Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 45 No. 1
January 2024

Numerical Modeling and Simulation of Parking in a Commercial Building

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Abstract - The investigation of fire incidents in the parking area of the commercial building was conducted using the Fire Dynamic Simulator code (FDS), which simulated different fire scenarios. The fire safety requirements for parking facilities were determined under various ventilation system conditions. Various parameters of the parking stairwell were compared under different conditions. The measurements were acquired at a elevation of 1.6 meter. The finding indicated that, within the first state, the temperature, visibility, and smoke concentration reached 80°C, 1 meter, and 0.003mole/mole, respectively, approximately 1200 second after the start of the fire. In the second state, the visibility reached 6.34 meters within a duration of 1200 seconds, representing 6.34 times improvement compared to the first state. During the 1200s, the temperature also decreased to 51.11°C. The temperature improved by 36.19% in comparison to its first state. During 1200s, the concentration of smoke reached 0.0002mole/mole, representing a 93% improvement compared to the first state. In the third state, following the 1200s, the temperature decreased 44.72°C. Additionally, the visibility in the third state was measured at 15.59m, representing 15.59 times improvement compared to the first state. In the third state, the concentration of smoke was measured at 0.00006 mole/mole in the 1200s, representing a 57.5% improvement compared to the first state.

Keywords: FDS; Fire scenarios; Ventilation system; Temperature; Visibility; Smoke Concentration.

Introduction: In today's advanced life, with urban development and population growth, many large commercial or residential buildings have been built. Closed car parks are used in the basement of these buildings [1]. During a fire in a closed parking lot, a significant quantity of hot smoke is produced, which makes evacuation necessary measure. In addition, car exhaust contains dangerous gases such as carbon monoxide. In this parking lot, the air is heavily polluted by exhaust gases from cars [2]; if a fire happens in these parking, in addition to the toxic gases from vehicles, the smoke from the fire, which contains toxic materials such as monoxide carbon, will cause people's death [3]. It is vital to investigate fires in closed parking lots and to simulate smoke. The purpose of fire simulation is to maintain the safety of residents to prevent casualties during a fire. In addition to heat and smoke, combustion also produces gases. The volume of hot gases in a closed space rises rapidly and fills the room. When a person is placed in an area full of smoke and heat, irreparable effects are brought to the person's body [4]. In 2001, vehicle fires in tunnels with various ventilation systems were simulated. The simulations showed vehicle fires caused by vital forced ventilation were ten times more prominent than natural ventilation [5]. In 2014, Zhang experimentally developed a method for predicting the temperature of smoke from fires in large spaces. It was found that by choosing the appropriate shape factor for the desired model, it is possible to predict the smoke temperature caused by fire in wide spaces [6].

In 2016, fire suppression of commercial buildings with sprinkler system was analyzed. In the paper, to investigate the fire of a large commercial complex with different fire scenarios, different activation modes of the sprinkler were studied numerically. The simulation results show that the sprinkler prevents the spread of fire at the very beginning of the fire, because the decomposition of combustible materials is controlled by heat, the fire slows down, and the evacuation time of people increases [7].

In 2017, Dionysios et al. observed the behavior of gypsum walls in a fire in a residential building using FDS. When gypsum is exposed to high-temperature environment, it leads to water vaporization and the dispersion occurs in the affected premise. In this research, the particular phenomenon was simulated by using FDS. The obtained results showed that when the dehydration phenomenon of very heat-absorbing gypsum is simulated, reducing the heat release and smoke temperature and wall surface temperature can be predicted [8].

In 2018, a fire was simulated in a garment factory [9]. The results showed that after 6s from the start of the fire, the smoke spread on the floor and stairs and reached the upper floors, and after 170.6 seconds, the situation became critical for the residents of the building.

In 2019, Erdelyiova et al. investigated the fire risks in multi-step parking with steel structure. They determined the temperature of the steel beams in the building that were not protected. To determine the temperature, the roof beam was tested and the maximum fire temperature was obtained. To solve the problem, they used 3D finite element models to measure temperature and get the structural analysis of the building [10].

With the advancement of technology, various numerical simulations are used by engineers. In 2019, Jianyong Shi et al. used Building Information Modeling (BIM) in numerical fire simulation in the Industry Foundation Classes (IFC) and Fire Dynamics Simulator (FDS) [11]. They studied a gym and compared the results. The results showed that using BIM models in the numerical simulation of fire results in more accurate calculations.

In 2019, Barsim et al. investigated an underground parking fire with the presence of impulse ventilation [12]. One of the things investigated was visibility due to fire. Visibility is a parameter that is very effective when evacuating people. They used a relationship for visibility. The results showed the accumulation of hot gases between cars, when the particular location was facing the wind, were increased the likelihood of occurrence fire.

Due to the importance of preserving thermal energy, air-tight buildings became very important. For this reason, fire in these buildings was noticed. In 2020, Brohez and Caravita built a laboratory setup to investigate fire hazards in these buildings and then used the laboratory results to validate the numerical simulation results in FDS. They check out the influence of the pressure and ventilation system on the fire [13].

In 2020, a devolatilization model was used to simulate small tunnel experiments with variable ventilation rates in unit fire boards as a fuel source. Decomposition behavior was effectively described, and optimized values were developed numerically [14].

In 2020, a numerical analysis of the fire caused by pressure changes was performed in an air-tight enclosure with ventilation devices. The pressure in the next room becomes so high that it becomes difficult to evacuate people. To reduce the pressure in the neighbor room, the leakage level at the bottom of the door between this room and the fire room is reduced, but this increases the pressure levels in the fire room [15].

In 2020, Sittisak et al. investigated the removal of carbon monoxide with different jet fan arrangements in an underground parking lot [16]. They measured the amount of carbon monoxide in the parking lot with the presence of a jet fan. The results displayed that the ventilation efficiency improved with the presence of the jet fan. A jet fan can eliminate the harmful effects of carbon monoxide by reducing its amount.

In 2020, smoke spread on a staircase was studied. In this study, the effect of external wind was considered. Wind flows through broken windows in the building and affects the spread of smoke. The results showed that the ascent speed of the plume (smoke mass) increases to a certain height with the wind speed. Figures for concentration of carbon monoxide were increased by 15% considering wind speed, which poses a significant danger to victims [17]. In 2021, the smoke expansion system was optimized in fire scenarios using a computational fluid dynamics model. The study provided guidelines for designing fire-safe buildings and evaluating their performance [18].

In 2021, Iringova and Vandlickova analyzed the thermal stress on the structure of a parking lot according to the laws of European countries [19]. With urban development, the risk of fire in parking lots increases. Obtaining the maximum temperature and the emission of fire-resistant smoke are essential issues that are taken into considered. In the research, they considered different types of cars with varying volumes of fuel. According to the considered cases, they determined how much of the parking space should be regarded as open in each case so that nothing happens to the people living in the parking lot.

In 2023, Lee et al. used Fire Dynamic Simulator (FDS) to validate the experimental results for different liquid pool fire scenarios in multiple compartments. They used a pyrolysis model for simulation. The output data from the FDS model and the experimental data were compared [20].

According to previous researches, the study of visibility, temperature profile, and smoke concentration on people's exit stairs has not investigated. For this reason, in this research, the effect of fan system on the temperature and visibility on the stairwells at a height of 1.6m were investigated.

Equation: Simulating fire was done in different situations and places using Fire Dynamics Simulator code. It studies the heat flow numerically by solving the equations set. The simulations in this article were done using the computational fluid dynamics code of FDS 6.7.9. One of the methods of examining turbulent flows is the simulation of large eddies. The equations are given below [21]:

- Continuity:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j)=0 \qquad (1)$$

- Momentum:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{u}_i)+\frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j\tilde{u}_i\right)=-\frac{\partial(\bar{P}-\overline{P_0})}{\partial x_i}+\bar{\rho}g_i\delta_{i3}+\frac{\partial}{\partial x_j}\left\{\mu\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial\tilde{u}_k}{\partial x_k}\right)\right\}+\frac{\partial\tau_{ij}}{\partial x_j} \qquad (2)$$

- Energy equation:

$$\frac{\partial}{\partial t}\left(\bar{\rho}C_p\tilde{T}\right)+\frac{\partial}{\partial x_j}\left(\bar{\rho}C_p\tilde{u}_j\tilde{T}\right)=\frac{\partial\overline{P_0}}{\partial t}+\frac{\partial}{\partial x_j}\left(k\frac{\partial\tilde{T}}{\partial x_j}\right)+\frac{\partial h_j}{\partial x_j}+\bar{q}_c+\bar{q}_r \qquad (3)$$

The parking is located in a commercial complex. The visibility and the temperature profiles in the parking fire were investigated. Parking space has dimensions of 48m×19m ×3m. Figure.1 shows schematic of parking. It is very important to check the stairs because people escape during the fire. Due to the importance of the stairs, the temperature measuring devices were placed on the first and third stairs.

According to firefighting standards, to simulate a fire in the close parking, the amount of heat released in the sample fire must be 4 MW. Hence, according to previous research, a fire with dimensions of 1m ×1m and heat release 4000kW/m² was considered in the northern part of the car park.

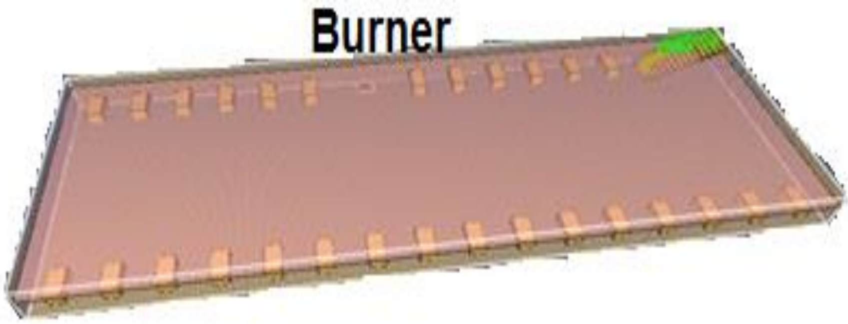

Fig.1. The parking geometry

Choosing the suitable grid size is very important in getting the accurate results. The ratio of the fire characteristic diameter to grid size, $D^*/\partial x$ is a measure of grid resolution. The grid size is considered between 0.1m and 0.6m. The temperature solution results were compared with each other in 120s. The temperature was showed at Fig.2. As can be seen from the figure, in the sizes 0.2m and 0.1m, the diagrams are almost aligned. Therefore, the solution was done for meshing with size 0.2m.

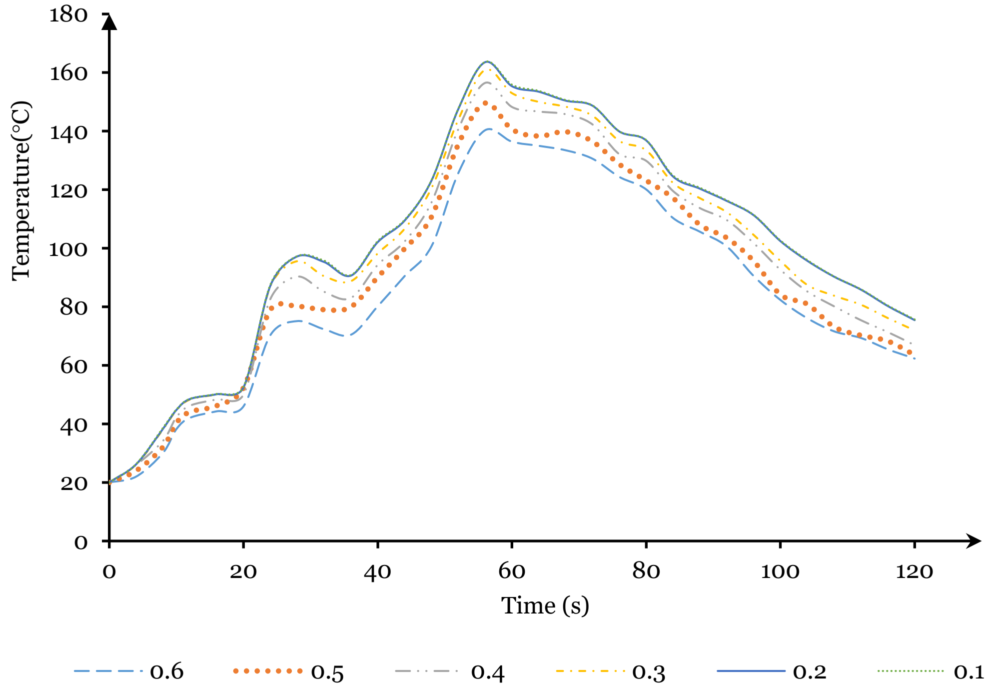

Fig.2. Temperature profiles in different mesh sizes

Validation: To check the results of the simulation, the results reported in this paper were compared to the experimental results of Ji [22]. In the research, a geometry using 1.5×2×0.5 meters is considered. Burned in the methane chamber, the surface of the fire source was 0.2m×0.2m, and the amount of heat released was 235 kilowatts per square meter. According to research data, simulation was done and compared with the results of laboratory data. The geometry used in validation can be seen in Fig.3.

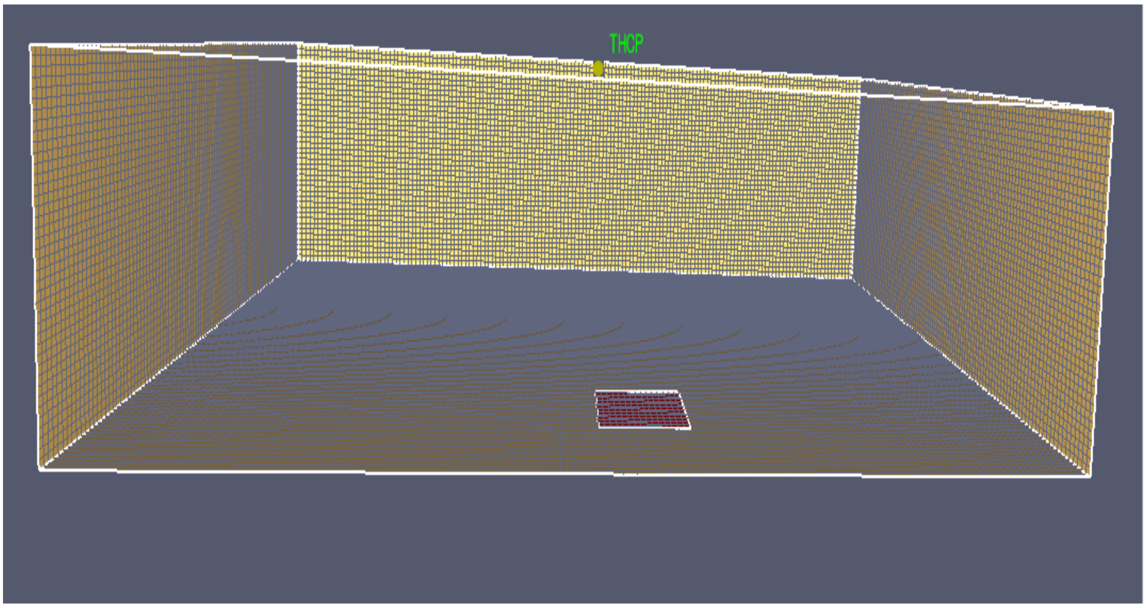

Fig.3. Simulated geometry to validate the results

To compare the results of the temperature, the fire temperature results were obtained in 600 seconds and compared to the results of Ji's paper. The temperature profile is shown in Fig.4. According to the obtained results; it was observed that the simulated temperature values are close to the experimental temperature values and have an error of 10.6% compared to the laboratory values.

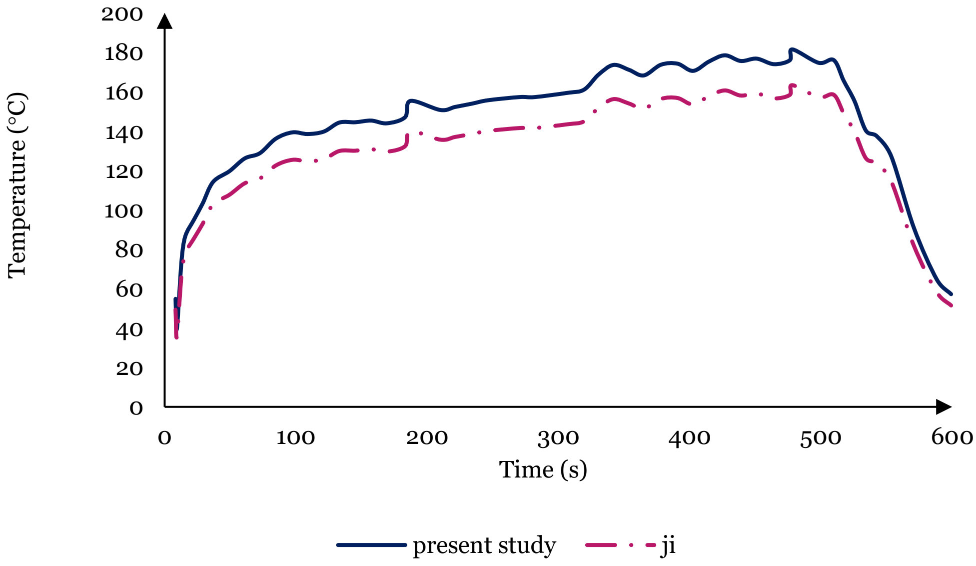

Fig.4. Comparison of the temperature profile in the present study and the Ji' paper

Result: In this study, three scenarios have been considered to investigate the fire. The first scenario, parking without ventilation was considered. In the second scenario, the parking lot was considered with a traditional ventilation system. In this case, a supply fan is used to dilute the smoke, and an exhaust fan is used to evacuate the smoke. The supply fan is on the south wall, and the exhaust fan is on the north wall. In the last scenario, parking with a Jet fan was considered. The jet fan used in the parking lot is F300 type, which withstands temperatures up to 300°C. The jet fan is located in the middle of the roof of the parking lot. The temperature and the smoke concentration profiles were obtained in all three scenarios for 1200 seconds.

In this study, to simulate fire, air exchange was considered ten times. All fans must be selected to resistant 300°C for one hour. The capacity of the supply fan should be 50% -75% of the exhaust air, so that the parking pressure remains negative. Negative parking pressure prevents parking air from penetrating other parts of the building. In this study, the capacity of the supply fan was considered to be 50% of the exhaust air.

In this study, the first scenario, parking without ventilation was considered. In the second scenario, the parking with traditional ventilation system was considered. In the last scenario, parking with Jet fan was considered. The temperature and the visibility profiles were obtained in all scenarios for 1200s.

The temperature of the stairs in the parking is very important. In fig.5, the temperatures of the stairs are compared in different scenarios. In the first scenario, the temperature is initially 20°C. With the start of the fire, this value increases to about 96°C in 600s, and then decreases to 80°C when the simulation is finished. In the second scenario, the temperature will increase to 87°C in 600s, but with the activation of the exhaust fans and supply fan, after 900s, the temperature will reach 70°C. It decreases to 51.11°C in 1200s. In the third scenario, where the jet fan is active, in 600s the temperature rises to 86.8°C, and after 900s it drops to 74.2°C, and in 1200s to 44.72°C.

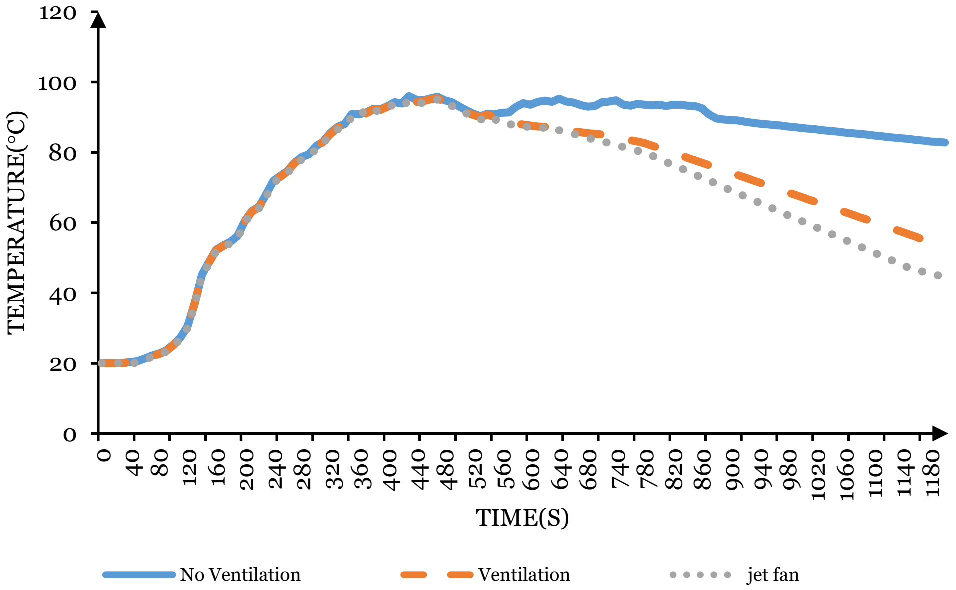

Fig.5. Temperature profiles in three scenarios

Visibility is the amount of distance that a person can see during a fire. In Fig.6, visibility in three different scenarios is contrasted. Visibility was 30m before the fire start. With the start of fire and the spread of smoke, this amount decreases to 1m in 30s. A person who is placed in a parking without ventilation, does not see the right way to escape. In the second scenario, in 30s the amount of visibility decreases to 1m, but with the activation of the fans, the visibility increases after 550s. It reaches 6.34m in 1200s. In the third scenario, the visibility decreases to 1m, but when the jet fan is activated, it reaches 15.59m in 1200s.

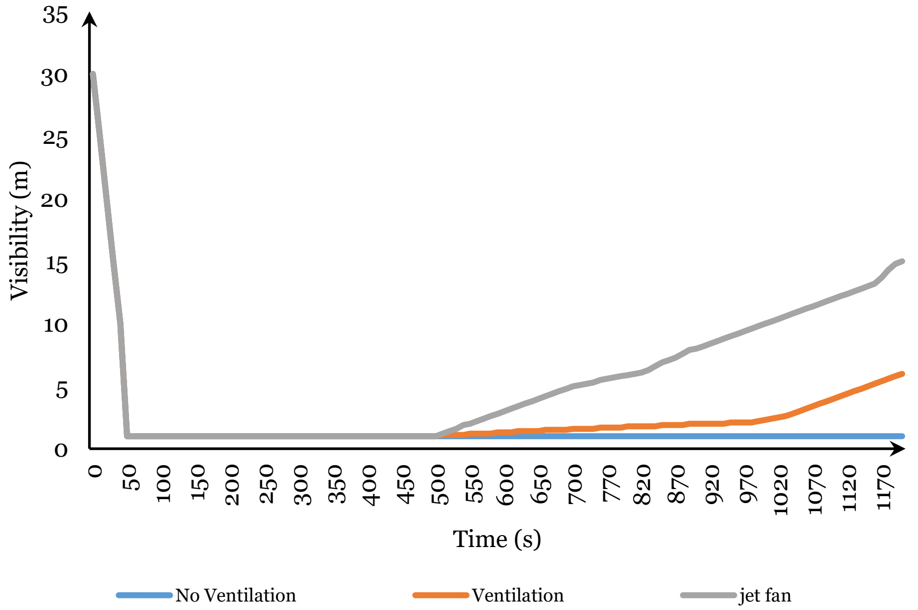

Fig.6. Visibility profiles in three scenarios

The smoke fills the entire parking space. In most cases of fire, the deaths are due to respiratory poisoning. Therefore, it is paramount to check the smoke and temperature profiles after the start of the fire. Fig.7 compares the concentrations of smoke in the three scenarios. Sensors in the stairwell measure concentration of smoke and temperature. In the absence of ventilation, it is evident that the smoke concentration increases to 0.003mole/mole. In the second case, when ventilation takes place and the smoke exhaust fan starts working after 30 seconds, the amount of smoke increases to about 0.003 mole/mole, and then with the exhaust smoke and the entry of fresh air by the supply fan, the amount of smoke decreases to about 0.0002 mole/mol. In the third case, when ventilation occurs and the jet fan starts working after 30 seconds, the amount of smoke increases to about 0.003 mole/mole, as in the second scenario, and then, over time, the amount of smoke decreases to about 0.00006 mole/mol. It can be seen that in the third scenario, the smoke is significantly reduced by using a jet fan.

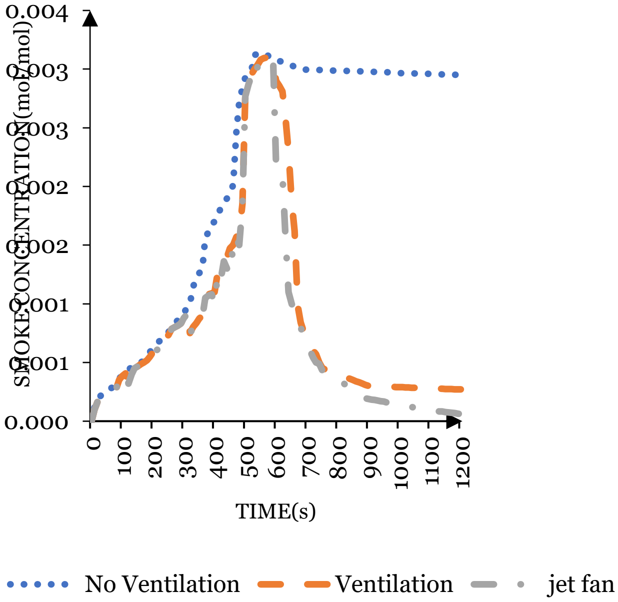

Fig.7. Diagram of smoke concentration in the three scenarios

Discussion: In this study, visibility, temperature profiles, and smoke concentration in parking were investigated. Three different scenarios were defined. In the first scenario, the parking is no ventilation. In the second scenario, parking was provided with ventilation. In the last state, Jet-fan was used for ventilation. The purpose of this article was to investigate the effect of ventilation system on visibility, temperature profiles, and smoke concentration stairwell at a height of 1.6m during fire. In the desired space, fire was simulated with heat release 4MW and at 1200s. Visibility, temperature, and smoke concentration were compared in three scenarios. According to the obtained results, it was found that in the first scenario, before the fire visibility was 30m. After the fire, the visibility decreased to 1m. In the second scenario, the visibility increased to 6.34m and improved 6.34 times. In the third scenario, the visibility increased to 15.59m, which improved by 15.59 times compared to the first scenario. In the first scenario, the temperature was initially 20°C. After the start of the fire, the temperature increased to 96°C, it reached 80°C at the end of the fire investigation. In the second scenario, the temperature increased to 87°C, but after 900s, it decreased to 70°C and at 1200s, it reached 51.1°C, which improved by 36.12% compared to the first scenario. In the third scenario, using a jet fan, the scenario, using a jet fan, the temperature reached 86.8°C after 600s, and after 900s it decreased to 74.2°C, and at 1200s it reached 44.72°C that compared to the first scenario, it has improved by 44.1%. . According to the obtained results, it was found that in the first scenario, after the fire, the smoke concentration increases to 0.003mole/mole and the increase in smoke concentration is a severe danger for people in the parking. In the second scenario, with the activation of the exhaust fan, the smoke concentration decreased to 0.0002mole/mole and improved by 93%. In the third scenario, using Jet fan, over time, the amount of smoke decreases to about 0.00006 mole/mole, which improved by 98% compared to the first scenario and 70% compared to the second scenario.

References

[1] F. a. R. A. Behnamfar, "A fire ignition model and its application for estimating loss due to damage of the urban gas network in an earthquake," *International Journal of Engineering,* pp. 1507-1519., 2016.

[2] F. R. G. V. V. a. B. R. Colella, "Multiscale modeling of transient flows from fire and ventilation in long tunnels," *Computers & Fluids,* pp. 16-29, 2011.

[3] B. J. A. a. M. H. S. Pordel Maragheh, "Effect of initial local failure type on steel braced frame buildings against progressive collapse," *International ournal of Engineering,* pp. 34-46, 2020.

[4] A. A. N. a. A. P. Varghese, "Influence of fiber on shear behavior of concrete exposed to elevated temperature," *International Journal of Engineering,* pp. 1897-1903, 2020.

[5] R. B. A. J. P. Carvel, "The influence of longitudinal ventilation systems on fires in tunnels," *Tunnelling and Underground Space Technology,* pp. 3-21, 2001.

[6] G.-w. Z. G.-q. a. Y. F. Zhang, "A whole process prediction method for temperature field of fire smoke in large spaces," *Procedia Engineering,* pp. 310-315, 2014.

[7] X. M. J. S. Y.-x. a. L. L.-y. Ye, "Suppression effect of sprinkler system on fire spread in large commercial buildings," *Procedia Engineering,* pp. 455-462, 2016.

[8] E. K. A. M. A. F. Dionysios I. Kolaitis, "Fire behaviour of gypsum plasterboard wall assemblies: CFD simulation of a full-scale residential building," *Case Studies in Fire Safety,* pp. 23-35, 2017.

[9] M. M. R. M. M. a. R. M. Khandoker, "Numerical simulation of fire in a multistoried ready-made garments factory using pyrosim," in *in AIP conference proceedings*, 2018.

[10] B. L. M. I. Romana Erdélyiová, "Risk and the result of the fire in multistorey car park," in *13th International Scientific Conference on Sustainable, Modern and Safe Transport*, Slovak Republic, 2019.

[11] J. D. L. J. a. Z. P. Jianyong Shi, "Research on IFC- and FDS-Based Information Sharing for Building Fire Safety Analysis," *Hindawi,* pp. 1-18, 2019.

[12] M. A. B. H. M. E.-B. Y. A. R. M. Mohsen M. Barsim, "Performance of impulse ventilation system in an underground car park fire: Case study," *Journal of Building Engineering,* pp. 1-25, 2019.

[13] I. C. S. Brohez, "Fire induced pressure in airthigh houses: Experiments and FDS validation," *Fire Safety Journal ,* pp. 1-15, 2020.

[14] X. F. C. a. S. M. Wang, "Applying the fds pyrolysis model to predict heat release rate in small-scale forced ventilation tunnel experiments," *Fire Safety Journal,* p. 102946, 2020.

[15] J. B. T. B. S. a. M. B. Li, "Cfd study of fire-induced pressure variation in a mechanically-ventilated air-tight compartment," *Fire Safety Journal,* p. 103012, 2020.

[16] T. C. B. C. Pornthep Sittisak, "Enhancement of carbon monoxide removal in an underground car park," *Tunnelling and Underground Space Technology,* pp. 1-10, 2020.

[17] J. Z. L. D. L. Y. L. a. W. H. Ji, "Numerical investigation of external wind effect on smoke characteristics in a stairwell," *Fire Technology,* pp. 1681-1702, 2020.

[18] T. S. E. S. F. G. V. a. C. L. Baalisampang, " Optimization of smoke extraction system in fire scenarios using cfd modelling," *Process Safety and Environmental Protection,* pp. 508-517, 2021.

[19] D. V. Agnes Iringová, "Fire safety of an over ground car park building – model solution," in *14th International scientific conference on sustainable*, 2021.

[20] B. K. S. L. W. G. S. Jaiho Lee, "Validation of the fire dynamics simulator (FDS) model for fire scenarios with two liquid pool fires in multiple compartments," *Fire Safety Journal,* p. 103892, 2023.

[21] X. G. Y. C. C. a. L. W. Zhang, "Numerical simulations on fire spread and smoke movement in an underground car park," *Building and environment,* pp. 3466-3475, 2007.

[22] Y. C. Z. K. J.Ji, "An Experimenal Investigation on Thermal Characteristics of Sidewall Fire in Corridor-like Structures With Varying Width," *Heat Mass Transf,* pp. 562-570, 2015.