Indoor Air Quality Performance of Ventilation Systems in Classrooms

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Abstract
This study aims to evaluate the field performance and the efficiency of ventilation systems in school buildings. Three classrooms installed with ventilation systems in a high school in Seoul were selected as a test bed for this study. The ventilation systems consisted of two types of multi air-conditioning ventilation system and a window type air-conditioning ventilation system. The ventilation performance was measured by the blower door and tracer gas methods as follows: (1) Evaluation of air tightness and air infiltration in the classrooms; (2) Indoor ventilation performance based on the operating condition of ventilation systems; (3) Ventilation performance based on the operating conditions of ventilation systems and air-conditioners; and (4) Local ventilation efficiency and performance based on the operating status of the ventilation systems and air-conditioners.

As a result, the ventilation efficiency was measured at 34.8%-97.8% for the duct type of ventilation and 82.6% for the window type ventilation. In this study, classroom characteristics such as high air infiltration low air tightness lowered the ventilation effectiveness. The ventilation efficiency varied based on the location of air inlet and outlet ducts and the existence of furniture. However, local ventilation efficiency was not significantly affected according to the results of this study. The results showed that a ventilation rate of 1000 cubic meters per hour (CMH) or more would be required to maintain 1000 ppm of CO₂ concentrations as per IAQ criteria for Korean classrooms.

Keywords: indoor air quality; performance of ventilation system; ventilation rate requirement; IAQ for classroom

1. Introduction
Young people spend a significant part of their day in school thereby making indoor air quality (IAQ) more important than the quality of other environments they inhabit. They are more vulnerable to bad environmental conditions and more sensitive to air quality related health problems than adults.

Children's right to have good air quality at school is recognized worldwide, and many efforts are made to ensure air standards requirements are met. Approximately 235 million people currently suffer from asthma making it the most common chronic disease among children according to publications published by the World Health Organization (WHO, 2015). Furthermore, many epidemiological studies have shown that allergic diseases and asthma incidence among young people are becoming more common (Daisey et al. 2003).

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This study aims to evaluate the field performance and the efficiency of ventilation systems in school buildings. Three classrooms installed with ventilation systems in a high school in Seoul were selected as a test bed for this study. The ventilation performance was measured by evaluating the air infiltration and air tightness in the classrooms; the indoor ventilation performance based on the operating condition of the ventilation system; the ventilation performance based on the operating conditions of the ventilation and air-conditioning systems; and the local ventilation efficiency and performance based on the operating conditions of the ventilation and air-conditioning systems. The measurements were made by a blower door method and a tracer gas method. Two types of multi-air-conditioning ventilation systems and a window type air-conditioning ventilation system were used for this study.

2. Experimental Methods

The classrooms used for this study have the same overall dimensions, orientation of windows, window systems, and interior finishing materials. This similarity ensured that the features of the test rooms did not influence the test results. As shown in Fig.1. and Fig.2., the dimensions of each test room were 8.93 m (W) x 7.30 m (L) x 2.65 m (H), and the space volume was 172.75 m$^3$.

Meanwhile, the locations of the air diffusers for Test Rooms 1 and 2 were installed opposite each other to verify the effect on the ventilation performance according to the location of the air diffuser. Table 2. notes the location and functions of the air diffusers in Test Rooms 1 and 2 based on the numbering scheme shown in Fig.1.

Supply air rate, infiltration rate and air change rate were calculated to assess the ventilation performance by the theoretical formulas. The effective air change rate and effective ventilation efficiency were derived from the measuring values by the blower door method and decay method. The infiltration rate is the volumetric flow rate of outside air into a building, typically in cubic meter per hour (CMH). The air exchange rate is the number of interior volume air changes that occur per hour (ACH). ACH is the hourly ventilation rate, divided by the building volume. It can be calculated by multiplying the building's CMH, and then dividing by the building volume. The calculation formulas of supply air rate and air change rate are shown below:

\[ Q = \frac{M(1 - e^{-\frac{Q_t}{V}})}{C_t - C_o - (C_t - C_o)e^{-\frac{Q_t}{V}}} \]

Where, \( Q \) is the air change rate (m$^3$/h); \( V \) is the indoor volume (m$^3$); \( t \) is the time (h); \( C_t \) is the concentration of CO$_2$ at the first measurement (m$^3$/m$^3$); \( C_o \) is the concentration of CO$_2$ after t hours (m$^3$/m$^3$); \( C_o \) is the concentration of CO$_2$ for supply air (m$^3$/m$^3$).

\[ N = \frac{F}{V} \]

Where, \( N \) is the number of air changes per hour (ACH); \( F \) is the volumetric flow rate of air in cubic meter per hour (CMH); \( V \) is the indoor volume (m$^3$).
3. Results

3.1 Ventilation Performance without Air-Conditioning

This study aimed to examine the effects of air conditioning on ventilation system performance.

The ventilation performance included the meaning of effective air change rate and effective ventilation efficiency, and it was measured based on heat recovery ventilation without the air conditioning system in operation.

The results are described in Table 3. The following data are to compare and review facility performances with uncontrolled indoor variables minimized. They may be utilized as reference values in selecting ventilation systems and air conditioners for classrooms. Further, in order to minimize the influence of variables, measurements were made without any occupant or furniture.

Ventilation efficiency for each system ranged from 44.1% to 51.7%, with the effective ventilation rates between 33.9% and 44.9%. This indicates that actual ventilation volume is small relative to supplied air volume and the researcher considers its cause is a
shortcut phenomenon resulting from the location of air diffusers on the same side (Fig.3. and Fig.4.). In the case of the ceiling air diffusers in Test Rooms 1 and 2, it was determined that the respective locations of the diffusers were found to affect ventilation efficiency. Measurements indicated that the air outlets installed in the center of a room were the most effective. For Test Room 3, the ventilation efficiency and ventilation rate were 101.1% and 44.9%, respectively. However, it was judged that the infiltration had a greater influence on the indoor ventilation performance because of the relatively smaller air volume.

A nominal time constant refers to the time necessary for a one-time exchange of the entire volume of indoor air in a room. A normal time constant is ordinarily calculated using supplied air volume of a ventilation system. However, in this paper, the normal time constant was derived from the actual air change rate as measured by the tracer gas method. This value accounted for the machine air change rate and the infiltration rate. The nominal time constant is inverse proportional to the air change rate for the same volume condition.

As shown by Fig.5., a larger air volume results in less time for the air to remain in the room. Nonetheless, ventilation efficiency is not directly proportional to the reciprocity of supplied air volume since the CO$_2$ removal efficiency was decreased for the experimental conditions presented. The CO$_2$ removal efficiency is related to the diffusion volume, the patterns of indoor airflow, and local distribution of CO$_2$.

### 3.2 Ventilation Performance with Air-Conditioning

Indoor ventilation performance was measured with the air conditioning operating in the test rooms. The results are presented in Table 4. The air change rate was measured from the center points of the test rooms.

Ventilation efficiency decreased in all the three test rooms when air conditioning was operational. Ventilation efficiency decreased to 17.8% for Test Room 1, 16.9% for Test Room 2, and 18.5% for Test Room 3. The average decrease in ventilation efficiency was approximately 18%. This decrease is due to several design issues. The first is that air stagnation occurs since the air discharge angle is fixed which then results in locally decreasing the ventilation performance despite the air conditioner promoting overall air mixing. Secondly, an air conditioner discharges air into the upper portion of a room and as a result the heavier CO$_2$ stagnates in the bottom half of the room. While the air conditioner inlet is located in the upper half of the room, the direction of airflow discharge is toward the lower half of the room. This design prevents complete discharge of any existing pollutants (Fig.6.).

Ventilation efficiency of Test Room 1 was higher than that of Test Room 2 because of the location of the air diffuser. In the two experiments, the location of the air diffuser was the only difference as all other conditions were constant. This result suggests that the direction of the airflow discharge from air conditioning affects ventilation efficiency, and it is probably because of the following two causes. First, the representation point was set at the room center and when air was supplied from the center, fresh air inflow around the measurement point was active, leading to high ventilation efficiency. This is similar to the situation where air conditioning is not operating. Air supply in the center of the room is considered more effective than air supply from outer locations due to high density of the occupants in the center of the room. Second, the locations of outlets and inlets of air contributed to such differences. In Test Room 1, four air outlets were installed at the center adjacent to the air conditioner. This enabled the outlet air to flow in similar directions of flow from the air conditioner. In contrast, in Test Room 2, air inlets were installed at the center of the room while air outlets were installed at the corners of the room. This design failed to generate smooth airflow from the inlets to the outlets and likely prevented smooth air discharge because of local over-pressure near the inlets (Fig.7.).

In the case of the heat recovery ventilation system in Test Room 3, an increase in the air change rate was relatively small compared to its basic infiltration rate. This is because the small volume of supplied air in conjunction with the concurrent air supply and discharge led to a high possibility of short circuits. As a result, ventilation efficiency was low relative to the air volume supplied by the system itself (Fig.8.).
3.3 Ventilation Performance Accounting for Furniture

The surfaces of the desks and other furniture will affect airflow as the air travels from the upper half of the room to the lower half. These influences on the airflow patterns will affect ventilation efficiency as well. Accordingly, desks and other types of furniture were installed in Test Rooms 1 and 2 to determine their effects. The ventilation efficiencies were then measured and compared with the measured values without such interior facilities. Table 5 shows the ventilation efficiency based on the status of furniture in the room.

According to the experimental results, the air change rate went up when there was furniture. There are several reasons for this increase in air change rate. One factor was that the room air volume decreased compared to the empty room air volume because of the presence of furniture.

| Physical factors         | Unit | Test Room 1 [Operating air-conditioner/Desk] | Test Room 2 [Operating air-conditioner/Desk] |
|--------------------------|------|---------------------------------------------|---------------------------------------------|
| Space volume             | m³   | 172.80                                      | 172.80                                      |
| Supply air rate          | CMH  | 975.00                                      | 975.00                                      |
| Infiltration rate        | CMH  | 107.87                                      | 107.87                                      |
| Air change rate          | CMH  | 503.70                                      | 425.10                                      |
| Ventilation efficiency   | %    | 51.70                                       | 43.60                                       |
| Effective ventilation efficiency | %   | 43.10                                       | 33.60                                       |

Fig.8. Comparing Total Air Change Rate and Infiltration Rate

Fig.9. Comparison of Measured Data Based on Furniture in the Test Rooms and Operational Status of the Air Conditioner
furniture. Additionally, the tops of the desks were at a height of approximately 80 cm from the floor, which disturbed the airflow that was previously directed to the bottom half of the room that created active air zones above the desks. As a result, ventilation efficiency increased by 10.4% in Test Room 1 and by 5.1% in Test Room 2. The absolute value of ventilation efficiency of Test Room 2 was very low at 39.9%. It was concluded that this efficiency value was due to the locations of air diffusers, as previously discussed. As a result, the ventilation efficiency at the occupants' height levels for breathing changed based on the existence of furniture in the rooms (Fig. 9).

4. Conclusion

The findings of the research are as follows. The ventilation efficiencies according to the type of ventilation systems were measured at 34.8% - 97.8% for the duct types and 82.6% for window type air conditioning. The test results indicated effective ventilation was affected by classroom characteristics such as high air infiltration and low air tightness.

The ventilation efficiency varied with the location of air inlet and outlet ducts and existence of interior furniture. However, the local ventilation efficiency was little changed in this study.

The results showed that the ventilation demand for classrooms would be required to be over 1,000 CMH in order to be satisfied with 1,000 ppm which was the value of IAQ criteria for Korean classrooms in the case of natural ventilation.

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