Study of Securing Required Ventilation Rates and Improving Mechanical Ventilation Systems for Underground Parking Lots

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Abstract

This study presents ventilation guidelines for underground parking lots for building designers. The guidelines are classified into those for natural ventilation and those for mechanical ventilation. CONTAMW was used to study the natural ventilation of underground parking lots. Computational fluid dynamics (CFD) was used to study the ventilation efficiency of the mechanical ventilation system. The study results are as follows: 1) Underground parking lots had the lowest seasonal natural ventilation rates in the period between winter and summer when the difference between the indoor and outdoor temperatures was small. 2) In an apartment building, the required ventilation rate for the underground parking lots could be secured for up to 40 parked cars by natural ventilation alone, regardless of season. 3) In business facilities, the required ventilation rate could be secured for up to 38 parked cars when the difference between the indoor and outdoor temperatures was 3°C in the period between winter and summer. 4) In the case of the mechanical ventilation of the underground parking lots, the best ventilation efficiency was observed with a downward air supply system of jet fans in combination with an air supply near the floor and an air exhaust near the ceiling.

Keywords: underground car park; required ventilation rate; ventilation efficiency; CFD

1. Introduction

In cities with small building sites, underground parking lots are increasingly being constructed in order to meet legal requirements for the number of parked cars without undermining the economic value of buildings. Generally, underground parking lots are susceptible to the accumulation of various pollutants produced by cars because of the enclosed space, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NOx), and volatile organic compounds (VOC) [1]. In the case of large underground parking lots, the planning of natural ventilation [2-5] and the review of mechanical ventilation [6-7] using jet fans have been conducted in order to secure indoor air quality. In these parking lots, the degree of indoor air pollution has been studied in detail through onsite measurements [8-11].

Unlike large underground parking lots, people tend not to invest in mechanical ventilation equipment for small and medium-sized underground parking lots. In many cases, building owners and occupants even avoid using installed ventilation equipment to save building maintenance costs [3].

According to Korea's "Parking Lots Act" and the "Indoor Air Quality Control in Public Use Facilities, etc. Act", the CO concentration in parking lots should be kept below 50 ppm and 25 ppm, respectively. It is necessary to introduce natural ventilation for underground parking lots to satisfy legal requirements and save maintenance costs. Previous studies [2-3], however, have not reviewed parking sizes that could satisfy the legal standards with natural ventilation alone. Moreover, studies on mechanical ventilation using jet fans [7, 12-13] have also not reviewed the relationship between the jet fan, the air supply opening, and the exhaust air openings.

The required ventilation rate for designing underground parking lots in Korea is calculated using the measured amount of CO emitted from cars from about 30 years ago. Because of continuous management of the atmospheric environment, both the amount of CO emitted from cars and the concentration of CO in the air have recently been decreasing conspicuously in Korea [14-15]. Thus, it is necessary to calculate the required ventilation rate for underground parking lots by reflecting this.
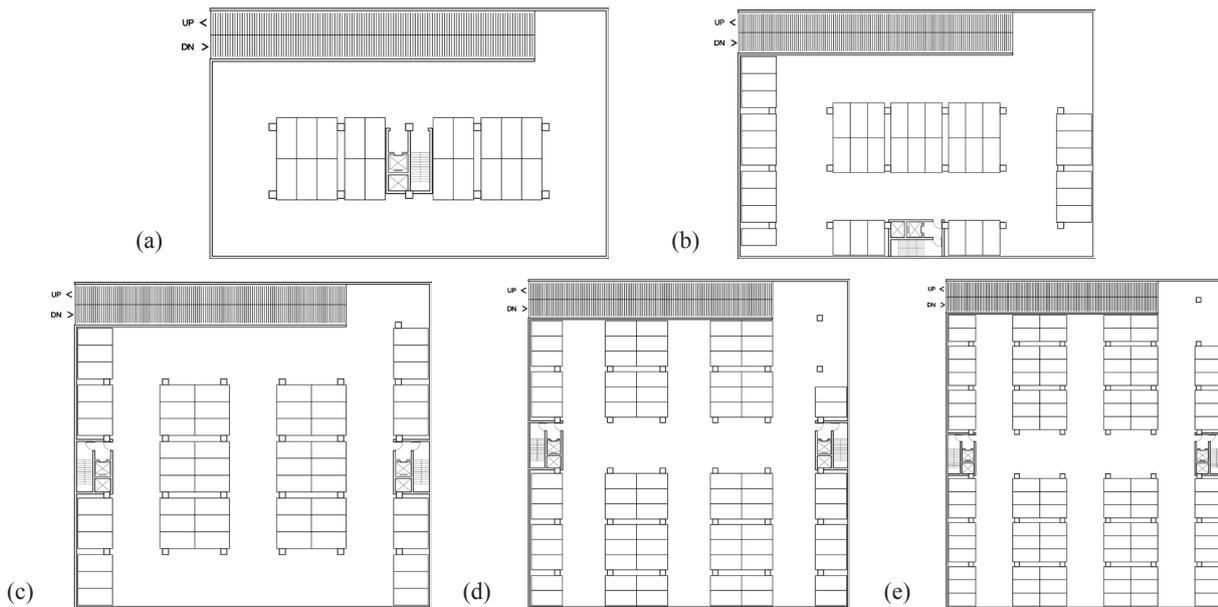
Fig.1. Overview of the Subject Spaces for the Calculation of the Required and Natural Ventilation Rates for Underground Parking Lots with Different Numbers of Parked Cars: (a) 20 Cars, (b) 40 Cars, (c) 60 Cars, (d) 80 Cars, (e) 100 Cars

The purpose of this study is to present ventilation guidelines for underground parking lots for building designers. The guidelines have been classified into those for natural ventilation and those for mechanical ventilation. In the case of natural ventilation, we present underground parking lot sizes that can satisfy the legal standards for air quality with natural ventilation alone according to building type. In the case of mechanical ventilation, we present a composition of jet fans, an air supply opening, and an exhaust air opening that can secure better indoor air quality.

The required ventilation rate for each underground parking lot was calculated by taking the building type and the number of parked cars into consideration. The natural ventilation rates for underground parking lots were calculated using CONTAMW based on a network model and focusing on the seasonal outdoor air temperatures in Seoul. The ventilation efficiency of the mechanical ventilation was calculated using Computational Fluid Dynamics (CFD).

2. Overview of the Required and Natural Ventilation Rates for Underground Parking Lots
2.1 Subject Spaces

Fig.1. shows the subject spaces for calculating the required and natural ventilation rates for underground parking lots. Each subject space was assumed to be a general underground parking lot in the first basement level with one entrance and exit. The number of parked cars was increased from 20 to 100 in intervals of 20, and the area was determined to be between 1,480 and 3,230 m².

2.2 Calculation Methods for the Required and Natural Ventilation Rates
1) Required Ventilation Rate

The required ventilation rate for an underground parking lot was calculated using Equation (1) to Equation (4). The amount of CO emitted from cars, M, is the sum of that from moving cars, M_1, and that from idling cars, M_2. M_1 was calculated using the amount from one car, G, the number of moving cars, T, and the moving distance, L, as shown in Equation (2).

A G value of 2.66 g/km was obtained from the National Institute of Environmental Research[14]. G is the CO generated when a gasoline or LPG car produced between 2000 and 2005 runs at 10 km/h. This value accounts for about 44.3% of the amount of CO emitted from cars used for designing existing underground parking lots (6 g/km). This was found using values for gasoline cars produced before 1990[15]. The moving distance L used for calculation was determined to be 0.7 times as high as the distance from the entrance of the parking lots to the farthest parking space. M_2 was calculated using the amount from one idling car, M_i, the number of idling cars, T_i, and the idling time, H_i. M_i is 17.51 g/min based on study results by Kwon *et al.*[4] The idling time was set as 2 minutes per car.

The average T and T_i per hour were used for the calculation. These values are based on 8 hours of cars frequently entering and exiting as prescribed by the "Parking Lots Act". The number of parked cars and turnover were also considered in their determination. The number of parked cars was determined based on the conditions shown in Fig.1. The parking turnover was 2.1, 3.6, 4.4, and 5.9 for an apartment building, business facilities, neighborhood facilities, and commercial facilities, respectively. These parking turnovers are generally used in designing underground parking lots in Korea.

The required ventilation rate Q for underground parking lots was calculated using M, the CO air concentration, C_o, and the legal CO concentration in parking lots, C_d. The C_o value used is the average value

between July and December 2014 determined by the Korean Statistical Information Service[16].

$$M = M_1 + M_2 \qquad (1)$$
$$M_1 = G \times T \times L \times \frac{1}{1000} \qquad (2)$$
$$M_2 = M_i \times T_i \times H_i \qquad (3)$$
$$Q = \frac{M}{C_d - C_o} \qquad (4)$$

2) Natural Ventilation Rate

The natural ventilation rates were calculated for the underground parking lots shown in Fig.1. using CONTAMW 3.1, which was developed by the National Institute of Standards and Technology. The calculation is based on Equation (5) from ASHRAE[17]. Each lot was zoned as a single space. Natural ventilation was assumed to result from the difference between the indoor and outdoor temperatures through the entrance and exit.

The Energy Saving Design Standards for Buildings by the Ministry of Land, Infrastructure and Transportation were used for the outdoor air temperatures in simulations. According to the standards, the reference temperatures for cooling system and heating system design in the summer and winter in the Seoul region are 31.2 °C and -11.3 °C, respectively. The outdoor air temperature in the intermediate period between winter and summer was assumed to be 25 °C.

The difference between the indoor and outdoor air temperatures in each lot was set between 1 and 9 °C. The difference was not specifically determined but has been widely reviewed because it may vary depending on the structural characteristics of the parking lots. The atmospheric pressure was assumed to be 101.3 kPa. The entrance and exit were assumed to be 6 m in width and 3.4 m in height. The airflow path was assumed as a two-way flow with one opening and no wind pressure.

$$Q_a = C_D A \sqrt{2g\Delta H_{NPL}\left(\frac{Temp_i - Temp_o}{Temp_i}\right)} \qquad (5)$$

3. Required and Natural Ventilation Rate Calculation Results According to Building Type

Fig.2. shows the relationship between the required and natural ventilation rates for each building type classified by seasonal period. The natural ventilation rate for each was determined by the size and shape of the entrance, the difference between indoor and outdoor temperatures, and indoor temperature, regardless of the number of cars parked in it. The natural ventilation rate in summer was 10,619-18,671 m^3/h when the difference between indoor and outdoor temperatures was 3-9 °C. The natural ventilation rate in winter was 13,095-22,303 m^3/h, and the natural ventilation rate in the intermediate period was 6,260-16,319 m^3/h when the difference between indoor and outdoor temperatures was 1-7 °C. In general, the difference in temperatures in the intermediate period is as big as in summer and winter, which is why the natural rate was smaller.
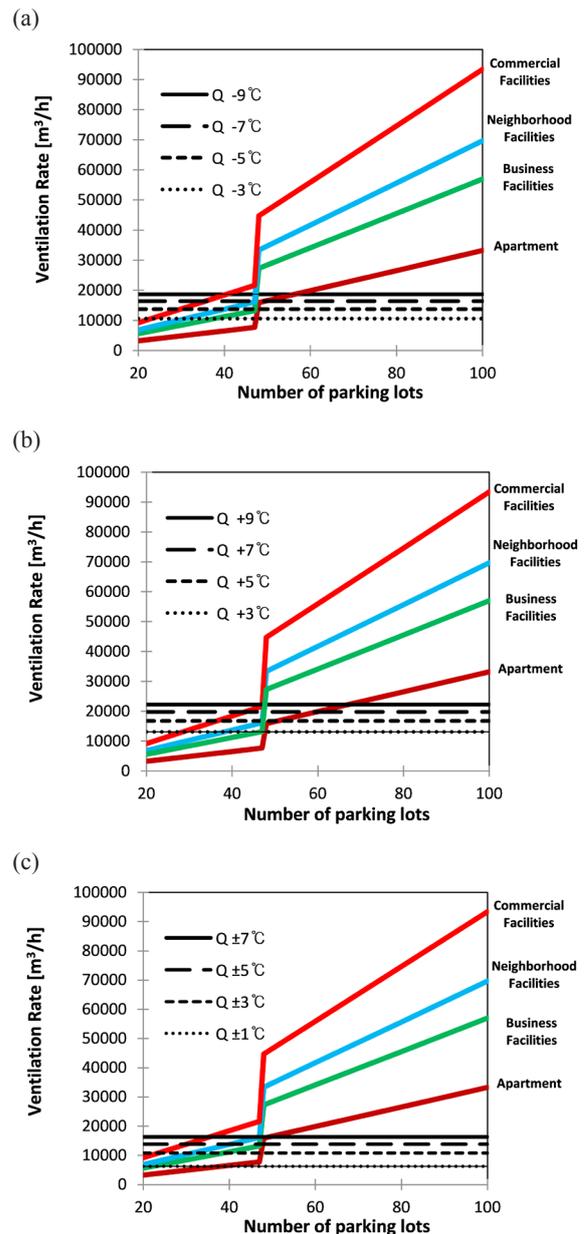
(a)

(b)

(c)

Fig.2. Required and Natural Ventilation Rates for Underground Parking Lots According to the Building Type and the Number of Parked Cars: (a) Summer, (b) Winter, (c) Intermediate Period, Black Lines are Natural Ventilation Rate, Colored Lines are Required Ventilation Rate

According to the "Indoor Air Quality Control in Public Use Facilities, etc. Act", the CO concentration should be below 25 ppm in indoor parking lots with floor area of 2,000 m^2 or more. The authors started with 48-parked cars in each lot, and the floor area was applicable under this law. The CO concentration is required to be below 50 ppm under the Parking Lots Act, which was applied to each lot with up to 47 parked cars. As a result, the required ventilation rate in each building increased rapidly when starting with 48-parked cars.

The relationship between the required and natural ventilation rates according to each building type is as follows. In the case of the apartment building, the
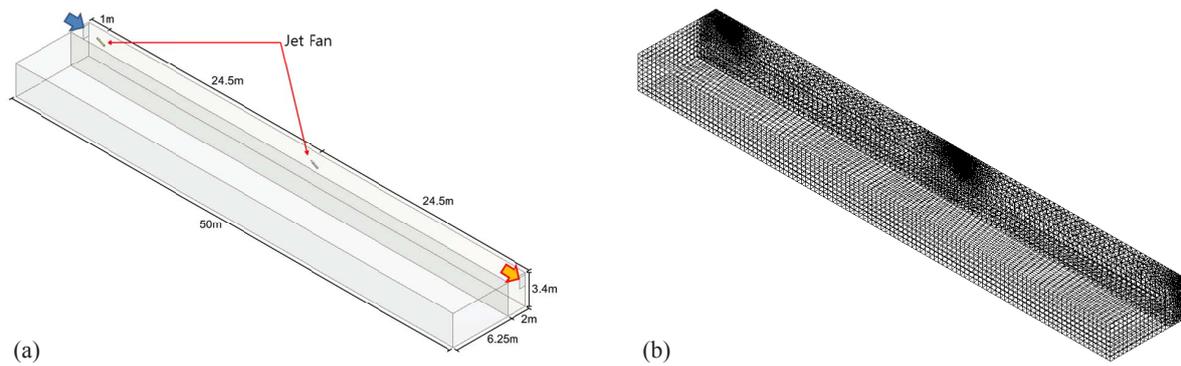
Fig.3. Target Space for CFD Analysis: (a) Size and Composition of the Target Space for Analysis, (b) Analysis Mesh
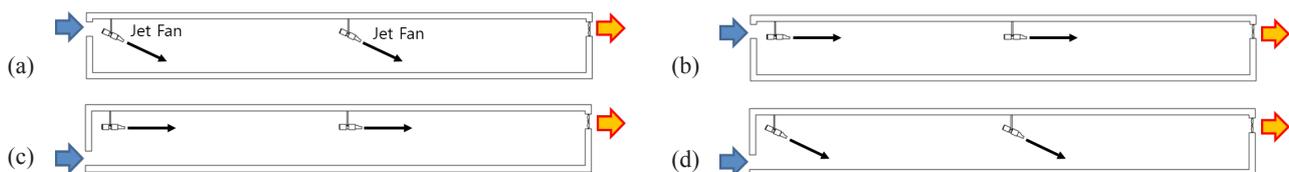

Fig.4. Summary of Analysis Cases: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4

Table 1. Boundary Conditions

Object	Conditions		
Exhaust air opening	• Opening size: 1.2m×1.2m	• Velocity Inlet: 2.64 m/s	• Turbulence intensity: 3%
	• Turbulence scale: 0.12m	• Airflow rate: 3.8016 m3/s	• Air change rate: 9.76 ACH
	• Temperature: 298.15 K	• Radiation emissivity: 0.95	
Supply air opening	• Opening size: 1.2m×1.2m	• Pressure inlet: 0 Pa	• Turbulence intensity: 3%
	• Turbulence scale: 0.12m	• Temperature: 298.15 K	• Radiation emissivity: 0.95
Jet fan	• Opening diameter: 0.175m	• Cell zone condition	• Velocity: 17.43 m/s
Surrounding walls	• Velocity and temperature: generalized log law		• Outside temperature: 294.15 K
	• Heat transfer coefficient:0.34 W/m²·K		• Radiation emissivity: 0.9
Car's supply air opening	• Opening diameter: 0.05m	• Velocity Inlet: 3.38 m/s	• Turbulence intensity: 5%
	• Turbulence scale: 0.005m	• Temperature: 304.62 K	• CO contaminant: 0.2918 kg/s

required ventilation rate could be secured sufficiently by natural ventilation alone for up to 47 parked cars in summer and winter. However, it could cover up to 40 parked cars when the difference between the indoor and outdoor temperatures is 1 °C and up to 45 parked cars when the difference is 3 °C in the intermediate period. Thus, the required ventilation rate in this case can be secured sufficiently by natural ventilation alone for up to 40 parked cars, regardless of season.

In the case of business facilities, the required ventilation rate could be secured for up to 38 parked cars in summer and up to 47 in winter when the difference between the indoor and outdoor temperatures is 3 °C. The required ventilation rate could be secured for up to 47 parked cars in both summer and winter when the difference between the indoor and outdoor temperatures is 5 °C or higher. However, the required ventilation rate could not be secured when the temperature difference was 1 °C in the intermediate period. The required ventilation rate could be secured for up to 38 parked cars when the temperature difference was 3 °C in the intermediate period.

Cars frequently enter and exit neighborhood facilities and commercial facilities. Thus, the difference between the indoor and outdoor temperatures needs to be high to ensure that the ventilation rate requirements are satisfied by natural ventilation. The required ventilation rate could be secured for 20 parked cars in the intermediate period. Thus, in these facilities, each lot with more than 20-parked cars must introduce mechanical ventilation.

4. Overview of CFD Analysis
4.1 Subject Spaces
CFD analysis was done for underground parking lots with mechanical ventilation and 40-parked cars each (see Fig.3.). To simplify the shape, the authors omitted the entrance, exit, elevators, staircases, etc. Each lot was 50 m in length, 8.25 m in width, and 3.4 m in height. The fan room or dry area that is generally installed in a lot was excluded for the analysis. However, an air supply opening and an exhaust air opening for mechanical ventilation were included in the inner wall of each lot.

An air supply opening, exhaust air opening, and jet fans were used together as a mechanical ventilation system for the lots. One jet fan was installed in a ceiling area with a clearance of 1 m, and the other one was in another ceiling area with a clearance of 25.5 m from the air supply opening. For the analysis meshes, each area where a jet fan was installed was created with a tetra mesh because of its very complex shape. The other areas were created with a hexagonal mesh. The number of partitions in each analysis mesh was about 360,000.

4.2 Analysis Cases and Boundary Conditions

The commercial code ANSYS FLUENT 15 was used for CFD analysis. The RNG k-Epsilon model was used as the turbulence model with the SIMPLE algorithm and the second-order upwind differencing scheme. The convective and radiative heat transfers were also analyzed, and the surface-to-surface method was used for radiative analysis. Four cases were reviewed for analysis, and a summary of each case is shown in Fig.4. Many cases require mechanical ventilation in the intermediate period, so the CFD analysis was based on the environment in this period. In all the analysis cases, the air exhaust for each lot was set up as a forced air exhaust using a mechanical fan. The air supply was set up as a natural air supply.

The air supply openings were installed in an area near the ceiling (Cases 1 and 2) and an area near the floor (Cases 3 and 4). The exhaust air opening was installed near the ceiling in all the cases. The air supply directions were downward (Cases 1 and 4) and parallel (Cases 2 and 3). The air supply and exhaust near the ceiling in Case 1 are used in existing lots.

The boundary conditions for CFD analysis are shown in Table 1. The air velocity in the exhaust air opening was set based on the required ventilation rate (3.8016 m^3/s) for 40 parked cars in neighborhood facilities. In the case of the air supply opening, the air pressure and the ambient temperature were set to 0 Pa and 298.15 K, respectively, which is based on the pressure inlet needed to ensure natural ventilation. For each jet fan, an empty cylinder with a diameter of 0.175 m was formed. At the end of the cylinder, a cell zone was formed, and the air velocity was set to 17.34 m/s. This velocity was obtained by measuring a product that is mainly used in underground parking lots. The heat transfer coefficient for the surrounding wall was set as 0.34 W/m^2K, and the outside temperature was 294.15 K. The outside temperature is the average underground temperature at a depth of 1.5 m below the ground level in the Seoul region according to the Korea Meteorological Administration[18].

4.3 Evaluation Method for Indoor Air Quality

The indoor air quality of each lot was evaluated by SVE3 (Equation (6)) and SVE6 (Equation (7)) from the scales for ventilation efficiency (SVEs) proposed by Kato et al.[19-20]. SVE3 corresponds to the age of air in the air supply opening, and SVE6 corresponds to the residual lifetime of air in the exhaust air opening. SVE3 estimates the length of time required for fresh air to arrive indoors, and SVE6 estimates the length of time required for polluted air to be discharged outdoors.

Each of these required lengths of time was expressed as the air change rate per hour (ACH). This means that the lower the values of SVE3 and SVE6 are, the higher the ventilation efficiency is. SVE3 and SVE6 were analyzed using the passive scalar method.

$$SVE3(X) = \frac{c'_X(X)}{c_s} \tag{6}$$

$$SVE6(x) = \frac{c''_X(X)}{c_O} \tag{7}$$

The contaminant removal effectiveness (CRE)[21] was evaluated for mechanical ventilation of CO from cars in each lot as expressed in Equation (8). The amount of CO emitted was measured using 0.2918 kg/s as proposed by Kwon et al.[4]. CRE was calculated using the passive scalar method for CFD.

$$CRE = \frac{c_e - c_s}{c_i - c_s} \tag{8}$$

5. Ventilation Efficiency for Different Mechanical Ventilation Systems

5.1 Analysis Results of SVE3 and SVE6

Fig.5. and Fig.6. show the analysis results of SVE3 and SVE6 for a lot in the intermediate period. The SVE3 results are as follows. In Case 1 and Case 4, the fresh air from the air supply opening was spread across the entire lots by the jet fans. As a result, SVE3 for the lower part of the lots showed a distribution of about 0.5-1.2.

In Case 2, the fresh air could not spread to the lower part of the lots but was immediately discharged into the exhaust air opening by the jet fans for parallel air supply. This occurred because the fresh air temperature was higher than the air temperature of the parking lots. As a result, SVE3 for the lower part of the lots was above 1.2. In Case 3, the fresh air rose slowly to the upper part of the lots under the influence of the buoyancy effect, after which it was discharged while being spread little by little by the jet fans for parallel air supply.

In the case of SVE6, Case 1 and Case 4 with downward air supply of the jet fans showed the lowest values around the exhaust air opening and in the lower part of the lots. Case 2 and Case 3 showed lower SVE6 values around the exhaust air opening in the upper part of the lots only. SVE6 showed high values above 1.2 near the floor of the lots in particular, and the air exhaust was not smooth.

The air breathed by people in an underground parking lots is not higher than 1.8 m from the floor, considering the thermal plume of the human body[22]. Fig.7. shows the average SVE3 and SVE6 values with a height of 0-1.8 m from the floor as the occupied
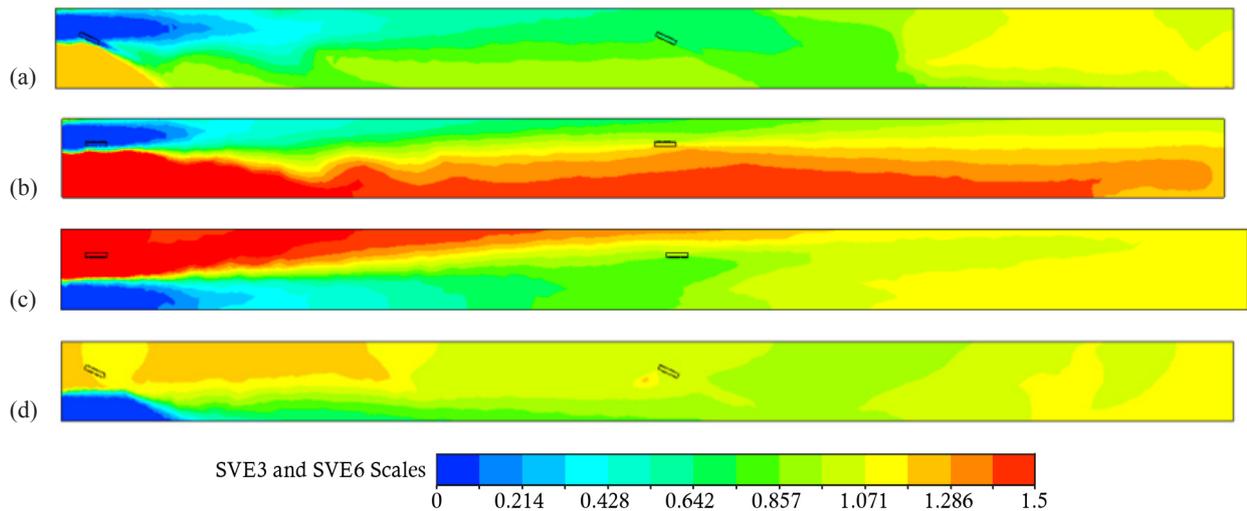
Fig.5. SVE3 Distribution by the Supply Air Opening: (a) Case1 (b) Case2 (c) Case3 (d) Case4
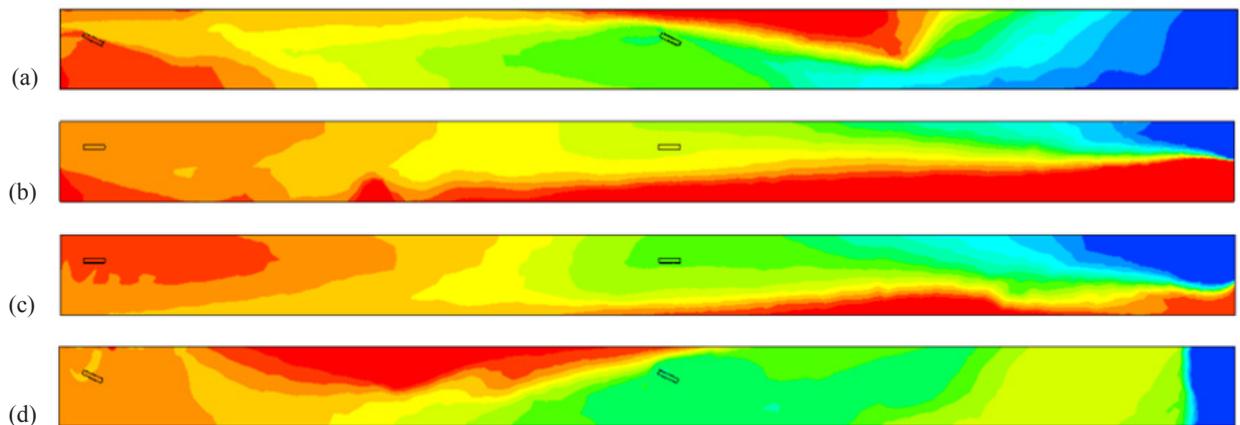

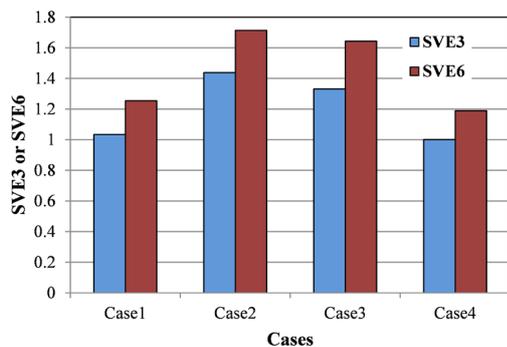Fig.6. SVE6 Distribution by the Supply Air Opening: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4

Fig.7. Average SVE3 and SVE6 in the Occupied Zone of Underground Parking Lots

zone. In Case 4, SVE3 and SVE6 showed the lowest values of 1.0 and 1.18, respectively. In Case 2, SVE3 and SVE6 were 1.43 and 1.713, respectively. Case 2 showed an increase of 43% in SVE3 and an increase of 44% in SVE6 in comparison with Case 1. SVE3 and SVE6 in Case 1 showed high values of 3% and 5% in comparison with Case 4.

5.2 Analysis Results of CRE

CRE was reviewed in Case 4, which showed the best ventilation efficiency in the analysis of SVE3 and SVE6, as well as Case 2, which showed the poorest ventilation efficiency. The CRE of the occupied zone in each case was calculated using the CFD analysis results. CRE was calculated in Case 4 and Case 2 as 0.8386 and 0.7652, respectively. In other words, Case 4 showed the contaminant removal effectiveness of about 10% in comparison with Case 2.

6. Conclusion

This study has presented ventilation guidelines for underground parking lots to building designers.

1) The CO emissions from cars used in designing lots in Korea were obtained before 1990. The amount emitted from cars in 2000 to 2005 accounted for about 44.3% of the established value.

2) The natural ventilation rates that occurred according to season were lowest in the intermediate period when the difference between the indoor and outdoor temperatures was small.

3) In the case of the apartment building, the required ventilation rate could be secured sufficiently by natural ventilation alone for up to 40 parked cars, regardless of season.

4) In the case of the business facilities, the required ventilation rate could not be secured by natural ventilation alone when the difference between the indoor and outdoor temperatures was 1°C in the intermediate period. However, the required rate could be secured for up to 38 parked cars when the difference was 3°C.

5) In the cases of the neighborhood facilities and the commercial facilities, each lot with more than 20-parked cars must introduce mechanical ventilation.

6) In the case of the mechanical ventilation, the best ventilation efficiency occurred with the system of downward air supply from jet fans in combination with an air supply near the floor and an air exhaust near the ceiling.

Symbols

1) A : cross-sectional area of opening (m^2)
2) C_o : outdoor carbon monoxide concentration (m^3/m^3)
3) Cd : allowed indoor carbon monoxide concentration (m^3/m^3)
4) C_D : discharge coefficient
5) C_e : contaminant concentration of the exhaust air (kg/kg)
6) C_s : contaminant concentration of the supply air (kg/kg)
7) C_i : contaminant concentration of occupied zone (kg/kg)
8) C_o, C_s : concentration under perfect mixing condition, $C_o, C_s = q/Q$
9) $C'_x(X)$: concentration at point X where tracer is uniformly generated through a room in total generation rate q (kg/s)
10) $C''_x(X)$: virtual concentration at point X where tracer is uniformly generated through a room in total generation rate q (kg/s) and time pass in reverse
11) G : average carbon monoxide emission caused by driving (g/km)
12) H_i : the average idling time (2min/car)
13) H_{NPL} : height of neutral pressure level above reference plane without any other driving forces (m)
14) L : average driving distance (m/car)
15) M : indoor carbon monoxide emission (m^3/h)
16) M_1 : carbon monoxide emissions caused by driving (g/h)
17) M_2 : carbon monoxide emissions caused by idling (g/h)
18) M_i : average carbon monoxide emissions caused by idling (g/min)
19) $SVE3(X)$: age of air at position X in spatial room
20) $SVE6(X)$: residual lifetime of air at position X in spatial room
21) T : the number of car accessed to parking lots (car/h)
22) T_i : the number of cars idling in the parking lots (car/h)
23) $Temp_i$: indoor temperature (K)
24) $Temp_o$: outdoor temperature (K)
25) Q : required ventilation rate (m^3/h)
26) Q_a : natural ventilation rate (m^3/s)

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