Article

Effects of ERV Filter Degradation on Indoor CO₂ Levels of a Classroom

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Abstract: Energy recovery ventilators (ERVs) are widely used to reduce energy losses caused by ventilation and improve indoor air quality for recently-constructed buildings. It is important for spaces with high occupancy density and longer residence times, such as classrooms. In classrooms, the ERV size is typically estimated by the target number of students in the design phase, but the design air volume flow rates (m³/h) of the ERV can decrease over time owing to filter degradation such as increased dust loading. In this study, field tests are conducted in a classroom to investigate filter degradation through a visual inspection and by measuring the air volume flow rates at the diffusers connected to the ERV. In addition, variations in carbon dioxide (CO₂) concentrations are also measured to verify the effects of filter degradation on the indoor CO₂ levels over the entire test period, which includes filter replacement, as well. As the tests are conducted during classes, several adjusting methodologies are proposed to match the different test conditions. The results show that the total air volume flow rate of the ERV increases after the filter replacement (546 to 766 m³/h), but it again decreases as time elapses (659 m³/h). Accordingly, the indoor CO₂ concentration decreases after the filter replacement by more than 300 ppm (1404 to 1085 ppm), clearly showing the effect of filter degradation. However, this CO₂ concentration remains similar for four months after the replacement, and the total air volume rate decreases again. An interpretation is made using computational fluid dynamics analysis that the measured CO₂ concentrations are affected by airflow patterns. The airflow in the cooling system may dilute CO₂ concentrations at the measuring location. Thus, periodic filter replacement and management are important to ensure the desired ERV air volume rates and consequently the desired indoor CO₂ concentrations.

Keywords: filter degradation; CO₂ concentration; energy recovery ventilator

1. Introduction

With an increased requirement for reducing building energy consumption, buildings have become more airtight, and the infiltration rates have decreased [1]. A decrease in air exchange rates of a building is good for energy conservation, but the contaminated air may remain indoors for a long time, such as PM_{2.5}, radon, formaldehyde, nitrous oxides, volatile organic compounds and carbon dioxide (CO₂), which are harmful to the health of the occupants [2–5]. Especially, CO₂, which is mainly produced by the respiration of occupants, may get accumulated in that space. High levels of CO₂ concentration are observed in a space with high occupancy density. This may cause problems such as headaches, fatigue, eye symptoms, throat symptoms and breathing difficulties. Consequences of such problems may be more serious when the room is used for mental work. For instance, Satish et al. [6] attempted to assess the effects of increased CO₂ on decision-making performance by means of chamber tests with six groups of four participants. The results showed statistically meaningful reductions in the

performance. A common place for such cases is a classroom. Several studies reported negative effects of high CO₂ level on educational attainment [7–12].

Many studies have been previously conducted on the CO₂ concentrations in school facilities. Turanjanin et al. [13] measured the CO₂ concentrations in classrooms of five schools in Serbia, which are naturally ventilated. Similarly, Shendell et al. [14] measured CO₂ concentrations in schools in Washington (WA) and Idaho (ID). The test classrooms were equipped with ventilation systems, and 45% of the classrooms showed CO₂ concentrations above 1000 ppm (35% in WA and 59% in ID). Corsi et al. [15] measured CO₂ concentrations in 115 elementary schools that are equipped with ventilation systems at a breathing zone located between 0.8 and 1.2 m from the floor of the classroom, and the mean value of CO₂ concentrations was 1440 ppm in that study. Santamouris et al. [16] analyzed 65 research papers that measured CO₂ levels in classrooms, of which 29 papers were naturally ventilated cases through window openings and 36 papers were related to mechanical ventilation systems. For the naturally ventilated cases that were collected from 287 classrooms among 182 schools in 17 countries, 25% of the classrooms showed lower than 1000 ppm, 47% showed higher than 1500 ppm and 18% showed more than 2000 ppm in CO₂ concentrations. For cases with mechanical ventilation systems, 52% of the total 900 classrooms showed less than 1000 ppm, 15% more than 1500 ppm and 18% showed more than 1800 ppm in CO₂ concentrations. Grimsrud et al. [17] measured CO₂ concentrations for eight mechanically ventilated schools in Minnesota, and it measured between 2500 and 3000 ppm when the ventilation systems were not operated and between 1500 and 1700 ppm when operated. Briefly, most of the classrooms that are ventilated naturally through window openings or with mechanical ventilation systems are effective at keeping CO₂ concentrations within a certain range, for instance 1000 to 2000 ppm. The unventilated classrooms or those with switched-off mechanical systems showed high CO₂ concentrations out of this range. Therefore, either proper natural ventilation or the operation of mechanical ventilation is required to keep the indoor CO₂ levels within a desired range for classrooms.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [18] recommended a minimum ventilation rate of 5 L/s per person or 0.6 L/s/m² for educational facilities. This ventilation rate would correspond to approximately 1000 to 1200 ppm of CO₂ levels in a typical classroom. According to the Building Bulletin 101 (BB101) guidelines on ventilation, thermal comfort and indoor air quality in schools (2017) [19], a mechanical ventilation system must keep below a daily average value of 1000 ppm as the CO₂ level. For naturally ventilated classrooms without mechanical systems, this level must not exceed a daily average value of 1500 ppm as the CO₂ level.

In Korea, according to the School Health Act of the Ministry of Education, it is recommended to maintain CO₂ concentrations for classrooms below 1000 ppm, but it is allowed up to 1500 ppm for classrooms equipped with mechanical ventilation systems [20]. This regulation aims to promote installation of mechanical ventilation systems. The government uses a favored regulation for mechanical ventilation systems because natural ventilation can considerably increase a building's energy consumption in the considered climate [21]. Another reason is that natural ventilation mainly occurs through window openings. Outdoor air is no longer fresh in Korea, particularly from winter to spring, because the outdoor concentration of particulate matter is high [22]. Therefore, ventilation through controlled air paths is favored so that energy recovery and air filtration can be applied.

In many countries, mechanical ventilation systems include energy recovery systems, and the whole system is commonly called an energy recovery ventilator (ERV). Here, energy indicates both sensible and latent heat [23–27]. Zhang and Niu [28] analyzed energy saving rates for an ERV system. The annual performance of a membrane-based energy recovery ventilation (MERV) system was analyzed, which covers a 100 square meter office with an occupancy density of 10 square meters per person for approximately six regions in Hong Kong. The MERV system saved about 58% of the energy required for conditioning fresh air, while only about 10% of energy is saved with a traditional sensible-only heat recovery ventilation system. In Korea, the ERV system has largely been installed for its high energy saving effects.

To protect the energy recovery exchanger inside the ERV system from indoor and outdoor dust and to induce only fresh air indoors, filters are installed at both the intake (supply) and outtake (exhaust) air sides of the ERV system. The recommended CO₂ concentration in a classroom can be achieved by properly sizing air volume flow rates of the ERV system for a given number of occupants. Sizing the total airflow rate of the ERV system can be achieved by multiplying the CO₂ emission rate per person and the expected number of occupants of the classroom. However, ventilation filters can degrade over time, particularly in classrooms, as indoor dust is abundant owing to high occupancy density and activities. Therefore, the following assumptions can be made. A proper maintenance of the filters is crucial to guarantee the ventilation performance set during the design because the filter state may affect the total air volume flow rate of the ERV system and consequently the indoor CO₂ concentrations.

In this study, field tests are conducted to investigate such assumptions. The test is to observe the degradation rate of the ERV filters over time and resulting variations of the indoor CO₂ levels. A few analysis methodologies are proposed to calibrate the test conditions that do not remain the same over long periods of tests. First, the field test case is introduced, and the filter degradation is observed by measuring the airflow rates at air inlet and outlet diffusers of a classroom. Further, the indoor CO₂ concentration is measured and its variation over time is analyzed. The analysis of the results using the proposed analysis methodologies is given in the Results Section.

2. Filter Degradation over Time

2.1. Description of Test Classroom

For the field test, a middle school located in Seoul, Korea, was selected. The school was built more than 20 years ago, but the test classroom is located on the second floor in a newly-attached building that was constructed three years ago. The classroom and connection area are well insulated, and ERV systems are installed in the classroom. Some images and detailed ERV duct configurations are shown in Figure 1. A total of two ERVs is installed in the ceiling space of the classroom, one of which also serves the adjacent classroom. However, both ERVs are operated according to the control of the test classroom. The first ERV is connected with three pairs of supply and exhaust ducts, while the other ERV is linked to a single set of ducts of the test classroom, as shown in Figure 1.

Figure 1. Layout of the test classroom and energy recovery ventilator (ERV)/electric heat pump (EHP) systems (red mark: location of the CO₂ sensor).

Both heating and cooling energies are provided by a multi-type electric heat pump (EHP) that is located at the center of the classroom. The CO₂ concentrations are measured below this EHP, where the indoor air is drawn from almost every direction to the inlet air grill of the EHP, when heating and cooling are operated. The installation of CO₂ sensors is limited to this restricted zone unless the classes are disturbed as this field test was conducted for several months. In this study, various additional simulation tests are presented to analyze the test results because some results cannot be fully understood under such limited measuring conditions.

As shown in Figure 2, the measuring height is 1.1 m near the occupancy zone when the occupants are sitting, but the sensor is located away from students' exhaled breath. The measuring instrument used is a 'Testo 480' IAQ probe, for which the measurement range is between 0 and 10,000 ppm with an accuracy of $\pm 3\%$. The systems of this test classroom are described in Table 1. The ERV capacity is given in CMH, which represents m³/h (cubic meter per hour), customarily used among manufacturers.

Figure 2. CO₂ sensors and measuring height.

Table 1. System description of the test classroom.

Description	Value
Volume	161.28 m ³
Number of EHP	1
Nominal EHP capacity	6 kW
Number of ERVs	2
Nominal ERV capacity	500 CMH
Number of supply diffusers	4
Number of exhaust diffusers	4

2.2. Measurement of Air Volume Flow Rates According to Filter Degradation

In a space with high occupancy density, the filters of the ERV system may be rapidly contaminated and degraded by the dust and pollution sources generated in the inner space, as well as by outdoor pollution. Filter contamination and performance degradation may result in reduced air volume flow rates in the ERV system. Therefore, we measure air volume flow rates for observing the degradation level instead of the typical method of measuring static pressure drop across the filters.

The existing filters of the ERV system and newly-replaced filters are compared, and the new filters are also tested four months after the filter replacement. Above all, a visual inspection is conducted for the comparisons, as shown in Figure 3. Figure 3a shows the current state of the mounted filters that have been used for over three years. Generally, a manufacturer recommends replacing the filter every six months, especially for classrooms; however, it is hardly fulfilled in practice. The top filter in Figure 3a was placed on the exhaust air side, and it is more deteriorated indicating more pollution indoors. After replacement (see Figure 3b), the new filters are quickly deteriorated in four months (Figure 3c). Here, the filter on the exhaust air side also becomes more degraded.

To quantitatively test the levels of degradation, we measured the air volume flow rates at every diffuser of supply, as well as exhaust air at the three different points of time considered in this study

(before and after the replacement and four months after the filter replacement). These tests were achieved with the ERV operation at maximum capacity and at a similar time of the day. The air volume flow rates were measured using an airflow measurement instrument (TSI barometer capture hoop), which has an accuracy of $\pm 3\%$. This test instrument is shown in Figure 4. The hood is used to draw or blow the supply or exhaust air, and the measuring sensor is placed at the inlet part of the instrument. The air volume flow rates were measured twice for each diffuser, as shown in Figure 4. These measurement results may indirectly show the levels of degradation of the filters. Lower air volume rates at the same diffuser indicate decreased performance of the filter.

Figure 3. (a) Currently-mounted filters that will be replaced (used for over three years), (b) new filter to be mounted for the test and (c) filters four months after the filter replacement (the left filter is the filter on the exhaust air side).

Figure 4. Measurement of air volume flow rates for each air supply and exhaust diffuser.

3. Analysis Methodologies for Adjusting Measured CO₂ Results

3.1. Mass Balance According to Ventilation Rates

In this study, a mass balance equation is used for result analysis, as represented by Equation (1). This is a global approach model that can predict the variation in the average CO₂ concentration according to the changes in boundaries (inputs), such as imposed air volume flow rates.

$$V \frac{dC_{in}}{dt} = \dot{m}_v(C_o - C_{in}) + \dot{m}_f(C_o - C_{in}) + N \cdot E \cdot CC \quad (1)$$

Here, C is the CO₂ concentration expressed in ppm, V represents the room air volume (m³), $\dot{m}_v$ (m³/h) is the ventilation rate provided by the ERV and $\dot{m}_f$ (m³/h) is the infiltration rate. The test is conducted when the ERV is fully operational, and thus, $\dot{m}_f$ is neglected in this study. This is because exfiltration and infiltration are negligible values when the ventilation system is activated, as assumed in another study [29]. The last term of the equation indicates the CO₂ emission caused by occupants exhaling. It is expressed by the number of occupants (N) and the CO₂ emission rate (L/s) per person (E) with a correction coefficient CC ($1/2.27778 \times 10^6$) converting L/s to ppm.

This model considers complete air mixing. Thus, the time evolution of the CO₂ concentration within an enclosure, C_{in} , is well described by the mass balance of the intake, outtake and generated CO₂. When the filter is degraded and the total ventilation rates are reduced, the average indoor CO₂ concentration is increased, and it can be predicted with this model. This is helpful in crosschecking the measured data and analyzing the effects of test condition changes on the indoor CO₂ levels. For example, the effects of the variation of the number of students is considered with this model by modifying the number N with an estimate of the emission rate per person E from the measured data.

3.2. Evaluation Method of the CO₂ Emission Rate per Student

To compare the indoor CO₂ concentrations by filter replacement, the same number of students must be guaranteed. However, the number of students in the classroom is changed during the test period because of the rearrangement of classrooms for a new semester. The number of students before the filter replacement was 26, and it is increased to 31. Therefore, this number of students after the replacement must be corrected back to the same number of students before the filter replacement. The supply and exhaust air volume flow rates, indoor and outdoor CO₂ concentration and number of students can be directly obtained through measurement, and only the amount of CO₂ emitted per student remains to be evaluated. This parameter allows matching the measurement condition. The emission rate per student is variable per the activities and degree of physical development of the students. As both conditions are similar during classes in this study, the E value is assumed as a constant. An optimization method is proposed to deduce the E value from the measured data. The particle swarm optimization (PSO) method is used [30,31]. This method arbitrarily distributes a group of values (swarm size) within a parameter bound, and the minimum error area is iteratively searched for a given time (max time). The swarm size is set to 2000; max time is 1000 s; and the lower and upper bounds are given as 0 L/s and 0.008 L/s, respectively. These bounds are set from the fact that the emission of a classroom sitting quietly is less than 0.25 L/min (=0.0041 L/s) [32].

3.3. Computational Fluid Dynamics Analysis

The field tests are conducted for over five months. During the period, the EHP operation modes are changed from heating to cooling. The indoor airflow patterns can be different according to these modes, so a single measuring point located at the same place during this period may reflect distinct cases. Therefore, computational fluid dynamics (CFD) analysis is performed to estimate the airflow pattern, particularly at the height of the measuring point.

Such CFD analysis is conducted using the ANSYS Fluent software. The k - ϵ realizable turbulence model was selected with a first order upwind method, and wall sides are set as a non-slip condition.

Three-dimensional modeling considers the installation location and shapes of EHP and diffusers of the ERV system (Figure 5).

The simulation is run only for obtaining air temperature distribution without considering CO₂ diffusion, which can be another research topic and is difficult to achieve. The simulation conditions are given in Tables 2 and 3.

Figure 5. 3D modeling of the test classroom for CFD analysis.

Table 2. Indoor initial temperature and internal heat gain condition.

Conditions	Cooling	Heating
Room initial temperature (°C)	30	10
Internal heat gain (W/m ³)	36.17	−25.29

Table 3. EHP and ERV simulation setting.

Conditions	Cooling	Heating
Discharge air temperature of ERV (°C)	26	14
ERV diffuser shape	Round shape	Round shape
Discharge air temperature of EHP (°C)	16	40
Discharge air volume flow rate of EHP (CMH)	14	14
EHP discharge air velocity (m/s)	2.33	2.33
EHP discharge air angle	Downward 40°	Downward 50°

4. Results

As given in Table 4, the measurements are estimated for three different points of time: before and after filter replacement and four months after filter replacement. The test conditions are not the same for each point of time. First, the number of students is changed over the filter replacement period, and the EHP mode is changed between the second and third time points. For the three cases, the outside CO₂ concentrations are similar showing approximately 440 to 460 ppm, as mentioned earlier.

Table 4. Changes in conditions during measurements.

Conditions	Before	After	After Four Months
Number of occupants	26	31	31
EHP mode	Heating	Heating	Cooling
Indoor temperature (°C)	21.4	20.6	23.4
Outdoor temperature (°C)	−2.1	5	30.5

4.1. Air Volume Flow Rate Measurement

According to the degradation of filters, the air volume flow rates can decrease with an increase in the pressure drop across filters. The air volume flow rates are measured at the three points of time. Table 5 gives the mean values of the supply and exhaust air volume flow rates expressed in CMH, which are obtained by averaging the results two times measured at each diffuser. The flow rates are measured for four pairs of supply and exhaust diffusers, as shown in Figure 1. As per the results, the air volume flow rates are improved at all supply and exhaust diffusers after the filter replacement. Specifically, the air volume flow rates at the exhaust diffusers are very much increased, and apparently, this is related to the fact that the filter on the exhaust air side was more degraded by dust, as shown in Figure 3a. However, the air volume flow rates are decreased again four months after the filter replacement, and this is an expected result as filter degradation occurs during that period. In this case, the exhaust side shows high drops in the air volume flow rates; for example, the total flow rate on the supply side drops by 64 CMH (from 881 to 817) and on the exhaust side by 107 CMH (from 766 to 659). Figure 6 shows the changes in the air volume flow rates during the test period. This shows a relevant relationship between levels of the filter degradation and the consequent airflow rates. Thus, periodic filter replacement is important to ensure the initially-designed flow rates.

Table 5. Results of the supply and exhaust air volume flow rate measurement.

		Before	After	After Four Months
Supply (CMH)	1	202	216	196
	2	189	209	203
	3	213	225	207
	4	210	231	211
Total		814	881	817
Exhaust (CMH)	1	144	225	173
	2	143	207	178
	3	135	199	176
	4	124	135	132
Total		546	766	659

Figure 6. Changes of total airflow rates around the filter replacement period.

4.2. CO₂ Level in the Classroom after Filter Replacement

In this study, a method to set a reference CO₂ concentration level is proposed for comparisons of the three cases (before, after and four months after the filter replacement) as the indoor CO₂

concentrations are largely time-variable, as shown in Figure 7. The results are obtained for a normal class day, just after the filter replacement. A fluctuation is caused by changes in occupants' activities and conditions related to the system and occupants. For example, when the ERV system is switched off, the CO₂ level increased, as observed for the first few hours. The short periods, where the CO₂ concentrations are decreased during the ERV-off interval, match the break time between classes, because some students leave the classroom and the doors are open. Such a break of approximately 10 min cannot reduce the accumulated indoor CO₂ concentration sufficiently, because the corridor is also air-tight in recently built buildings. The high level of CO₂ concentration reaches about 3000 ppm within two hours. This proves the necessity of installing ventilation systems for classrooms, particularly in modern air-tight buildings.

When the ERV is switched on, the CO₂ concentration is rapidly decreased and maintained at a certain level, and the upper bound is close to 1500 ppm. This level follows the national regulation [18], but with only new filters. As shown in Figure 7, the green area represents the class time of 45 min. Interestingly, the concentration level at the end of every class is similar even with different initial CO₂ concentrations. This means that the capacity of the installed ERV system is sufficient to get a quasi-steady-state condition within 45 min. This allows the use of CO₂ concentrations, measured at the end of a class, for comparisons when other conditions are the same.

Figure 8 is a magnified graph of the second class marked with a green box in Figure 7. When the class begins, and the students sit, the CO₂ concentrations are decreased by a low CO₂ emission rate of quiet activities during the class. The CO₂ concentrations is maintained at around 1200 ppm after 25 min from the beginning of the class. In this study, an average value of the CO₂ concentration during the last 10 min of a class is set to be the reference measured data at the targeted point of time.

Figure 7. Daily variation of CO₂ concentration in the test classroom.

Figure 8. Variation of CO₂ concentration during a class of 45 min (the second green box in Figure 7).

4.3. CO₂ Level Comparison between Cases of before and after Filter Replacement

The level of CO₂ concentrations shown in Figure 8 is compared to that measured a few days before the filter replacement. As mentioned above, the same measuring method is adopted for the results. Figure 9 shows the CO₂ levels during the last 10 min of the classes on different days, before and after filter replacement. The left figure pertains to the data measured before the replacement, showing an average concentration of 1404 ppm, while the CO₂ value after the replacement is 1182 ppm. From these results, the effect of filter replacement on the indoor CO₂ level is evident, which shows a difference of more than 200 ppm. Furthermore, the number of students is increased across the filter replacement period (see Table 4). Thus, more important effects can be expected if the number of students is considered to be the same.

Figure 9. Comparison of CO₂ concentrations measured during the last 10 min of classes on different days (**left**: before the filter replacement and **right**: after the replacement).

4.4. Analysis Methodologies I: Number of Students

To correctly compare the CO₂ levels between cases before and after the filter replacements, the number of students must be adjusted. An evaluation method for a CO₂ emission rate per student was proposed in Section 3.2, and the CO₂ emission rate per student for the test class was evaluated in a way that it covers the whole data of Figure 9. The PSO loop includes two sub-simulation loops, where the emission rate E (Equation (1)) is equal, but the number of students is different. The PSO algorithm iteratively provides a value E to both the sub-simulation loops until the error between the simulation and measurement results is minimized. In this way, the target E can be obtained. Therefore, the measured data can be adjusted by simulation with Equation (1) and the obtained E for a case of a different number of students.

The PSO simulation deduces a value of 0.00411 L/s for the CO₂ emission rate per person, as given in Table 6, which is close to the level for seated and quite activities proposed by ASHRAE [32]. As the number of students was increased after the filter replacement by a new school year, it was expected that the total CO₂ emission rate would also be higher and thus overestimated. Thus, the corrected CO₂ level can be lower than the measured values. The adjusted CO₂ concentration after the filter replacement becomes 1085 ppm, when the number of students is modified to 26 students. By this adjustment, the measured CO₂ concentration is decreased by approximately 100 ppm. Finally, this shows a more than 20% reduction in the indoor CO₂ concentrations by filter replacement.

Table 6. CO₂ concentration rates in the classroom by adjusting the number of students.

Conditions	Before Filter Replacement	After Filter Replacement
Number of students	26	31
Number of students (after adjustment)	26	26
Average CO ₂ concentration rate (ppm)	1404	1182
Average CO ₂ concentration rate after adjustment (ppm)	1404	1085 ($E = 0.00411 \text{ L/s}$)

4.5. Comparison of Cases after the Filter Replacement and Four Months after the Replacement

To confirm the increasing effect of indoor CO₂ levels according to filter degradation, the CO₂ concentrations, four months after the filter replacement, are measured. A value higher than the case just after the replacement is expected, as the filter degradation occurs during this period. The supply and exhaust air volume flow rates are decreased as time proceeds after filter replacement (see Table 5). However, there was almost no difference between the cases, as shown in Figure 10. The CO₂ concentration of around 1182 ppm (for 31 students) after filter replacement is kept unchanged, showing 1167 ppm as the average value, as shown in Figure 10. The number of students between the two measurements was the same (Table 5), but the EHP operation in the classroom was shifted from heating to cooling as the seasons changed. The CO₂ level is sensitive to indoor airflow patterns; thus, the concentration distribution can vary depending on the air temperature distribution [33,34]. Therefore, the room temperature distributions according to the different indoor airflow patterns caused by distinct operations of the EHP and ERV are investigated, and the results are presented in the following section.

Figure 10. Comparison of CO₂ concentrations after the filter replacement and four months after replacement (**left:** after the replacement and **right:** four months after the replacement).

4.6. Analysis Methodologies II: EHP Operation Mode

CFD simulations are run with the conditions demonstrated in Section 3.3. Figure 11 shows the airflow patterns and room temperature distribution results for the heating (left) and cooling (right) modes for EHP and ERV. The marks in the figure represent the measuring point for CO₂ concentrations in the classroom. The airflow patterns in the classroom by the EHP and ERV are shown in Figure 11a. The air stream does not reach to the bottom in the heating period, while the stream vertically falls for the cooling mode. The cross-sectional temperature distribution and the CO₂ concentration measuring location are given in Figure 11b. In the heating period, the temperature difference was approximately 7 °C between the heights of 0.5 m and 2 m, and the temperature at the measuring point at 1.1 m is

close to the upper mixed temperatures. In the cooling period, the temperature difference according to the height is smaller than 1 °C.

From the results, a temperature stratification in the classroom is observed for the heating period, expecting that the emitted CO₂ is likely to remain in the upper zone, including the measuring point. Thus, the measured CO₂ concentration in the heating period can be higher than the average value. Moreover, the CO₂ measured at the cooling period seems to be very close to the average value as the air is well mixed. This can be interpreted as the CO₂ concentration measured four months after the filter replacement would be adjusted by a higher value when the same heating conditions are assumed. The incoherent results of the measured CO₂ concentrations between the last two points of time are likely due to the air stratification effects shown in the CFD results. As a result, the same effect of filter degradation on the indoor CO₂ level would be observed over the entire test period.

Figure 11. (a) Side view of airflow patterns and (b) cross-sectional temperature distributions marked with the measuring height (left: heating and right: cooling).

5. Conclusions

The purpose of the study was to investigate the filter degradation of ERVs and its effects on the indoor CO₂ levels through field tests in a classroom. For such tests, the existing filters mounted in the ERV system for the past three years were replaced by new ones, and the resulting air volume flow rates and CO₂ concentrations were measured. The tests were conducted during classes, in which the test conditions were different, and thus, several methodologies are proposed to match the conditions and compare the results. First, an optimization method is proposed to deduce the CO₂ emission rate per student, which can be used to adjust the number of students, which was distinct over the tests. Second, CFD analysis is proposed to simulate the indoor airflow patterns in different EHP operations. This can give an interpretation of the measured CO₂ concentrations, but at a single measuring point. Finally, the last ten minutes of each class are selected as a reference interval for obtaining average CO₂ concentrations, as a quasi-steady-state value can be obtained during the interval regardless of the initial values.

The test results are summarized as follows:

- The air volume flow rates increased after the filter replacement by more than 200 CMH at the exhaust air side of the ERV.
- The air volume flow rates decreased as time elapsed since the filter replacement.
- The resulting indoor CO₂ levels were affected by the measured air volume flow rates when the test conditions were similar.
- After the filter placement, the value of indoor CO₂ concentrations was decreased by more than 300 ppm, showing 1085 ppm, sufficiently meeting the national recommended value.

- The PSO gave a value of 0.0148 CMH for the CO₂ emission rate per student, which is within the standard ranges proposed by ASHRAE.
- The CFD simulation can give different airflow patterns in heating and cooling conditions, and this result can be used for interpreting the CO₂ concentration measured at a single measuring point.

This work focuses on the apparently different test conditions to match them for comparison purposes, and thus other, factors that may affect indoor CO₂ concentrations such as levels of ambient dust are not fully investigated. In addition, more detailed tests on the indoor airflow in various temperature and pressure conditions do not accompany those performed. These are to be carried out in future work. However, the proposed analysis methodologies can help with interpreting and adjusting other measured results that are obtained in different test conditions often encountered in field tests.

This study clearly shows the importance of filter replacement and management for ensuring the initially-designed air volume flow rates and resulting indoor CO₂ concentration level related to student comfort and educational attainment. A new regulation such as installing a pressure drop gauge across the filter can be required in the future, and it is helpful in letting maintenance personnel know the need for filter replacement.

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Nomenclature

V	Volume of the classroom (m)
C	CO ₂ concentration in the room (ppm)
C_o	Outdoor CO ₂ concentration (ppm)
C_i	Indoor CO ₂ concentration (ppm)
C_{in}	Initial CO ₂ concentration in the room (ppm)
CC	Correction coefficient
CMH	cubic meter per hour (m ³ /h)
$\dot{m}_v$	Ventilation air volume flow rate (m ³ /h)
$\dot{m}_f$	Infiltration air volume flow rate (m ³ /h)
N	Number of occupants (-)
E	CO ₂ emission rate per student (L/s)

References

1. McQuade, J. *A System Approach to High Performance Buildings*; Technical Report; United Technologies Corporation: Washington, DC, USA, 2009.
2. Apte, M.G.; Fisk, W.J.; Daisey, J.M. Associations between Indoor CO₂ Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994–1996 BASE Study Data. *Indoor Air* **2000**, *10*, 246–257. [[CrossRef](#)] [[PubMed](#)]
3. Seppänen, O.; Fisk, W.; Mendell, M. Association of Ventilation Rates and CO₂ Concentrations with Health and other Responses in Commercial and Institutional Buildings. *Indoor Air* **1999**, *9*, 226–252. [[CrossRef](#)] [[PubMed](#)]
4. Clausen, G. Ventilation Filters and Indoor Air Quality: A Review of Research from the International Centre for Indoor Environment and Energy. *Indoor Air* **2004**, *14*, 202–207. [[CrossRef](#)] [[PubMed](#)]

5. Csobod, E.; Annesi-Maesano, I.; Carrer, P.; Kephelopoulous, S.; Madureira, J.; Rudnai, P.; de Oliveira Fernandes, E.; Barrero-Moreno, J.; Beregszászi, T.; Hyvärinen, A. *SINPHONIE: Schools Indoor Pollution & Health Observatory Network in Europe*; Final Report; Publications Office of the European Union: Luxemburg, 2014.
6. Satish, U.; Mendell, M.J.; Shekhar, K.; Hotchi, T.; Sullivan, D.; Streufert, S.; Fisk, W.J. Is CO₂ an Indoor Pollutant? Direct Effects of Low-to-Moderate CO₂ Concentrations on Human Decision-Making Performance. *Environ. Health Perspect.* **2012**, *120*, 1671–1677. [[CrossRef](#)] [[PubMed](#)]
7. Branco, P.; Alvim-Ferraz, M.; Martins, F.; Sousa, S. Children's Exposure to Indoor Air in Urban Nurseries-Part I: CO₂ and Comfort Assessment. *Environ. Res.* **2015**, *140*, 1–9. [[CrossRef](#)] [[PubMed](#)]
8. Jaber, A.R.; Dejan, M.; Marcella, U. The Effect of Indoor Temperature and CO₂ Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia. *Energy Procedia* **2017**, *122*, 451–456. [[CrossRef](#)]
9. Cetin, M. A Change in the Amount of CO₂ at the Center of the Examination Halls: Case Study of Turkey. *Stud. Ethno-Med.* **2016**, *10*, 146–155. [[CrossRef](#)]
10. Bornehag, C.; Sundell, J.; Hägerhed-Engman, L.; Sigsgaard, T. Association between Ventilation Rates in 390 Swedish Homes and Allergic Symptoms in Children. *Indoor Air* **2005**, *15*, 275–280. [[CrossRef](#)] [[PubMed](#)]
11. Lee, S.; Chang, M. Indoor Air Quality Investigations at Five Classrooms. *Indoor Air* **1999**, *9*, 134–138. [[CrossRef](#)] [[PubMed](#)]
12. Daisey, J.M.; Angell, W.J.; Apte, M.G. Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information. *Indoor Air* **2003**, *13*, 53–64. [[CrossRef](#)] [[PubMed](#)]
13. Turanjanin, V.; Vučićević, B.; Jovanović, M.; Mirkov, N.; Lazović, I. Indoor CO₂ Measurements in Serbian Schools and Ventilation Rate Calculation. *Energy* **2014**, *77*, 290–296. [[CrossRef](#)]
14. Shendell, D.G.; Prill, R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. Associations between Classroom CO₂ Concentrations and Student Attendance in Washington and Idaho. *Indoor Air* **2004**, *14*, 333–341. [[CrossRef](#)] [[PubMed](#)]
15. Corsi, R.; Torres, V.; Sanders, M.; Kinney, K. Carbon Dioxide Levels and Dynamics in Elementary Schools: Results of the TESIAS Study. *Indoor Air* **2002**, *2*, 74–79.
16. Santamouris, M.; Synnefa, A.; Assimakopoulos, M.; Livada, I.; Pavlou, K.; Papaglastra, M.; Gaitani, N.; Kolokotsa, D.; Assimakopoulos, V. Experimental Investigation of the Air Flow and Indoor Carbon Dioxide Concentration in Classrooms with Intermittent Natural Ventilation. *Energy Build.* **2008**, *40*, 1833–1843. [[CrossRef](#)]
17. Grimsrud, D.; Bridges, B.; Schulte, R. Continuous Measurements of Air Quality Parameters in Schools. *Build. Res. Inf.* **2006**, *34*, 447–458. [[CrossRef](#)]
18. ANSI. *Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers; ANSI/ASHRAE Standard 62.1-2016; ASHARE: Atlanta, GA, USA, 2013.
19. Department for Education. *Building Bulletin 101 (BB101)-Guidelines on Ventilation, Thermal Comfort and Indoor Air Quality in Schools*; Department for Education: London, UK, 2017.
20. Korea Ministry of Education. The standards for maintenance and management of the air quality in school buildings Table IV-2. In *Enforcement Rule of the School Health Act, 2017.03*; Article 3-2; Korea Ministry of Education: Sejong, Korea, 2017.
21. El Fouih, Y.; Stabat, P.; Rivière, P.; Hoang, P.; Archambault, V. Adequacy of Air-to-Air Heat Recovery Ventilation System Applied in Low Energy Buildings. *Energy Build.* **2012**, *54*, 29–39. [[CrossRef](#)]
22. Kang, C.; Sunwoo, Y.; Lee, H.S.; Kang, B.; Lee, S. Atmospheric Concentrations of PM_{2.5} Trace Elements in the Seoul Urban Area of South Korea. *J. Air Waste Manag. Assoc.* **2004**, *54*, 432–439. [[CrossRef](#)]
23. Roulet, C.; Heidt, F.; Foradini, F.; Pibiri, M. Real Heat Recovery with Air Handling Units. *Energy Build.* **2001**, *33*, 495–502. [[CrossRef](#)]
24. Fehrm, M.; Reiners, W.; Ungemach, M. Exhaust Air Heat Recovery in Buildings. *Int. J. Refrig.* **2002**, *25*, 439–449. [[CrossRef](#)]
25. Lazzarin, R.M.; Gasparella, A. Technical and Economical Analysis of Heat Recovery in Building Ventilation Systems. *Appl. Therm. Eng.* **1998**, *18*, 47–67. [[CrossRef](#)]
26. Dodoo, A.; Gustavsson, L.; Sathre, R. Primary Energy Implications of Ventilation Heat Recovery in Residential Buildings. *Energy Build.* **2011**, *43*, 1566–1572. [[CrossRef](#)]
27. Bakó-Biró, Z.; Clements-Croome, D.; Kochhar, N.; Awbi, H.; Williams, M. Ventilation Rates in Schools and Pupils' Performance. *Build. Environ.* **2012**, *48*, 215–223. [[CrossRef](#)]

28. Zhang, L.; Niu, J. Energy Requirements for Conditioning Fresh Air and the Long-Term Savings with a Membrane-Based Energy Recovery Ventilator in Hong Kong. *Energy* **2001**, *26*, 119–135. [[CrossRef](#)]
29. Lu, X.; Lu, T.; Viljanen, M. Estimation of space air change rates and CO₂ generation rates for mechanically-ventilated buildings. In *Advances in Computer Science and Engineering*; InTech: London, UK, 2011.
30. Shi, Y. Particle swarm optimization: Developments, applications and resources. In Proceedings of the 2001 Congress on Evolutionary Computation, Seoul, Korea, 27–30 May 2001; pp. 81–86.
31. Wang, Z.; Yang, R.; Wang, L. Multi-agent control system with intelligent optimization for smart and energy-efficient buildings. In Proceedings of the IECON 2010—36th Annual Conference on IEEE Industrial Electronics Society, Glendale, AZ, USA, 7–10 November 2010; pp. 1144–1149.
32. Dougan, D.S.; Damiano, L. CO₂-Based Demand Control Ventilation: Do Risks Outweigh Potential Rewards? *ASHRAE J.* **2004**, *46*, 47–53.
33. Ning, M.; Mengjie, S.; Mingyin, C.; Dongmei, P.; Shiming, D. Computational Fluid Dynamics (CFD) Modelling of Air Flow Field, Mean Age of Air and CO₂ Distributions Inside a Bedroom with Different Heights of Conditioned Air Supply Outlet. *Appl. Energy* **2016**, *164*, 906–915. [[CrossRef](#)]
34. Chung, K.; Hsu, S. Effect of Ventilation Pattern on Room Air and Contaminant Distribution. *Build. Environ.* **2001**, *36*, 989–998. [[CrossRef](#)]

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