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Experimental Study on CO_2 and Radon Mitigations in an Apartment Using a Mechanical Ventilation System

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Abstract: The public interest in indoor air quality has rapidly increased in Korean society, and ventilation systems can play an essential role in improving indoor air quality. This study aims to estimate the reduction in indoor CO_2 and radon, which can be effectively mitigated by air exchange, according to the operation of mechanical ventilation in an apartment with the national standard housing size (85 m^2) and shape in Korea. The time required to meet Korea's mandatory indoor CO_2 standard (1000 ppm) was 167, 98, 66, and 51 min under air change rates of 0.5, 1.0, 1.5, and 2.0 ACH (air change per hour), respectively. Regarding indoor radon, the removal rate increased with increased ventilation volume, and the minimum concentration level was low and sustained for a prolonged duration. Nonetheless, an air change rate of 0.5 ACH may not offer sufficient ventilation. Additionally, it is imperative to note that indoor radon concentrations tend to escalate swiftly when a mechanical ventilation system is deactivated. Thus, to enhance indoor air quality, it is necessary to reconsider strategies to augment the air change rate and guarantee uninterrupted ventilation.

Keywords: indoor CO_2; indoor radon; mechanical ventilation system; indoor air quality; apartment

Citation: Jeong, J.; Cho, K. Experimental Study on CO_2 and Radon Mitigations in an Apartment Using a Mechanical Ventilation System. *Buildings* **2023**, *13*, 1439. https://doi.org/10.3390/buildings13061439

Academic Editor: Zhenjun Ma

Received: 18 April 2023
Revised: 17 May 2023
Accepted: 29 May 2023
Published: 31 May 2023

1. Introduction

From the viewpoint of public health concerns, the importance of indoor air quality management has begun to draw attention to the issue of sick building syndrome (SBS) [1,2]. The adverse health effects of indoor air pollution are clear. Approximately 3.2 million premature annual deaths are related to household air pollution, which causes respiratory diseases, immune system impairment, and a reduction in oxygen-carrying capacity. Therefore, indoor air quality problems are considered crucial worldwide risk factors for human health [3,4]. Moreover, improved built technologies have improved energy consumption efficiency and comfort for occupants but have led to worse indoor air quality [5–7].

Source control, one of the typical approaches for reducing pollution, is becoming increasingly insufficient, technically infeasible, and economically unviable [8]. Therefore, air purifiers have spread rapidly as an alternative tool to improve indoor air quality. These devices effectively remove pollutants from physiochemical or biological sources by filtering or sanitizing them without source control or incomplete air exchange practices. Despite several advantages of air purifiers, such as ease of handling, location, and relocation, they may generate harmful intermediates, such as ozone and aldehyde [9–11]. One of the most significant issues in using air purifiers is that the air is recirculated through filter media in enclosed spaces; therefore, the proportion of indoor and outdoor air exchange is rarely expected. Owing to evolving technologies for air cleaning, many indoor pollutants are now controllable. However, some gaseous substances, such as carbon dioxide (CO_2) and radon, can still be effectively reduced by increasing the ventilation of indoor and outdoor air, instead of relying solely on an air purifier.

CO_2 is a trace gas, one of the components of the Earth's atmosphere that plays many roles in various indices—a contributor to climate change, a byproduct of fossil fuel combustion, the end product of cellular respiration, and an indicator of indoor air quality acceptability. Although CO_2 is not classified as a toxic or harmful compound to the human body, exposure to elevated levels of CO_2 has caused specific health problems. As inhaled CO_2 accumulates in the body, the heart rate increases while blood pH decreases. This leads to symptoms such as headache, dizziness, fatigue, confusion, anxiety, drowsiness, and stupor, which are related to the respiratory, cardiovascular, and central nervous systems [12–15]. Based on previous epidemiological evidence, Korea's national indoor CO_2 standard has an upper limit of 1000 ppm, which is similar to many other countries [12,16].

Radon, another major pollutant that can be removed via indoor and outdoor air exchange, occurs naturally in the decay chain of uranium and is ubiquitous in the Earth's crust, rock, and soil and stone-based building materials. Radon and its decay products are well-known Group 1 carcinogens (known to be carcinogenic to humans) [17] that can enter the human body through the respiratory tract by inhalation and repeatedly cause damage until it becomes the final decay product. Noble-gas radon has several isotopic forms, specifically radon-222, radon-220, and radon-219. This study considered only the most essential radioisotope, radon-222 (radon).

The effects of pollutants are studied in a dose–response relationship, and exposure is used as an essential concept. Because the exposure dose is calculated as the time integral of the concentration, countermeasures are required to either shorten the exposure duration or lower the concentration to minimize adverse effects. People typically have a routine for managing their time, and time indoors is hardly shortened in dwellings; therefore, the health effects of indoor air quality can be reduced only by lowering the pollutant concentration. In this regard, ventilation can help mitigate the health issues and social costs caused by indoor air pollution.

With the growing recognition of the importance of indoor air quality, numerous studies have been conducted to examine the impact of controlling pollutants on ventilation. Many researchers have studied the air exchange rates of ventilation and indoor air pollutants, including carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compounds (VOCs), and various sizes of particulate matter (PMx). Some were focused on naturally ventilated places [18–20], while others compared the effects of ventilation types [21–24] or strategies [25–27]. These studies have converged on a certain agreement that increasing ventilation rates results in a notable reduction in the levels of indoor air pollutants. Nevertheless, some problems remained. In some cases, the measured levels of pollutants can exceed recommended values, even with satisfactory ventilation rates [18]. The actual performance of ventilation systems varies depending on circumstances, making it difficult to accurately represent the ventilation requirements for all types of buildings [26]. Toftum et al. (2015) [22] reported that the spread of the maximum CO_2 level in schools with natural ventilation was three times wider than in mechanically ventilated ones. Furthermore, much of the earlier research on indoor radon behavior using numerical modeling is worthwhile [28–30], but more detailed information for management in actual living environments is still necessary.

In Korea, regulations have been strengthened regarding laws related to ventilation facilities, which, at present, include the mandatory installation of ventilation facilities in apartments with 30 or more households [31]. However, the legal minimum standard for ventilation facilities installed in apartments is an air change rate of 0.5 per hour (ACH). According to the relevant rule, mechanical ventilation systems for apartment buildings should be manufactured to control the ventilation volume in three stages, including one stage at 0.5 ACH. Approximately 90% of the mechanical ventilation devices installed in residential spaces have shown that the maximum level of air change volume is less than 1.0 ACH, and the question of whether this is a sufficient quantity of ventilation has arisen in previous studies [26,32]. Additionally, it is worth mentioning that there are only indoor radon recommendations for public-use facilities and newly built apartments under current

Korean law [33]. Therefore, this study aimed to establish quantitative data on indoor CO_2 and radon levels by using mechanical ventilation systems in an apartment and contribute to developing effective plans for managing indoor pollutants in residences.

2. Materials and Methods

2.1. Research Sequence

This study aimed to confirm a mechanical ventilation system's CO_2 and radon removal performance by conducting a field experiment in an apartment. Accordingly, the subject of the experiment was an apartment of 85 m^2, defined as national standard housing in the Housing Act in Korea [34]. Indoor pollutant removal experiments by mechanical ventilation were conducted under the same experimental conditions to compare the behavior of CO_2, which was used as an indicator for calculating the required ventilation rate, to indoor radon. For the results to be meaningful for verifying the CO_2 and radon removal performances of mechanical ventilation systems in dwellings, this study considered the following:

1. Preliminary test for understanding the characteristics of experimental space

Many researchers have shown that the amount of infiltration affects indoor air quality as unregulated air flow can occur through cracks and leaks in the building envelope [21,35,36]. In this study, the fan pressurization method, according to ISO 9972 [37], was used to measure the air permeability of the subject space. The possibility of influence from the outdoor environment on the indoor environment was identified using blower door test equipment.

2. Determination of experimental cases of air change rate

As a result of checking Korea's five major commercial mechanical ventilation systems and examining their air volume at each stage of operation, the air volume was set in three stages in the range of 0.3 ACH to 1.5 ACH. Therefore, 0.5 ACH, the legal minimum standard ventilation volume, was set as the condition for Case 1, while Case 0 was unventilated as a control condition. The air change rate of 1.0 ACH was used in Case 2, and Case 3 was set to 1.5 ACH, which is the largest figure that can be implemented with existing devices. Additionally, 2.0 ACH was used in Case 4 to investigate whether the others were sufficient.

3. Survey for traditional and achievable levels of indoor CO_2 and radon

Following a literature review and survey, the possible levels of indoor CO_2 and radon, which are both routinely observable and concerning, were investigated in residential areas, and these levels were set as target values for indoor pollutants. The achievable levels of indoor pollutants after ventilation, as the final concentrations in the experiments, were essentially the same or lower than the recommended values. The details are presented in Section 2.3.

The experiments proceeded in the following order by referring to the sampling conditions for newly built apartments in indoor air sampling and evaluation standard methods in Korea [38].

Step I. Controlling base level of indoor air quality

All openings facing the outside were fully opened for more than 30 min to control the initial concentration by discharging the target pollutants (i.e., CO_2 and radon) that may have accumulated in the indoor area.

Step II. Creating the indoor concentrations up to the target values

While maintaining an airtight state, the pollutants were distributed indoors until the indoor concentration reached the target level. Chemically pure CO_2 gas (N50 purity, 40 kg, and 150 mBar cylinder) was uniformly released into the indoor space at a constant flow rate of 20 L/min until it reached a concentration of 3000 ppm. This was achieved by connecting a gas regulator and a mass flow controller (ISVT500 model, ISVT, Yongin, Republic of Korea) to the cylinder containing CO_2 gas. In the experimental area, a small fan was used to ensure adequate mixing of the indoor air, and its concentration was monitored closely. Radon, especially radon-222, is produced as a direct decay product of radium-226. Therefore, this study collected soil samples that are rich in radium from a nearby mining region in Korea. The radium-rich soil samples were sieved and conditioned at a temperature of 20 ± 2 °C and 50 ± 5% relative humidity before being placed in the experimental area to serve as a source of radon emission. Preliminary tests were performed to investigate the relationship between the quantity of soil samples and the levels of indoor radon.

Step III. Reducing indoor concentration to reach the achievable level

The fan motor speed and diffusers linked to the mechanical ventilation system were controlled using a dedicated program to adjust the ventilation volume. The mechanical ventilation system was continuously operated to lower the pollutants to the target value in each case, and the removal performance was estimated.

2.2. Information on Subject Space and Measurements of Indoor Pollutants

Figure 1 shows the floor plan of the subject space and schematics of the duct configuration based on the preferred size of Korean apartments.

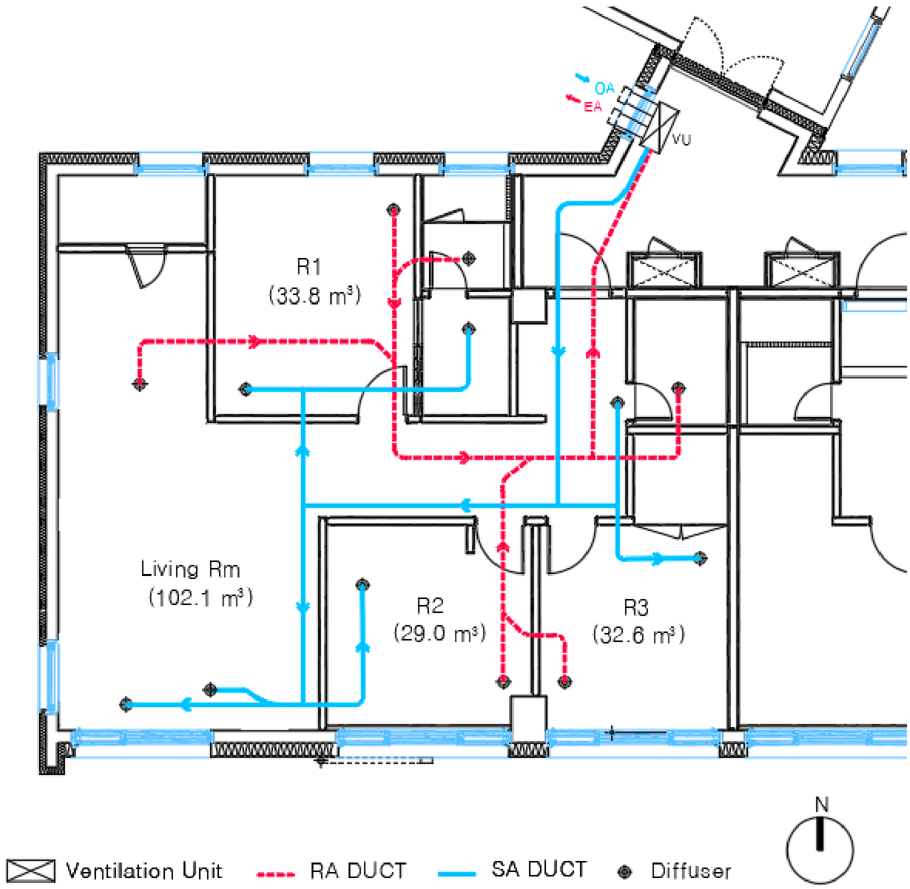


Figure 1. The duct work plan of the apartment and the subject space (R2) for the experiments.

In R2, a large window with a height of 2.3 m, which achieved the first grade in airtight performance according to KS F 2278 [39], was installed on the southern wall (Figure 1). One set of fan-type diffusers for supply air (SA) and return air (RA) was installed on the ceiling, and the operating rate of the diffuser was adjusted for precise air volume control (Figure 2). An airflow transmitter (Airtron, Sejin S&P, Seoul, Republic of Korea) provided a variable air volume. It is a high-performance airflow meter with a built-in micro differential pressure sensor and a CPU. The static pressure of the duct was measured using a Pitot probe, and the air volume was calculated. The margin of error certified by the manufacturer is ±1% of FS. According to the Korean standard method for environmental testing and inspection [38], the measurement point was set at 1.5 m above the ground at the center of

R2 (Figure 3a). It was the midpoint at 0.5 m from the ceiling and 1 m from the SA and RA diffuser in the area.

(**a**)

(**b**)

Figure 2. The variable air volume controlling system: (**a**) flow metering system (FMS); (**b**) motor diffuser closed (upper) and opened (lower).

(**a**)

Figure 3. *Cont*.

(**b**) (**c**)

Figure 3. The measurements in R2: (**a**) measurement point; (**b**) EE820 sensor for CO_2; (**c**) AlphaGUARD DF2000 for radon.

Indoor CO_2 concentrations were monitored using an EE820 sensor (HV3 model, E+E Elektronik Ges.m.b.H, Engerwitzdorf, Austria), and data were recorded using a portable logging system (GL840, Graphtec, Yokohama, Japan) (Figure 3b). The EE820 sensor is based on the principle of dual-wavelength nondispersive infrared technology and is one of the most widely used sensors for CO_2 gas detection [40]. The analytical measurement range varies from 0 ppm to 10,000 ppm, and operation ranges were as follows: air temperature ranged from −20 °C to 60 °C, and relative humidity ranged from 0% to 100%. Although this device is small, simple, and inexpensive, it provides good accuracy (approximately ±2% of the measured value) and reliable temperature independence.

The continuous measurements of the activity concentrations were performed using a current ionization chamber. When the air sample containing radon entered the ionization chamber, it caused the emission of 5.5 MeV alpha particles as a result of the radioactive decay chain. Each alpha particle creates ionization currents, and the resulting signal is proportional to the activation concentration of radon. AlphaGUARD (DF2000 model, Bertin Instruments, Frankfurt, Germany) was used for continuous radon measurements in the indoor air (Figure 3c). It contains 3D-alpha spectroscopy, a radon detector pulse-ionization chamber, and an active air sampling system with a radon progeny filter to prevent detection errors. Integrated sensors were used to measure multiple environmental parameters simultaneously, such as air temperature, relative humidity, and atmospheric pressure. The AlphaGUARD can measure radon between 2 Bq/m^3 and 2,000,000 Bq/m^3 (as a concentration of Rn-222) within a linearity error of 3%. The manufacturer calibrated the instrument, and the deviation of the measured value was below ±2% for the target value; the calibration is traceable. Data were collected every 10 min during the experiments to monitor changes in indoor radon concentrations. Moreover, a 0.5 L/min air sample was passed through a HEPA filter to protect the interior of the ionization chamber from contamination by unwanted aerosols.

The quality control of the instruments confirmed that the background value was less than 1.0 ppm of CO_2 and 2.0 Bq/m^3 of radon by measuring high-purity nitrogen (N50) gas. The measurement accuracy of each device was established in the field tests to be within ±2% of 3000 ppm CO_2 and 300 Bq/m^3 radon. The AlphaGUARD was purged several times to remove the radon gas that may have remained inside the ionization chamber for every batch of experiments.

2.3. Survey and Preliminary Test for Experimental Setup Conditions

2.3.1. Indoor CO_2 Level

The indoor CO_2 concentration mainly depends on human metabolism; the amount created by certain activities associated with combustion, such as cooking or burning a candle, can be negligible. It is directly affected by occupancy patterns; therefore, possible residential behaviors were analyzed. Generally, a family of four lives in a house of 85 m^2 with parents and two children in Korea, according to the national survey [41]. Among the behavioral patterns in R2, the activities expected to increase the CO_2 concentration the most can be summarized as three hours of two people working (i.e., two children studying together) and eight hours of a child sleeping.

Assume that the initial concentration is 420 ppm, considering the annual average level of ambient background CO_2 (Anmyeon-do station in Korea [42]), and that two occupants are in R2 from 8 p.m. to 11 p.m., with only CO_2 infiltration not being ventilated, given an air change rate of 0.2 ACH for the average infiltration rate of the Korean apartments according to a previous study [43]. The CO_2 concentration can increase to 3222 ppm at 11 p.m. in R2 with a 0.2 ACH air change rate using Equation (1):

$$V\frac{\partial C}{\partial t} = Q(C_0 - C_i) + G(t) \quad (1)$$

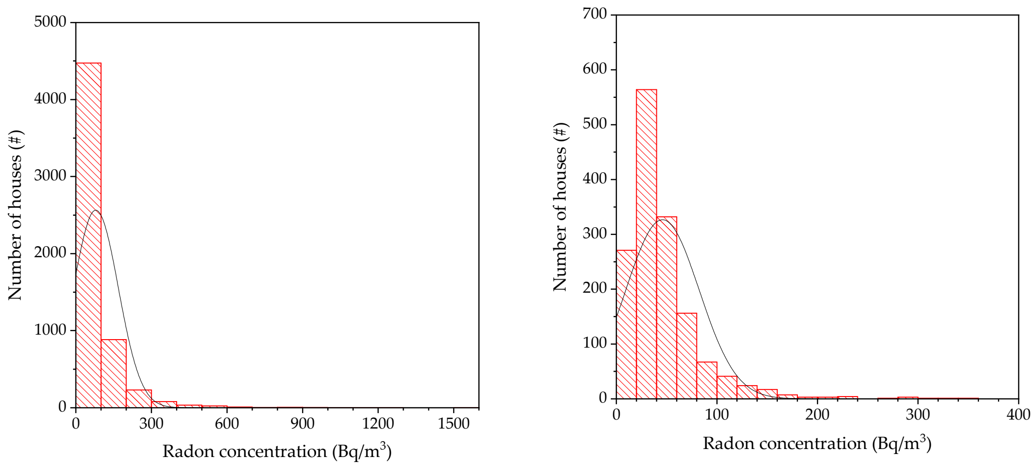
where V, C, t, Q, C_0, C_i, and $G(t)$ represent the space volume (m^3), CO_2 level (mg/m^3), duration (h), air change volume (m^3/h), outdoor CO_2 concentration (mg/m^3), indoor CO_2 concentration (mg/m^3), and CO_2 generation rate per unit time (mg/h), respectively.

However, the survey mentioned earlier reported that a family is generally expected to return home at 7:30 p.m. and have dinner within 30 min to 1 h after showering and preparing dinner; therefore, the possible continuous residence time is 2 h to 2.5 h in R2. Accordingly, the CO_2 concentration was recalculated, and 3000 ppm was set as the target level for this study, whereas the achievable concentration was 1000 ppm, the same as the mandatory indoor air standard in Korea.

2.3.2. Indoor Radon in Dwellings

In Korea, there is little information on radon in residential areas because the Indoor Air Quality Control Act applies only to multi-use facilities and newly built apartment buildings. Despite the lack of indoor radon data, nationwide radon concentrations in residential areas have been investigated intermittently. The average concentration in Korean homes in 2018 was 72.4 $\pm$ 82.5 Bq/m^3, with the range of 7.0 Bq/m^3 to 1504 Bq/m^3 distributed normally [44]. Approximately 80% of the houses showed indoor radon concentrations below the reference level (100 Bq/m^3) proposed by the WHO; however, 698 cases exceeded the Korean recommended level of indoor air quality (148 Bq/m^3) (Figure 4).

The tenth percentile of radon concentrations in Korean homes was 18.7 Bq/m^3 (Table 1). In addition, the atmospheric levels of radon are in the order of 10 Bq/m^3 worldwide [45], and in Korea, the atmospheric concentration in the urban area of Seoul was reported to be 7.62 $\pm$ 4.11 Bq/m^3 [46], whereas the background level was monitored at 2.48 $\pm$ 6.28 Bq/m^3 at Gosan station on Jeju Island [47]. This is comparable to the atmospheric level in Hong Kong (9.3 Bq/m^3) [48], when considering the differences in the measurement period, area, and detection method. Therefore, we set indoor radon's target and final concentrations to approximately 148 Bq/m^3 and 20 Bq/m^3, respectively.



(**a**) (**b**)

Figure 4. The distributions of indoor radon concentrations in dwellings in Korea [44]: (**a**) detachment houses; (**b**) multi-family houses.

Table 1. Statistics of indoor radon levels nationwide in Korea [44].

Types of Houses	Mean	SD	Q10	Q25	Q50	Q75	Q90	N
Detached house	79.4	89.4	20.0	31.5	53.2	92.6	162.2	5745
Multi-family house	45.9	36.5	15.6	23.5	36.0	56.4	83.8	1496
Nationwide	72.4	82.5	18.7	29.2	48.5	84.2	144.7	7241

Descriptive statistics are as follows: mean, arithmetic mean; SD, standard deviation; Q, each percentile value of the dataset (10th to 90th percentile); N: number of houses. The units of data were Bq/m^3 except for N.

2.3.3. Calculating Removal Rates

The equation for the removal rate (%) is represented by η, where C_{in} is the initial concentration before ventilation, and C_t is the concentration at time t. The concentration is measured in ppm of CO_2 or Bq/m^3 of radon. The equation is as follows:

$$\eta = \frac{C_{in} - C_t}{C_{in}} \times 100 \quad (2)$$

For the environmental pollutant concentration, the shorter the measurement interval, the more fluctuating the measured data may appear, even for a short period [49]. Therefore, in this study, the average of 3 measurements was used as the C_t value in Equation (2) to calculate the removal rate during a specific time period following the operation of the mechanical ventilation system, with the aim of minimizing data bias.

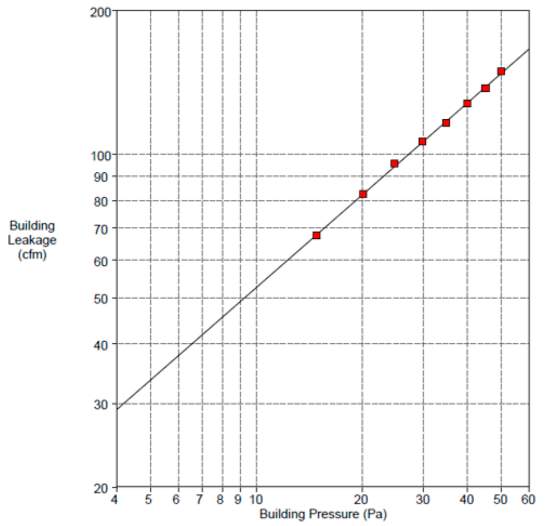
3. Results

3.1. Airtightness and Air Infiltration

Indoor air pollutants such as CO_2 [5,50], VOCs [6,51], and particulate matter [52,53] tend to accumulate quickly in airtight buildings. The airtight performance of this experimental building was recorded at 0.1 ACH or less when the blower door test was conducted for the apartment unit. However, because the experiments targeted only R2, it was necessary to check the airtightness of R2. Therefore, to quantify the characteristics of the subject space, a blower door test was conducted according to ISO 9972 to analyze the infiltration characteristics of the room. The airtightness of R2 was determined by performing a blower door (Minneapolis Blower Door, Energy Conservatory, Minneapolis, MN, USA) test using the fan pressurization method. The room was pressurized from 15 to 50 Pa in increments of 5 Pa, and the flow rate was measured using this method. The TECTITE 3.2 software was used for instrument operation and monitoring. No special sealing was installed to measure the infiltration value, which reflects the real environment.

The subject space was located 13.62 m above the ground and had a ceiling height of 2.3 m. The test was performed in June, the outdoor air temperature was 21 °C~25 °C, and the wind speed was less than three m/s on a sunny day. The interference due to the pressure difference can be excluded because the product of the indoor/outdoor air temperature difference multiplied by the building height gave a result below 200 m·K [37]. The instrument was installed on the door, and the airflow rates were measured by changing the indoor/outdoor pressure difference from 0 to 60 Pa at 5–10 Pa intervals (Figure 5). It was measured from 8.67 ACH50 to 8.73 ACH50 and calculated as 0.43 to 0.44 ACH at atmospheric pressure using the simplified formula from the literature [43].

(**a**)



(**b**)

Figure 5. The blower door test result of the R2: (**a**) a setup of the blower door test equipment; (**b**) blower door test result graph.

3.2. Removal of Indoor CO_2

As in the experimental conditions presented in Section 2.3.1, the time required to remove CO_2 was checked for each ventilation rate and compared with the radon reduction performance. During this experiment, the space pressure monitor DP2 was installed on the wall of the hallway of R2. It can measure the difference in atmospheric pressure between R2 and the corridor. This prevents pressurization or decompression in R2 because of the difference in the air supply and exhaust volume.

For the next step, the CO_2 level reduction times were measured at the ventilation rates in the range of 0.0 ACH to 2.0 ACH using a mechanical ventilation system with all doors and windows closed, and each experiment was repeated three times (Table 2).

Table 2. The removal rates of indoor CO_2 concentrations with various ventilation volumes.

Air Change Rate	(Case 0) 0.0 ACH	(Case 1) 0.5 ACH	(Case 2) 1.0 ACH	(Case 3) 1.5 ACH	(Case 4) 2.0 ACH
Calculated value	455 min	183 min	92 min	51 min	46 min
Measured value (max.)	701 min	184 min	109 min	72 min	54 min
Measured value (min.)	610 min	155 min	91 min	61 min	47 min

Calculated value is delivered using Equation (1), and assumptions are described in Section 2.3.1.

Without ventilation, the concentration gradually decreased from 3000 ppm of CO_2 in the indoor space to below the mandatory standard value of 1000 ppm. In this study, it took almost 11 h for natural reduction to occur because of the infiltration of the building. However, it showed apparent trends that the larger the air change rate of ventilation, the shorter the time required to meet Korea's mandatory indoor air quality standard. As a result, it took 167, 98, 66, and 51 min to reach a 1000 ppm of indoor CO_2 at air change rates of 0.5, 1.0, 1.5, and 2.0 ACH, respectively. (Figure 6). In other words, depending on the air change rate, it is necessary to continuously operate the mechanical ventilation system for approximately 1–3 h to achieve an indoor air quality of 1000 ppm or less. It is worth mentioning that the results of this study reflect a scenario in which any additional CO_2 emissions are considered negligible. Therefore, trends in mitigation can vary depending on indoor activities that release CO_2, such as the presence and behavior of occupants.

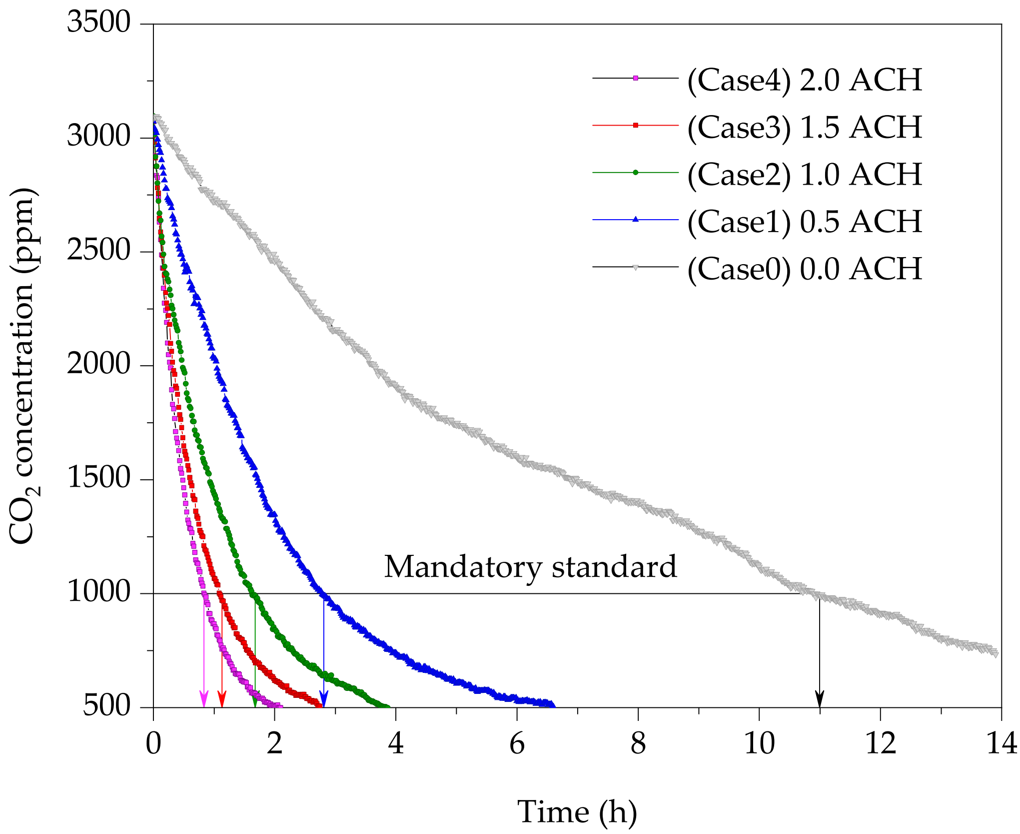


Figure 6. The concentration changes of indoor CO_2 due to operating mechanical ventilation systems with different air change rates.

3.3. Removal of Indoor Radon

Where there was no mechanical ventilation (as in Case 0), the indoor radon level declined slightly, and the indoor radon concentration reduced from 102.7 Bq/m^3 to 88.9 Bq/m^3 at last. After 15 h, the reduction was almost 10 Bq/m^3 because of the radioactive decay chain of radon and the building's air infiltration (Figure 7). The fact is that the effects of natural reductions are insufficient to ensure reliable indoor air quality in airtight buildings.

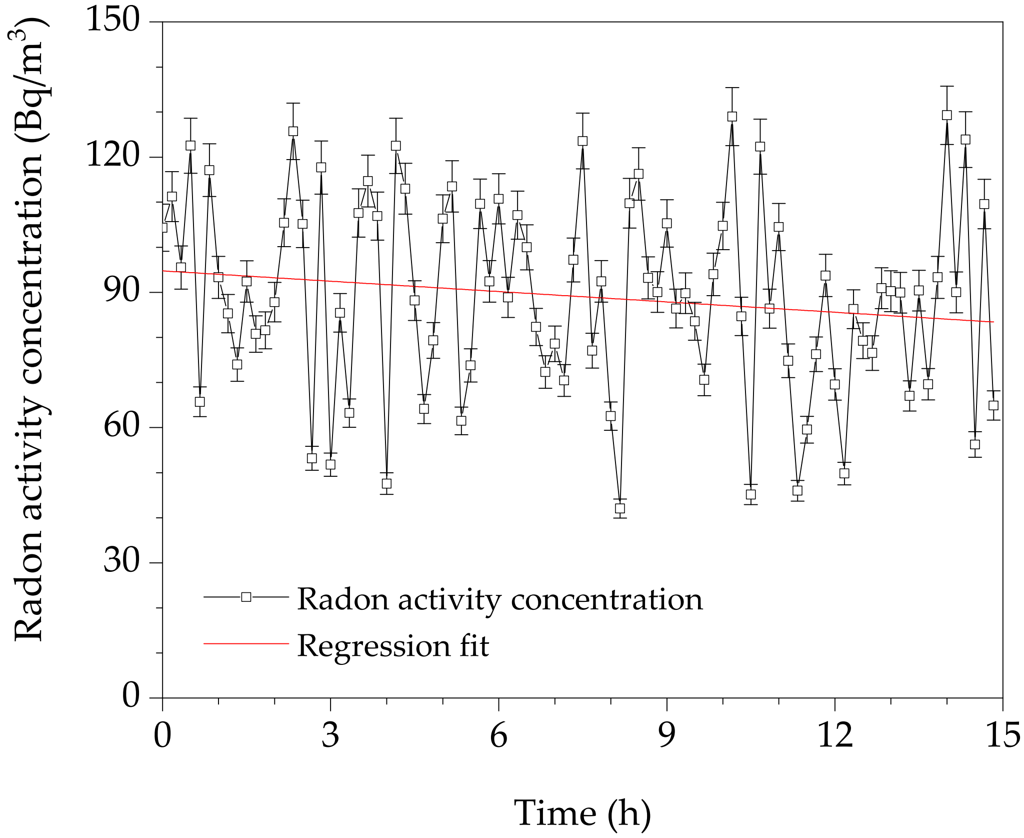


Figure 7. The temporal variation of indoor radon activity concentration in R2 without ventilation (Case 0).

Under all mechanically ventilated conditions, the radon concentration decreased rapidly at the beginning, the decrease slowed when it reached approximately 30 Bq/m^3, and the concentration increased immediately after the ventilation system was stopped. In the case of 0.5 ACH, the indoor radon concentration, which had been increasing before ventilation, could be reduced starting from the mechanical ventilation system operation, even though the indoor radon concentration could not be controlled entirely for the first hour of ventilation (Figure 8a). It showed a steeper decrease at 1.0 ACH compared to 0.5 ACH, and when ventilation continued for approximately four hours, the indoor radon concentrations decreased to less than 20 Bq/m^3. However, the indoor radon level rose again and recovered to 60 Bq/m^3 within an hour after the ventilation stopped (Figure 8b). Under the condition of 1.5 ACH, there was an immediate sharp decline, and the increase in indoor radon concentration was suppressed for several hours without ventilation, maintaining approximately 30 Bq/m^3 levels (Figure 8c). In the 2.0 ACH ventilation condition, the initial decreasing trend was evident, as was the case for the 1.5 ACH ventilation condition. It reached the lowest concentration of 6.5 Bq/m^3 by operating the ventilation system for four hours. The indoor concentration did not increase for two hours after the ventilation system stopped operating (Figure 8d).

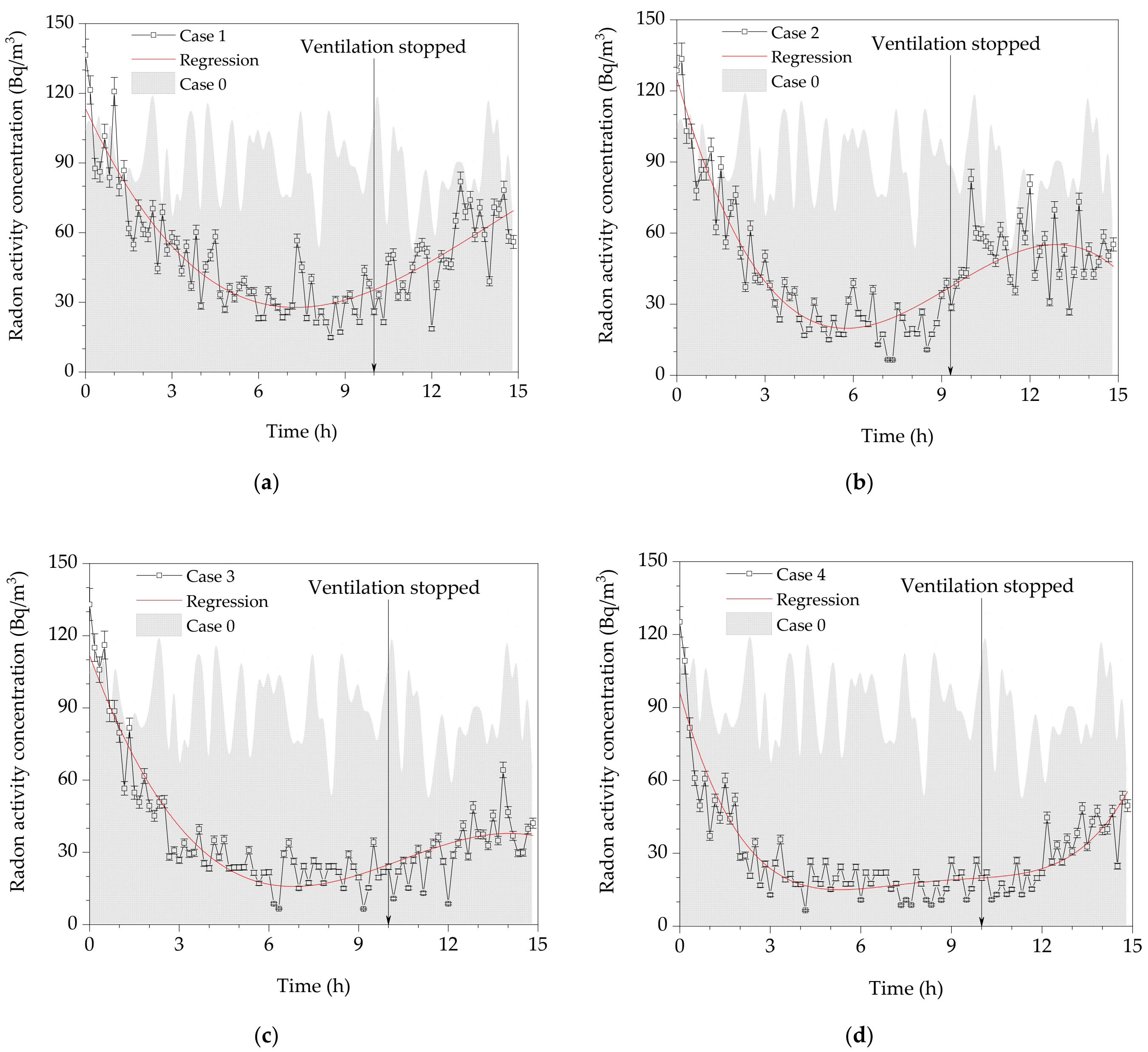


Figure 8. The concentration changes of indoor radon activity due to operating mechanical ventilation system with different air change rates: (**a**) Case 1—0.5 ACH; (**b**) Case 2—1.0 ACH; (**c**) Case 3—1.5 ACH; (**d**) Case 4—2.0 ACH.

When comparing the removal rates for the same ventilation duration, the removal rate increased in proportion to the air change rates in the early stages of ventilation. After one hour of ventilation, the removal rates were 23.5%, 30.4%, 39.7%, and 60.2% at air change rates of 0.5, 1.0, 1.5, and 2.0 ACH, respectively, compared to 4.1% without ventilation (Table 3). When the mechanical ventilation system was operated for six hours continuously, it converged with a removal rate of approximately 75% under 0.5, 1.0, and 1.5 ACH ventilation conditions. In the 2.0 ACH condition, the removal rate was over 80% in three hours of ventilation, maintained at 82.8~89.1%. The indoor radon concentration at this time was 10.8~22.1 Bq/m^3. This shows that indoor radon cannot be removed entirely below the detection limit of the measurement equipment and that the minimum indoor radon activity concentration that mechanical ventilation can reach is approximately 10 Bq/m^3, similar to the atmospheric activity concentration in ambient air.

Table 3. The removal rates of indoor radon concentrations with various ventilation volumes.

Time of Ventilation (h)	(Case 0) 0.0 ACH	(Case 1) 0.5 ACH	(Case 2) 1.0 ACH	(Case 3) 1.5 ACH	(Case 4) 2.0 ACH
0	-	-	-	-	-
1	4.1	23.5	30.4	39.7	60.2
2	(2.1)	44.8	48.6	58.1	70.8
3	7.5	51.9	66.7	68.2	82.8
4	(4.5)	61.2	76.0	72.1	89.1
5	(0.1)	72.5	78.7	77.6	83.6
6	6.9	76.5	77.6	77.5	84.8
7	11.6	77.5	81.7	78.1	85.4
8	21.5	74.7	81.7	78.7	86.6
9	14.5	76.4	75.4	77.8	83.4

All values are presented in percentiles, and parentheses indicate negative values.

4. Discussion

According to the theoretical calculations, the indoor CO_2 concentration exceeded 3000 ppm within three hours, and it could be challenging to maintain it below 1000 ppm in the case of two people staying in the subject space without ventilation. Furthermore, in buildings with excellent airtight performance, the decrease in radon concentration due to infiltration and radioactive decay was tiny, with almost 10 Bq/m^3 in 15 h. This indoor radon activity concentration was below the recommended level of the current Indoor Air Quality Control Act in Korea; however, the adverse effects of radon exposure remain considerable. The United Nations Scientific Committee on the Effects of Atomic Radiation reviewed epidemiological studies of residential exposure to radon over two decades and concluded that the excess relative risk of lung cancer from exposure to 100 Bq/m^3 of residential radon was approximately 16% for smoking and non-smoking occupants [54]. Generally, reference levels and optimization are key parameters for managing and protecting against radiation. The reference level of indoor radon is a value set based on the effective radiation exposure dose, which is approximately 10 mSv per year [45,55]. The average annual practical exposure dose limit is highly recommended to be 1 mSv [56,57]. Therefore, consistent efforts to create indoor radon concentrations that are as low as possible are essential, and ventilation can be a valuable tool for removing and diluting indoor air pollutants.

A heating, ventilation, and air conditioning (HVAC) system adopts a filtration part to mechanically remove airborne particles and prevent the introduction of particulate matter of outdoor origin [58]. Some experimental studies have been conducted to filter or absorb indoor radon [59] and CO_2 [60]; however, removing gaseous substances via filtration is not widely practiced. Therefore, it is challenging to expect CO_2 and radon removal effects by filtration mechanisms because gaseous substances are diluted and removed mainly by the inflow of outdoor air and the exhaust of indoor air to the outside. This means sufficient ventilation must be secured, and indoor pollutant levels in the ventilated area directly affect the ambient air concentration. Indoor radon levels are often linked to the concentration of outdoor air, and in tropical climates, the indoor and outdoor concentrations are similar because of the rapid exchange between indoor and outdoor air [54]. Additionally, radon emissions from pollutant sources can vary depending on the indoor environment and entry into buildings, and the concentration of indoor pollutants is affected by changes in temperature and relative humidity owing to ventilation [30].

As a result, mechanical ventilation guaranteed immediate indoor CO_2 and radon reduction with air change rates from 0.5 ACH to 2.0 ACH. The indoor CO_2 concentration sharply decreased as the ventilation volume increased. However, in the case of radon, there were some differences in the removal rate at the beginning of ventilation and the achievable indoor concentration level, and there was an upward trend after the ventilation system stopped. The indoor radon removal rate, which could be obtained in one hour of continuous ventilation, increased in proportion to the ventilation volume, expressed as the air change rate, and could be reduced to less than half of the initial concentration under the condition of 2.0 ACH within one hour eventually. In addition, if a sufficient ventilation volume is secured, an increase in radon concentration can be suppressed for a few hours after ventilation stops.

5. Conclusions

Public concerns about indoor air quality and its health effects are growing in Korean society, and indoor radon has emerged as a severe problem. In addition to CO_2—one of the most abundant bio-effluents in indoor air, radon can be efficiently controlled by indoor/outdoor air exchange. Mechanical ventilation is a system that supplies and discharges a constant amount of air to an indoor space; however, actual experimental data on the removal effect of specific pollutants using mechanical ventilation systems are still needed. This study was conducted to confirm the reduction in indoor CO_2 and radon concentrations with the operation of mechanical ventilation in an apartment with the national standard housing size and shape in Korea and to provide basic information for managing gaseous pollutants using a mechanical ventilation system. The process and results are summarized as follows:

1. As a result of evaluating the air permeability of the subject space to be tested according to the ISO 9972 fan pressurization method, the general airtight performance of Korean apartments was evaluated according to existing research.
2. The main experimental conditions, air change rate per hour, and indoor air pollutant concentrations (target and achievable) were determined using statistical data and previous surveys. Every batch of the experiment was started at an indoor concentration of 3000 ppm CO_2 and nearly 148 Bq/m^3 radon, and then a mechanical ventilation system was operated with an air change rate of 0.0 ACH, 0.5 ACH, 1.0 ACH, 1.5 ACH, and 2.0 ACH with all doors and windows closed until the concentration reached 1000 ppm CO_2 and 20 Bq/m^3 radon.
3. Because of the excellent airtightness of the subject space, the indoor CO_2 and radon were barely removed without ventilation. The indoor CO_2 concentration met the mandatory standard (1000 ppm) after more than ten hours, despite excluding emission activities. In the case of radon, the reduction due to infiltration and radioactive decay was insignificant, and the base level in an unventilated indoor area reached approximately 100 Bq/m^3, which is still considerable.
4. The removal rate of indoor CO_2 significantly improved when the ventilation volume increased. Under simultaneously ventilated conditions, indoor CO_2 levels declined to 1000 ppm almost linearly within 1–3 h at air change rates of 0.5 to 2.0 ACH. As a result of this study, when the level of indoor CO_2 exceeded 3000 ppm, an air change rate of 0.5 ACH, legally recommended by the Korean government, should be maintained for at least three hours, even in the absence of additional emissions.
5. The indoor radon could not be effectively controlled within a short period with the legally recommended ventilation air volume of 0.5 ACH, and it was possible to lower it to the level of 20 Bq/m^3 only when the air change rate was 1.0 ACH or higher. At 1.5 ACH and 2.0 ACH, indoor radon concentrations did not increase for a few hours after the mechanical ventilation system stopped in this subject space. As the mechanical ventilation system operated continuously, the indoor radon was removed at a similar outdoor concentration, and over 75% removal rates were obtained within six hours.

These results were obtained by conducting experiments assuming a statistical situation; therefore, they may differ from an actual living environment. Still, there is an implication that it is difficult to secure reliable indoor air quality below the recommended level with the ventilation rate of 0.5 ACH suggested by the Korean government. In particular, radon decays radioactively according to its half-life and partially decreases; however, because the inflow and accumulation from the emission source are also affected simultaneously, it is essential to lower the indoor radon concentration using active ventilation with a sufficient volume of air exchange.

Author Contributions: Conceptualization, K.C. and J.J.; methodology, J.J.; software, K.C. and J.J.; validation, K.C.; formal analysis, K.C.; investigation, J.J.; resources, J.J.; data curation, K.C.; writing—original draft preparation, J.J.; writing—review and editing, K.C.; visualization, J.J.; supervision, K.C.; project administration, K.C.; funding acquisition, K.C. All authors have read and agreed to the published version of the manuscript.

Funding: This study is part of a research project conducted with funding from the Ministry of Trade Industry and Energy in Korea (grant number 20009795).

Data Availability Statement: Data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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