layer production rate, kg/s).

For example, for the high fuel loads the amount of gases escaping from the ceiling compared to the produced gases is considered a small percentage so, in most of the cases, by increasing the opening size the time to flashover will increase by a relatively small amount. However, for the low fuel loads, the amount of gases produced is comparable to the amount of gases escaping from the small openings so the time to flashover will be highly sensitive to the presence of small openings.




(a) (b)

**Fig. 5.** (a) HRR and (b) Temperature curves for the 270 MJ/m$^2$ cases measured at 5 cm below the ceiling.




(a) (b)

**Fig. 6.** (a) Burning (Flashover) prediction method (410 MJ/kg), (b) Compartment Mass Balance.

It was also found that the time to reach flashover is sometimes longer for higher fuel loads (e.g. comparing 270_10 and 410_10). This could be due to the bulk density of the wood cribs, as explained by Heselden *et al*. [17], that even for the same fuel load, the higher the bulk density of the wood cribs inside the compartment, the longer the growth phase will be. Alternatively, it may be that the end of the growth phase was incorrectly defined leading to some errors.

**Heat flux to the surroundings**

The heat flux was estimated at 1.0 m away from the centre of the window and the centre of the door, and averaged over the full burning time. It was found that the horizontal opening effectively decreased the heat flux to the surroundings by up to 35% as calculated by Eqn. 3 and shown in Table 3. Figure 7 shows a comparison of the average value of the heat flux at 1.0 m from the window compared to the default cases for each fuel load. Firstly, Fig. 7 shows that, regardless of the fuel load magnitude, the larger horizontal opening always reduces the heat flux to the surroundings. Secondly, for the same horizontal opening size, there were negligible heat flux reductions when the fuel load changed, with the difference ranging between 6 and 8%.

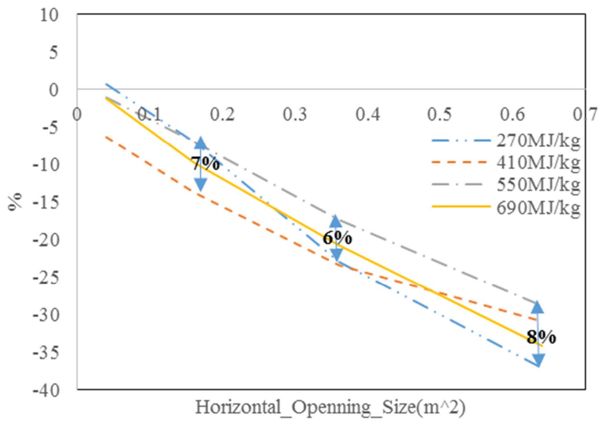



**Fig. 7.** Average heat flux for different fuel loads at 1.0 m from the centre of the window.

**Flame length**

Within this paper, the size of a flame ejecting out of an opening is determined using 880 °C as a threshold value for the continuous burning zone [5]. Cells of and above this value were therefore considered to be a flame, and the length of the flame averaged across both the burning period and the vertical axis. The flame length was compared for different cases using temperature slices in the middle of the window and the door and it was found that the flame length is shorter from the door compared to the window in most cases, so the focus in this section will be only on the flames ejected from the window. Temperatures within 1.0 m of the front wall were averaged and an example is presented in Fig. 8 (a) with a fuel load of 690 MJ/m$^2$, all other cases were analysed using the same method. It was found that, irrespective of fuel load magnitude, larger horizontal openings produced shorter and hotter external flames. Smaller horizontal openings (0.4 and 0.16 m$^2$) reduced the external flame by approximately 6% on average compared to approximately 28% on average for larger openings (0.36 and 0.64 m$^2$).

The percentage change difference for the opening sizes and the default case, presented in Fig. 8 (b), was found to range from 18% to 30%. This is almost three times the difference found in the average heat fluxes, and varied greatly. The variation could be due to the influence of cell size on the measurements, therefore future analyses will look at this aspect. However, a general trend that increasing the opening size decreases the average flame length can be observed and thus it is apparent that taking heat flux as the sole comparison indicator could be misleading.

**Table 3. Modelling cases [Fuel Load horizontal opening side length (cm)], results and comparative analyses to default fuel load cases**

| Case | Fuel load (MJ/m$^2$) | Horizontal ventilation Area (m$^2$) | Time of steady burning (Seconds) | % of m.0 (Time to reach Flashover) | Average Heat Flux window (kW/m$^2$) | Average Heat Flux door (kW/m$^2$) | % of m.0 (Window Heat Flux) | % of m.0 (Door Heat Flux) | Average flame length (m) | % of m .0 (Window Flame Length) |
|---|---|---|---|---|---|---|---|---|---|---|
| 270_0.0 | 270 | 0.0 | 27-162 | - | 66.8 | 55.2 | - | - | 0.75 | - |
| 270_10 | | 0.04 | 30-165 | +10% | 67 | 54 | +0.7% | +1% | 0.80 | +6.6% |
| 270_20 | | 0.16 | 36-162 | +34% | 62 | 56 | -7% | -6% | 0.75 | 0% |
| 270_30 | | 0.32 | 54-156 | +100% | 51 | 46 | -23% | -15% | 0.60 | -20% |
| 270_40 | | 0.64 | 50-171 | +85% | 42 | 40 | -37% | -25% | 0.55 | -26% |
| 410_0.0 | 410 | 0.0 | 36-216 | - | 84.6 | 69.7 | - | - | 0.60 | - |
| 410_10 | | 0.04 | 36-216 | 0 | 79 | 69 | -6% | -0.5% | 0.60 | 0% |
| 410_20 | | 0.16 | 39-183 | +10% | 73 | 67 | -13% | -4% | 0.55 | -8.3% |
| 410_30 | | 0.32 | 48-225 | +34% | 64 | 61 | -24% | -11% | 0.35 | -41.6% |
| 410_40 | | 0.64 | 60-216 | +66% | 58 | 55 | -31% | -21% | 0.45 | -25% |
| 550_0.0 | 550 | 0.0 | 33-198 | - | 58.4 | 53.2 | - | - | 0.45 | - |
| 550_10 | | 0.04 | 33-198 | 0 | 57 | 52 | -1% | -1% | 0.45 | 0% |
| 550_20 | | 0.16 | 33-240 | 0 | 54 | 51 | -7% | -4% | 0.40 | -11.1% |
| 550_30 | | 0.32 | 63-240 | +90% | 48 | 47 | -17% | -11% | 0.40 | -11.1% |
| 550_40 | | 0.64 | 57-186 | +109% | 41 | 41 | -29% | -23% | 0.30 | -33.3% |
| 690_0.0 | 690 | 0.0 | 30-225 | - | 51.19 | 46.9 | - | - | 0.45 | - |
| 690_10 | | 0.04 | 33-345 | +10% | 50 | 44 | -1.2% | -5% | 0.40 | -11.1% |
| 690_20 | | 0.16 | 36-327 | +20% | 46 | 42 | -10% | -10% | 0.35 | -22.2% |
| 690_30 | | 0.32 | 66-312 | +110% | 40 | 37 | -21.5% | -20% | 0.35 | -22.2% |
| 690_40 | | 0.64 | 66-305 | +110% | 33 | 32 | -35% | -31% | 0.25 | -44.4% |

$$\%\ of\ m.0 = \frac{Time\ to\ flashover,\ \ Average\ HF\ or\ FL\ for\ the\ default\ case\ (m\_0.0) - Average\ HF\ or\ FL\ for\ case\ (m\_n)}{Average\ HF\ or\ FL\ for\ the\ default\ case\ (m\_0.0)}, \tag{3}$$

where m is the fuel load (270, 410, 550 or 690 MJ/m$^2$) and n is the horizontal opening length (10, 20, 30 or 40 cm).

**Model uncertainties**

As with any fire modelling, the presented cases have some associated uncertainties in particular:

- In cases *m*_10, the borders of all four cells that represent the holes have two sides with the ceiling as a boundary; this will affect the solution of the fluid dynamics within these holes. More analysis of this is therefore required.
- The heat transfer through the walls might not be realistic as the steel sheets are quite thin for the cell size used to effectively compute the heat losses.
- The thermal properties of the fuel packages are either taken from literature or estimated by the authors to satisfy the needed fire spread; these properties are assumed constant for all the simulations.
- The assumption that the hole covering materials will have the same temperature as the gas layer is a simple one and the heat balance between the materials and the surrounding temperatures was not addressed in this study. This should be an important factor to investigate in future studies.
- To the authors' knowledge there was little validation work in literature for either an ISO room with both horizontal and vertical openings or work that addressed such sudden changes in ventilation, therefore, additional experiments are planned to examine such cases and also to further understanding of the behaviour of these materials as candidates for this application.

Some of the uncertainties mentioned would affect the end results and the comparisons between different cases, but this primarily parametric study was done to give a mainly qualitative analysis of the idea with some associated, and caveated, quantitative data. Therefore, further investigations are needed and planned for the extended study.

However, from this primarily parametric study it can be concluded that, in most cases, the effect of the size of the horizontal opening is greater than that of the fuel load. The fuel load - as expected - did not have a big effect on the fire post-flashover as the burning within the compartment will be fuel controlled. However, better understanding of the effect of adding horizontal openings is needed. It could also be concluded that, for the dwellings with horizontal openings bigger than 0.16 $m^2$, the time to flashover will significantly increase and the heat flux to the surroundings and the external flaming average length will significantly decrease.

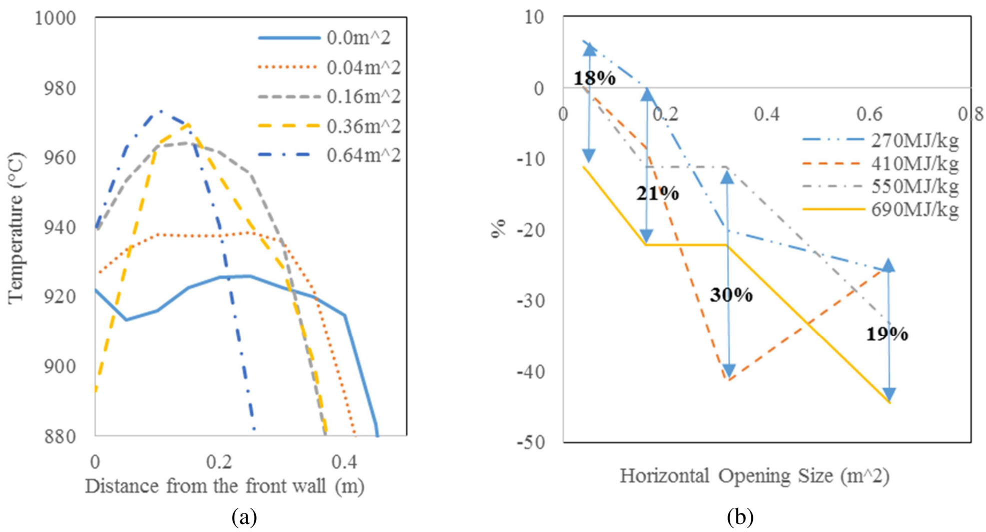



**Fig. 8.** (a) Estimating the flame length for the external flaming for the fuel load of 690 MJ/$m^2$, (b) Average flame length for different fuel loads from the centre of the window (right).

## CONCLUSIONS

This paper has presented a computational analysis highlighting the effect of adding horizontal roof openings to informal settlement dwellings to decrease the fire spread risk. The main intent was to understand computationally the effect of these openings with different fuel loads and with different opening sizes. Based on 20 cases with different ventilation conditions and fuel loads it can be concluded that, by incorporating horizontal openings in the roof:

- The time to flashover can be significantly increased, by up to 110%;
- Significant reductions can be observed in the average heat flux measured 1.0 m from the door and window (up to 37% and 35%, respectively);
- Flame length out of windows can be significantly reduced, by up to 44%;
- Horizontal opening size has a greater influence on the above metrics than fuel load magnitude; and
- Openings larger than 0.16 $m^2$ have a greater impact than those of 0.16 $m^2$ or smaller.

The time to flashover was found to be a critical and difficult parameter to define. Therefore, the current study developed a definition of the time to flashover based on the relative change in temperature from one time step to the next. A more accurate and quantifiable definition of flashover would allow greater quantitative comparisons between different cases.

This paper has shown that potentially significant increases to time to flashover, and reductions in heat fluxes and flame lengths, can be observed when horizontal openings are introduced into the roofs of informal settlement dwellings. If this concept is applied to dwellings within an informal settlement, it is assumed that the risk of fire spread could be reduced, thus increasing the robustness of the informal settlement to such fire disasters. However, further research is required to provide experimental studies to validate the computational work and also to understand the complexity of the mass and heat balance.

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