An Investigation of the Factors Affecting the Mechanical Smoke Extraction System for A Building with an Atrium

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Abstract

The purpose of this paper is to better understand the behavior of smoke movement in an atrium. Thus, gives first responders and civilians in and out of the building a better understanding of the best ways to save lives and minimize losses Due to fire or smoke damage.

This study aims to investigate the operation efficiency analysis of the atrium proposed ventilation system using axial exhaust fans mounted at the atrium void high level in achieving smoke clearance and suitable conditions for safe egress of occupants during a fire scenario that lasts for 10 minutes.

This study consists of a fire and smoke propagation analysis which consists of the descriptive part, a general principle of operation of the axial smoke fans ventilation fans to achieve smoke clearance during an axisymmetric atrium fire scenario, for that purpose a simplified fire scenario of fire and ventilation parameters are considered and discussed and the following chapters describe the software used to perform numerical calculations, results and conclusions and recommendations from the analysis.

With the advancements of modern technology, computers, and software make simulation models possible such as fire models to simulate fire and smoke movements, in this paper computational fluid dynamic (CFD) software Fire Dynamic Simulator (FDS) PyroSim is used to conduct a series of atrium tests to investigate the effectiveness of smoke exhaust systems.

FDS solves the Navier-Stokes equations appropriate for low-speed flows ($Ma < 0:3$) with an emphasis on smoke, heat transport, and CO2 concentrations from fires, the default turbulence model used in FDS simulation is the Large Eddy Simulation (LES), which is the solution of Navier-Stokes equations at the low speed [1].

In this study, the compartment tested was 38 m×5.7 m×13 m in height, and the measured exhaust rates used ranged from 2.0 to 5.0 kg/s with thermocouples placed at various heights to see the upper smoke layer and the lower air layer along with the convective boundary layer or interface layer the building smoke rises from the origin

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of fire due to its buoyancy [2].

CO2 concentrations, heat release rates, and temperatures are looked at to better understand the behavior of smoke, it is only a short-term test of 600 seconds of simulation time.

1. Introduction

Fire in an atrium building requires more complicated operational approaches than other buildings because smoking in atriums can spread to communication spaces and other occupied parts of buildings and threaten occupants and safe evacuation so it is so difficult for firefighters to enter the building and protect egress routes. Occupants in the building have difficulties evacuating rapidly and safely because elevators do not offer an appropriate exit during a fire expansion. As it rises, it entrains more air and fills the upper region of the space forming a hot upper layer. Once the smoke layer is formed, its depth increases with time as more gases from the fire plume enter the hot layer [3].

A considerable amount of toxic gases will produce when building materials burn, which is the main cause of death.

A Smoke control system is an integrated system that rises smoke in atriums continuously through floors by mechanical ventilation system or by natural ventilation to extract smoke from the atrium and maintain the smoke height on the last floor at least 2 m above the egress route.

Automatic sprinkler systems are the most effective in controlling fires in spaces with a relatively low ceiling height.

Smoke management is a term used to describe the methods implemented to passively or actively control the movement of smoke within the built environment in the interest of providing safety to occupants, firefighters, and property [4].

2. The Mathematical Model for Atrium Mechanical Smoke Extraction

2.1. The equation of smoke layer height

Under mechanical smoke exhaust conditions, the change in total smoke is mainly reflected in the relationship between the amount of air entrainment and the amount of smoke evacuation [5]. According to the mass conservation equation, the upper layer of the smoke must be:

$$\frac{d[A\rho_s(H-z)]}{dt} = m_e - m_{exh} \qquad (1)$$

$$m_{exh} = \rho_s V_s \qquad (2)$$

where, ρ and V are the density and the volume of the smoke layer, respectively. m_e is the flow rate of the fire plume, A is the floor area of the room, H is the ceiling height, and z is the smoke layer interface height.

NFPA 92B [6] for large space of smoke production using axisymmetric plume model:

$$m_e = 0.071\, Q_c^{1/3}\, Z^{5/3} + 0.0018\, Q_c \qquad (3)$$

Substituting eq. (2) and eq. (3) into eq. (1), mechanical smoke exhaust smoke layer height under the condition of time can be::

$$-\frac{dz}{dt} = 0.071\ \frac{Q_c^{\frac{1}{3}}\ Z^{5/3}}{A\rho_s} + 0.0018\ \frac{Q_c}{A\rho_s} - \frac{V_s}{A} \qquad (4)$$

<u>2.2 Smoke exhaust rate to maintain a certain smoke layer height</u>

For the steady-state process, the rate of smoke should be equal to the height of the plume entrainment rate [4], making $\frac{dz}{dt} = 0{:}V_s \quad = 0.071\ \frac{Q_c^{\frac{1}{3}}\ Z^{5/3}}{\rho_s} + 0.0018\ \frac{Q_c}{\rho_s}$ (5)

The smoke temperature and density can be obtained by the formula:

$$T_s = T_0 + \frac{Q_c}{m_e\ C_p}$$

$$\rho_s = \frac{353}{T_s} \qquad (6)$$

Under normal conditions, T_0 = 20 C ^{0}, Cp = 1.02 KJ/KG.C [4], therefore, keeping a certain smoke layer height requires mechanical smoke exhaust rate for:

$$V_s = 0.059\ Q_c^{1/3}\ \ Z^{5/3} + 0.0043\ Q_c \qquad (7)$$

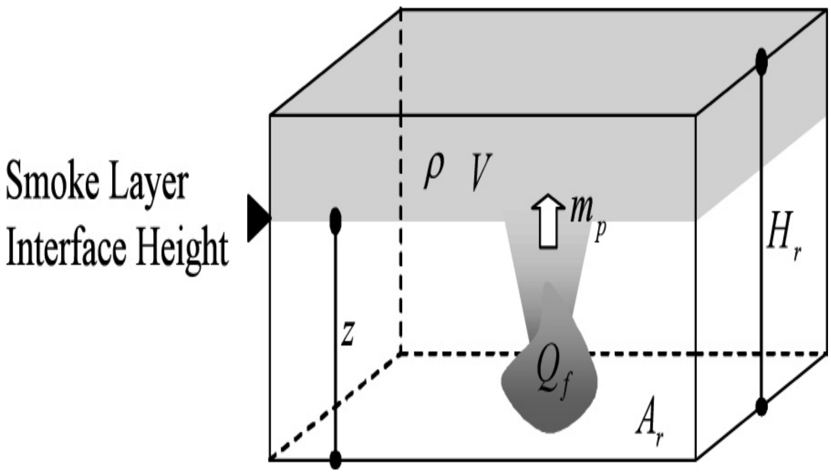


Figure .1 Schematic of the calculation model

3. Discussion and Result

In this study, a numerical simulation using CFD for fire and smoke modeling inside atriums is laid out.

The mechanical ventilation system procedures for the atrium are developed, and hydraulic calculation is applied to the selected case study to check manual calculations, computer software (CFD) is used.

CFD has been used by Fatemeh Salehi et al.2021 [7] to increase the fire safety of buildings during an emergency evacuation.

The calculation explains the effectiveness of the proposed mechanical ventilation system for the atrium.

The theoretical mass flow rate of the plume is also calculated at every meter of height by using the axisymmetric plume correlation (Equation 5) [8], [9]

As a result, this research has a direct and indirect impact on human health and economic conditions due to the following:

● the impact on human health from fire emissions (smoke) must be understood. Smoke exposure can increase both morbidity and mortality.

● using computer modeling would help to design a fire extraction system with high safety conditions and low energy consumption.

The performance characteristics that influence the smoke extraction in the atrium which will be studied can be listed as follows:

a- Temperature distributions inside the space with different scenarios of the fire onset.
b- Air velocity according to different fire scenarios.
c- Distribution of fresh and exhaust air outlets.

4. Fire scenarios

Figure 2. shows the Fire source & Location of the scenarios

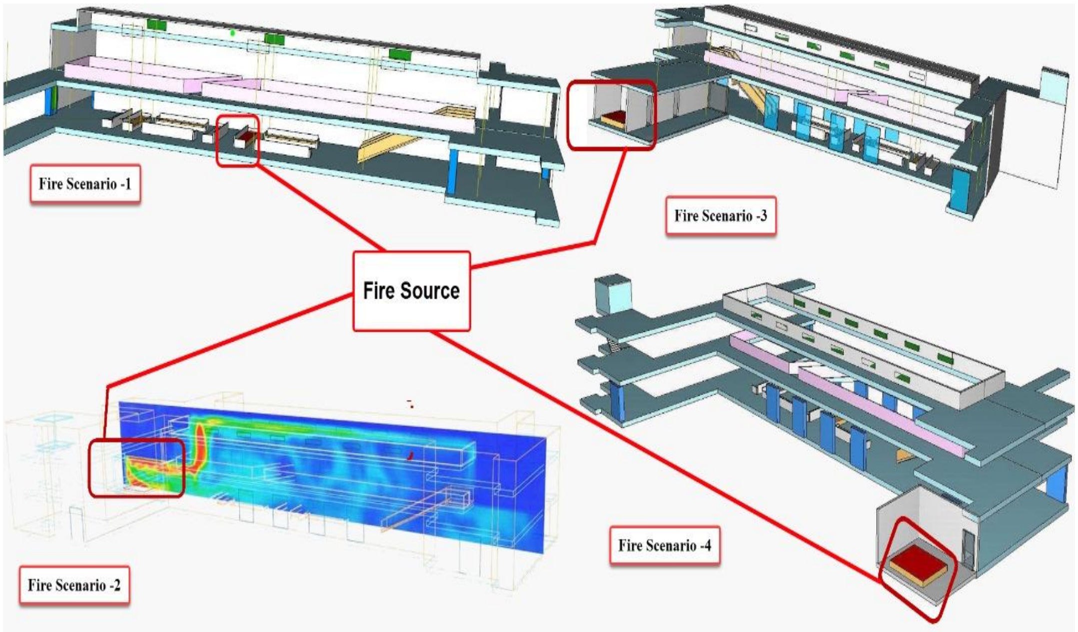


Figure 2 Fire source & Location of scenarios

4.1 Fire Scenario 1

Figure 3 shows the building cross-section, where the fire is taking place in the middle of the atrium.

In this figure, several places contain:

- fire source.
- makeup air intake.
- exhaust fans.
- detectors.
- devices to measure smoke height.

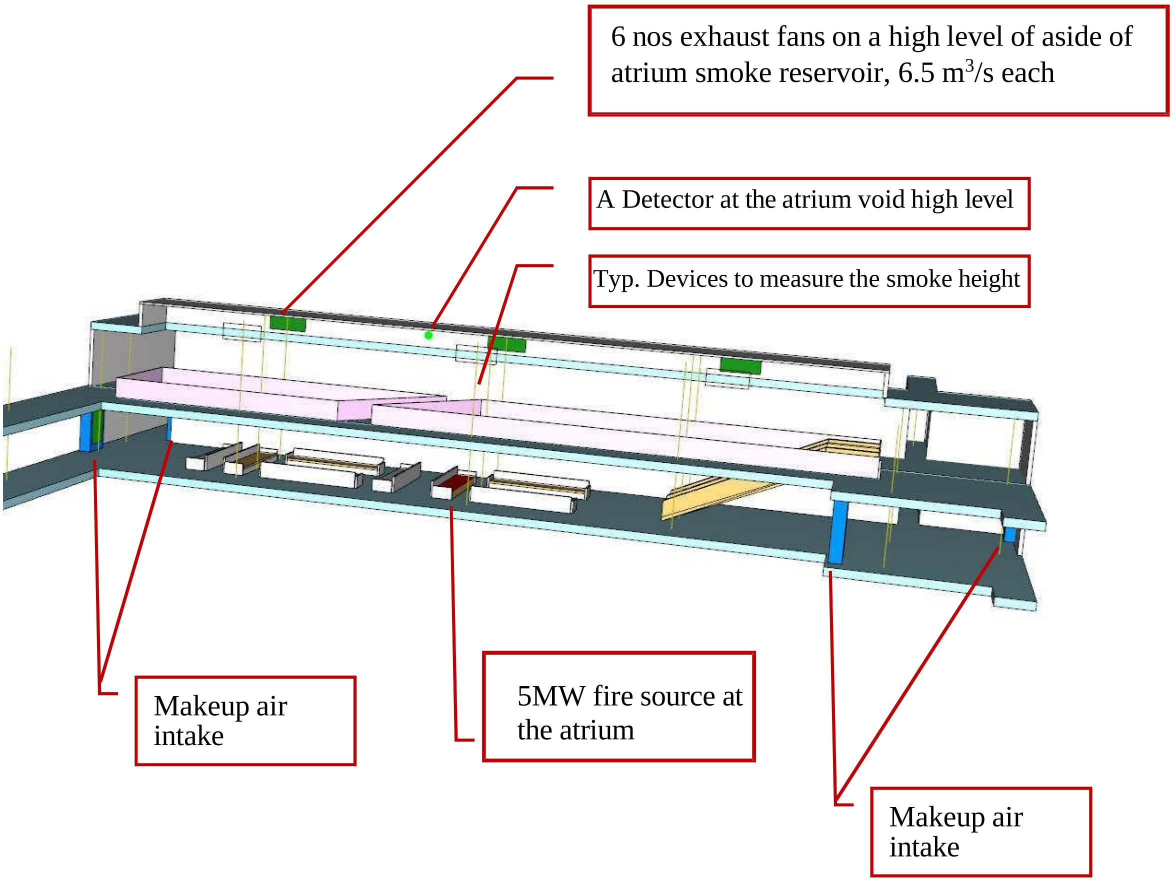


Figure 3 fire scenario-1 & smoke ventilation system

The smoke layer at the top floor will descend to fill the entire floor with smoke once the fire reaches a peak heat release rate of 5MW.

The lower floor will have a smoke-free height of 2 meters on average during the entire simulation time, which is acceptable for occupants' evacuation.

The smoke height will descend to fill the majority of the atrium and will have a smoke-free height of 1.5-2.0 meters in the atrium floor vicinity.

The maximum high-level temperature within 5 meters radius of the fire source will not exceed 120 degrees, while the smoke temperature at the fire source will not exceed 170 degrees which indicate that a rating of 400 degrees is more than enough for the axial exhaust fans.

As shown in figure 3, the following was noted:

● Fresh air intakes will have an average velocity of 2.5-3.0 m/s.
● Exhaust air openings will have an air velocity of 3:4.0 m/s.

From figures 4& 5 HRR reached 1000 kW after 3 minutes and increased to 5000 kW after 8 minutes which will stay constant for a long period due to the location of a fire in the middle of the atrium, which has renewable oxygen, which Helps with ignition.

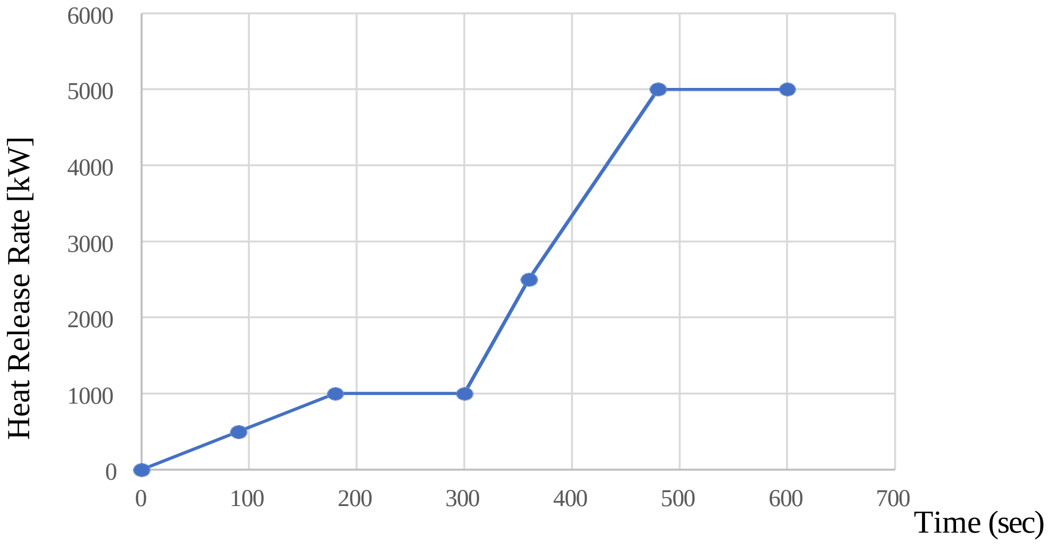


Figure 4 The heat release rate (HRR) versus time in scenario -1

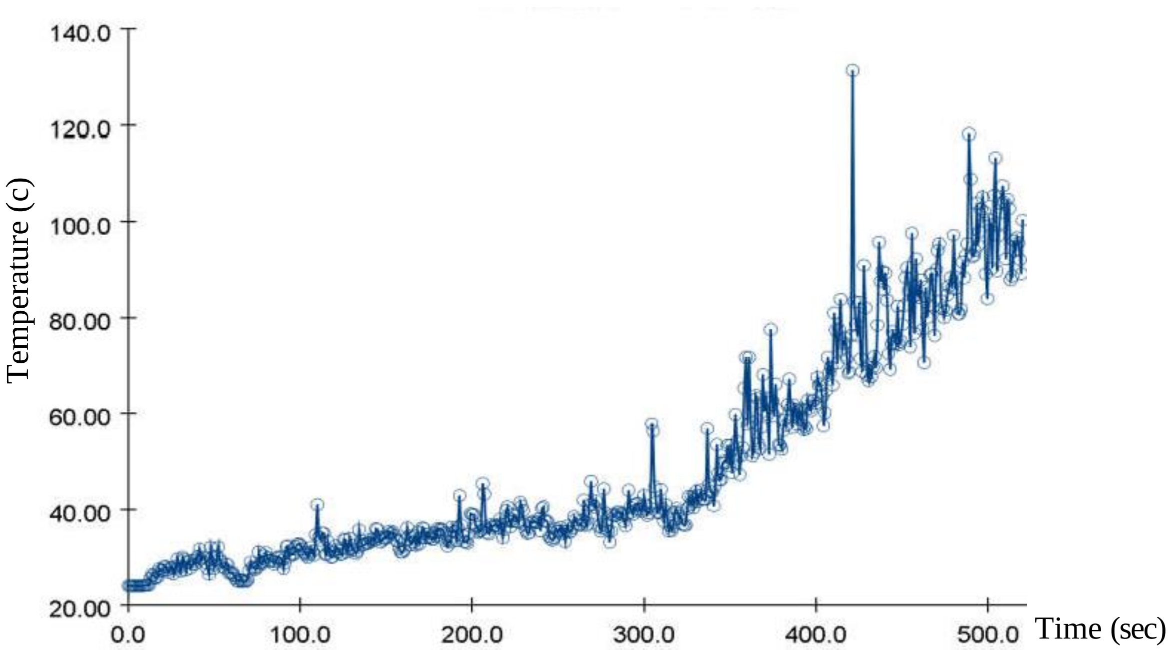


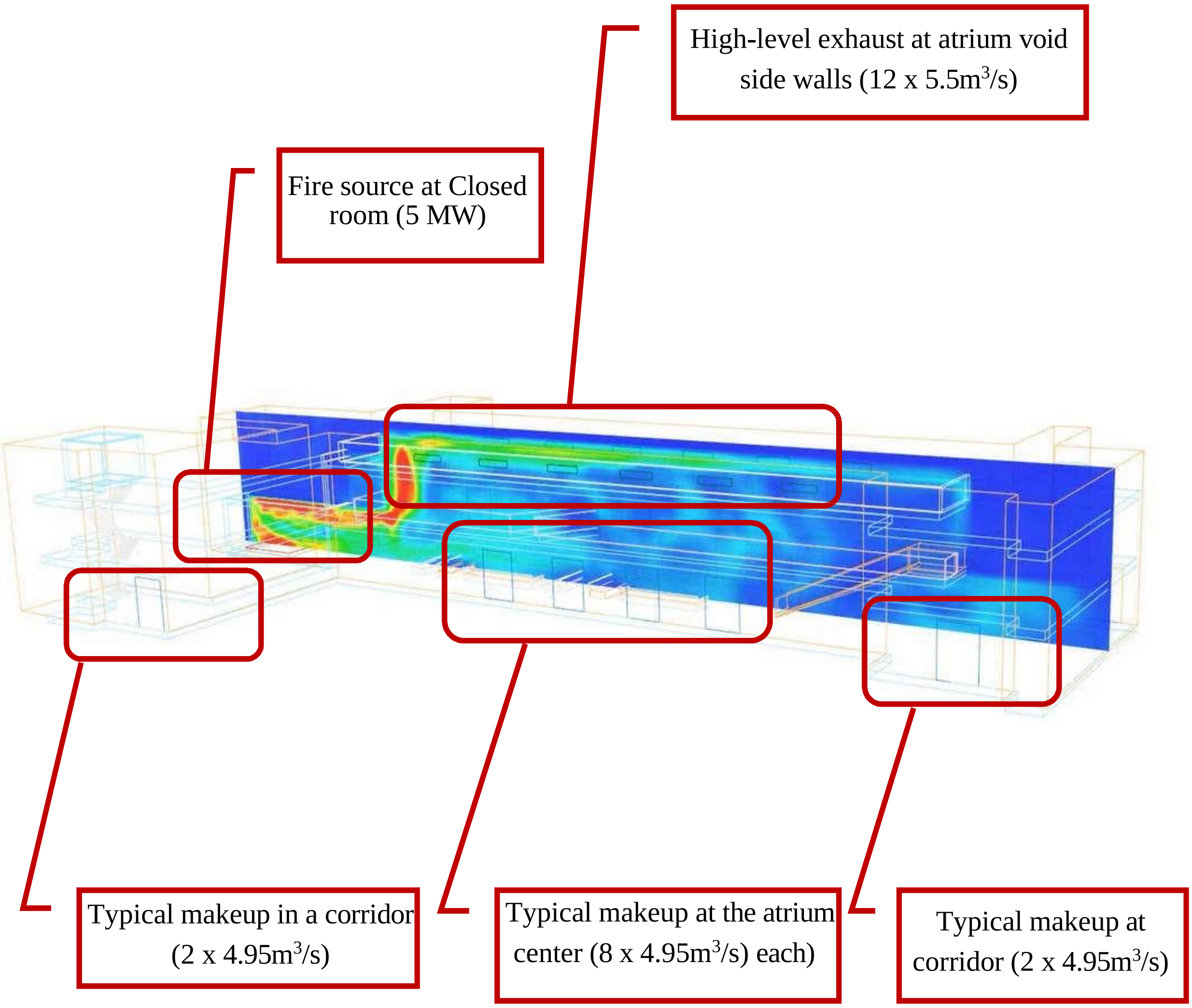
Figure 5 smoke temperature versus time in scenario -1

4.2 Fire Scenario 2

Figure 6 shows the building cross-section, where the fire is taking place in the HR room.

In this figure, several places contain:

- fire source.
- makeup air intake.
- exhaust fans.
- detectors.
- devices to measure smoke height.



Figures 6 - fire scenario -2 & smoke ventilation system

The smoke layer at the top floor will descend to fill the entire floor with smoke once the fire reaches a peak heat release rate of 5MW.

The smoke layer interface will range between 8-5 meters at the atrium area during the fire simulation duration time, which is acceptable for occupants' evacuation.

The smoke height will descend to fill the vicinity of the retail side having the fire scenario.

The maximum high-level temperature within 5 meters radius of the fire source will not exceed 120 degrees, while the smoke temperature at the fire source will not exceed 170 degrees which indicate that a rating of 400 degrees is more than enough for the axial exhaust fans.

As shown in figure 6, the following was noted:

● Fresh air intakes will have an average velocity of 1.0 m/s.

● Exhaust air openings will have an air velocity of 3:4.0 m/s.

From figures 7 & 8 HRR reached 1000 kW after 1 minute and increased to 5000 kW after 2 minutes which will stay constant to reach at 4 minutes then decrease to 0 at 5 minutes due to the location of the fire a closed room which has not renewable oxygen which Helps to ignition.

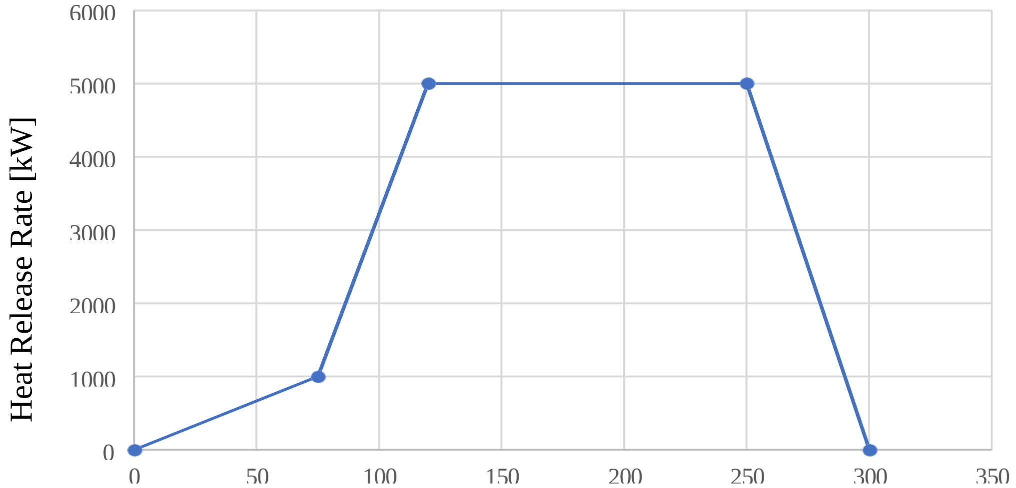


Figure 7 the heat release rate (HRR) versus time in scenario -2

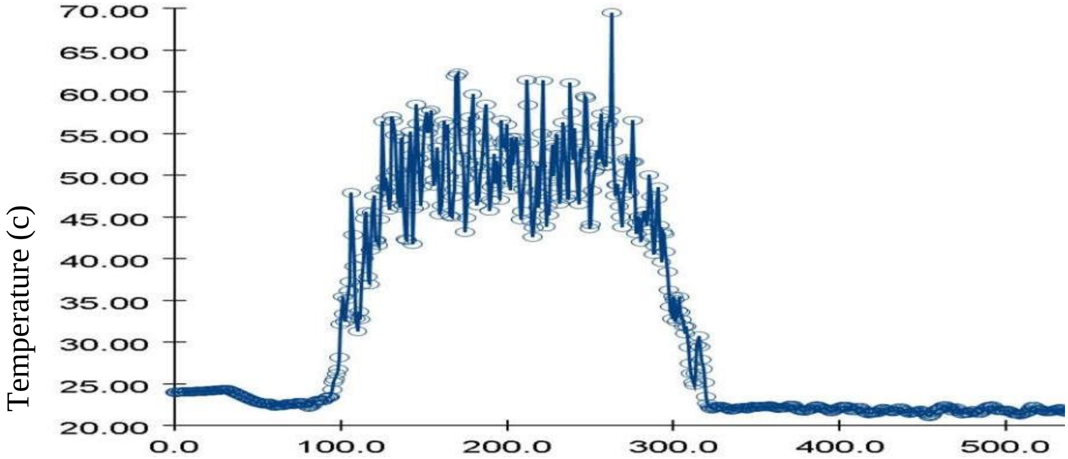


Figure 8 smoke temperature versus time in scenario (2)

4.3 Fire Scenario 3

Figure 9 shows the building cross-section, where the fire is taking place in the Medical supplies room.
In this figure, several places contain:

- fire source.
- makeup air intake.
- exhaust fans.
- detectors.
- devices to measure smoke height.

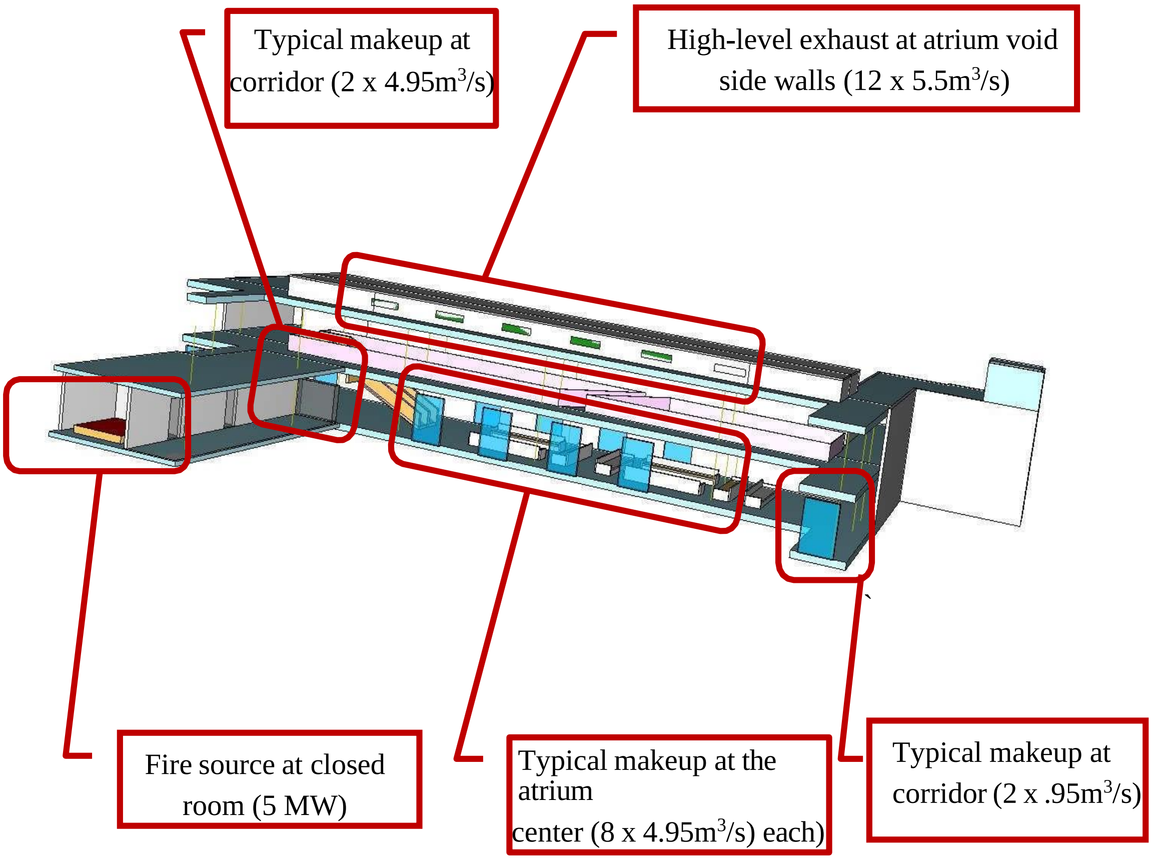


Figure 9 fire scenario-3 & smoke ventilation system

The smoke layer at the top floor will descend to fill the entire floor with smoke once the fire reaches a peak heat release rate of 5MW.

The smoke layer interface will range from 4 meters at the atrium area near makeup air intakes and around 2-3 meters near the balcony spill plume of fire during the fire simulation duration time, which is acceptable for occupants' evacuation.

The smoke height will descend to fill the vicinity of the retail side, having the fire scenario with a smoke and flames temp. Inside the shop, reaching 425 degrees.

The maximum high-level temperature within 5 meters radius of the fire source will not exceed 130 degrees, while the smoke temperature at the fire source will not exceed 175 degrees which indicate that a rating of 400 degrees is more than enough for the axial exhaust fans.

As shown in figure 9, the following was noted:

● Fresh air intakes will have an average velocity of 0.6-1.0 m/s.

● Exhaust air openings will have an air velocity of 2.5:3.5 m/s.

From figures 10 & 11 HRR reached 1000 kW after 1.25 minutes and increased to 5000 kW after 2 minutes which will stay constant level to reach 4 minutes and then decrease to 0 kW at 5 minutes due to the location of the fire in closed room which has not renewable oxygen which Helps to ignition.

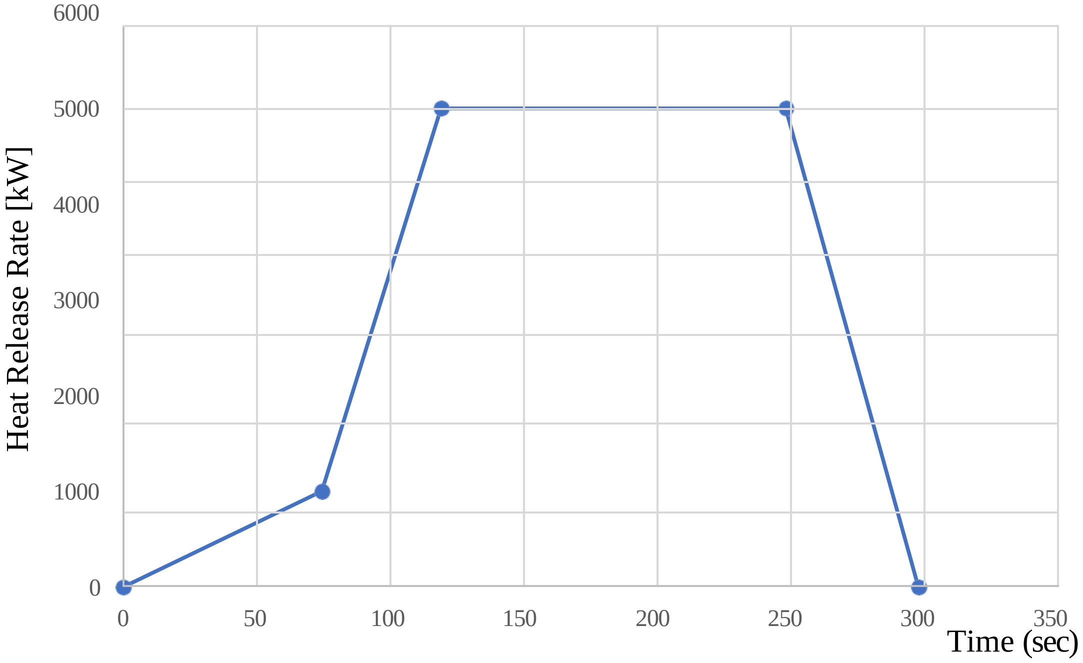


Figure 10 The heat release rate (HRR) versus time in scenario 3

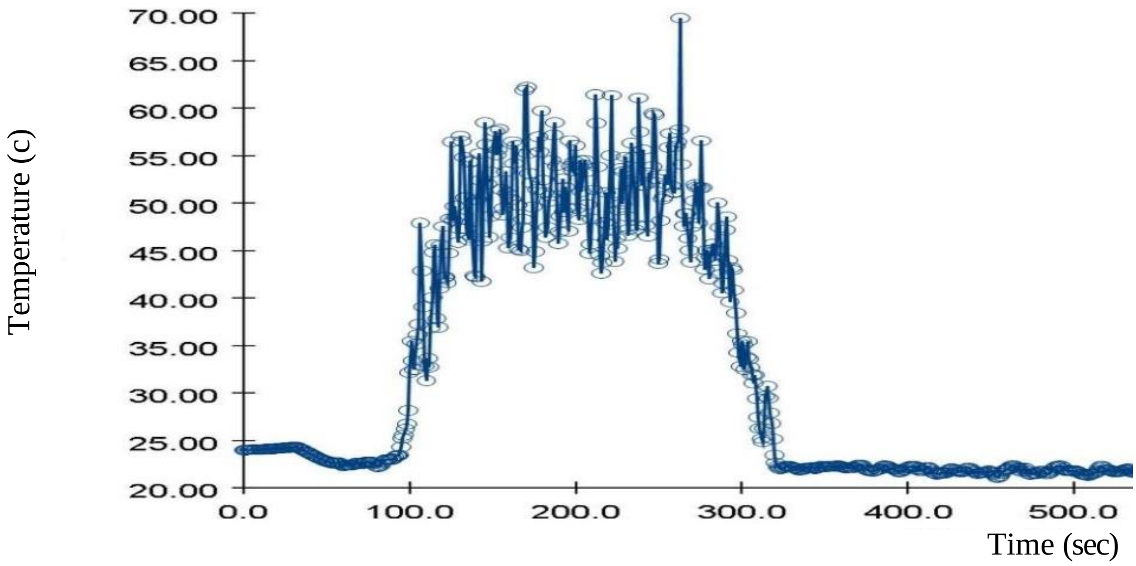


Figure 11 smoke temperature versus time in scenario 3

4.4 Fire Scenario -4

Figure 12 shows the building cross-section, where the fire is taking place in the medical waste room.

In this figure, several places contain:

- fire source.
- makeup air intake.
- exhaust fans.
- detectors.
- devices to measure smoke height.

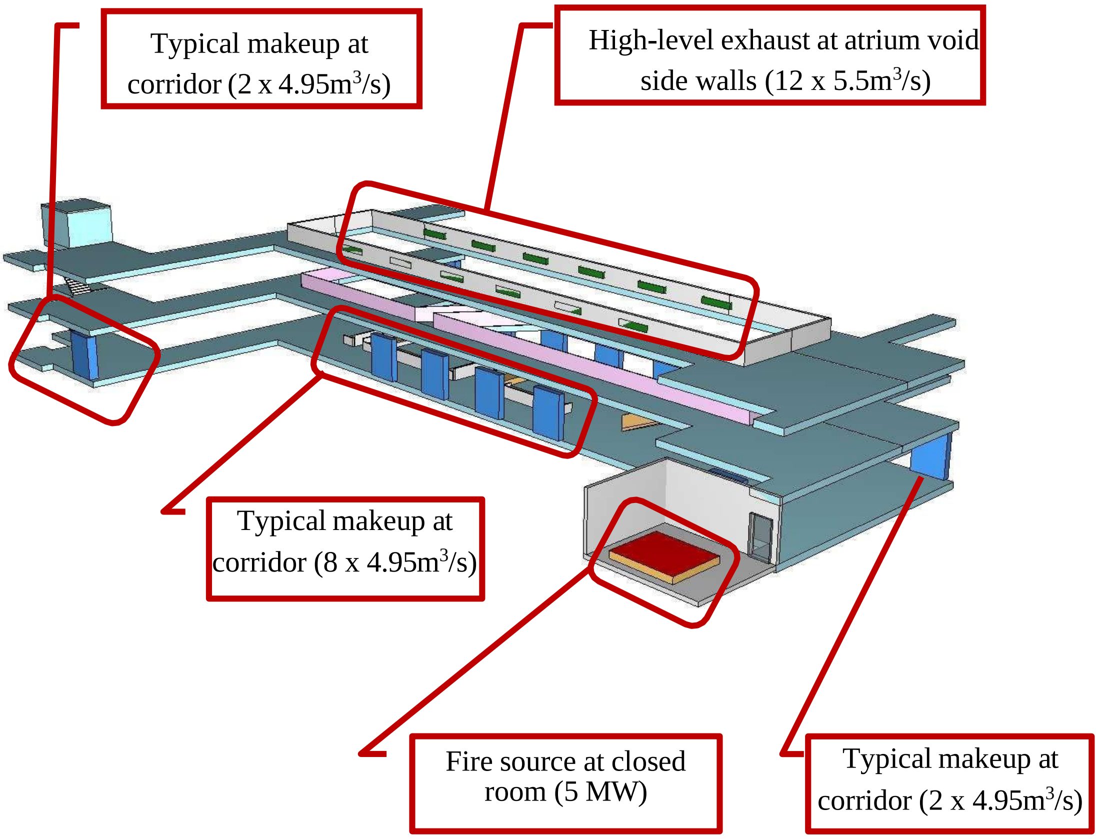


Figure 12 fire scenario-4 & smoke ventilation system

The smoke layer at the top floor will descend to fill the entire floor with smoke once the fire reaches a peak heat release rate of 5MW.

The smoke layer interface will range from 4 meters at the atrium area near makeup air intakes and around 2-3 meters near the balcony spill plume of fire during the fire simulation duration time, which is acceptable for occupants' evacuation.

The smoke height will descend to fill the vicinity of the retail side, having the fire scenario with a smoke and flames temp. Inside the shop, reaching 450-575 degrees.

The maximum high-level temperature within 5 meters radius of the fire source will not exceed 130 degrees, while the smoke temperature at the fire source will not exceed 175 degrees which indicate that a rating of 400 degrees is more than enough for the axial exhaust fans.

As shown in figure12, the following was noted:

- Fresh air intakes will have an average velocity of 1-1.5 m/s.

● Exhaust air openings will have an air velocity of 1.5:3.0 m/s.

From figures 13 & 14 HRR reached 1000 kW after 1.25 minutes and increased to 5000 kW after 2 minutes which will stay constant level to reach 4.25 minutes and then decrease to 0 (kW) at 5 minutes due to the location of fire at a closed room which has not renewable oxygen which Helps to ignition.

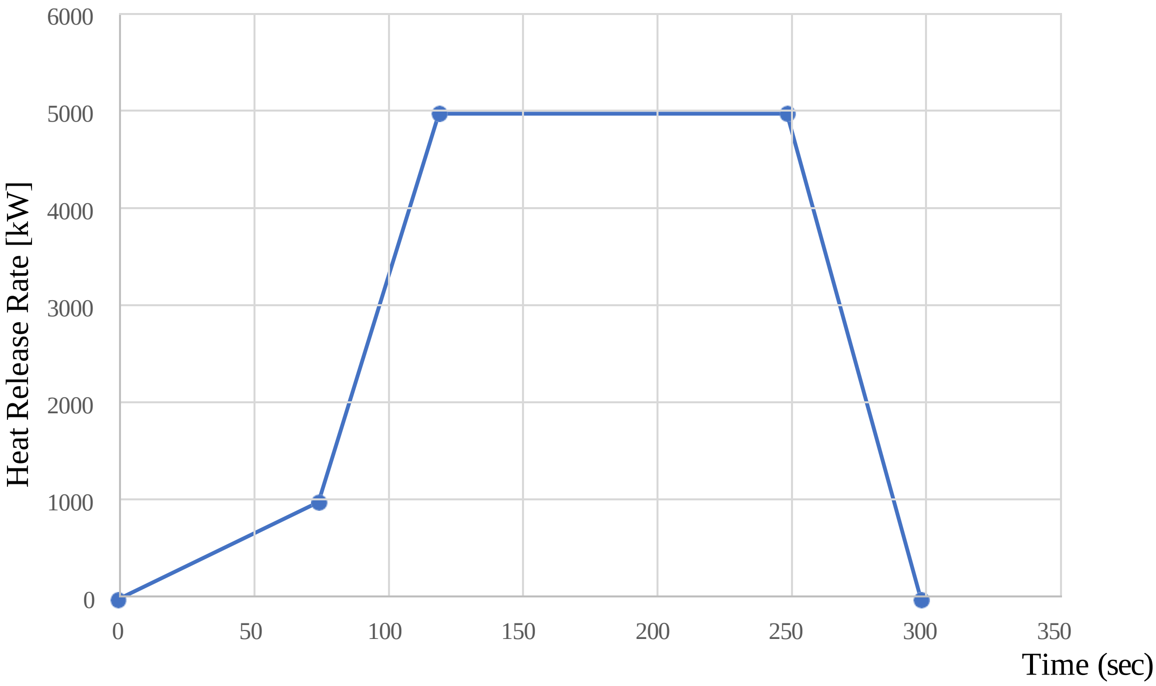


Figure 13 The heat release rate (HRR) versus time in scenario -4

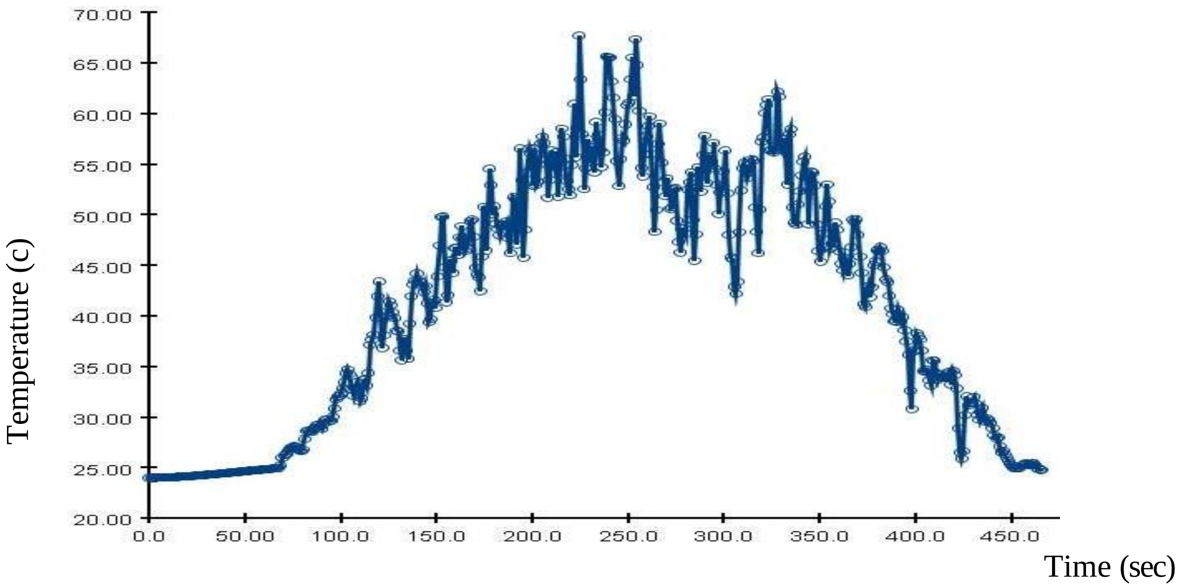


Figure 14 smoke temperature versus time in scenario -4

5. Conclusion

In this work, four scenarios of smoke extraction had been investigated numerically
1) Middle of the atrium.
2) HR room.
3) Medical supplies room.
4) Medical waste room.

For the simulation of these scenarios, PyroSim software was used.

Due to the ventilation system, it may be concluded that the increase in fire rate could be controlled by an evacuation system from propagation

Meanwhile, it is not recommended to operate the evacuation system without a fire extinguishing system within 2 minutes max.

From all of the above results, it is maybe concluded that mechanical ventilation is very important at the beginning of a fire due to decreasing in the ceiling temperature from growth.

On the other hand, the mechanical ventilation should be closed after a certain time to let the fire extinguishing system be activated.

The melting point of the materials the fire material suggested as wood construction, (wood, plastic, etc.) in the ceiling are getting between 130-1500 Celsius degrees and fire is replaced with heat of 5 MW, [12] That is why we prove that this study is effective in that the sprinklers system effect in this scenario will take in considers [13] and should start activating after 2 minutes from fire beginning where HRR is concerned with the type of fire which is ordinary hazard according to NFPA 13[14].

A tenable environment is one in which the products of combustion, including heat, smoke, and toxic gasses, are at levels that are not life-threatening or adversely impact the ability to egress; maximum air temperatures of 70°C are allowed for 6 min & Door and the wall should be visible from 10 m distance & Co concentration averaging 1500 PPM or less for the first 6 minutes of the exposure [15].

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