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Energy and Air Quality Benefits of DCV with Wireless Sensor Network in Underground Parking Lots

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Abstract

This study measured and compared the variation of ventilation rate and fan energy consumption according to various control strategies after installing wireless sensor-based pilot ventilation system in order to verify the applicability of demand-controlled ventilation (DCV) strategy that was efficient ventilation control strategy for underground parking lot. The underground parking lot pilot ventilation system controlled the ventilation rate by directly or indirectly tracking the traffic load in real-time after sensing data, using vehicle detection sensors and carbon monoxide (CO) and carbon dioxide (CO_2) sensor. The ventilation system has operated for 9 hours per a day. It responded real-time data every 10 minutes, providing ventilation rate in conformance with the input traffic load or contaminant level at that time. A ventilation rate of pilot ventilation system can be controlled at 8 levels. The reason is that a ventilation unit consists of 8 high-speed nozzle jet fans. This study proposed vehicle detection sensor based demand-controlled ventilation (VDS-DCV) strategy that would accurately trace direct traffic load and CO sensor based demand-controlled ventilation (CO-DCV) strategy that would indirectly estimate traffic load through the concentration of contaminants. In order to apply DCV strategy based on real-time traffic load, the minimum required ventilation rate per a single vehicle was applied. It was derived through the design ventilation rate and total parking capacity in the underground parking lot. This is because current ventilation standard established per unit floor area or unit volume of the space made it difficult to apply DCV strategy according to the real-time variation of traffic load. According to the results in this study, two DCV strategies in the underground parking lot are considered to be a good alternative approach that satisfies both energy saving and healthy indoor environment in comparison with the conventional control strategies.

Keywords: Demand-controlled ventilation (DCV), Energy saving potential, Indoor air quality, Underground parking facilities, Wireless sensor network

1. Introduction

After 1990s, the heating, ventilating, and air conditioning (HVAC) design industry realized that there was a high percentage of time that our buildings were not fully occupied, and therefore during these times of partial occupancy, it is acceptable to reduce inefficient energy consumption by controlling ventilation rate (Jeannette and Phillips, 2006). Demand-controlled ventilation (DCV) strategy is defined the automatic control of ventilation rate according to the concentration of suspended indoor contaminants generated by human activities (Raatschen, 1992). It means that carbon dioxide (CO_2), primary contaminant emitted from human beings, is used as an indicator of determining whether the space is occupied. The outdoor air intake rate for ventilation is adjusted based on the variation of CO_2 level (Jones et al., 2001). However, some of researchers pointed out a problem of not satisfying the acceptable level of indoor air quality due to other contaminants if ventilation rate provided indoors went below a certain level as the number of occupants decreased (Emmerich and Persily, 2001; Musser and Persily, 2002). As the solution to the problem, ASHRAE Standard 62.1-2004 additionally stipulated the required ventilation rate per unit floor area for removing or diluting the contaminants emitted from the building itself while the building is not occupied (Taylor, 2006).

DCV strategy was able to gain various benefits such as energy savings, indoor air quality enhancement, and building occupancy information acquisition owing to the great development of sensor technology (Fisk and De Almeida, 1998). It is important to accurately trace indoor occupancy level in real-time so as to gain potential benefits through the application of DCV strategy (Leephakpreeda et al., 2001). Recently, data on measuring the occupants of building is collected and evaluated by using various sensors (Li et al., 2012; Kuutti et al., 2014). The key to the data measurement for the successful application of DCV strategy is the repeatability of the sensing system or method (Dougan and Damiano, 2004).

Because there are various contaminants indoors, DCV strategy can be applied not only CO_2 but also other specific contaminants as indicator. As an example, there is a case of evaluating the applicability of contaminants such

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as volatile organic compounds (VOC) and humidity besides CO_2, the contaminant indicator of DCV strategy (Fahlen et al., 1992). In another case, a simulation has been performed in consideration of a variation in the concentration of VOC during the period of non-occupancy (Musser and Persily, 2002). A ventilation system was optimized through the comparison of CO_2 and Radon (Rn) concentration in the experiment conducted in a lecture theatre, Hong Kong (Chao and Hu, 2004). And DCV strategy has been applied based on CO_2 concentration and absolute humidity level in the outdoor air and exhaust air (Nielsen and Drivsholm, 2010).

Recently, studies relating to DCV strategy are actively in progress, focusing on the occupied space such as public assembly space, office building, residential building, multi-purposed facilities, school and sports facilities (Chao and Hu, 2004; Nielsen and Drivsholm, 2010; Mysen et al., 2005; Owen et al., 2011), but the actual condition is that DCV studies on the unoccupied space such as parking facilities or industrial facilities are insufficient. However, according to the International tunneling and underground space association (ITA) Working Group report in 1995, it was predicted that the construction of underground parking lot would steadily increase around the densely populated areas (Godard, 1995). Until recently, the requirement of more parking spaces has been continuously shown as well (Litman, 2011). Besides, around the developed big cities with, the high percent of private car ownership rates, a demand for parking spaces is shown to be more inevitable (Al-Fouzan, 2012).

The conventional ventilation system of constant volume control (CVC) used for the mechanical ventilation in underground parking lot demonstrates performance that greatly conforms to requirements in the aspect of indoor air quality. However, problems are still reported in terms of the excessive fan energy consumption. On the other hand, the ventilation system of simple binary control reduces fan energy consumption through intermittent operation. However, deterioration is inevitable in the aspect of indoor air quality. Therefore, it is required to apply DCV strategy to the underground parking lot in order to improve the fan evergy savings and the indoor air quality at the same time.

Required ventilation rate for removing or diluting carbon monoxide (CO) until its concentration is below acceptable level in the underground parking lot can satisfy the requirement that the concentration of other indoor contaminants should be below a certain level. It means that the indicator of contamination in the underground parking lot is presented based on CO (ASHRAE, 2007). In general, established ventilation standard of each country is defined as the minimum required ventilation rate to maintain CO concentration below acceptable level. Each recommended ventilation rate is normalized for the unit floor area or unit volume of space, as shown in Table 1 (Krarti and Ayari, 2001). It is considered that current ventilation standard for underground parking lot makes it difficult to integrate into DCV strategy based on the real-time traffic load.

Therefore, this study defined the required ventilation rate per a single vehicle that is the primary source that directly generates contaminants in order to apply the DCV strategy to the underground parking lot as well. It was derived based on the design ventilation rate and total parking capacity in the underground parking lot. An underground parking lot pilot ventilation system based on wireless sensor network was installed on the basis of pre-study through simulation (Cho et al., 2013). And then, it was intended to verify the applicability of DCV strategy based on real-time traffic load through the comparison in terms of fan energy consumption and indoor air quality in accordance with various control strategies.

2. Experiments

2.1. Demand-controlled pilot ventilation system

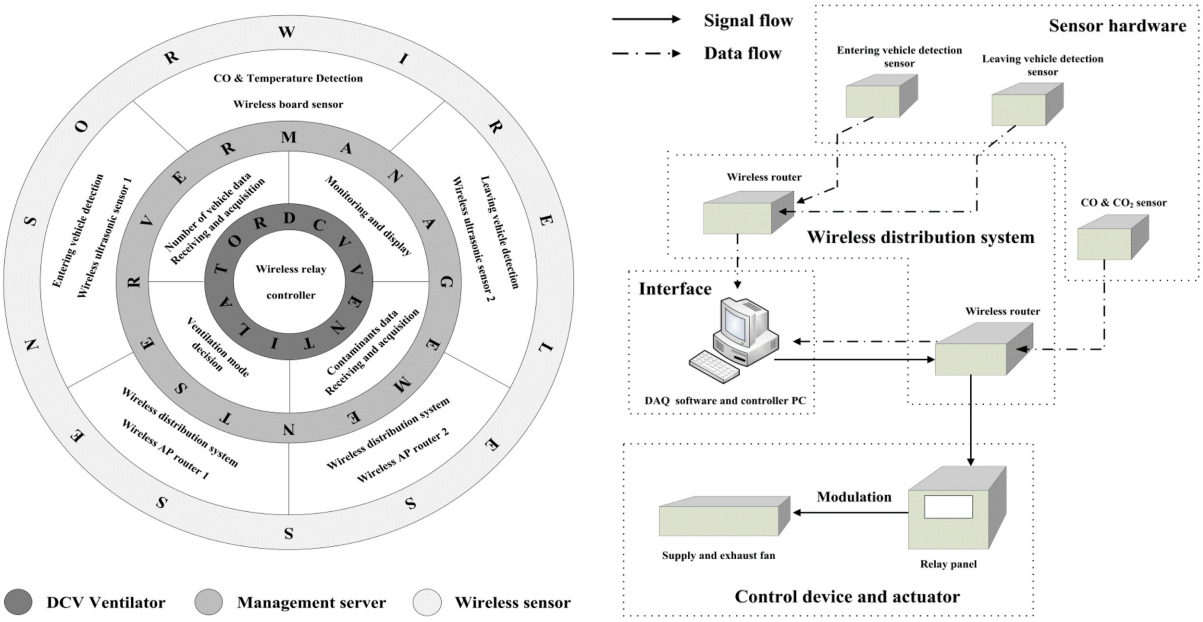
As shown in the Fig. 1A, the pilot ventilation system is classified into three concepts. It consists of wireless sensor part that acquires data for operating the underground parking lot pilot ventilation system and sends the data to the controller computer; management server part that saves and manages the received data and decides on the ventilation control strategy and then displays on the monitor; and DCV ventilator part that modulates ventilation rate through controlling a wireless relay controller according to the signal.

Fig. 1B depicts the schematic of pilot ventilation system. The information acquired by two vehicle detection sensors that count the entering and leaving vehicles and a sensor that measures indoor contaminants (CO, CO_2) is

Table 1. Ventilation rates for enclosed parking garages

	ASHRAE (USA)	Finland	France	Germany	Korea	Sweden	U.K
Period [hr]	$8^a/1^b$	$8^a/0.25^b$	$8^a/0.33^b$	-	8^a	-	$8^a/0.25^b$
CO [ppm]	$25^a/35^b$	$30^a/75^b$	$50^a/100^b$	-	25^a	-	$50^a/300^b$
Ventilation rate	27 [m^3/hr-m^2]	9.7 [m^3/hr-m^2]	594 [m^3/hr-car]	11.9 [m^3/hr-m^2]	27 [m^3/hr-m^2]	3.3 [m^3/hr-m^2]	6-10 ACH

Note: [a] Time Weighted Average concentration (TWA), [b] Short term exposure limit (STEL)
(e.g. 8-hour exposure limitation is for 25ppm, and 1hour exposure limitation is for 35ppm on ASHRAE 2007)[8]



(a) Concept of pilot ventilation system

(b) Schematic of pilot ventilation system

Figure 1. Demand controlled pilot ventilation system.

sent to data acquisition (DAQ) program in the controller personal computer (PC) through access point (AP) wireless network. The acquired data can be monitored in real-time through central controller PC. An interface is so built that users can set up ventilation control strategy. If the user decides on the ventilation control strategy in the user interface, a signal is sent to the controller through wireless network. And then, ventilation system starts to control the ventilation rate according to the chosen control algorithm.

2.2. Description of underground parking lot

The pilot ventilation system was installed in the 4th underground floor of underground parking lot in a university building (with 4 stories below and 15 above the ground) located in Seoul. A 3,895 m^2 of floor area and 13,243 m^3 of volume in the underground parking lot is selected for the DCV experiments. The design parking density is 3 cars/108 m^2, so the parking space is able to accommodate 122 vehicles. As shown in Fig. 2, apparatuses required for the underground parking lot pilot ventilation system were installed. First of all, ultrasonic based vehicle detection sensors were arranged on both sides of entrance in the 4th underground floor of underground parking lot, and then overall counting error was kept within 5% by continually carrying out calibration. Besides, the counting error according to lane departure was prevented from occurring by installing a center divider so as to minimize the counting error. With regard to wireless router, AP wireless network was set by using a single channel utilizing wireless distribution system. One AP router was installed between vehicle detection sensors and controller PC. And the other AP router was installed between CO and CO_2 sensor and controller PC. The CO and CO_2 sensor board were attached to the pillar at the center of underground parking lot, at a height of 1.5 above the floor. The greatest feature of pilot ventilation system is the construction of supply and exhaust ventilation unit by combining 8 high-speed jet nozzle fans. Ventilation rate was enabled to be controlled according to the 8 individual fan control signals. Each high-speed jet nozzle fan has 6,500 CMH of supply and exhaust air flow rate. The total design ventilation rate is set to 52,000 CMH. Each high-speed jet nozzle fan has 200 Pa of static pressure, and 550 W of power consumption.

2.3. Pilot ventilation system control strategies

- Constant volume control (CVC): It is a general ventilation control strategy applied to the underground parking lot ventilation system. It is a method that continuously provides constant or fixed design ventilation rate. It is appropriate for underground parking lot with the high usage rate or circulation rate. However, a lot of fan energy consumption is inevitable. On the other hand, there are advantages that a complicated control algorithm is not required, and automatic control is available by entering a simple schedule data.
- Simple binary control: Simple binary control is a typical ventilation control strategy applied internationally owing to the efficiency of control and advantage in the energy savings. Simple binary control is regarded as a kind of DCV strategy (Martin, 2001). It is a method that indoor CO centration is monitored in real-time. And then, when the indoor CO centration reaches at its upper limit

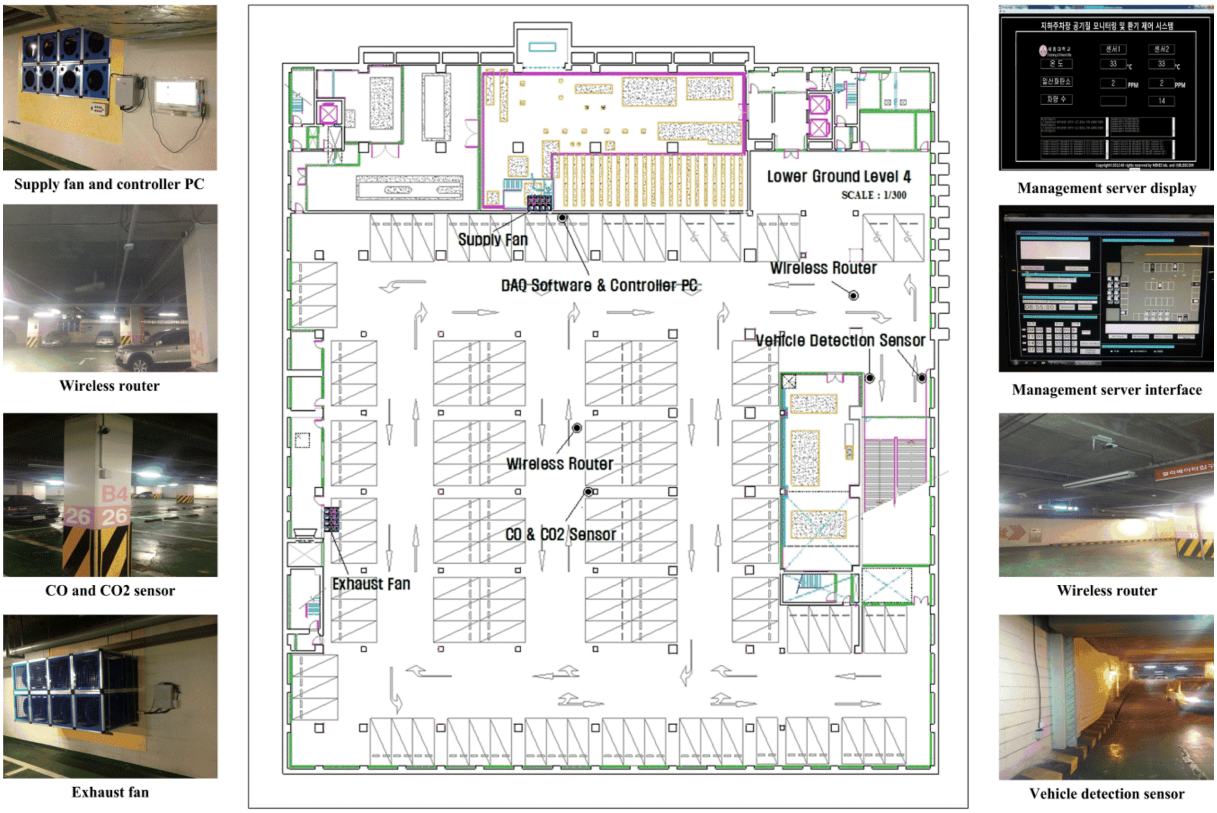


Figure 2. Experimental setup on underground parking lot.

level, constant volume ventilation system are activated and supply design flow until the CO concentration is back to normal.

• CO-DCV: DCV strategy through monitoring the concentration of representative indoor contaminant in the buildings or air-conditioned spaces has been attracting many interests. The CO-DCV is similar to carbon dioxide based demand-controlled ventilation (CO_2-DCV) strategy generally considered in the indoor space. It uses CO detection sensor for estimating real-time variation of the traffic load by monitoring the indoor CO concentration variation, and modulating the ventilation rate. The CO sensor can be installed inside of underground parking space or exhaust tower.

• VDS-DCV: The VDS-DCV is based on the actual number of traffic load monitored by the counting sensors installed at the entrance and exit of the underground parking lot. Based on the real-time variation of the traffic load, the ventilation rate can be controlled. When a tendency is considered according to the development of information and communication technology (ICT) and various sensors, it is expected that DCV strategy can be effectively connected through central control if a vehicle detection sensor is linked with real-time vehicle monitoring system. It is also anticipated that a big energy saving impact can be produced as contrasted with the initial cost of sensor installation. However, VDS-DCV strategy requires a premise that the whole occupant traffic load is assumed to be a potential contamination source because it is impossible to uniformly predict the driving and idling pattern of real-time traffic load in the VDS-DCV strategy.

3. Results and Discussion

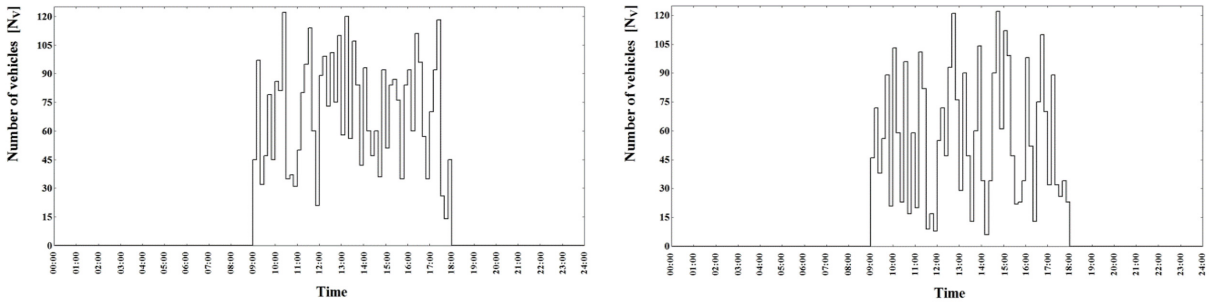
This study measured and compared fan energy consumption according to the ventilation control strategies for underground parking lot where the pilot ventilation system is installed so as to verify the applicability of DCV strategy. In case of operating the ventilation system, the actuator responds to the real-time monitored data every 10 minutes. Ventilation rate was provided in conformance with the input traffic load or contaminant level at that time. The reason why the pilot ventilation system was set to respond every 10 minutes was that the minimum operation time was set for 10 minutes in consideration of the overload of ventilation units due to the frequent change of operation. The experiments have been performed that in the condition where the ventilation system has operated during 9 hours per a day.

3.1. VDS-DCV

In the VDS-DCV strategy, the required ventilation rate per a single vehicle is calculated by the ratio of design ventilation rate to total number of parking capacity in the

Table 2. Ventilation rates for VDS-DCV strategy

VDS-DCV strategy								
Traffic load [cars]	0~15	16~30	31~45	46~60	61~75	76~90	91~105	106~
Ventilation rates [CMH]	6,500	13,000	19,500	26,000	32,500	39,000	45,500	52,000
Operating fans [fans]	1	2	3	4	5	6	7	8



(a) Traffic load schedule 1st (b) Traffic load schedule 2nd

Figure 3. Traffic load schedule for VDS-DCV strategy.

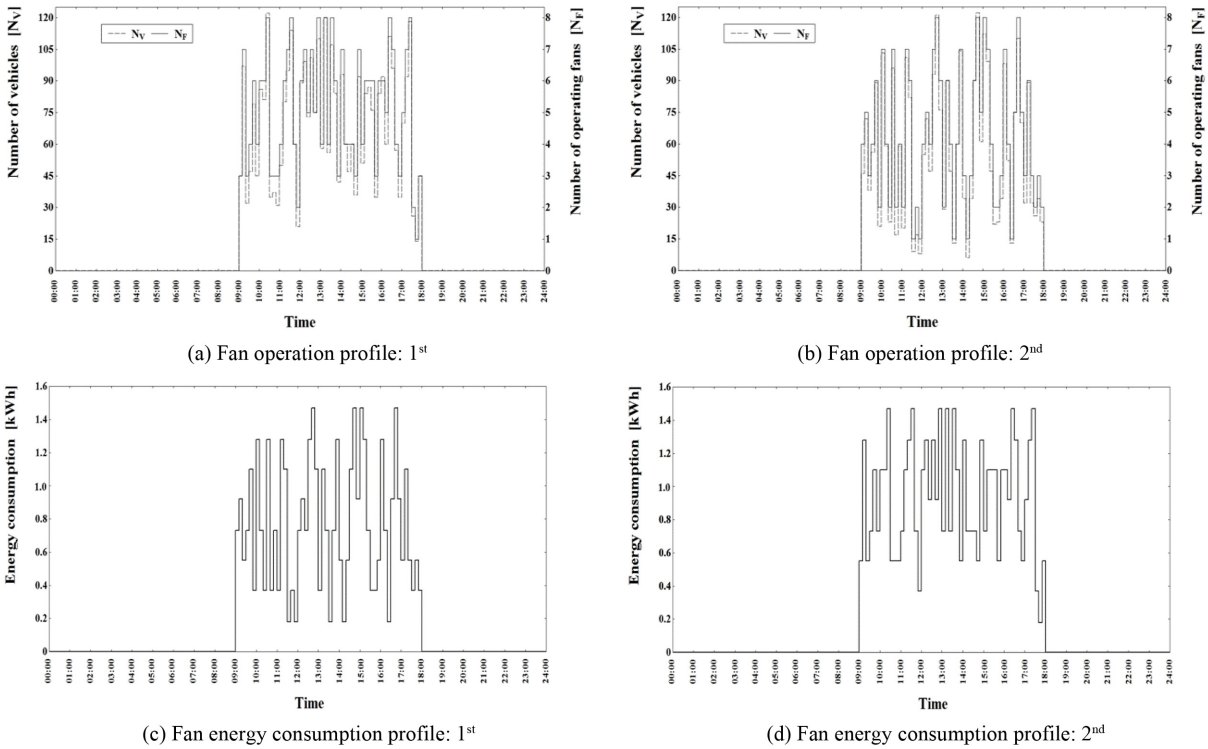
underground parking lot. The provided ventilation rate according to the real-time traffic load can be automatically controlled at 8 levels, as shown in Table 2. In this experiment, a traffic load schedule reflected every 10 minutes is defined as shown in Fig. 3. The variation of supply air flow rate was measured by implementing the traffic load schedule through the recognition of sensor. Especially, in the 2nd experiment, it was intended to additionally examine the impact of DCV strategy according to the fluctuation of traffic load by getting the fluctuation of traffic load to be relatively larger than that of the 1st experiment. On the other hand, because CVC strategy is not a ventilation control strategy using a contamination source in the underground parking lot, and the ventilation rate does not change according to the fluctuation of traffic load, it was excluded from the experiment. However, the assumed results were mentioned for quantitative comparison with VDS-DCV strategy.

A variation in the number of the operating ventilation unit and fan energy consumption profile was shown according to the real-time traffic load in Fig. 4. In case of the experiment results of VDS-DCV strategy, it is possible to find that the ventilation air flow is adjusted according to the traffic load range specified in Table 2 in response to the variation of real-time traffic load data measured through the sensor. One may see that a change in the operation of ventilation system is shown to be bigger in the 2nd experiment where the fluctuation of traffic load is larger (Fig. 4A, 4B). Therefore, it is expected that a fan energy saving impact will be much bigger according to the application of VDS-DCV strategy in underground parking lot where the fluctuation of traffic load is large. This is because the number of operating ventilation unit ingreases and decreases proportionally to the fan energy consumption due to the pilot ventilation system characteristics (Fig. 4C, 4D). It is shown that development of information and communication technology (ICT) can realize the application of VDS-DCV strategy which accurately traces traffic load that is direct contamination source of underground parking lot similarly to radio frequency identification technology based demand-controlled ventilation (RFID-DCV) strategy of occupied space.

3.2. Simple binary control and CO-DCV

Simple binary control and CO-DCV strategy is what controls a ventilation system based on CO concentration that is the contamination indicator of underground parking lot. However, this study carried out the simulated experiment of two control strategies after replacing CO with CO_2 for indicator of contamination that can be caused by traffic load. Because it is difficult to artificially generate CO for the same condition of experiment. Another reason is that the actual variation of CO concentration was not large according to the traffic load. The simulated experiment using the concentration of CO_2 means the automatic control of ventilation unit according to the corresponding CO_2 concentration after injecting a certain amount of CO_2 that is tracer gas to the underground parking space.

For comparison of the simulated experiment of CO-DCV strategy and simple binary control strategy, the same experimental condition was planned. The experiments consisting of different CO_2 injection quantity and injection time were carried out 2 times (Fig. 5). Before carrying out the experiment (22 p.m. to 23 p.m.), indoor concentration of underground parking lot was kept equal to the reference of the outdoor air through the operation of ventilation system. As shown in the Fig. 5, CO_2 was injected indoors at regular intervals of time. Simple binary control strategy activates the ventilation system in case indoor CO_2 concentration exceeds 2500 ppm. It was set to pro-



(a) Fan operation profile: 1st

(b) Fan operation profile: 2nd

(c) Fan energy consumption profile: 1st

(d) Fan energy consumption profile: 2nd

Figure 4. VDS-DCV strategy.

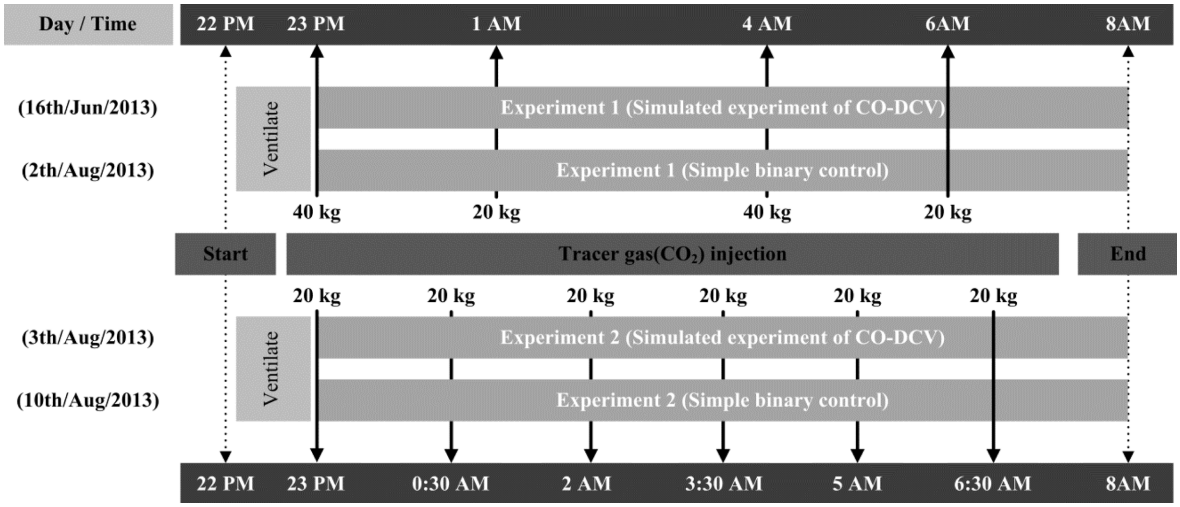


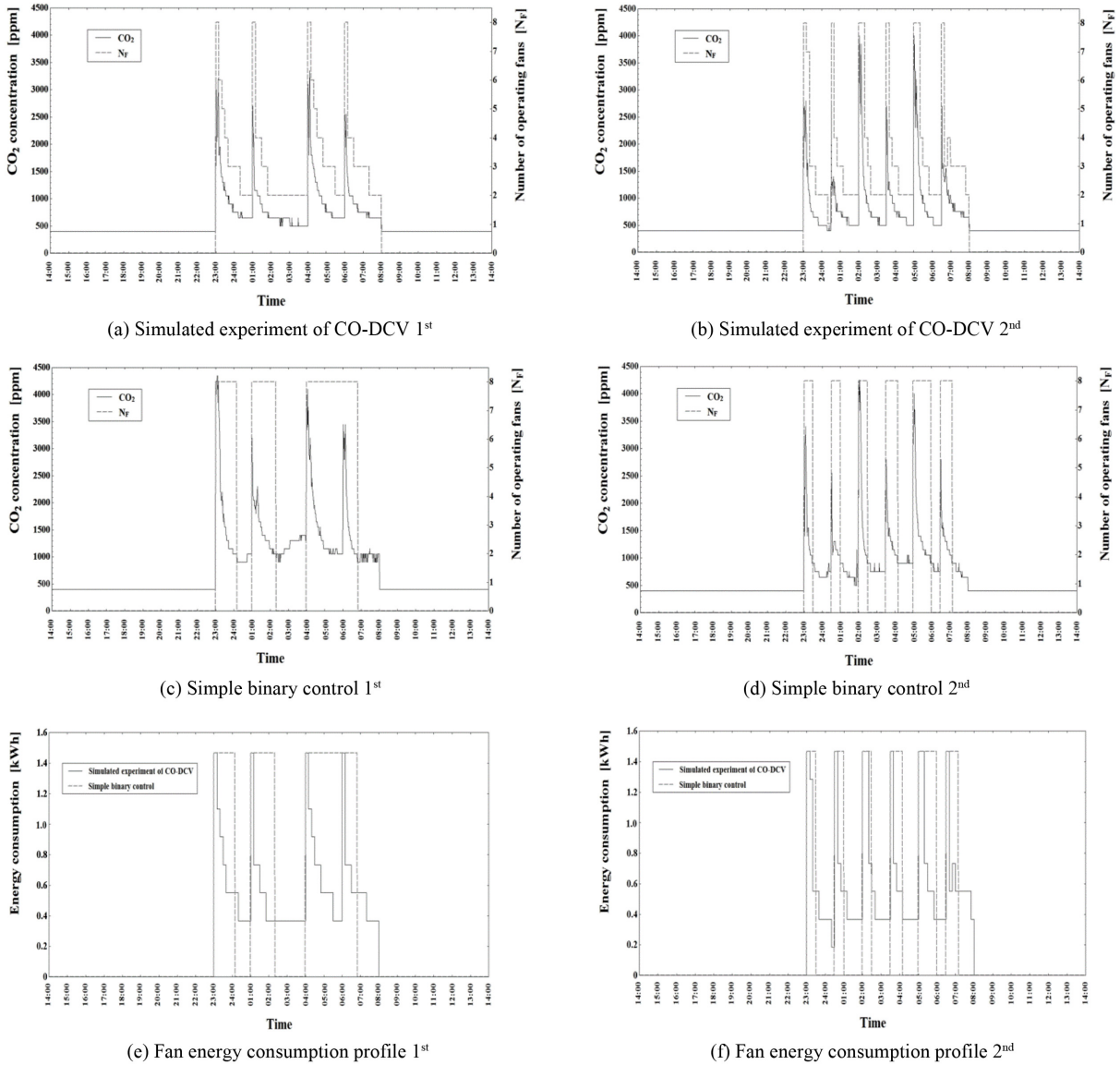
Figure 5. Experimental schedule for simple binary control and simulated experiment of CO-DCV.

vide the maximum ventilation rate regardless of the variation of indoor CO_2 concentration so as to enable the concentration to rapidly fall back below threshold CO_2 limit of 1000 ppm in the underground parking lot. On the other hand, in the simulated experiment of CO-DCV strategy, the ventilation system was continuously operated from 23 p.m. to 8 a.m. regardless of 2500 ppm of initial trigger point. Based on the assumption that the variation of CO_2 concentration was due to the fluctuation of traffic load, the required ventilation rate was controlled at 8 levels by monitoring the variation of CO_2 concentration (Table 3). However, the reason why the required ventilation rate is controlled according to the CO_2 concentration change of 300 ppm is that the value is calculated by classifying 2500 ppm of trigger point and 400 ppm of CO_2 concentration in the outdoor air into 8 levels so as to compare its performance with that of simple binary control strategy that is the conventional ventilation control strategy.

Fig. 6 shows a variation in the number of operating ventilation unit and energy consumption profile according

Table 3. Ventilation rates based CO_2 concentration for control strategy

Ventilation rates by CO_2 concentration								
CO_2 concentration [ppm]	Over 2500	2500~2200	2200~1900	1900~1600	1600~1300	1300~1000	1000~700	700~400
Simple binary control	Maximum ventilation rate (Initial trigger point is 2500 ppm)						No operation	
Simulated experiment of CO-DCV [CMH]	52000	45500	39000	32500	26000	19500	13000	6500



(a) Simulated experiment of CO-DCV 1st

(b) Simulated experiment of CO-DCV 2nd

(c) Simple binary control 1st

(d) Simple binary control 2nd

(e) Fan energy consumption profile 1st

(f) Fan energy consumption profile 2nd

Figure 6. Simple binary control and simulated experiment of CO-DCV.

to the variation of CO_2 concentration in the underground parking lot. In case of simulated experiment of CO-DCV, it can be shown that the required ventilation rate continuously modulates according to the variation of indoor CO_2 concentration (Fig. 6A and 6B). However, in case of simple binary control strategy, it is possible to find that the provided ventilation rate is kept at 52,000 CMH of the maximum design ventilation rate until indoor CO_2 concentration reaches 1000 ppm of normal level after the operation of ventilation system (Fig. 6C and 6D). The profile of same pattern is observed in the aspect of energy consumption equally (Fig. 6E and 6F). Though it was simulated the applicability of DCV strategy according to the variation of concentration by using CO_2 tracer gas simple to realistically measure, it is considered that it is also possible to implement CO-DCV strategy which directly uses CO concentration as indicator in the underground parking lot.

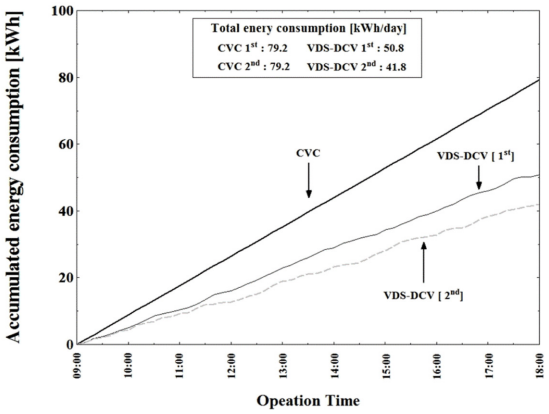
Table 4. Averaged ventilation performance for control strategies

	1st Simple binary control	1st Simulated experiment of CO-DCV	2nd Simple binary control	2nd Simulated experiment of CO-DCV
Local mean age of air	0.54 [hr]	0.52 [hr]	0.67 [hr]	0.65 [hr]
Nominal Time constant	0.25 [hr]	0.48 [hr]	0.46 [hr]	0.42 [hr]
Air-exchange efficiency	24.4 [%]	47.3 [%]	34.5 [%]	32.8 [%]
Averaged CO_2 level	1426.8 [ppm]	908.7 [ppm]	1098.4 [ppm]	925.5 [ppm]

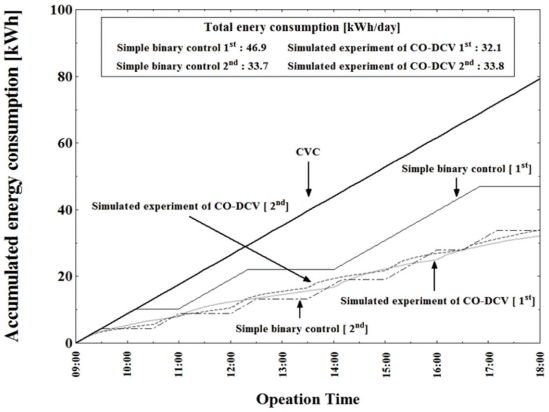
It was intended to simultaneously carry out evaluation of indoor air quality by using concentration decay method as well as the variation of ventilation rate for the two control strategies (Table 4). In order to evaluate ventilation performance in the aspect of air environment, air-exchange efficiency was calculated according to the injection time of CO_2 tracer gas respectively (Etheridge and Sandberg, 1996). And then the results were averaged. In the 1st experiment, local mean age of air in the underground parking lot was similar to 0.54 hr and 0.54 hr respectively. However, more excellent air-exchange efficiency of 47.3% was shown in case of the simulated experiment of CO-DCV which slowly supplied air indoors. On the other hand, in the 2nd experiment, air-exchange efficiency according to the two control strategies shows similar results of 34.5% and 32.8% respectively. Meanwhile, it was shown that only the simulated experiment of CO-DCV satisfied the requirements that the average CO_2 concentration should be below acceptable limit of 1000 ppm for the total operating time of ventilation system. The reason is that threshold CO_2 limit was set for 1000 ppm in case of simple binary control strategy. If the acceptable level is set for a value which is lower than the present one, simple binary control can also satisfy the standard that the average CO_2 concentration should be below 1000 ppm of indoor acceptable level. However, it is expected that the increase of fan energy consumption will be inevitable due to this.

3.3. Energy savings

The accumulated energy consumption changes for the operating time of ventilation system, as shown in Fig. 7. It was found that VDS-DCV strategy through the accurate tracking of traffic load shows the slowly increasing tendency of fan energy consumption in comparison with CVC strategy. A difference in the accumulated energy consumption gradually increases over time (Fig. 7A). It was also shown that the total energy consumption of the 2nd experiment which had relatively large fluctuation of traffic load was 41.8 kWh/day, and fan energy saving impact is bigger in comparison with 50.8 kWh/day of the 1st experiment. Fig. 7B shows the variation of the accumulated energy consumption in the simulated experiment of CO-DCV and simple binary control strategy which was the ventilation control strategy using the variation of CO_2 concentration in the underground parking lot. It is possible to find that the simulated experiment of CO-DCV strategy



(a) CVC and VDS-DCV



(b) Simple binary control and simulated experiment of CO- DCV

Figure 7. DCV impact on accumulated fan energy consumption.

with continuous operating ventilation system shows lower total energy consumption (32.1 kWh/day) than simple binary control strategy (46.9 kWh/day) with intermittent operation pattern in the 1st experiment. On the other hand, in case of the 2nd experiment, energy consumption pattern was different from each other, but total energy consumption shows similar results of 33.7 kWh/day and 33.8 kWh/day respectively.

3.4. Discussion

The existing underground parking lot satisfies the requirements that CO concentration should be below accepta-

ble level through ventilation system operation of CVC strategy. However, problems are still reported about the excessive fan energy consumption. For this reason, the greatest advantage of applying the DCV strategy to the underground parking lot is the fan energy saving. Table 5 was intended to show fan energy saving impact in accordance with the application of DCV strategy through the quantitative results of fan energy performance according to each ventilation control strategy of pilot ventilation system.

VDS-DCV strategy providing ventilation rate with tracing accurate traffic load in the underground parking lot shows higher energy saving rate of approximately 36~47% in comparison with CVC strategy (Table 5). It is considered that sufficient benefits can be gained the energy savings through the application of VDS-DCV based on traffic load that is direct contamination source in the underground parking lot, similarly to DCV strategy that counts the number of occupants in the occupied space. On the other hand, in case of the experiment of VDS-DCV strategy, fan energy analysis was performed using the implementation of arbitrary traffic load schedule, but it was impossible to directly evaluate the indoor air environment. However, when considered on the basis of pre-study (Cho et al., 2013), it is expected that there will be an advantage in the aspect of indoor air quality owing to the continuous supply of the outdoor air to the underground parking lot.

What can be considered through the results shown in Fig. 4 is that VDS-DCV strategy does not require any complicated mathematical model, but it is important to accurately trace traffic load over time. For VDS-DCV strategy, high accuracy and technical supplement with regard to the error is required through the installation of high-performance vehicle detection sensor. Especially, it is considered that a camera-based vehicle detection sensor will show very suitable performance in comparison with the conventional ultrasonic sensor and infrared sensor (Ichihashi et al., 2010). In particular, it is expected that VDS-DCV strategy can offer additional benefits of real-time parking management information inside the building (Teodorović and Lučić, 2006; Giuffrè et al., 2012) which has been actively studied for the recent 10 years through integration with sensor technology based on the wireless network.

According to the results of simulated experiment of CO-DCV, it was found that an energy saving impact of an average of 18.1% can be produced in comparison with the conventional simple binary control strategy. However, the results of simulated experiment of CO-DCV show a slight difference between the 1st experiment and the 2nd one. In the 1st experiment, the simulated experiment of CO-DCV continuously responding to the variation of CO_2 concentration shows the energy saving impact of approximately 31.6% in comparison with the conventional simple binary control strategy. And it is also found that more excellent performance was shown in terms of indoor air environment (Table 4). On the other hand, it is possible to find that similar performance is shown in both energy savings and air-exchange efficiency in the 2nd experiment (Table 4 and 5). It is considered that this is because the simple binary control strategy shows a kind of the same operation effect as that of DCV strategy due to the emission of a relatively small amount of contaminant at short time intervals in the 2nd experiment.

The biggest difference between the two control strategies in terms of indoor air quality is well illustrated by the Fig. 6A and 6C which is the result of the 1st experiment. One may see that the indoor CO_2 concentration increases when the ventilation system deactivates in case of the intermittently operating simple binary control strategy. On the other hand, a certain level of concentration is constantly maintained through the continuous operation of ventilation system in case of DCV strategy. This is one of the greatest advantages of DCV strategy in terms of indoor air quality. Therefore, one may conclude that DCV strategy continuously supplying the outdoor air can become a better alternative strategy in comparison with the conventional simple binary control when it is considered good

Table 5. Summary of fan energy performance with different ventilation strategies

Experiment	Strategy	Total air volume [m^3/day]	Fan energy consumption [kWh/day]	Savings [%]
1st	CVC	468000	79.2	-
	VDS-DCV	300082	50.8	35.9
	Simple binary control	277136	46.9	-
	Simulated experiment of CO-DCV	189682	32.1	31.6
2nd	CVC	468000	79.2	-
	VDS-DCV	247000	41.8	47.2
	Simple binary control	199136	33.7	-
	Simulated experiment of CO-DCV	199727	33.8	-0.3
Average	CVC	468000	79.2	-
	VDS-DCV	273541	46.3	41.5
	Simple binary control	238136	40.3	-
	Simulated experiment of CO-DCV	194705	33.0	18.1

indoor air quality as well as fan energy saving.

Meantime, what should be considered in order to realistically apply the CO-DCV strategy is that a CO sensor of excellent performance should be used because a CO sensor of high resolution and accuracy enables the control of ventilation rate minutely reflecting a variation of CO concentration. Besides, in order to provide ventilation rate complying with demand, indoor CO concentration should be accurately measured, and periodic recalibration and elaborate maintenance of CO sensor is required.

4. Conclusion

This study was intended to expand a study relating to the space to which the existing demand-controlled ventilation (DCV) strategy would be applied to the unoccupied space such as underground parking lot. It was verified the applicability of DCV strategy through the progress of study through three phases. In the first phase of applying the DCV strategy to the underground parking lot, the current ventilation standard for underground parking lot is defined as traffic load that is primary contamination source. It enables DCV strategy to be applied to the underground parking lot because it is possible to modulate ventilation rate as much as necessary by responding to the changing traffic load in real-time. That is to say, it was considered that ventilation rate per unit floor area or unit volume of the space, which is the existing ventilation standard, is a factor that makes it difficult to apply DCV strategy to the underground parking lot. In the second phase, it was verified that DCV strategy had advantages by simultaneously showing the potential of maintaining the acceptable indoor air quality and reducing the unnecessary energy consumption occurring in the conventional ventilation system through the operation of pilot ventilation system based on real-time traffic load. In the final phase of applying the DCV strategy to the underground parking lot, it was mentioned that the advantages of DCV strategy through the real-time direct and indirect tracing of traffic load would not be limited to the aspect of energy saving and indoor air quality. The proposed DCV strategy could directly provide people using the underground parking lot with information about energy, air environment, and space use as an aggregate of various information and communication technologies (ICT) in the near future.

In this study, it was measured and compared the variation of ventilation rate and fan energy consumption according to various ventilation control strategies after installing wireless sensor-based pilot ventilation system in order to verify the applicability of DCV strategy that was efficient ventilation control strategy for underground parking lot. Indoor air quality was also evaluated at the same time in case of the simulated experiment of CO-DCV, which indirectly predicted traffic load according to the variation of concentration of contaminant. In conclusion, though it is impossible to mutually compare the simulated experiment of CO-DCV strategy with VDS-DCV strategy, experiment results is shown that the two DCV strategies in the underground parking lot will be a good alternative strategy which will satisfy both energy saving and healthy indoor environment requirement in comparison with the conventional control strategy. And in the underground parking lot applying DCV, it is also considered that a design should be achieved in reflection of characteristics of traffic load schedule and traffic load fluctuation of the space.

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