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Natural and Mechanical Ventilations for Reducing the Severity of Hot Gases and Smoke in Fires of Large Stores

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Abstract

This study investigates numerically the effectiveness of using natural and mechanical ventilations in reducing the severity of hot gases and smoke in fires of multi-floor-stores and large shopping centers. Fire behavior in both Single- and Double-Floor-Stores (SFS & DFS) are simulated. Fire Dynamics Simulator (FDS), provided by NIST, has been used to run the simulations for all proposed cases. For the assumed scenarios, the values of hot gas temperature and smoke are extracted at different points, especially inside the hot layer near the ceiling, for further analysis. Final results show noticeable reduction in the severity of fire in the presence of natural and mechanical ventilation systems, for both (SFS & DFS). Thus, appropriate ventilation system can be used as an efficient tool to improve the safety level in multi-floor-stores and large shopping malls.

Keywords: Fire simulation; Large enclosures; Multi-Floor-Stores; Natural ventilation; Mechanical ventilation.

1. Introduction

Reducing the severity of hot gases and smoke inside multi-floor-stores and large shopping centers can offer better environment for civilians and firefighter in such places in case of fire. Ventilation systems play the key role in changing the behavior of fire and, thus, reducing the severity of hot gases and smoke inside these enclosures.

This study investigates numerically the effect of adding different ventilation systems, both natural and mechanical ones, in modifying the fire behavior inside multi-floor-stores and large shopping malls.

The availability of powerful computers in the later years and, thus, the well validated numerical programs and related fire simulators have led to the significant development of fire simulations in complex geometries under wide varieties of parameters, conditions and assumptions. Several fire simulators have been developed and used for different case studies and fire scenarios. For example, CFAST (Consolidated model of Fire and Smoke Transport) [1] is a two-zone fire model simulator that has been used to study fire behavior and related changes in the hot gas temperature and smoke inside large enclosures. It solves the conservation equations by dividing the compartment into two distinct "zones" [2, 3]. The first zone is the cooler lower layer, and the second zone is the hot upper layer. Both layers are assumed to be of uniform temperature and composition. The two-zone fire model allows for the consideration of specific building materials, ventilation conditions, and room furnishings. However, this model assumes uniform treatment of each layer with relatively low computational expensive, which limits it applicability to large compartments [4, 5]. CFAST has been used to simulate fire in large hall (i.e. atrium) [6] and found that the mechanical ventilation provides better safety environment for people inside the building to evacuate.

Fire Dynamics Simulator (FDS) [7] has been widely used for simulation of fire in public compartments and large enclosures, such as atrium [6], supermarket [8] and rooms [9]. FDS is a Computational fluid dynamics (CFD) model, which solves the full, partial differential equation set for the conservation of mass, momentum, energy and species. This model can also deal with characteristics of the compartments, such as building materials, ventilation conditions, and room furnishings. However, this model is the most detailed approach available to modeling fire behavior. Therefore, it can be used to accurately predict fire behavior in large compartments, but with relatively higher computational expensive compared to the two-zone fire model [2, 5, 7]. Lassus et al. [10] identified three different regimes in fire of closed compartment, depending on the concentration of oxygen available for combustion. They [11] have later established an empirical relationship to determine the concentration of carbon monoxide, carbon dioxide, hydrogen and total hydrocarbon concentrations, depending on oxygen concentration. Regarding the optical properties of the smoke, Heskestad plume equation for the

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velocity in the plume centerline and the ceiling jet theory and the maximum velocity equation is analytically applicable [12]. Numerical simulations of fire inside different basic models show changes in the harmful properties of the hot gases, in terms of temperature, smoke visibility and concentration of different smoke particles [13]. Evacuation process has been investigated numerically for fire in closed places to check the effect of the smoke concentration on the evacuation speed [14]. Zhang et al. [15] used Pyrosim code to perform an indoor fire simulation in a simple room. They analyzed and reported changes in temperature, smoke layer height, and heat flow under different ventilation conditions.

In this study, Fire Dynamics Simulator (FDS) [7], developed by the National Institute of Standards and Technology, is used as a CFD tool to simulate the fire behavior. Both Fire Dynamics Simulator (FDS-6.8.0) and Smoke View (SMV-6.8.0) have been downloaded and used to run all cases in the current study. Both are open-source codes and available as a one package. This code has been validated numerically and experimentally by many researchers [16]. The grid resolutions for all simulations have been tested to find the optimum value that plays no role in the numerical results and found to be 10 control volumes per meter in all directions. Finer grids produce the same results, too. FDS numerically solves a form of the Navier-Stokes equation that can be used for “low-speed, thermally-driven flow.” Turbulence is modeled using Large Eddy Simulation (LES). The combustion model uses a single step, mixing-controlled chemical reaction that uses three lumped species (i.e., air, fuel and products) and radiative heat transfer is solved for using the radiation transport equation for grey gas [7, 16].

Many buildings such as stores must take into account materials used in the construction and the safety and evacuation plans. Stores have normally flammable substances and, therefore, require the highest safety standards to ensure that fire emergencies are anticipated and covered by the best possible systems for life safety and property protection. In case of fire, everyone in the store should be able to escape safety, easily and quickly. Unique safety solutions proposed in the current study could be beneficial for both single- and double- floor stores, which would be applicable in the future. They can incorporate modified structures with natural and mechanical smoke ventilation systems to maximize the safety level in case of fire in the place.

Delaying the growth of fires inside closed shopping stores with multiple floors can play a crucial role in saving lives and improving the safety level in such large enclosures. Dealing with fires and the associated hot gases, chemicals and smoke needs a careful attention and more complicated safety procedure. Natural ventilation system, on one hand, produces a buoyancy effect in the burning compartment (also known as chimney effect), which helps get rid of hot gases and smoke inside the place and, thus, let more cool air to come in to the burning area. Mechanical ventilation, on the other hand, can offer the required driving forces to do the same effect. The appropriate ventilation effect can keep the floor area with lower level of hot gases and smoke and, thus, offers safer exits for the firefighters and civilians inside such buildings in case of fire.

2. Materials and Methods

This study investigates two different structures:

- **Single-Floor-Store (SFS):** Single-Floor-Store (SFS) is the first case study. It has a (20 m) width, (20 m) length and (6 m) height, as shown in figure1.a, and consists mainly of a horizontal inlet door, located at the half of front face. The door has a width of (6 m) and aheight of (4 m). The store ceiling, walls and floor are all made of gypsum board (1/2 in), covered by Wood Plastic Composite (WPC) sheets like that made of Polymethyl methacrylate (PMMA)-graphene nano-composites [17] have been investigated.
- **Double-Floor-Store (DFS):** Double-Floor-Store (DFS) is the second **case** study. The first floor of the DFS is very similar in dimensions and materials of construction to the SFS. The second floor of DFS has (18 m) width, (18 m) length and (6 m) height. The 18x18 m’s floor is “flying” at (6 m) height above the first one, as shown in figure 2.a, with a one-meter gap between the rim of the second floor and the building walls in all direction.

The proposed design of the “flying” floor, with the proposed gap between the second-floorrim and walls of the building will create a venturi effect inside the gap and, also, offers better lighting and cool air circulation systems under the normal daily conditions. The cost of the lighting and air conditioning system for this structure would be cheaper and go hand-on-hand with the environmental green solutions.

Hot gas behavior is numerically investigated, in case of fire in the store, for different scenarios. Only the early fire growth stage, at the first ten minutes from the beginning of the fire, is simulated and analyzed, i.e. the simulation time is (600 s)for all assumed scenarios. The fire source (fuel)assumed for all cases is sofa, or any similar bunch of goods, which give the same equivalent heat release rate. Figure 1.a shows the burning sofa that touches the floor of SFS at wall center, position (X_W), in front of the store’s main door. The location of the burning sofa for DFS calculations, shown in figure2.a, is also fixed at position (X_W) for all running simulations.

3. Results and Discussion

The store ceiling, walls and floor are all made of gypsum board (1/2 in), covered by Wood Plastic Composite (WPC) sheets like that made of Polymethy l methacrylate (PMMA)-graphene nano-composites [17, 18]. Polymeric sheets are thermally stable over a wide range of temperatures from -30 to 90 C and start to deform at 250 C and above [19-21]. Many different options of the covering sheets, such as recycled and/or improved materials are available nowadays [22-30].

For analyzing, and hopefully improving, the safety level inside both stores, proposed different scenarios are numerically simulated and introduced for both SFS and DFS. Theses, scenarios are investigated next for further details and discussion.

Single-Floor-Store (SFS): Figure 3 shows the hot gas temperature inside SFS as a function of time (t). For this case, the store has no vents except the main door. The main door is assumed to be fully open all the time. The first curve shows (T_A) directly above the fire at (1 m) below the ceiling level, i.e. (4.5 m) above the sofa. The second curve gives the average temp (T_{Avg}) of the hot gas at (1 m) below the ceiling level.It is clear that (T_A) reaches about (84 C) within (90 s)and stays almost constant for the next (500 s), at least. Average temp (T_{Avg}) increases gradually, in the hot layer, and it takes (240 s) to reach almost a constant value of (46 C) for the same period of time.

Figure1.b introduces the natural ventilation added to the center of the ceiling. The vent has a square shape of (4 m x 4 m) with a total area of (16 m^2), which is equivalent to the 2/3rd of the total area of the main door. Figure4 shows changes in the temperature after adding the natural ventilation. Adding the vent reduces (T_A) by 4 degrees, from (84 C) to about (80 C). Average temp (T_{Avg}) for the store, in the hot layer, decreases by 9 degrees, from (46 C) to (37 C) for the same period of time, due to the presence of natural ventilation.

Figure1.cintroduces the mechanical ventilation (fan) added to the system. The system has no additional vents, except the main door. Figure 5 shows changes in the temperature after adding the mechanical ventilation (fan) to the system. The fan has a total area of (4 m^2) and sucks out a (10 m^3/s) of the hot gas from the SFS. Adding the fan reduces efficiently (T_A) by 47 degrees, from (84 C) to about (37 C). Average temp (T_{Avg}) decreases by 9 degrees, from (46 C) to (37 C) for the same period of time, as a result of adding fan to the building.

Double-Floor-Store (DFS): For Double-Floor-Store (DFS), the 18x18 m's floor is "flying" at (6 m) height above the of the first one, with a one-meter gap between the rim of the second floor and the building walls in all direction. The one-meter gap between the "flying" floor (18x18 = 324 m^2) and the building wall has a total area of (20x20 - 18x18 = 76 m^2). This gap will create a venturi effect between both first and second floors with a throat-to-inlet area ratio (also known as beta ratio) of (76/400 = 0.19). The assumed beta ratio applied in current study can offer a very reasonable balance between (the created Rynolds number inside the gap, with the related coefficient of discharge, on one hand) and (keeping the area of the second floor as large as possible, on the second hand). By assuming that the hot gas passes the gap has a density of about (1.2 kg/m^3) and a volumetric flow rate of average value of (10 m^3/s), the equation of venturi can be applied. A simple calculation shows that the venturi effect produces a vacuum pressure inside the gap of (0.01 Pa). This drop in pressure is good enough to replace the hot gas inside the first floor within 4 minutes and that inside both floors within 8 minutes. The calculated average velocity of the hot gas inside the gap is of value of ((10 m^3/s) / (76 m^2) = (0.13 m/s) or 7.9 m/min), which gives quite good and smooth flow of the hot gas passing the gap.

Figure 6 shows the hot gas temperature inside SFS as a function of time (t). For this case, the store has no vents except the main door. The main door is assumed to be fully open all the time. The first curve shows (T_A) directly above the fire at (1 m) below the ceiling level of the first floor, i.e. (4.5 m) above the sofa. The second curve gives the average temp (T_{Avg}) of the hot gas at (1 m) below the ceiling level of the first floor. Here, (T_A) reaches about (63 C) within (60 s) and stays almost constant for the next (500 s), at least. Average temp (T_{Avg}) increases gradually, in the hot layer, and it takes (240 s) to reach almost a constant value of (30 C) for the same period of time.

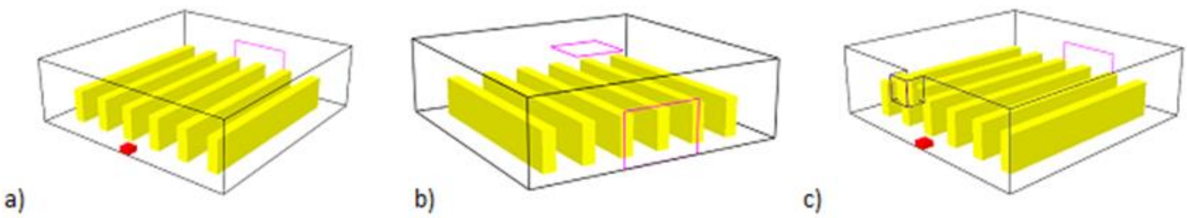

Figure 1. a) Single-Floor-Store (SFS) used as the first case study with main door only. b) SFS with main door and top vent (natural ventilation). c) SFS with main door and side fan (mechanical ventilation).

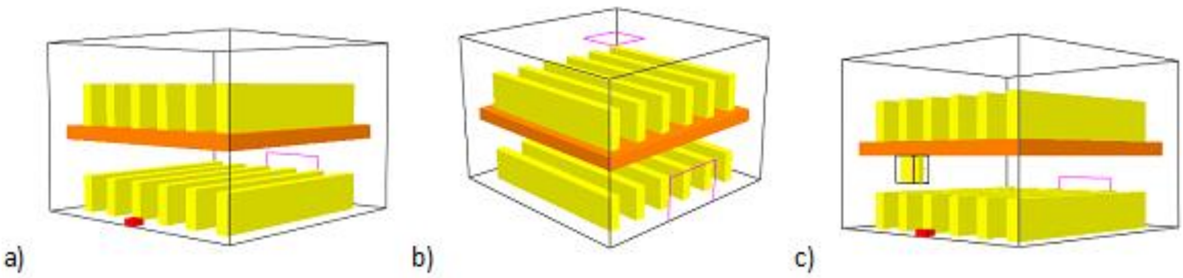

Figure 2. a) Double-Floor-Store (DFS) used as the second case study with main door only. b) DFS with main door and top vent (natural ventilation). c) DFS with main door and side fan (mechanical ventilation).

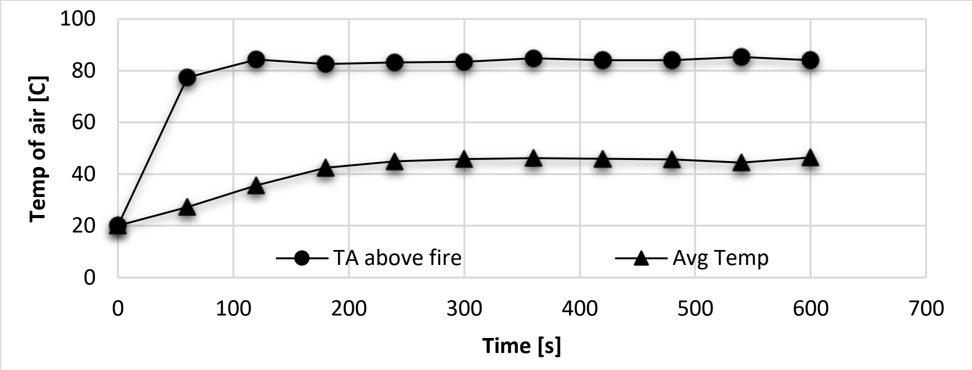

Figure 3. Temperature of hot gas/air (T_A) as a function of time (t) for a burning sofa at position (X_W) inside SFS. Here, SFS has no vents, except the fully opened door. First curve is for (T_A)at (4.5 m) directly above the sofa, i.e. (1 m) below the ceiling level. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level.

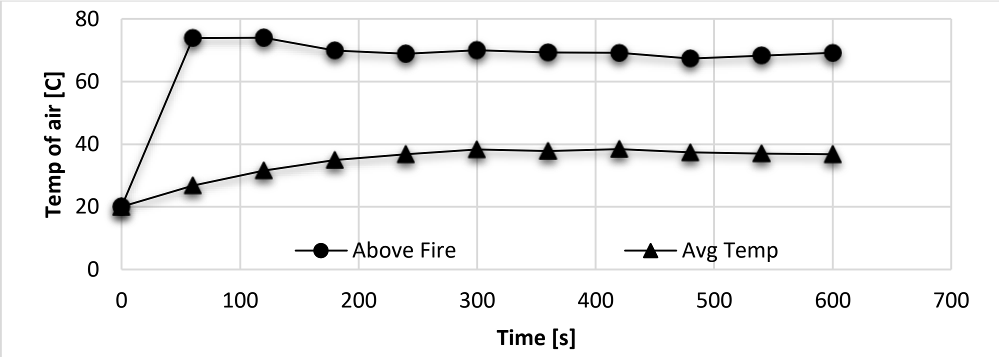

Figure 4. Temperature of hot gas/air (T_A) as a function of time (t) after adding natural ventilation to the system. No additional vents, except the main door is added to SFS. First curve is for (T_A) at (4.5 m) directly above the sofa, i.e. (1 m) below the ceiling level. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level.

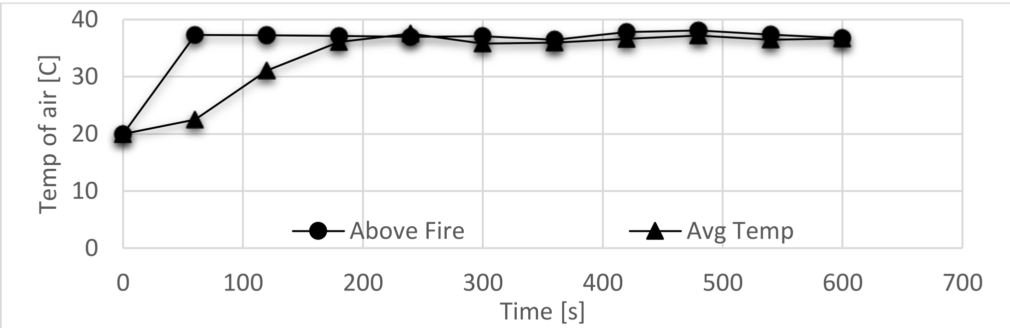

Figure 5. Temperature of hot gas/air (T_A) as a function of time (t) after adding mechanical ventilation (fan) to the system. No additional vents, except the main door is added to SFS. First curve is for (T_A) at (4.5 m) directly above the sofa, close to the fan center. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level.

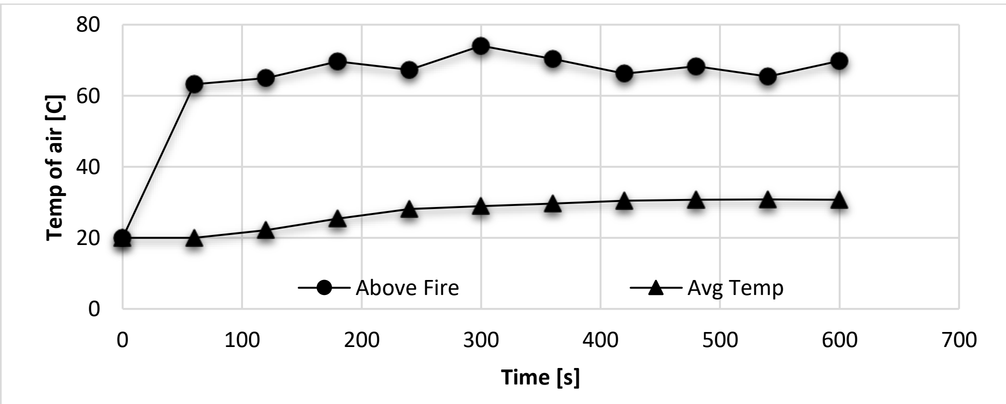

Figure 6. Temperature of hot gas/air (T_A) as a function of time (t) for a burning sofa at position (X_W) inside DFS. Here, DFS has no vents, except the fully opened door. First curve is for (T_A) at (4.5 m) directly above the sofa, i.e. (1 m) below the ceiling level of the first floor. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level of the first floor.

Figure 7 shows changes in the temperature after adding the natural ventilation, shown in figure 2.b. Adding the vent reduces (T_A) by 13 degrees, from (63 C) to about (50 C). Average temp (T_{Avg}) for the store, in the hot layer, decreases by 10 degrees, from (30 C) to (20 C) for the same period of time, due to the presence of natural ventilation.

Figure 2.c introduces the mechanical ventilation (fan) added to DFS. The system has no additional vents, except the main door. Figure 8 shows changes in the temperature after adding the mechanical ventilation (fan) to the system. The fan has a total area of (4 m^2) and sucks out a (10 m^3/s) of the hot gas from the DFS. Adding the fan reduces efficiently (T_A) by 27 degrees, from (63 C) to about (36 C). Average temp (T_{Avg}) decreases by 1 degree, from (30 C) to (29 C) for the same period of time, as a result of adding fan to the building.

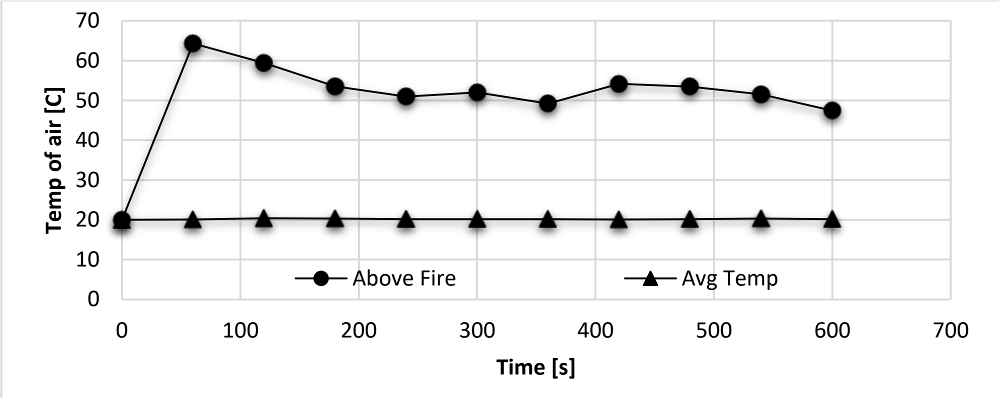

Figure 7. Temperature of hot gas/air (T_A) as a function of time (t) after adding natural ventilation to the system. No additional vents, except the main door is added to DFS. First curve is for (T_A) at (4.5 m) directly above the sofa, i.e. (1 m) below the ceiling level of the first floor. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level of the first floor.

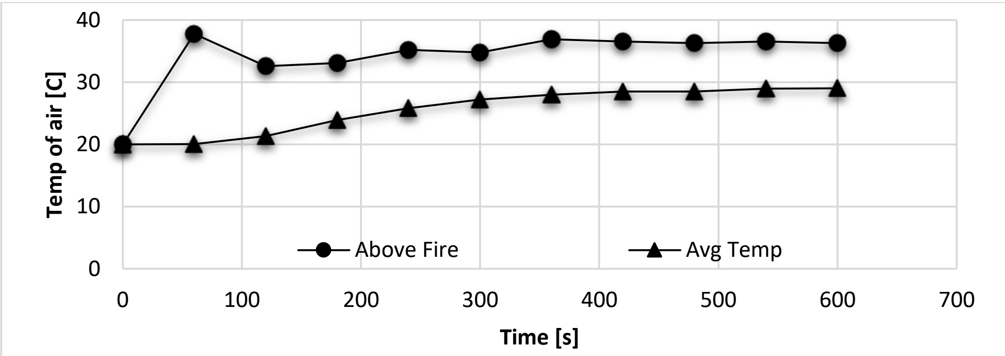

Figure 8. Temperature of hot gas/air (T_A) as a function of time (t) after adding mechanical ventilation (fan) to the system. No additional vents, except the main door is added to DFS. First curve is for (T_A) at (4.5 m) directly above the sofa, close to the fan center. The second curve is for the average temp (T_{Avg}) at (1 m) below the ceiling level of the first floor.

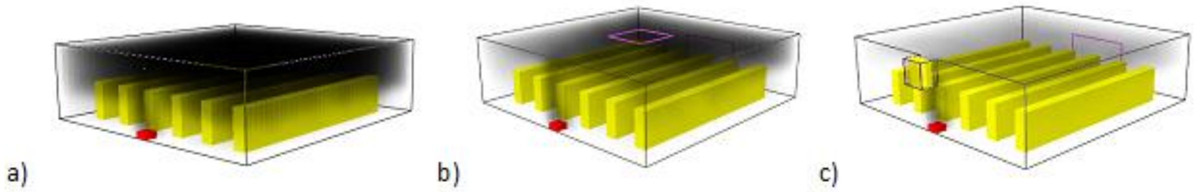

Figure 9. A smoke in the building after 10 minutes from the beginning of fire for, a) SFS with no vent, except the opened door, b) SFS with natural ventilation, c) SFS with mechanical fan.

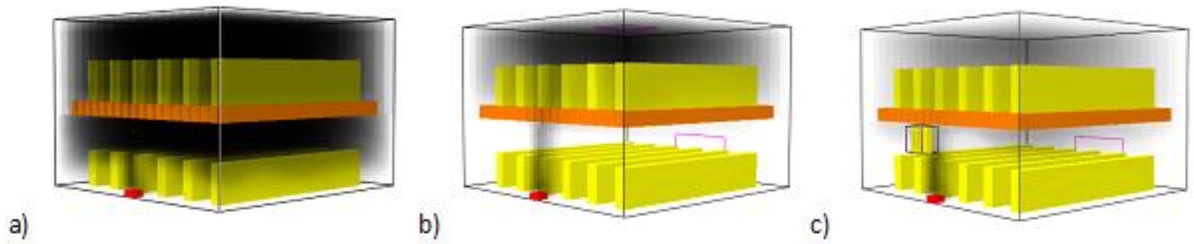

Figure 10. A smoke in the building after 10 minutes from the beginning of fire for, a) DFS with no vent, except the opened door, b) DFS with natural ventilation, c) DFS with mechanical fan.

4. Conclusions

Stores must take into account materials used in the construction, including safety and evacuation plans. Stores have normally flammable substances and, therefore, require the highest safety standards to ensure that fire emergencies are anticipated and covered by the best possible systems for life safety and property protection. In case of fire, everyone in the store should be able to escape safety, easily and quickly.

Unique safety solutions proposed in the current study could be beneficial for both single- and double- floor stores, which would be applicable in the future. They can incorporate modified structures with natural and mechanical smoke ventilation systems to maximize the safety level in case of fire in the place.

The numerical results show that fire in the store increases the smoke temperature strongly up to (+90 C) close to the ceiling level. Temperature reaches about (+250 C) around the fire source. Without introducing cool air reduce temperature in the burning place, civilians will not survive. Under such condition, WPC and covering sheets cannot also survive for longer period of time without deformation damages.

Fire Dynamics Simulator (FDS-6.8.0) code for low-speed flows is used in this study to generate the numerical data. FDS is an open-source software provided by NIST. This code has been validated numerically and experimentally by many researchers [16]. The grid resolutions for all simulations have been tested to find the optimum value that plays no role in the numerical results and found to be 10 control volumes per meter in all directions.

Natural ventilation and mechanical ventilation systems in both single- and double- floor stores are investigated numerically in this study to improve the safety level, in case of fire. For Double-Floor-Store (DFS), leaving a gap between the rim of the second floor and the building walls are suggested to improve the safety level in case of fire. The proposed gap in the structure can help apply natural ventilation efficiently in the building, by creating a venturi effect inside the gap. For Single-Floor-Store (SFS), natural ventilation can help reduce the temperature of the hot layer, like the mechanical ventilation (fan). However, mechanical ventilation can do better for the region around burning sofa, figure 9.

Natural ventilation can reduce the temperature, due to the buoyancy effect (i.e. chimney effect) in the burning region. This helps get rid of the hot gas and smoke from the place and, thus, let more cool air to come in to the smoky area. The effect of natural ventilation, thus, keeps the floor area with lower level of hot gases and toxic smoke, which will offer safer exits for the firefighters and civilians inside the building.

Natural ventilation in DFS, will not only offer cheaper and cleaner solutions to improve the safety level and environment inside the building, but will also improve the lighting in the place and go hand-on-hand with the green solutions and, thus, can reduce the energy cost of such places, figure 10.

The proposed green solutions could be an effective passive strategy applied more widely in the future to improve the safety level in the new or modified buildings. In addition to the higher safety level, it will offer natural lighting, too, and can save more money in the cooling/heating system in the place.

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