Impact of Outdoor Air Exchange Rates on Sleep Quality and the Next-Day Performance with Application of Energy Recovery Ventilator

ผลกระทบของอัตราการแลกเปลี่ยนอากาศภายในห้องต่อคุณภาพในการนอนหลับและการทำงานในวันรุ่งขึ้นจากการใช้เครื่องเติมอากาศแบบแลกเปลี่ยนพลังงาน

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Abstract

Sleep quality can affect human health and the next-day performance. High indoor CO_2 concentration levels due to insufficient supplied air ventilation could cause poor sleep quality. Bedrooms in condominium in Thailand commonly use a wall mounted split type system without supplied outdoor air ventilation. The rooms are typically constructed having airtight envelope which have air infiltration rates ranging 0.4-0.64 ACH. This study aims to evaluate the impact of increased ventilation rates on sleep quality and the next-day performance, which the surveys were collected from two occupants living in a one bedroom condominium. The field measurement and survey were conducted for twenty days with supplied outdoor airflow rates at 0, 40, and 60 $m^3\ hr^{-1}$ through an energy recovery ventilator (ERV). The room air exchange rates were calculated from a linear regression method obtained from a decay tracer gas technique using indoor carbon dioxide generated by occupants. To overcome the maximum limit of CO_2 concentration level specified in the standard health guidelines, the ERV unit has to supply outdoor air ventilation rate at 60 $m^3\ hr^{-1}$. Overall, the increase of outdoor air ventilation rates can improve sleep quality by 2-13 percent and occupants have better work performance in the next day by 2-20 percent. The increase of outdoor air ventilation through the ERV unit does not affect indoor relative humidity.

Keywords
Air Exchange Rate
Energy Recovery Ventilator
Sleep Quality
Next-day Performance
Bedroom Condominium

บทคัดย่อ

คุณภาพในการนอนหลับสามารถส่งผลกระทบต่อสุขภาพของคนและการทำงานในวันถัดไป ระดับค่าก๊าซคาร์บอนไดออกไซด์ภายในห้องที่มีค่าสูงซึ่งเกิดจากการระบายอากาศไม่เพียงพอส่งผลให้คุณภาพการนอนหลับที่แย่ ห้องพักในคอนโดมิเนียมในประเทศไทยโดยทั่วไปใช้ระบบปรับอากาศแบบแยกส่วนโดยไม่มีระบบการเติมอากาศบริสุทธิ์จากภายนอก ลักษณะห้องถูกสร้างให้มีเปลือกอาคารที่แน่นซึ่งสามารถป้องกันการรั่วซึมของอากาศจากภายนอกเข้ามายังภายในห้องได้เป็นอย่างดีโดยมีอัตราการรั่วซึมของอากาศอยู่ในช่วง 0.4–0.64 ต่อชั่วโมง งานวิจัยนี้มุ่งศึกษาการประเมินการระบายอากาศของห้องที่ส่งผลต่อคุณภาพการนอนหลับและประสิทธิภาพในการทำงานในวันถัดไปของผู้พักอาศัยจำนวน 2 คนที่อาศัยอยู่ในห้องนอนในคอนโดมิเนียม การศึกษานี้มีการวัดค่าและทำแบบสำรวจใช้เวลา 20 วัน โดยมีการปรับเปลี่ยนอัตราการเติมอากาศที่ 0 40 และ 60 ลูกบาศก์เมตรต่อชั่วโมงผ่านเครื่องเติมอากาศแบบแลกเปลี่ยนพลังงาน (ERV) อัตราการแลกเปลี่ยนอากาศของห้องถูกคำนวณโดยใช้สมการถดถอยจากอัตราการลดลงของระดับก๊าซคาร์บอนไดออกไซด์ภายในห้อง สำหรับการกำหนดอัตราการแลกเปลี่ยนอากาศของห้องให้มีค่าคาร์บอนไดออกไซด์ผ่านค่ามาตรฐานด้านสุขภาพ เครื่องแลกเปลี่ยนอากาศ (ERV) จะต้องเติมอากาศบริสุทธิ์จากภายนอกที่อัตรา 60 ลูกบาศก์เมตรต่อชั่วโมง โดยภาพรวมการเติมอากาศเข้ามาภายในห้องสามารถเพิ่มคุณภาพในการนอนหลับได้ร้อยละ 2–13 และผู้อยู่อาศัยมีประสิทธิภาพในการทำงานในวันถัดไปเพิ่มขึ้นประมาณร้อยละ 2–20 การเพิ่มอัตราการแลกเปลี่ยนอากาศโดยใช้เครื่องเติมอากาศแบบแลกเปลี่ยนความร้อนไม่ส่งผลกระทบต่อค่าความชื้นสัมพัทธ์ภายในห้อง

คำสำคัญ
อัตราการแลกเปลี่ยนอากาศ
เครื่องเติมอากาศแบบแลกเปลี่ยนพลังงาน
คุณภาพการนอนหลับ
ประสิทธิภาพในวันรุ่งขึ้น
ห้องนอนในคอนโดมิเนียม

1. Introduction

Sleep quality is generally considered to be a significant role on learning and memory function (National Institutes of Health [NIH], 2012). It is recommended that people sleep at least 8 hours/day. Less sleep could make people unhealthy and lose concentration on their daily living. Moreover, it might lead to loss of memory and cognitive ability (Slats, Claassen, Verbeek & Overeem, 2013, pp. 188-200). Lack of sleep also influences working ability, safety issues, and financial cost (Rosekind et al., 2010, pp. 91-98; Mulgrew et al., 2007, pp. 42-53). Furthermore, previous studies showed that the less sleep had positive correlation with employee productivity (Mulgrew et al., 2007, pp. 42-53). Workers who do not get enough sleep or have sleep problem usually come to work late and produce low outcome. According to Rosekind et al.'s study (2010), an individual productivity was dropped due to sleepiness, which further made the company loss an average annual cost of $1,967 per employee. According to these evidences, sleep problem is an important issue which affects physical health, productivity, as well as organization's economy.

Insufficient ventilation rate resulting in poor indoor air quality has been considered as an influential factor on poor sleep habits. Low ventilation rate leads to high indoor carbon dioxide concentration levels, which cause sleeplessness. Few studies investigated the impact of high carbon dioxide concentration due to insufficient ventilation rate on subject's sleep efficiency and ability to concentrate. The tenants who live in the environment with high ventilation rates usually feel asleep easier, get more rest, and have better mental state. These evidences show significantly greater when the ventilation rate is increased (Fisk et al., 2013; StrØm-Tejsen et al., 2014; StrØm-Tejsen et al., 2016, pp. 679-686). Fisk et al. (2013) investigated the effects of high indoor carbon dioxide concentration levels on subject's decision-making performance. Their results revealed that people who live in the condition with low carbon dioxide concentration levels had better decision-making performance for doing basic and applied activities, task orientation, initiative, and information utilization. At present, limited studies have investigated the impacts of air ventilation on indoor concentration levels that adversely affects the subject's sleep quality and their next-day performance.

Theoretically, building ventilation accounts outdoor air intake through mechanical system and unintentional airflow called air infiltration through adventitious or leaks on building envelopes. The room studio and one bedroom types in condominium in Thailand generally use a wall mounted split type air conditioning unit, which its system typically does not provide outdoor air ventilation. Consequently, the ventilation in these room types mostly relies on the air infiltration only. However, the air infiltration is not accepted to be a good air quality as defined in the ASHRAE Standard 62.1-2010 since the quality of air and amount of the air taking into the space cannot be controlled. As a consequent, such insufficient ventilation and quality of the air infiltration could lead to high concentration of indoor-generated pollutants, which further increases sick building syndrome problems in these room types.

The energy recovery ventilator (ERV) is one of solutions to enhance both quality and quantity of the outdoor air before it was supplied into the room while maintaining energy efficiency. The ERV system transfers heat and humidity of the outside air via energy transfer process, which makes the condition of the supplied outdoor air closes to the room conditions before the air is supplied into the space. Previous studies revealed that the ERV unit could save cooling energy by 18-49 percent depending on the climate conditions (Fan et al., 2014, pp. 412-422; Wang et al., 2015, pp. 47-52; Yang et al., 2015, pp. 438-445).

In summary, the existing ventilation rate from the air infiltration through leakage paths on building envelope might be insufficient to provide acceptable indoor air quality. Such significant issue could cause sleep deprivation or insomnia, which further affects subject's working ability, safety, and business's financial cost. According to the literatures, the number of field studies regarding the relationship among ventilation, indoor air quality, and sleep quality, which impact the subject's working ability are limited. Consequently, this present study aims to investigate the potential use of the ERV unit to improve indoor air quality, which could promote the better subject's sleep quality and next-day performance.

2. Research Methodology

The experiment was performed in the project's sale gallery room with an area of 10 m^2 and 2.7 m. ceiling height and two occupants had lived in a master bedroom during the test period. A 9,000 Btu wall-mounted split type air conditioning unit provides not only human thermal comfort but also the air movement in the space. The layout of the test room and the installation locations of three sets of sensors are presented in Figure 1.

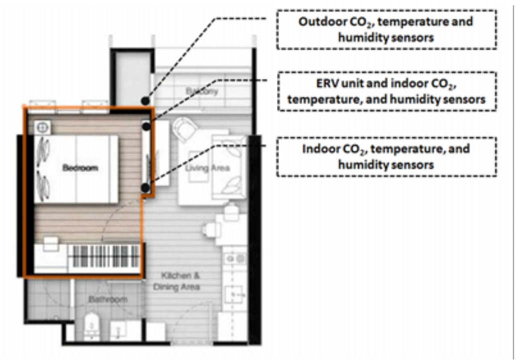


Figure 1. A layout of the test room and the installation locations of three sets of sensors.

The experiment of this study comprises of two parts as the followings:

1) To assess the air exchange rates in the test room for normal operation when the ERV unit was switched off (no outdoor air intake), and

2) To evaluate the impacts of outdoor air ventilation rates on indoor carbon dioxide concentration levels in relation to the occupant's sleep quality as well as next-day performance.

The experiment had performed for four weeks with three-step controlled ventilation: 0, 40, and 60 m^3 hr^{-1}. The schedule of controlled ventilation rates is shown in Table 1. During the test period, two male occupants were asked to perform daily activities and spend their normal lifestyle. They were asked to leave the room in the morning and come back to the room in the evening.

Table 1. Schedule of the supplied outdoor ventilation rates through the ERV unit during the test period.

Outdoor air ventilation rate ($m^3.hr^{-1}$)	1^{st} week	2^{nd} week	3^{rd} week	4^{th} week	
	Mon-Fri	Mon-Fri	Mon-Fri	Mon-Tue	Wed-Fri
0	■				■
40		■			
60			■	■	

3. Assessment of Room Air Exchange Rates

For the air exchange rate assessment, this present study chose a tracer gas decay method since it is the simplest technique and requires less instruments than other tracer gas techniques. The carbon dioxide generated by occupants was used as a tracer gas. During the test period, the gas sample, air temperature, and relative humidity were collected every five-minute interval using a HOBO MX carbon dioxide data logger, which has an accuracy of ±0.21 °C for temperature sensor, ±50 ppm for carbon dioxide sensor, and ±2% RH for relative humidity sensor. Three sets of sensors were validated by the manufactory. This present study did calibrate the sensors by placing them together and compared the results. The carbon dioxide concentration level of one sensor had lower reading so the sensor was adjusted against with two others. Two sets of sensors were installed in the room and one set of sensor was used to measure the ambient condition outside the room. One set of the indoor sensors was installed at 1.1 m to prevent high error reading from direct exposure to the occupants and another set of sensor was placed at the exhaust of the ERV unit (as shown in Figure 2).

Figure 2. Installation locations of the indoor and outdoor sensors and the ERV unit.

The regression model, Equation (1), as defined in the ASTM E741-11 (2011) was used to calculate the outdoor air exchange rates. The equation was obtained from the plot of difference between the logarithms of the initial carbon dioxide concentration level (after the occupants left the room) and final concentrations (when the carbon dioxide reached the background concentration) divided by the time period. "a" (in Equation (1)) represents a term of outdoor air exchange rate (A), ACH, in Equation (2). X is elapsed time (t), min. "b" represents the logarithmic function of the difference between the initial indoor carbon dioxide concentration ($C_{(0)}$), ppm, and the background carbon dioxide concentration ($C_{(a)}$), ppm. Y represents the logarithmic function of the difference between indoor carbon dioxide concentration at time t ($C_{(t)}$), ppm, and the background carbon dioxide concentration, ppm.

$$Y = aX+b \quad (1)$$

$$ln(C_{(t)}-C_{a}) = -At+ln(C_{(0)}-C_{a}) \quad (2)$$

$$Vbz = Rp*Pz+Ra*Az \quad (3)$$

According to the ASTM E741-11 (2011), the tracer gas decay measurement is effectively applied in the buildings, which have constant airflow rate and well-mixed condition. In order to investigate the mixing condition of the test room, the difference of indoor carbon dioxide concentration levels monitored from the two sensors was calculated. Before the sensor installation, three HOBO MX carbon dioxide data loggers were tested the consistency of the instrumentations.

The calculated air exchange rates were then compared to the calculation of required outdoor air ventilation rate *(Vbz)* (shown in Equation (3)), as defined by the ventilation rate procedure (VRP) prescribed under the ASHRAE Standard 62.1-2010. *Rp* is the minimum occupancy based ventilation rate, Ls^{-1} $people^{-1}$. *Pz* is number of people, people. *Ra* is the minimum floor area based ventilation rate, Ls^{-1} m^{-2}. *Az* is floor area, m^{2}.

4. Recommended Air Exchange Rate for the Test Room

The ventilation rate procedure (VRP) defined in the ASHRAE Standard 62.1-2010 recommends ventilation rate based on building types and functions. The floor area based ventilation rates recommended for dwelling unit is 0.6 Ls^{-1} m^{-2} and occupancy based ventilation rate is 2.5 Ls^{-1} $person^{-1}$. Besides the calculated ventilation rates based on the VRP method, this study also used the indoor air quality procedure method (IAQP) to determine the appropriate outdoor air ventilation rate, which can control indoor carbon dioxide concentration levels under the maximum limit of 1,000 ppm (NIOSH, 2002). However, the ASHRAE Std. 62.1-2010 allows the target of indoor carbon dioxide concentration levels, which should not exceed the local outdoor concentration by more than 650 ppm. The calculated air exchange rates obtained from the tracer gas measurement were used to determine the volume airflow rates when the ERV unit was switched off (Q_{OA_nor}) using Equation (4). Then the source strength (S) can be obtained from Equation (5). In order to determine the new outdoor air exchange rate which provides acceptable indoor carbon dioxide contaminant levels, it is assumed that the indoor carbon dioxide concentration levels (C_{SS}) should not exceed 1000 ppm. Consequently, Q_{OA_new} can be calculated using Equation (6).

$$ACH = \frac{Q_{OA\_nor}}{volume} \quad (4)$$

$$Q_{OA\_nor} = \frac{S}{C_{SS\_nor} - C_{OA}} \quad (5)$$

$$Q_{OA\_new} = \frac{S}{C_{SS} - C_{OA}} \quad (6)$$

5. Survey of Sleep Quality and Next-Day Performance

A questionnaire used for evaluation the occupant's sleep quality and the next day performance contains six topics including 1) personal information, 2) daily activity, 3) working performance, 4) indoor environment satisfaction, 5) sleep performance, and 6) building related illness. The survey related to personal information was conducted before the test period. Another survey asked how occupant were satisfied the indoor conditions including air temperature, humidity, air movement, lighting quality, and noise level (with five ordinal responses) in the test room and this survey had been conducted before the occupants fell asleep and after they woke up for four weeks. Regarding the survey of sleep performance, this present study used the questionnaire developed by the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989, pp. 193-213), which contains seven components regarding subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction, to evaluate the occupant's sleep quality and irritating symptoms. The sum of scores from the seven components represents how quality of sleep is. The total score greater than 5 (> 5) means poor sleep quality.

In this present study, the survey data on Sunday night was not used in order to allow the occupants could adapt themselves to the room environment. Only the survey data collected from Monday night to Friday morning was used for analysis. Each survey took 3 to 5 minutes to complete.

6. Results

Figure 3 presents the outdoor and indoor carbon dioxide concentration levels when the ERV unit was turned off and the shaded area on the figure represents the time period when the occupants lived in the room. When the bedroom was unoccupied, the indoor carbon dioxide concentration levels ranged from 350-480 ppm, which had the same range as ambient carbon dioxide concentration levels. After the occupants come in the test room, the indoor carbon dioxide concentration levels increased above 2000 ppm with an average value of 1,722 ppm (s.d. = 530). To calculate outdoor air exchange rates for the test room, the indoor carbon dioxide concentration levels in the time period after the occupants left the room were extracted for data analysis. The indoor carbon dioxide concentration levels were plotted on the axes of the logarithmic function of C(t) against the time period, t, as prescribed in the ASTM E741-2011. The examples of the plotted data are shown in Figure 4. The outdoor air exchange rates were calculated using a linear regression model. The room air exchange rates when the ERV unit was not operated (no outdoor air intake) ranged from 0.50-0.64 ACH with an average value of 0.54 ACH (s.d. = 0.09). This range was within the air infiltration range investigated in Thai modern houses (Jareemit, 2015). Such room air exchange rates were quite low, which could lead to poor indoor air quality while the recommended outdoor air ventilation rate calculated based on the VRP prescribed in ASHRAE Standard 62.1-2010 required 1.07 ACH (28 m^3 hr^{-1}). From the Figure 4, the concentration levels monitored at 9.00 pm. in Day 1 and Day 2 were dropped since the occupants left the test room and came back around 11.00 pm.

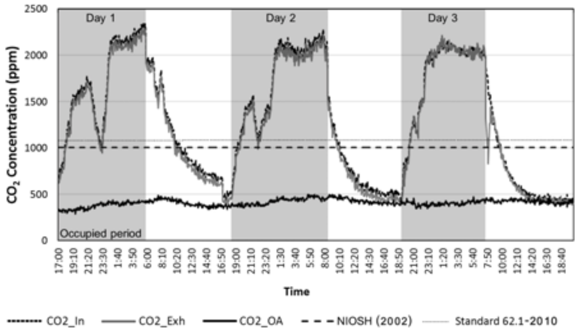


Figure 3. Measurement of indoor CO_2 concentration levels when the ERV unit was switched off (no outdoor air ventilation).

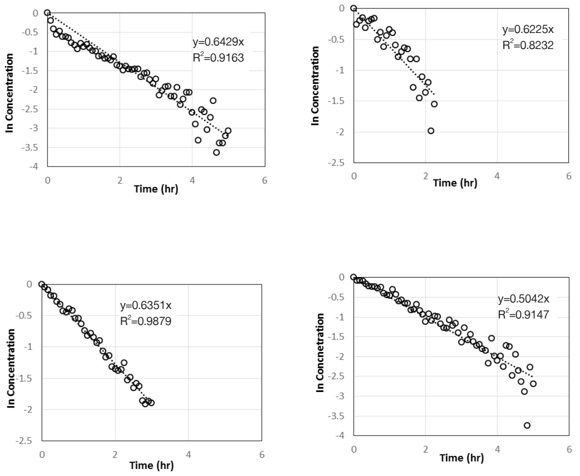


Figure 4. The plot of ln(C_t) against time period, which further used for calculating the room air exchange rates when the ERV unit was turned off (no outdoor air intake).

Figure 5 illustrates the indoor carbon dioxide concentration levels when the outdoor air intake rate of 40 m^3 hr^{-1} (1.5 ACH) was added into the room through the ERV unit. The night-time indoor carbon dioxide concentration levels dramatically dropped to 1,000-1,250 ppm with an average value of 930 ppm (s.d. = 210), with an exception to Day 4 when the occupants forgot to switch on the ERV unit. Although the supplied outdoor ventilation rate was increased by 1.4 times of the rate recommended by the VRP method, the night-time carbon dioxide concentration levels were still above the maximum limits of 1,000-1,200 ppm as defined by the ASHRAE Standard 62.1-2010 and NIOSH (2012), which did not meet the IAQP method.

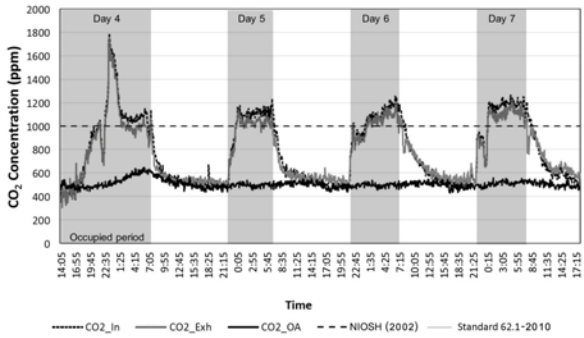


Figure 5. Measurement of indoor CO_2 concentration levels when the outdoor air ventilation rate of 40 m^3 hr^{-1} was added into the room through the ERV unit.

This present study increased the supplied outdoor air ventilation with the rate of 60 m^3 hr^{-1}. The increased ventilation rate could reduce the night-time indoor carbon dioxide concentration levels to 800-900 ppm with an average value of 869 ppm as shown in Figure 6. However, some scatter points were above 1,000 ppm, since the ERV unit was switched off.

According to the results, the required ventilation rate calculated based on the VRP method could not maintain indoor carbon dioxide concentration levels in this test room within the standard health guidelines. To maintain good indoor air quality, the outdoor air ventilation rate supplied in the test room needed to be increased by twice.

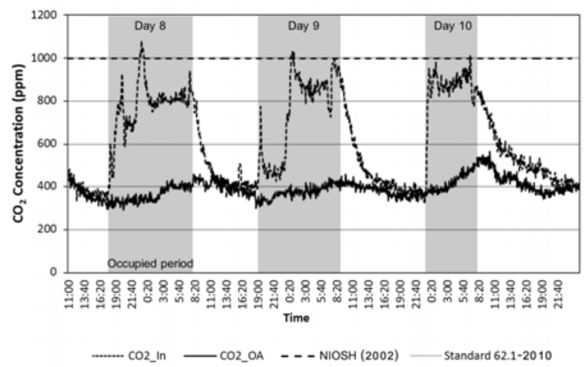


Figure 6. Measurement of indoor CO_2 concentration levels when the outdoor air rate of 60 m^3 hr^{-1} was added into the room through the ERV unit.

Table 2 summarizes an average room air exchange rate when the ERV unit supplied outdoor air ventilation rates at 0, 40, and 60 m^3 hr^{-1}. For normal operation when the ERV unit was switched off, the room air exchange rates (air infiltration) varied due to an influence of local wind speeds.

Table 2. Average room air exchange rate when the ERV unit supplied the outdoor air ventilation rates at 0, 40, and 60 m^3 hr^{-1}.

Outdoor air ventilation rate (m^3 hr^{-1})	Average room air exchange rate (ACH)
0	0.54 (s.d. = 0.09)
40	1.5
60	2.3

7. How occupants were satisfied indoor thermal condition when increasing the room air exchange rates?

During the test period, the survey was asked two male occupants on how they were satisfied with indoor temperature, humidity, air quality, air movement, lighting, and noise before they went to bed and after they wake up. Figure 7 presents the psychrometric plots of average values of indoor air temperature and relative humidity during the room was occupied when the ERV unit was operated at 0, 40, and 60 m^3 hr^{-1}. According to the ASHRAE Std. 55-2010, the graphical plot can be used for determining thermal comfort in the space where the occupants have activity levels with metabolic rates between 1.0 met and 1.3 met. Consequently, the sleep and reclining activity (0.8 met), is not covered in the ASHRAE Standard 55. However, besides the sleep, the occupants usually do seat or relax (met = 1.0) when they live in the bedroom. Consequently the plots on the chart were used to determine the thermal comfort for seating and relaxing activity. Most of the time, the indoor air conditions were not within the comfort zone defined by the ASHRAE Std. 55-2013 due to the air had high humidity although the air temperatures were kept in a range of 23-25 °C. From the plots, the increase of outdoor air ventilation rates could not affect the change of indoor air temperature and humidity. According to the survey results, both occupants did feel comfortable at high humidity and temperature at no more than 24-25 °C.

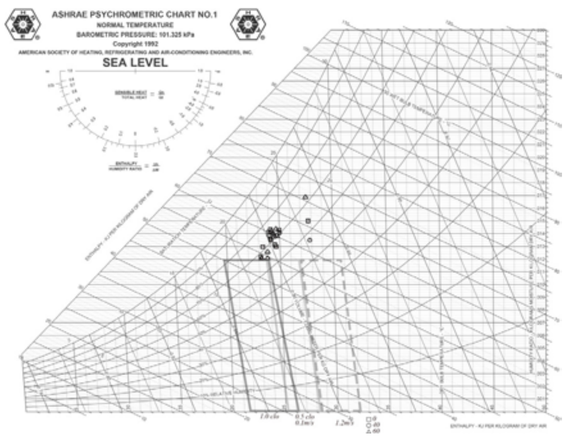
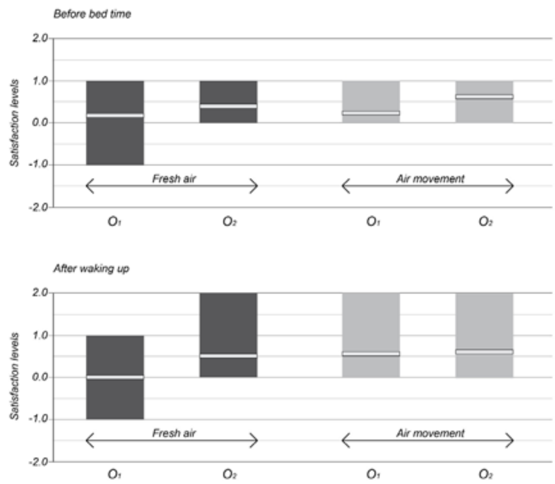


Figure 7. Plots of indoor air temperature and relative humidity on the psychrometric chart.

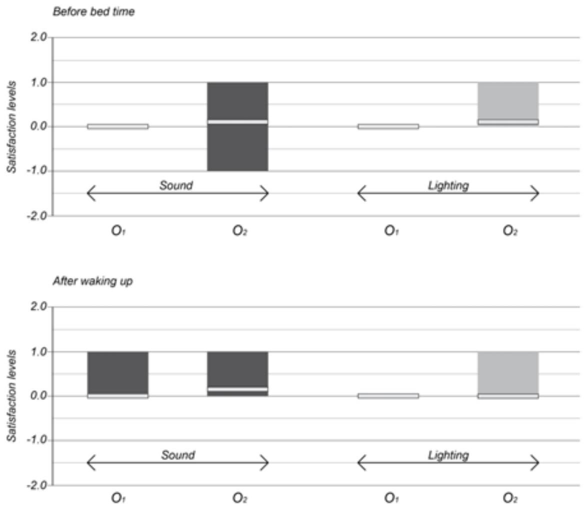
The five-scale point survey was used to evaluate occupants' satisfaction on air quality, air movement, lighting, and noise level. Interestingly, both occupants were satisfied with the air cleanliness and air movement before they went to sleep (Figure 8a) and after they woke up (Figure 8b) in the condition when the ERV unit did not supplied outdoor air ventilation. They had neutral satisfaction for lighting quality and noise level as shown in Figure 9.



2 – very satisfied 1 – satisfied 0 – neutral
-1 – dissatisfied -2 – very dissatisfied

Note: O1 and O2 are occupant 1 and occupant 2, respectively

Figure 8. Occupant's satisfaction ranges (shaded area) and average value (horizontal line) on indoor air cleanliness and air movement in the condition when the ERV was turned off. The questionnaires were conducted before occupants fell asleep (a) and after they woke up (b).



2 – very satisfied 1 – satisfied 0 – neutral
-1 – dissatisfied -2 – very dissatisfied

Note: O1 and O2 are occupant 1 and occupant 2, respectively

Figure 9. Occupant's satisfaction ranges (shaded area) and average value (horizontal line) on noise level and lighting quality in the condition when the ERV was turned off. The questionnaires were conducted before occupants fell asleep (a) and after woke up (b).

Table 3. Improvement of occupant's satisfactions on air cleanliness, air movement, noise level, and lighting quality when the ERV unit supplied outdoor air ventilation rate at 40 and 60 m^3 hr^{-1} comparing when the ERV unit was turned off.

Occupant's satisfaction		Before bedtime		After waking up	
		40vent	60vent	40vent	60vent
Air cleanliness	Occupant 1	3%	7%	13%	15%
	Occupant 2	15%	19%	22%	24%
Air movement	Occupant 1	3%	12%	7%	11%
	Occupant 2	12%	7%	24%	22%
Noise level	Occupant 1	0%	5%	0%	0%
	Occupant 2	8%	1%	2%	1%
Lighting quality	Occupant 1	0%	0%	0%	0%
	Occupant 2	-4%	-4%	-2%	-3%

Table 3 presents the occupant's satisfaction on air cleanliness, air movement, lighting quality, and noise level when the ERV unit supplied outdoor air ventilation at the rates of 40 and 60 m^3 hr^{-1}. Increasing the room air exchange rates could increase occupant's satisfaction, especially indoor air movement and quality of air. When supplying outdoor air ventilation rate at 40 and 60 m^3 hr^{-1}, occupant's satisfactions on the air cleanliness and air movement were increased up to 24 percent and up to 22 percent, respectively, comparing to those when the ERV unit was switched off (no outdoor air intake). However, the increase of the outdoor air ventilation rates slightly affected occupant's satisfactions on lighting quality and noise level, which indicated that the occupants could accept mechanical noise when the ERV unit supplied more outdoor air intakes.

8. Impact of the increase of outdoor air ventilation rates on the subject's sleep quality and next-day performance

Overall, the increase of outdoor air ventilation rates dramatically improved the occupant's sleep performance. Table 4 presents the improvement of occupant's sleep performance when the ERV unit supplying outdoor air ventilation rates at 0 (no ventilation), 40 (40vent) and 60 (60vent) m^3 hr^{-1}. For normal condition when the ERV unit was switched off, the Occupant 1 and Occupant 2 had an average time before asleep of 17 minutes (s.d. = 5) and 14 minutes (s.d. = 4) after they went to bed. The average actual sleep hour for Occupant 1 and Occupant 2 was 5.4 hours (s.d. = 0.5) and 6.1 hours (s.d. = 0.27) respectively. When adding the outdoor air intake rates at 40 m^3 hr^{-1}, the average time before the occupant fell asleep was reduced to 14 minutes (s.d. = 4) for Occupant 1 and 12 minutes (s.d. = 3) for Occupant 2. The average sleep hour was increased to 6 hours (s.d. = 0.24) for Occupant 1 and 6.2 hours (s.d. = 0.18) for Occupant 2. The increase of outdoor air ventilation rate to 60 m^3 hr^{-1} could decrease the time before asleep to 11.7 minutes (s.d. = 2.) for Occupant 1 and 7.8 minutes (s.d. = 1.8) for Occupant 2, respectively. The actual sleep hour surveyed from Occupant 1 and Occupant 2 was increased to 6.2 hours (s.d. = 0.2) and 6.6 hours (s.d. = 1.5). The sleep satisfaction is increased when the room has more outdoor air ventilation. The Occupant 1 was satisfied with the night sleep up to 57 percent when the ERV unit supplied outdoor air ventilation rate at 60 m^3 hr^{-1} whereas the sleep satisfaction of the Occupant 2 gradually increased only 9 percent.

Table 4. Improvement of occupant's sleep performance when the room had no outdoor air ventilation (No vent), with supplied outdoor ventilation rates at 40 (40vent) and 60 (60vent) m^3 hr^{-1}.

Sleep performance		No ventilation	40vent	60vent
Time spent on bed before fall asleep, min (% improvement)	Occupant 1	17	13.8 (18%)	11.7 (31%)
	Occupant 2	14	12.1 (14%)	7.8 (44%)
Actual sleep hour, hr (% improvement)	Occupant 1	5.4	6.0 (10%)	6.2 (13%)
	Occupant 2	6.1	6.2 (2%)	6.6 (8%)
Sleep satisfaction, %	Occupant 1	-	32%	57%
	Occupant 2	-	3%	9%

The sleep quality score was calculated from the survey data of seven components defined by the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989, pp. 193-213). When the test room had no outdoor air ventilation, the calculated score obtained from the questionnaire was 5 (greater than 5 scores mean poor sleep quality). It represents that the occupants had quite good sleep quality even though there was no outdoor air ventilation. The results showed a significant improvement of the occupant's sleep quality after adding the outdoor air ventilation into the test room through the ERV unit. The total score was significantly decreased to 3-4 scores when the ERV unit supplied outdoor air ventilation rate of 40 m^3 hr^{-1} and 1-3 scores with the ventilation rate at 60 m^3 hr^{-1}.

This present study also investigated how ventilation rates affected the occupant's next-day performance using the questions regarding level of concentration, enthusiasm, falling asleep during the day, and overall working performance. Both occupants had better enthusiasm and level of concentration on their work. The enthusiasm in the work was increased by approximately 4 percent when the room was supplied with the outdoor air ventilation rate of 40 m^3 hr^{-1} and 9 percent with the supplied rate of 60 m^3 hr^{-1}as presented in Table 5. The occupants were more focused on their tasks by approximately 8 and 13 percent when the outdoor air ventilation rate was increased to 40 and 60 m^3 hr^{-1}, respectively. Furthermore, the increase of outdoor air ventilation rates could improve the occupant's sleep duration, which results in the less next-day sleepiness. Falling asleep during the day was dropped by 5-26 percent and the overall daily work performance was improved from 2-20 percent, which showed that the occupants had more ability to work.

Table 5. Improvement of occupant's next-day performance when the outdoor air ventilation rate was increased to 40 and 60 m^3 hr^{-1} comparing to the condition with no outdoor air ventilation.

Next-day performance		40vent	60vent
Enthusiasm at work	Occupant 1	4%	9%
	Occupant 2	4%	9%
Concentration on work	Occupant 1	12%	13%
	Occupant 2	8%	13%
Fall asleep during the day	Occupant 1	-5%	-7%
	Occupant 2	-25%	-26%
Overall working performance	Occupant 1	2%	9%
	Occupant 2	10%	20%

In this present study, the survey of sleep quality and next-day performance was conducted only two male occupants living in the test room due to the limit of the test period and number of the ERV unit. Consequently, the results can be applied for specific case study. To obtain more reliable data for general implementation or using these findings as a reference, the future study should investigate more number of respondents and monitor real time conditions on their sleeping and working performances. Another research limitation, this present study only focused on the effects of the test room conditions, especially the indoor carbon dioxide concentration levels, air temperature, and humidity, on the occupant's next-day performance. However, we did not monitor or control the environmental conditions of the occupant's workplace, which can also affect the occupant's working performance. In order to mitigate this effect, the future studies should control or monitor the workplace conditions, which could provide more accurate results. In addition, the future works might study the relationship among occupant's physical factors such as sex, age, activity, sleep quality, and the next-day performance.

9. Conclusions

This present study investigates the impacts of increasing the outdoor air ventilation rates through the ERV unit on the occupant's sleep quality and next-day performance. The air exchange rates were calculated using the tracer gas decay technique. When the ERV unit did not supply outdoor air ventilation into the test room, the room had outdoor air ventilation contributed by air infiltration rate ranging from 16.5 to17 m^3 hr^{-1} (0.50-0.64 ACH), which resulted in the night-time indoor CO_2 concentration levels exceeded 2000 ppm. Adding the outdoor air ventilation rate at 40 m^3 hr^{-1} (1.5 hr^{-1}) could reduce the indoor concentration by one-half. However, the ventilation rate of 40 m^3 hr^{-1} could not control the night-time indoor CO_2 concentration levels within the maximum limit as defined by the IAQP method. Consequently, the recommended outdoor air ventilation rate for this test room should be 60 m^3 hr^{-1} (2.3 hr^{-1}). The mechanical noise when the ERV unit operating at high airflow rates did not disturb the occupant's living. Both occupants had more satisfaction on air movement and indoor air quality when increasing the outdoor air ventilation rates. In addition, the increase of outdoor air ventilation rates significantly improves the occupant's sleep quality and their next-day performance. The occupants felt asleep faster and had better sleep duration of 6.4-6.6 hours than when the room had no outdoor air ventilation. Regarding to the next-day performance, the increase of outdoor air ventilation rates could provide occupants better enthusiasm and concentration on their work. The overall next-day performance was improved from 2-20 percent.

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