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Performance of a heat recovery ventilation system for controlling human exposure to airborne particles in a residential building

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ABSTRACT

Heat recovery ventilation (HRV) system is emerging as a sustainable technology to reduce human exposure to air pollutants in residential buildings. However, there is a lack of information on the HRV system performance for controlling both indoor-generated and outdoor-generated particles in a residential building. To fill this knowledge gap, we conducted field monitoring of indoor airborne particles with two representative HRV system operating modes (ventilation and circulation modes) in a full-scale residential testbed. The results reveal that the filter efficiency, airflow rate, and filter bypass factor of the HRV system play important roles in indoor particle concentrations. The indoor/outdoor concentration ratio is reduced by 72%–92% when operating the HRV system. For both circulation and ventilation modes, the bypass factor is crucial for the particle removal performance of the HRV system. A 20% filter bypass factor leads to up to a 50% increase in indoor exposure to outdoor-originated and indoor-generated $PM_{2.5}$ compared to the no-bypass scenario. Although circulation mode performed better than ventilation mode, both operating modes with a minimal bypass factor can effectively remove particles generated from indoor emission sources (e.g., incense stick burning and bacon pan frying). The study results suggest that HRV system can reduce human exposure to indoor-generated particles by 56%–90% and particle control performance hinges upon minimizing HRV filter bypass.

1. Introduction

Epidemiological studies found that long-term exposure to airborne particulate matter (PM) can cause adverse health impacts such as respiratory and cardiovascular disease [1–4]. Since people spend most of their time indoors [5], controlling indoor particle concentration is key to mitigating human exposure to airborne particles. Given that particle emission sources exist both inside and outside buildings [6–11], building ventilation/filtration systems are responsible for controlling both outdoor-originated and indoor-generated particles.

Mechanical ventilation systems with air filters are mainly found in offices and commercial buildings. Many residential buildings rely on natural ventilation to control indoor-generated particles using fresh outdoor air. However, in several regions with severe urban air pollution and wildfire, natural ventilation can contribute to increasing the indoor particle concentration of outdoor origin [11–14]. Accordingly, there has been a growing need for mechanical ventilation systems for residential buildings. South Korea is one of the countries with exacerbated urban air pollution. The country has implemented a law requiring new residential buildings to be equipped with a heat recovery ventilation system (HRV) (Indoor air quality control in publicly used facilities, 2016). Note that an HRV system is an outdoor air ventilation system with a heat exchanger due to its energy-saving benefits [15,16]. It also has air filters on the air pathway to remove particles and supply fresh air. However, it is not equipped with cooling/heating coils and mainly used for ventilation in residential buildings.

Previous studies reported that mechanical ventilation systems in residential buildings could yield a 50% particle removal effect on the daily average particle concentration [17–20]. However, even with the filter efficiencies used in these studies (higher than that of MERV 11 rating), the total particle removal effect in a whole house could be smaller than 50%. This is mainly because indoor particle emission sources increase concentration in residential buildings [6,21–23]. Cooking, one of the major particle emission sources in residential buildings, can lead to indoor particle concentrations more than 100 times higher than the background concentration, and it often takes

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several hours until the concentration is reduced back to the background level [21,24,25]. Furthermore, due to improper installations or poor sealing, unintended air leakages could occur through HRV air filters and duct systems [26,27], resulting in more outdoor-originated particles transported indoors.

Previous studies reveal that indoor emission sources significantly affect elevated human exposure to indoor particles. However, very little measurement data are available regarding how effectively residential HRV systems control indoor-generated and outdoor-originated particles. Given this background, the primary objective of this study is to examine the particle removal performance of residential HRV systems with common indoor emission sources under representative building operating conditions. Based on field measurements along with material balance analysis, this study quantifies the effects of HRV filter efficiency, airflow rate, and the filter bypass factor on the total particle removal performance of the HRV system.

2. Methods

2.1. Heat recovery ventilation system

Heat recovery ventilation (HRV) system can improve indoor air quality and energy conservation because the outdoor ventilation air passes the HRV air filter and exchanges energy with the exhaust air. HRV systems typically provide two operating modes: 1) ventilation mode and 2) circulation mode. Ventilation mode is a conventional operating mode that supplies 100% outdoor air, while circulation mode recirculates 100% indoor air without taking outdoor air (Fig. 1). The size of an HRV system used in this study is 72 cm x 55 cm x 34 cm (length x width x height). It has a heat exchanger with a heat transfer efficiency of 70% for the heating/cooling and two HEPA grade of H13 filters (higher filtration efficiency than MERV16 rating). It operates with three ventilation airflow rates, 130, 200, and 230 m^3/h, and this study tested only 200 m^3/h based on the outdoor air requirements for kitchens [28].

2.2. Testbed and sampling

Field measurements were conducted in 2020 from February 21st to April 3rd at a typical residential apartment in Seoul, South Korea. The apartment unit is on the 15th floor of a 26-story building constructed in 2017. The apartment had three bedrooms, two bathrooms, and one dress room with a floor area of 84 m^2 and a total air volume of 205 m^3. The indoor temperature was set to 20 °C and controlled by the floor radiant heating system. During the experiment, all windows were closed, and only two researchers were present in the testbed to set up the experimental conditions and perform indoor particle generation/decay tests. Fig. 2a shows the floor plan of the testbed and the ductwork layout. Note that the HRV system was installed in the mechanical room outside the apartment, and each room has at least one supply and exhaust register connected to the HRV system ductwork. To minimize the air infiltration from other apartment units, we sealed openings with potential vertical air paths, such as the bathroom, as shown in Fig. 2a. Additionally, we sealed any potential leakage sites, including duct joints and the outer

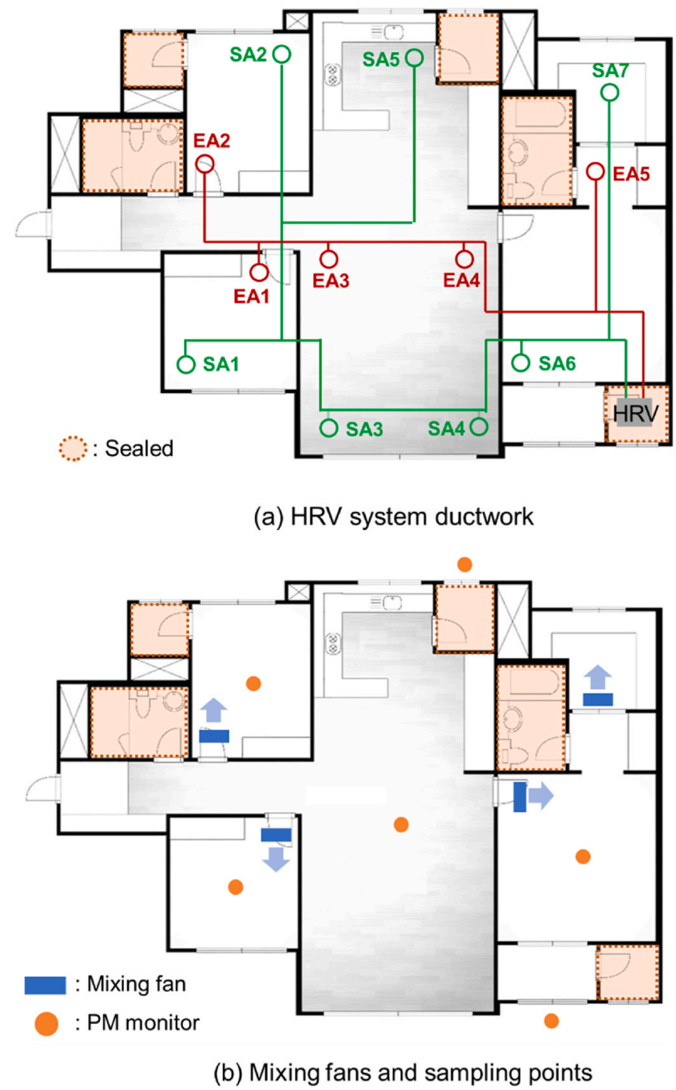

Fig. 2. Apartment floor plan: (a) HRV system ductwork and (b) mixing fans and sampling points. Note that "SA" and "EA" denote supply and exhaust diffusers, respectively.

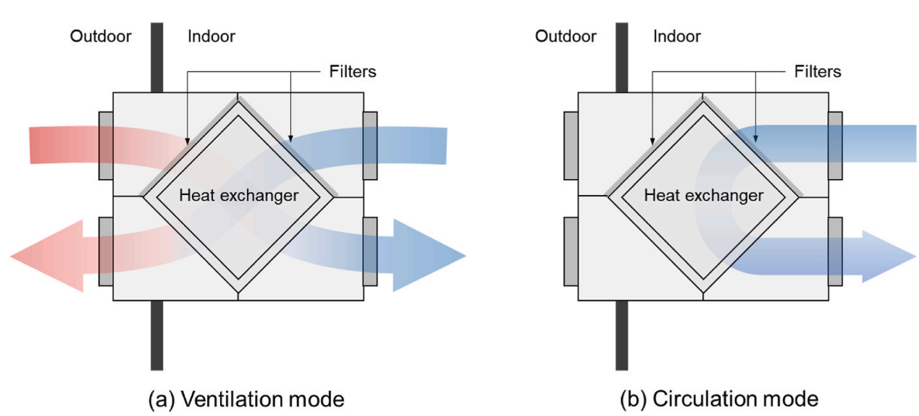

Fig. 1. Operating modes of HRV system: (a) ventilation mode and (b) circulation mode.

shell of the HRV system, to ensure that the HRV system operates at the designed airflow rate of 200 m^3/h. Table 1 summarizes the airflow rate of each diffuser with ventilation and circulation modes based on the measurement with an anemometer (TESTO 417, TESTO, USA).

Sidepak (AM520, TSI, USA), an optical light scattering sensor, was used to measure $PM_{2.5}$ and PM_{10} every 2-min. Sidepak has a detectable particle size range of 0.1 μm–10 μm with an uncertainty of 1 μg/m^3, and its sampling flow rate was 1.8 L/min. Before the measurement campaign, collocation tests for all sensors were performed [29]. In addition, temperature and relative humidity were measured every 2-min (MCH-383SD, LUTRON, Taiwan). Sidepak sensors were placed 1.2 m above the floor in each bedroom and outside, as shown in Fig. 2b and Fig. S1.

Along with PM measurements, the air change rate was measured during each experiment using the tracer gas decay method. First, SF_6 tracer gas was released at a rate of 15 L/min to each bedroom and living room, while four mixing fans operated at an air speed of 2 m/s to make the well-mixed condition. After a sufficiently high and uniform tracer gas concentration of 50 ppm was obtained for all rooms, the decay test started. SF_6 concentrations were measured at a sampling interval of 10 min for both emission and decay periods,. The measured average (±SD) air change rate was 0.12 (±0.10) h^{-1} during HRV system off mode, which is much lower than the geometric mean air change rate of residential buildings in the U.S., 0.5 h^{-1} [30,31]. Table S1 summarizes all environmental and concentration data measured during the experiment.

2.3. Indoor particle emission tests under different HRV system operation modes

Indoor emission tests were performed under three HRV system operating modes: 1) HRV off mode, 2) Ventilation mode, and 3) Circulation mode. Since cooking and candle/incense burning are common indoor particle emission sources [22], incense stick burning and bacon pan frying were selected as particle emission sources. For the repeatability of the test, the particle generation test was performed based on the protocols described below:

Incense stick burning: One incense stick was ignited using a pocket torch gas lighter for 7 min in the kitchen. After 7 min of burning, it was covered with wet tissue to distinguish it completely.

Bacon pan frying: 40 (±1) g of bacon was fried using a 24 cm diameter pan without cooking oil on the electric stove in the kitchen. The pan was preheated until the pan surface temperature reached 230 °C, and then bacon was fried for 3 min for one side and 2 more minutes for the other side. After bacon pan frying, the pan was covered completely.

Note that before each indoor emission test, we cleaned the floor and all surfaces of the residential testbed to minimize the effect of particle resuspension from the surfaces. Table 2 shows the experiment condition of particle emission tests. During the test, the mixing fans were operated to make the room air well-mixed.

In general, the kitchen range hood is widely used to remove cooking-generated particles during cooking. Combined kitchen range hood and HRV system can be more effective than using the HRV system solely [32]. However, some houses have a non-vented range hood that only circulates the air without exhausting cooking-generated particles to outdoors [33]. In such case, mechanical ventilation systems such as a HRV system might be an alternative method to control indoor-generated particles. Furthermore, it should be noted that this study tested cooking and incense burning as only two indoor emission sources and future studies should examine further other common indoor emission sources (e.g., combustion and chemical emissions).

Table 2
Experiment conditions.

Mode	Days	Indoor particle generation	Air change rate (h^{-1})	Peak $PM_{2.5}$concentration (μg/m^3)
HRV off	10	Incense stick burning	0.11	55
	11	Bacon pan frying	0.12	231
Ventilation mode	7	Incense stick burning	0.98	56
	7	Bacon pan frying	0.98	203
Circulation mode	8	Incense stick burning	0.13	52
	4	Bacon pan frying	0.10	166

2.4. Estimation of the particle removal efficiency

Using the measurement data, we estimated the particle removal efficiency while considering HRV operating modes and the filter bypass factor. After calculating input parameters (see Supporting information: Estimation of the penetration coefficient, deposition rate, and particle emission rate), an analytical mass balance model was established to investigate the effects of the outdoor particle concentration, airflow rate of the HRV system, two operating modes and the bypass factor on the particle removal performance of the HRV system.

Without the HRV system, outdoor particles enter indoors through infiltration, so the indoor particle concentration at time *t* can be written as Eq. (1), [34,35]. On the other hand, when the HRV system operates with ventilation mode, indoor particle concentration is expressed as Eq. (2), where particle filtration occurs with the outdoor ventilation air. For circulation mode, since 100% indoor air recirculates via the HRV system, particle removal only occurs with the indoor particles as Eq. (3), [36].

$$\frac{dC_{in}(t)}{dt} = a_{inf}PC_{out}(t) - (k + a_{inf})C_{in}(t) + \frac{E(t)}{V} \quad \text{(Eq. 1)}$$

$$\frac{dC_{in}(t)}{dt} = a_{inf}PC_{out}(t) + (1-\eta_{vent})a_{vent}PC_{out}(t) - (k + a_{inf} + a_{vent})C_{in}(t) + \frac{E(t)}{V} \quad \text{(Eq. 2)}$$

$$\frac{dC_{in}(t)}{dt} = a_{inf}PC_{out}(t) - (k + a_{inf})C_{in}(t) - \eta_{cir}a_{cir}C_{in}(t) + \frac{E(t)}{V} \quad \text{(Eq. 3)}$$

Table 1
Airflow rate of supply and exhaust diffusers.

Mode		Airflow rate (m^3/h)							Sum
		1	2	3	4	5	6	7	
Ventilation	SA[a]	28.5	21.3	26.8	23.4	–	60.4	32.0	192.4
	EA[b]	27.1	31.7	34.3	39.6	74.5	–	–	207.2
Circulation	SA	29.0	22.2	26.9	23.3	–	60.7	33.4	195.5
	EA	25.8	29.7	31.3	38.1	67.9	–	–	192.8

[a] SA: supply diffuser.
[b] EA: exhaust diffuser.

Where $C_{in}(t)$ is the indoor particle concentration at time, t ($\mu g/m^3$), $C_{out}(t)$ is the outdoor particle concentration at time, t ($\mu g/m^3$), a_{inf} is the air change rate by infiltration (h^{-1}), a_{vent} is the air change rate by the HRV system (ventilation mode) (h^{-1}), a_{cir} is the air change rate by the HRV system (circulation mode) (h^{-1}), P is the penetration coefficient (dimensionless), k is the deposition rate (h^{-1}), $E(t)$ is the emission rate at time t ($\mu g/h$), V is the total room volume (m^3), η_{vent} and η_{cir} are the total particle removal efficiency of the ventilation mode and the circulation mode, respectively, including the effects of the air filter and bypass (dimensionless).

With the discrete time step approach proposed by Ref. [34], Eqs (1)–(3) can be rewritten as Eqs (4)–(6), respectively. This approach is valid under the following conditions: 1) The relatively small-time step is necessary to approximate the exponential decay of indoor particle concentration by the linear model, and 2) there are no other indoor emission sources. To satisfy these conditions, we set the time step of PM sensors as 2 min and collected particle concentration data up to 24 h from the start of each particle emission test.

$$C_{in}(t) = a_{inf}PC_{out}(t)\Delta t + \left(1 - \left(k + a_{inf}\right)\Delta t\right)C_{in}(t-1) \quad \text{(Eq. 4)}$$

$$C_{in}(t) = (1-\eta_{vent})a_{vent}C_{out}(t)\Delta t + (1-(k+a_{vent})\Delta t)C_{in}(t-1) \quad \text{(Eq. 5)}$$

$$C_{in}(t) = a_{inf}PC_{out}(t)\Delta t + \left(1 - \left(k + a_{inf} + \eta_{cir}a_{cir}\right)\Delta t\right)C_{in}(t-1) \quad \text{(Eq. 6)}$$

Where Δt is the time step (2 min), and $C_{in}(t-1)$ is the indoor particle concentration one time step before t ($\mu g/m^3$).

Note that the penetration coefficient (P) and the deposition rate (k) were calculated first using Eq (4). They are applied to Eqs (5) and (6) to estimate the particle removal efficiency for ventilation mode (η_{vent}) and circulation mode (η_{cir}).

Additionally, we assume that 1) the penetration coefficient (P) and the deposition rate (k) do not change over time, and 2) in the ventilation mode, outdoor-indoor infiltration flow rate is negligible compared to the HRV flow rate. Note that the average air change rate with ventilation mode was 0.98 h^{-1} (Table 2), which is equal to the air change rate based on the HRV system flow rate, 0.98 ($\pm$0.12) h^{-1}. Therefore, the particle gaining term due to infiltration was not considered in Eq (5).

2.5. Effect of filter bypass

The total particle removal efficiency of an HRV system is a function of air filter efficiency, filter bypass, air leakage, and particle deposition and resuspension in ductworks [26,37,38]. Among others, filter bypass is a critical factor for particle control because even small amounts of filter bypass could decrease particle removal performance and increase heat exchanger fouling [39].

Since all potential leakage components of the HRV system ductwork were sealed and double-checked before the experiment, determinant factors of the total particle removal efficiency of ventilation mode (η_{vent}) and circulation mode (η_{cir}) are the filtration efficiency of the air filter and bypass factor as Eq (7), [26].

$$\eta_{vent} \text{ or } \eta_{cir} = 1 - \left(F_{bypass} + \left(1-\eta_{filter}\right)\left(1-F_{bypass}\right)\right) \quad \text{Eq (7)}$$

Where F_{bypass} is the bypass factor that represents the ratio of the airflow rate not passing the air filter to the total airflow rate (dimensionless), and η_{filter} is the particle filtration efficiency of the air filter (dimensionless).

2.6. Parametric analysis

The particle removal performance of the HRV system was estimated for representative ranges of the outdoor particle concentration, the airflow rate, and the particle removal efficiency under ventilation and circulation modes. Table 3 provides the summary of the input variables for the parametric analysis. The ranges of the particle removal efficiency and bypass factor were selected based on the experiment result on the bypass factor through the air filter [26]. Four outdoor $PM_{2.5}$ concentrations, 12 μg/m^3, 35 μg/m^3, 55 μg/m^3, and 100 μg/m^3, were based on the concentration standard set by the United States Environmental Protection Agency (EPA) (https://www.epa.gov/naaqs/particulate-matter-pm-air-quality-standards). In addition, the initial $PM_{2.5}$ concentration and air change rate by infiltration were set as 15 μg/m^3 and 0.12 h^{-1} based on the average values from the measurement (Table S1), and the infiltration airflow rate was only applied to the circulation mode.

Table 3
Input variations for parametric analyses.

HRV system operating mode	Ventilation mode
	Circulation mode
Particle source	Bacon pan frying(3.1x10^5 μg/h)
Air change rate by infiltration	0.12 h^{-1}
Initial $PM_{2.5}$ concentration	15 μg/m^3
Outdoor $PM_{2.5}$ concentration	12 μg/m^3
	35 μg/m^3
	55 μg/m^3
	100 μg/m^3
Bypass factor	0%–40%
Airflow rate of HRV system	200 m^3/h
	400 m^3/h

Finally, to quantify indoor exposure to particles associated with the HRV system, 4-hr integrated $PM_{2.5}$ exposure was calculated for each operating mode, expressed as time-integrated indoor $PM_{2.5}$ concentration over 4 h from the start of the cooking emission.

$$PM_{2.5}\ exposure = \int_{t1}^{t2} tC_{in}(t)dt \quad \text{Eq (8)}$$

Where $t1$ is the time when cooking starts and $t2$ is 4 h after $t1$.

3. Results and discussion

3.1. Indoor particle concentrations with HRV system operation

Fig. 3 illustrates time-series indoor $PM_{2.5}$ concentration with two indoor emission sources under three HRV system operating modes. For incense burning, regardless of the HRV system operation, indoor $PM_{2.5}$ concentration reaches the peak of 55 μg/m^3; however, the particle concentration decays faster with the HRV system operating. With the HRV circulation mode, $PM_{2.5}$ concentration decreases to the background concentration within 4 h, whereas the concentration remains above 25 μg/m^3 even after 6 h from incense burning with the HRV system off.

For bacon pan frying, under the HRV system off mode, the concentration is notably high, up to 231 μg/m^3; however, HRV operating with ventilation and circulation modes yield peak concentrations of 215 μg/m^3 and 165 μg/m^3, respectively (Fig. 3b). $PM_{2.5}$ concentration trend similar to the incense stick burning was observed with the HRV system operation, in which $PM_{2.5}$ concentration decreases to the background concentration within 4 h, while the concentration remains greater than 68 μg/m^3 more than 6 h with the HRV system off.

Fig. 4 demonstrates that under the HRV system off mode, approximately 36 h are required for indoor $PM_{2.5}$ concentration to reach the background concentration. Meanwhile, under the HRV system operating condition, only 4 h are needed for indoor $PM_{2.5}$ concentration to be lower than 5 μg/m^3.

Comparing the two HRV modes, the circulation mode was expected to eliminate indoor particles more effectively than the ventilation mode due to indoor air recirculation through the air filter (HEPA grade H13) without introducing outdoor particles. However, the two modes make marginal differences in reducing indoor $PM_{2.5}$ concentration (Fig. 3), given the similar concentration decay pattern and peak concentration.

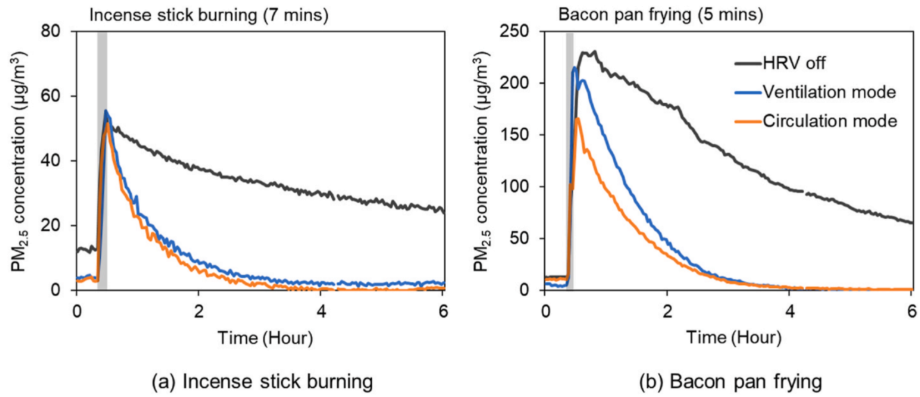

Fig. 3. Indoor $PM_{2.5}$ concentration with particle sources and HRV system operating modes.

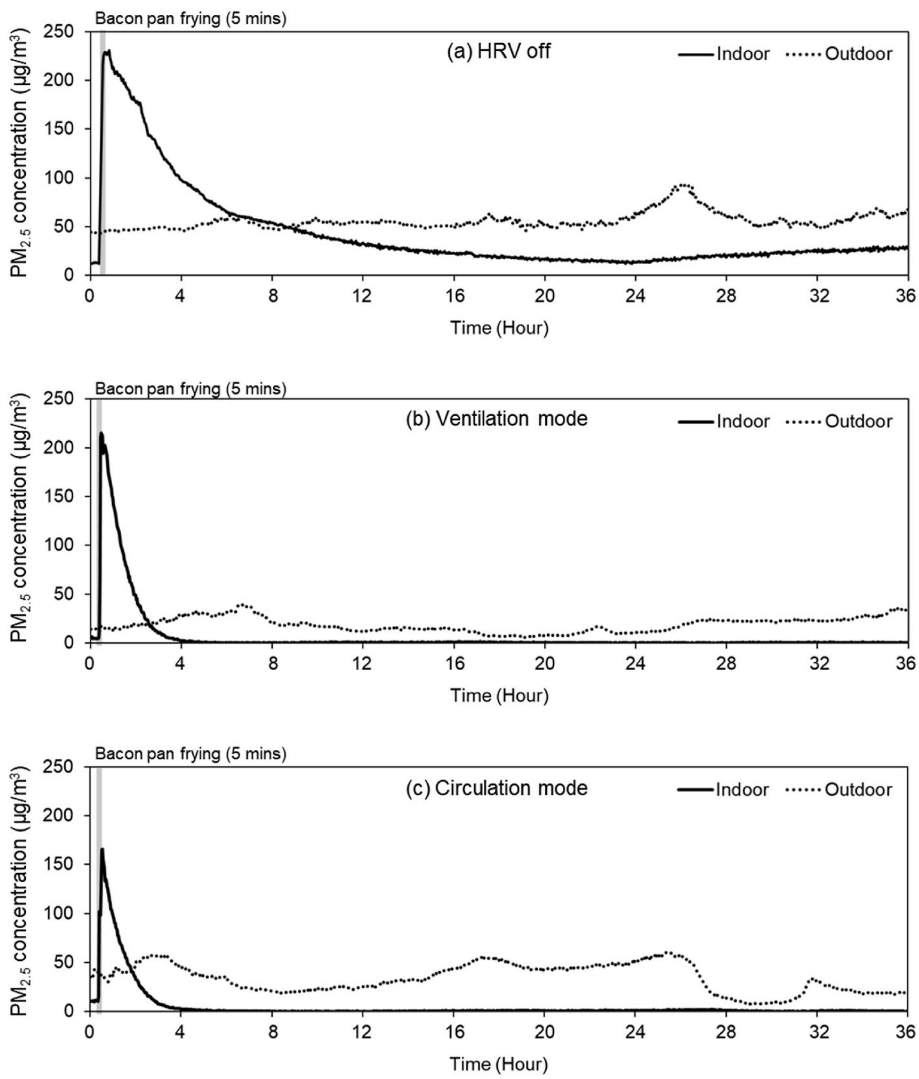

Fig. 4. 36 h $PM_{2.5}$ concentration with HRV system operating modes: (a) HRV system off, (b) ventilation mode, and (c) circulation mode.

This pattern is mainly because the average outdoor $PM_{2.5}$ concentration was 20.1 μg/m^3 under the ventilation mode, which made a negligible outdoor influence on indoor particle concentrations (Fig. 4). This result suggests that both ventilation and circulation modes are effective in indoor particle removal when the outdoor particle concentration is lower than 20 μg/m^3

Even though operating the HRV system can reduce human exposure to indoor particles during cooking, the indoor particle concentration can surge (>150 μg/m^3), as shown in Fig. 3b. Furthermore, cooking accompanies the heat source that accelerates particle diffusion [40] and occupants are likely to be exposed to high peak $PM_{2.5}$ concentrations. In such cases, the HRV system appears insufficient to control indoor-generated particles; therefore, during the cooking emission period, additional source controls or filtrations are necessary to control acute exposure to $PM_{2.5}$ For example, a kitchen range hood installed near the cooktop can remove around 70% of contaminants from cooking [25,32,41]. Furthermore, using a portable air cleaner could be an effective measure to reduce human exposure to cooking-derived particles [42–44].

3.2. Indoor to outdoor particle concentration ratios

Table 4 summarizes the average indoor to outdoor particle concentration ratio (I/O ratio) that varies with the HRV system operating mode under no indoor emission condition. When the HRV system is off, the average I/O ratios are 0.40 for $PM_{2.5}$ and 0.36 for PM_{10}. The I/O ratios of $PM_{2.5}$ and PM_{10} decrease by 72%–80% with ventilation mode and 80%–92% with the circulation mode. Note that average indoor $PM_{2.5}$ and PM_{10} concentrations decrease by 56%–90% with the HRV system operation (Table S1). These results resonate with those of previous studies that at least 50% particle removal can be achieved by using mechanical ventilation systems in residential buildings [17–20].

The circulation mode yields about a 40% lower average I/O ratio than the ventilation mode (Table 4). This is mainly because ventilation mode continuously introduces outdoor-originated particles into the room through the air filter. On the other hand, circulation mode continuously recirculates 100% indoor air through the air filter, while the impact of outdoor particles is negligible with the relatively small infiltration rate (0.12 h^{-1}). The discrepancy between two operating modes is expected to vary with the outdoor air condition and particle filtration efficiency, which is discussed more in detail in section 3.4.

3.3. Particle removal efficiency for ventilation and circulation modes

The particle removal efficiencies estimated based on Eqs. (5) and (6) are 0.85 for $PM_{2.5}$ and 0.89 for PM_{10} under ventilation mode, while they are 0.95 for $PM_{2.5}$ and 0.96 for PM_{10} under circulation mode (Table S2). The range of particle removal efficiency observed in the present study is higher than the reported values of 50%–85% from previous studies [18,45]. One possible explanation is that double-checking air sealing of the HRV system ductwork before each test minimizes the filter bypass and improves the particle removal efficiency of the HRV system.

Circulation mode shows an 8%–12% higher particle removal efficiency than ventilation mode, mainly because the circulation mode has only one (i.e., recirculation) air path via the air filter, while it appears that more air leakage and bypass occur when the air passes the heat exchanger for the ventilation mode.

The detailed effect of the bypass through the air filter on the particle removal efficiency of the HRV system based on Eq (7) revealed the relationship between the bypass and particle removal efficiency. The bypass factors for $PM_{2.5}$ are estimated as 5% under the circulation mode and 15% under the ventilation mode.

3.4. Indoor $PM_{2.5}$ concentrations and time-integrated exposure

Fig. 5 compares measured and predicted $PM_{2.5}$ concentrations based on the parametric analysis (Table S2). For bacon pan frying, the difference between the predicted and measured concentrations was 9%–15%. For incense burning, the difference was less than 8%. In addition, the decay pattern of the predicted and measured $PM_{2.5}$ concentrations show a reasonable agreement with an R^2 value > 0.97 for all cases.

Table 4
Indoor and outdoor PM concentration ratio (I/O ratio).

Mode		Average I/O ratio (±SD)
$PM_{2.5}$	HRV system off	0.40 (±0.22)
	Ventilation mode	0.11 (±0.40)
	Circulation mode	0.07 (±0.32)
PM_{10}	HRV system off	0.36 (±0.27)
	Ventilation mode	0.19 (±0.42)
	Circulation mode	0.12 (±0.39)

Fig. 6 illustrates 4-h integrated $PM_{2.5}$ exposure under two HRV system operating modes for varying outdoor particle concentrations (i.e., 12 μg/m^3,35 μg/m^3, 55 μg/m^3, 100 μg/m^3) and two supply airflow rates (i.e., 200 m^3/h, 400 m^3/h). Note that the HRV filter bypass factor can be translated to the particle removal efficiency of the system based on Eq (7). For the ventilation mode, 4-hr integrated $PM_{2.5}$ exposure varies noticeably with the outdoor $PM_{2.5}$ concentration. For instance, at an outdoor $PM_{2.5}$ concentration of 12 μg/m^3, an increase in the bypass factor from 0% to 40% yields a 7% increase in $PM_{2.5}$ exposure at the flow rate of 200 m^3/h. However, at the outdoor $PM_{2.5}$ concentration of 100 μg/m^3, a 60% increase in $PM_{2.5}$ exposure is observed at the same flow rate. Furthermore, the effect of the bypass factor is amplified as the supply airflow rate increases; at the airflow rate of 400 m^3/h, $PM_{2.5}$ exposure dramatically increases by about 230% as the bypass factor increases from 0% to 40%.

Fig. 6 shows that a bypass increase yields a reduced particle removal efficiency of the HRV system, ultimately resulting in a higher risk of indoor particle exposure. For example. a bypass factor of 20% leads to a 30%–50% increase in $PM_{2.5}$ exposure at an outdoor $PM_{2.5}$ concentration of 100 μg/m^3 compared to the no-bypass scenario. In general, the bypass significantly degrades the total particle removal efficiency of the system, and its negative effect is pronounced as the filter is loaded with particles, the airflow rate increases, and the filter efficiency is high [37,46,47]. Previous studies reported that a 0.1 mm gap yields up to 60% penetration of particles [48], and the bypass through a 10 mm gap could completely nullify the filtering efficiency [26]. Moreover, such filter bypass increases the penetration of fine particles <2.5 μm, which have more severe health impacts than coarse particles [49,50]. In cases where the filter is not installed and maintained properly, increasing the airflow rate of ventilation system could increase exposure to fine particles of outdoor origin, especially for buildings located near strong outdoor particle emission sources [51,52].

Fig. 7 compares 4-hr integrated $PM_{2.5}$ exposure under ventilation and circulation modes depending on the removal efficiency, the airflow rate, and outdoor $PM_{2.5}$ concentration. It shows that when outdoor air is polluted (e.g., $PM_{2.5}$ concentration >100 μg/m^3), operating circulation mode is better to mitigate $PM_{2.5}$ exposure than the ventilation mode. On the other hand, when the outdoor air is clean (e.g., $PM_{2.5}$ concentration <15 μg/m^3), ventilation mode can lower $PM_{2.5}$ exposure more than the circulation mode as far as the total particle removal efficiency is <85%.

3.5. Study implications and limitations

Overall, our study results reveal that the HRV circulation mode is beneficial for reducing indoor particle concentration, particularly in areas where the outdoor air is highly polluted with particles. For instance, the daily average ambient outdoor $PM_{2.5}$ concentration exceeds 100 μg/m^3 in most megacities [53–59], and areas impacted by wildfire [12–14,60]. In such cases, circulation mode could better protect occupants from $PM_{2.5}$ exposure than ventilation mode. However, since indoor environments have other contaminants generated by various indoor activities, such as CO, VOCs, NO_x and CO_2 [43,44,61–63], operating circulation mode for a long time is likely to accumulate other indoor pollutants. Taken together, indoor particle and indoor CO_2 concentrations (a commonly used indoor air quality index) can be considered to determine the operating strategy for the HRV system. A previous study [64], proposed an energy-efficient strategy for the HRV system that controls the operating mode based on both outdoor and indoor pollution conditions. For example, for conditions of indoor CO_2 concentration <1000 ppm and indoor $PM_{2.5}$ concentration >35 μg/m^3, circulation mode can be applied [64]. reported that the maximum airflow rate of 600 m^3/h is required to ensure adequate indoor air quality in the typical residential house. However, considering that the emission rate due to cooking (e.g., bacon pan frying) is often more than

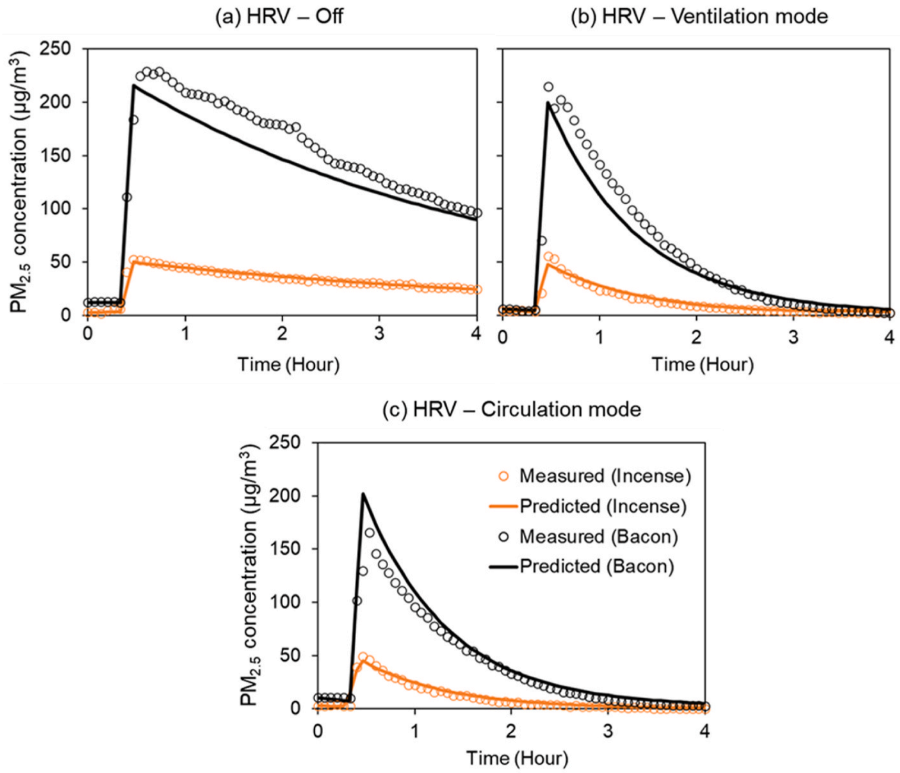

Fig. 5. Measured indoor $PM_{2.5}$ concentration versus predicted indoor $PM_{2.5}$ concentration.

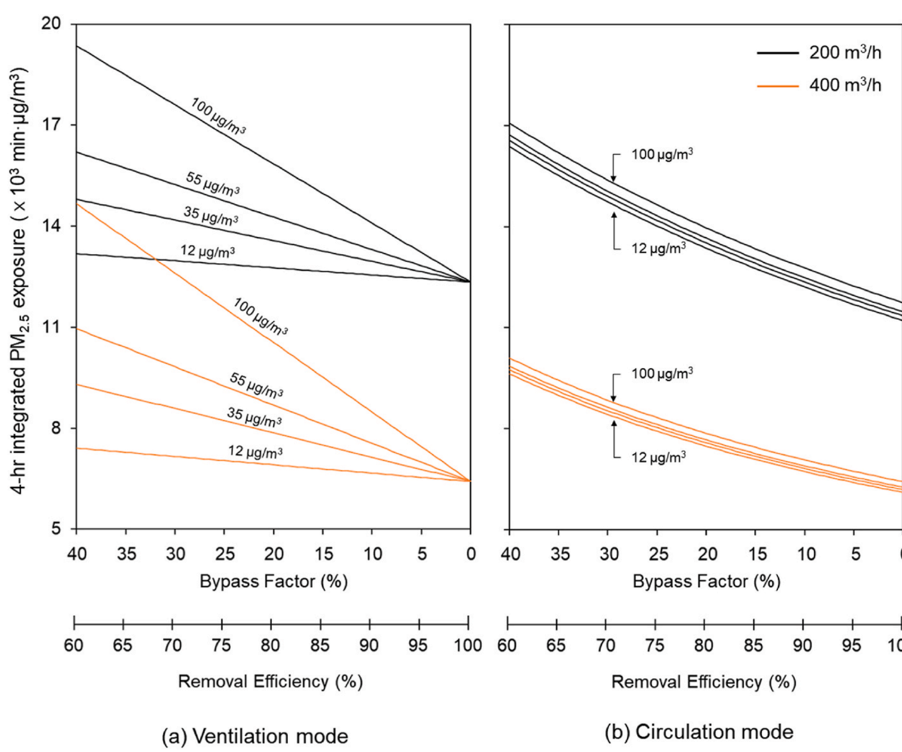

Fig. 6. 4-hr integrated $PM_{2.5}$ exposure to depending on the bypass factor and the outdoor $PM_{2.5}$ concentration (on the graph). Note that the particle source is bacon pan frying.

10 times higher than the emission rate used in the study by Ref. [64], it will be desirable that the HRV system can operates with the kitchen range hood and/or portable air cleaners to control indoor-generated pollutants. Furthermore, the efficiency of the air filter is crucial for reducing both fine and ultrafine particles (UFP, <0.1 µm). Many indoor emission sources including incense and cooking, are the major source of indoor UFP. For instance, cooking using a gas stove and candle burning can produce UFP of more than 3 × 10^5 cm^{-3} [65]. Besides indoor

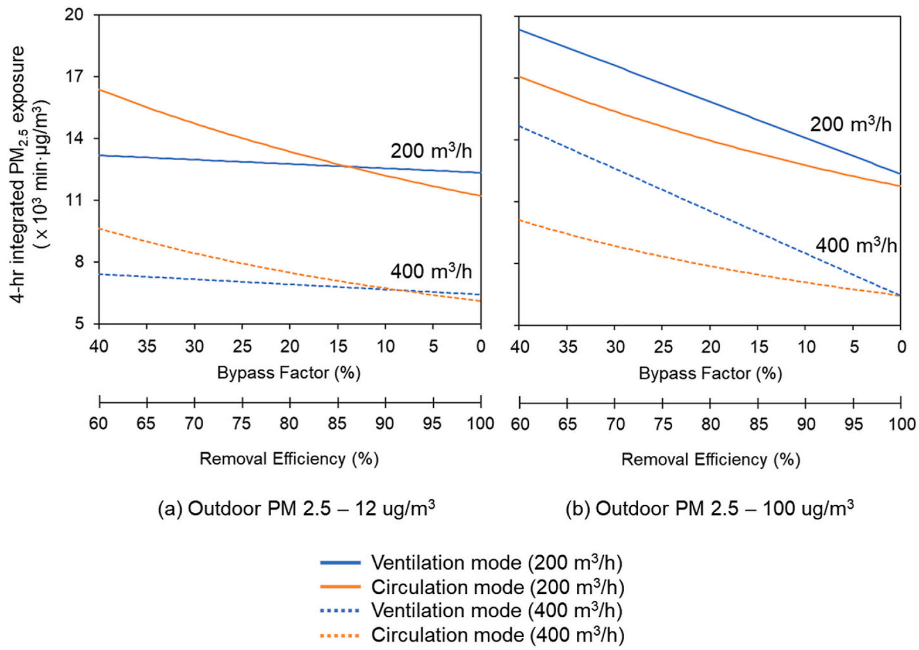

Fig. 7. Comparison of 4-hr integrated $PM_{2.5}$ with two HRV system operating modes, ventilation mode and circulation mode. Note that the particle source is bacon pan frying.

sources, many urban cities have high outdoor particle concentrations; thus, the HEPA grade filter is desirable due to its higher removal efficiency for all size particles (>99%) [66,67]. Additionally, appropriate filter maintenance is required because of degraded performance and secondary VOC emissions of overloaded filters [68,69].

A few limitations of our study should be noted. First, we tested only two particle emission sources, incense stick burning and bacon pan frying. Second, we performed the experiment with one air filter (HEPA grade H13) and one supply air flow rate of 200 m^3/h. Based on our parametric analysis, operating the HRV system with a higher airflow rate and a higher-grade air filter is expected to reduce indoor exposure to particles. However, it should be noted that a higher airflow rate and air filter efficiency are likely to be accompanied with a higher pressure drop, which could increase the filter bypass and degrade the total particle removal efficiency of the HRV system [37]. Future studies are warranted to investigate how much the filtration efficiency and airflow rate affect the filter bypass in the supply air under the realistic environmental conditions of residential buildings. In addition, while several other studies examined energy saving benefits of the heat recovery systems or energy recovery systems, future studies can further evaluate co-benefits in energy saving and indoor pollution control of a HRV system in highly populated megacities [36].

4. Conclusion

The present study investigated the performance of an HRV system in controlling indoor-generated and outdoor-originated particles with two operating modes (i.e., ventilation mode and circulation mode). Based on the field measurement data, an analytical mass balance model was established to examine the effect of the outdoor particle concentration, the HRV airflow rate, and the particle removal efficiency of the HRV system. The following major findings are obtained.

1) For an airtight residential building (0.12 h^{-1}), it takes up to 36 h to fully eliminate particles from cooking with no HRV system, while particle concentration decreases to the background concentration within 4 h with operating a HRV system. However, the HRV system alone marginally reduces the peak concentration during the cooking emission period.
2) Operating the HRV system reduces the indoor average $PM_{2.5}$ and PM_{10} concentrations by 56%–90% compared to HRV off mode. Moreover, the indoor/outdoor concentration ratio shows that circulation mode has better particle control, with a 92%–97% reduction, than ventilation mode, with a 72%–80% indoor particle reduction.
3) The outdoor particle concentration is a critical factor for the HRV ventilation mode, while it has a marginal effect on circulation mode. However, for both modes, the bypass factor is a determinant factor of indoor exposure to particles. The bypass factor of 20% yields an increase in $PM_{2.5}$ exposure up to 50%, suggesting that control of the HRV filter bypass is key to improving the particle removal efficiency of the HRV system.

CRediT authorship contribution statement

Seongjun Park: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Shinhye Lee:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Myoung-Souk Yeo:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Donghyun Rim:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110412.

References

[1] R.J. Delfino, C. Sioutas, S. Malik, Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health, Environ. Health Perspect. 113 (8) (2005) 934–946, https://doi.org/10.1289/ehp.7938.
[2] World Health Organization, Air Quality Guidelines: Global Update 2005: Particulate Matter, Ozone, Nitrogen Dioxide, and Sulfur Dioxide, World Health Organization, 2006.
[3] Y.F. Xing, Y.H. Xu, M.H. Shi, Y.X. Lian, The impact of PM2. 5 on the human respiratory system, J. Thorac. Dis. 8 (1) (2016) E69, https://doi.org/10.3978/j.issn.2072-1439.2016.01.19.
[4] J.S. Apte, M. Brauer, A.J. Cohen, M. Ezzati, C.A. Pope III, Ambient PM2. 5 reduces global and regional life expectancy, Environ. Sci. Technol. Lett. 5 (9) (2018) 546–551, https://doi.org/10.1021/acs.estlett.8b00360.
[5] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, W. H. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (3) (2001) 231–252, https://doi.org/10.1038/sj.jea.7500165.
[6] E. Abt, H.H. Suh, P. Catalano, P. Koutrakis, Relative contribution of outdoor and indoor particle sources to indoor concentrations, Environ. Sci. Technol. 34 (17) (2000) 3579–3587, https://doi.org/10.1021/es990348y.
[7] D. Rim, L. Wallace, S. Nabinger, A. Persily, Reduction of exposure to ultrafine particles by kitchen exhaust hoods: the effects of exhaust flow rates, particle size, and burner position, Sci. Total Environ. 432 (2012) 350–356, https://doi.org/10.1016/j.scitotenv.2012.06.015.
[8] B.H. Lee, S.W. Yee, D.H. Kang, M.S. Yeo, K.W. Kim, Multi-zone simulation of outdoor particle penetration and transport in a multi-story building, in: Building Simulation, vol. 10, Tsinghua University Press, 2017, pp. 525–534, https://doi.org/10.1007/s12273-016-0340-1. No. 4.
[9] S.C. van der Zee, M. Strak, M.B. Dijkema, B. Brunekreef, N.A. Janssen, The impact of particle filtration on indoor air quality in a classroom near a highway, Indoor Air 27 (2) (2017) 291–302, https://doi.org/10.1111/ina.12308.
[10] J. Kim, S. Park, H. Kim, M.S. Yeo, Emission characterization of size-resolved particles in a pre-school classroom in relation to children's activities, Indoor Built Environ. 28 (5) (2019) 659–676, https://doi.org/10.1177/1420326X17707565.
[11] K. Kang, T. Kim, H. Kim, Effect of indoor and outdoor sources on indoor particle concentrations in South Korean residential buildings, J. Hazard Mater. 416 (2021), 125852, https://doi.org/10.1016/j.jhazmat.2021.125852.
[12] P. Gupta, P. Doraiswamy, R. Levy, O. Pikelnaya, J. Maibach, B. Feenstra, K.C. Mills, Impact of California fires on local and regional air quality: the role of a low-cost sensor network and satellite observations, GeoHealth 2 (6) (2018) 172–181, https://doi.org/10.1029/2018GH000136.
[13] D.A. Stauffer, D.A. Autenrieth, J.F. Hart, S. Capoccia, Control of wildfire-sourced PM2. 5 in an office setting using a commercially available portable air cleaner, J. Occup. Environ. Hyg. 17 (4) (2020) 109–120, https://doi.org/10.1080/15459624.2020.1722314.
[14] R. Aguilera, T. Corringham, A. Gershunov, T. Benmarhnia, Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California, Nat. Commun. 12 (1) (2021) 1–8, https://doi.org/10.1038/s41467-021-21708-0.
[15] Z. Liu, W. Li, Y. Chen, Y. Luo, L. Zhang, Review of energy conservation technologies for fresh air supply in zero energy buildings, Appl. Therm. Eng. 148 (2019) 544–556, https://doi.org/10.1016/j.applthermaleng.2018.11.085.
[16] ASHRAE, Chapter 26: Air-To-Air Energy Recovery Equipment. ASHRAE Handbook – Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 2021.
[17] J.S. Park, N.Y. Jee, J.W. Jeong, Effects of types of ventilation system on indoor particle concentrations in residential buildings, Indoor Air 24 (6) (2014) 629–638, https://doi.org/10.1111/ina.12117.
[18] S.L. Wallis, G. Hernandez, D. Poyner, R. Birchmore, T.A. Berry, Particulate matter in residential buildings in New Zealand: Part I. Variability of particle transport into unoccupied spaces with mechanical ventilation, Atmos. Environ. X 2 (2019), 100024, https://doi.org/10.1016/j.aeaoa.2019.100024.
[19] L. Zhao, J. Liu, Operating behavior and corresponding performance of mechanical ventilation systems in Chinese residential buildings, Build. Environ. 170 (2020), 106600, https://doi.org/10.1016/j.buildenv.2019.106600.
[20] X. Sui, Z. Tian, H. Liu, H. Chen, D. Wang, Field measurements on indoor air quality of a residential building in Xi'an under different ventilation modes in winter, J. Build. Eng. 42 (2021), 103040, https://doi.org/10.1016/j.jobe.2021.103040.
[21] C.M. Long, H.H. Suh, P. Koutrakis, Characterization of indoor particle sources using continuous mass and size monitors, J. Air Waste Manag. Assoc. 50 (7) (2000) 1236–1250, https://doi.org/10.1080/10473289.2000.10464154.
[22] C. Isaxon, A. Gudmundsson, E.Z. Nordin, L. Lönnblad, A. Dahl, G. Wieslander, A. Wierzbicka, Contribution of indoor-generated particles to residential exposure, Atmos. Environ. 106 (2015) 458–466, https://doi.org/10.1016/j.atmosenv.2014.07.053.
[23] Y. Xiao, L. Wang, M. Yu, H. Liu, J. Liu, Effects of source emission and window opening on winter indoor particle concentrations in the severe cold region of China, Build. Environ. 144 (2018) 23–33, https://doi.org/10.1016/j.buildenv.2018.08.001.
[24] L.A. Wallace, S.J. Emmerich, C. Howard-Reed, Source strengths of ultrafine and fine particles due to cooking with a gas stove, Environ. Sci. Technol. 38 (8) (2004) 2304–2311, https://doi.org/10.1021/es0306260.
[25] K. Kang, H. Kim, D.D. Kim, Y.G. Lee, T. Kim, Characteristics of cooking-generated PM10 and PM2. 5 in residential buildings with different cooking and ventilation types, Sci. Total Environ. 668 (2019) 56–66, https://doi.org/10.1016/j.scitotenv.2019.02.316.
[26] M. Ward, J.A. Siegel, Modeling filter bypass: impact on filter efficiency, Build. Eng. 111 (1) (2005) 1091–1100.
[27] C. Aydin, B. Ozerdem, Air leakage measurement and analysis in duct systems, Energy Build. 38 (3) (2006) 207–213, https://doi.org/10.1016/j.enbuild.2005.05.010.
[28] ANSI/ASHRAE, Standard 62.1-2022 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2022.
[29] S. Park, S. Lee, M. Yeo, D. Rim, Field and laboratory evaluation of PurpleAir low-cost aerosol sensors in monitoring indoor airborne particles, Build. Environ. 234 (2023), 110127, https://doi.org/10.1016/j.buildenv.2023.110127.
[30] ASHRAE, Chapter 17: Ventilation and Infiltration. ASHRAE Handbook – Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 2017.
[31] W.W. Nazaroff, Residential air-change rates: a critical review, Indoor Air 31 (2) (2021) 282–313, https://doi.org/10.1111/ina.12785.
[32] Y.S. Eom, D.H. Kang, D. Rim, M. Yeo, Particle dispersion and removal associated with kitchen range hood and whole house ventilation system, Build. Environ. (2023), 109986, https://doi.org/10.1016/j.buildenv.2023.109986.
[33] L. Sun, L.A. Wallace, Residential cooking and use of kitchen ventilation: the impact on exposure, J. Air Waste Manag. Assoc. 71 (7) (2021) 830–843, https://doi.org/10.1080/10962247.2020.1823525.
[34] D. Rim, L. Wallace, A. Persily, Infiltration of outdoor ultrafine particles into a test house, Environ. Sci. Technol. 44 (15) (2010) 5908–5913, https://doi.org/10.1021/es101202a.
[35] W. Xie, Y. Fan, X. Zhang, G. Tian, P. Si, A mathematical model for predicting indoor PM2. 5 concentration under different ventilation methods in residential buildings, Build. Serv. Eng. Res. Tecnol. 41 (6) (2020) 694–708, https://doi.org/10.1177/0143624420905102.
[36] T. Ruan, D. Rim, Indoor air pollution in office buildings in mega-cities: effects of filtration efficiency and outdoor air ventilation rates, Sustain. Cities Soc. 49 (2019), 101609, https://doi.org/10.1016/j.scs.2019.101609.
[37] J. VerShaw, D.B. Chojnowski, P.J. Nigro, Implications of filter bypass, Build. Eng. 115 (2009) 191.
[38] B. Stephens, J.A. Siegel, Comparison of test methods for determining the particle removal efficiency of filters in residential and light-commercial central HVAC systems, Aerosol. Sci. Technol. 46 (5) (2012) 504–513, https://doi.org/10.1080/02786826.2011.642825.
[39] J. Siegel, Particle Deposition on HVAC Heat Exchangers, University of California, Berkeley, 2002. Ph. D. Dissertation.
[40] L. Kong, J. Liu, J. Ren, S. Liu, J. Li, J. Wang, Experimental study on particle splash pollution from cooking with fluorescent droplets, Build. Environ. 179 (2020), 106973, https://doi.org/10.1016/j.buildenv.2020.106973.
[41] B.C. Singer, R.Z. Pass, W.W. Delp, D.M. Lorenzetti, R.L. Maddalena, Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes, Build. Environ. 122 (2017) 215–229, https://doi.org/10.1016/j.buildenv.2017.06.021.
[42] R. Sharma, R. Balasubramanian, Evaluation of the effectiveness of a portable air cleaner in mitigating indoor human exposure to cooking-derived airborne particles, Environ. Res. 183 (2020), 109192, https://doi.org/10.1016/j.envres.2020.109192.
[43] C.H. Huang, J. Xiang, E. Austin, J. Shirai, Y. Liu, C. Simpson, E. Seto, Impacts of using auto-mode portable air cleaner on indoor PM2. 5 levels: an intervention study, Build. Environ. 188 (2021), 107444, https://doi.org/10.1016/j.buildenv.2020.107444.
[44] L. Huang, H. Cheng, S. Ma, R. He, J. Gong, G. Li, T. An, The exposures and health effects of benzene, toluene and naphthalene for Chinese chefs in multiple cooking styles of kitchens, Environ. Int. 156 (2021), 106721, https://doi.org/10.1016/j.envint.2021.106721.
[45] C. Howard-Reed, L.A. Wallace, S.J. Emmerich, Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse, Atmos. Environ. 37 (38) (2003) 5295–5306, https://doi.org/10.1016/j.atmosenv.2003.09.012.
[46] J. Ren, J. Liu, X. Cao, Y. Hou, Influencing factors and energy-saving control strategies for indoor fine particles in commercial office buildings in six Chinese cities, Energy Build. 149 (2017) 171–179, https://doi.org/10.1016/j.enbuild.2017.05.061.
[47] L. Ji, J. Pei, W. Liu, Long-term performance of fibrous ventilation/air-cleaner filters for particle removal, Build. Environ. 160 (2019), 106222, https://doi.org/10.1016/j.buildenv.2019.106222.
[48] P.A. Baron, J.S. Bennett, Calculation of leakage and particle loss in filter cassettes, Aerosol Sci. Technol. 36 (5) (2002) 632–641, https://doi.org/10.1080/02786820252883865.

[49] N. Englert, Fine particles and human health—a review of epidemiological studies, Toxicol. Lett. 149 (1–3) (2004) 235–242, https://doi.org/10.1016/j.toxlet.2003.12.035.
[50] C.Y. Hsu, H.C. Chiang, M.J. Chen, T.T. Yang, Y.S. Wu, Y.C. Chen, Impacts of hazardous metals and PAHs in fine and coarse particles with long-range transports in Taipei City, Environ. Pollut. 250 (2019) 934–943, https://doi.org/10.1016/j.envpol.2019.04.038.
[51] L. Edelman, Air filtration: air filter media—an industry evolves, Filtrat. Separ. 45 (9) (2008) 24–26, https://doi.org/10.1016/S0015-1882(08)70368-9.
[52] W. Feng, Y. Zhang, L. Huang, Y. Li, Q. Guo, H. Peng, L. Shi, Spatial distribution, pollution characterization, and risk assessment of environmentally persistent free radicals in urban road dust from central China, Environ. Pollut. 298 (2022), 118861, https://doi.org/10.1016/j.envpol.2022.118861.
[53] Y.C. Hong, X.C. Pan, S.Y. Kim, K. Park, E.J. Park, X. Jin, H. Kim, Asian dust storm and pulmonary function of school children in Seoul, Sci. Total Environ. 408 (4) (2010) 754–759, https://doi.org/10.1016/j.scitotenv.2009.11.015.
[54] B.E.Y.H.A.N. Pekey, Z.B. Bozkurt, H.A.K.A.N. Pekey, G.Ü.R.A.Y. Doğan, A. Zararsız, N. Efe, G. Tuncel, Indoor/outdoor concentrations and elemental composition of PM10/PM2. 5 in urban/industrial areas of Kocaeli City, Turkey, Indoor Air 20 (2) (2010) 112–125, https://doi.org/10.1111/j.1600-0668.2009.00628.x.
[55] R. Goyal, P. Kumar, Indoor–outdoor concentrations of particulate matter in nine microenvironments of a mix-use commercial building in megacity Delhi, Air Qual. Atmosph. Health 6 (4) (2013) 747–757, https://doi.org/10.1007/s11869-013-0212-0.
[56] D.H. Choi, D.H. Kang, Infiltration of ambient PM2. 5 through building envelope in apartment housing units in Korea, Aerosol Air Qual. Res. 17 (2) (2017) 598–607, https://doi.org/10.4209/aaqr.2016.06.0287.
[57] D. Rim, E.T. Gall, J.B. Kim, G.N. Bae, Particulate matter in urban nursery schools: a case study of Seoul, Korea during winter months, Build. Environ. 119 (2017) 1–10, https://doi.org/10.1016/j.buildenv.2017.04.002.
[58] A. Wheida, A. Nasser, M. El Nazer, A. Borbon, G.A.A. El Ata, M.A. Wahab, S. C. Alfaro, Tackling the mortality from long-term exposure to outdoor air pollution in megacities: lessons from the Greater Cairo case study, Environ. Res. 160 (2018) 223–231, https://doi.org/10.1016/j.envres.2017.09.028.
[59] N. Li, Z. Liu, Y. Li, N. Li, R. Chartier, A. McWilliams, D. Xu, Estimation of PM2. 5 infiltration factors and personal exposure factors in two megacities, China, Build. Environ. 149 (2019) 297–304, https://doi.org/10.1016/j.buildenv.2018.12.033.
[60] C.E. Yang, J.S. Fu, Y. Liu, X. Dong, Y. Liu, Projections of future wildfires impacts on air pollutants and air toxics in a changing climate over the western United States, Environ. Pollut. 304 (2022), 119213, https://doi.org/10.1016/j.envpol.2022.119213.
[61] N. Bruce, E. Rehfuess, S. Mehta, G. Hutton, K. Smith, Indoor Air Pollution. *Disease Control Priorities in Developing Countries*, second ed., 2006.
[62] W. Ye, X. Zhang, J. Gao, G. Cao, X. Zhou, X. Su, Indoor air pollutants, ventilation rate determinants and potential control strategies in Chinese dwellings: a literature review, Sci. Total Environ. 586 (2017) 696–729, https://doi.org/10.1016/j.scitotenv.2017.02.047.
[63] N. Zannoni, P.S. Lakey, Y. Won, M. Shiraiwa, D. Rim, C.J. Weschler, J. Williams, The human oxidation field, Science 377 (6610) (2022) 1071–1077, https://doi.org/10.1016/j.scitotenv.2022.155241.
[64] J.H. Kim, Ventilation and Filtration Control Strategy Considering Indoor and Outdoor Particle Environmental Conditions of Apartment Building, Seoul national university, Seoul, Korea, 2018. Doctoral dissertation, Ph. D. Thesis.
[65] D. Rim, J.I. Choi, L.A. Wallace, Size-resolved source emission rates of indoor ultrafine particles considering coagulation, Environ. Sci. Technol. 50 (18) (2016) 10031–10038, https://doi.org/10.1021/acs.est.6b00165.
[66] P. Azimi, D. Zhao, B. Stephens, Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin, Atmos. Environ. 98 (2014) 337–346, https://doi.org/10.1016/j.atmosenv.2014.09.007.
[67] C. Chen, W. Ji, B. Zhao, Size-dependent efficiencies of ultrafine particle removal of various filter media, Build. Environ. 160 (2019), 106171, https://doi.org/10.1016/j.buildenv.2019.106171.
[68] J. Pei, L. Ji, Secondary VOCs emission from used fibrous filters in portable air cleaners and ventilation systems, Build. Environ. 142 (2018) 464–471, https://doi.org/10.1016/j.buildenv.2018.06.039.
[69] J. Pei, W. Dai, H. Li, J. Liu, Laboratory and field investigation of portable air cleaners' long-term performance for particle removal to be published in: building and environment, Build. Environ. 181 (2020), 107100, https://doi.org/10.1016/j.buildenv.2020.107100.