Printed in the Republic of Korea
ANALYTICAL SCIENCE
& TECHNOLOGY
Vol. 33 No. 1, 49-57, 2020
https://doi.org/10.5806/AST.2020.33.1.49

The effect of ventilation on reducing the concentration of hazardous substances in the indoor air of a Korean living environment

Hyunjoo Kim[1], Jin Seog Kim[2], Jongman Lee[2], and Dalho Kim[2,★]

[1]*School of Liberal Arts and Sciences, Korea National University of Transportation, 50 Daehak-ro, Chungju, Chungbuk 27469, Korea*

[2]*Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Korea*

(Received November 18, 2019; Revised February 5, 2020; Accepted February 5, 2020)

Abstract: Controlling the quality of indoor air is important in order to maintain a healthy life. In this study, we investigated the correlation between the hazardous substance concentration of indoor air and circulation based on different ventilation methods in the apartment, which is one of the representative housing types in Korea. As target substances, we considered the hazardous substances which are generated during the cooking process and radon gas which is originated from building materials. We measured the concentrations of carbon dioxide and fine particles in relation to type of food and ventilation methods in order to determine the change in the concentration levels of hazardous substances which are generated during the cooking process. On the other hand, we measured the concentration of radon gas before and after letting fresh air into a room through windows in order to determine the change in the concentration level of radon gas which is originated from building materials. The results show that turning on the ventilation fan plays a major role in reducing the concentration levels of hazardous substances in the kitchen, and that it is more effective to turn on the ventilation fan during cooking than after cooking to prevent the diffusion of hazardous materials produced by cooking through the indoor air. Also, the results indicate that letting fresh air into a room through windows more than one time a day is necessary to reduce the concentration level of radon gas in the room to safe concentration range.

Key words: Korean living environment, hazardous substances, fine particle, radon, ventilation

1. Introduction

As modern people spend a substantial amount of time indoors, indoor air quality, along with the relatively recently surfaced sick house syndrome, is closely related to health. The impact of indoor air pollution on the human body has been reported in numerous cases.[1] Indoor air is polluted by a variety of sources, including the inflow of polluted air from the outside, building materials, household goods, smoking, and cleaning. Furthermore, various hazardous substances produced during cooking and radon gas have recently been highlighted as some causes of pollution. The types of hazardous contaminants generated during

---

★ Corresponding author
Phone : +82-(0)42-868-5356 Fax : +82-(0)42-868-5042
E-mail : dhkim@kriss.re.kr

This is an open access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons. org/licenses/by-nc/3.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

www.kci.go.kr

cooking vary according to the type of cooking. When using a gas stove, complete or incomplete combustion of gas produces carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen dioxide (NO_2). When cooking, particulate matter (PM) of various sizes and components, such as oil mist, (agglomerate of) volatile organic compounds (VOCs), and black carbon (which is produced by heating and combustion of organic substances) is generated, which impacts the human body and has been reported as the major cause of lung cancer among non-smoking women.[2-5]

Fine particles refers to liquid or solid particles with a diameter of 10 μm or smaller (PM10) that are suspended in air, and ultrafine particles refers to particles with a diameter of 2.5 μm or smaller (PM2.5), and their concentrations are denoted by $\mu g/m^3$. Furthermore, as the concentration of PM10 contains the concentration of PM2.5, the concentration of PM10 is always equal to or greater than that of PM2.5. Size and chemical composition of PM are the major criteria for assessing their impact on human health. According to the World Health Organization's (WHO) air quality guidelines, the regulatory standard for PM10 based on a 24-hour average is 50 $\mu g/m^3$. In Korea, the regulatory standards for PM2.5 were established in 2011 by the Framework Act on Environmental Policy; the 24-hour and annual averages (which were initially set at 50 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively), were revised to 35 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively, in 2018.[6]

Radon, one of the inactive gases, is a naturally occurring radioactive substance that has been present since the formation of earth, and it has been classified as group I carcinogen by the WHO.[7] Among three natural radon isotopes, the focus has been on ^{222}Rn. However, as revealed in the 2018 radon bed crisis in Korea, substances with high thorium (^{232}Th) concentrations are utilized in household goods and direct-contact products; thus, health concerns regarding ^{220}Rn has grown.[8] Along with the well-known inflow of radon gas from soil, radon gas that is consistently emitted from building materials or direct-contact products pollutes air in a closed space.

Numerous studies have been conducted on the health risks of radon. The International Commission on Radiological Protection (ICRP) doubled the probability index for lung cancer of radon and radon decay products in its publication 115,[9] and the WHO reports that up to 14 % of all lung cancer cases are caused by radon exposure.[10] The health risks of radon are known to be caused by radon decay products created through a series of radioactive decay.[9,10] In other words, radioactive decay products generated from radioactive decays of inactive radon gas is adsorbed onto air-suspended particles and subsequently deposited in the lungs through the respiratory organs (where it undergoes further radioactive decay), thereby emitting high-energy alpha rays including various type of radiation. Therefore, the health risks of radon are closely associated with air radon concentrations as well as indoor air quality (e.g., PM10) containing radon. The US Environmental Protection Agency (US EPA) set an action level of indoor radon to 148 Bq/m^3 (4 pCi/L) or lower in 1986. Korea has also set an indoor radon recommendation level to 148 Bq/m^3.

As previously described, various hazardous gases, such as VOCs, PM, and radon, generated by cooking, and from various industrial goods and buildin materials pollute indoor air and affect our health.

As all hazardous substances are dispersed from their source and present in indoor air, it can be assumed that they pollute the air and are released outdoors in a similar way during dispersion and ventilation. Although measuring all hazardous substances of interest to assess the impact of ventilation would be meaningful, it would be inefficient (as the process is high in cost and time-consuming). As ineffective ventilation elevates CO_2 concentrations of indoor air, CO_2 concentrations are utilized as an indicator of indoor air ventilation.[11-13] During cooking, a high concentration of CO_2, various hazardous gases, and PM are emitted from combustion and heating at the cooking site. For this reason, by measuring the changes in CO_2 concentration, changes in the concentrations of other hazardous substances can be estimated without directly measuring them.

Clean indoor air can be maintained by reducing pollutant sources or when necessary, by using air purifiers to remove pollutants. The most economic

www.kci.go.kr

and simplest method to maintain clean indoor air is proper ventilation. Many reports have been published regarding indoor air ventilation, including changes in CO_2 and PM concentrations during cooking in multi family housing,[14] changes in CO_2, CO, PM, and formaldehyde concentration in dormitories,[15] changes in radon concentration in multi family housing,[16] and changes in formaldehyde concentration in multi family housing.[17] However, due to complicated ventilation methods and corresponding results for indoor air contaminant concentrations, it was difficult to establish simple and efficient ventilation methods that can be utilized in our daily living.

Therefore, this study aims to present an effective ventilation method to promote healthy life by investigating the changes in indoor hazardous substance concentrations in apartments (which are among the most common types of housing in Korea). We chose target contaminants, $CO_{2,}$ PM and radon, which are generated by cooking or emitted from building materials.

To analyze the changes in concentrations of the target substances, we used the infrared optical sensor method for CO_2, light scattering method for PM, and pulse ion chamber method for radon gas.

2. Experiment and Methods

2.1. Instruments

CO_2 concentration was measured using Airwell Plus III Indoor Air Quality Monitor (KINSCO Technology, Seoul, Korea). This monitor is equipped with an infrared detector and a pump.

PM concentration was measured using the portable aerosol spectrometer (PAS model no. 1.109; Grimm Technologies, Ainring, Germany). It includes a laser source, a pump that intakes air at 72 L/h, and an optical detection unit that senses the amount of light scattered by PM.

Indoor air radon concentration was measured using the pulsed ion chamber-type radon monitor (model RD 200; FTlab, Inc., Seoul, Korea). This device is capable of continuous monitoring of radon with an internal volume of 200 mL and sensitivity of 13 $\text{min}^{-1}/(\text{kBq/m}^3)$, according to the manufacturer. Indoor air containing radon naturally disperses within the measurement chamber, and the sensor in the chamber detects alpha-rays emitted by radon and radon decay products, which is subsequently cumulatively computed during pre-set time intervals to present calibrated radioactivity concentrations in real-time.

2.2. Instrument calibration

The CO_2 monitor was calibrated prior to use by using high-purity nitrogen and three standard gases, namely ES0008676 (503.4 ± 0.5 μmol/mol), YA0003530 (998 ± 2 μmol/mol), and YA002283 (2007 ± 5 μmol/mol; 95 % expanded uncertainty; confidence level $k = 2$) manufactured by the Korea Research Institute of Standards and Science (KRISS) using the gravimetric method. To calibrate the device, the standard gas was released at 500 mL/min using a pressure regulator, and the pressure at the sample introducing part was equated with the atmospheric pressure by connecting a T-shape tube until the meter was stabilized. *Fig.* 1 shows the calibration curves for each standard gas. A linear correlation existed between the certified values of the standard gases and the device measurements within the range of measurement ($R^2 = 0.9996$), and the measurements were adjusted using the calibration factor.

The spectrometer, which had been calibrated by the manufacturer using the National Institute of Standards and Technology (NIST)-certified polystyrene

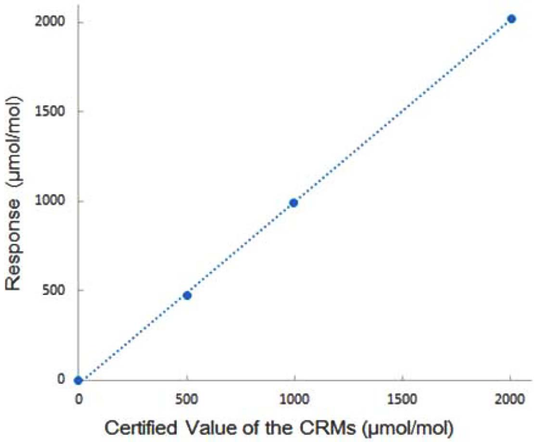

Fig. 1. Calibration curve of the carbon dioxide monitor.

www.kci.go.kr

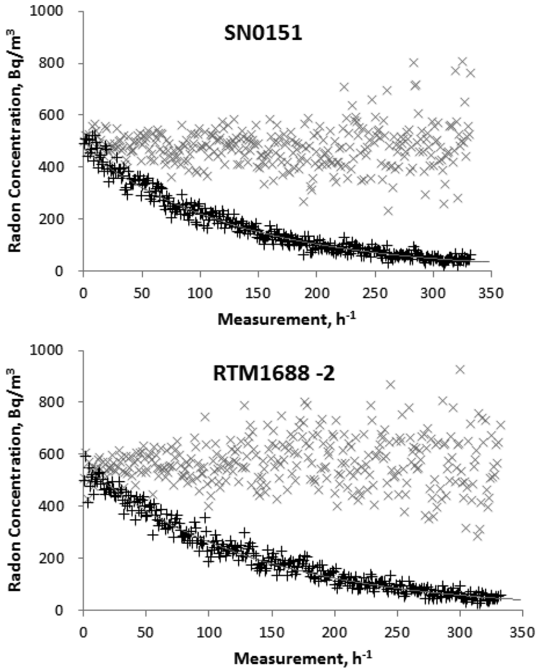

Fig. 2. Test results of radon continuous monitor (SN0151) used in the experiment and a reference monitor (RTM1688-2) used for sensitivity and accuracy comparison.

material,[18] was used to measure PM without further calibration. To test the sensitivity and accuracy of the radon monitor used in this experiment, we placed this radon monitor and the KRISS reference device in a closed 1.245 m^3 chamber (used to calibrate continuous radon monitors), introduced radon gas, and monitored the changes of radioactivity concentration. The changes of radon radioactivity concentration are shown in *Fig.* 2. In the figure, x is the measured radon radioactivity concentration adjusted by the time of monitoring initiation, and the range of this change is inversely proportional to the sensitivity of the monitor. The sensitivity and accuracy of the monitor used in this experiment did not markedly differ from those of the reference device.

2.3. Experimental method

The experiment to measure changes in CO_2 and PM concentrations generated during cooking was conducted in the kitchen of a 109 m^2 (33 pyeong) apartment in Seoul. The CO_2 monitor and PM spectrometer were placed on the countertop, which was 1 m away from the gas stove. All windows of the house were closed while cooking to prevent an inflow of air, and the gas stove was set to medium heat. When the ventilation fan was used, it was set to level 1 or 3. We chose grilled fish, Korean pancake, meat patty for the experiment, and the foods were cooked with a frying pan with varying amounts of oil depending on the food ingredient. No oil was used for grilling fish (which was already oily), and less oil was used for cooking the meat patty than for the Korean pancake.

To measure the changes in indoor radon concentration, one room in the study apartment was selected, and the radon monitor was placed on a table in the room. The monitor was 50 cm away from the walls and the floor, and the radon concentration was cumulatively recorded in one-hour units. The radon concentration was continuously measured (in a closed space) while the window and the door were either both open or closed. A 109 m^2 (33 pyeong) apartment on the 15th floor in Seoul and 112 m^2 (34 pyeong), third-floor apartment in Daejeon were chosen as the residential spaces for the experiment.

3. Results and Discussion

3.1. Changes in CO_2 concentration according to the method of ventilation

There were no differences in the changes of CO_2 concentrations generated during cooking (according to the type of cooking), and there were similar patterns pertinent to the duration of cooking and ventilation. *Fig.* 3 shows the changes in CO_2 concentrations generated from the gas stove when grilling fish in a frying pan. During cooking (grilled fish), the ventilation fan was set to level 1 for the first 30 min and turned off for the following 30 min. After cooking, the gas was turned off, and the ventilation fan was turned on at level 1 for 10 min, followed by level 3 for the next 10 min. Next, the ventilation fan was turned off, and the window was opened for ventilation for 12 min.

As shown in *Fig.* 3, the CO_2 concentration slightly

www.kci.go.kr

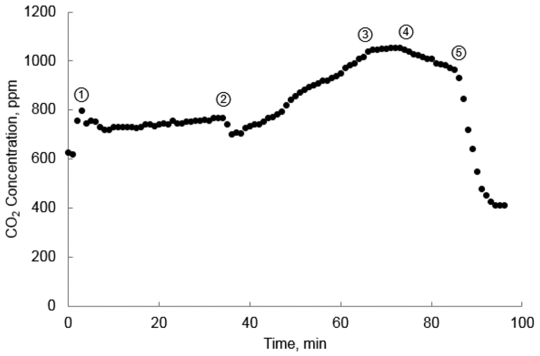

Fig. 3. Changes in CO_2 concentration according to ventilation while cooking fish; ① gas stove on, fan on (level 1), and start cooking ② gas stove on, fan off, continue cooking ③ gas stove off, fan on (level 1) ④ gas stove off, fan on (level 3), ⑤ gas stove off, fan off, window open.

increased (720–770 ppm) during 30 min of cooking with the ventilation fan on. CO_2 concentration continued to increase to 1010 ppm during 30 min of cooking with the ventilation fan off. Even when the ventilation fan was turned on at level 1 for 10 min after the gas was turned off, the elevated CO_2 concentration did not decrease; moreover, it slightly increased to 1050 ppm. CO_2 concentration decreased to 970 ppm when the ventilation fan was turned on at level 3 for the next 10 min and to 400 ppm in 10 min with ventilation by opening the window. The fact that the CO_2 concentration did not increase substantially when the ventilation fan was turned on at the beginning of cooking showed that the ventilation fan could effectively ventilate the CO_2 generated during cooking. On the other hand, the fact that CO_2 concentration did not quickly diminish even after turning on the ventilation fan (after cooking with the fan off) suggests that CO_2 is dispersed throughout the entire indoor space, and therefore, it takes a long time to restore the normal concentration with only the ventilation fan that has limited airflow. We can hypothesize that the various hazardous gases generated during cooking follow a similar dispersion model to that of CO_2 gas. Thus, turning on the ventilation fan during cooking, as opposed to turning it on after cooking, is crucial and the efficient way to maintain the concentrations of CO_2 and various other hazardous gases generated during cooking within a safe range.

3.2. Changes in PM concentration according to ventilation method

Fig. 4 shows the changes in PM concentration generated while grilling the fish with a frying pan. *Fig.* 4A shows the changes in PM10 and PM2.5 concentrations during 30 min of cooking with the ventilation fan on. *Fig.* 4B shows the changes in PM10 and PM2.5 concentrations when the ventilation fan was turned on (after cooking with the ventilation fan turned off). Specifically, in *Fig.* 4B, the concentrations correspond to: ① when the ventilation fan turned off for the first 30 min of cooking, ② when the ventilation fan was turned on at level 1 for 10 min after cooking and turning off the gas, ③ when the ventilation fan was set at level 3 for the next 10 min, and ④ when the ventilation fan was turned off and the window was opened for 12 min

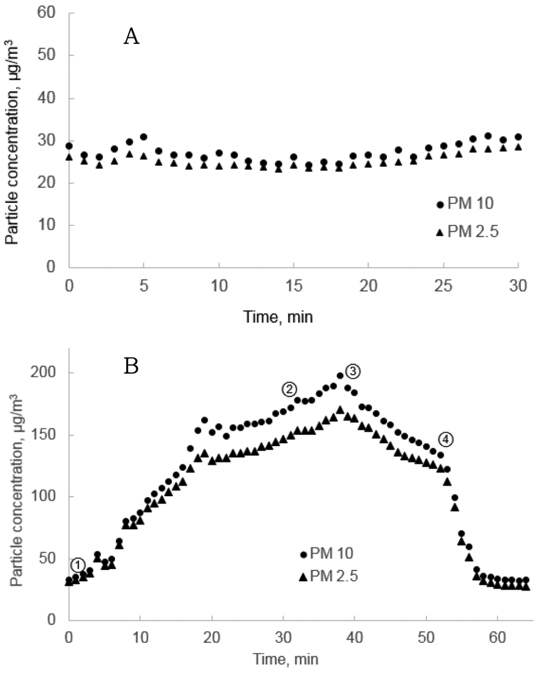

Fig. 4. Changes in fine particle (PM10) and ultra-fine particle (PM2.5) concentrations while cooking fish. A: ventilation fan on from the beginning of cooking to the end, B: ventilation fan on after cooking; ① gas stove on, fan off ② gas stove off, fan on (level 1), ③ gas stove off, fan on (level 3) ④ gas stove off, fan off, window open.

www.kci.go.kr

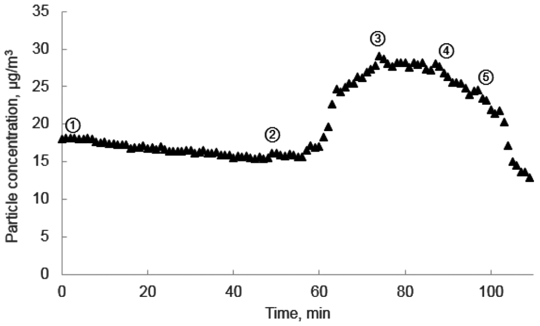

Fig. 5. Changes in ultra-fine particle (PM2.5) concentration according to ventilation while cooking Korean pancake; ① gas stove on, fan on (level 1), ② gas stove on, fan off, ③ gas stove on, fan on (level 3) ④ gas stove off, fan on (level 3), ⑤ gas stove off, fan off, window open.

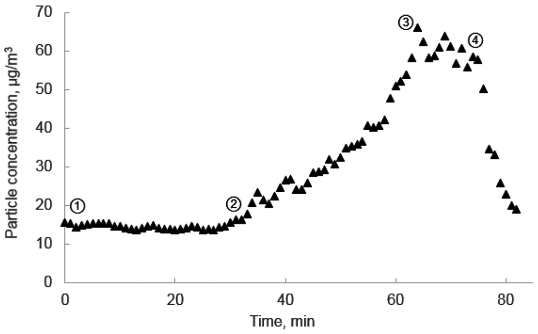

Fig. 6. Changes in ultra-fine particle (PM2.5) concentration according to ventilation while cooking meat patty; ② gas stove on, fan on (level 1), ① gas stove on, fan off, ③ gas stove off, fan on (level 1) ④ gas stove off, fan off, window open.

for ventilation. As shown in *Fig.* 4, there are similar trends in the changes of PM10 and PM2.5 concentrations, and PM2.5 accounts for the majority of the PM10 generated while cooking. *Fig.* 4A shows that PM2.5 concentration is consistently below 30 µg/m^3 when cooking with the ventilation fan on. As shown in *Fig.* 4B, PM2.5 concentration increased to 170 µg/m^3 when cooking with the ventilation fan off, and although it declines when the fan is turned on after cooking and turning off the gas, it takes a considerable amount of time to return to the pre-cooking concentration. These results were well accorded with trends of changes in CO_2 concentration according to the ventilation method. Therefore, turning on the ventilation fan or opening the window for ventilation from the start of cooking is effective to maintain the concentration of PM generated during cooking within a safe range.

Figs. 5 and 6 show the differences in PM2.5 concentration according to the type of cooking (Korean pancake, meat patty). *Fig.* 5 illustrates the changes in PM2.5 concentration when cooking Korean pancake in a frying pan. When cooking the pancake, ① the ventilation fan was turned on at level 1 for the first 45 min, and ② it was turned off for the next 32 min of cooking. Next, ③ the ventilation fan was turned at level 3 for another 12 min of cooking. ④ After finishing cooking, the gas was turned off and the ventilation fan was turned at level 3 for 10 min. Next, ⑤ the ventilation fan was turned off and the window was opened for ventilation for 7 min.

Fig. 6 shows the changes of the concentration in PM2.5 generated during cooking meat patty using a frying pan. When cooking the meat patty, ① the ventilation fan was turned on at level 1 for the first 28 min, and ② it was turned off for the next 33 min of cooking. ③ After finishing cooking, the gas was turned off and the ventilation fan was turned at level 1 for 11 min. Next, ④ the ventilation fan was turned off and the window was opened for ventilation for 7 min.

Comparing *Figs.* 4B, 5, and 6 reveals that cooking fatty food leads to high PM2.5 concentration. *Fig.* 4B shows that PM2.5 concentration is very high even without adding cooking oil when the food ingredient is fatty. As shown in *Figs.* 5 and 6, the meat patty, which is a greasy type of food, generates more PM2.5 than the Korean pancake, even when a smaller amount of cooking oil was used. *Figs.* 4A and 6 confirm that even when cooking fatty food, PM2.5 concentration can be maintained below 30 µg/m^3 by cooking with the ventilation fan on. These results suggest that the ventilation fan should be turned on from the start of cooking to effectively lower the health impact of PM generated during cooking.

3.3. Changes in radon concentration according to ventilation method

Fig. 7 shows the changes in radon concentrations

www.kci.go.kr

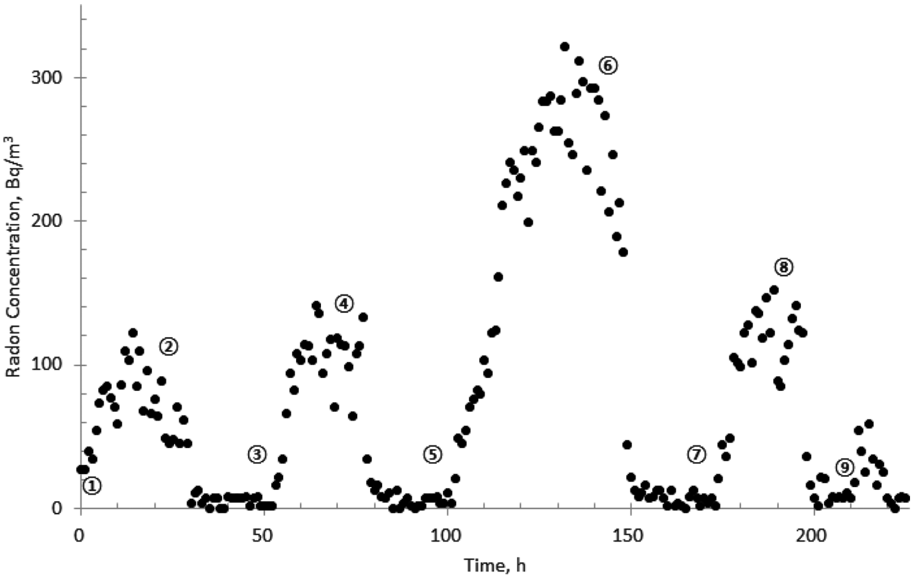

Fig. 7. Changes in radon concentrations of indoor air measured in an apartment in Seoul for 9 days; ① 24 h closed, ② 24 h opened, ③ 24 h closed, ④ 24 h opened, ⑤ 48 h closed, ⑥ 24 h opened, ⑦ 24 h closed, ⑧ 24 h opened, ⑨ 10 h closed.

measured with and without ventilation in a 109 m^2 (33 pyeong) apartment in Seoul over nine days in the summer (July). During ventilation, the room's door and windows were opened to enable easy inflow of fresh outside air, and during the closed experiment, it was ensured that the door and windows were closed and remained closed throughout the experiment. The results showed that radon concentration increased to 120-150 Bq/m^3 within 24 hours and to 320 Bq/m^3 within 48 hours of starting the closed experiment. This is either similar to or double the indoor radon recommendation level (148 Bq/m^3), depending on the duration. As the measurements were taken inside an apartment on the 15th floor, rock-derived building materials are speculated to be the cause of radon gas contamination.

Fig. 8 shows the changes in radon concentrations inside a 112 m^2 (34 pyeong) apartment on the third floor in Daejeon over three days in the spring (April). The room was sufficiently ventilated prior to the measurement, and radon concentrations were measured under a closed condition (in which the room's door and windows were closed) and ventilated conditions (in which the room's door and windows were opened).

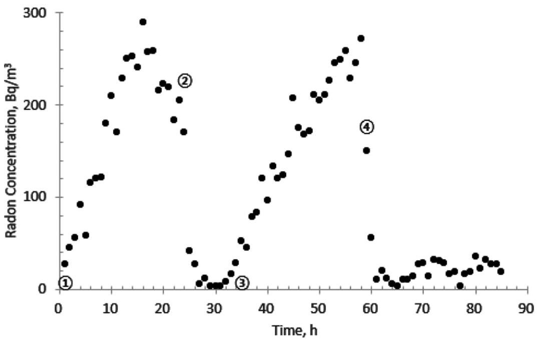

Fig. 8. Changes in radon concentrations of indoor air measured in an apartment in Daejeon for 4 days; ① 23 h closed, ② 11 h opened, ③ 24 h closed, ④ opened.

The results showed that radon concentrations increased to nearly 300 Bq/m^3 (within 16–24 hours), which is twice the indoor radon recommendation level. As rocks are one of the primary building materials used for the apartment, rock-derived building materials are speculated to be the cause of radon gas contamination. In this apartment, opening the door and windows to allow an inflow of fresh air, caused the radon concentration to fall below 30 Bq/m^3.

The results of the experiments conducted in Seoul

www.kci.go.kr

and Daejeon confirmed that there are similar trends in the changes in radon concentrations in apartments according to ventilation, regardless of time and place. The results suggested that many apartments in Korea may be vulnerable to high radon concentrations that exceed the recommendation level and are therefore in need of proper ventilation. Further, these results show that radon concentration may exceed the recommendation level with a prolonged duration without ventilation and particularly that people should be cautious of the accumulation of radon gas over time in closed spaces. Although the elevated radon concen- tration in a closed space drops to below the atmospheric level of 25 Bq/m^3 once the door and windows were opened, it took a substantial amount of time to reach this level from the peak value. This result differs from the previous result (*Figs.* 3 and 4B) where opening the window amid high CO_2 or PM concentrations rapidly decreases said concentrations within 10 min. As both radon and CO_2 are gases and their concentrations drop with inflow of outside air by the same principle, we examined the principles of measurement of the radon monitor we used. The substantial amount time required to reach a minimum level (from maximum level) with the radon monitor was due to the monitor's response time and the structure of the sensors. The radon monitor takes several measurements of a sample and generates an average once an hour, and instead of actively introducing the air sample into the measurement chamber, the radon gas reaches the chamber via natural circulation and dispersion. The radon sensor is placed within the chamber; thus, even after the indoor air is completely replaced by fresh outside air, it takes a considerable amount of time for new air to reach the chamber and achieve equilibrium. Therefore, in consideration of the CO_2 results, leaving the door and windows open for 5–10 min would be sufficient for complete ventilation. On the other hand, in a closed environment, radon gas is gradually emitted from building materials used for the floor, walls, and ceilings, and is accumulated, thereby gradually elevating radon concentration in the indoor air. Thus, the elevation of radon concentration after closing the door following complete ventilation may be relatively accurate in reflecting the actual radon concentration in indoor air at each time point (despite the shortcomings of the radon monitor).

Our results suggest that although frequent ventilation is the most desirable, in the winter time during which opening the windows and doors for prolonged periods is difficult, ventilating the house at least once or twice a day before bedtime and/or in the morning for 5 min would significantly alleviate the health risks of radon.

4. Conclusions

Various hazardous gases and PM generated during cooking, and radon gas emitted from building materials have been issued as the major indoor air pollutants that cause lung cancer and various diseases. In this study, we measured the changes in CO_2, PM, and radon concentrations (according to ventilation conditions) to establish effective ventilation methods that reduce various hazardous air pollutants generated by cooking and building materials.

CO_2 and PM concentrations were measured to examine the changes in the concentrations of hazardous substances generated from cooking. The results showed that CO_2 and PM concentrations in indoor air were maintained at a consistent level during cooking with the ventilation fan on. CO_2 and PM concentrations continuously rose beginning cooking with the ventilation fan off in a closed space, and even when the ventilation fan was turned on after finishing cooking, the CO_2 and PM concentrations decreased very slowly. The results confirmed that turning on the ventilation fan when beginning cooking prevents the dispersion of hazardous gases or PM generated during cooking through the indoor air, and that turning on the ventilation fan after finishing cooking has no marked impact on lowering the concentrations of the dispersed hazardous substances.

The most effective way to reduce dispersion of hazardous gases or the PM generated during cooking (in the indoor air) is to cook with the windows open. However, leaving the windows open during cooking

www.kci.go.kr

is practically difficult in apartments, considering the heating and air conditioning during the winter and summer, respectively. Therefore, in the winter when the windows cannot be left open, turning on the ventilation fan during cooking can prevent the indoor accumulation of hazardous substances generated from cooking.

To examine the changes in the concentration of radon gas, which is one of the hazardous substances emitted from building materials, we measured the radon concentrations (according to ventilation conditions) using a pulsed ion chamber-type radon monitor. By measuring the changes in radon concentrations in apartments in Seoul and Daejeon under prolonged closed and ventilated conditions, we confirmed that Korean apartments may be vulnerable to the risk of exceeding the indoor radon recommendation level. Our results show that radon gas is accumulated where it is emitted over time in a closed, unventilated apartment, which calls for precautions to be taken. Although frequently ventilating the indoor space is desirable to prevent the health risks of radon, when it is difficult to leave windows and doors open in the winter for prolonged periods, ventilating for 5–10 min once or twice a day could alleviate the health risks of radon.

Acknowlegements

This was supported by Korea National University of Transportation in 2018.

References

1. J. M. Samet, M. C. Marbury and J. D. Spengler, *Am. J. Respir. Crit. Care Med.*, **136**(6), 1486-1508 (1987).
2. W. T. Kwon and W. S. Lee, *Culi. Sci. & Hos. Res.*, **22**(8), 149-156 (2016).
3. M. Dennekamp, *Occup. Environ. Med.*, **58**, 511-516 (2011).
4. Y. C. Ko, *Am. J. Epidemiology*, **151**(2), 140-147 (2000).
5. Joongang Ilbo, https://news.joins.com/article/23577594, Assessed 13 Nov 2019.
6. Ministry of Environment, 'Enforcement Decree of the Framework Act on Environmental Policy, Environmental Standards Table', Republic of Korea, 2019.
7. National Council on Radiation Protection and Measurements, 'Measurement of Radon and Radon Daughters in Air', NCRP Report No. 97, Bethesda, MD, USA, 1988.
8. S. G. Kim, *Industrial Health-Korean Industrial Health Assoc.*, **362**(10), 6-19 (2018).
9. M. Tirmarche, J. D. Harrison, D. Laurier, F. Paquet, d E. Blanchardon and J. W. Marsh, *Ann. ICRP*, **40**(1), 1-64 (2010).
10. H. Zeeb and F. Shannoun, 'WHO Handbook on Indoor Radon: A Public Health Perspective', WHO, Geneva, Switzerland, 2009.
11. H. J. Chang, *J. Regional Assoc. Architect. Inst. Korea*, **12**(4), 229-236 (2010).
12. J. S. Park, N. Y. Jee and J. W. Jeong, *Indoor Air*, **24**(6), 629-638 (2014).
13. U. Satish, M. J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert and W. J. Fisk, *Environ. Health Perspect.,* **120**(12), 1671-1677 (2012).
14. J. B. Kim, J. Y. Lee, K. H. Kim, S. H. Ryu, G. G. Lee, S. B. Lee and G. N. Bae, *J. Odor Indoor Environ.* **16**(3). 199-210 (2017).
15. Y. J. Choi, G. Y. Lee, G. H. Baek and N. E. Kang, *J. Korean Soc. Environ. Technol.,* **26**(6), 609-622 (2017).
16. T. U. Min, K. S. Chung and Y. I. Kim, *Proceedings of The Society of Air-conditioning and Refrigerating Engineers Conference*, 431-434 (2015).
17. G. S. Hwang, *J. Korean Society for Environmental Technology*, **19**(1), 10-17 (2018).
18. T. M. Peters, D. Ott and P. T. O'Shaughnessy, *Ann. Occup. Hyg.*, **50**(8), 843-850 (2006).

Authors' Positions

Hyunjoo Kim : Professor
Jin Seog Kim : Principal research scientist
Jongman Lee : Principal research scientist
Dalho Kim : Principal research scientist

www.kci.go.kr