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Research article

The residential application of chain recooling energy recovery ventilator system in a hot and humid climate

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ABSTRACT

The Energy Recovery Ventilator (ERV) is proven efficient for residential ventilation applications. Yet, certain drawbacks, including a more confined space due to descended ceiling, a lengthy accompanying duct system, and over-ventilation issues that result in extensive energy consumption, need to be addressed. In this study, a novel Chain Recooling Energy Recovery Ventilator (CR-ERV) system is proposed to replace the typical ERV system design to solve the shortcomings above. By conducting an experiment on a three-bedroom condo in a hot and humid climate, it was found that compared to the natural ventilation strategy, the proposed system can help reduce the mean indoor carbon dioxide (CO_2) concentration from 976 to 677 ppm and $PM_{2.5}$ concentration from 6.4 to 4.1 μg/m^3, representing a 29% and 34% reduction, respectively. From the regulatory perspective, only 64.4% of the natural-ventilated hours have a CO_2 concentration below the 1000 ppm limit per the local air quality Act. This fraction can be improved to 99% after adopting the proposed ventilation system. All these benefits come at the cost of a slight 2.3% increase in electricity consumption. In summary, the proposed system is proven efficient, and its implementation is fairly straightforward and economical; thus might be worth integrating into future residential building projects.

1. Introduction

Residential comfort has gradually attracted attention in recent years since people spend most of their time at home [1]. Among the prerequisites for a comfortable indoor environment, including thermal comfort, visual comfort, acoustic comfort, and indoor air quality (IAQ) [2], indoor air quality is arguably the most important factor since many types of pollutants have been recognized carcinogenic to Humans [3], making it a serious public health issue to suppress those pollutants to an acceptable level. State of art approaches for removing various pollutants from the air include the adsorption and filtering method, in which the former is often utilized to capture gaseous pollutants such as formaldehyde (HCHO) [4], carbon dioxide (CO_2) [5], and other volatile organic compounds (VOC) [6] while the latter is more applicable dealing with physical particles like small particulate matters with a diameter 2.5 μm or less (PM 2.5) [7]. However, these advanced but dedicated technologies mostly treat only part of the pollutants. As a result, using a ventilation system to draft in outside air to dilute indoor air pollutants remains a simple, economical yet total solution.

The major drawback of this dilution approach is that it requires a significant amount of outside air to be introduced into the building. If the weather differs from the indoor air condition, it could cause a considerable ventilation load, especially in hot and humid

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climates. Because of that, scientists were dedicated to reducing ventilation load and had proposed a variety of feasible solutions, which can be as straightforward as an occupancy schedule-based control [8] or a complicated computer vision-based approach [9]. Today, one of the most promising approaches is the energy recovery ventilator (ERV), which has been thoroughly studied, and extensive literature is readily available [10–12].

An ERV is essentially a heat exchanger, and the following scenario might help explain its working principle. On a hot and humid day, when a certain amount of high-enthalpy outside air is introduced into the building as the makeup air, the same amount of low-enthalpy indoor air must be exhausted simultaneously. Suppose both air streams can be guided through a heat exchanger and make contact indirectly. In that case, the enthalpy of makeup air will be lowered closer to the indoor air's enthalpy, which also means a reduced ventilation load since it is directly proportional to the enthalpy difference between makeup and indoor air.

Although ERV was proven an energy-efficient solution while maintaining acceptable indoor air quality in residential applications [13,14], several drawbacks do exist, and trade-offs must be made when installing such a system. One of the major drawbacks is that its installation consumes a considerable amount of ceiling height. Since ceiling height is a factor of people's beauty judgments on a room space [15] and a higher ceiling benefits occupants' ability to perform freedom thinking [16], it can be considered a precious asset, especially in units of a condominium building. Unfortunately, to accommodate an ERV and its accompanied enormous supply and return duct systems, the entire ceiling of the dwelling usually has to be lowered by 300–500 mm depending on different ERV models and duct configurations, resulting in a more confined atmosphere.

On the other hand, the typical ERV's parallel air distribution system is problematic. In order to ensure a proper ventilation level of each room in a dwelling, the famous residential ventilation design guide ASHRAE 62.2, published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), clearly states that "air shall be supplied to or returned from all rooms in the habitable space through an air-handling system" [17]. As a result, an ERV is usually designed to supply fresh air to each zoom with a pre-defined allocation ratio based on assumptions made on certain room types (i.e., two occupants in the master bedroom and an additional occupant for each extra bedroom by default [18]). However, occupants in a dwelling are far from stationary but move randomly; the fixed ventilation allocation thus inevitably causes over-ventilation for specific rooms in a particular period. A vivid example is that when the whole family gathers in the living room throughout the holiday, a large amount of fresh air is still delivered to unoccupied bedrooms and then wastefully exhausted. Even though workable solutions like multi-zone demand control ventilation are readily available and applied in commercial buildings [19–21], they are less practically implemented in budget-driven residential projects due to their cost and control complexity.

In order to address the issues mentioned above, the previously proposed "chain recooling system" concept [22] is taken to a residential application in this study. For a three-bedroom condo example illustrated in Fig. 1, the installation scheme of a typical ERV and an ERV coupled with a chain recooling system (CR-ERV) can be illustrated in Figs. 2 and 3, respectively. It can be found that the significant difference between these two systems is the air distribution logic. For example, for a typical ERV, the air is supplied to and exhausted from each room in parallel. In a chain recooling ERV, all rooms are sequenced, and the fresh air exit the ERV is instead delivered to only the first room (the main bedroom in this example); then, a booster fan redirects air of the first room through a duct to the second room, and so on. Finally, the last room's (the living room) air is pulled into the ERV and then exhausted after the energy recovery process.

As can be observed in Fig. 2, a typical ERV must be deployed at the center of a dwelling to ensure proper air distribution to each air-conditioned zone. Otherwise, zones closer to the ERV may receive excessive while farther zones have little to no airflow. This

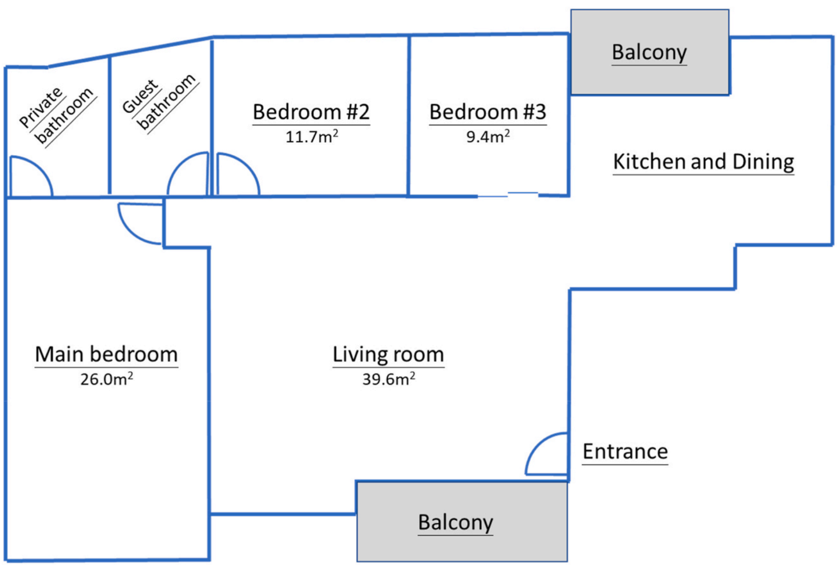


Fig. 1. Floorplan of a three-bedroom condo.

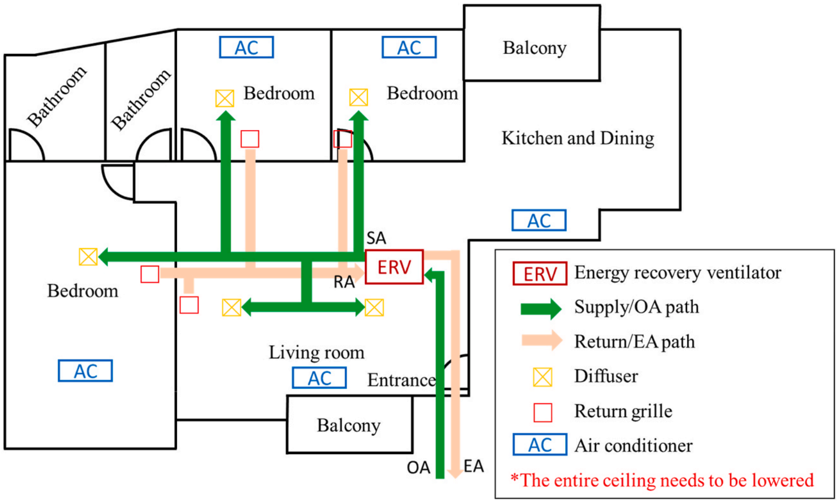


Fig. 2. Installation scheme of a typical ERV for the three-bedroom condo.

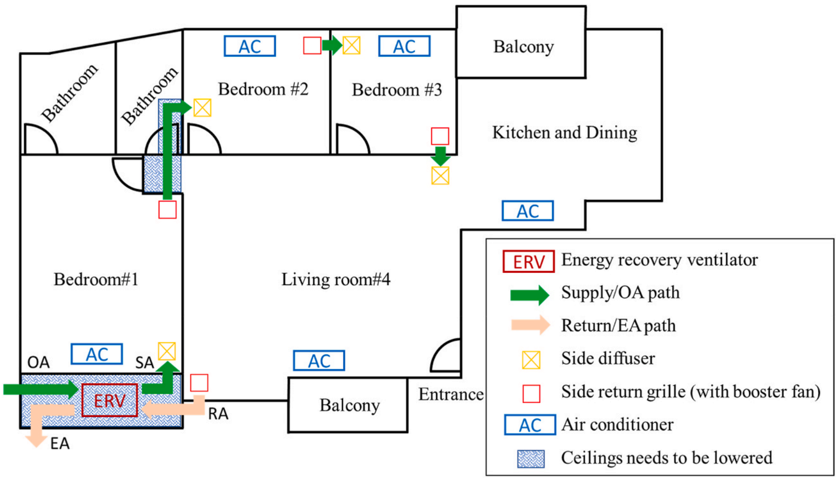


Fig. 3. Installation scheme of a CR-ERV for the three-bedroom condo.

requirement results in a huge accompanying duct system and unavoidable ceiling drop for the whole dwelling. When using the CR-ERV, as illustrated in Fig. 3, the total length of accompanied ducts can be substantially reduced. In the above-demonstrated example, the typical ERV requires more than 40 m of long ducts in total, while the CR-ERV requires less than 10 m only, representing beyond 75% reduction.

Furthermore, by applying wall-mounted side diffusers (except the one connecting the ERV for supply air flow), it is no longer required to lower the whole ceilings of the dwelling to install chain recooling ERV. Instead, just a portion of the main bedroom's ceiling where the ERV is located, a part of the guest bathroom's side ceiling, and the short aisle where the duct passes must be descended. Meanwhile, when using a chain recooling ERV, fresh air passes through each room in sequence and eventually encounters all occupants regardless of their room; thus, the over ventilation issue can be solved.

Although the new CR-ERV system seems to have many advantages, they are merely theoretical and have not yet been realized. Thus, this study aims to examine the feasibility of implementing the CR-ERV mentioned above in a condo in hot and humid climates. Meanwhile, comparisons between using the proposed CR-ERV as the ventilation system and natural ventilation through the exterior windows will be made in various aspects, including.

1. Zonal air quality differences
2. Whole-house ventilation rate
3. Power consumption differences of the air conditioners (A/C).
4. Power consumption differences from other equipment.

2. Methodology

2.1. The experiment site condo description

In order to evaluate the effectiveness of the proposed CR-ERV system, a three-month-long experiment was conducted in the Summer of 2021 in an experiment site condo. The condo has roughly 120 square meters and is in a hot and humid climate in Taoyuan, Taiwan. The condo's layout is three bedrooms, two bathrooms, one living, and one dining room. Each room is equipped with a dedicated air conditioner, except for the two bathrooms. The cooling capacity of those air conditioners is rated at 2.2 kW, except the one in the living room, rated at 4. 6 kW. The operating schedules of the air conditioners, including the temperature set-points of all rooms, remain unchanged during the entire experiment. The two bathrooms have exhaust fans which are activated only when occupied. Because occupants spend a very limited time in a bathroom within a day, exhaust fans' effect is neglected. The floor plan of the condo consisting of each air conditioner's location is illustrated in Fig. 1.

An aforementioned "CR-ERV" system, consisting of an energy recovery ventilator (VEB150AT, Delta, rated 80/110/150 CMH at low/medium/high speed mode), six-inch round ducts, and booster fans (VFA15AXP, Delta, rated 100/160 CMH at low/high speed mode), is installed per Fig. 3 in the condo lived in by a small family of three, including young parents and a pre-kindergarten child. Before the experiment, the participants signed an informed consent to confirm that they understood the study procedure and that the result might be published in the future. The male parent is an engineer in a science park, and the female parent is a housewife. To avoid bothering the household with a complicated experiment process, a simplified "one week on, one week off" cyclic scheme is adopted throughout the experiment period. During the "system-on week," the CR-ERV system remains online 24/7 in high-speed mode, and the condo owner is instructed to close all known exterior doors/windows. In contrast, the system remains offline throughout the "system-off week" while the owner is told to "open as many windows you feel comfortable with just like before." Lastly, the owner is instructed to operate all the air-conditioners according to the same habit as usual during the entire experiment period.

It is worth mentioning that Taiwan was suffering a COVID-19 case outbreak during the experiment period, so the male parent worked mostly from home at that time. According to the male parent's self-description of daily living time, he frequently stays in the

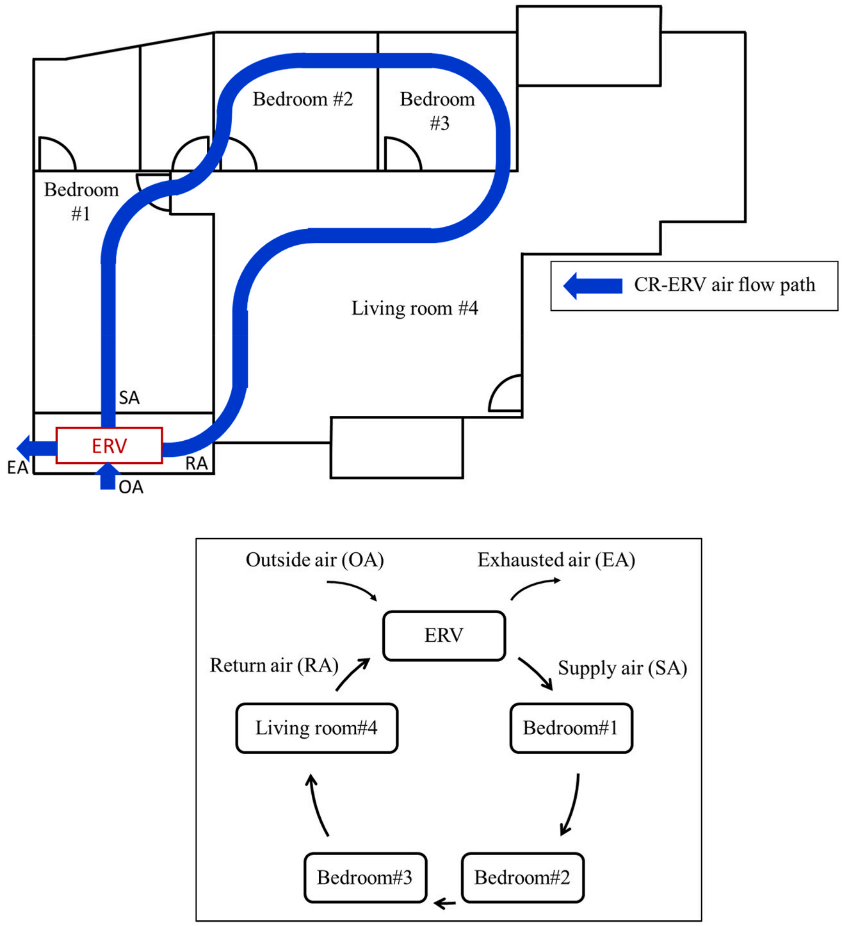


Fig. 4. The airflow path of the CR-ERV system.

living room till late night or even early morning before going to sleep in bedroom #1, sometimes for attending international conference calls and sometimes for entertainment activities. In addition, the child plays around in the house during the daytime and usually sleeps around 10:00 p.m. with the female parent in bedroom #2. Bedroom #3 is the storage room, except for a corner used as a playground.

The four occupied zones (three bedrooms and one living room) are arranged in the following order: main bedroom (BR#1), kid's bedroom (BR#2), study room (BR#3), and lastly, the living room (LIV#4). The installed ERV brings all outside air directly into the main bedroom, then the same amount of air is guided through all occupied zones sequentially using ducts and booster fans, as illustrated in Fig. 4.

In each of the occupied zones, the concentration of carbon dioxide and particulate matter with a diameter of 2.5 μm or less (PM 2.5) is selected to represent air quality and recorded continuously once per 3 min using pre-calibrated air quality sensors (PTQS-1005, Plantower, CO_2 accuracy ±50 ppm + 5% of reading, PM 2.5 accuracy ±10% μg/m^3) deployed per Fig. 5. Meanwhile, a 24-channel multi-loop power meter (AEM-DRA, Adtek, current measuring accuracy ±0.2%) with current transformers (OPCT10AL, Nanjing UP Elec., max current 10 A, accuracy ±0.5% F.S.) is installed in the distribution board to measure the power consumption of each electricity loop, including lighting, receptacle, air conditioner (A/C), and an independent loop for the CR-ERV system. The detailed power meter channel assignment is summarized in Table 1.

2.2. Projection of the whole-house average ventilation rate

Measuring the ventilation rate becomes challenging when adopting the natural ventilation strategy through windows. Thus, the whole-house average ventilation rate is projected from the average CO_2 concentration using the steady-state mass balance equation [17]:

$$Q_o = \frac{G}{C_{in} - C_{out}} \tag{1}$$

The occupants' total CO_2 generation rate G is determined by the sum of each occupant's own CO_2 generation rate V_{CO_2}:

$$G = \sum_i (V_{CO_2})_i \tag{2}$$

A more recently published method is then adopted to calculate the individual CO_2 generation rate V_{CO_2} of each occupant [23]:

$$V_{CO_2} = 0.000179 \bullet BMR \bullet M \bullet \frac{T}{P} \tag{3}$$

$$BMR = \begin{cases} 0.085m + 2.033, \textit{for the child (female, age } 3 \sim 10) \\ 0.034m + 3.538, \textit{for the female parent (age } 30 \sim 60) \\ 0.048m + 3.653, \textit{for the male parent (age } 30 \sim 60) \end{cases} \tag{4}$$

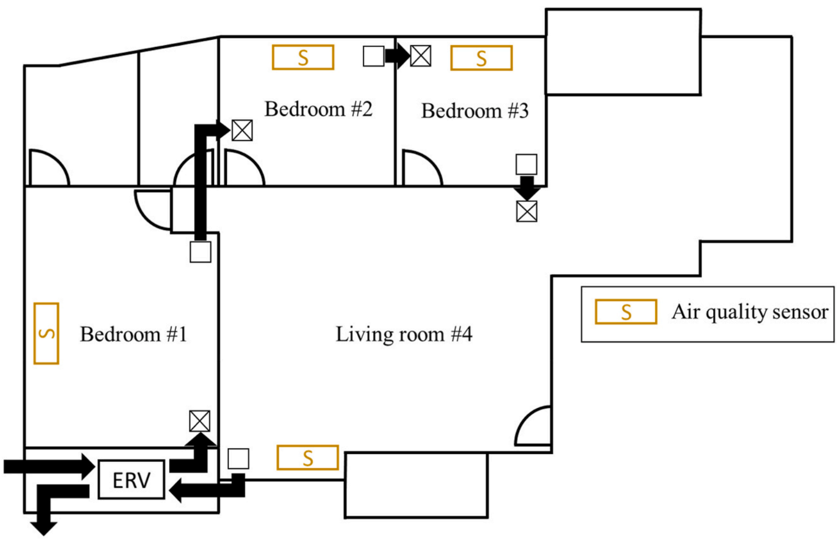


Fig. 5. Locations of the air quality sensors.

Table 1
Channel assignment of the 24-channel multi-loop power meter.

ID	Description	ID	Description
A1	ERV for the CR-ERV system	B1	Lighting load of the living room #4 and bedroom #1
A2	No use	B2	Lighting load of other zones
A3	Booster fans for the CR-ERV system	B3	Toilet fan heater
A4	Kitchen island receptacle load	B4	Kitchen receptacle load
A5	Bathroom receptacle load	B5	Kitchen appliance cabinet A
A6	Living room #4 AC	B6	Kitchen appliance cabinet B
A7	Bedroom #1 AC	B7	Kitchen appliance cabinet C
A8	Bedroom #3 AC	B8	Kitchen appliance cabinet D
A9	Bedroom #2 AC	B9	Living room #4 receptacle load
A10	Dining room AC	B10	Dining room receptacle load
A11	Bedroom #3 receptacle load	B11	Bedroom #2 receptacle load
A12	Pumping motor	B12	Bedroom #1 receptacle load

$$M=\begin{cases} 0.95, \textit{Sleeping} \\ 1\sim 1.3, \textit{Lying or sitting quietly} \\ 1.3, \textit{Sitting reading, writing, typing} \\ 1.5, \textit{Sitting tasks, light effort (e.g, office work)} \\ 2\sim 3, \textit{Child care} \\ 3.3, \textit{kitchen activities} \\ 3.8, \textit{Cleaning, sweeping—moderate effort} \\ 8.0, \textit{Calisthenics—vigorous effort} \end{cases} \tag{5}$$

Estimating the average level of physical activity M can be challenging since the occupants' daytime activities were not monitored due to privacy concerns. However, per the male parent's description, all family members, including himself, are likely sleeping during 4:00–9:00 a.m., and a fairly stable CO_2 concentration was indeed found during that period. Thus, the average ventilation rate will be determined by the average CO_2 concentration during 4:00–9:00 a.m. with an assumption of $M = 0.95$. In the meantime, the indoor temperature and absolute pressure are assumed to be constant at 298 K (25 °C) and 101.3 kPa, respectively. Finally, the body mass of the male parent, female parent, and child are told to be 80, 55, and 15 kg, respectively.

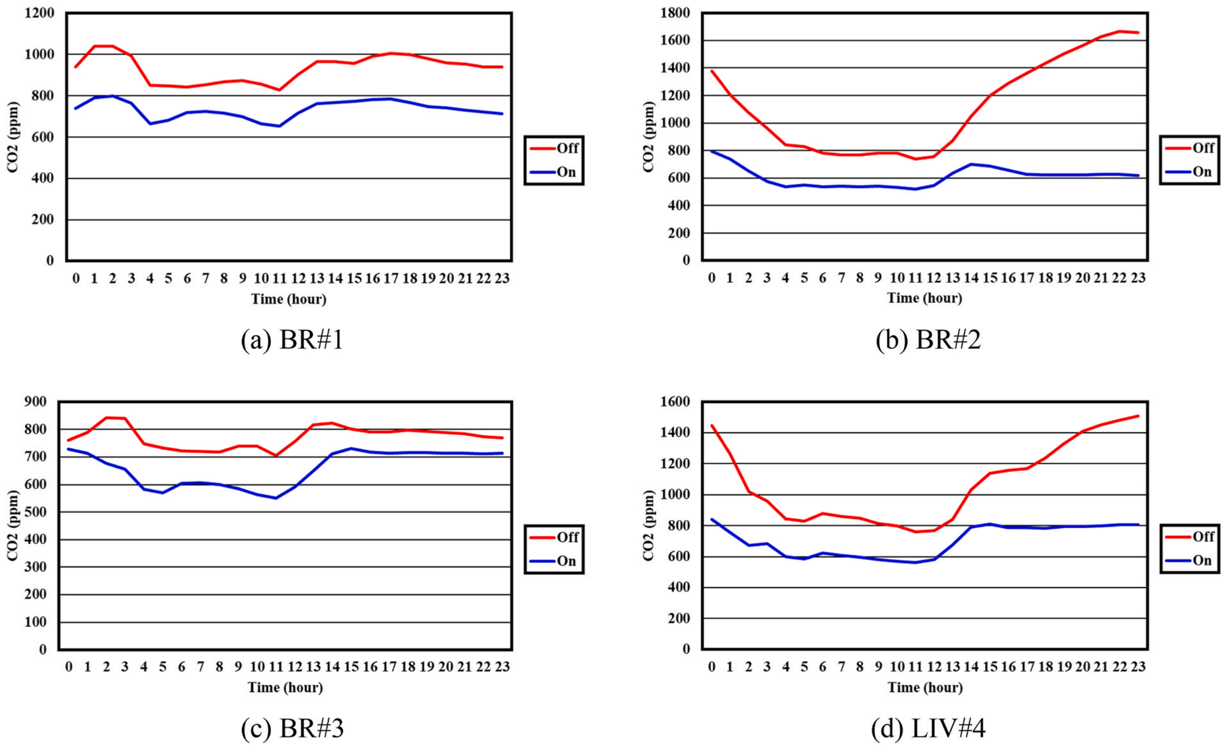


Fig. 6. The hourly average CO_2 concentration difference in each monitored zones between the CR-ERV system on and off periods. (a) BR#1, (b) BR#2, (c) BR#3, (d) LIV#4.

3. Results and discussions

3.1. The air quality analysis

The hourly average CO_2 concentration differences in each monitored zones between the CR-ERV system on and off periods are summarized in Fig. 6 (6a for BR#1, 6b for BR#2, 6c for BR#3, and 6d for LIV#4, respectively). An overall decline in CO_2 concentration can be observed in the figure when the CR-ERV system is switched on. The declines are particularly noticeable in BR#2 and LIV#4 at night, showing that the CR-ERV system effectively suppresses CO_2 concentration in occupied rooms (per the owner's description, BR#2 and LIV#4 are the most occupied zones at night times). With few exceptions, the average hourly CO_2 concentrations can be kept below 800 ppm in all monitored zones when the CR-ERV system is switched on but exceed 1600 ppm (BR#2, 22:00–23:00) when it is turned off.

Statistical results of the same data are summarized in Table 2. It can be found that the mean CO_2 concentration reductions range from 15% (BR#3, storage room) to 46% (BR#2, kid's bedroom), 29% on average. The results comply with the expectations that the reductions should be rather significant in more occupied zones than in less occupied zones. Still, it is somehow surprising that the main bedroom (BR#1) seems rarely occupied, like the storage room. Meanwhile, it can also be observed that a significant reduction in the standard deviation of zonal CO_2 concentration occurs when the system is on, indicating that the CR-ERV system can help maintain the CO_2 concentration at a more consistent level compared to the natural ventilation strategy. Similar conclusions can be made by looking into the maximum CO_2 concentration. For example, when the CR-ERV system is turned off, the living room CO_2 concentration can go up to 3404 ppm. However, it falls to only 2004 ppm after the system is switched on, representing a 41% reduction. On the other hand, the minimum CO_2 concentration is less affected by the CR-ERV system, and the reductions range from 2.7% (LIV#4) to 13% (BR#3) in different zones. However, the minimum CO_2 concentration differences are within the 12–54 ppm range, which is within the error margin per the sensors' specifications. In terms of the zonal CO_2 fluctuation range, defined as the maximum minus minimum observed CO_2 concentration of each zone, the reductions are found to be from 5.4% (BR#2) to 47% (LIV#4).

Most of the results mentioned above do comply with the expectations. For example, the minimum CO_2 concentration should occur when no one is home, so there is little difference with or without mechanical ventilation at that time. On the other hand, the natural ventilation rate is known as strongly dependent on unstable wind conditions [24], while the CR-ERV system can provide a rather consistent ventilation rate. As a result, the maximum and standard deviation of CO_2 concentration are both significantly reduced when the system is on. A rather surprising result is that there is only a 5.6% reduction in maximum CO_2 concentration for BR#2 when the system is switched on. After checking the raw data, there is a fluke in the CO_2 concentration records for BR#2. A possible explanation is that the room was temporarily overcrowded, and the ventilation rate of the CR-ERV system was insufficient to suppress the increasing CO_2 concentration within that short period.

The comparison in hourly average CO_2 concentration difference between monitored zones during the CR-ERV system on and off periods are summarized in Fig. 7(a) and Fig. 7(b), respectively. It can be found that when the system is turned off, the zonal CO_2 concentrations significantly depend on the usage schedule and ranges from 500 to 1700 ppm. During the daytime, all of the zonal concentrations are relatively close. However, the CO_2 concentration of BR#2 and LIV#4 rise significantly compared to others in the nighttime; this result complies with the known room usage that the family members tend to stay in these two rooms at night. When the CR-ERV system is switched on, all the CO_2 concentrations can be kept at a fairly consistent level, mostly ranging from 500 to 800 ppm.

It is worth mentioning that since the ventilation flow of the CR-ERV system passes the zones sequentially, the back zones are expected to have a worse air quality (higher CO_2 concentration) than the front zones. Per Fig. 7(b), the zonal CO_2 concentration rankings do coincide with the zone order except BR#1, which is expected to have the lowest CO_2 concentration level but instead among the top two highest concentrations most of the time. Since all CO_2 sensors were pre-calibrated by the standard gas in the same controlled environment, and after swapping the sensors, the one being deployed into the main bedroom still shows a similar result, it was presumed due to the interference issue in the main bedroom. It is worth mentioning that during the experiment, the owner reported a perceptible odor only in the main bedroom (BR#1) and asked if it was caused by the CR-ERV system. After investigation, it is confirmed that the odor comes mainly from the main bedroom toilet, which is long after identified due to certain retrofitting issues. As a result, the unknown gas is suspected to be the source of both odor and CO_2 interference.

Similarly, the hourly average $PM_{2.5}$ concentration differences in each monitored zones between the CR-ERV system on and off periods are summarized in Fig. 8 (8a for BR#1, 8b for BR#2, 8c for BR#3, and 8d for LIV#4, respectively). It can be found that with few exceptional hours, switching on the CR-ERV system results in a lower $PM_{2.5}$ concentration than the natural ventilation strategy.

Table 2
Statistical results of hourly zonal CO_2 concentration during the CR-ERV system on and off periods.

Statistical results of CO_2 concentration (ppm)	BR#1			BR#2			BR#3			LIV#4		
CR-ERV mode	Off	On		Off	On		Off	On		Off	On	
Mean	932.3	734.2	−21%	1120	610.1	−46%	772.8	660.2	−15%	1077	703.8	−35%
Median	922	735	−20%	1041	579	−44%	759	666	−12%	971	701	−28%
Standard Deviation	185.2	111.1	−40%	418.6	193	−54%	151.3	115.4	−24%	398.8	145	−64%
Maximum	1583	1193	−25%	2810	2652	−5.6%	1346	1043	−23%	3404	2004	−41%
Minimum	459	434	−5.4%	420	390	−7.1%	418	364	−13%	437	425	−2.7%
Fluctuation range (Max. – Min.)	1124	759	−33%	2390	2262	−5.4%	928	679	−27%	2967	1579	−47%

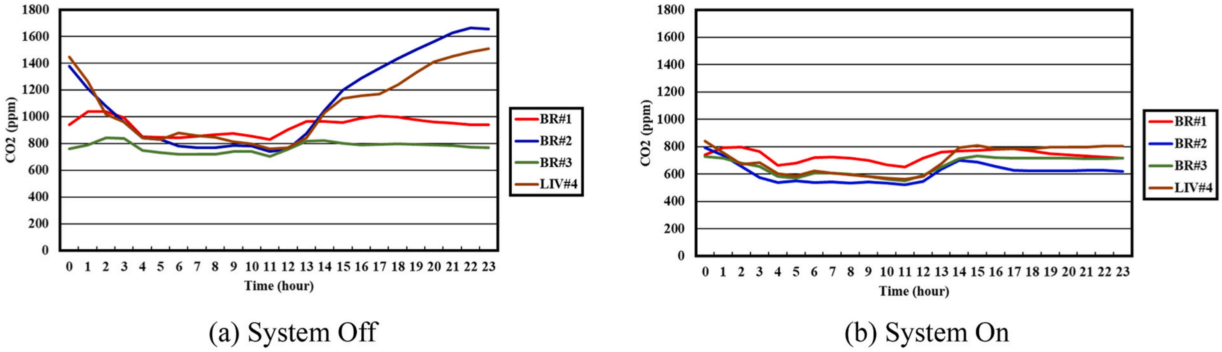


Fig. 7. The hourly average CO_2 concentration difference in each monitored zones between the CR-ERV system on and off periods. (a) System Off, (b) System On.

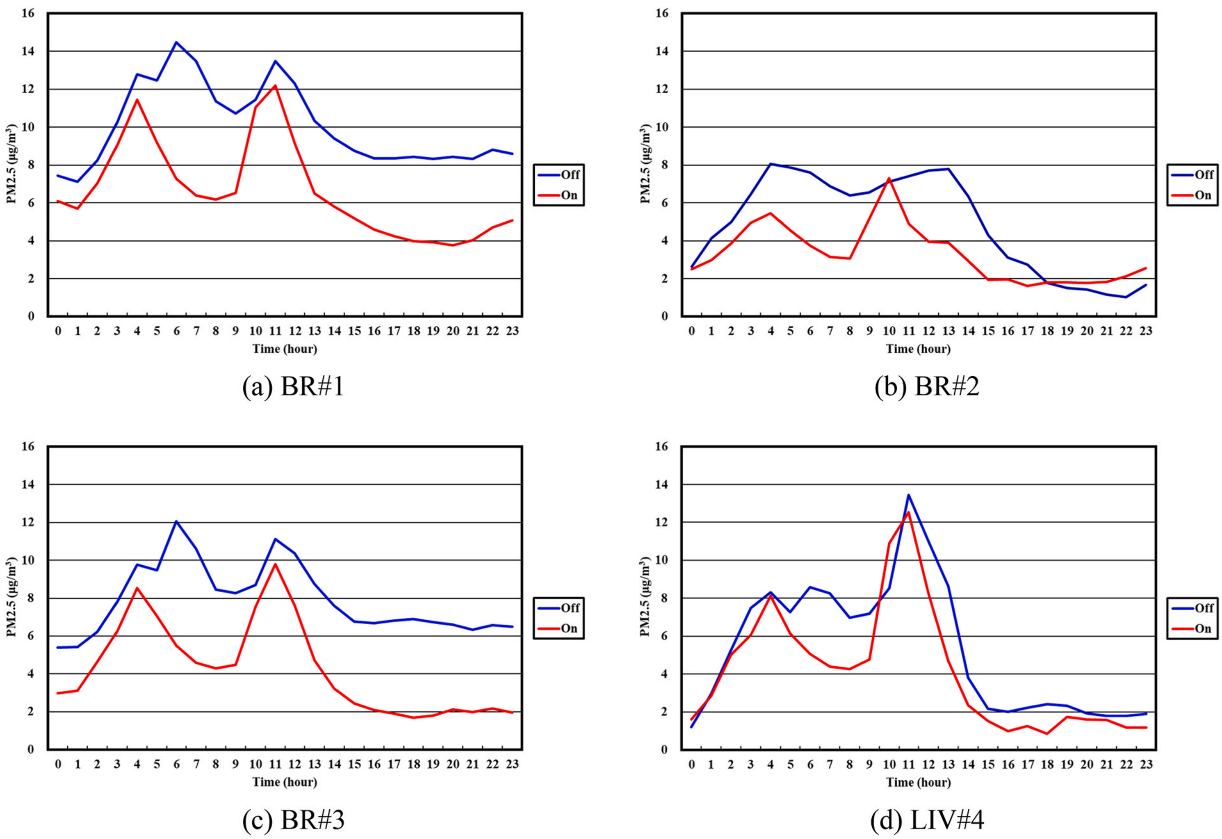


Fig. 8. The hourly average $PM_{2.5}$ concentration difference in each monitored zones between the CR-ERV system on and off periods. (a) BR#1, (b) BR#2, (c) BR#3, (d) LIV#4.

Meanwhile, it can also be observed that the kid's room (BR#2) has a relatively lower $PM_{2.5}$ concentration compared to other zones. However, it was due to the fact confirmed by the owner that there is a supplementary air purifier working continuously in the room to enhance the air quality to protect the kid's health. Another interesting finding is that all the zones have their $PM_{2.5}$ concentration peak at around 10–11 a.m. A possible explanation is it's the time frame in which the family members woke up, and a previous study had demonstrated that bedding-related activities could temporarily cause a significant PM2.5 concentration rise [25].

In order to investigate the effect of the background (outdoor) $PM_{2.5}$ concentration, the hourly outdoor $PM_{2.5}$ concentrations during the experiment period obtained from the Environmental Protection Administration (EPA) of Taiwan are compared with the hourly whole-house average in Fig. 9(a) and Fig. 9(b). It can be observed that although the system-on periods do have a lower background $PM_{2.5}$ concentration, the concentration reductions are more significant than the system-off period. Similar conclusions can also be made when looking into the statistical results of the zonal $PM_{2.5}$ concentrations summarized in Table 3, where the mean $PM_{2.5}$

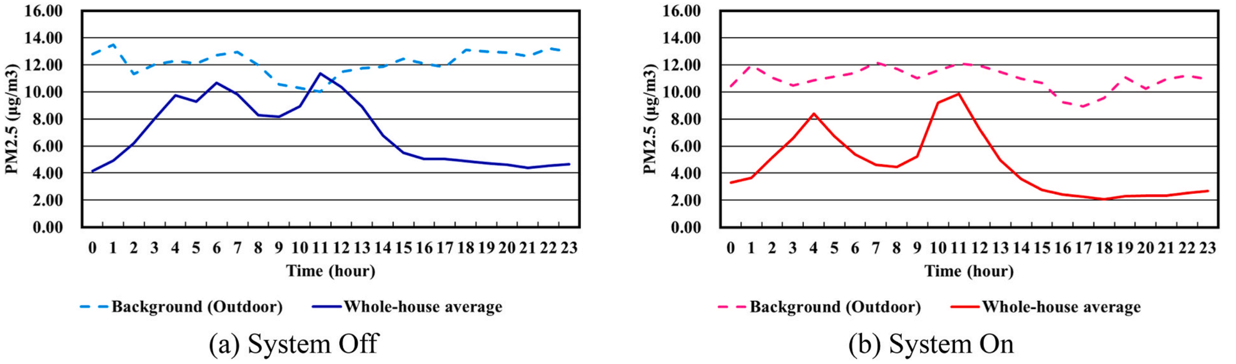


Fig. 9. The hourly background (outdoor) versus whole-house average $PM_{2.5}$ concentration in the CR-ERV system on and off periods. (a) System Off, (b) System On.

Table 3
Statistical results of hourly zonal $PM_{2.5}$ concentration during the CR-ERV system on and off periods.

Statistical results of $PM_{2.5}$ concentration ($\mu g/m^3$)	BR#1			BR#2			BR#3			LIV#4		
CR-ERV mode	Off	On		Off	On		Off	On		Off	On	
Mean	9.38	6.15	−34%	4.42	3.08	−30%	7.35	3.82	−48%	4.46	3.46	−22%
Median	7.77	5.38	−31%	3.56	2.27	−36%	5.79	2.76	−52%	2.76	1.68	−39%
Standard Deviation	5.54	3.81	−31%	3.97	2.97	−25%	4.86	3.33	−31%	5.24	4.1	−22%
Maximum	30.14	20.32	−33%	16.79	17.42	4%	25.96	15.89	−39%	26.3	20.5	−22%
Minimum	0.96	0.35	−64%	0.01	0	−100%	0.28	0.01	−96%	0	0	N/A
Fluctuation range (Max. – Min.)	29.2	20	−32%	16.8	17.4	4%	25.7	15.9	−38%	26.3	20.5	−22%

concentration reduction range from 22% (LIV#4) to 48% (BR#3), 34% on average after the system is switched on. The minimum $PM_{2.5}$ concentrations of zones are all approximately zero with or without the system, so the reduction percentages are trivial. One interesting finding is that the maximum $PM_{2.5}$ concentrations of BR#2 during the system on and off periods are essentially the same, which can be explained again by the supplementary air purifier in the kid's room. In general, these results are as expected since most makeup air will be filtered by the built-in High-Efficiency Particulate Air (HEPA) filter of the ERV when the system is on, but rather by the mosquito window screens with extra-large pores and poor filtering performance when adopting the natural ventilation through the windows.

From the regulatory perspective, the percentage of hours meeting the pollutant concentration standard per the local indoor air quality control Act [26]. during the CR-ERV system on and off periods are summarized in Table 4. Regarding CO_2 concentration, the percentage of hours meeting the standard ranges from 47% to 91.6%, depending on the zone usage rate. It makes sense since a less occupied zone would have a lower CO_2 load and more likely meets the standard without mechanical ventilation. When the CR-ERV system is on, the percentage of hours is improved to at least 98.5% for all zones, indicating that the system can help control the indoor CO_2 concentration more effectively than the natural ventilation strategy. On the other hand, all experiment hours have a $PM_{2.5}$ concentration below the standard regardless of the system status.

3.2. The projected ventilation rate

As mentioned in the methodology section, the whole-house ventilation rate will be projected using the average CO_2 concentration of the house from 4:00 to 9:00 a.m., which is found to be 806 and 608 ppm for the system off and on period, respectively. By plug-in these values into equations (1)–(5), the projected average ventilation rate is summarized in Fig. 10. It can be found that when the CR-ERV system is switched on, the ventilation rate is projected as 140.34 CMH, which is slightly less than the rated value in the specification of the ERV (150 CMH). By taking into account the friction losses, the result is fairly reasonable. It can also be found that when adopting the natural ventilation strategy, the average ventilation rate was basically cut in half. However, it has to be noted that the results are valid only from 4:00 to 9:00 a.m. In summer, these are the hours when the indoor-outdoor temperature difference becomes relatively small, leading to a weaker stack effect that is considered one of the driving forces of natural ventilation [27]. As a result, the natural ventilation rate is expected to be higher in other periods.

The 24-h variation of whole-house average CO_2 concentration is plotted in Fig. 11. By looking at the blue line (system on) first, two transitional and two stable periods can be observed clearly. Here the transitional periods are denoted as T1 (0:00 to 4:00) and T2 (10:00 to 14:00), while the stable periods are marked as S1 (4:00 to 10:00) and S2 (14:00 to 23:00), respectively. The gradually declined trend of CO_2 concentration in the first transitional period, T1, is as expected since the occupants should be prone to go to bed when the time gets closer to late night. Meanwhile, it can be found that the lowest CO_2 concentration occurs in the T2 period at 11:00 because the male or female parent usually goes out starting at this time to bring back lunch for the whole family. Sometimes the entire

Table 4
The percentage of hours meeting the pollutant concentration standard during the CR-ERV system on and off periods.

	BR#1	BR#2	BR#3	LIV#4	Average
Hours of CO_2 below 1000 ppm (System Off)	66.4%	47%	91.6%	52.7%	64.4%
Hours of CO_2 below 1000 ppm (System On)	99%	98.5%	99.7%	98.6%	99%
Hours of $PM_{2.5}$ below 35 μg/m^3 (System Off)	100%	100%	100%	100%	100%
Hours of $PM_{2.5}$ below 35 μg/m^3 (System On)	100%	100%	100%	100%	100%

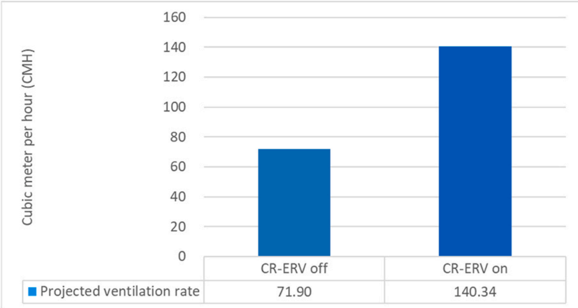


Fig. 10. The projected whole-house average ventilation rate during the CR-ERV system on and off periods (from 4:00 to 9:00 a.m.).

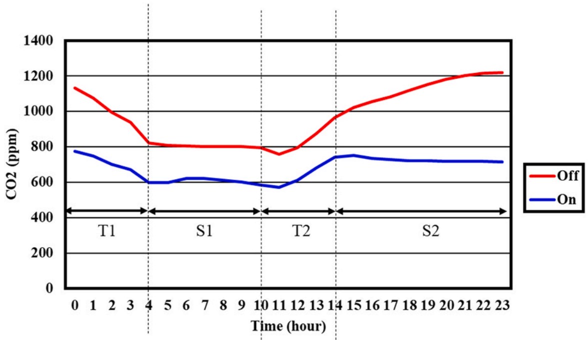


Fig. 11. The 24-h variation of whole-house average CO_2 concentration during the CR-ERV system on and off periods.

family will go out for lunch and grocery shopping and return home late, which explains the transitional CO_2 concentration from 10:00 to 14:00 since the occupants are not always at home during this period.

Understandably, the CO_2 concentration will remain stable if both the level of physical activity of the occupants and the ventilation rate are approximately constant, which is the case from 4:00 to 10:00 since family members mostly sleep during this period while the CR-ERV system provides a fixed ventilation flow rate. On the other hand, the same stable trend that occurred on the blue line from 14:00 to 23:00 is somehow interesting; it basically suggests that when the occupants are awake and all at home, the hourly average

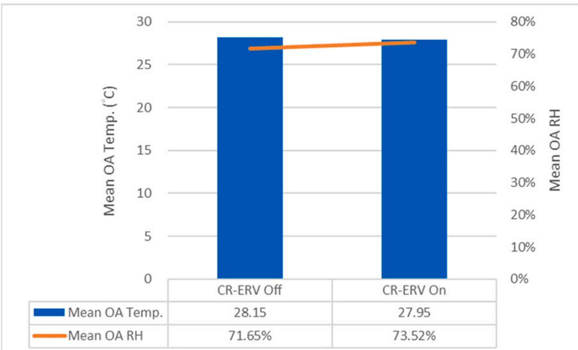


Fig. 12. The comparison of mean outdoor temperature and relative humidity during the CR-ERV system on and off periods.

level of physical activity is approximately the same. However, on the contrary, the red line (system off) during the same period S2 does not remain stable but gradually moves upwards. This behavior can be explained by the fact that while the level of physical activity supposes to be constant, just like when the system is on, the natural ventilation rate might decrease gradually since the indoor-outdoor temperature difference will be progressively smaller from 14:00 to 23:00 in the summertime.

3.3. The power consumption analysis

Before performing the power consumption analysis, the outdoor temperature and relative humidity during the CR-ERV system on and off periods, gathered from the Central Weather Bureau of Taiwan, are compared in Fig. 12. The mean OA temperature and relative humidity differences between the system on and off periods are small that do not exceed 0.2 °C and 2%, respectively. It indicates the influence of weather conditions on the air-conditioners' power consumption can be considered negligible.

The average power consumption of each electrical loop during the CR-ERV system on and off periods is summarized in Fig. 13. All the air conditioners consume less power when the CR-ERV system is switched on, except the one in the dining room, which is not on the airstream loop of the system. It can also be observed that the ERV (channel A1) still consumes a little electricity when being switched off and in standby mode. Meanwhile, the categorical power consumption is outlined in Fig. 14. It can be found when the system is on, the power consumption of other equipment remains essentially the same, the power consumption of the A/Cs drops by approximately 28 W, but the CR-ERV system itself consumes an additional 55 W on average. As a result, the overall power consumption rises to 1174 W, 2.3% higher than the system-off period. The power reduction on the A/C loops indicates that the ERV works as expected so that even if the ventilation rate is substantially increased, the ventilation load is, on the contrary, reduced due to heat recovery.

3.4. Potential drawbacks of the CR-ERV system

Although the proposed CR-ERV system has considerable advantages over a typical ERV system, there is still some drawback worth discussing. The major drawback is that if the air in the front zones is highly polluted, it will be delivered to the next several zones on the same chain. On the other hand, a typical ERV system does not have this issue since all zones are parallelly ventilated. Thus, the order of zones should be carefully decided to minimize this issue. In this study, the living room is arranged in the back, following all bedrooms exactly because occupants typically eat in the living room rather than in the bedroom.

4. Conclusions

In this study, a novel "Chain Recooling Energy Recovery Ventilator" (CR-ERV) is proposed and implemented in a three-bedroom condo in a hot and humid climate. In a three-month-long experiment held during the summer season, it was found that compared to the natural ventilation strategy, the proposed system brings around 140 CMH of ventilation flow on average, which is about twice as much as the 72 CMH of natural ventilation during the night hours. The significantly larger ventilation rate helped reduce the mean indoor CO_2 concentration from 976 to 677 ppm and $PM_{2.5}$ concentration from 6.4 to 4.1 μg/m^3, representing a 29% and 34% reduction, respectively. From the regulatory perspective, only 64.4% of the natural-ventilated hours have a CO_2 concentration below the 1000 ppm limit per the local air quality Act. This fraction can be improved to 99% after adopting the proposed ventilation system, and all these benefits come at the cost of a slight 2.3% increase in electricity consumption.

Compared to a typical residential ERV with a parallel air distribution system, the proposed CR-ERV has a serial air distribution system that brings considerable advantages, including more space available for occupants, shorter duct length, and the elimination of over-ventilation. Furthermore, the proposed system's implementation is fairly straightforward and economical and thus might be worth integrating into future residential building projects.

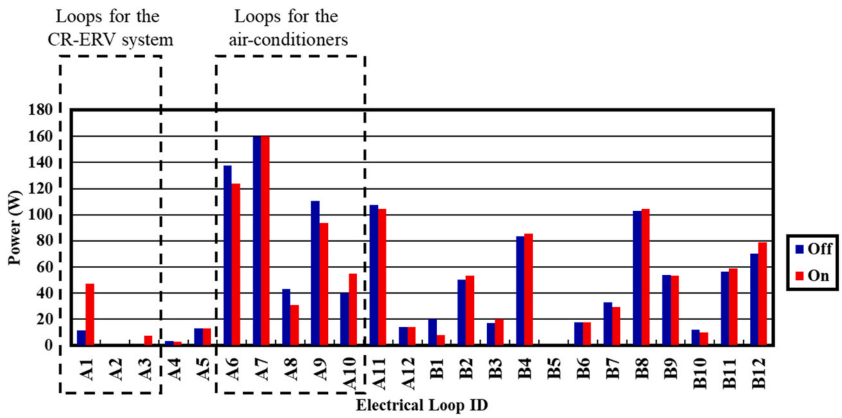
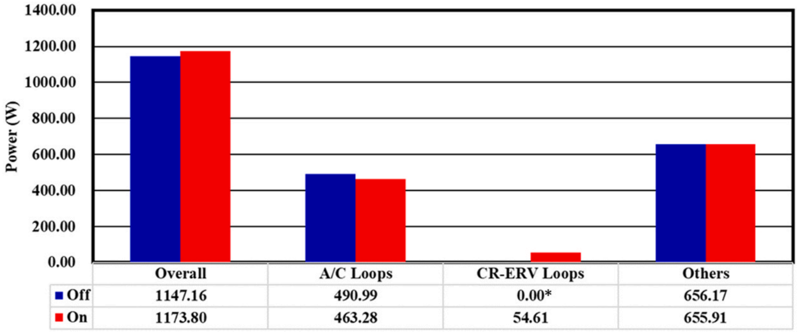


Fig. 13. The average power consumption of each electrical loop during the CR-ERV system on and off periods.



*The standby power consumption of the CR-ERV system is removed for the sake of fairness

Fig. 14. The categorical power consumption during the CR-ERV system on and off periods.

Author contribution statement

Hwa-Dong Liu: Analyzed and interpreted the data; Wrote the paper.
Ping-Hsun Shen: Performed the experiments.
Wei-Jen Chen: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

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.

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Nomenclature

BMR	Basal metabolic rate (MJ/day)
C_{in}	Indoor CO_2 concentration (ppm)
C_{out}	Outdoor CO_2 concentration (assumed a constant 400 ppm)
G	The occupants' total CO_2 generation rate (L/s)
M	Level of physical activity (met)
m	Body mass of the occupant (kg)
P	Indoor absolute pressure (kPa)
Q_o	The whole-house ventilation rate (L/s)
T	Indoor temperature (K)
$(V_{CO_2})_i$	Individual CO_2 generation rate of the ith occupant (L/s)

References

[1] T.-P. Teng, W.-J. Chen, Relative humidity sensor compensation for a portable residential refrigeration dehumidifier, Case Stud. Therm. Eng. 35 (2022), 102096, https://doi.org/10.1016/J.CSITE.2022.102096.
[2] P. Šujanová, M. Rychtáriková, T.S. Mayor, A. Hyder, A healthy, energy-efficient and comfortable indoor environment, a review, Energies (2019), https://doi.org/10.3390/en12081414.
[3] G. Sérafin, P. Blondeau, C. Mandin, Indoor air pollutant health prioritization in office buildings, Indoor Air (2021), https://doi.org/10.1111/ina.12776.
[4] B. Robert, G. Nallathambi, Indoor formaldehyde removal by catalytic oxidation, adsorption and nanofibrous membranes: a review, Environ. Chem. Lett. (2021), https://doi.org/10.1007/s10311-020-01168-6.
[5] J. Wang, Y.K. Park, Y.M. Jo, Sequential improvement of activated carbon fiber properties for enhanced removal efficiency of indoor CO2, J. Ind. Eng. Chem. (2020), https://doi.org/10.1016/j.jiec.2020.06.011.

[6] Z. Shayegan, M. Bahri, F. Haghighat, A review on an emerging solution to improve indoor air quality: application of passive removal materials, Build. Environ. 219 (2022), 109228, https://doi.org/10.1016/J.BUILDENV.2022.109228.
[7] T. Xia, C. Chen, Toward understanding the evolution of incense particles on nanofiber filter media: its influence on PM2.5 removal efficiency and pressure drop, Build. Environ. (2020), https://doi.org/10.1016/j.buildenv.2020.106725.
[8] S. Zhang, Z. Ai, Z. Lin, Occupancy-aided ventilation for both airborne infection risk control and work productivity, Build. Environ. 188 (2021), 107506, https://doi.org/10.1016/J.BUILDENV.2020.107506.
[9] S. Wei, P.W. Tien, T.W. Chow, Y. Wu, J.K. Calautit, Deep learning and computer vision based occupancy CO2 level prediction for demand-controlled ventilation (DCV), J. Build. Eng. 56 (2022), 104715, https://doi.org/10.1016/J.JOBE.2022.104715.
[10] R. Al-Waked, M.S. Nasif, D.B. Mostafa, Enhancing the performance of energy recovery ventilators, Energy Convers. Manag. (2018), https://doi.org/10.1016/j.enconman.2018.05.105.
[11] 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. (2019), https://doi.org/10.1016/j.applthermaleng.2018.11.085.
[12] R.L. Hwang, W.J. Liao, W.A. Chen, Optimization of energy use and academic performance for educational environments in hot-humid climates, Build, Environ. Times 222 (2022), 109434, https://doi.org/10.1016/J.BUILDENV.2022.109434.
[13] X. Zhong, W. Wu, I.A. Ridley, Assessing the energy and indoor-PM2.5-exposure impacts of control strategies for residential energy recovery ventilators, J. Build. Eng. 29 (2020), 101137, https://doi.org/10.1016/J.JOBE.2019.101137.
[14] W. Wei, H.M. Skye, Residential net-zero energy buildings: review and perspective, Renew. Sustain. Energy Rev. 142 (2021), 110859, https://doi.org/10.1016/J.RSER.2021.110859.
[15] O. Vartanian, G. Navarrete, A. Chatterjee, L.B. Fich, J.L. Gonzalez-Mora, H. Leder, C. Modroño, M. Nadal, N. Rostrup, M. Skov, Architectural design and the brain: effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions, J. Environ. Psychol. (2015), https://doi.org/10.1016/j.jenvp.2014.11.006.
[16] J. Meyers-Levy, Z. Rui, The influence of ceiling height: the effect of priming on the type of processing that people use, J. Consum. Res. (2007), https://doi.org/10.1086/519146.
[17] ASHRAE, ANSI/ASHRAE, Standard 62.1-2019, in: Ventilation for Acceptable Indoor Air Quality, 2019.
[18] AHSRAE, ANSI/ASHRAE, Standard 62.2-2019, in: Ventilation for Acceptable Indoor Air Quality in Residential Buildings, 2019.
[19] C. Zhuang, K. Shan, S. Wang, Coordinated demand-controlled ventilation strategy for energy-efficient operation in multi-zone cleanroom air-conditioning systems, Build. Environ. (2021), https://doi.org/10.1016/j.buildenv.2021.107588.
[20] B. Li, B. Wu, Y. Peng, W. Cai, Tube-based robust model predictive control of multi-zone demand-controlled ventilation systems for energy saving and indoor air quality, Appl. Energy (2022), https://doi.org/10.1016/j.apenergy.2021.118297.
[21] G. Jing, W. Cai, X. Zhang, C. Cui, H. Liu, C. Wang, An energy-saving control strategy for multi-zone demand controlled ventilation system with data-driven model and air balancing control, Energy (2020), https://doi.org/10.1016/j.energy.2020.117328.
[22] W.J. Chen, D.E. Claridge, J. Liao, Using a chain recooling system on buildings in hot and humid climates, Build. Environ. (2018), https://doi.org/10.1016/j.buildenv.2017.12.008.
[23] A. Persily, L. deJonge, Carbon dioxide generation rates for building occupants, Indoor Air (2017), https://doi.org/10.1111/ina.12383.
[24] W. Pan, S. Liu, S. Li, X. Cheng, H. Zhang, Z. Long, T. Zhang, Q. Chen, A model for calculating single-sided natural ventilation rate in an urban residential apartment, Build. Environ. (2019), https://doi.org/10.1016/j.buildenv.2018.08.047.
[25] Y.C. Yen, C.Y. Yang, K.D. Mena, Y.T. Cheng, C.S. Yuan, P.S. Chen, Jumping on the bed and associated increases of PM10, PM2.5, PM1, airborne endotoxin, bacteria, and fungi concentrations, Environ. Pollut. (2019), https://doi.org/10.1016/j.envpol.2018.11.053.
[26] Taiwan Government, Indoor Air Quality Control Act, 2012.
[27] V. Filis, J. Kolarik, K.M. Smith, The Impact of Wind Pressure and Stack Effect on the Performance of Room Ventilation Units with Heat Recovery, Energy Build, 2021, https://doi.org/10.1016/j.enbuild.2020.110689.