*Journal of Applied Fluid Mechanics*, Vol. 15, No. 3, pp. 659-671, 2022.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
https://doi.org/10.47176/jafm.15.03.33252

# Investigation of the Smoke Ventilation and Evacuation Strategies to Decrease Smoke Poisoning Risk by Coupling Fire and Evacuation Simulations

G. Coskun[1,3†], U. Demir[2] and H. S. Soyhan[1,3]

[1] *Department of Mechanical Engineering, Sakarya University, 54100 Sakarya, Turkey*
[2] *Department of Mechanical Engineering, Bingöl University,12000 Bingöl, Turkey*
[3] *Fire Application and Research Center, Sakarya University, 54100 Sakarya, Turkey*

†*Corresponding Author Email:gcoskun@sakarya.edu.tr*

(Received August 2, 2021; accepted November 12, 2021)

## ABSTRACT

In this study spread of smoke from a possible fire in a University building and the evacuation time of occupants were simulated. Fire dynamic simulations (FDS) have been done for natural and forced smoke evacuation with different scenarios; at the same time, evacuation simulations have also been done for various scenarios for different exits at the building. While occupants move through changing CO, $CO_2$, and $O_2$ concentrations, Fractional Effective Dose (FED) was gathered to obtain results from both simulations. FED results were evaluated for poisoning risk of occupants. According to comparative results, the combination of scenarios that forced smoke evacuation by fan and evacuation of occupants from all exits at the basement of the building has the lowest FED value. On the other hand, depending on the fire source and smoke movement, sometimes occupants cannot use all exits. Therefore, evacuation simulation has been done separately from each exit and evaluated with all FDS results.

**Keywords**: Fire dynamic simulator; Evacuation simulation; Smoke movement; Fractional effective dose.

## NOMENCLATURE

| | |
|---|---|
| $A$ | volume of the cube root of grid |
| CFD | Computational Fluid Dynamics |
| *FED* | Fractional Effective Dose |
| FDS | Fire Dynamics Simulator |
| HRR | Heat Release Rates |
| LES | Large Eddy Simulation |
| *NFPA* | National Fire Protection Association |
| NIST | National Institute of Standards and Technology |
| $\bar{S}_{ij}$ | symmetric rate of strain tensor |
| $C_s$ | Smagorinsky constant |
| $g$ | gravitational acceleration |
| $Par_t$ | turbulent Prandtl number |
| $Sc_t$ | turbulent Schmidt number |
| $\rho$ | density |

## 1. INTRODUCTION

Depending on NFPA Fatal Effects of Fire reports (Hall 2011), approximately half of the deaths appeared from smoke inhalation. Overall, one-quarter of fire deaths were related to both smoke inhalation and burns. Therefore, careful planning and implementation of fire and smoke protection become critical issues for substantially preventing life and property losses. Protective measures such as smoke, fire, and gas detectors enable rapid-fire evacuation and notification of fire to the Fire Department, often implemented in existing buildings. There is dense smoke and toxic gas emission in the event of a fire in buildings, especially from high-tech equipment with dense plastic content and chemicals with high flammable properties. It is evident that rapid ventilation of intense smoke is crucial for people trying to evacuate buildings, which will contribute significantly to the fact that fire intervention teams quickly reach and control the fire.

Figure 1 shows the cause of death during a fire as a percentage (Hall 2011). Smoke inhalation and burn

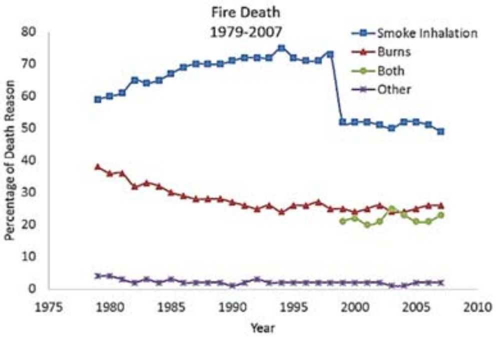


**Fig. 1. Statistic of fire death.**

statistics have not included in the statistics until 1999. Deaths from smoke inhalation were around 70% until 1999. Since 1999, data have been added to the statistics to determine if the cause of death is a combination of both events. It is understood that some of the deaths caused by smoke inhalation have been transferred to the situation realized by both events.

For this reason, it appears that there is a decrease in the rate of deaths caused by only smoke inhalation. It is known that smoke emissions of petroleum-derived plastic materials are much higher than the other materials. Because of the increase in the proportion of plastic materials used in office furniture or home furnishings, smoke-inhalation-related deaths have increased over the years. Therefore, smoke ventilation during the fire becomes essential to earn extra evacuation time for occupants.

The studies on ventilation techniques, which will facilitate smoke ventilation in a fire, show that the ventilation system can effectively help smoke ventilation. Fang *et al*. (2007) studied smoke movement and control in buildings by using experiments and models which they found out that the ventilation system directly affecting the height of the smoke. Chaudhary *et al*. (2021) studied the effect of ventilation on fire growth in a compartment fire experimentally. This study shows that reduction in ventilation results in oscillating flame behavior and increases in upper layer gas temperature. In another study by Chaudhary *et al*. (2018), door ventilation for different door openings effects on mass loss rate were investigated. They found that reducing the door ventilation from full door to quarter door did not significantly affect the fire size. Jie *et al*. (2010) studied smoke ventilation systems that provide natural ventilation and mechanically forced airflow. They have experimentally examined the effects of smoke evacuation speed and ventilation height. Froude number is an essential parameter in smoke evacuation. They tried to determine the optimum ventilation height and speed by evaluating Froude number according to different ventilation heights, carbon monoxide (CO), and smoke velocities. It has been proved that smoke ventilation efficiency is not the sole effect of ventilation height. This study demonstrates that smoke ventilation decrease as the ventilation height and the smoke evacuation rate decreases in small ventilation ducts and high smoke evacuation speeds.

Recent developments in software technologies have increased studies on codes that can simulate fire and smoke emissions. One software is Fire Dynamics Simulator (FDS) (Mcgrattan *et al*. 2015), which can simulate computational fluid dynamics (CFD), and the other is Smokeview which can visualize the resulting data. FDS and Smokeview are free and open-source software tools provided by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce (Mcgrattan *et al.* 2015). Furthermore, PyroSim (2021) software is developed as an interface of FDS. The FDS code uses the Large Eddy Simulation (LES) turbulence model can simulate smoke movements in a highly realistic way (Chow 1996). The accuracy of simulations with FDS code was supported by experimental data, and reliability was determined (Zou and Chow 2005, Hu *et al*. 2007, Hadjisophocleous and Jia 2009). Hu *et al*. (2007) compared the experimental results for smoke and carbon monoxide spread at the 88-meter-long canal with FDS simulation results. In the direction of the results, it was determined that the concentration of carbon monoxide increased linearly with the height from the ground and decreased substantially too far distances from the fire. This only applies if the floor height remains the same. Smoke intensity increases when the floor height of the other rooms or compartments transmit smoke (Oven and Cakici 2009). Kerber and Milke (2007) investigated smoke layer interface height in a simple atrium using FDS. They examined various air-supply arrangements and velocities to find the best strategy for smoke removal. Gao *et al*. (2013) aimed to establish a safe route for smoke-free and fresh air passage for tunnel evacuation in case of fire. It is stated by the Occupational Safety and Health Administration (OSHA) that the CO emission limit for safe evacuation should be 50 ppm. In this study, the CO emission is kept around 10 ppm thanks to the jet fans in the evacuation passenger way. This enables safe evacuation. Yan *et al*. (2020) investigated ambient pressure effects on fire smoke movement in vertical tunnels using FDS. They observed that the critical Richard number decreases at lower ambient pressure because of the higher smoke temperature and velocity. Guo *et al*. (2013) studied an extended heterogeneous lattice gas (E-HLG) model as an experimental and simulation developed by introducing an altitude factor into the heterogonous lattice gas model. This model was tested in a terrace classroom with FDS. It is found that the E-HLG model gave better results in very dense populations. It is quite difficult to determine the damages caused by possible building fires and the precautions to be taken because it is impossible to carry out experimental studies for all types of buildings. With computer simulations, a possible fire scenario can be modeled. In this way, it is possible to examine the development and progress of the fire and the chaotic events that are difficult to predict, such as smoke movements that can behave differently depending on the ventilation system and the design of the building can be visualized. In 2003, a sabotaged fire site was investigated using FDS software to investigate the development of fire and smoke spread on the seventh floor of a hotel with a 10-story multi-room event and entertainment center in Taoyuan, Taiwan. With this study, the situation of heat, smoke and poisonous gases were investigated at the crime scene and the study of the fire area was supported. The observations of the fire in the hotel and the simulation study were compared and similar results were obtained (Shen *et al.* 2008). In building fires, furniture, electronic goods, electrical equipment, and cars in the car park can burn. Zhang *et al*. (2007) modeled the fire spread in a large underground car park and smoke movement using FDS software. They have recommended 12 minutes for safe evacuation in the direction of simulation results. In their study, Gannouni and Maad (2016) estimated CO emission and maximum smoke temperature using FDS software for tunnels of different lengths. Previous experimental studies have determined high accuracy. In addition, the highest CO emission was detected at the points close to the fire source. Also, as the aspect ratio increased, the CO emission decreased. Zhang *et al*. (2011) thought that buses were more commonly used as public transport in everyday life. With FDS, they have simulated the bus fire for several scenarios. They investigate the time-dependent change in the heat release rate according to whether the doors are open or closed. Smoke movement in high-rise building stairwells was simulated using FDS by Zhao *et al*. (2017). Li *et al*. (2014) compared simulation results with experimental studies for temperature and smoke movement. The simulation result for the temperature inside the stairwell showed good agreement. However, smoke moved much faster in simulations than in experiments. Brahim *et al*. (2013) investigated the effect of temperature distribution and ventilation during a fire in the tunnel using FDS in their study. They found that the smoke emission layers can reach the lower layers with ventilation and make it difficult for human evacuation. They suggested that this should be taken into account for ventilation ducts in places such as tunnels. Yang *et al*. (2018) investigated plug-holing phenomenon under lateral smoke extraction systems in tunnel fire. They obtained that exhaust rate increasing didn’t change significantly the exhaust efficiency. However plug-holing phenomenon decrease the lateral smoke exhaust system performance. Lim (2020) was investigated flow and temperature fields around a burning car inside a tunnel under natural ventilation condition. Three different inlet velocities as 1.8, 3.0 m/s and no velocity adopted to their model. They were also included windows breaking model that when the temperature reached critical values windows of the car was deleted from the model.

FED is a measure of airborne contaminants absorbed by an occupant. Hazards such as carbon monoxide and carbon dioxide ($CO_2$) are accumulated during the occupant’s movement through a burning building. FED can be calculated using Purser's (2003) equation using gas-phase concentrations of $O_2$, $CO_2$, and CO. Xu *et al*. (2014) have determined the most appropriate escape routes for evacuation by simulating fire with FDS in a subway station and a primary school. They also identified the locations of the firetraps and developed scenarios in which firefighters could do their rescue work most efficiently. To determine the best rote, they calculated integrated hazard in the path using two different FED data derived from the 6-Gas model and heat. Yang *et al*. (2013) were simulated fire evacuation in a subway station using FDS+Evac. They simulated 18 scenarios by changing heat release rates (HRR), occupant load, stairs, ventilation system, grown time of the fire. Using FED data, they could determine the effect of variables on total dead. Jafari *et al*. (2011); using the code they developed for tunnel fire, a heavy vehicle fire was simulated with a fire load of 25 MW. Tunnel fire 2D simulations have been validated by experimental work. They suggested that the code developed due to the software results overlapping with the experimental study can be used for tunnel fire simulations. Qu *et al*. (2013) were estimated the number of fatalities for road tunnel fires by using FDS. Using the concentration of CO, $CO_2$, and $O_2$, they could predict the concentration of toxic gases at any position in the tunnel and the number of fatalities. Lou *et al*. (2017) determined the flow rate of jet fans according to maximum smoke temperature and fire size by using FDS software for a fire with 10, 20, and 30 MW power in a full-size tunnel with half-duplex ventilation ducts. They determined the maximum smoke temperature and smoke spread characteristics, especially in areas with no smoke extraction.

As can be understood from the literature, no comprehensive study was found in which different smoke ventilation and evacuation scenarios were run together to obtain FED data. Therefore, in this study, a university building has been modeled as a fire resulting from the ignition of the main switch and plastic cables that overheat in the server room due to electricity short circuit or overloading. At the simulation study, PyroSim (2019) software was used to prepare a fire model to solve in the FDS version of 6.7.5. It is aimed to observe and investigate the progress of smoke in a fire in the server room, where has the highest probability of fire in a building. Five different scenarios depending on natural and forced smoke evacuation from the building were simulated.

Furthermore, occupant evacuation simulations were performed to calculate total evacuation time depending on the human population and possible exits of the building. Pathfinder (2019) software was used to simulate evacuation from a building. Five different occupant evacuation scenarios depending on exit doors from the building were simulated. Results from both smoke and occupant evacuation simulations were used to obtain FED data for selected occupants from each scenario. Thus, best and worst smoke and occupant evacuation scenarios were evaluated by using FED data.

## 2. NUMERICAL MODEL OF FDS

FDS is dynamic fire software that solves fire and smoke flow by using CFD. This software solves low Mach number flow applications using Navier – Stokes equations for fire smoke movement using governing equations are described as follows:

The conservation of mass

$$\frac{\delta\rho}{\delta t} + \nabla.(\rho u) = 0 \tag{1}$$

Conservation of momentum

$$\rho\left(\frac{\delta u}{\delta t} + (u.\nabla)\mathrm{u}\right) + \nabla p = \rho g + f + \nabla.\tau \tag{2}$$

Conservation of energy

$$\frac{\delta(\rho h)}{\delta t} + \nabla.\rho h u - \frac{Dp}{Dt} = \dot{q}''' - \nabla.q_r + \nabla.q_r + \nabla.k\nabla T + \nabla\textstyle\sum_l h_l(\rho D)_l\nabla Y_l \tag{3}$$

Conservation of species

$$\frac{\delta(\rho Y_l)}{\delta t} + \nabla.\rho Y_l u = (\rho D)_l\nabla Y_l + w_i''' \tag{4}$$

Turbulence calculation can be solved either by the Direct Numerical Simulation (DNS) or the Large Eddy Simulation (LES) (McGrattan *et al.* 2015). DNS model is needed a very dense mesh structure; therefore takes too much time to solve. LES turbulence model, which was originally developed by Smagorinsky used in this study. LES model calculates the large-scale eddies and models the small scales dissipative process as viscosity, thermal conductivity, and material diffusivity. LES Sub-grid turbulent viscosity in FDS is model by the following equations;

$$\mu_t = \rho(C_s\Delta)^2\left[2\bar{S}_{ij}\colon\bar{S}_{ij} - \tfrac{2}{3}(\nabla\bar{u})^2\right]^{1/2} \tag{5}$$

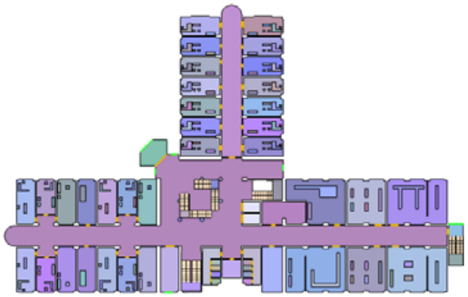
Where $C_s$ is Smagorinsky constant and specified as 0,2 . Δ is the filter width, and A is the volume of the cube root of the grid. $\bar{S}_{ij}$ is the symmetric rate of the strain tensor. Other diffusive parameters, like mass and thermal diffusivity, are related to the turbulent viscosity;

$$k_t = \frac{\mu_t C_p}{Pr_t},\ (\rho D)_t = \frac{\mu_t}{Sc_t} \tag{6}$$

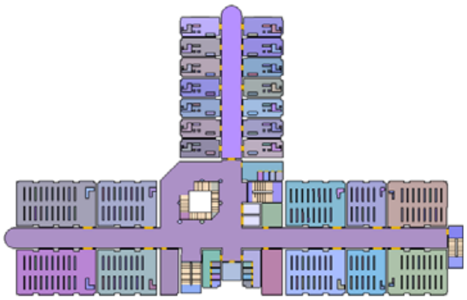
Where $Pr_t$is the turbulent Prandtl and $Sc_t$ is the turbulent Schmidt number are used as constant in the current simulations is equal to 0.5. The values of $C_s$ is 0.20, $Pr_t$ and $Sc_t$ are 0.5 used based on experimental data of Zhang *et al*. (2001).

## 2.1. Physical Model Setup

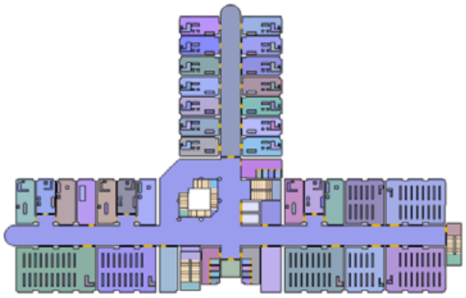
Sakarya University Mechanical Engineering, Metallurgical, and Materials Engineering building 2D drawings of all floors are given in Fig. 2. For all scenarios, the fire source is an electrical panel in the server room in the basement. In the building, there are 18-laboratory rooms, 4-computer laboratories, 69-office rooms, 24 classrooms, 12 WC Furthermore, 98 academic staff and ten administrative staff are continuously working in the building. However, student numbers in lectures vary depending on daily and weekly course programs. For this reason, the number of students in the building is constantly changing. The number of students can vary from 250 to 750 within one day.



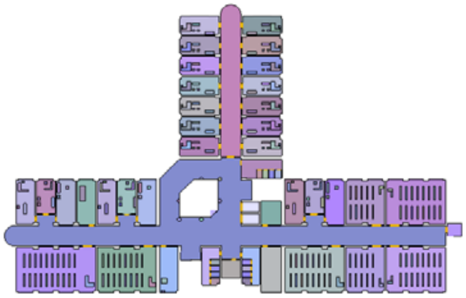
Basement



1st floor



2nd floor



3rd floor

**Fig. 2. 2D drawings of all floors of the building.**

Generally, fires lead from kitchen or cooking areas, offices, machinery, switchgear areas, or transformer vault rooms for high-rise and shorter office buildings (Ahrens 2016). The current building that simulations are performed has classes, academic staff offices, laboratories and a switchgear room. After making fire risk analyses, it was observed that the switchgear room has a higher potential of being a fire source. Because in the switchgear room includes an oversized master switch cabin and server cabinet together, which are continuously supplying with high electrical current. Furthermore, there is no fire-extinguishing system, cable ducks are not isolated, cables are overhanging, and the air condition system is not active in the server room.

Figure 3 shows the switchgear room location on the basement floor with a 3D model of the master switch cabin, server cabinet, and cable ducts. The main switch, server cabinets, and cable ducts were added

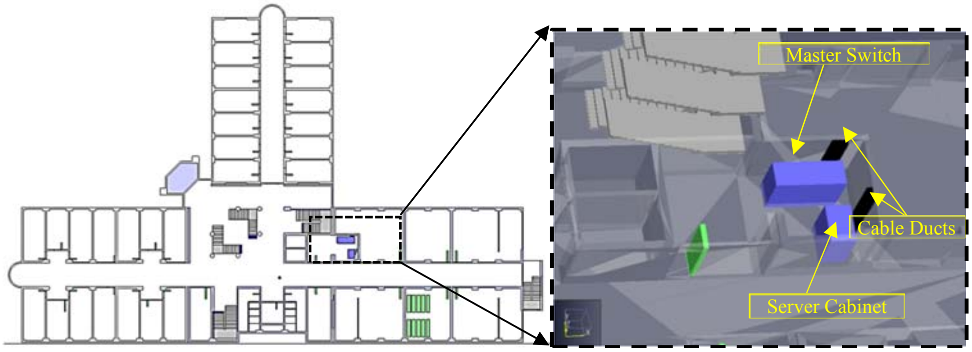


**Fig. 3. Switchgear room location at the basement floor with a 3D model of the master switch cabin, server cabinet, and cable ducts.**

to the model by drawing in their actual dimensions as seen in the room on the basement floor. The flare-up location is defined as the upper area of the main switch cabinet since the fire is more likely to come out of the main switch.

## 2.2. Simulation parameter and mesh size

In the simulation study, since the smoke distribution was examined, the heat release rate was defined on the master switch cabin (Fig. 4) where the fire started and the smoke came out of the source where the fire was defined. In addition to the heat dissipation rate of the fire, PVC cable material is defined for the electrical panels in the master switch room. The fire was thought to be 464 kW (Nureg/CR-6850) peak HRR for 0.168 $m^2$ defined to switchgear room cabinet fire. Also 250 kW/m$^2$ (NUREG/CR-7010) HRR $(0.6m \times 2.46m)$ for thermoplastic cable fire included to fire. Therefore totally 834 kW (3000 kW/m$^2$) peak HRR was entered as the fire source. The rump-up time was calculated t$^2$ formula and reaches the maximum energy in 60 seconds. In the master switch cabin, which is thought to be burning PE/PVC material, the combustion reaction of this material was calculated with a single-step chemical model. For PE/PVC material combustion properties, heat of combustion, soot yields factor and CO yield factor were used as respectively 2.09E4 kJ/kg, 0.136 kg/kg and 0.147 kg/kg (Hurley *et al.* 2015).

**Fig. 4. Master switch cabin and cable ducts in switchgear room where fire load defined in the simulation.**

In the study where the simulation will be done depending on time, the model for the designed fire was operated for 500 seconds, and during this time, the diffusion of smoke inside the building was examined. From the preliminary evacuation simulation studies, the evacuation of the ground floor was completed in approximately 100th seconds. For this reason, in the fire simulation, the right emergency exit door of the ground floor is closed with a command entered into the model in 100th seconds so that the fire smoke does not go to the emergency evacuation stairs. Details of the simulation parameters were given in Table 1.

**Table 1. Details of Simulation parameters**

| **Simulation parameters** | **All FDS cases** |
|---|---|
| Initial temperature (°C) | 20 |
| Initial pressure (atm) | 1 |
| Relative humidity (%) | 70 |
| Simulation type | LES, transient |
| Computational domain (m$^3$) | 84 × 23.2 × 17<br>21 × 29 × 14 |
| Turbulence | Deardorff model (default) |
| Schmidt and Prandtl number | 0.5 |
| Fire source | The surface heat release rate |

In the case of Smoke Removal Fan Active, the selected fan can absorb smoke with a maximum flow rate of 18 m$^3$/s and 300 Pa pressure. Also, during simulation, as the fan detects the smoke by the smoke detector placed in the switchgear room, a command is entered into the model to be activated.

In FDS simulations, it is stated that the mesh size should be at least 1/5 of the value calculated by characteristic fire diameter calculation (Mcgrattan *et al.* 2015). When this calculation is made for the building where the simulation work is done, it is understood that a solution with approximately 5 million total numbers of cells is required. This cell size calculation method was developed for capturing fire plumes sufficiently accurately. It was thought that a different method should be used for the optimum mesh size required to solve the smoke distribution correctly. Therefore cell optimization study was conducted to investigate the effect of cell size on smoke height. For this purpose, time-

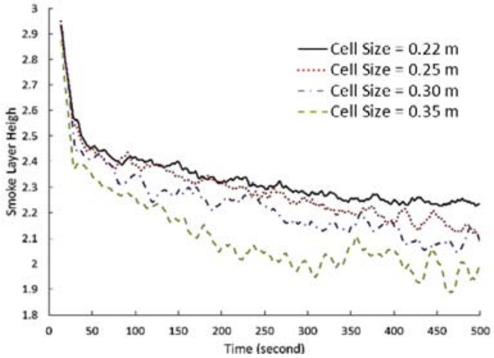


**Fig. 5. Smoke height over time for different cell sizes.**

dependent smoke altitude data was obtained from a line up to 3 meters from the ground near the building's atrium. In FDS simulation, each mesh is divided into structural rectangular cells. Simulations for different cell sizes 0.35, 0.3, 0.25, 0.2 m were run for the same model, and the resulting smoke heights are given in Fig. 5 for grid independence study. These different cell sizes were distributed uniformly at the computational fluid domain for each simulation. For example, 0.25 x 0.25 x 0.25 m cell size applied all domains for one case. Accordingly, while smoke height is significantly different between 0.35 and 0.25 m cell size, a negligible difference between 0.25 and 0.22 m cell size was obtained especially up to approximately 300 seconds. 0.25 m cell size corresponds to approximately 2,740,000 total number of grids, while 0.22 m cell size corresponds to approximately 3,858,000 total numbers of grids. There is approximately 1,000,000 total numbers cell differences between 0.22 m with 0.25 m. However there is a significant reduction in solution time and negligible solution differences. Therefore 0.25 m cell size was selected for CFD simulations. In addition, since the effects of fire smoke on human beings, in this study, are evaluated through FED data, It was shown in a study by Jeong (2014) that the larger cell size had little effect on FED data. In his CFD simulations with 0.05, 0.1, and 0.2 m cell size, Jeong obtained the FED data for three different cells with a slight difference of 0.3% on average.

### 2.3. Fractional Effective Dose (FED)

Combined effects of CO, $CO_2$ and low oxygen on occupants describe by FED. Equation of the FED is defined in SFPE Handbook (Hurley *et al*. 2015) by the following equation.

$$FED_{total} = FED_{CO} \times V_{CO_2} + FED_{O_2} \quad (7)$$

where $FED_{CO}$ is the function of CO. A hyperventilation coefficient describes by $V_{CO_2}$acts as a multiplier of effects. $FED_{O_2}$ is a function of time and accumulates when $O_2$ is less than 20.9%. It has been stated that fire smoke has a minor effect on occupants for $D_{total} > 0.01$, low effect for $0.01 > FED_{total} > 0.3$ , serious effect for $0.3 > FED_{total} > 1$, lethal effect for $FED_{total} > 1$ (Gann and Bryner 2008, Oven and Cakici 2009).

## 3. EVACUATION MODEL

In Pathfinder software, occupants who will be evacuated from the university building have been added to the offices, classrooms, and laboratories with as many settlements as possible. Classes were filled entirely according to the seating arrangement, occupants were placed in at least one person in the offices, and additional occupants were placed in the corridors and laboratories. In total, there are 885 occupants defined in the building. While random distribution was made in the corridors, regular distribution was applied for classrooms and offices, as shown in Fig. 6. Occupants move with a walking speed of 1,19 m/s during evacuation. Movement speeds are defined at walking speed. The reason for this would be the longest evacuation when the structure is full, and in this case, it was aimed to determine smoke and its affection rates faced upon the occupants. Since the occupants in the structure consist of biologically mature people, shoulder widths were taken as 42.65 cm (Zhang *et al*. 2011). No gender discrimination between occupants, and in the building simulations were made considering the situation that there were no disabled occupant and all occupants could leave the building with their own efforts.

The steering-collision handling (Li *et al*. 2014) method was used for the evacuation behavior of occupants. Furthermore, according to the data obtained from PyroSim (FDS) simulations, it was observed that smoke reached the fire alarm system in the Switchgear room 28 seconds after the fire started. Therefore, during all evacuation activities, occupants started to evacuate with a delay of 30 seconds. $O_2$, $CO_2$ and CO data from PyroSim software were then transferred to Pathfinder software. FED data was created for occupants selected from each scenario in

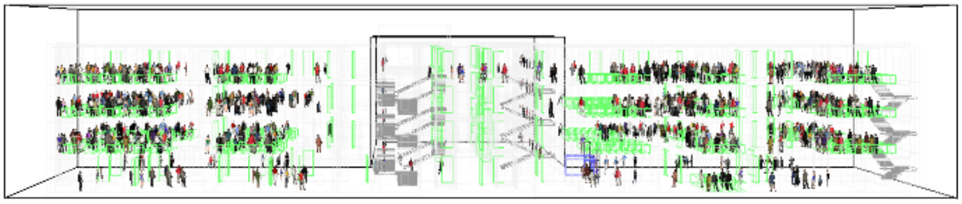
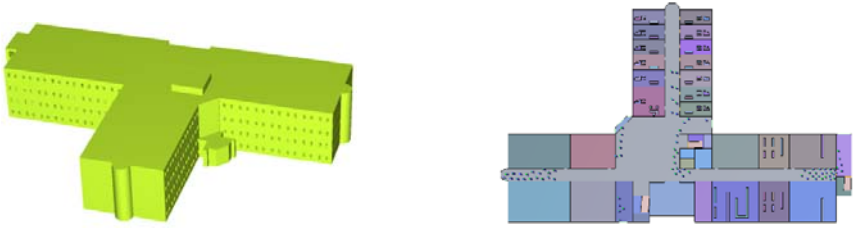


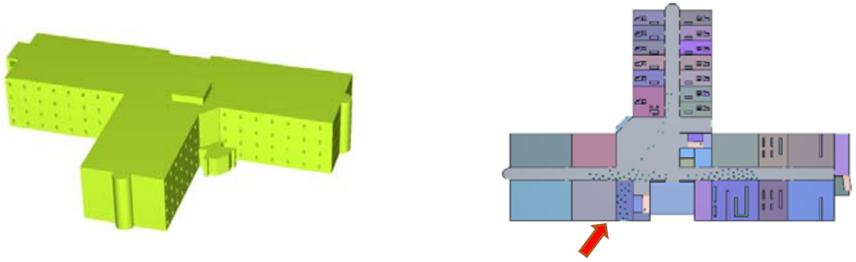
**Fig. 6. 3D view of the building with occupant distribution (totally 885 occupants).**

**Scenarios for Smoke Extraction** **Scenarios for Occupants Evacuation Exit Door**



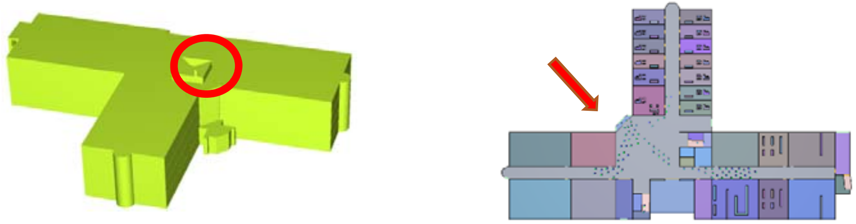
1) Double Casement Open

A) All Exit Doors (Evacuation time: 274,9 s)



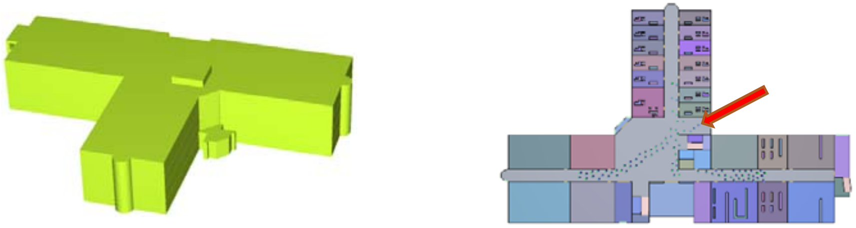
2) Single Casement Open

B) Rear Exit Door (Evacuation time: 408,3 s)



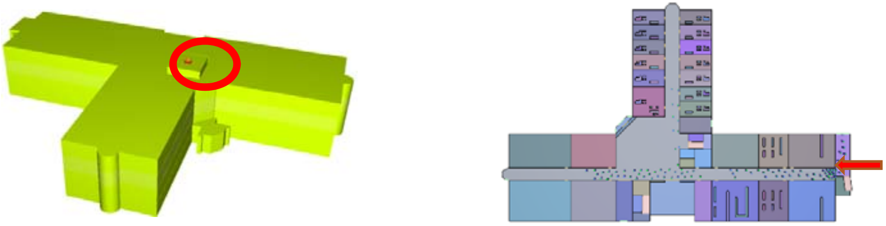
3) Sky Lighting Window Open

C) Front Main Exit Door (Evacuation time: 388,3 s)



4) All Casement Close

D) Car Park Exit Door (Evacuation time: 403 s)



5) Smoke Removal Fan Active

E) Emergency exit door (Evacuation time: 669,2 s)

**Fig. 7. Scenarios for smoke extraction and occupants' evacuation.**

evacuation studies. Occupant selection for FED data is based on a specific criterion. According to this criterion, FED data were extracted by selecting the occupant faced with smoking for the longest time in each scenario. Accordingly, in all scenarios except the left emergency exit door, it was observed that occupants who left the building the most lately were faced to smoke much more. Within the scope of the left emergency exit, it was observed that the occupants on the ground floor were exposed to direct fire smoke; therefore, the FED data of the last occupant leaving the ground floor was used.

Five scenarios have been developed for smoke distribution and evacuation within the structure. These scenarios are arranged with two wings of all windows open, one wing of all windows open, and a natural top window with a ventilator open. In addition, five evacuation scenarios have been developed for the evacuation of occupants. The details of these scenarios and the total evacuation times obtained by evacuation simulations are given in Fig. 7.

## 4. SIMULATION RESULTS

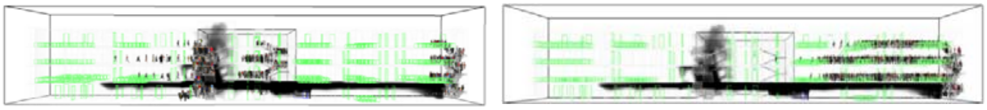
As a result of fire simulations run for 500 seconds for each scenario, time-dependent changes in smoke distribution and occupants' evacuation in the structure were obtained visually for 100, 250 and 500 seconds. At the same time, in each evacuation scenario, the FED data of the last occupants exiting the building were obtained for each smoke evacuation method and plotted graphically. Through the comparative FED data obtained according to the scenarios, evacuation and smoke distribution scenarios have been obtained in which the occupants, exposed to smoke for the most time, are affected by the smoke most and most minor.

### 4.1. Time Depended Smoke and Human Interaction for Different Scenarios

According to the data obtained because of the simulations, the dispersion of the smoke in the building because of a possible fire in the Switchgear room in the university building and the position of the occupants are shown in Fig. 8 100 seconds after the start of the fire. Accordingly, in all scenarios except Scenario 1, the smoke first proceeded upward through the atrium cavity and reached the structure's third floor. In the first scenario, it is seen that the smoke progresses to the last floor of the building. In all scenarios, smoke moves towards the emergency exit gate, which is assumed open during the simulation on the ground floor. Smoke reaches the smoke detector attached to Scenario 5 at the thirtieth second, so the signal sent by the detector activates that fan. After 30 seconds, the fan operated continuously and discharged 18 m3 of air out of the building per second. In the 100th second, in the scenario where the fan is used, the smoke progresses less than the others do. This has been shown to increase air circulation and reduce the formation of dark smoke by continuously pumping air through the fan to the outside. The main connection room of the main switch-room where the fire starts is the only connection to the outdoor environment, and there is no ventilation system inside, so it has been observed that the vacuum effect created by the operation of the fan prevents some air from entering the room to feed the fire. In the scenario where all windows were open, it was seen that the smoke reached the roof faster than the others did. This situation is thought to be due to the scenario where the air circulation in the building is the highest because all the windows are open. In the scenario where all windows were closed, it was understood from the simulation results that the smoke layer progressed more slowly due to the low indoor air velocity. When the scenarios are examined in terms of human evacuation, it is seen that people trying to leave the building through all the exit doors tend to use the stairs at the back of the building. However, it has been observed that the smoke moves up these stairs and that people encounter this smoke during the evacuation, and these people will inevitably be affected by smoke. In addition, it was observed that the last four of the people who left the building only by using the emergency exit door and

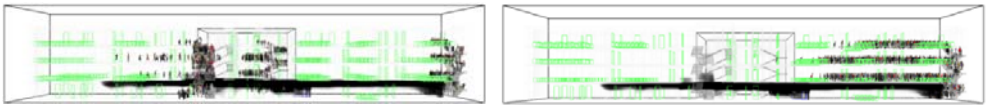
Double Casement Open (1)- All Exit Doors (A)**(exited 208/885)**

Double Casement Open (1)- Emergency exit door (E)**(exited 159/885)**



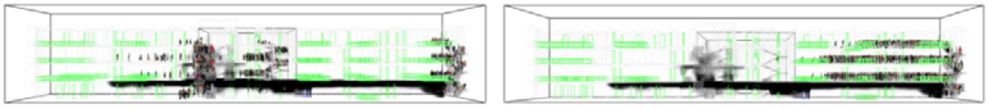
Single Casement Open(2)- All Exit Doors (A)**(exited 208/885)**

Single Casement Open(2)- Emergency exit door (E)**(exited 159/885)**



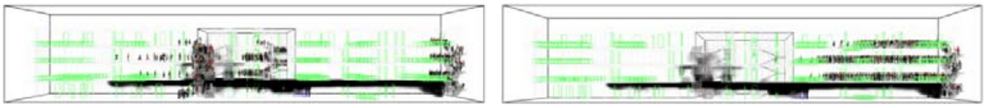
Sky Lighting Window Open(3)- All Exit Doors (A)**(exited 208/885)**

Sky Lighting Window Open(3)- Emergency exit door (E)**(exited 159/885)**



All Casement Close (4)- All Exit Doors (A)**(exited 208/885)**

All Casement Close (4)- Emergency exit door (E)**(exited 159/885)**



Smoke Removal Fan Active(5)- All Exit Doors (A) **(exited 208/885)**

Smoke Removal Fan Active(5)- Emergency exit door (E)**(exited 159/885)**

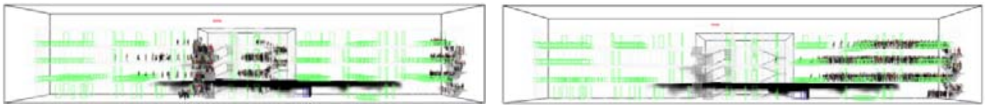


**Fig. 8. State of Smoke and People inside the building at the 100th second.**

who were evacuated from the ground floor were exposed to smoke except for the fan evacuation scenario. In a smoke evacuation with fan scenario, the smoke has not yet reached the evacuated people in 100 seconds.

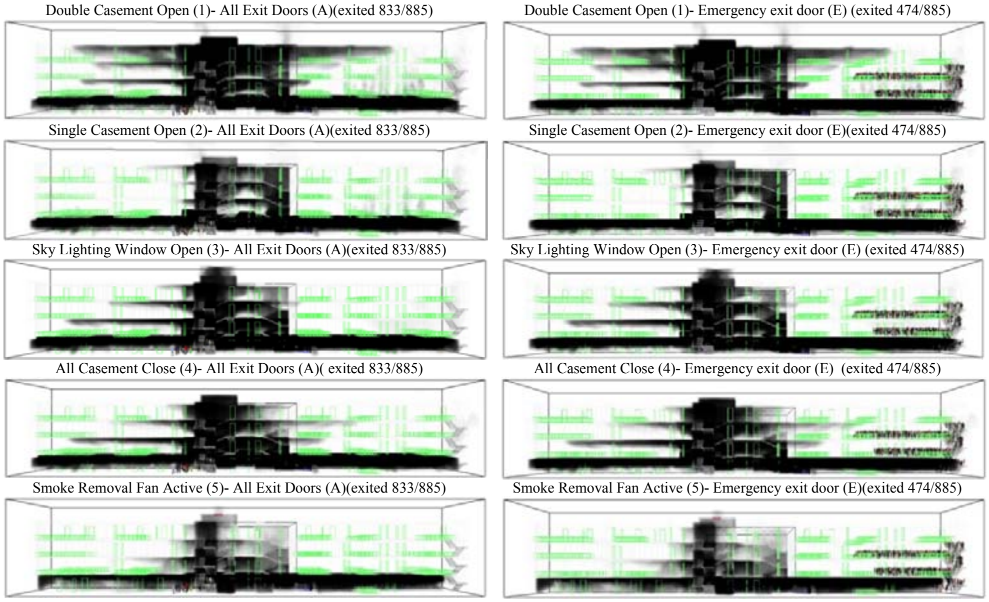
Figure 9 shows that in scenarios other than the fan model for the 250th second, the smoke is extensively spread on all floors due to the effect of airflow and heat transfer. In this case, it is no longer possible to reach the emergency exit door from the ground floor, and according to the existing evacuation scenario, it is observed that only the people using the emergency door of the ground floor leave the building in 115th seconds. The most intense and rapid smoke emission occurs in the scenario where all windows are open, while the most minor distribution occurs in scenario five where all windows are closed and the fan is running.

Unexpectedly, it has been observed that the smoke has not yet spread through the corridors of the mezzanine floor when the single sashes of the windows are open. Scenario 3, where natural ventilation dampers are used, is the second case in which smoke is emitted the fastest. Thus, it is understood that the opening of the natural ventilation damper for the building has no positive effect on the smoke evacuation. However, in the scenario where the fan is used, it is seen that the smoke density is relatively low and the speed of the progress inside the building is slower than in the other scenarios. It is understood that the fan gives a considerable amount of time to people evacuated from the building and even to the teams that will intervene in the fire. After the emergency exit door of the ground floor was closed, it was seen that no one from the other floors who had left the building through the emergency exit door had been exposed to fire smoke on the emergency stairs. This situation, obtained from the simulations, re-emphasizes the importance of the smoke sealing feature of the emergency exit door and the emergency stairs.

In Fig. 10, it is seen that the smoke density is at the highest level in the ground floor and atrium area due to the structure being atrium in all scenarios for the 500th second. Except for scenario 1 where all windows open and scenario 5 where the fan is operated, the smoke distributions on the ground floors are shown similarity; however, for the situation that all the windows are open, it is seen that there is greater smoke density utilizing the effect of airflow on the top floor. In Scenario 1, it is seen that the smoke is quite dense on all floors except the first floor, but in the scenario where the fan is operated, it is seen that smoke is present as a thin layer of fog in some of the floors except the ground floor. In the fan scenario, it is thought that there is no smoke in the corridors on the side of the emergency exit door and this is caused by the suction of the fresh air inward through the vacuum effect of the doors that remain open during evacuation. In addition, in fire simulations, emergency doors on the other floors, except the ground floor, were kept open at all times.

### 4.2. FED Results

Pathfinder software can calculate the FED as occupants move through changing CO, $CO_2$, and $O_2$ concentrations. Figure 11 shows the FED data of the occupants that have been exposed to the smoke for the most extended period, obtained from all simulations of smoke emission and evacuation scenarios. When all smoke evacuation scenarios are examined, it is seen that the lowest FED data occurs when the smoke evacuation fan is used. In addition, the highest FED data of the users occurred in all scenarios except for the case where the ventilation



Double Casement Open (1)- All Exit Doors (A)(exited 833/885)

Double Casement Open (1)- Emergency exit door (E) (exited 474/885)

Single Casement Open (2)- All Exit Doors (A)(exited 833/885)

Single Casement Open (2)- Emergency exit door (E)(exited 474/885)

Sky Lighting Window Open (3)- All Exit Doors (A)(exited 833/885)

Sky Lighting Window Open (3)- Emergency exit door (E) (exited 474/885)

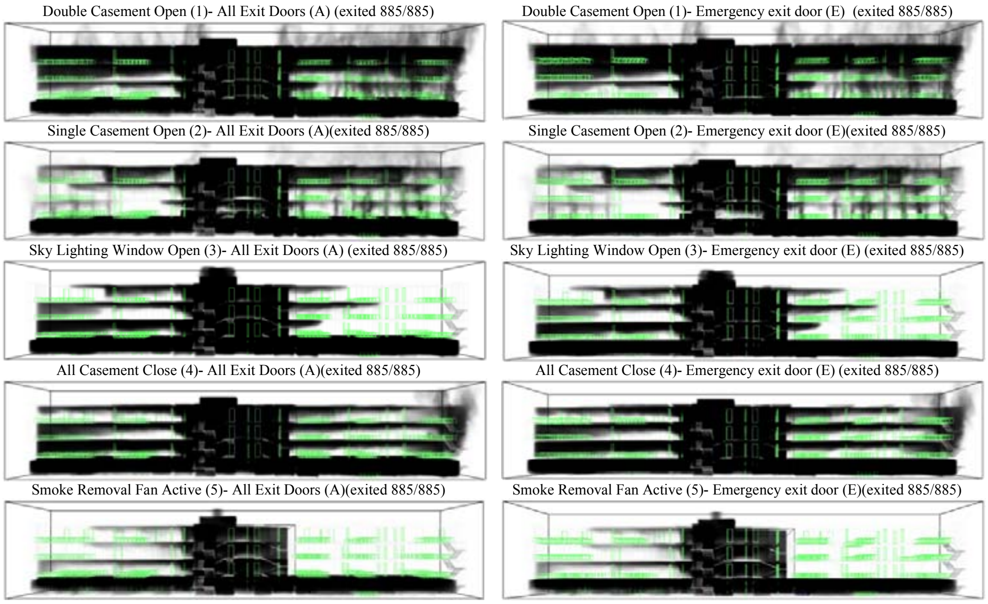
All Casement Close (4)- All Exit Doors (A)( exited 833/885)

All Casement Close (4)- Emergency exit door (E) (exited 474/885)

Smoke Removal Fan Active (5)- All Exit Doors (A)(exited 833/885)

Smoke Removal Fan Active (5)- Emergency exit door (E)(exited 474/885)

**Fig. 9. Spread of Smoke inside the Building after 250th second.**



Double Casement Open (1)- All Exit Doors (A) (exited 885/885)
Double Casement Open (1)- Emergency exit door (E) (exited 885/885)
Single Casement Open (2)- All Exit Doors (A)(exited 885/885)
Single Casement Open (2)- Emergency exit door (E)(exited 885/885)
Sky Lighting Window Open (3)- All Exit Doors (A) (exited 885/885)
Sky Lighting Window Open (3)- Emergency exit door (E) (exited 885/885)
All Casement Close (4)- All Exit Doors (A)(exited 885/885)
All Casement Close (4)- Emergency exit door (E) (exited 885/885)
Smoke Removal Fan Active (5)- All Exit Doors (A)(exited 885/885)
Smoke Removal Fan Active (5)- Emergency exit door (E)(exited 885/885)

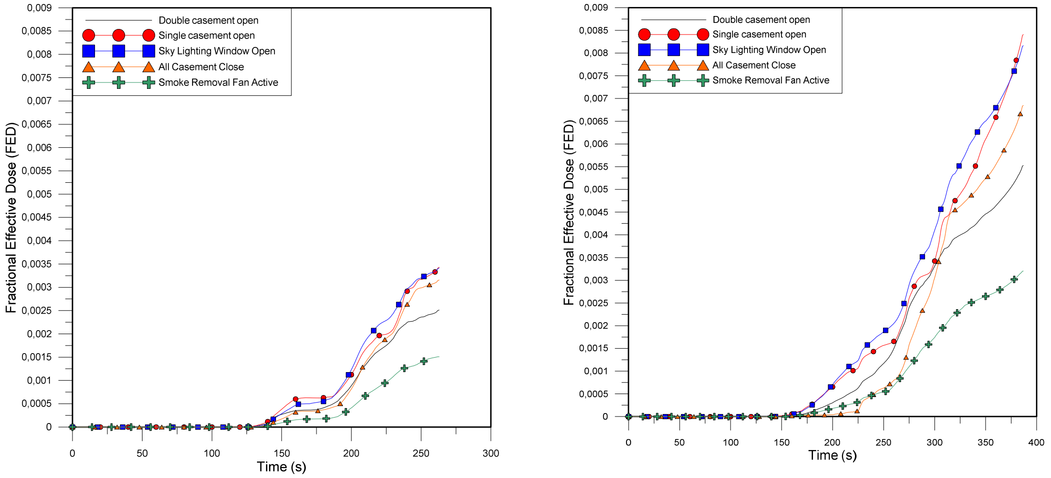
**Fig. 10. Distribution of Smoke inside the Building after 500 Seconds.**

**Table 2. Different smoke ventilation and evacuation strategies affects on max FED and exposure time.**

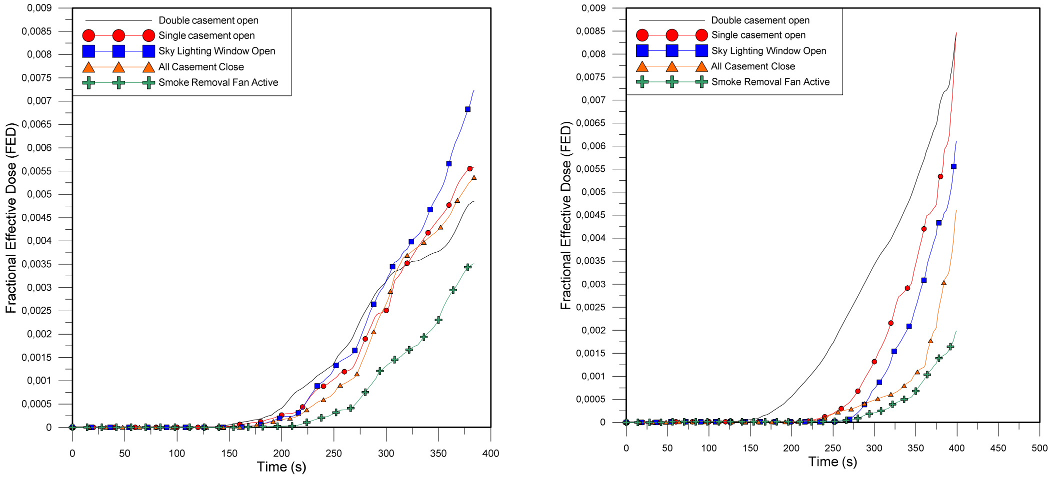
| ↓ **Evacuation Scenario** | → **Smoke Ventilation Scenario** | **Double Casement Open** | **Single Casement Open** | **Sky Lighting Window Open** | **All Casement Close** | **Smoke Removal Fan Active** |
|---|---|---|---|---|---|---|
| **(A) All Exit Doors** | Max FED<br>Exposure Time (s.) | 0,0025<br>157 | 0,0034<br>156 | 0,0032<br>162 | 0,0030<br>161 | 0,0015<br>157 |
| **(B) Rear Exit Door** | Max FED<br>Exposure Time (s) | 0.0055<br>238 | 0.0084<br>222 | 0.0081<br>205 | 0.0068<br>199 | 0.0032<br>237 |
| **(C) Front Main Exit Door** | Max FED<br>Exposure Time (s) | 0,0048<br>257 | 0,0055<br>193 | 0,0072<br>174 | 0,0053<br>178 | 0.0035<br>191 |
| **(D) Car Park Exit Door** | Max FED<br>Exposure Time (s) | 0,0084<br>267 | 0,084<br>254 | 0,0061<br>271 | 0,0046<br>271 | 0,0019<br>270 |
| **(E) Emergency exit door** | Max FED<br>Exposure Time (s) | 0,0057<br>90 | 0,0056<br>90 | 0,0056<br>90 | 0.0056<br>90 | 0.0002<br>86 |

damper was open in scenarios A, B and C, where the two wings of the windows were open in Scenario D, and in the case of smoke extraction in scenario E where the smoke extraction fan was operating. According to different human evacuation scenarios, scenario E takes the first place with the 100th Seconds when the users start to be affected by smoke. In this scenario, it is understood that in the smoke evacuation method in which only the smoke extraction fan is used, the occupants start to be affected by the smoke in about 120th Seconds. Scenario A takes second place with approximately 130th seconds. In scenarios B and C, around 160th seconds, and in scenario D, it is understood that in all scenarios except the smoke evacuation where both windows are open, around 250th seconds, users are affected by smoke. Although the time to start to be affected by smoke is essential data for human evacuation, it is known that the most critical factors in terms of smoke poisoning are the duration of exposure to smoke.

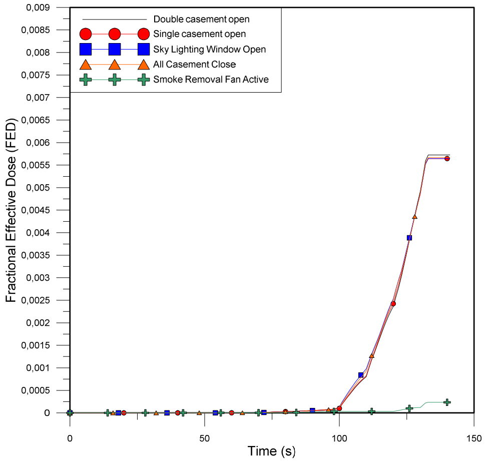
Table 2 shows exact values of different smoke ventilation and evacuation strategies effects on max FED and exposure time. When FED data are analyzed in this respect, smoke exposure times are approximately 155 seconds in scenario A, approximately 220 seconds in scenario B, approximately 210 seconds in scenario C, approximately 265 seconds in scenario D and approximately 90 seconds in scenario E. In this case, scenario E is deficient compared to other evacuation scenarios with a smoke exposure time of 90 seconds. According to all these results, it is understood that evacuation must be done through the emergency door in scenario E with the smoke extraction fan running in terms of smoke exposure rate and smoke exposure time according to FED. Furthermore, it is understood that the smoke extraction fan must be operated to provide the least amount of poisoning if an emergency door cannot be used for evacuation and other exit doors should be used.



(A) All Exit Doors (B) Rear Exit Door



(C) Front Main Exit Door (D) Car Park Exit Door



(E) Emergency exit door

**Fig. 11. FED data obtained from all smoke emission and evacuation scenarios.**

## 5. CONCLUSION

In this study, the distribution of the smoke produced in a university building in the event of a fire in the building according to five different scenarios in which the windows in the building are closed, open, semi-closed as well as the skylight window open for natural smoke evacuation and also the smoke evacuation fan are examined with CFD simulation. In addition, five different human evacuation simulations were performed using different exit doors for the same building. The data obtained from the smoke distribution simulation were transferred to the evacuation simulation and visually modeled the human exposure to smoke. In addition, the FED data of the people with the highest smoke exposure time was obtained and comparatively, the strategy that provided the most negligible impact from smoke among all scenarios was developed.

The study can be evaluated under the following headings as follows;
For the analysis results, the distribution of the smoke in the building is considerably less than in other scenarios in the simulation where the smoke evacuation fan, which is not physically present and added according to the scenario, is operated. In the light of the data obtained, it is understood that a smoke evacuation fan, which will be added to the building and activated in case of fire, can provide a significant amount of smoke evacuation. This means that the possibility of a loss of life from smoke poisoning is less than in other scenarios. In addition, it will be possible to provide intervention that is more convenient to the responsible personnel and fire brigades that intervene in the fire.

In cases where the double sashes of the windows are open, it is understood that the smoke diffuses into the building much faster. However, when the FED data were examined, it was found that in many scenarios, people, who were evacuated, decreased their smoke exposure due to the ventilation effect.

In the scenario where natural smoke evacuation takes place by opening the skylight window, it is seen that the smoke is less diffused in the building than when the windows are closed, half-open and fully closed. However, when the FED data are examined, it is understood that people are affected by more smoke in evacuation scenarios A, B and C.

It has been found that operating the smoke extraction fan ensures the lowest FED values in all smoke extraction scenarios.

In the scenario where the evacuation is performed only through emergency evacuation gates, it is understood that the last person on the ground floor is exposed to smoke in a shorter time (in 100th seconds) than other scenarios and exposed to a shorter time (90 seconds). However, in the scenario where the smoke extraction fan is operated, it is seen that the moment of encountering the smoke is later (125th seconds) but it is exposed to a shorter time (86 seconds) and at a lower dose. Therefore, it was concluded that the most effective evacuation was carried out with the scenario where emergency stairs were used and the smoke extraction fan was operated. This study shows that fire and evacuation simulations should be done and report to prepare smoke ventilation and evacuation strategies at the architectural design phase of the building. It is recommended that similar studies be carried out for buildings such as hospitals and nursing homes where people with walking disabilities are difficult to evacuate.

## ACKNOWLEDGEMENTS

This work was supported by grants from the Scientific Research Projects Unit of Sakarya University (BAP) (Project No: 2017-01-06-026).

## REFERENCES

Ahrens, M. (2016). *High Rise Building Fires. National Fire Protection Association*. Quincy, USA.

Brahim, K., B. Mourad, E. C. Afif and B. Ali. (2013). Control of Smoke Flow in a Tunnel. *Journal of Applied Fluid Mechanics* 6(1), 49–60.

Chaudhary, A., M. K. Tiwari, A. Gupta and S. Kumar (2021). Effect of ventilation on fire growth in diesel-fueled compartment fire. *Experimental Heat Transfer*, 1-21.

Chaudhary, A., A. Gupta and S. Kumar (2018). Studies on Jatropha Oil Pool Fire. *Thermal Science and Engineering Progress* 6, 104-127.

Chow, W. K. (1996). Application of Computational Fluid Dynamics in Building Services Engineering. *Building and Environment* 31(5), 425–436.

Fang, Lui, P. V. Nielsen and H. Brohus (2007). *Investigation on Smoke Movement and Smoke Control for Atrium in Green and Sustainable Buildings.* Department of Civil Engineering, Aalborg University.

Gann, R. and N. Bryner (2008). *Combustion Products and Their Effects on Life Safety*. National Fire Protection Assoc., Quincy, USA.

Gannouni, S. and R. B. Maad (2016). Prediction of CO Concentration and Maximum Smoke Temperature beneath Ceiling in Tunnel Fire with Different Aspect Ratio. *Journal of Applied Fluid Mechanics* 9(4), 1945–1953.

Gao, R., A. Li, W. Lei, Y. Zhao, Y. Zhang and B. Deng (2013). A Novel Evacuation Passageway Formed by a Breathing Air Supply Zone Combined with Upward Ventilation. *Physica A: Statistical Mechanics and its Applications* 392(20), 4793–4803.

Guo, X., J. Chen, S. You and J. Wei. (2013). Modeling of Pedestrian Evacuation under Fire Emergency Based on an Extended Heterogeneous Lattice Gas Model. *Physica A: Statistical Mechanics and its Applications*. 392(9), 1994-2006.

Hadjisophocleous, G. and Q. Jia. (2009). Comparison of FDS Prediction of Smoke Movement in a 10-Storey Building with Experimental Data. *Fire Technology* 45, 163–177.

Hall, J. R. (2011). *Fatal Effects of Fire*. Fire Analysis and Research Division National Fire Protection Association. Quincy, USA.

Hu, L. H., N. K. Fong, L. Z. Yang, W. K. Chow, Y.

Z. Li and R. Huo (2007). Modeling Fire-Induced Smoke Spread and Carbon Monoxide Transportation in a Long Channel: Fire Dynamics Simulator Comparisons with Measured Data. *Journal of Hazardous Materials* 140(1–2), 293–298.

Hurley, M. J., D. T. Gottuk, J. R. Hall and K. Harada. (2015). *SFPE Handbook of Fire Protection Engineering*. 5th ed. Springer.

Jafari, M. J., A. Karimi, A. E. Usachov and H. K. Moghaddam. (2011). The Fire Simulation in a Road Tunnel. *Journal of Applied Fluid Mechanics* 4(1), 121–138.

Jeong, B. J. (2014). *Combination of CFD and evacuation models for determination of FED and FEC levels*. MSc thesis, the Lund University, Lund, Sweden.

Jie, J., L. Kaiyuan, Z. Wei and H. Ran. (2010). Experimental Investigation on Influence of Smoke Venting Velocity and Vent Height on Mechanical Smoke Exhaust Efficiency. *Journal of Hazardous Materials* 177(1–3), 209–215.

Kerber, S. and J. A. Milke (2007). Using FDS to Simulate Smoke Layer Interface Height in a Simple Atrium. *Fire Technology* 43(1), 45–75.

Li, L. J., J. Ji, C. G. Fan, J. H. Sun, X. Y. Yuan and W. X. Shi (2014). Experimental Investigation on the Characteristics of Buoyant Plume Movement in a Stairwell with Multiple Openings. *Energy and Buildings* 68(Part A): 108–120.

Lim, H. C. (2020) Numerical Study on Natural Ventilation around a Burning Car inside a Tunnel. *Journal of Applied Fluid Mechanics* 14(4), 1065-1076.

Lou, B., Y. Qiu and X. Long. (2017). Maximum Smoke Temperature in Non-Smoke Model Evacuation Region for Semi-Transverse Tunnel Fire. *Journal of Applied Fluid Mechanics* 10(4), 1139–1151.

Mcgrattan, K., S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk and K. Overholt (2015). *Fire Dynamics Simulator User's Guide*. National Institute of Standards and Technology, USA.

NUREG/CR-6850 (EPRI 1011989), EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, 2005.

NUREG/CR-7010, Cable Heat Release, Ignition, and Spread in Tray Installations during Fire (CHRISTIFIRE), Phase 1: Horizontal Trays, National Institute of Standards and Technology, Gaithersburg, MD, 2012.

Oven, V. A. and N. Cakici (2009). Modelling the Evacuation of a High-Rise Office Building in Istanbul. *Fire Safety Journal* 44(1), 1–15.

*Pathfinder Software* (2019). Linked at https://www.thunderheadeng.com/pathfinde.

Purser, D. A. (2003). *Toxicity Assessment of Combustion Products*. In SFPE Handbook of Fire Protection Engineering, Quincy, USA.

Pyrosim Software (2019) Linked at https://www.thunderheadeng.com/pyrosim/.

Qu, X., Q. Meng and Z. Liu (2013). Estimation of Number of Fatalities Caused by Toxic Gases Due to Fire in Road Tunnels. *Accident Analysis and Prevention* 50, 616–621.

Shen, T. S., Y. H. Huang and S. W. Chien (2008). Using Fire Dynamic Simulation (FDS) to Reconstruct an Arson Fire Scene. *Building and Environment* 43(6), 1036–1045.

Zhang, X., X. Wang and Y. Zhou (2011). Numerical Simulation Study on Bus Fire. *In 2011 International Conference on Remote Sensing, Environment and Transportation Engineering*, IEEE, Nanjing, China.

Xu, Z., X. Lu, H. Guan and A. Ren (2014). A Virtual Reality-Based Fire Training Simulator with Smoke Hazard Assessment Capacity. *Advances in Engineering Software* 68, 1–8.

Yan, G., M. Wang, L. Yu, R. Duan and P. Xia (2020). Effects of Ambient Pressure on Smoke Movement Patterns in Vertical Shafts in Tunnel Fires with Natural Ventilation Systems. *Building Simulation* 13, 931-941.

Yang, P., C. Li and D. Chen (2013). Fire Emergency Evacuation Simulation Based on Integrated Fire-Evacuation Model with Discrete Design Method. *Advances in Engineering Software* 65, 101–111.

Yang J., X. Pan, Z. Wang, M. Hua and J. Jiang (2018). Numerical Study on the Smoke Flow Characterization and Phenomenon of Plug-Holing under Lateral Smoke Exhaust in Tunnel Fire. *Journal of Applied Fluid Mechanics* 11(1), 115-126.

Zhang, X.G., Y.C. Guo, C.K. Chan and W.Y. Lin (2007). Numerical Simulations on Fire Spread and Smoke Movement in an Underground Car Park. *Building and Environment* 42(10), 3466–3475.

Zhang W., N. Ryder, R.J. Roby and D. Carpenter (2001) Modeling of the Combustion in Compartment Fires Using Large Eddy Simulation Approach. In Proceedings of the 2001 Fall Technical Meeting, Eastern States Section. Combustion Institute, Pittsburgh, Pennsylvania, December.

Zhao, G., T. Beji and B. Merci. (2017). Study of FDS Simulations of Buoyant Fire-Induced Smoke Movement in a High-Rise Building Stairwell. *Fire Safety Journal* 91, 276–283.

Zou, G. W. and W. K. Chow (2005). Evaluation of the Field Model, Fire Dynamics Simulator, for a Specific Experimental Scenario. *Journal of Fire Protection Engineering* 15(2), 77–92.