การศึกษาเปรียบเทียบการระบายอากาศของห้องพักอาศัยคอนโดมิเนียมโดยวิธีการสลายของแก๊ส และการอัดอากาศ

Comparative Study of Air Exchange Rates in A High-Rise Residence by Using Both Tracer Gas Dilution and Fan Pressurization Methods

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Abstract

High-rise condominium living is becoming increasingly popular in the city while urban heat island effect has caused residents to close windows and use air conditioning unit all night. There is a buildup of indoor carbon dioxide (CO_2) concentration within bedroom(s) of residential unit that will affect the quality of sleep and productivity on the following day. Thus, providing sufficient bedroom air exchange is highly important in order to maintain low CO_2 concentration level within the residence. This study investigates room air change rate by conducting fan pressurization and tracer gas dilution experiments in a 30 m^2 one-bedroom type unit of a condominium in Bangkok, Thailand. The two method yields similar air exchange results, achieving 1.215 ACH via fan pressurization and 1.387 ACH via tracer gas dilution when bedroom and living room spaces are connected to each other. The air exchange rate and CO_2 concentration level are acceptable since the measured air change rate is higher than that required by design standards and CO_2 concentration level is found to be lower than 1,000 ppm. After closing the bedroom door, however, CO_2 concentration rises rapidly above 1,000 ppm while ACH drops to a level lower than suggested by design standards. Based on this experiment, it can be concluded that bedroom of conventional high-rise residential unit requires higher air exchange rate to ensure appropriate CO_2 concentration level at night while occupants are sleeping.

Keywords
Air Exchange Rate
CO_2 Concentration
Field Investigation
Fan Pressurization

บทคัดย่อ

การพักอาศัยในคอนโดมิเนียมแนวสูงกำลังเป็นที่นิยมมากขึ้นในเขตเมือง ในขณะที่ผลกระทบจากความร้อนในเมืองจากภาวะ urban heat island ผู้พักอาศัยต้องนอนปิดหน้าต่างและเปิดเครื่องปรับอากาศตลอดทั้งคืน พฤติกรรมดังกล่าวส่งผลให้มีการสะสมของระดับความเข้มข้นของคาร์บอนไดออกไซด์ (CO_2) ในห้องนอนที่มากขึ้น ซึ่งจะส่งผลต่อคุณภาพของการนอนหลับและประสิทธิภาพในการทำงานวันรุ่งขึ้นของผู้อยู่อาศัย การระบายอากาศที่เพียงพอของห้องนอนเพื่อรักษาปริมาณความเข้มข้นของคาร์บอนไดออกไซด์ในปริมาณที่เหมาะสมจึงเป็นสิ่งสำคัญ คณะผู้วิจัยได้ทำการทดสอบปริมาณการแลกเปลี่ยนอากาศของห้องพักอาศัยจริงขนาด 1 ห้องนอน (30 ตร.ม.) ในคอนโดมิเนียม โดยวิธีการอัดอากาศ (fan pressurization) และวิธีการสลายของแก๊ส (tracer gas dilution) การทดสอบทั้งสองวิธีให้ผลใกล้เคียงกัน คือ 1.215 ACH โดยวิธีการอัดอากาศ และ 1.387 ACH โดยวิธีการสลายของแก๊ส โดยทั้ง 2 วิธี มีข้อดีและข้อเสียแตกต่างกันและสามารถพิจารณาเลือกใช้แต่ละวิธีให้เหมาะสมตามสถานการณ์ได้ นอกจากนี้ เมื่อประตูห้องนอนในยูนิตพักอาศัยถูกเปิดไว้ พบว่า ระดับความเข้มข้นของคาร์บอนไดออกไซด์และการแลกเปลี่ยนอากาศ (ACH) ภายในยูนิตอยู่ในระดับที่สามารถยอมรับได้ แต่เมื่อประตูห้องนอนถูกปิด ห้องนอนจะต้องการการแลกเปลี่ยนอากาศที่มากขึ้น เนื่องจากพบค่าความเข้มข้นของ CO_2 สูงขึ้นอย่างรวดเร็ว และมีค่า ACH ต่ำกว่าที่แนะนำโดยมาตรฐานการออกแบบ

คำสำคัญ
การระบายอากาศ
ความเข้มข้นของคาร์บอนไดออกไซด์
การทดสอบประสิทธิภาพในอาคารจริง
การอัดอากาศ

1. Introduction

High-rise condominium living has become increasingly popular in the city. The rise in temperature as a consequence of urban heat island effect has caused residents to close windows and use air conditioning unit all night. As a result, there is a buildup of indoor carbon dioxide (CO_2) concentration within bedroom(s) of residential unit that will affect occupants' quality of sleep and productivity on the following day. More percentage of sleep quality improvement is presented with higher room ventilation rate (Jareemit, Julpanwattana & Choruenwiwat, 2017, pp. 22-32). Brain fatigue and ability to concentrate on the following day is also affected (Strøm-Tejsen, Zukowska, Wargocki & Wyon, 2014). Minimum bedroom ventilation rate has been suggested by standards such as ASHRAE 62.1-2010, ASHRAE 62.2-2016, CIBSE Design Guide, DIN EN 15251 and Thai regulation.

Many studies have been conducted for bedroom ventilation and air exchange rate assessment with different methods suggested. Sreshthaputra (2016) studied condominium room ventilation and the effect of door-sided operable shutter using fan pressurized method to account for the installed equipment success in letting residents benefit from natural ventilation. Another commonly-used method of experiment is tracer gas dilution. In order to optimize short-term ventilation supplied to bedroom, Ai, Mak, Cui & Xue (2016) uses carbon dioxide exhaled by human overnight as a tracer gas in his study. Similarly, Cheng & Li (2018) investigates overnight infiltration rate of residential bedrooms has been investigated using CO_2 produced by the sleeping occupants due to cost-effectiveness. Based on reviewed literature, tracer gas dilution has been suggested as the simplest and most direct method to assess room air change rate. Nevertheless, fan pressurization can assist in identification of building envelope leakage size while able to be performed simultaneously with multiple alternatives.

In this experiment, both tracer gas and fan pressurization is conducted in a normal residential unit with no additional design strategies for ventilation. The result from both methods will be compared and discussed with the rate suggested by design standards. Tracer gas method experiment can assess the increasing pattern of CO_2 concentration during occupancy and propose design suggestions. In addition, fan pressurization will be performed simultaneously to analyze the improvement of room air change rate for the proposed design.

2. Research Methodology

2.1 Climate Condition and Room Details

Thailand is a tropical country with high temperature and humidity all year round. The annual average temperature for most areas of Bangkok is 28°C with 74% relative humidity. The diurnal temperature range between 7°C - 11°C. Prevailing wind speed varies from 5-25 m/s, with wind mainly from southwest and south direction.

Located on the 5th floor of a high-rise condominium building, the room used in the experiment is 28.9 m^2 with 2.8 m ceiling height. Thus, total volume calculated is 53.6 m^3. Bedroom volume is accounted for 31.08 m^3. Bedroom fenestration is constructed by aluminum frame with fixed glass and 2 operable 1.05 m^2 casement windows, as illustrated in Figure 1.

Figure 1. Opening

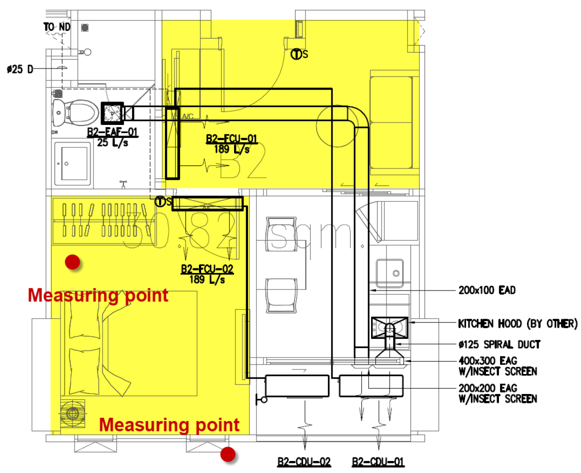

Figure 2. Room Layout

2.2 Regulation and Design Standards

Required outdoor air change rates (ACH) by various design standards are shown in Table 1.

Table 1. Outdoor Air Change Rate (ACH) Required by Design Standards

Standard	Outdoor Air Requirements	Required OA (ACH)
ASHRAE 62.1-2010	A combination of outdoor air rate determined by room area and number of occupancy	0.72
ASHRAE 62.2-2016	Table lookup determined by total unit area and number of bedroom	0.63
CIBSE	Flat rate for bedroom and living room	0.4-1
Thai regulation	2 CMH/m^2, for air conditioned residential unit	0.71
DIN EN 15251	The maximum value among those determined by flow rate per whole unit area, occupancy and main living area	1.29

2.3 Tracer Gas Dilution

To find ACH from gas tracing using CO_2 from human source, this study utilized the method suggested by Cheng & Li (2018). The room is occupied by 2 adult male occupants with doors and windows closed. Room temperature is set to 25°C. During the experiment, CO_2 concentration (ppm) inside the room is recorded every 5 minutes interval. Sensor, Lutron MCH-383SD, has been installed inside the bedroom at the location indicated in Figure 2. Outdoor temperature and CO_2 concentration is recorded at the beginning and after finish the experiment. All collected data to be be calculated using the mass balance equation of tracer gas dilution for a single-zone which can be written in Equation 1. The exhalation rate of CO_2 (F_{CO_2}) from occupants can be estimated using Equation 3 proposed by Persily & Jonge (2017).

$$F_{CO_2} + Qc_e = v_{zone}\frac{dc}{dt} + Qc \qquad (1)$$

where

- Q is a ventilation rate (m^3/h)
- c_e is an outdoor CO_2 concentration (ppm)
- c is an indoor CO_2 concentration (ppm)
- v_{zone} is a room volume (m^3)

which can be written in a simultaneous form as:

$$\Delta c = \frac{\Delta t}{v_{zone}}\left(F_{CO_2} - Nv_{zone}(c_1 - c_e)\right) \qquad (2)$$

where

- N is an air change rate (h^{-1})
- t is a time step (h)
- F_{CO_2} Is the exhalation rate of CO_2 from sleeping occupants (m^3/h)

$$F_{CO_2} = RQBMRM\left(\frac{T}{P}\right)0.000211 \qquad (3)$$

where

- RQ is a respiratory quotient (0.85)
- BMR is a basal metabolic rate, equal to 3.00625 MJ/day, calculated from age and height by the equation shown in Table 2 (Schofield, 1985)
- M is a metabolic rate (1.2 met for filing seated occupants, 0.95 for sleeping occupants)
- T is an air temperature (K)

P is an air pressure (kPa)

Table 2. Calculation of BMR

Age (y)	Females	Males
0-3	0.244 m – 0.130	0.249 m – 0.127
3-10	0.085 m + 2.033	0.095 m + 2.110
10-18	0.056 m + 2.898	0.074 m + 2.754
18-30	0.062 m + 2.036	0.063 m + 2.896
30-60	0.034 m + 3.538	0.048 m + 3.653
≥60	0.038 m + 2.755	0.049 m + 2.459

Substitute all parameters into a simultaneous form of Equation 1, written in Equation 2, and solve for the air change rate, N (h^{-1}).

2.4 Fan Pressurization

To find ACH by using fan pressurization method, the experiment is setup in accordance with ASTM E 779-03. Pressure difference is induced by 6,500 cfm fan equipped with VSD controller. Pressure difference is measured by Testo 510 digital manometer. Airflow rate is measured by Testo 454. Annual average air exchange (ACH_{nat}) will represent ACH for the room (Sherman, 1987, pp. 81-86). To calculate ACH_{nat}, air change at differential pressure of 50 Pa wind velocity (ACH_{50}) must be divided by 20 (Equation 4). ACH_{50} can be determined by Equation 5.

$$ACH_{nat} = \frac{ACH_{50}}{20} \tag{4}$$

$$ACH_{50} = \frac{Q_{50}}{v_{zone}} \tag{5}$$

Q_{50} is interpolated from the polynomial function by the relationship of airflow rate (Q_i) and differential pressure (dP_i) where dP is occurred by 50 Pascal wind velocity (dP_{50}). The dP_{50} can be found by Equation 7 where airflow rate (Q_{fan} : m^3/s) is from the fan sectional area multiplied by wind velocity at 50 Pa (V_{50Pa}) calculated by Equation 6. Letting air pressure (P) = 50 Pa, air density (ρ) = 1.164 kg/m^3, V_{50Pa} will become 2.959 m/s. Then, airflow rate (Q_{fan}) is equal to 0.6779 m^3/s.

$$P = 0.5\rho V_{50Pa}{}^2 \tag{6}$$

$$Q_{fan} = C\,(dP_{50})^n \tag{7}$$

In order to find C and n, log transformation of airflow rate and pressure difference is plotted as Equation 8 and Equation 9

$$x_i = \ln(dP_i) \tag{8}$$

$$y_i = \ln(Q_i) \tag{9}$$

Then, solve C and n from the linear function below:

$$y = \ln(C)+nx \tag{10}$$

After all parameter are known, input dP_{50} into the polynomial function of airflow rate and differential pressure to get Q_{50}.

3. Results

3.1 Air Change Rate from Tracer Gas Dilution Method (with CO_2 Concentration): Whole Dwelling Unit

Data for this part is collected from 18:30 – 23:30 when the volume of bedroom and living room are connecting to each other representing the whole conditioned area of the residential unit. CO_2 concentration is plotted in Figure 3.

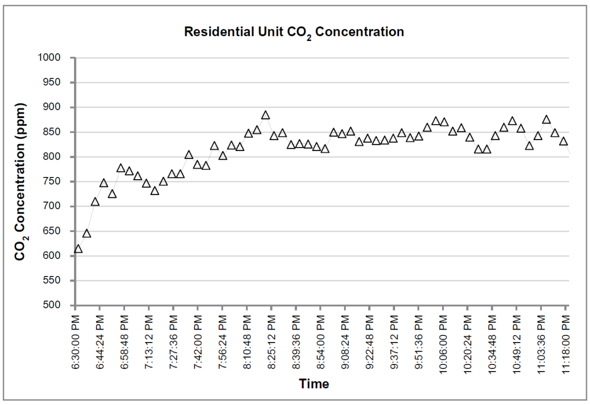

Figure 3. CO_2 Concentration inside the Residential Unit (18:30-23:30)

Since both occupants are 1.7 meters height and aged between 18-30 years, *BMR* becomes 3.0063 MJ/day per person. Air temperature is 77 K. Air pressure is 100.63 kPa. Thus, F_{CO_2}) is 0.000495 m3/h per occupant. Average air change rate, N, acquired from Equation 2 becomes 1.387 ACH.

3.2 Air Change Rate from Tracer Gas Method (with CO_2 concentration): Bedroom

Data for this part is collected from 24:00-01:30 and 06:00-08:00 when the living room is disconnected by closing the bedroom door. CO_2 concentration within the bedroom is shown in Figure 4. For 23:30-01:30, CO_2 concentration rises approximately 200 ppm/hr by sleeping occupants. For 06:00-08:00, CO_2 concentration rises approximately 400 ppm/hr when occupants stay awaked. Calculated air change rate, *N*, ranges from 0.13-0.83 ACH.

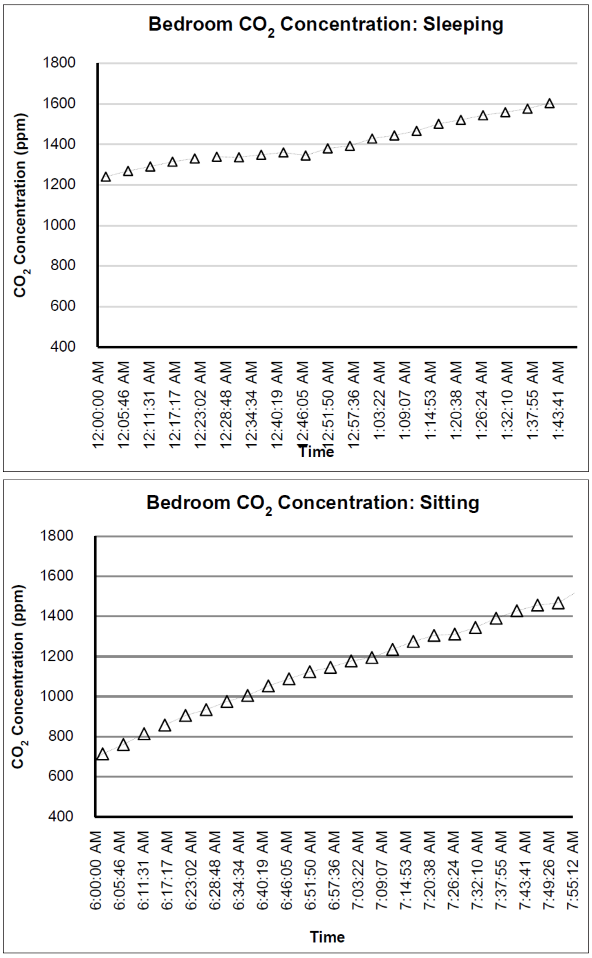

Figure 4. Bedroom CO_2 Concentration (24:00-01:30 and 06:00-08:00)

3.3 Air Change Rate from Fan Pressurization Method: Whole Dwelling Unit

Pressure difference (Pa) per air flow rate (m^3/s) and its log transformation are plotted below.

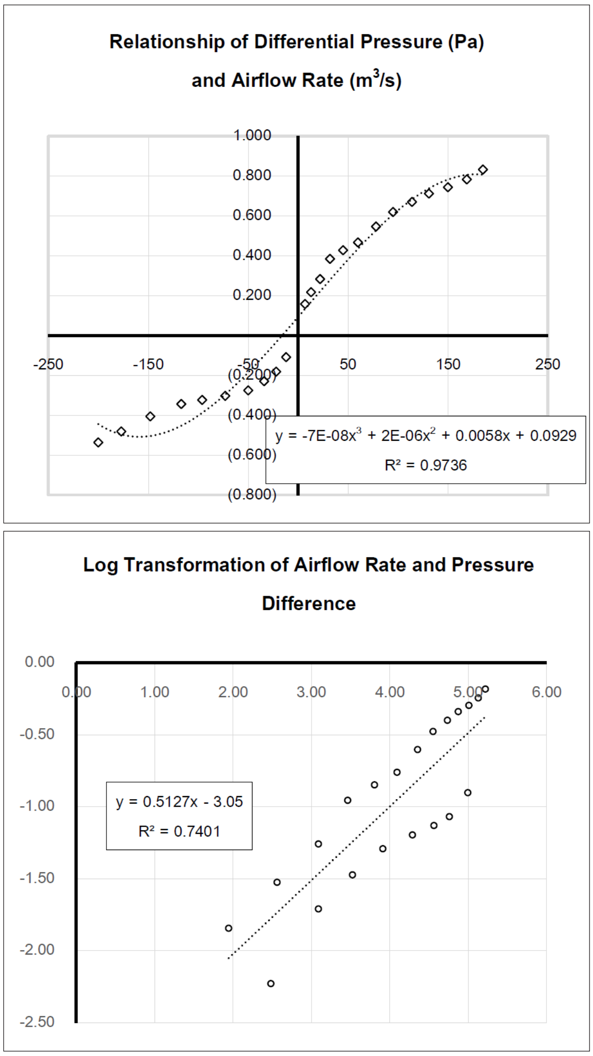

Figure 5. Differential Pressure per Airflow Rate and Log Transformation

Obtained from the relationship of differential pressure (dP_i) and airflow rate (Q_i), differential pressure when 50 Pascal wind is blown through (dP_{50}) is 114.43 Pa. From log transformation, C and n are solved and input into Equation 7. Q_{50} can be solved as 0.538 m^3/s. Then, ACH_{50} and ACH_{nat} become 24.3 and 1.215.

4. Discussion

4.1 Comparison of Room ACH Acquired by Tracer Gas Dilution and Fan Pressurization

1. Averaged room air change rate calculated from Tracer Gas method (1.387 ACH) is slightly higher than that of fan pressurize method (1.215). Difference in the results may occur due to various factors.

2. For Tracer Gas method, the direction of airflow through the leakage for each time interval can be effected by an outdoor wind pressure apart from the CO_2 concentration. Residents' activities can also be a factor (i.e. swing the door, use toilet and inevitably turn-on an exhaust fan). For the concentration of CO_2 source, Basal Metabolic Rate (*BMR*) in the formula is varied by only age and height of the residents. If constant CO_2 source from a cylinder is used, the cost is arguably high. However, the actual CO_2 concentration level during occupancy for each air change rate can be realized by this method. Besides, the air exchange rate of distinct room volume can be obtained easily.

3. Errors from fan pressurized method can occur due to leakage through electrical components in plumbing system. These indoor components are not designed to endure a high-pressure condition. Once the indoor pressure is going too positive or too negative, components can collapse and cause leakage through the seams resulted in lower pressure differential. Limitation of a fan pressurized method is that it cannot perform in a big room volume when fan capacity is not enough. Nevertheless, this method can be conducted continuously to see the performance of various design alternatives in a short period of time. The result can be determined during construction period and occupancy. Moreover, it can be performed under a small external wind pressure.

4.2 Actual Room Air Change Rate (ACH) Compared with that Required by Design Standards

1. The actual ACH through leakage for the whole residential unit is higher than outdoor air exchange rate required by most standards. Thus, the residential unit may have sufficient outdoor air while bedroom door left open. As shown in Figure 3, CO_2 concentration inside the residential unit has been maintained below 900 ppm.

However, CO_2 concentration becomes higher when room volume is decreased – residents stayed the bedroom and closed the door. While sleeping with no other air movement activities, the CO_2 concentration can increase above 1,000 ppm. Increasing rate during sleep (200 ppm/hr) and sitting activity (400 ppm/hr) can make the bedroom CO_2 concentration reach 1,000 ppm within 1-3 hours. The calculated outdoor air exchange rate becomes 0.13-0.83 which is lower than expected by design standards. Thus, a bedroom needs more air exchange to maintain CO_2 concentration level below 1,000 ppm during the bedtime while the door is closed.

5. Conclusion

Air change rate accounted by both methods is found to be similar, with 1.215 ACH from fan pressurize method and 1.318 ACH from tracer gas method. Each method has its own advantages and is likely to be selected in a different situation. The current designed air exchange rate, as supplied by conventional residential unit, is acceptable if overall room spaces are open and connected to each other. Conversely, when bedroom door is closed, the decrease in volume for room ventilation has caused air exchange rate to drop to a level lower than suggested by design standards. It can be concluded that higher air exchange rate is needed to maintain CO_2 concentration below 1,000 ppm during bedtime for better sleeping quality and next day performance.

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