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NUMERICAL ANALYSIS OF SMOKE AND HEAT CONTROL FOR FIRE SCENARIO IN AN UNDERGROUND CAR PARK

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ABSTRACT

When ventilation installation is designed in a car park, two main elements should be considered. There are discharge of harmful vehicle exhaust gases and discharge of smoke to outside environment under possible fire scenario. For this purpose, recently, jet fan ventilation systems are commonly preferred to discharge the smoke to sustain the ambient air within breathable limits under possible fire scenario in closed environments such as tunnels, car parks, metro stations etc. Instead of traditional ventilation methods, these systems are preferred due to easy mounting and higher efficiency. In this study, a car park with 50m x 50m x 3m dimensions was used for simulating ventilation with jet fans under fire scenario. Analyses were repeated for different fan flows and different fire sizes. Accordingly, for the first 360 seconds that the fire is the most effective and first aid is necessary, temperature, smoke, and air speed distributions for time and locations were identified inside the car park.

Key words: Fire, Heat release rate, Smoke and heat control, Jet fans, Car parks

1. INTRODUCTION

Today, in line with population growth in large cities, numbers of vehicles in these cities are increasing. This causes finding parking space problem in limited areas. Especially, in areas such as city centre, cinema, theatre, airport, and shopping malls that has high number of people, this problems is tried to be solved with multi storey car parks. However, this causes other problems. In any fire scenario in these crowded environments, to evacuate people in safe way, there is need for effective car park ventilation system. In short, high number of visitors in car parks increased the importance of smoke extraction system that should be active in case of emergency under fire scenario increases.

Smoke extraction systems are designed for easier and effective evacuation and intervention by firefighters in case of fire emergency. Since multiple storey car parks are located in basement floor of buildings, these garages have no openings such as windows or doors to outside environment that enables natural ventilations. Therefore, in case of fire, smoke cannot be extracted with natural methods. In such cases, in short time, complete car park volume can be filled with smoke created as a result of burning reaction. In short, extraction of people inside car park and intervention of firefighters become impossible. For this purpose, jet fans used in car park ventilation captures smoke during fire in certain area and offers great advantage for excavation and fire intervention. Literature review regarding car park fire scenario and smoke control was conducted and related studies are presented below.

Deckers et al. (2013) experimentally analysed full-scale possible fire scenario in large car park. Parameters such as heat release rate (HRR) and smoke output flow were changed, and temperature and smoke distribution were analysed. In another study (Deckers et al., 2013) in line with this study, numerically analysed smoke control under fire scenario in car park. Different simulations were conducted for different HRR ratio, smoke extraction flow, input air apertures, and number of beams in the space. This way, under fire conditions, effect of smoke and heat control system (SHC) on smoke motion was observed. For 4 MW fire, it was determined that air speed should be approximately 1.1 m/s. If there are beams in the space, authors stated that average air speed should be higher. Merci and Shipp (2013) focused on smoke and heat control for fires in car parks. For this purpose, different aspects of smoke and heat control (SHC) systems were evaluated in terms of smoke and heat dynamics based on information provided in previous studies.

Khalil and Gomaa (2017) numerically analysed jet fan use in car park for smoke extraction with Ansys Fuent 14.0 package program. Authors compared obtained CFD results and correlations. As a result, it was determined that temperature increase was limited with fire origin region. Authors determined that temperature distribution observed in car park was within acceptable range. Additionally, based on CO2 propagation, simulations to decrease smoke intensity with jet fans was conducted. Authors expressed that dividing car parks is necessary for smoke control. Horváth et al. (2013) numerically analysed smoke motions under fire scenario in a car park. Based on the obtained data, authors analysed smoke and fire characteristics within car park.

Viegas (2010) conducted numerical studies to offer ventilation solutions to underground car parks and smoke control under fire scenario. For this purpose, simulations were conducted by changing fire source location, fire intensity, distances between jet fans, exhaust outlet speed, and dimensions of exhaust outlet aperture. As a result, design parameters were analysed for optimum smoke control and ventilation. Lu et al. (2011) numerically analysed possible fire scenario in underground car par with IVS (impulse ventilation system) control. For different number of jet fan, jet fan speed, extract rate, and fire positions, analysis were conducted with Fire Dynamic Simulator 5.30 package program. As a result, authors determined that using jet fans prevented smoke propagation in car park as well as provided clear view for intervention to fire. However, for extremely high jet fan speeds, authors observed that there was intense smoke circulation inside car park. Tilley et al. (2012) numerically analysed the relationship between ventilation speed and smoke blowback distance for large car park. Authors conducted simulations by changing heat dissipation ratio, area of fire source, height of car park, and width of car park. As a result, for car park with flat ceiling and single-way ventilation, authors formulated equations for smoke speed and blowback distance.

Yuan et al. (2011) numerically analysed sprinkler system and impulse ventilation system in an underground car park. As a result, authors suggested that using jet fans decreased smoke on top part of fire, thus, intervention may be easier. Authors observed that when jet fans are used with sprinkle systems, fire intervention was more effective. Deckers et al. (2010) numerically analysed effects of forced mechanic ventilation in car park on smoke motion in possible fire case. For this purpose, different simulations for different fire scenarios were conducted with OpenFoam and Fire Dynamics Simulator (FDS 5) package programs. Authors tried to determine effects of ventilation flow speed, distance of fire source to wall, and existence of neighbouring cars on created flow area. Márton et al. (2015) modelled a fire in open car park with Fire Dynamic Simulator (FDS). Authors observed that propagation of fire inside the car park was significantly related with geometric sequence of cars in the car park. Authors determined that distance between cars had significant effect on fire propagation speed. Especially, when distance between two parked cars was 40-60 cm, fire can propagate faster than 12 minutes.

Zhang et al. (2007) numerically analysed car fire propagation and smoke motions in an underground car park. For this purpose, a large underground car park was determined, and different fire scenarios were analysed with Fire Dynamic Simulator code. Authors identified that fire in car park developed in four stages. These four stages were starting stage, development stage, extinction and reignition stage, and new development stage respectively. Authors determined that after certain time passed from the start of fire, the fire consumed oxygen inside and transferred to extinction stage. However, with ventilation, as fresh air is supplied to car park, fire accelerated and transferred to reignition stage. Hsu et al. (2017) modelled fire in an underground car park with Fire Dynamic Simulator. Authors investigated effects of mechanical ventilation system on development of smoke layer inside car park. After the analysis, authors determined that using mechanical ventilation system delayed smoke accumulation time inside car park where this provided additional time for people to evacuate car park. However, as mechanical ventilation system supplied fresh air inside the car park, size of fire increased accordingly. Alianto et al. (2017) numerically modelled fire smoke control in underground car park with Fire Dynamics Simulator (FDS) 6.0 software. For this purpose, a three-storey basement with 60 x 30 x 3 m dimensions was modelled. In a fire with 2MW fire release rate (HRR), analyses were conducted for different fire scenario. As a result, authors determined optimum design parameters for their system.

Schoor et al. (2013) analysed risk created by LPG (liquefied petroleum gas) vehicles in car park with FLACS that is a specialised CFD analysis program. For this purpose, in a car park with 30 x 30 m dimensions and LPG fuelled vehicles, 26 different event scenario were tested. Based on analysis results, authors identified that 70 litre LPG fuel tank can create 200 m^3 vapour cloud inside car park. To dilute this vapour cloud in fast way, authors expressed that there is need for 0.060m^3/s ventilation flow speed for each square meter area of car park. Li et al. (2017) experimentally analysed smoke temperature and fire propagation resulting from burning full-scale test car. For this purpose, two full-scale sedan vehicles were parked side by side and propagation of fire to adjacent vehicle was observed. In their study, authors determined that fire jumped to second vehicle, 20 minutes after the fire started in first vehicle. Authors expressed that temperature inside the vehicle reached 900 ^oC. Smoke temperature was measured between 89-285 ^oC.

2. DEFINITION OF THE PROBLEM AND MATHEMATICAL FORMULATION

In this study, ventilation and smoke control simulation by using jet fans under fire scenario in underground car park was numerically conducted with FDS software. There simulations were repeated for different fan flow and different fire sizes for an empty car park. Since first 360 seconds is the critical period where the fire has highest effect and critical time for evacuation of people, temperature, smoke and air speed distribution within car park were determined for time and location.

Top view of analysed problem geometry was schematically represented in Figure 1. Dimensions of car park was determined as 50 m x 50 m x 3 m. 5 jet fans were placed to guide the smoke inside car park under fire scenario and 6 outlet fans were placed to extract the swept smoke by jet fans to outside environment. Fire scenario inside car park was designed as a square with 2 m edge length and (x=25 m, y=37 m) central coordinates.

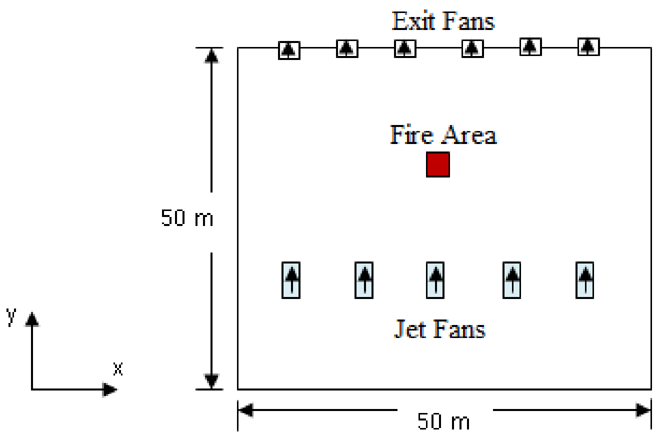

Figure 1. Schematic representation of top view of problem geometry

2.1. Problem equations

Differential equations of the problem are given below (Malalasekera and Versteeg, 2005)

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \rho u = 0 \quad (1)$$

Momentum Conservation Equation

$$\rho\left[\frac{\partial u}{\partial t} + (\mathrm{u}\nabla)u\right] + \nabla p = \rho g + f + \nabla \tau \quad (2)$$

Energy Conservation Equation

$$\frac{\partial}{\partial t}(\rho h) + \nabla \rho h u = \frac{Dp}{Dt} - \nabla q_r + \nabla k \nabla T + \sum_l \nabla h_l \rho D_l \nabla Y_l \quad (3)$$

Species Conservation Equation

$$\frac{\partial}{\partial t}(\rho Y_l) + \nabla \rho Y_l u = \nabla(\rho D)_l \nabla Y_l + \dot{m}_l''' \quad (4)$$

2.2. Boundary conditions

Since outside walls of car park in this problem were isolated, initial ambient temperature inside car park was set as 20C. Jet fan flows that will provide air ventilation inside car park were accepted as 8 m^3/s, 2.2 m^3/s, 2.6 m^3/s, and 3 m^3/s. Outlet fans direct the ambient air to outside environment with 1 atm pressure. Heat release ratio of the fire was determined as 500 kW and 1000 kW.

3. FINDINGS AND DISCUSSION

In this study, ventilation and smoke control simulation by using jet fans under fire scenario in car park was numerically conducted. These simulations were conducted for 8 m^3/s, 2.2 m^3/s, 2.6 m^3/s, and 3 m^3/s jet fan flow values and 500-1000 kW heat release ratio (HRR) range. Differential equations of the problem was solved for time-based and with turbulence and from start of the fire until first 360 seconds were the fire has the largest effect, temperature, smoke, and air speed distributions were obtained for time and location. The results were evaluated below.

In Figure 2, with heat release ratio (HRR) of 1000 kW and jet fan flow of 3 m^3/s, for plane on z=1.62 m coordinate, top view of smoke distribution for different time intervals were presented. Graphics were presented for t = 30 s, 140 s, 250 s, 360 s time. As seen from figure, smoke propagation started at 30th second of fire and can easily be swept to outside environment with jet fans. However, as time passes, smoke inside car park increases. Therefore, jet fans struggle to extract smoke to outside environment where some part of the smoke could be extracted, and remaining part propagates inside car park by impinging on the wall. This could clearly be seen on 360th second. Non-extracted portion of smoke propagated inside car park from two side regions of car park. As seen, at the end of 6th minute, almost half of solution area was covered with smoke where the remaining part was covered with clean air. Under fire scenario, smoke distribution in first 6 minutes that is important to evacuate people to safe zone without risk of poisoning, protecting people from fire, and enabling teams to intervene had acceptable structure.

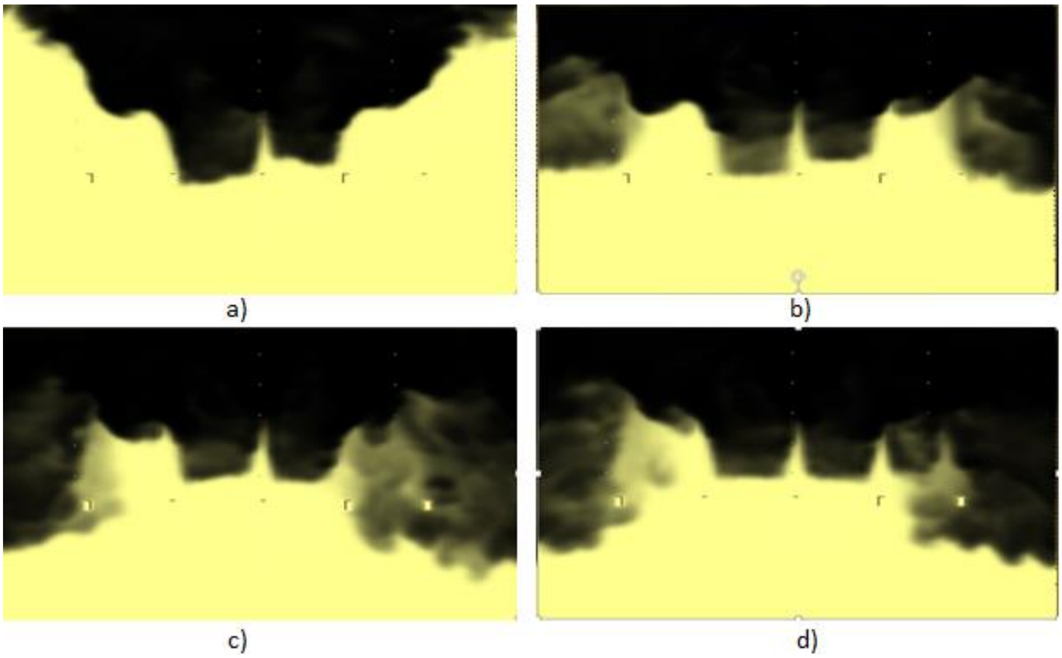

Figure 2. For HRR=1000 kW, z=1.62 m, and fan flow 3 m^3/s, smoke distribution during different time frames of fire a) t=30 s, b) t=140 s, c) t=250 s and d) t=360 s

In Figure 3, with heat release ratio (HRR) of 1000 kW and jet fan flow of 3 m^3/s, for plane on z=1.62 m coordinate, top view of temperature distribution for different time intervals were presented. As seen from figure, at the end of half a minute, high temperature values was visible in regions near to the centre. As time passes, these high temperature areas propagated inside car park. However, air flow supplied with jet fans decreased dissipation speed with forced convection. When fire time 360 s was reached, high temperature values were observed in regions near outlet fans and fire origin and this structure was similar to smoke distribution. However, two thirds of car park had temperatures that were unproblematic for people trapped in car park.

In Figure 4, speed distribution for heat release rate 500 kW, t=360 s, plane for z=1.62 m and 1.8 m^3/s, 2.2 m^3/s, 2.6 m^3/s and 3 m^3/s fan flows were given respectively. As seen from figures, flow structures inside solution region of all flows were similar. Air pushed by jet fans accelerated and directed to outlet. Some portion of air reaching to opposing surface with high speeds was extracted with outlet fans while remaining part impinged to wall and returned inside car park. Generally, this behaviour was similar in all fan rotations. However, in line with increased fan flow, air flow speed observed inside car park increased as well.

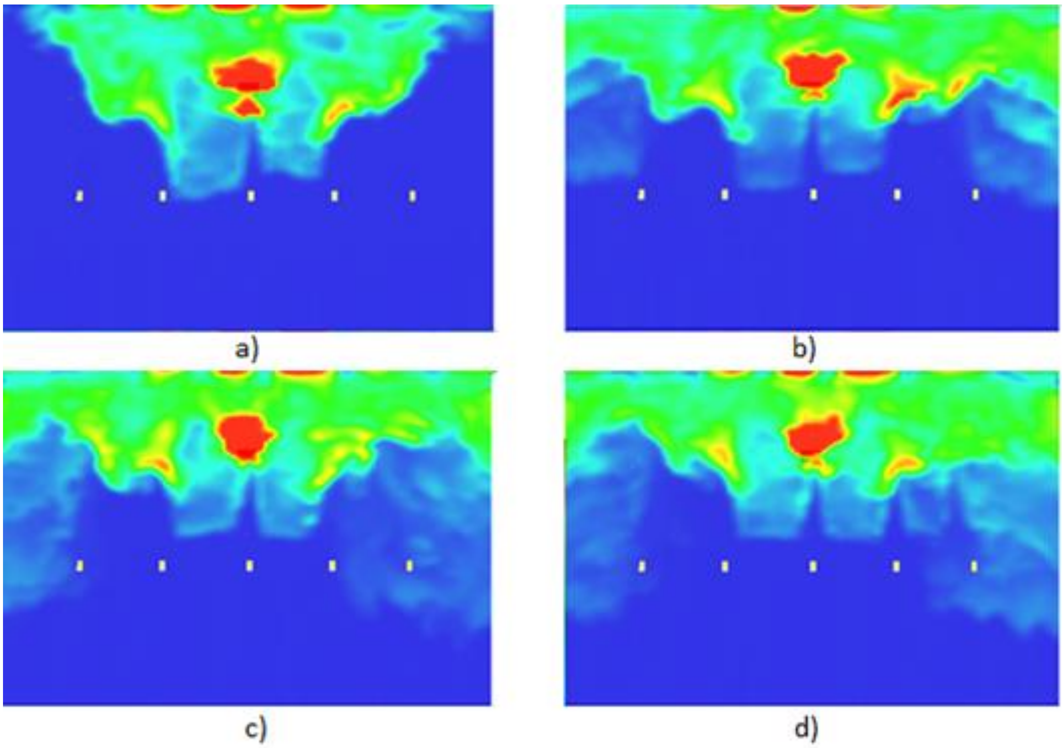

Figure 3. For HRR=1000 kW, z=1.62 m, and fan flow 3 m^3/s, temperature distribution during different time frames of fire a) t=30 s, b) t=140 s, c) t=250 s and d) t=360 s

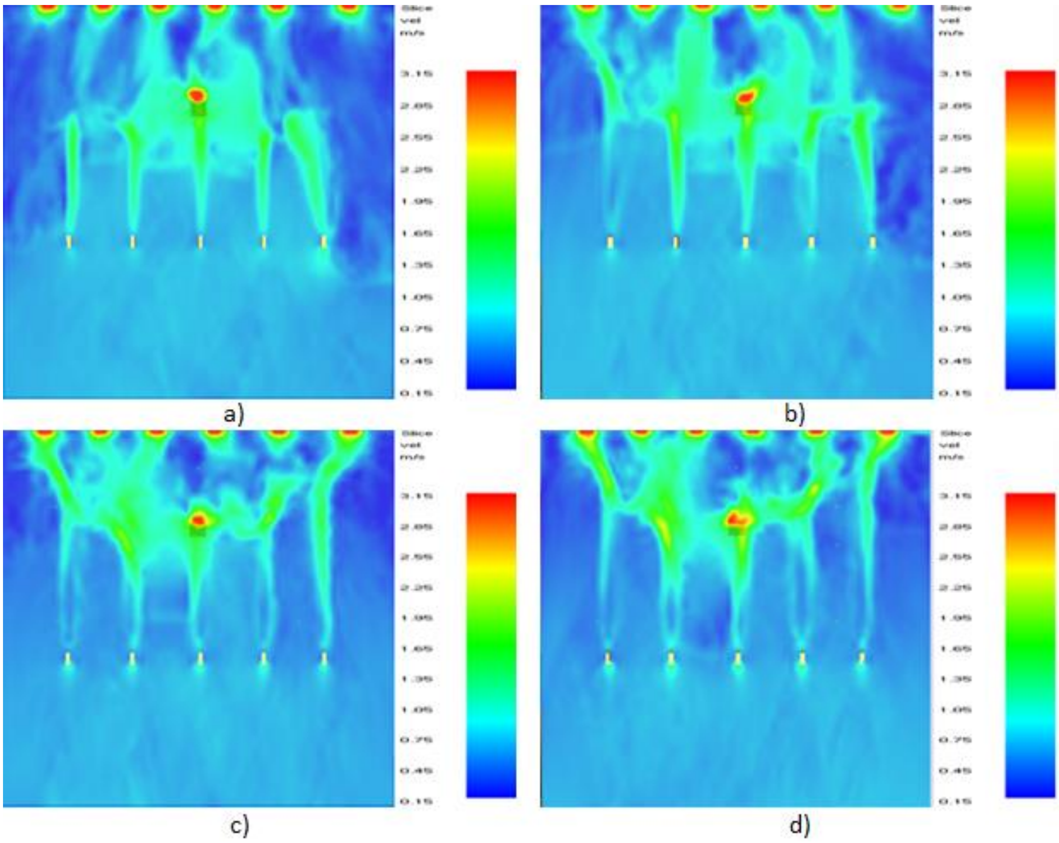

Figure 4. For HRR=500 kW, z=1.62 m, and t=360 s speed distribution for different fan flows, a) 1.8 m^3/s, b) 2.2 m^3/s, c) 2.6 m^3/s and d) 3 m^3/s

In Figure 5, smoke distribution for heat release rate 500 kW, t=360 s, plane for z=1.62 m and 1.8 m^3/s, 2.2 m^3/s, 2.6 m^3/s and 3 m^3/s fan flows were given respectively. For low fan flow, at the end of sixth minute, outlet fan region of car park was covered with smoke. It could be said that this was caused as air flow speed for low fan flows struggled sweeping smoke. For 1.8 m3/s fan flow, although smoke collected close to side surfaces of car park and propagated to other sections, when car park was considered in general, smoke was trapped in certain region. As fan flow increased, air flow swept smoke in easier way. Especially for fan flow of 2.6 m^3/s and higher, almost all smoke was extracted to outside environment and remaining were captured in certain region. Thus, majority of car park presented safe conditions for human health. Therefore, for geometry analysed in this study, under heat release ratio (HRR) of 500 kW, selecting 2.6 m3/s fan flow would be adequate for safe smoke control.

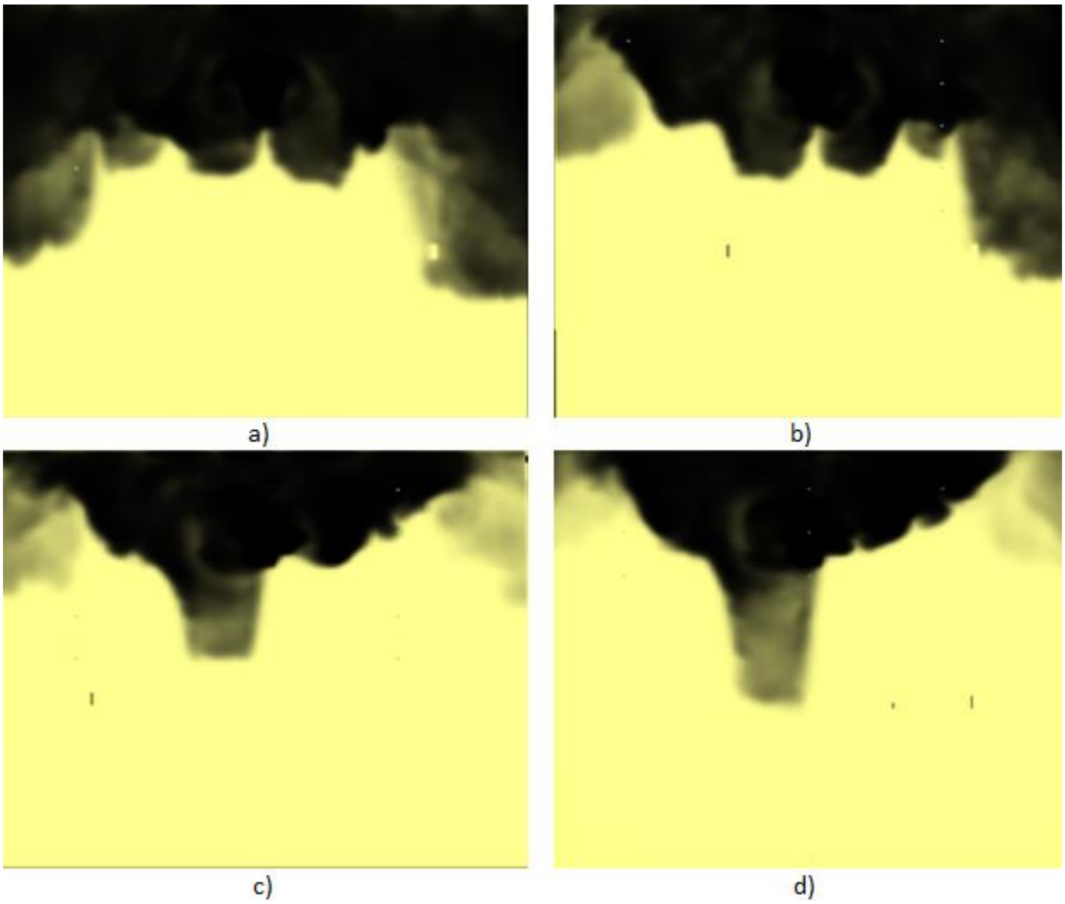

Figure 5. For HRR=500 kW, z=1.62 m, and t=360 s smoke distribution for different fan flows, a) 1.8 m^3/s, b) 2.2 m^3/s, c) 2.6 m^3/s and d) 3 m^3/s

In Figure 6 for 2.2 m^3/s jet fan flow, t=360 s, plane for z=1.62 m, and 500 kW and 1000 kW heat release ratio respectively, smoke and temperature distributions were given together. As seen from figure, under fire scenario, smoke distribution and temperature distribution indicated similar structure. Therefore, as smoke was extracted during fire, temperature was extracted as well. In other words, as the amount of extracted smoke increased, it could be said that ambient temperature increasing value would decrease.

When Figure 6 was analysed in detail, for constant fan flow, it could be seen that with increased heat release ratio, amount of smoke and ambient temperature within solution region increased and covered larger volume inside car park. This was related with increased fire with increased heat release ratio. When figures were analysed, for the geometry analysed in this study, and for 2.2 m^3/s jet fan rate, and fire with HRR=500 kW value, it can be seen that smoke control was achieved and more than half of the environment was kept under safe conditions. However, as fire size increased and heat release ratio reached 1000 kW, it was observed that released smoke covered most of the car park and ambient temperature in these regions reached higher values. For these conditions, it could be said that this ventilation was insufficient. Therefore, smoke amount and ambient temperature increased with increased fire size. To extract this increased smoke to outside environment, flow of jet fans should be increased.

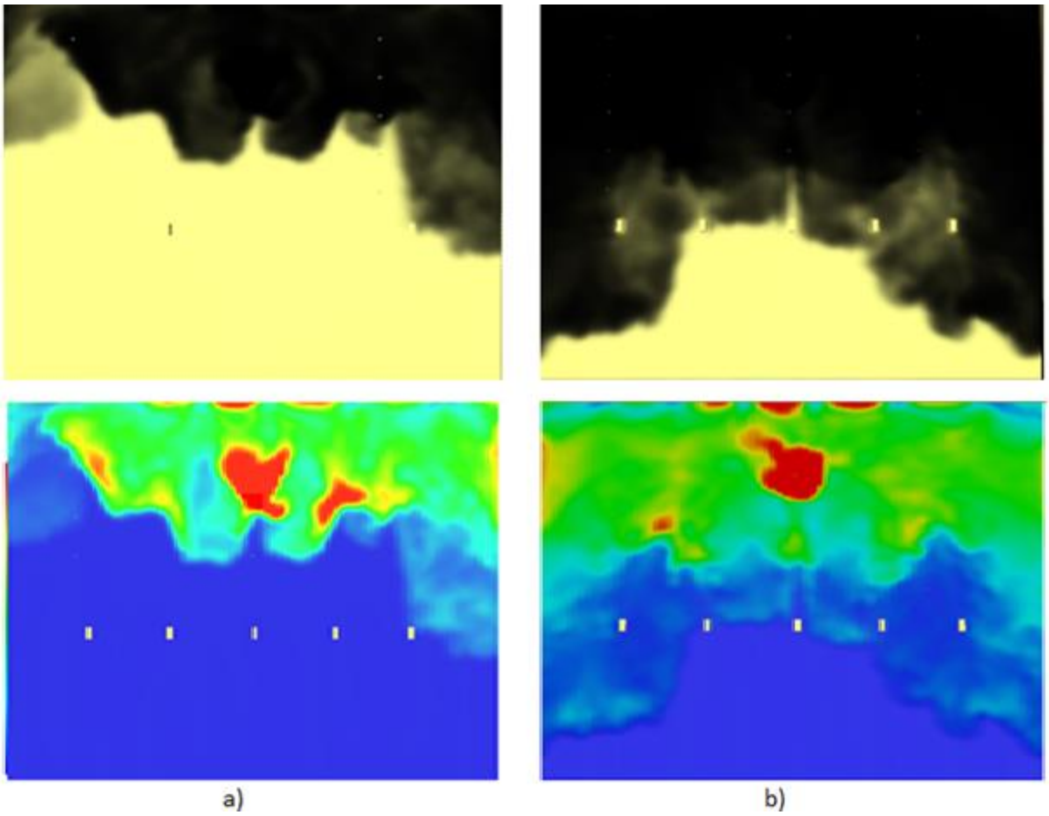

Figure 6. For fan flow 2.2 m^3/s, z=1.62 m, and t=360 s, smoke and temperature distribution for fires with different heat release ratio a) HRR=500 kW, b) HRR=1000 kW

In Figure 7, obtained temperature values for HRR=500 kW, in x=25 m, z=2.35 m coordinates, on 360. second, along y axis were given with jet fan flow changes. When figure was analysed, for all fan flows, temperature for y=25 m and x=30 m were close to room temperature. For first 30 m, there was no temperature increase due to fire. However, temperature started to increase for y=35 m. Especially when jet fan flow was 1.8 m^3/s, compared to other flow values, there was significant increase. This is because for low fan flow, fan was insufficient to sweep hot smoke and hot smoke propagated inside car park. More than half of car park was within secure temperature limits. However, in 40th meter, maximum temperature was observed for all fan flows. This point represented next location after the origin of fire. There were two reasons to observe maximum temperature in this region. First, generated hot smoke was pushed towards outlet. Second, hot smoke previously pushed to outlet, yet, impinged and returned inside car park accumulated in this region. Around outlet fans, temperature had tendency to decrease. For y=45 m, temperature significantly decreased as the most of hot smoke extracted to outside environment and remaining hot smoke propagated to large volume.

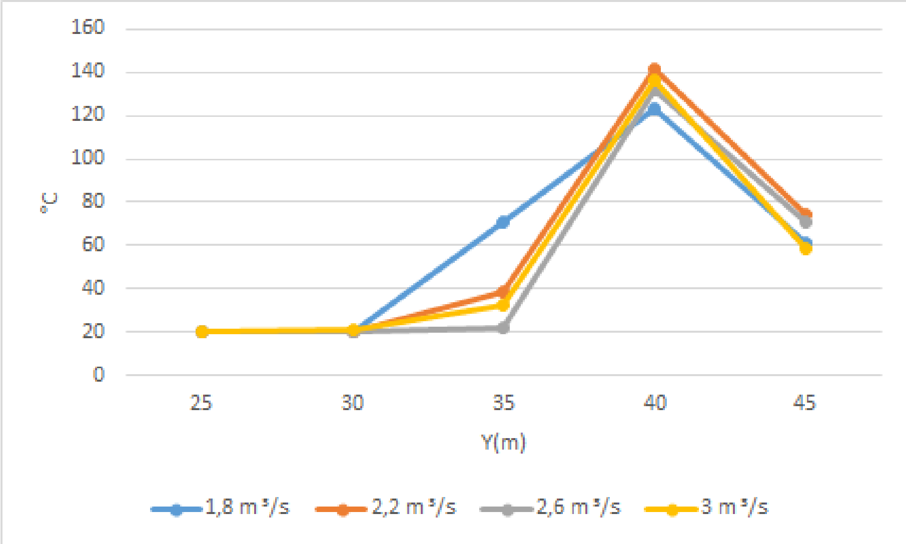

Figure 7. For HRR=500 kW, x=25 m, z=2.35 m, and t = 360 s change of temperature with fan flow along y axis

In Figure 8, obtained temperature values for HRR=1000 kW, in x=25 m, z=2.35 m coordinates, on t=360. second, along y axis were given with jet fan flow changes. When figure was analysed, this figure was similar to previous profile with HRR=500 kW. Ambient temperature increased closer to fire origin, when central coordinate was passed, maximum values were observed, and decreased in outlet fans. This situation was similar for all fan flows. However, temperature values obtained for HRR=1000 kW was higher than previous state due to higher fire size. For first 30 meters, safe temperatures were observed. However, it was seen that temperatures were higher in regions closer to fire centre.

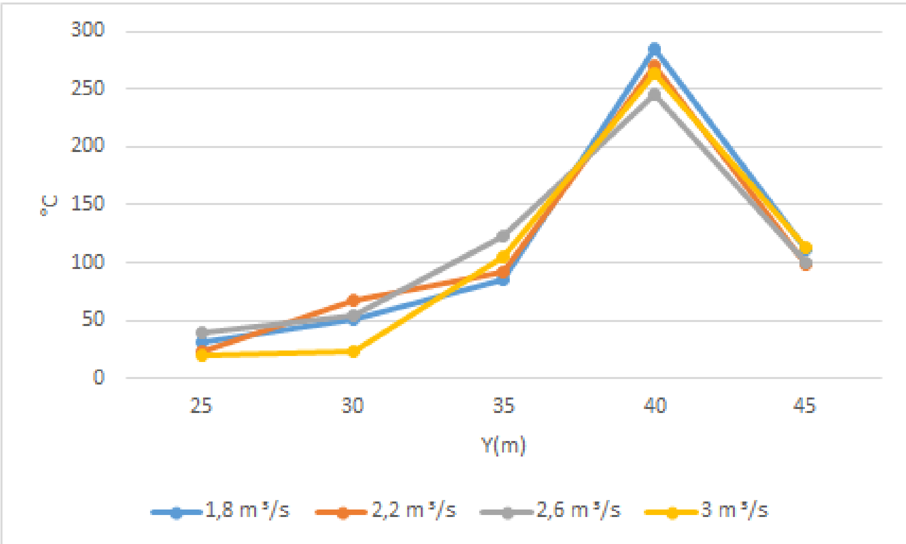

Figure 8. For HRR=1000 kW, x=25 m, z=2.35 m, and t = 360 s change of temperature with fan flow along y axis

4. RESULTS

In this study, ventilation of underground car park with jet fans and smoke control in case of fire was analysed numerically. Analyses were conducted for different fan flows and different fire sizes. Since first 360 seconds is the critical period where the fire has highest effect and critical time for evacuation of people, temperature, smoke and air speed distribution within car park were determined for time and location. It was observed that as jet fan flow increased, air flow swept smoke in easier way, and ambient temperature decreased. Yet, with increased fire size, it was observed that amount of fire and ambient temperature increased. For parameters adopted in this study, smoke after first 6 minutes was captured in half of car park. Additionally, temperature levels were kept constant in two thirds of car park to prevent problem for trapped people inside car park. This enables great opportunities for people trapped in fire to escape secure areas and enable effective intervention of offers who will intervene to fire. Therefore, it can be said that using jet fans inside car park is beneficial for smoke and temperature control under fire scenario.

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