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Estimation of appropriate capacity of ventilation system based on the air infiltration rate in Korean classrooms

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Abstract

The appropriate capacity of a ventilation system based on the air infiltration rate in Korean classrooms is investigated to obtain optimal design conditions for ventilation systems. Theoretical and the experimental analyses are performed to estimate the proper ventilation capacity with a consideration of the air infiltration, the indoor air quality, and the ventilation rate. The air infiltration rate of the classroom is measured within the range of 0.5-1.5 1/h, and the required ventilation rate should be decided not by the contaminants (Formaldehyde and TVOC) emitted from the construction materials but by the carbon dioxide (CO_2) emitted from human breath. The appropriate capacity of the ventilation system based on the air infiltration rate of the classroom for elementary schools is 500CMH and for middle and high schools is 800 CMH. The measured and the estimated values of CO_2 concentrations are very similar and the modeling equation of CO_2 concentration can be used as a reference for the proper estimation of ventilation rate in Korean schools.

Keywords: School ventilation; Air infiltration rate; Required ventilation rate; Ventilation efficiency; Indoor air quality

1. Introduction

Recently, from the perspective of saving energy in buildings, high performance of insulation and air tightness for improving the heating and the cooling efficiency has brought the positive effect into an economical view [1-3]. However, these building energy-saving technologies cause a lack of ventilation, which is the direct cause of increasing the indoor contaminants, and it is also very harmful to residents because they spend 90% of their time in the indoor area. Therefore, mechanical ventilation is important not only to keep indoor environment clean but also to save energy consumption. However, an excessive amount of ventilation over the requirement for keeping the indoor environment clean causes unnecessary energy loss and indoor noise by increasing the heating and cooling load and the fan capacity. Therefore, the appropriate calculation of the ventilation system suitable for the use of buildings is necessary. The amount of ventilation to improve the indoor air quality can be expressed as the difference between the required ventilation rate and the air infiltration rate [4, 5]. In order to estimate the appropriate capacity of a ventilation system, it is necessary to obtain data of the air infiltration rate that represents the air tightness of the building envelope by experiments and theoretical analyses about the required ventilation rate [6].

Infiltration means unintentional inflow from the outdoor air through the exterior cracks due to the pressure difference between the indoor and the outdoor of the building. The quantitative measurement of the amount of the unintentionally infiltrated air through

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through the exterior cracks of the building is important to control the building environment and to determine the energy consumption [7, 8].

Mussel and Yuill [9] proposed the infiltration coefficient enabling the calculation of the equivalent infiltration area of the building and the air infiltration rate from the building by the multiple regression analysis of the measured data after estimating the air tightness of two houses in Canada built in 1978 and 1980. Kiel et al. [10] calculated the infiltration coefficient and the infiltration index of the building from estimating the air tightness of 515 houses in the U.S. and Canada, and demonstrated that the air tightness and the infiltration index have a great deal of relations. Mills [11] developed measurement and design methods of the air tightness and proceeded with a diversity of studies from energy saving to economic analysis. Jokisalo and Kurnitski [12] analyzed the effect of the air tightness on the energy consumption of residential houses in a cold area by building energy simulation. The simulation results of Emmerich and Persily [13] show that the infiltration of the office buildings in the U.S. is 3% of the cooling load and 13% of the heating load. As such, the issues on the ventilation and the infiltration of the houses have been analyzed by various researches; however, the research on those for the classroom where many residents stay for a long time in a specific area is not being performed enough. Yanai et al. [14] estimated the average time of the classroom ventilation for 14 classrooms of 11 schools in Japan by the tracer gas method to be 0.47 1/h; and Kwon et al. [15] estimated the amount of natural ventilation of the classroom by the control method of the classroom door and the variation of the carbon dioxide (CO_2) amount in the classroom. But systematic research on the ventilation for controlling the indoor air contamination of a classroom has not been performed.

This study aims to calculate the appropriate capacity of the ventilation system for environmental improvement in the classroom. A theoretical analysis for estimating the required ventilation rate is suggested with a consideration of the concentration and the emission of contaminants, the ventilation efficiency and the appropriate capacity of the ventilation system based on the amount of the air infiltrated through the cracks of the building. The air infiltration rate and the indoor air quality are also measured to verify the theoretical analysis.

2. Theory

2.1 Required ventilation rate depending on the contaminant emissions from human breath

The typical contaminant emitted from human breathing is CO_2 and its criterion in a classroom is 1,500 ppm. The amount of CO_2 emitted from a human breath depends on the activity and this is specified in Korean Standard KS F 2603 [16] "Method for measuring amount of room ventilation (carbon dioxide method)."

Table 1 shows the CO_2 amount emitted from human breath. The condition of "Working while seated" is applicable to the students taking classes in a classroom and the number of high school students is considered similar to that of adults. Therefore, the minimum ventilation amount per person is calculated by Eq. (1) to be 12-21 CMH and its average value is 17.5 CMH. The required ventilation rate to keep the CO_2 concentration in the classroom under the criterion is proportional to the number of students and expressed by Eq. (2).

$$Q_{REQL} = \frac{M}{C_i - C_0} \quad (1)$$

$$Q_{PEPL} = \delta \cdot q_1 \cdot N \quad (2)$$

$$\delta = 0.25 \cdot (i+1) \quad (3)$$

Where Q_{REQL} is the required ventilation rate (m^3/h), M is the emitted amount of the indoor contaminants

Table 1. CO_2 amount emitted from human breath [16].

RMR(Relative Metabolic Rate) during working		Exhale amount of CO_2 (m^3/h)	Average RMR for 8 working hours	Average exhale amount of CO_2 for 8 working hours (m^3/h)
Taking a rest	0	0.011	-	-
Working while seated	0~1.0	0.0129~0.0230	Below 0~0.8	0.0129~0.0184
Walking slowly	1.0~2.0	0.0230~0.0330	0.8~1.5	0.0184~0.0248
Light labor	2.0~3.0	0.0330~0.0548	1.5~2.6	0.0248~0.0350
Ordinary labor	3.0~4.0	0.0538~0.0840	2.6~3.5	0.0350~0.0420
Heavy labor	4.0~5.0	Over 0.0840	Over 3.5	Over 0.0420

* For women, 90% of the values in Table 1. For children, 50% of the values in Table 1.

(mg/h), C_i is the allowable concentration of the indoor contaminants (mg/m³), C_0 is the concentration of the outdoor contaminants (mg/m^3), Q_{PEPL} is the required ventilation rate by contaminant emission from a person, q_1 is the required ventilation rate per person (m^3/person · h), N is the number of students and δ is the index of the school level (elementary, middle and high school) and expressed as Eq. (3). That is, if i=1, this means elementary school and if i=2, middle school, and if i=3, high school.

2.2 Required ventilation rate depending on the contaminant emissions from building materials

Contaminants such as HCHO (Formaldehyde) and VOCs (Volatile organic compounds), emitted from the construction materials are not easy to estimate for the exact amount. In addition, since the emitted amount decreases as time passes, it is not reasonable to calculate the required ventilation rate by setting the initial emitted amount as the standard.

The total amount of contaminants emitted from the construction materials in the classroom is the product of the emitted amount per unit area and the exposed wall area (including the area of floor and ceiling) and is expressed as Eq. (4).

$$M = \dot{m} \cdot (\eta \cdot A_{wall}) \tag{4}$$

$$\eta = (A_{wall} - A_{window}) / A_{wall} \tag{5}$$

Where $\dot{m}$ is the emitted amount of the contaminants per unit area (mg/m^2·h), η is the ratio of the wall area and expressed as Eq. (5), A_{wall} is the wall area of the classroom including the ceiling and floor (m^2), and A_{window} is the window area (m^2).

Assuming that the respective area emitting HCHO and TVOC is the same because it is emitted in finishing materials of walls, floor and ceiling of classroom, the q_2 in Eq. (6) can be considered as the higher concentration out of HCHO and TVOC.

$$Q_{MATL} = \eta \cdot q_2 \cdot A_{wall} \tag{6}$$

Where Q_{MATL} is the required ventilation rate by contaminant emission of construction materials.

The required ventilation rate of the classroom is not the sum of the required ventilation rate of each contaminant, but the required ventilation rate of the main contaminant out of the emitting sources and it is expressed as Eq. (7). Eq. (7) also considers the ε_v of ventilation efficiency.

$$Q_{REQL} = MAX[Q_{PEPL}, Q_{MATL}] / \varepsilon_v \tag{7}$$

2.3 Estimation of the appropriate capacity of the ventilation system

It is considered that the air infiltration rate is insufficient in the required ventilation rate, so the rest of the required ventilation rate should be charged on the mechanical ventilation. That is, the mechanical ventilation rate is the difference between the required ventilation rate and the air infiltration rate.

The air infiltration rate of the classroom can be theoretically estimated by using the pressure difference between indoor and outdoor through the cracks inside of the building; however, it is difficult to obtain the data to prove its reliability. Therefore, air tightness tests such as the tracer gas or pressure difference method in order to calculate the air infiltration rate can be used. The air infiltration rate is expressed as the product of the ventilation time and the volume of the classroom, so the mechanical ventilation rate can be expressed as Eq. (8).

$$Q_{MECH} = (MAX[\delta \cdot q_1 \cdot N, \eta \cdot q_2 \cdot A] / \varepsilon_v - n \cdot V) \cdot \varepsilon_s \tag{8}$$

Where, Q_{MECH} is the mechanical ventilation rate (m^3/h), Q_{INFL} is the air infiltration rate (m^3/h), n is representative of the air infiltration rate as the air change rate (1/h), V is the volume of classroom (m^3), and ε_s is the safety factor based on the resistance of a curved duct, a diffuser and a cap grill, and the pressure loss of a blower.

3. Experiment

3.1 Measurement of air infiltration rate

In this study, the air infiltration rate of the classroom is measured for 62 schools (38 elementary schools, 19 middle schools and 5 high schools) in the middle and southern region of Korea by using the measurement method of the pressure difference (during the period between 2004 and 2005). In general, the pressure difference between indoor and outdoor is 1 - 4 Pa in normal condition, and with this pressure difference it is very difficult to measure the air infiltration rate. Therefore, after choosing two classes from each school and reducing the classroom pressure from 50 to 4 Pa, we made the measurements twice. The experimental setup for the measurement of the pressure difference (Fig. 1) consists of a speed controllable fan blower to keep a constant pressure difference between indoor and outdoor, a differential pressure gauge (Energy Conservatory, DG-700) and a frame for fixing the fan to be installed on the entrance door and windows.

3.2 Measurement of indoor air quality

Korean education courses consist of elementary, middle and high school, depending on age. This causes the difference of the exhaled amount of CO_2, and it is the main parameter affecting the calculation of the indoor air quality and the appropriate capacity of the ventilation system of the classroom. Therefore, the indoor air quality of the classroom is measured by categorized schools such as elementary, middle and high school.

The classroom measurements are performed during

Table 2. Specifications of the measurement devices.

Measured item	Model/Maker	Measurement range	Accuracy
CO_2	454/TESTO	0~10,000 ppm	1 ppm
HCHO	Z-300XP/ Environmental Sense	0.01~30 ppm	0.01 ppm
TVOC	PGM-5210/IAQRAE	0.01~999ppm	0.01 ppm
PM_{10}	Digital Aerosol Monitor/ Kanomax, 3421	0~4 mg/m³	0.001 mg/m³

Fig. 1. Photograph of the experimental setup for the measurement of pressure difference.

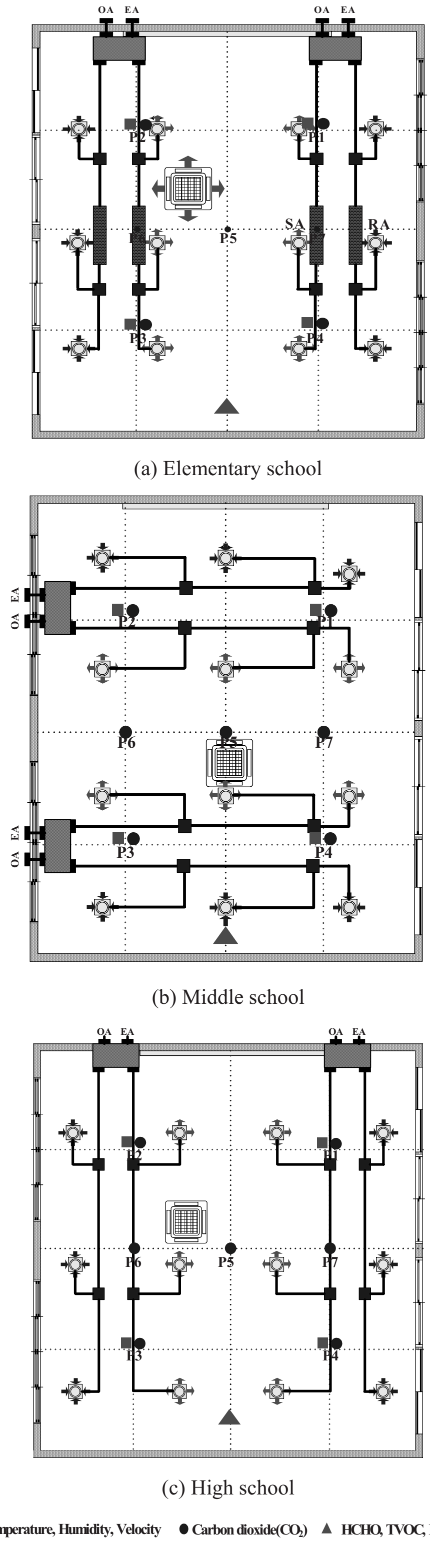


Fig. 2 Installation overview of the air conditioning system, the ventilation system, and the measurement sensors

the winter season with the presence of students. The main variable is the ventilation rate. The indoor air quality of the classroom is evaluated by the concentration of CO_2, HCHO, TVOC and PM_{10}.

Table 2 shows the detailed specifications of the experimental devices for the measurement of CO_2, HCHO, TVOC, and PM_{10}, respectively.

Fig. 2 shows the schematic installation diagram of the air conditioning system, the ventilation system, and the measurement sensors in each school. To prevent the interference of air stream, OA (Outdoor air) of the heat exchanger is separated from EA (Exhaust air) over 800 mm. In order to improve the efficiency of the air circulation, the air inlets are arranged near the 4-way cassette air conditioner and the air outlets are located around the periphery of the classroom.

The indoor ventilation rate is measured in accordance with the KS F 2603 [16]. The location of the sensors for the detection of CO_2 can be seen in Fig. 2. The HCHO, TVOC and PM_{10} are measured behind the center of the classroom so as not to disturb the class. The outdoor CO_2 concentration affecting the variation of the indoor CO_2 concentration is almost constant, so it is measured for 30 minutes after the completion of experiments of the day.

4. Results and Discussion

4.1 Air infiltration rate

The air tightness of a classroom is expressed with average air infiltration rate at the 50 Pa of pressure difference between indoor and outdoor and with air change rate. The effective infiltration area is defined as the area of a specific nozzle having the same air flow rate as the case of 4 Pa of pressure difference between indoor and outdoor.

Table 3 shows the measurement results of the air tightness. The air infiltration rate at 50 Pa is within the range of 27.5-82.6 $m^3/m^2 \cdot h$, and its average is 52.8 $m^3/m^2 \cdot h$. The air change rate is within the range of 8.9-28.9 1/h, and its average is 18.8 1/h. At a pressure difference of 4 Pa, the mean value of effective infiltration area is 13.3 cm^2/m^2. According to the ASHRAE Standard 119-1988 [17], "Air leakage performance for detached single-family residential buildings," it is classified as a very undesirable air tightness (12.5-16.9 cm^2/m^2). It means that considerable energy losses occur; however, it is very helpful to improve the indoor environments. The reason why it has poor air tightness is that many years have passed since it was installed.

Table 3. Measurement results of the air tightness.

Item			Number	Air infiltration rate at 50Pa ($m^3/m^2 \cdot h$)		Air change rate at 50Pa (1/h)		Effective infiltration area at 4Pa (cm^2/m^2)	
				Avg.	Dev.	Avg.	Dev.	Avg.	Dev.
Number of the measured classroom			62	52.8	13.7	18.8	4.8	13.3	3.9
Region		Middle	8	46.6	10.6	16.8	3.9	12.2	2.9
Region		Southern	54	53.8	14.0	19.1	4.8	13.5	4.0
Region		Jeju	-	-	-	-	-	-	-
Window	Multiple pane	Aluminum	22	55.9	13.4	20.0	4.6	14.2	4.2
Window	Multiple pane	Plastic	12	50.3	12.0	18.0	4.1	12.5	3.2
Window	Double pane	Aluminum + Wood	4	58.0	11.2	20.6	3.8	15.6	2.7
Window	Double pane	Aluminum + Plastic	24	50.4	15.1	17.8	5.2	12.6	3.9
Entrance door		Sliding	59	53.0	13.9	18.8	4.8	13.4	3.9
Entrance door		Swinging	3	49.2	11.9	17.9	4.1	12.8	2.6

* Average floor area: 63.8 m^2, Average ceiling height: 2.8 m

Korea is divided into three regions (Middle, Southern and Jeju), and different insulation thicknesses are applied to the construction. The insulation thickness of 65 mm and 50 mm is used in middle and southern regions, respectively. The average air infiltration rate and the effective infiltration area of the classrooms in the middle region are calculated to be 46.6 $m^3/m^2 \cdot h$ and 12.2 cm^2/m^2, respectively, and each 11.7%, 8.3% lower than the entire average, and 13.6%, 9.8% lower than that of the southern region. This shows that there is a strong relationship between the insulation performance and the air tightness of the classroom. High insulation performance makes for poor air infiltration performance.

The type of window is classified into multiple pane and double pane and their average area is calculated to be 12.8 m^2, 11.4 m^2, respectively. The effect of the type of window and its area on the air tightness of the classroom is analyzed. The area of the multiple pane is 1.4 m^2 larger than that of the double pane; however, the average air infiltration rate and the effective infiltration area are respectively 1.1 $m^3/m^2 \cdot h$, 0.8 cm^2/m^2 smaller than the cases of double pane. The window is categorized by its material and the air tightness of the frame affects the air infiltration rate of the classroom.

The frame material of the multiple pane and the double pane is classified into aluminum, plastic, aluminum+wood and aluminum+plastic. Depending on the frame material, the average air infiltration rate and the effective infiltration area became larger in the order of plastic < aluminum+plastic < aluminum < aluminum +wood.

Entrance doors are classified by sliding door and swinging door, depending on the open and close method, and their average areas are 3.3 m^2 and 2.6 m^2, respectively. The average air infiltration rate of the swinging door is 2.8 $m^3/m^2 \cdot h$ smaller than that of the sliding door, and the effective infiltration area of the swinging door is 0.6 cm^2/m^2 smaller than that of the sliding door. The area of the swinging door is smaller than that of the sliding door, and the gap between the entrance door and the inside wall is smaller.

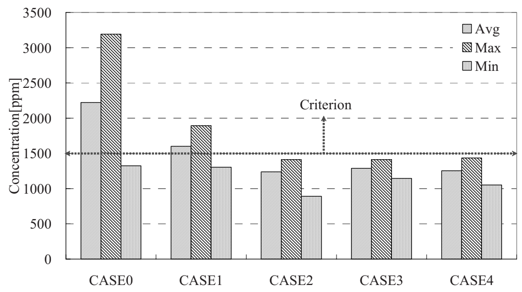
Table 4. Experimental cases for indoor air quality in the classroom.

Category	Ventilation rate (CMH)				
	CASE 0	CASE 1	CASE 2	CASE 3	CASE 4
Elementary school	0	270	540	660	840
Middle school	0	260	610	860	990
High school	0	390	680	1,050	1,330

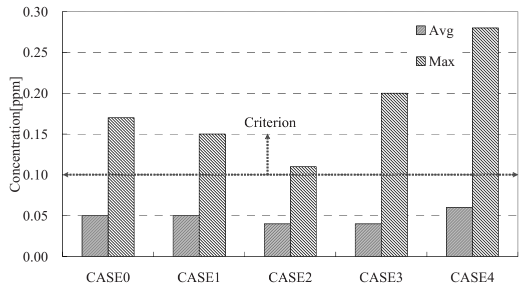
4.2 Indoor air quality

Table 4 shows the test conditions of ventilation rate for the measurement of indoor air quality. The tests are performed in five different cases, and the ventilation rates are changed according to the grade of schools such as elementary, middle and high school.

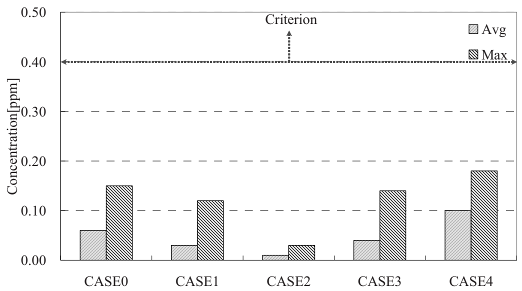
Fig. 3(a) shows the CO_2 concentration distribution depending on the various ventilation rates; it is measured at an elementary school under the conditions that the number of the students is 39, the outdoor CO_2 concentration is 430 ppm. The average CO_2 concentrations of CASE1, CASE2, CASE3, and CASE4 are 1,600 ppm, 1,238 ppm, 1,288 ppm, and 1,254 ppm, respectively, and the concentration of CO_2 is reduced to 620-990 ppm compared to CASE0. If the ventilation rate is 270-540 CMH, the allowable concentration of the indoor can be satisfied. Fig. 3(b), (c) and (d) are concentration variations of HCHO, TVOC and PM_{10}, respectively. The CO_2 concentration is distinctly decreased with the increase of ventilation rate; however, clear trends are not found in the concentration variations of HCHO, TVOC and PM_{10}. This can be explained by two reasons. The first is the wandering of the students, and the second is the location of measurement. The CO_2 concentration is averaged from 7 measuring points, so it does not have serious



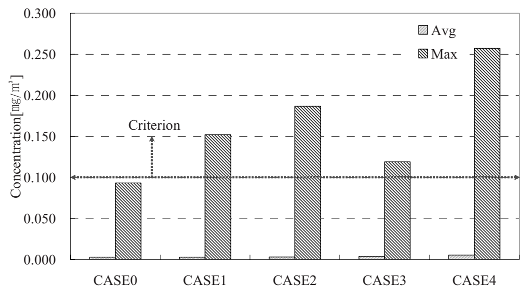
(a) CO_2 concentration distribution



(b) HCHO concentration distribution

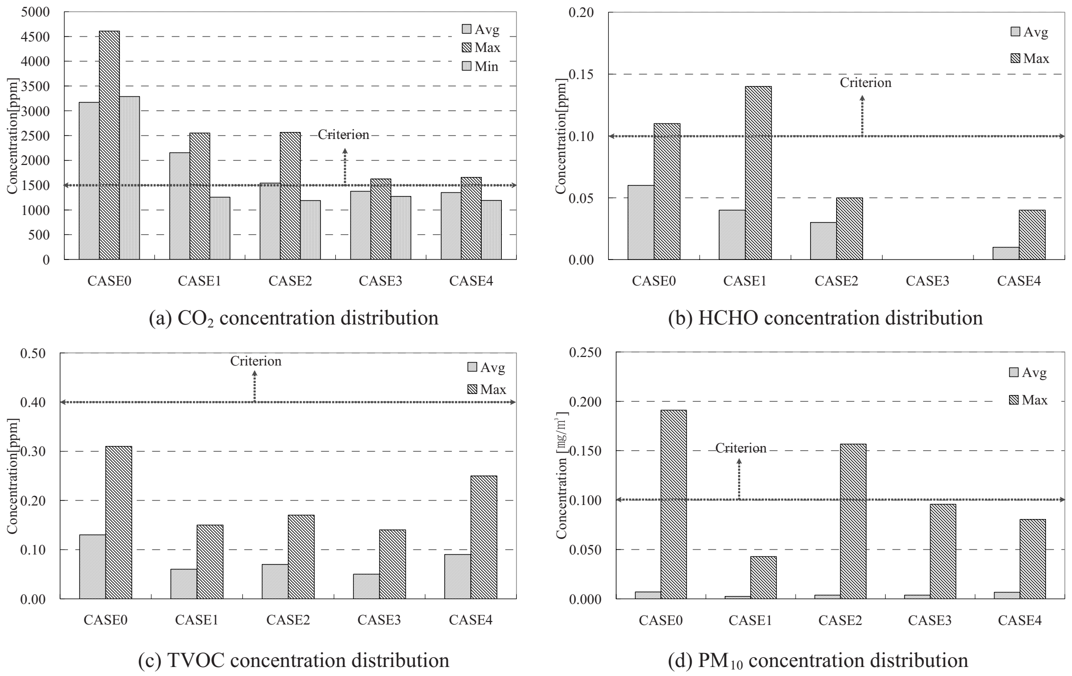


(c) TVOC concentration distribution



(d) PM_{10} concentration distribution

Fig. 3. Measurement results of the indoor air quality of the classroom in the elementary school.



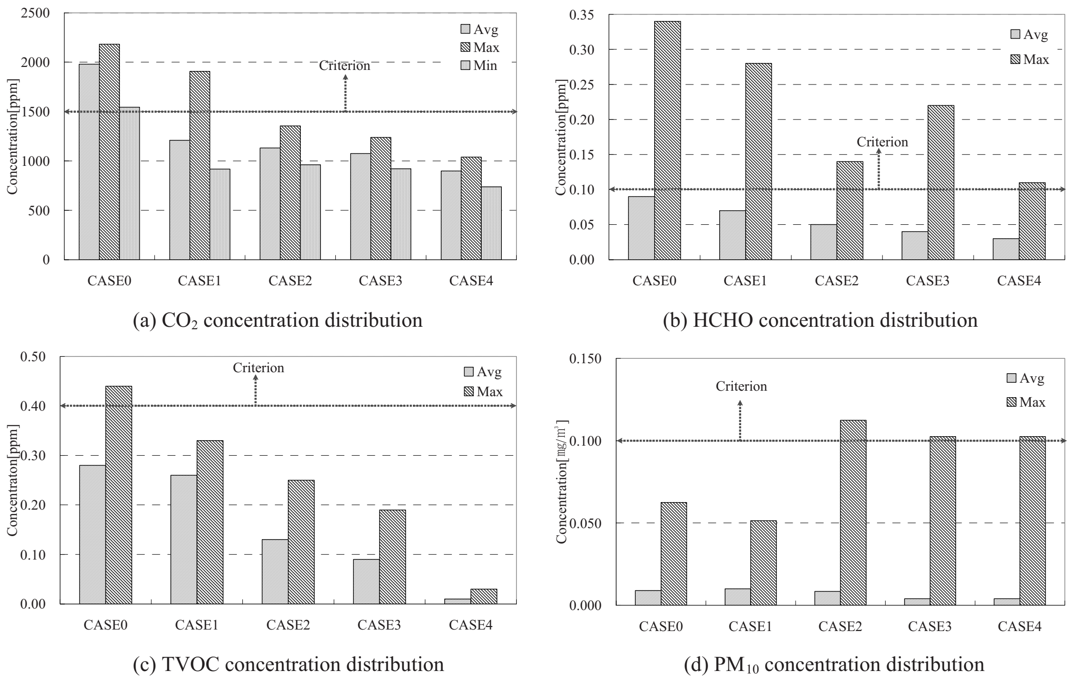
(a) CO_2 concentration distribution

(b) HCHO concentration distribution

(c) TVOC concentration distribution

(d) PM_{10} concentration distribution

Fig. 4. Measurement results of the indoor air quality of the classroom in the middle school.



(a) CO_2 concentration distribution

(b) HCHO concentration distribution

(c) TVOC concentration distribution

(d) PM_{10} concentration distribution

Fig. 5. Measurement results of the indoor air quality of the classroom in the high school.

effects from circumstances except the ventilation rate. But the concentrations of HCHO, TVOC and PM_{10} are measured from only one point, so they have fluctuations and do not show a decreasing tendency with increasing the ventilation rate.

Fig. 4(a) shows the CO_2 concentration distribution of a middle school classroom depending on the variation of the ventilation amount. It is measured under the conditions that the number of students inside is 40 and the outdoor CO_2 concentration is 415 ppm. The average CO_2 concentrations of CASE1, CASE2, CASE3, and CASE4 are 2,155 ppm, 1,540 ppm, 1,376 ppm, and 1,350 ppm, respectively, and 1,015-1,820 ppm of the CO_2 concentrations are decreased compared to CASE0. Therefore, if the ventilation rate is 860-990 CMH, the allowable concentration of the indoor can be satisfied. Fig. 4(b), (c) and (d) are concentration variations of HCHO, TVOC and PM_{10}, respectively. The CO_2 and the HCHO concentrations are distinctly decreased with the increase of ventilation rate; however, clear trends are not found in the concentration variations of TVOC and PM_{10}.

Fig. 5 shows the concentration variations of CO_2, HCHO, TVOC and PM_{10} of a high school classroom depending on the variation of the ventilation rate. It is measured under the conditions of 25 people inside and at 425 ppm of the outdoor CO_2 concentration. The average CO_2 concentrations of CASE1, CASE2, CASE3, and CASE4 are 1,209 ppm, 1,132 ppm, 1,075 ppm, and 897 ppm, respectively, and 770-1,082 ppm of the CO_2 concentrations are decreased compared to CASE0. Also, if the ventilation amount is 390 CMH, the allowable concentration of the indoor can be satisfied. The average concentrations of HCHO, TVOC and PM_{10} in Fig. 5(b), (c) and (d) are distinctly decreased with the increase of ventilation rate. It can be concluded that ventilation is an effective way to reduce the indoor contaminants.

According to the measurement results of the indoor air quality during heating, the concentration of HCHO and TVOC emitted from the furniture, the construction materials in the classroom and the concentration of the PM_{10} from the outdoor air and the clothes are measured to be lower than the allowable concentrations. Therefore, the appropriate capacity of the ventilation system should not be calculated by the contaminants emitted from the furniture and the construction materials because their emitted amount decreases as time passes, but by CO_2 from human breath.

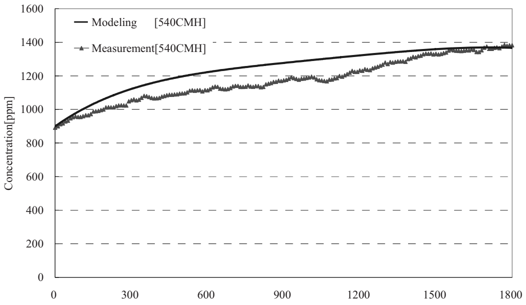
The capacity of the ventilation system for satisfying the allowable concentration of indoor has been calculated by simple linear regression between the ventilation rate and the CO_2 concentration, and thereby the CO_2 amount emitted from the people is calculated and its results are represented as Table 5. As for high schools, due to the aberrance of the measurement values of the indoor CO_2 concentration caused by the people inside opening doors and windows during measurement, the capacity of the ventilation system and breath is considered to be somewhat underestimated compared to those of middle schools. It is noticeable that the activity of the students in the classroom is "working while seated" and when comparing the result of Table 1 with that of Table 5, they are similar except for that of high schools. It is estimated that the students of elementary schools emit 50% of the CO_2 amount emitted by adults, and those of middle schools emit as much as that of adults. That of high school students can be considered to be that of adults, and when considering the aberration of the measurement values, their CO_2 amount seems to be considered the same as that of middle school students.

Table 5. The CO_2 emission per person inside and the estimation of capacity for ventilation system.

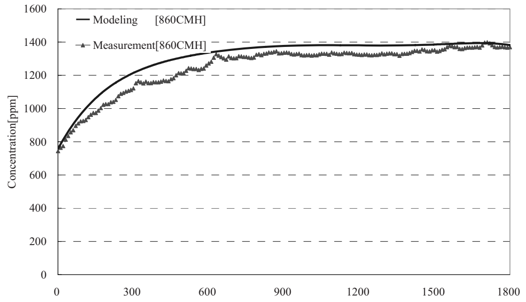
School	Number of Student	Breathing amount (m^3/person·h)	Ventilation rate (CMH) (Regression analysis)
Elementary	39	0.013	467 (C = -1.2Q + 2,060, R^2=0.84)
Middle	40	0.021	767 (C = -1.8Q + 2,880, R^2=0.89)
High	25	0.015	343 (C = -0.7Q + 1,740, R^2=0.78)

* C : Concentration (ppm), Q : Ventilation rate(CMH)

The air flow supplied through the supplier installed in the classroom is 90% of the designed air flow of the ventilation system. This is due to the resistance of the duct curve, the resistance of the diffuser and cap grill and the decrease in the ventilation rate caused by the pressure loss of the blower fan. That is, when estimating the appropriate capacity of the ventilation system, this should be considered as the safety coefficient and 1.1 would be proper. According to the current Korean educational course, the number of students in one class is 35, and this will be reduced to 30 in the future. When the educational course and the safety factor are considered, the capacity of the ventilation systems is 463 CMH for elementary schools and 749 CMH for middle and high schools. But the design scales of ventilation systems are 50 CMH for less than 500 CMH of ventilation rate, and 100 CMH for over 500 CMH of ventilation rate. Considering this, it seems reasonable that the appropriate capacity of the ventilation system based on the air infiltration rate of Korean classroom for elementary schools is



(a) Elementary school[CASE2]



(b) Middle school[CASE3]

Fig. 6. Comparison of the CO_2 variations between the modeling and the experimental results.

500 CMH and for middle and high schools, 800CMH.

Students in a classroom emit CO_2, one of the contaminants, and if this is not removed, its concentration will increase with time. When the concentration of the contaminants is diluted by ventilation, assuming that the indoor air is completely replaced by the outdoor air, the indoor CO_2 density will change exponentially as Eq. (9).

$$C(t) = C_0 + (C_S - C_0)e^{-\frac{Qt}{V}} + \frac{M}{Q}\left(1 - e^{-\frac{Qt}{V}}\right) \tag{9}$$

The first term of Eq. (9) is the CO_2 concentration, the second term is the attenuation of the initial density due to the ventilation, and the third term is the increase of the concentration due to the contaminants. The ventilation rate (Q) is based on the air infiltration rate through the exterior cracks.

Fig. 6 shows the variations of the CO_2 concentration in the classroom under the operation of the ventilation system during a class. The experimental data were measured until the CO_2 concentration reached asymptotic value and compared with the modeling data. The modeling of CO_2 emission in the classroom is calculated based on the CO_2 emission per person and the number of students as provided in Table 5; the mechanical ventilation rates are based on the values of CASE2 for elementary schools and of CASE3 for middle schools. The experimental data for high schools are neglected for inaccuracy because the windows or the doors were opened by students.

The air infiltration rates are considered as 0.87 1/h for elementary schools and 0.57 1/h for middle schools. The difference between the measured and the estimated values of CO_2 concentration for elementary schools is 70 ppm and for middle schools is 54 ppm. And the reasons of the differences are as follows:

- The difference of the air infiltration rate when the ventilation system is operated or not.
- The aberration of modeling that assumes the indoor air is completely mixed with the outdoor air.
- The fact that the ventilation system could not ventilate the entire classroom.

If the above problems are minimized, the difference of the CO_2 concentration between the measured and the estimated values will be minimized.

5. Conclusions

In this study, an evaluation method of the appropriate capacity of the ventilation system to improve the indoor environment of the classroom is proposed. For this purpose, theoretical and experimental analyses were performed on the appropriate capacity of a ventilation system and the required ventilation rate depending on the allowable concentration of the indoor and the emission of the indoor contaminants. Also, the air infiltration rate of the classroom and the indoor air quality are measured depending on whether a ventilation system exists or not and the variation of the ventilation rate.

The average air infiltration rate and the effective infiltration area of the middle region are, respectively, 13.6%, 9.8% lower than those of the southern region; and there a strong relation exists between the insulation thickness and the air tightness of a classroom.

The distribution of air infiltration rates of Korean classrooms is estimated below 0.5-1.5 1/h, and the average air change rate of the classrooms of 62 schools is 0.94 1/h. This means that the contaminated air is replaced by the air as much as the volume of the classroom per hour through the exterior cracks of the building.

The concentration of HCHO and TVOC emitted from the furniture and the construction materials of the classroom and the concentration of the PM_{10} from the outdoor air and clothing are below the allowable concentration of indoor. Therefore, the proper required ventilation rate of the classroom should be evaluated not by the contaminants emitted from the furniture and the construction materials of which emission of the contaminants decreases as time passes, but by CO_2 emitted from human breath.

Considering the current Korean educational courses, it seems reasonable that the appropriate capacity of the ventilation system based on the air infiltration rate of the classroom for elementary schools is 500 CMH and for middle and high schools, 800 CMH.

The measured and the estimated values of CO_2 concentrations are very similar, and the modeling equation of CO_2 concentration can be used as a reference for the proper estimation of ventilation rate in Korean schools.

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