Ventilation in Small-Compartment Fires: The Potential of Fire Retardancy

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ABSTRACT

Modern architecture expands building openings to take advantage of natural light, which may have detrimental effects in case of fire occurrence. The falling panes by the high temperatures may cause fire to spread and endanger lives and property. Based on that and by using Pyrosim software, the current study investigated the effect of natural ventilation on small-compartment fire development and on the latter reaching the flashover phase. The simulated enclosure was a 3.6 m × 3.6 m × 2.9 m room with a closed door of 0.90 m × 2.10 m. The study analyzed the impact of the ventilation opening size and dimensions on fire development and the neutral plane height. The results showed that the ventilation area, rather than its dimensions, was the factor with the most significant impact. Higher ventilation areas reduced the temperatures well below the flashover conditions. The current study reveals the potential of employing natural ventilation to help prevent compartment fires from reaching the flashover stage as well as its consequences on lives and property.

Keywords-CFD; fire simulation; compartment fires; natural ventilation; flashover

I. INTRODUCTION

Building fires, either deliberate or accidental, can cause death, property loss, and structural instability. The severity of these fires has been remarkably increased, posing a substantial risk to the community. Fire incidents between 1993 and 2015 claimed the lives of over one million people worldwide [1]. Enclosure fires with varying dimensions of vertical vents may exhibit distinct behaviors due to flows at the opening. Vents and the resulting flows play a crucial role in fire development and propagation [2]. Fires in rooms are also affected by ventilation openings, whether them being natural or mechanical

[3]. The presence of these openings may affect the fire spread to neighboring areas, which stresses the need to conduct a research that investigates the extent of these openings' effect on fire development, including the change in temperature and pressure in the room and the heat release rate. Also, considerable research has focused on fire development in enclosures with various opening configurations and dimensions. Most of these investigations relied on tests carried out in enclosures with predetermined sizes. The fire behavior was then scaled up to fit other enclosure dimensions [4-9]. However, this method may involve serious errors, especially when there is no adequate model for dealing with the situation. An alternative solution to this is to use simulation programs that have proven modeling capabilities.

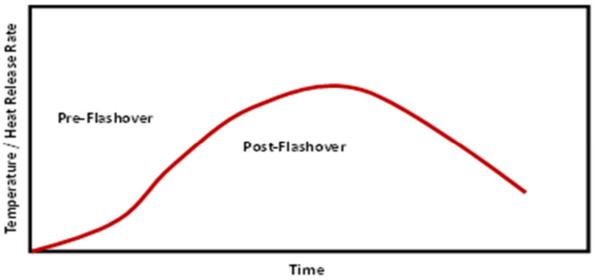


Fig. 1. Development curve for enclosure fires.

Figure 1 shows a typical growth curve for enclosure fires. Several factors determine the development of a fire, including fuel load, ventilation, compartmentation, etc. [10]. Compartment fire starts with fuel smoldering and igniting, followed by the pre-flashover, flashover, and post-flashover stages. The temperature increases with time in the pre-flashover stage and continues to rise in the post-flashover stage until it reaches a maximum value before it rapidly declines. The pre-and post-flashover stages are crucial for life safety, while the post-flashover phase is essential for structural stability [1]. In the flashover zone, the fire becomes ventilation-controlled. In this stage, the thermal parameters change enormously, especially carbon monoxide concentration, which rises by several orders of magnitude. In the post-flashover period, all thermal parameters reach their maximum value, and the fire evolves in a fully developed quasi-steady-state phase, up to fuel complete consumption. In the pre-flashover phase, combustion produces several toxic gases, which can be fatal to humans within minutes [11-12] The gases include carbon monoxide, hydrogen cyanide, and phosgene. Combustion smoke contains soot particles and toxic vapor that might aggravate the eyes and the respiratory system. Smoke can be more fatal than the fire itself [13]. Smokes may also hinder evacuation, thus increasing the possibility of exposing residents to toxic gases and lack of oxygen, and subsequently putting their lives at risk. In the post-flashover phase, temperatures usually reach hundreds of degrees Celsius, affecting the properties of the materials used in the construction of the facilities and posing a danger to their safety that may lead to premature collapse [10, 14]. The fire development curve does not necessarily apply to all cases of fire, as some of them cannot continue to grow as a result of being affected by several factors. Active and passive fire protection, such as sprinklers and partitions, and ventilation may prevent a fire from reaching the flashover stage, especially in compartment fires. The heat release rate and temperature are the main parameters that govern flashover occurrence [15-16].

The fire safety of buildings starts from their design and concludes with the availability of skilled firefighting and rescue teams to deal with fire incidents. Fire safety includes passive and active measures. As societies grow and become more sophisticated, fire protection techniques and control equivalently develop. To be able to predict the onset and potential development of a fire in different scenarios, it is necessary to conduct experiments that simulate the reality of the surrounding environment. Nevertheless, since conducting experiments is often expensive and difficult to implement, especially regarding buildings, mathematical modeling, and a pre-developed software and Computational Fluid Dynamics (CFD) are deployed for simulating the fire scenarios in buildings and facilities [17].

Fire modeling involves defining the target, determining the scenario, choosing a prediction method, assessing results, and exploring uncertainties. Selecting the correct model based on its assumptions, limits, and correlations can result in valid findings [18]. Several fire simulators have been developed and used in numerous case studies. Fire modeling is a vital instrument of fire safety engineering because it predicts heat transfer, fire and smoke spread, detector activation, and egress of building occupants [19].

A. *Fire Analytical Computer Programs*

There have been increasing advances in the analytical models employed for engineering research and predicting fire behavior since 1960 [20-24]. Zone models, which divide the volume into an air layer and an upper smoke layer, and Computational Fluid Dynamics (CFD), which segments the volume into multiple cells with their own mass and energy transfer balance, provide accurate tools for investigating the dynamics of the gas phase in fire. CFAST is an example of a zone model. It predicts smoke, gases, and temperature evolutions throughout a structure during a fire. It segmentizes the compartment into two layers. The software can also track multiple fires independently in one or more compartments of a building. [24]. Fire Dynamics Simulator (FDS) is a CFD model of fire-driven fluid flow. FDS numerically solves Navier-Stokes equations for low-speed, which are thermally-driven flows focusing on smoke and heat transport from fires. It enables simulating fires in public compartments and large enclosures such as atriums, and supermarkets [24-26]. FDS displays simulation results using Smokeview. It also permits the analysis of smoke and heat transport utilizing mass, momentum, and energy conservation equations for low-speed, thermally driven flows of gas mixtures [27].

B. *Importance and Objective of the Study*

Modern architecture extends and expands building openings to take advantage of natural light, which may have a detrimental effect in case of fire occurrence. However, high temperatures during compartment fires make window glass crack and fall out, creating vent openings, thus affecting fire development. The falling panes could endanger people and firefighter lives. The vents may also facilitate the propagation of fire plumes. Yet, the cold air draft entering the compartment may cool the fuel surfaces, hindering fire growth.

Preventing the spread of fire from enclosures to adjacent spaces is extremely important in rescuing lives and enhancing safety. Dealing with fire, produced gases, chemicals, and smoke requires cautiousness and more complicated safety procedures. Ventilation (mechanical or natural) may spread the fire outside the room, and it may simultaneously work to suppress the fire by sucking cold air from the outside into the interior, thus cooling the fuel surface and suppressing the fire [3]. Ventilation may maintain the floor area at a lower level of the hot gases and smoke, and hence, provide safer exits for the firefighters and civilians inside the burning building. Based on this, the current study investigated the impact of the opening area on fire development, concentrating mainly on temperature evolution and neutral plane.

II. METHODOLOGY

The current study examined how window dimensions could affect the hot gas temperature and neutral plane height in an office room fire employing PyroSim software. PyroSim is a CFD tool for simulating fire and low-speed, thermally driven flow. PyroSim is the user interface for the FDS software. The FDS model can predict smoke and temperature development, HRR, pressure distribution, neutral plane, carbon monoxide evolution, and other hazards caused by fires.

A. *The Simulated Room*

Figure 2 portrays the simulated fire scenarios developed in a 3.6 m × 3.6 m × 2.9 m room, with the size of the door being 0.90 m × 2.10 m. Table I displays the sizes of the investigated windows. The window is a part of the wall next to the closed door. Its lower side is 1.00 m above the room floor. The window has a cloth curtain. The room walls are made of concrete. The furnishings include a false ceiling, fabric-covered sofa, wooden office table, and synthetic leather chair. The room and window dimensions investigated in this study are the most commonly used dimensions for rooms and windows in Jordanian societies.

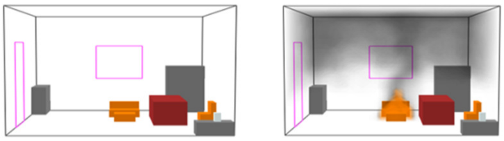


Fig. 2. A schematic of the simulated room (3.6 m × 3.6 m × 2.9 m).

TABLE I. INVESTIGATED WINDOW CONFIGURATIONS

Case	Height (m)	Width (m)	Area (m^2)
1	0.50	0.50	0.25
2	1.34	0.50	0.67
3	1.00	1.00	1.00
4	1.8	1.00	1.80
5	1.00	1.80	1.80
6	1.34	1.34	1.80

III. RESULTS AND DISCUSSION

A. *Temperature Evolution Profiles*

For a fire protection practitioner, predicting the temperature of hot gases in a fire compartment is critical. This information is crucial for evaluating the thermal behavior of various fuels and identifying hazardous conditions, flashovers, and structural elements that may be at risk of collapse. The following section discusses the temperature evolution with time at different heights in the room.

B. *Hot Gas Temperature Near the Window*

Figure 3 shows the temperature development curves for the 0.5 m × 0.50 m high window scenario. At all levels, the temperature increased rapidly with time, reaching a maximum value after which it remained approximately constant. Moreover, the temperature reached its maximum value in about 100 s of ignition. The results also reveal that the maximum temperature increased with the level. As evidenced in Figures 4-8, the other scenarios also exhibited a similar temperature variation trend with time at all levels. The maximum attained temperatures at all levels were well below the flashover (500-600 ^{0}C) and decreased as the window area increased.

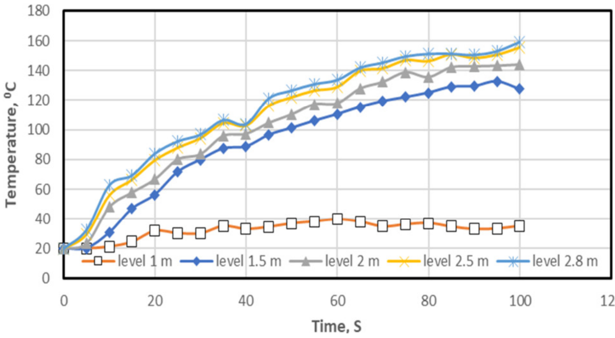


Fig. 3. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (window 0.50 m × 0.50 m).

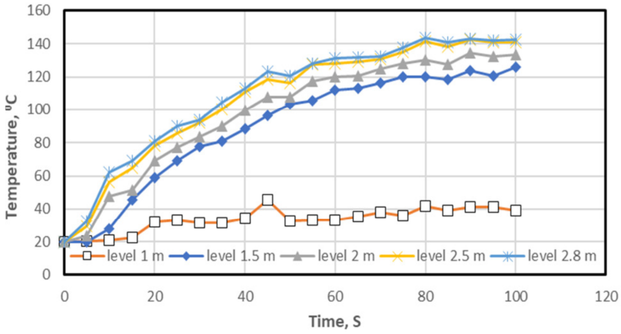


Fig. 4. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (window 1.34 m × 0.50 m).

Additionally, the results disclose how ventilation in a room can appreciably delay the flashover of a fire. Using CFast the Time To Flashover (TTF) of the ventilated compartment fire with different configurations and areas was calculated in [28].

It was found that the ventilation area and height varied linearly with the TTF. It is possible to delay flashover either by ventilating or suffocating the fire. A ventilation opening allows the hot gases to escape and the cold air to flow into the room, reducing the temperature of the hot gases, hence delaying the occurrence of the flashover. However, the lack of ventilation discourages flashover by limiting the oxygen supply. On the other hand, over-ventilation may increase the flame intensity and temperature by permitting more oxygen to flow into the fire, thus encouraging flashover. Using ventilation to retard fire requires careful structure design and knowledge of the fire scenarios [28].

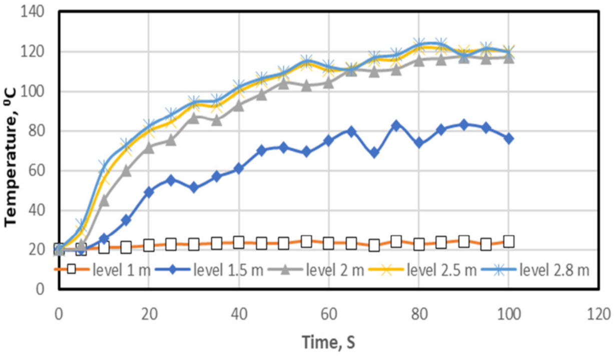


Fig. 5. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (window 1.00 m × 1.00 m).

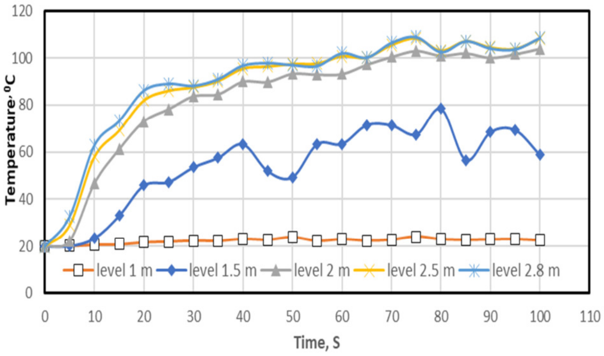


Fig. 6. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (window 1.80 m × 1.00 m).

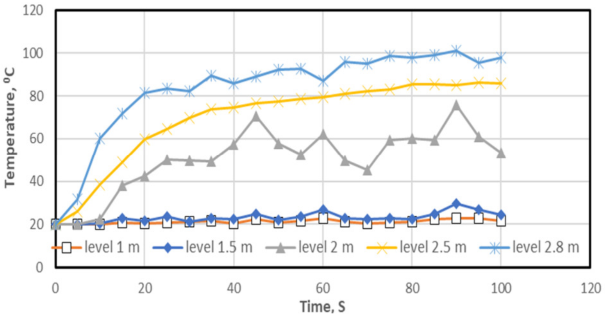


Fig. 7. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (window 1.00 m × 1.80 m).

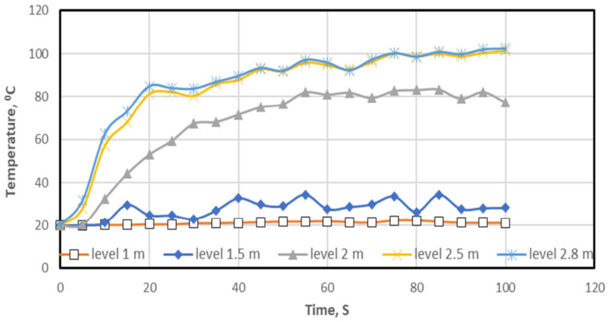


Fig. 8. Temperature of the hot gas near the window as a function of time at different levels from the room's ground (1.0, 1.5, 2.0, 2.5, and 2.8 m) (Window 1.34 m × 1.34 m high).

Figures 6-8 depict the temperature evolution near three windows that are different in dimensions but cover the same area. These curves illustrate that the maximum temperatures near the ceiling are close in the three scenarios. This finding may suggest that the ventilation area, rather than the window's configuration, is the most significant factor in determining the ceiling temperature. This conclusion is consistent with the International Code Council (ICC), which expresses the ventilation area as a percentage of the enclosure floor area [29]. The TTF versus the ventilation opening area slope is much greater than its corresponding value of TTF versus the ventilation height, which supports the current findings, as shown in [28].

C. Variation of Hot Gas Temperature with the Level Near the Window

Figure 9 showcases the temperature evolution of the hot gas near the window at different levels from the room's ground and for various window sizes. The temperature firstly rises rapidly and then becomes almost constant. As observed, the temperature gradient becomes steeper as the window area decreases; this could be because of the heating effect of the smoke ceiling jet's movement and radiation from the ceiling. Moreover, higher temperatures prevail at all levels at lower vent areas, which is consistent with previous studies [30-33].

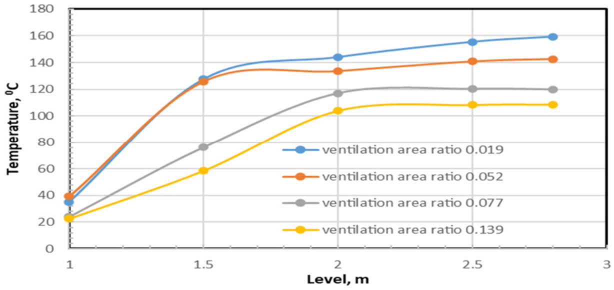


Fig. 9. Temperature of the hot gas near the window at different levels from the room's ground for different window dimensions after 100 s.

The slope change signifies the boundary between the fire's hot and cold layers in the compartment. As the ventilation area increases, the interface between the layers becomes less noticeable, probably owing to the higher mixing in larger areas, as demonstrated by the smooth temperature change.

Figures 10 and 11 illustrate the hot gas temperature variation taking into account the ventilation factor and ventilation area ratio near the window at different levels. As noted, the figures reveal similar temperature variation trends. Therefore, either method may be appropriate for presenting the temperature distribution in accordance with the level. The ICC expresses the ventilation area as a percentage of the ventilated space area [29].

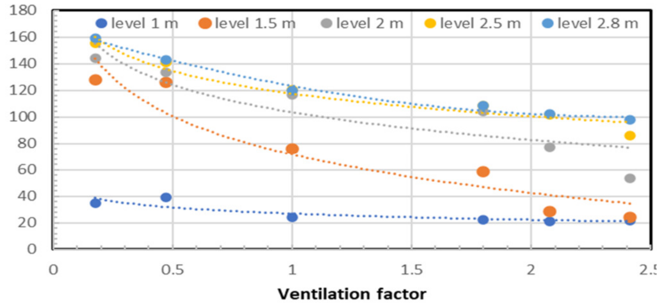


Fig. 10. Temperature of the hot gas near the window vs ventilation factor at different levels from the room's ground after 100 s.

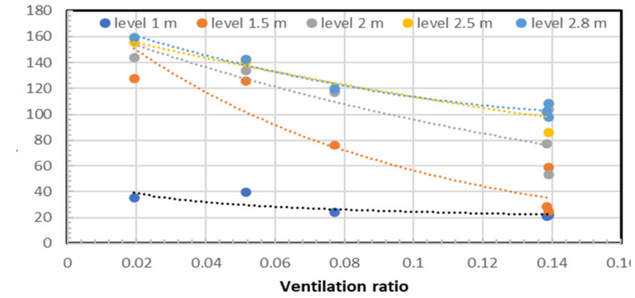
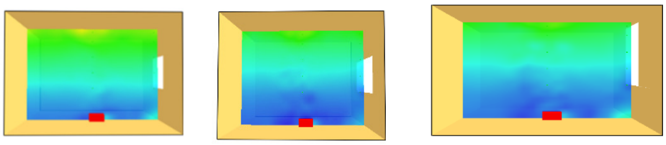


Fig. 11. Temperature of the hot gas near the window vs ventilation area ratio at different levels from the room's ground after 100 s.

D. The Neutral Plane

Neutral plane levels can provide critical information about fire development in ventilated enclosures. The neutral plane divides the enclosure during a fire into two layers. A higher pressure than the outside one characterizes the upper layer because of the accumulation and expansion of gases produced from combustion, thus allowing hot gases to flow out. In the lower layer, the pressure is less than the outside pressure, permitting cold air to flow in. A high neutralization plane may imply that the fire is not intense and the hot gas accumulation is still insignificant. In contrast, if the former is low, it suggests that the produced gases have accumulated, raising pressure and temperature, signifying that the fire is approaching the flashover.

Figure 12 presents the pressure cloud diagrams for the investigated window sizes. As shown, the neutral planes of the scenarios 1.8 m × 1.0 m high and 1.0 m × 1.8 m high exist at the same level, which implies that the window area, rather than its configuration, is the significant factor in determining the neutral plane level. The neutral plane levels occur at 1.4 m, 1.6 m, and 1.6 m for the windows of 1.0 m × 1.0 m, 1.8 m × 1.0 m high, and 1.0 m × 1.8 m high, respectively. This result supports the previous conclusion that the area available for ventilation could be the limiting factor that delays the flashover being reached by the compartment fires. The higher the neutral plane level is, the greater is the area available for cold air to flow into the room, which may control the temperature rise and avert the fire from reaching the flashover.



1.0 m × 1.0 m high 1.8 m × 1.0 m high 1.0 m × 1.8 m high

Fig. 12. Neutral plane for simulated fire scenarios.

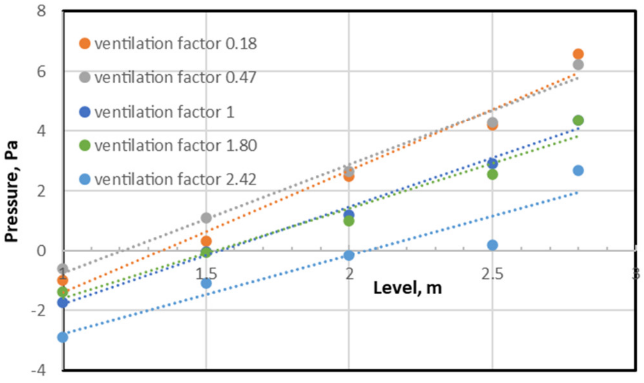


Fig. 13. Neutral plane near the window at different ventilation factors.

Figure 13 displays the pressure inside the room against the level of different window sizes. It reveals that, as a general rule, as the ventilation factor increases, the height of the neutral plane increases, which implies that the height of the hot gas layer decreases. The higher the neutral plane is, the more cold air enters the room. These results are consistent with those of previous studies [33-35]. It is clear that the larger the window area is, the higher is the neutral plane level, and the air becomes more effective in cooling the fire [34].

IV. CONCLUSIONS

Using the Pyrosim software, the current study investigated the effect of natural ventilation on small-compartment fire development and the latter reaching the flashover stage. It analyzed the impact of ventilation opening size and dimensions on fire development and the neutral plane height. The results showed that the ventilation area, rather than its dimensions, was the significant influence factor. Higher ventilation areas reduced the temperatures well below the flashover conditions.

Previous works focused on studying the effect of ventilation on fires in enclosures, and there was no specificity for fires in small rooms or for the use of natural ventilation as a tool for retarding fire development and preventing flashovers. However, the present research examined the possibility of using natural ventilation to prevent fires in small rooms from reaching the flashover stage.

The current study revealed the great potential of employing fire passive protection (i.e., natural ventilation design as part of the construction design) to limit fire reaching the flashover stage, besides its role in slowing the spread of fire. The results also demonstrated that natural ventilation areas may play a significant role in the occurrence of the flashover stage of a fire in small rooms. Achieving that requires factual building and window designs based on the knowledge of potential fire scenarios and the class of building occupancy.

The current findings confirm the significant effects of the ventilation area but not its configuration on fire development. The hot gas temperature inversely varies with the ventilation area. According to the building codes, expressing the ventilation area of a building in general terms as a percentage of the enclosure area may be inappropriate. Besides linking ventilation to the building area, it may also be more accurate to link it to the occupancy and construction type. Conducting a study aims to correlate the ventilation area to factors, such as the heat release rate, hot gas layer temperature, pressure inside the room, and the time for the fire to reach the flashover.

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