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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

The CFD Analysis of Ventilation and Smoke Control System with Jet Fan in A Parking Garage

Kapalı Bir Otoparkın Jet Fanlı Havalandırma ve Duman Kontrol Sisteminin CFD Analizi

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Abstract

Basements of buildings are generally used as parking garages and vehicles located in there release harmful gases. It is generally not possible to ventilate parking garages with natural ventilation methods. For this reason, ventilation systems should be used to keep the concentration of harmful gases below certain limits. One of these ventilation systems is jet fan system. It can also be used for smoke control and exhaust of harmful gases in case of fire. In this study, the jet fan system was designed for a parking garage and its performance has been observed by Computational Fluid Dynamics (CFD). Carbon monoxide concentration and air velocity parameters were investigated according to the different car occupancy rates with the CFD analyses for daily ventilation. In the results, when the number of cars increased, the air velocities decreased in the areas where the cars located and exhaust of the CO gas took longer time. In fire analyses, the same parameters were analyzed according to the different jet fan hanging heights. In the fire ventilation results, when the jet fan hanging height was increased, distribution of the air velocity profiles changed and it took longer time to exhaust the CO gas from the car park.

Keywords: CFD, Parking garages, Smoke control, Jet fan, Car park ventilation

Öz

Binaların genellikle bodrum katları kapalı otopark alanı olarak kullanılmakta ve otoparklarda bulunan araçlardan zararlı gazlar yayılmaktadır. Otoparkları doğal havalandırma yöntemleriyle havalandırmak genellikle mümkün değildir. Bu nedenle, zararlı gaz konsantrasyonunu belirli sınırların altında tutmak için havalandırma sistemleri kullanılmalıdır. Bu havalandırma sistemlerinden biri jet fan sistemidir. Ayrıca bu sistem yangın durumunda duman kontrolü ve zararlı gazların atılması için de kullanılmaktadır. Bu çalışmada, bir otopark için jet fan sistemi tasarlanmış ve sistemin performansı Hesaplamalı Akışkanlar Dinamiği (CFD) ile gözlemlenmiştir. Günlük havalandırma için karbon monoksit konsantrasyonu ve hava hızı parametreleri farklı araç doluluk oranlarında incelenmiştir. Sonuçlarda, araba sayısı arttıkça araçların konumlandığı bölgelerde hava hızının azaldığı ve CO gazının daha uzun sürede egzoz edildiği gözlemlenmiştir. Yangın analizlerinde, aynı parametreler farklı jet fan asma yüksekliklerine göre analiz edilmiştir. Yangın havalandırması sonuçlarına göre, jet fanların asıldığı yükseklik arttırıldığında, hava hızı profillerinin dağılımının değiştiği ve CO gazının daha uzun sürede egzoz edildiği gözlemlenmiştir.

Anahtar Kelimeler: CFD, Otoparklar, Duman kontrolü, Jet fan, Otopark havalandırma

I. INTRODUCTION

In recent years, jet fan system is preferred more than ducted system for parking garages due to its advantages. This system can be used to provide daily ventilation and smoke control in case of fire. Jet fans are used in locations that need large amounts of air with high velocity for example in car parks and tunnels [1]. Jet fans accelerate fresh air supplied from fresh air sources inside parking lot and transmit it to exhaust fans by the effect of thrust power. In the event of a possible fire in parking garages or tunnels, toxic gases and fumes generated by the combustion will spread rapidly into the car park and the spread smoke will limit the visibility. If the ventilation system is not installed in the area, it will be difficult for firefighters

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to intervene the fire. Many national and international studies on smoke exhaust systems are conducted.

S. Lu et al. [2] investigated smoke control capacity of jet fan system in a parking garage. The study also includes the comparison of jet fan system with ducted system. According to the results, increased jet fan air speed can cause smoke circulation. The results show that the jet fan system not only prevents smoke spreading, but also provides good visibility to fire fighters when compared to the ducted ventilation system. Z. Spiljar et al. [3] examined effect of partition walls of parking garage on the jet fan system. According to the results jet fan system is not suitable for all parking garages that especially includes partition walls. Because, these walls obstruct to air distributions. For such garages, ducted ventilation systems are more suitable than jet fan system. X. Deckers et al. [4] examined the effects of the smoke heat control system in case of fire with CFD simulation. According to the results, in cases where the flow is unilateral, increasing the rate of heat release and decreasing the smoke exhaust rate causes back layering of the smoke. In addition, it was observed that when smoke recirculation occurred, increasing the exhaust rate did not constitute a solution. S.C. Li et al. [5] investigated the influence of the make-up air amount on smoke exhaust efficiency by performing numerical simulations. An atrium fire is analyzed with simulations. According to the results, the amount of make-up air should be 30% of the amount of smoke exhaust. Because it is observed that the efficiency decreases when the amount of supply air is increased. The jet fan system is used to reduce density of toxic gases in daily ventilation, to reduce the smoke density during the fire and to increase the visibility for tunnels and parking garages. It is difficult to ventilate the underground parking garages by natural ventilation so special ventilation systems are needed to remove the dirty exhaust air emitted by motor vehicles. Dirty and harmful gases emitted from vehicle engines are generally CO, hydrocarbons and nitrogen oxides. The most important factor in terms of human health is the density of CO, so studies to improve air quality in car parks are generally focused on CO gas, but nitrogen oxides, sulfur oxides, other odorous and polluted gases cause the air quality of the car parks to decrease [6] . CO is an odorless, colorless and toxic gas. It is not possible to see, taste or smell this gas. It is possible to be exposed to this gas without notice. The CO joins the hemoglobin faster than oxygen and prevents the oxygen from entering the body by forming oxyhemoglobin [7]. Many institutions around the world have published criteria for acceptable levels of concentrations for toxic gases .The US EPA accepts 35 ppm concentration limit value for 1 hour exposure. [8]

Jet fans are mounted near the ceiling. In cases where the jet fans are very close to the walls, the air flow becomes adhered to the surface because of the induced air and low pressure due to unilateral in near wall installations. This situation is called as coanda effect. Witt K.C et al. were studied with Witt & Sonn AG [9] related with the jet fans that are used in tunnels. They compared traditional jet fans with banana jets for observing the effect of coanda. Banana jet is formed by bending the silencers at the suction and blowing side of the conventional jet fans at certain angles. Thus, coanda effect was reduced with the use of banana jet.

In this study, a suitable jet fan system was designed for the parking garage according to the needed capacity of fans of the system and checked them by CFD analyses. According to the analyses results, there is no dead space unventilated. Thus, the accuracy of the jet fan system and the equipment layouts has been confirmed. Three dimensional drawing of the car park were made by Blender program and CFD analyses were carried out with Fire dynamic simulator (FDS) program that was developed on fire simulations. The car park was drawn in full scale and its physical structures that are ramps, beams, columns, fresh air shaft, exhaust shafts and cars were added to the drawing. Jet fans and exhaust fans of the system were drew and their technical properties were processed to the FDS program. For daily ventilation analyses, air velocity profiles and CO concentration in the closed parking garage were investigated with CFD analyses according to the different car occupancy rates. In the fire analyses of this study, air velocity profiles and CO concentrations were observed according to the different jet fan hanging heights.

II. MATERIAL AND METHOD

2.1 CO Emission Calculation

A vehicle emits CO in two conditions. These are the cold emission when the engine is started up and the hot emission when the engine is warm. Motor vehicle emission factors for hot and cold-start operation given in ASHRAE 2007 Handbook are shown in Table 1.

Table 1. Predicted CO Emissions in Parking Garages [10]

Season	Hot emission (mg/s)		Cold emission (mg/s)	
	1991	1996	1991	1996
Summer, 32°C	42,33	31,5	71,17	61
Winter, 0 °C	60,17	56,33	345,67	316

The CO generation rate per unit floor area G (mg/m^2s) rate can be determined using Equation (1) [10].

$$G = N \times E / A_f \quad (1)$$

N is number of cars in parking garage, E (mg/s) is average CO emission rate for a typical car, and A_f (m^2) is total floor area of parking garage.

2.2 Exhaust Fan Selections

According to the regulation on fire protection of buildings of Turkey at least 10 air changes per hour extract rate must be provided in the parking garages [11]. Area of the parking garage is 2033m² and ceiling height is 4.75 m. The exhaust flow rate, Q (m^3/h) can be determined using Equation (2).

$$Q = A \times h \times ACH \quad (2)$$

Q is exhaust flow rate, h is ceiling height and ACH is air change per hour. Calculated exhaust flow rate is 96567.5 m³/h. The exhaust flow rate is provided by two pieces exhaust fans. They were selected from a manufacturer catalog and they were located in the exhaust shafts of the parking garage. Flow rates of the selected exhaust fans are shown Table 2.

Table 2. The air flow rates of the exhaust fans

Fans	Flow rate (m³/h)
EF-1	51277
EF-2	51277

Total 7 pieces jet fans were placed in the parking garage and it was checked whether any unventilated areas. The velocity contours are shown in Figure 1. As can be seen in Figure 1, there is no dead or unventilated areas that are not ventilated by the jet fan system.

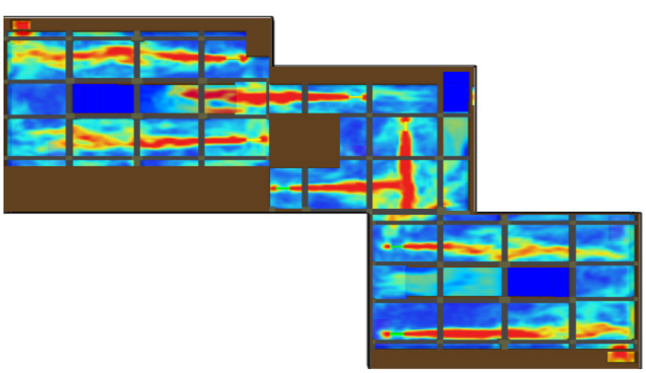

Figure 1. The ventilated areas by jet fans

The thrust powers and blowing distances of the jet fans are given in Table 3.

Table 3. The thrust powers and blowing distances of the jet fans

Jet Fan Number	Thrust Power (N)	Blowing Distances (m)
1	50	34
2	50	34
3	50	34
4	50	34
5	80	50
6	80	50
7	80	50

Location of the jet fans, fresh air opening, exhaust shafts, garage and fire(burning car) are shown in Figure 2.

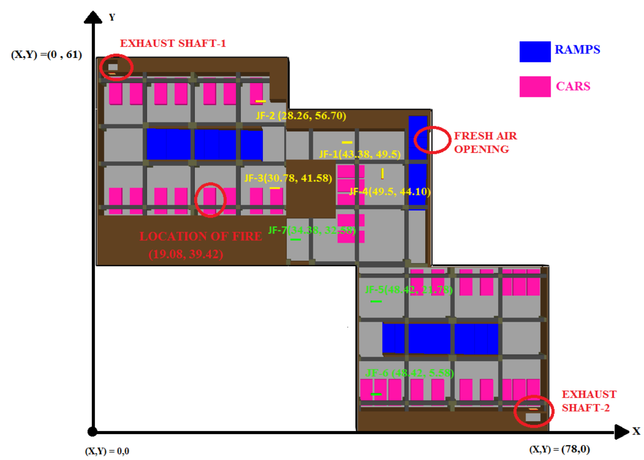

Figure 2. The Jet fans, exhaust shafts and fresh air openings

2.3 Inputs of Daily and Fire Ventilation Simulations

There are 9 case studies about daily and fire ventilation of the parking garage. Case Study-1, 2, 3, 4, 5, 6 and 7 are belong to the the daily ventilation simulations. In these studies, influence of the number of cars and car occupancy rates on performance of the jet fan system were observed. For fire analyses, Case-8 and 9 were performed and the effect of the jet fan hanging heights were compared on the jet fan system performance.

2.3.1 Daily Ventilation

The parking garage was filled with 50 ppm CO in initial conditions. Simulation time is 900 seconds for all daily ventilation case studies. The CO concentration and exhausting time were examined according to the different car occupancy rates of the car park.

Maximum 38 pieces car can be parked in the parking garage. Case study-1, Case Study-2 and Case-Study-3 were performed to examine the effect of the cars located in the garage on air velocity profiles. In the case studies, 4, 19 and 38 cars were placed in the simulations, respectively. Dimensions of the cars are 2.16 m width, 4.168 m length and 1.1 m height. Each one is defined as an obstacle at a height of 1.1 meters and air velocity profiles were examined at a height of 0.55 meters from the floor.

In the Case Study-4, Case Study-5, Case Study-6 and Case Study-7, car occupancy rates were increased as 10%, 25%, 50% and 100% respectively. To measure the CO concentrations, 13 measuring points are determined in the parking lot. These points are located at 2.1 meters height from the floor and distributed throughout parking garage. Location of the measuring points are shown in Figure 3.

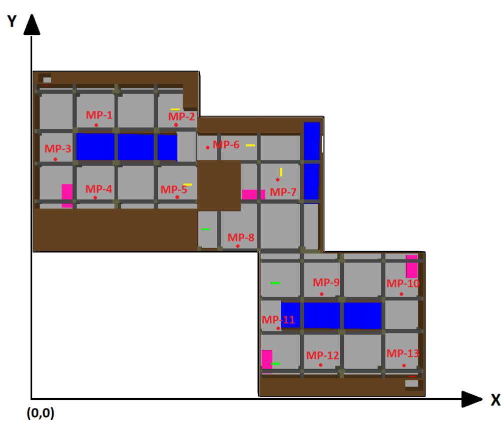

Figure 3. Locations of the measuring points

Coordinates of the measuring points are given in Table 4.

Table 4. Coordinates of the measuring points

Numbers of Measuring Points	Coordinates (x,y) (m)
1	12.24,56.52
2	28.44,56.52
3	3.96 ,49.68
4	12.24,42.12
5	28.44,42.12
6	34.74,49.14
7	48.96,42.84
8	41.04,32.40
9	57.60,22.68
10	74.16,23.04
11	49.32,15.84
12	57.60 , 8.28
13	74.16 , 8.28

During 900 seconds time period, changing of CO concentrations are measured from the points. After measuring CO concentrations, the average of CO values the points were calculated every two seconds of 900 seconds time period. In addition the CO concentrations at the 1.65 meters height section of the parking garages were given in the results of this study.

2.3.2 Fire Ventilation

Case Study-8 and Case Study-9 have been performed with CFD analyses to observe and compare the air velocities and exhaust time of CO due to the jet fan hanging heights. In these simulations, 4 MW HRR a car fire were analyzed. The center point of the burning car is (19.08, 39.42) on X-Y coordinates of the parking garage. The jet fans started to work in 300th seconds and the fire reached the maximum level in 900 seconds. The total simulation time is 1500 seconds. The jet fans hanging heights are 2.91 m and 3.63 m, for Case-8 and Case-9 respectively. The heights of analyses result section for both cases are 1.65 meters. This height is from the floor to the ceiling.

III. RESULTS AND DISCUSSIONS

3.1 Daily Ventilation Simulation Results

According to the CFD results, air velocities was low in the regions where the cars were located and high in the empty regions without the cars. Air velocity profiles for Case Study-1, 2 and 3 are shown in Figure 4. In study of Ž. Špiljar et al. [3], partition walls have been found to cause air stagnation. In our study also, cars that are identified as obstacle in CFD, caused to air stagnation where they located. It is seen that all kinds of obstacles placed in the parking lot causes air stagnation. Therefore, the placement of the jet fan system is very important for efficient ventilation.

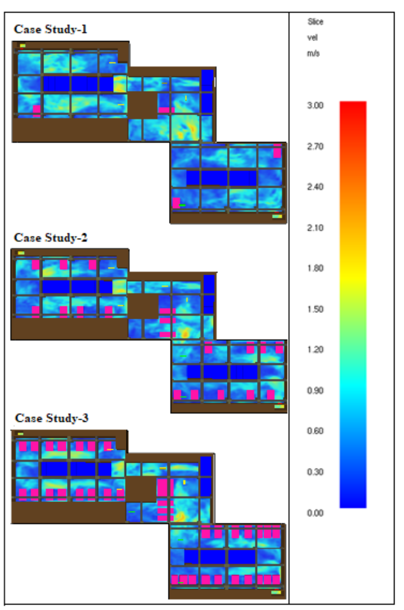

Figure 4. The air velocity contours according to the number of cars at 0.55 meter height from the floor

For Case Study-4, Case Study-5, Case Study-6 and Case Study-7, the car occupancy rates are 10%, 25%, 50% and 100%, respectively. In this study, E value were assumed 46.25 mg/s. This value is average of the 31.5 mg/s (hot emission) and 61 mg/s (cold emission) from Table 1. Calculated generations rates of the Case Study-4, Case-Study 5, Case-Study 6 and Case-Study-7 are given in Table 5.

Table 5. Calculated CO generation rates due to the car occupancy rates

Case study number	Car occupancy rate	E, Average CO emission rate (mg/s)	G,CO generation rate (mg/m²s)
4	10%	46.25	0.086448598
5	25%	46.25	0.216121495
6	50%	46.25	0.432242991
7	100%	46.25	0.864485981

CO Concentrations of the Case Study-4, Case Study-5, Case Study-6 and Case Study-7 are between 0-15 ppm, 0-29 ppm, 0-45 ppm and 0-67 ppm respectively, at the end of simulations and at 1.65 meters height from the floor. Simulation results of the each case studies depends on time are shown in Figure 5.

The graph that includes the variation of the CO concentrations depends on time for each cases is shown in Figure 6**.** The results that are shown in the graph are obtained from the measuring points located in 2.1 meter height from the floor of the parking garage. As shown in Figure 6, CO concentrations increased due to the increased car occupancy rates.

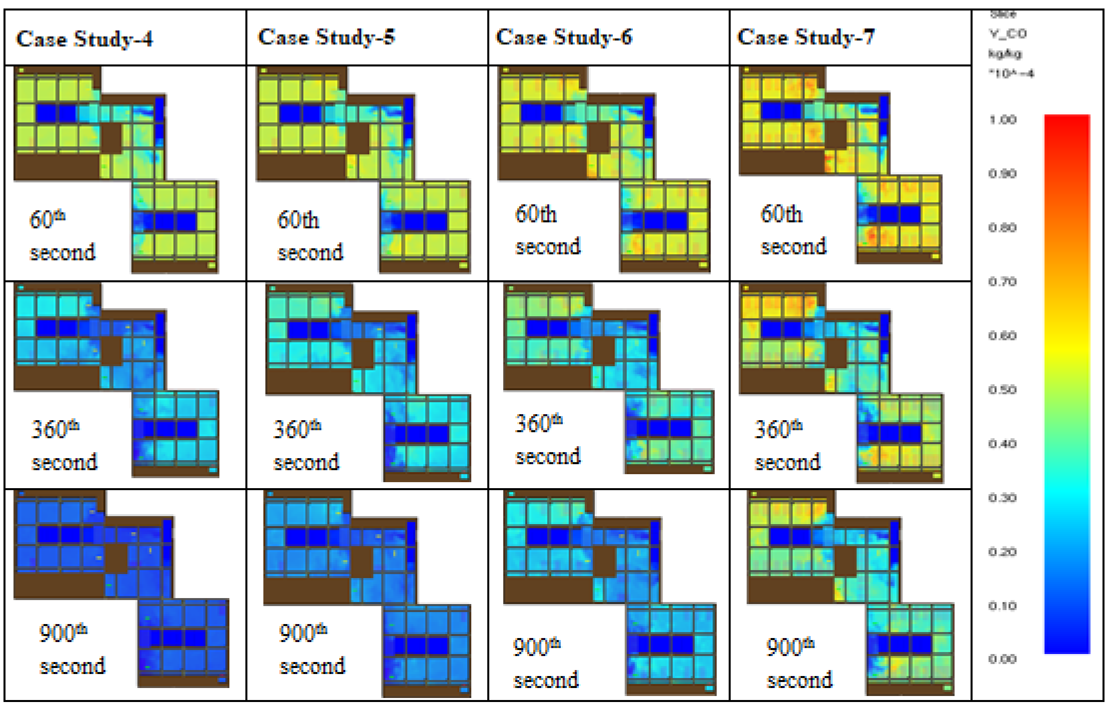

Figure 5. The CO concentration variations of Case-4, 5, 6 and 7 at 1.65 meter height from the floor

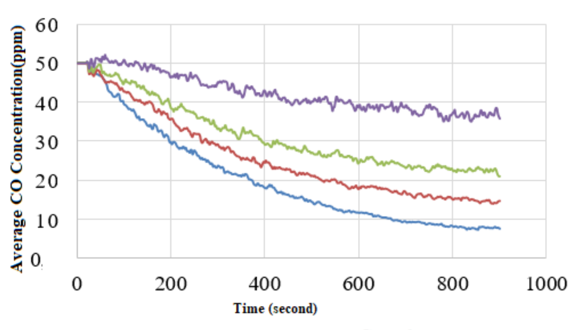

Figure 6. The variations of the CO concentration depend on time

3.2 Fire Ventilation Simulation Results

Air velocity profiles are shown in Figure 7 for Case Study-8 and 9. CFD simulations shows that as jet fans move away from the ceiling, jet profile improves and air velocity increases in the cross section. In the opposite case, as jet fans close the ceiling, the jet speed profile takes a form that is adhered to the wall and the air velocity in the cross section drops with the effect of coanda.

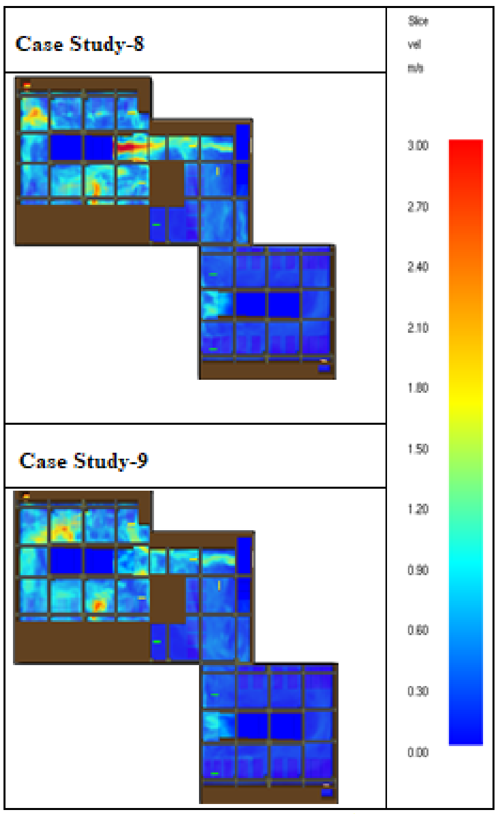

Figure 7. Air velocity profiles of Case-8 and Case-9 at 1.65 meter section height from the floor

Results of CO gas analyses show that jet fan hanging height have influence on exhaust of the CO gas. Air velocities decreased with coanda effect when jet fans closed to the ceiling. In the literature, the coanda effect has been generally investigated for jet fans used in tunnels. One of these studies is belong to the Witt K.C et al. [9]. They mentioned in their work that air adhere to the wall with the effect of coanda. The same result was observed in the results of our study. The graph of the CO concentration variation depends on time around the fire source is shown in Figure 8. As shown in the graph, the CO concentration of the Case-9 more than Case-8. The CO concentrations were measured by Measuring Point-4 (MP-4) which is near the fire source.

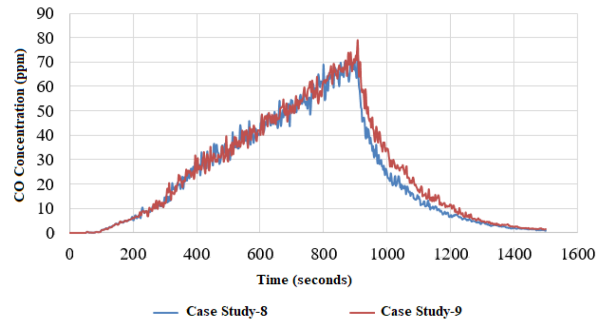

Figure 8. The CO concentration variations around the fire for Case Study-8 and 9

It was observed that exhaust of CO gas took longer time in Case Study-9 when compare with Case Study-8. According to the results, time of decreasing CO concentration below 35 ppm is 1020 seconds in Case Study-8 and 1058 seconds in Case Study-9. The simulation results CO concentrations variations depends on time for both case studies is shown in Figure 9. As it can see from the simulation results, jet fans hanging height has significant effect on CO exhaust.

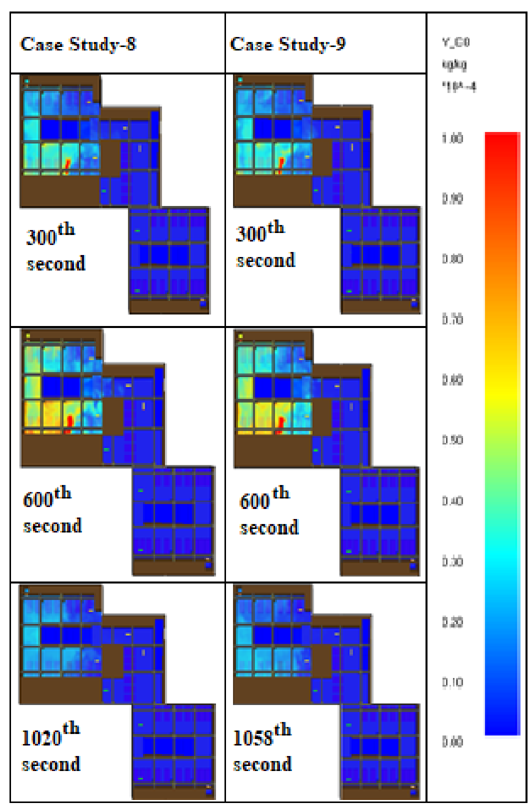

Figure 9. The CO concentration simulation results for the Case Study-8 and 9 @1.65 meter section height from the floor.

IV. CONCLUSIONS

In this study, the jet fan system was designed for the parking garage. The applicability of the jet fan system has been checked by means of CFD analyses and it has seen that the designed jet fan system is suitable. Both daily ventilation analyses and fire ventilation analyses were performed for the parking garage and the simulation results were shared.

CO concentrations and air velocity profiles depending on car occupancy rate were investigated in daily ventilation simulations. In Case Study-1, 2 and 3 the number of cars were changed and air velocities were examined in the regions where the cars were placed. Cars were defined as 1.1 meter height obstacles in FDS software. When the velocity profiles were examined, it was observed that the air velocity was low in the areas where the obstacles located.

In case studies 4, 5, 6 and 7, it was observed that the CO concentrations increased as the car occupancy rate increased. Thus, CO exhaust time is increased as car occupancy rate increased. For Case Study-4, 5, 6 and 7 the concentration of CO are between 0-15 ppm, 0-29 ppm, 0-45 ppm and 0-67 ppm respectively at the end of 900 seconds simulation time.

In the fire ventilation analyses that are Case Study-8 and Case Study-9, the effect of jet fans hanging heights on air velocity and CO exhaust time in fire ventilation analyses have been investigated. In Case Study – 8 and 9 jet fans were hanged 2,91 meter and 3,63 height from the floor, respectively. In this way, coanda effect was observed. When the jet fans near the ceiling, it was observed that the air velocity profile adhered to the ceiling. In this case, the CO exhaust time is longer in Case Study-9 when compared with Case Study-8. In Case Study-8 and Case Study-9, CO concentration decreased below to 35 ppm in 1020 and 1058 seconds time, respectively. Therefore, it was concluded that the jet fans hanging heights should be well optimized.

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