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Impact of Vertical Void Design on Ventilation Performance of Boarding Houses in Hot Humid Climate

Muhammad Naufal Hakim[1], Sri Nastiti Nugrahani Ekasiwi*[2] , FX Teddy Badai Samodra[3]
Institut Teknologi Sepuluh Nopember [1, 2, 3]
E-mail: [1]6013231012@student.its.ac.id, [2*]ekasiwi@its.ac.id, samodra@its.ac.id[3]

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Abstrak_ *Void vertikal dapat meningkatkan kinerja penghawaan alami untuk pendinginan fisiologis dan kualitas udara dalam ruangan (IAQ), khususnya pada rumah kos sebagai bentuk hunian bersama. Pengaruh void terhadap penghawaan ditentukan oleh berbagai variabel desain seperti proporsi bukaan, rasio void terhadap bangunan, aspek rasio void, dan posisi void. Melalui modifikasi variabel-variabel desain tersebut, efek void vertikal terhadap penghawaan dapat ditingkatkan. Untuk menyelidiki pengaruh variabel desain terhadap kinerja penghawaan, penelitian dilakukan melalui survei lapangan dan pengukuran kondisi iklim mikro. Metode statistik deskriptif digunakan untuk menganalisis pengaruh desain yang berbeda pada dua rumah kos terhadap kinerja penghawaan. Hasil penelitian ini dapat digunakan sebagai pertimbangan desain hunian bertingkat rendah untuk meningkatkan kinerja penghawaan alami. Temuan menunjukkan bahwa kualitas udara yang ditentukan oleh konsentrasi* CO_2 *tetap berada di sekitar 400–600 ppm. Hal ini disebabkan oleh tingkat habitasi yang rendah dan volume void yang besar, terlepas dari desain void atau kecepatan udara. Kecepatan aliran udara sebagai indikator pendinginan fisiologis bervariasi antara siang dan malam. Penghawaan pada siang hari lebih efektif untuk lantai atas karena daya apung termal dan kecepatan angin yang lebih tinggi. Penghawaan malam hari kurang memadai dengan aliran udara yang lebih lemah, terutama untuk pendinginan fisiologis di lantai atas. Penyesuaian rasio void dapat meningkatkan kinerja penghawaan alami. Void yang sempit meningkatkan aliran udara ke atas pada malam hari, sedangkan rasio aspek void yang lebih besar meningkatkan aliran udara pada siang hari.*

Kata kunci *: Void Vertikal; Penghawaan, Pendinginan; Kualitas Udara*

Abstract_ Vertical voids can enhance the performance of natural ventilation, improving physiological cooling and indoor air quality (IAQ), particularly in boarding houses as shared living spaces. The effect of void design on ventilation is influenced by various design variables, such as the proportion of openings, the void-to-building ratio, the void aspect ratio, and the void's position within the building. The effects of vertical void towards ventilation efficiency can be improved by modifying these variables. This study investigates the impact of these design variables on ventilation performance through field surveys and microclimate measurements. Descriptive statistical methods were used to analyze the effects of different designs on two boarding houses. The results of the study can be considered in low-rise housing design as a way to improve natural ventilation performance. The findings show that CO2 concentrations remain stable at 400–600 ppm, which is attributed to low occupancy levels and large void volumes, regardless of the void design or air velocity. Airflow as an indicator of physiological cooling varied between day and night, with daytime ventilation being more effective on upper floors due to stronger thermal buoyancy and wind speeds. Nighttime ventilation was less effective, with weaker airflow, especially on the upper floors, affecting physiological cooling. Adjusting the void's aspect ratio can improve natural ventilation performance; narrower voids enhance upward airflow at night, while larger aspect ratios improve ventilation during the day.

Keywords: Vertical Void; Ventilation; Cooling, Air Quality

INTRODUCTION

Passive ventilation is regarded as one of the best strategies for mitigating thermal environments, especially in regions characterized by hot humid climates (Olgyay et al., 2015). Besides thermal factors, perception of thermal environment is also influenced by indoor air quality (Gou et al., 2018). Higher air velocity may increase the positive perception of occupants towards thermal satisfaction and air quality. Indoor air quality (IAQ) is measured by various air contaminants such as CO_2 and excessive water vapour. Both are vital since they are produced by the building occupants regardless of the outdoor condition (Allard & Ghiaus, 2005). As a passive cooling strategy, natural ventilation plays a critical role in thermal comfort improvement (Nagasue et al., 2024; Nicol & Roaf, 2008). Ventilation can improve qualities that contribute to thermal comfort as well as indoor air quality (Farea et al., 2015; Kotani et al., 2003; Parsons, 2002; Szokolay, 2008). In hot humid climates, a vertical void appears as a suitable solution for enhancing passive ventilation performance, especially in high-density areas (Murakami et al., 2004). The stack mechanism induced by vertical void is especially effective for multiple-story buildings in hot humid climates (Dezfuli et al., 2023). Vertical void has a significant role in improving thermal comfort and IAQ by amplifying natural ventilation performance in the living units of multi-story housing (Muhsin et al., 2017). Buoyancy force caused by temperature differential at the top and bottom of vertical void drives air flow which amplify ventilation performance (Passe & Battaglia, 2015). Besides buoyancy effect, air movement through a building is a result of outdoor wind and pressure difference between two building sides.

Vertical voids are commonly found in multi-story residential buildings in the form of open or closed courtyard (Kubota et al., 2017; Kumar et al., 2022; Kumar et al., 2021, 2023b; Nugroho, 2023), stairwells (Nugroho et al., 2020), and interior void (Farea et al., 2015; Nugroho et al., 2020). Boarding house emerges as one of the solutions to accommodation high demand in the form of co-living (Indah & Wardono, 2021). Boarding houses typically include common rooms, which play a significant role in enhancing social well-being and improving environmental quality. Common room facilitates social interaction, which up to 47% of occupants use at high frequency (Ristanto et al., 20 21). In co-living environment, communal spaces like common room and corridor are needed to circulate air which is vital to provide a sense of comfort in carrying out activities (Oktavallyan et al., 2021). Improving indoor environmental quality should improve thermal comfort and increase IAQ (Diaz et al., 2018). CO2 generation is determines by the number occupants and generation rate per person. More occupants means higher CO2 concentrations, which reduces productivity and limits cognitive performances, as well as inducing healthy risks to building occupants (Jia et al., 2021).

Boarding house design tends to maximize land use, which contributes to higher building density. Airflow is often reduced in high-density regions, which results in poor air quality and thermal conditions (Chauytong et al., 2022). Poorly designed ventilation in boarding houses results in minimum airflow, high humidity levels and air temperature, which consequently end up in uncomfortable thermal conditions (Latif et al., 2019).

Vertical void designs for improving ventilation performance are predominantly implemented in multi-story residential buildings, influenced by various design variables. Building orientation and placement of openings are related to prevailing wind direction, determining the effectiveness of ventilation (Ghaffarianhoseini et al., 2015). Upward airflow is most effective with perpendicular wind direction towards the windward side (0°) (Farea et al., 2015). Wind pressure is relatively stable between 0° and 40°, decreased by shifting wind direction (Kumar et al., 2022). Strategically placed openings ensure constant airflow throughout the void and enhance ventilation on the leeward side (Kumar et al., 2023a, 2023b). Void aspect ratio is also critical in determining ventilation effectiveness across various void types. Generally, narrower voids exhibit better ventilation performance. The three-story building shows better thermal performance (Muhaisen, 2006), while staggered courtyards (one story) reduce night air temperatures and deeper courtyards (two stories) decrease peak air temperature and humidity (Kubota et al., 2017). Smaller W/H ratios between 0.1 and 0.15 increase upward airflow particularly in dense urban settings (Kumar et al., 2022, 2023b). Building to void ratio is crucial, with a 50% void ratio enhancing air change rate by up to four times and increasing air velocity by 30% (Muhsin et al., 2016; Muhsin et al., 2017; Murakami et al., 2004). However, increased void size beyond the optimal threshold may reduce airflow since a larger volume causes the airflow to dissipate (Muhsin et al., 2017). Well-designed vertical voids should optimize airflow and ventilation effectiveness (Muhsin et al., 2017), therefore improving thermal condition and air quality in boarding houses.

In naturally ventilated buildings, higher air velocity increases the positive perception of occupants towards thermal conditions and IAQ. Generally, air velocity between 0.2 and 0.5 m/s is considered pleasant for most users, while air movement above 1 m/s may start to be regarded as uncomfortable (Szokolay, 2008). Airflow required for physiological cooling depends on the overall thermal condition governed by air temperature, relative humidity and radiation. Airflow is crucial in living space to improve sweat evaporation and diminish excessive humidity (Kubota et al., 2017). Given the indoor air velocity of 0.15 m/s and humidity of less than 80%, occupants can tolerate a maximum air temperature of 29°C (Nejat et al., 2021). CO_2 and pollutant concentration in indoor air is governed by the exchange of fresh air supply. Estimated CO_2 concentration based on the number of occupants, each generates 5.3 x 10-6 m3/s of CO_2. Exhaled air from respiration generally contains about 4% of CO_2, which is considered as non-toxic. However, higher concentrations may expose health risks for building occupants. Higher CO_2 concentration reduces productivity and limits cognitive performances, as well as inducing healthy risks to building occupants (Jia et al., 2021). A CO_2 concentration of 5000 ppm affects perceived indoor air quality and performance (Du et al., 2020), and some evidence shows that a concentration of 1000 ppm affects cognitive function (Fisk et al., 2019). Indoor CO2 concentration is considered acceptable up to 1080 ppm, which is three times the ideal condition (360 ppm) (Samudro et al., 2023). Levels beyond this threshold indicate that ventilation improvement or other remediation is necessary to ensure occupants' health.

It is important to evaluate ventilation performance in terms of thermal conditions and indoor air quality (Kumar et al., 2021). Therefore, the study investigated the effects of vertical void design and its design variables configuration towards passive ventilation performance in terms of physiological cooling and CO_2 concentration for low-rise boarding houses in hot humid climates.

METHODS

The study was conducted in Surabaya, Indonesia with two boarding houses with different characteristics. The microclimate measurement was conducted using Thermal environment Measurement Tools (TMT), which were developed in DeLCA, SATREPS to measure thermal parameters, including air temperature, white and black globe temperature, relative humidity, and air velocity. Indoor CO_2 concentration is measured in ppm by RTR-576 CO_2 level meter. The measurement point is 1.1 m which is representative of standing occupants as well as corresponds to body level height for seated occupants (ASHRAE, 2017; Parsons, 2002). Previous studies used the 1.1 m reference height for measurement points including measurement of microclimate in the courtyard (Nugroho, 2023; Rajapaksha et al., 2003), as well as CO_2 concentration (Alfata et al., 2015). The height is significant for thermal comfort and IAQ evaluation, as it provides a reliable measure for assessing the temperature distribution and air quality regarding to breathing zone (Cheng et al., 2014; Lestinen et al., 2017; Mareed & Hussen, 2020). Height around 1.1 to 1.2 meters, is typically considered as breathing zone height for seated individuals (Liu et al., 2019). Boarding houses used in this study are designated as B1 and B2, which characteristics are outlined in the next chapter. The measurement was conducted in October, during the hottest month, to observe how the design withstand the most extreme condition. Based on each building design, measurement points were positioned at the void of each level with an addition at the ground level common room (B1, B2) as well as openings at the upper floor (B2) (Figure 1). Measuring points at the pilotis were decided as the air inside the vertical void is supplied by air movement from the pilotis of the building (Kumar et al., 2022, 2023a). Additional points at the openings were meant to measure the air velocity at the upper openings as the horizontal openings highly affect the upward airflow velocity in a vertical void (Farea et al., 2015). Air supply from the opening induces indoor air velocity for physiological cooling, and also drives air change inside the void, which determines the IAQ.

Figure 1. Measurement points on B1 (top) and B2 (bottom).

The analysis of ventilation performance is based on the requirement for physiological cooling and CO2 level which signifies indoor air quality. Ventilation performance effect on physiological cooling is evaluated by the air velocity requirement (Vc).

$$Vc = 0.15\left(DBT - UCT + \left(\frac{0.8\,(RH-60)}{10}\right) + \left(\frac{0.55\,(MRT-38)}{2.8}\right)\right) \quad (1)$$

Air velocity (V) requirement for physiological cooling is calculated using Equation (1), where DBT – dry bulb temperature; UCT - upper dry-bulb temperature; RH – relative humidity; and MRT – mean radiant temperature (Samodra, 2017). Overall ventilation performance is evaluated using a quadrant diagram combining the ventilation effects used in the evaluation of simulated ventilation performance regarding thermal comfort and IAQ. The diagram represents the distribution of air velocity and CO_2 concentration for each measurement point. Better thermal performance is indicated by higher air velocity while better impact on IAQ is shown by lower CO_2 concentration. The center of each axis evaluation criteria is determined by the minimum required value of each indicator. A chart of V and Vc was also used to analyze the ventilation performance.

RESULTS AND DISCUSSION

A. Boarding House Design

Both boarding houses are characterized by several design variables regarding vertical void design. The void at B1 is used as a common area by using a trellis as the floor, while at B2, the void is used as a stairwell (Figure 2). The void at B1 is not connected to openings since there are no openings at the front side. The other sides do not have any openings since these boarding houses are built attached to other houses. B1 presents a unique case where the common room which connects every other room practically acts as a void as a result of steel trellis usage as floor. B2 is a more common variation, in which the units are aligned alongside a corridor that is connected to the void/stairwell.

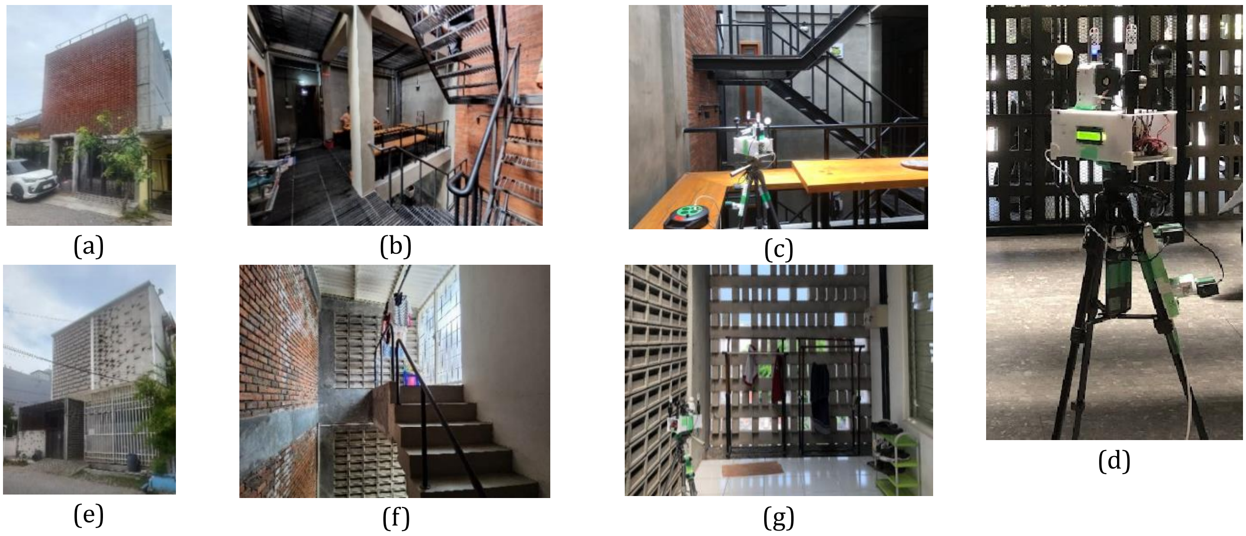


Figure 2. Boarding house B1 (top); (a) front side, (b), void and isolated common area, (c) isolated void without horizontal opening, and (d) TMT and CO_2 meter installed at the void. Boarding house B2 (bottom); (e) front side, (f) void as the stairwell, and (g) front opening which is connected with the void via the corridor.

Table 1. Building design variable.

Design Variable	B1	B2
Building area	96.1 m2	79.3 m2
Building area ratio (W/L)	0.6	0.3
Front side WWR	0.23	0.58
Orientation	South	East
Void type	Permeable Floor	Stairwell

Design Variable	B1	B2
Void-to-building ratio	0.3	0.06
Void aspect ratio (W/H)	0.49	0.17
Void size ratio (L/W)	0.9	1.5
Void position	Middle	End
Street aspect ratio (H/W)	2	1

B1 void is located in the middle of the building, with building area ratio (W/L) of 0.6, while at the B2, the void is located at the back side, with W/L of 0.3, making the B2 building area significantly narrower (Table 1). The void in B2 is located at the far rear side, 19 m from the front side. B2 building proportion is 0.3, significantly narrower than B1.

B. Microclimate Condition and Indoor Air Quality

Figure 3 below shows the measurement results of thermal and air quality parameters in both boarding houses that were recorded during three consecutive days. In both boarding houses, the highest air temperature was recorded on the third floor during mid-day. At boarding house B1, the maximum air temperature reached 37.3 °C, measured at the void on the third floor. In comparison, at boarding house B2, the peak air temperature was slightly lower at 39.9 °C, recorded on the third floor near the windward opening facing East direction. The difference between peak air temperature is 2.6 °C, with the air temperature at B1 being lower.

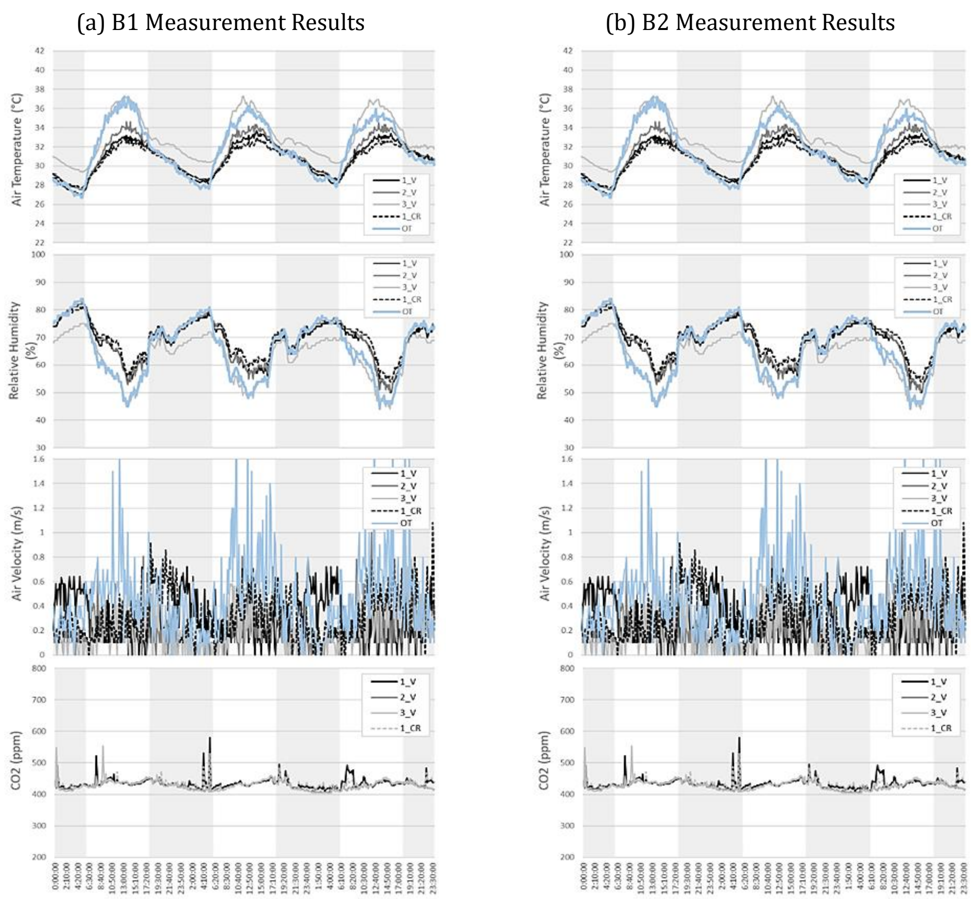
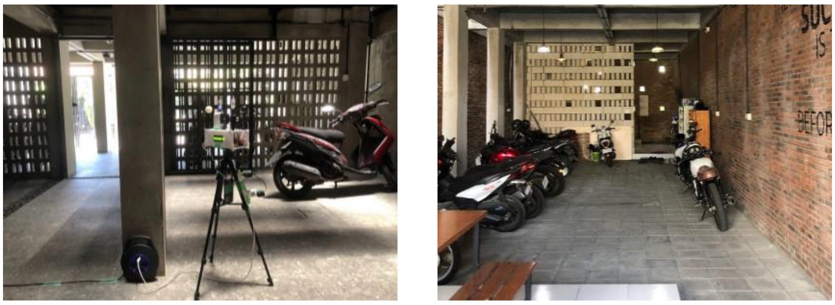


Figure 3. Measurement results from B1 (left) and B2 (right), from top to bottom; air temperature, relative humidity, air velocity, CO_2 concentration.

Relative humidity level reached its lowest during the peak air temperature, especially on the third floor, with an average of 57.9% and 57.6% on B1 and B2. In both cases, the area with the lowest relative humidity was the third floor, which was the area with the highest air temperature. The highest relative humidity was recorded at the first-floor pilotis during the night time, with an average of 73.1% and 76% for each B1 and B2. At the same place, the relative humidity decreased during the daytime, with an average of 63.7% and 67.9%. Relative humidity at the void on the ground and the second floor is higher than the third floor, each by 68.0% and 67.2%. The average relative humidity on the third floor is 63.0%. Humidity level is lower at both the void and opening of the third floor, with each value of 66.2% and 62.4%.

The highest air velocity was recorded on the first floor which in both cases were in the form of pilotis (Figure 4). In B1, the average void air velocity ranges from 0.20 m/s (first level) to 0.27 m/s (third level) during the day and 0.15 m/s (second level) to 0.38 m/s (first level) during the night. In B2, the average air velocity inside the vertical void ranges from 0.19 m/s (second level) to 0.45 m/s (first level) during the day, At night the air velocity ranges between 0.15 m/s (second level) to 0.38 m/s (first level) during the night.



(a) (b)

Figure 4. B1 pilotis (a) and B2 pilotis (b).

Levels of CO_2 concentration in both buildings are relatively similar. However, some spontaneous spikes in CO_2 levels were recorded. The pattern of CO_2 spikes on B2 is more regular, with most occurrences happening during the nighttime. This is possibly caused by occupancy since the increase in CO_2 level is affected by the number of occupants. The increase of CO_2 in B1 is more irregular compared to B2.

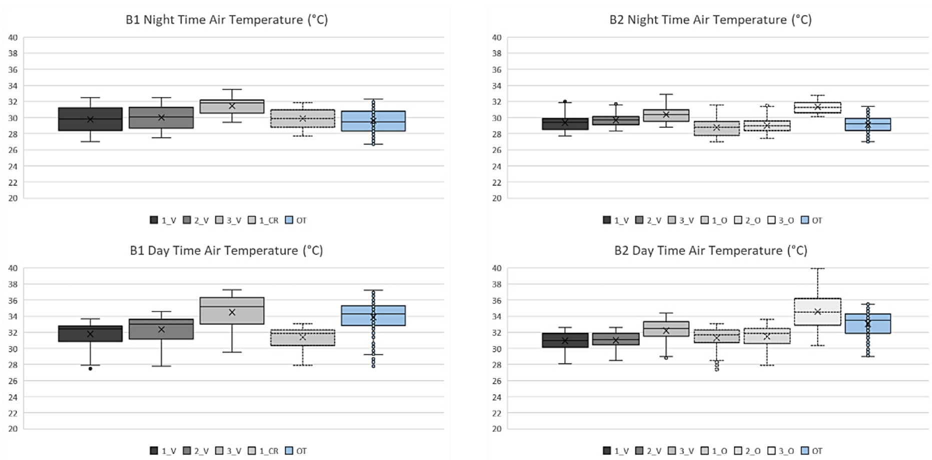


Figure 5. Air temperature comparison from B1 (left) and B2 (right) during night (top) and day (bottom).

Across both boarding houses, temperatures tend to peak on the third-floor void, with the highest maximum recorded at 33.7 °C and during the day, while lower levels show slightly reduced temperatures (Figure 5). During the night, third-floor temperatures remain relatively high, with the maximum reaching 33.5 °C. This pattern shows that the upper levels experience higher temperatures likely due to solar heat gain and reduced ventilation effectiveness.

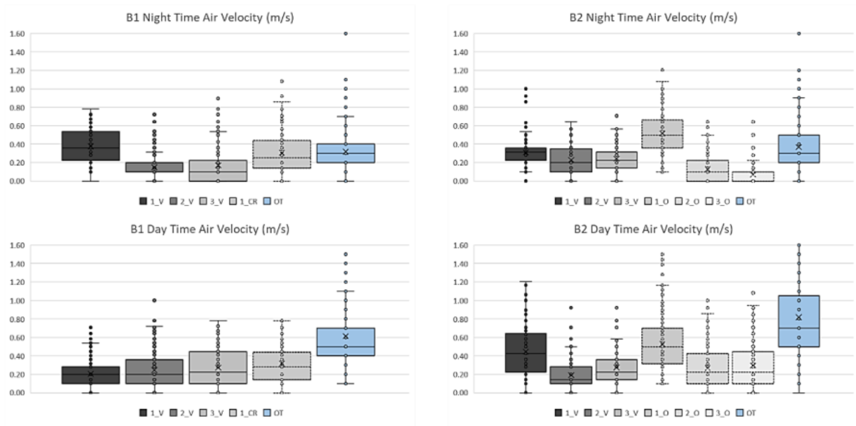


Figure 6. Air velocity comparison from B1 (left) and B2 (right) during night (top) and day (bottom).

For B1, the average air velocity across all measurement points during the day is relatively low (Figure 6). On average, the third-floor void has slightly higher air velocity (0.27 m/s) compared to the first-floor void (0.20 m/s) and the second-floor void (0.25 m/s). The common room on the first floor showed a similar average air velocity (0.32 m/s). Daytime air velocity is generally higher compared to nighttime. The average air velocity across the void levels from top to bottom are 0.38 m/s, 0.15 m/s and 0.17 m/s. In B2, the highest average indoor air velocity during the day was recorded on the first floor (0.45 m/s) followed by the third-floor void (0.27 m/s) and the second-floor void (0.19 m/s). The third floor near the opening had a slightly higher average air velocity (0.30 m/s) compared to the third-floor void. Similar to B1, air velocity during the day is generally higher. The average nighttime air velocity in each void level from bottom to top are 0.31 m/s, 0.23 m/s, and 0.24 m/s. Air velocity at the opening decreases noticeably at night, with an average of 0.07 m/s at the third level opening. Both boarding houses show a consistent trend of reduced air velocity at night compared to the day. During the day, the upper level in both boarding houses tends to have slightly higher air velocity compared to the night time.

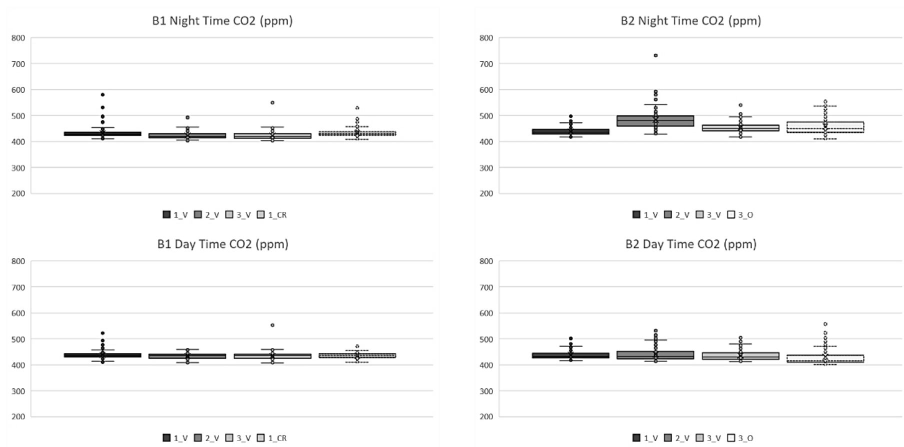


Figure 7. CO2 level comparison from B1 (left) and B2 (right) during night (top) and day (bottom).

Outdoor CO_2 concentration was not measured since the generation of CO_2 in indoor settings is mostly affected by occupancy instead of outdoor conditions. During the nighttime, the average CO_2 concentration in the void of B1 ranges between 422 ppm (third floor) and 433 ppm (common room), while the maximum CO_2 values range from 492 ppm to 580 ppm (Figure 7). A slightly higher CO_2 level in the common room is expected since the area is more enclosed compared to the void. In B2, the average concentration in the void ranges between 439 ppm (first floor) and 458 ppm (third floor), with maximum CO_2 values ranging from 497 ppm to 731 ppm.

In the daytime, the average CO_2 concentration in the B1 void area is slightly higher, ranging between 433 ppm (second floor) and 437 ppm (first floor). Maximum values range from 472 ppm to 553 ppm. In B2, the average CO_2 concentration ranges between 431 ppm (third-floor opening) and 440 ppm (second-floor void). Maximum values range from 512 ppm to 557 ppm. Both buildings show an increase in CO_2 levels during the night, which is more prevalent in B2. This suggests that the void in B1 distributes air more evenly.

C. Ventilation Effects Towards Air Velocity and CO_2 Concentration

The ventilation performance of both boarding houses was analyzed in terms of air velocity (V) and its relationship with the physiological cooling requirement (Vc) across different levels of the void. CO_2 concentration was also evaluated as an indicator of air quality. It was found that CO_2 levels remained relatively stable across both voids. However, the findings regarding air velocity and its ability to meet physiological cooling requirements varied depending on the position and time.

a) B1 Ventilation Performance

Across all void levels, CO_2 concentration was clustered around 400 to 500 ppm regardless of the air velocity, which ranged around 0 and 1.1 during nighttime (Figure 8). The limit of CO_2 concentration indicated by the axis intersection was set at 1000 ppm. Air velocity on the left side of the Y axis is lower than the limit for pleasant sensation which is 0.2 m/s (Szokolay, 2008). Details of the relationship between velocity and Vc requirement show that on the first, second, and third levels, the occurrences of air velocity larger than Vc are only 34%, 27%, and 30%.

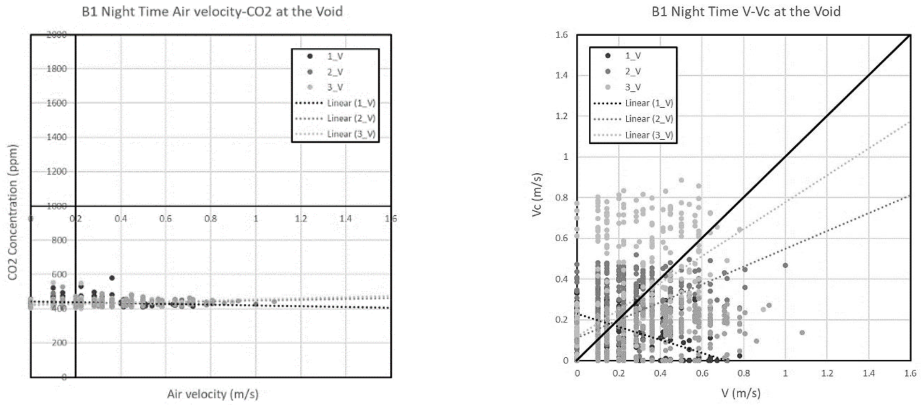


Figure 8. B1 night-time ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on first floor), 2_V (void on second floor), 3_V (void on third floor).

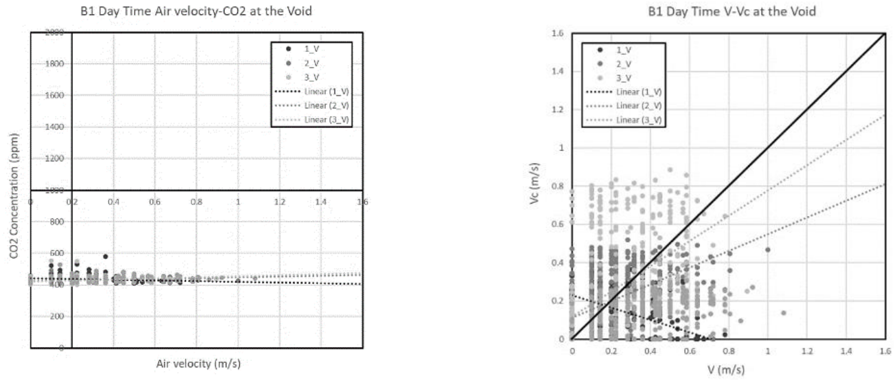


Figure 9. B1 daytime ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on first floor), 2_V (void on second floor), 3_V (void on third floor).

Similarly, during the day, CO_2 concentration was clustered around 400 to 500 ppm while the air velocity ranged around 0 and 1.1. Based on physiological cooling necessities, air velocity at each level from bottom to top which exceeded the minimum Vc was only 31%, 27%, and 21% of the time (Figure 9). This ratio is lower than the night-time ratio, especially on the third level, as the daytime minimum Vc (0.53%) is three times higher than the night time (0.16 m/s).

While the CO2 concentration exhibits a similar pattern, air velocity in the common room and void at the first level shows a different trend. The common room, which is located at the rear side after the void, requires an average Vc of 0.18 m/s in the nighttime, slightly lower than the void Vc (0.23 m/s). 63% of the time this requirement was surpassed, resulting in a negative relationship between V and Vc (Figure 10).

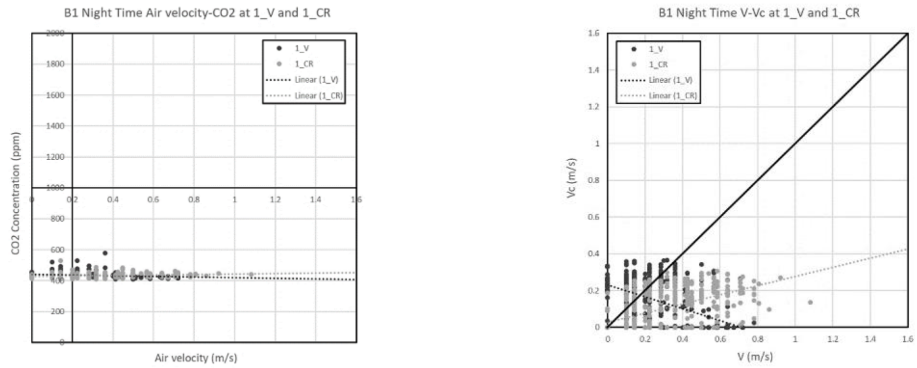


Figure 10. B1 night-time ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on the first floor), 1_CR (common room on the first floor).

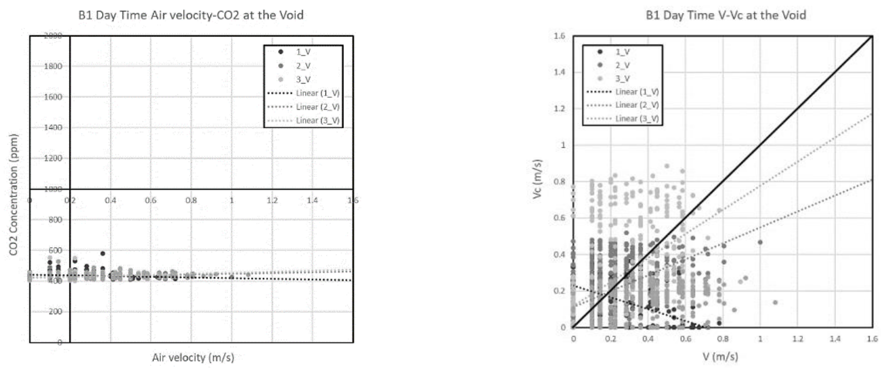


Figure 11. B1 daytime ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on the first floor), 1_CR (common room on the first floor).

During that time, a similar pattern occurred, with V surpassing Vc 48% of the time (Figure 11). However, it still shows that for both the void and common room, a great proportion of recorded air velocity is still insufficient (V < Vc). Due to high air temperature and radiation, the third level requires more Vc, with an average of 0.53 m/s. At night, this required Vc is decreased to 0.16, signifying how radiation amplifies the need for air velocity for physiological cooling.

b) B2 Ventilation Performance

At night, CO_2 concentration in the void was clustered around 400 to 600 ppm while the air velocity ranged between 0 and 1.2 (Figure 12). A maximum CO_2 level of 731 ppm was recorded for a short period, indicating that there was activity nearby during that time. This maximum concentration is still within the health limit of 1080 ppm, therefore remediation is not necessary (Samudro et al., 2023). Compared to B1, there were more occurrences where V was larger than Vc on each void level from bottom to top by 43%, 32%, and 46%. This indicates that B2 benefits from larger WWR on the front side, improving ventilation, especially on upper levels.

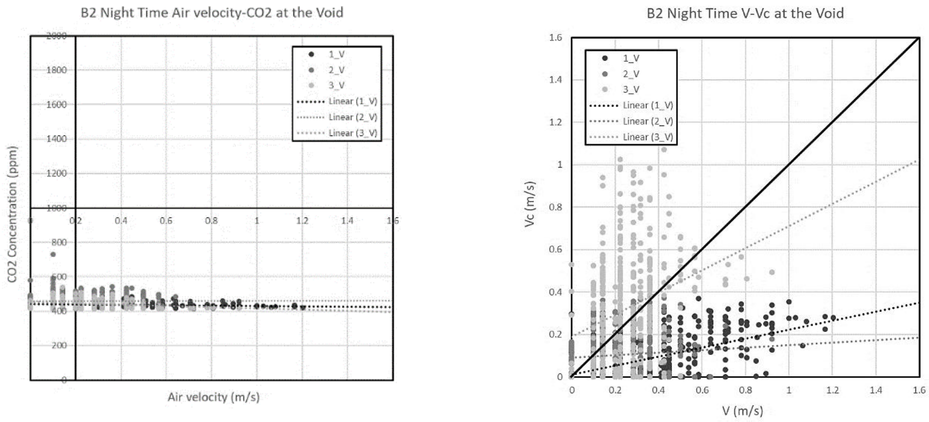


Figure 12. B2 night-time ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on first floor), 2_V (void on second floor), 3_V (void on third floor).

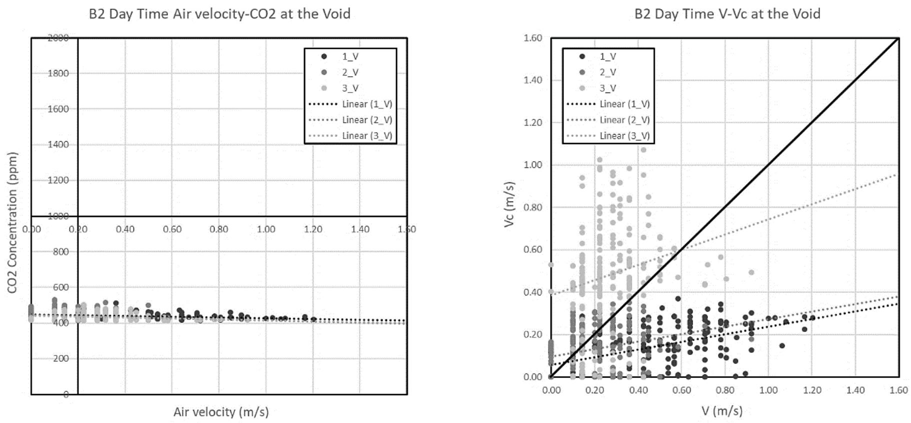


Figure 13. B2 daytime ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 1_V (void on first floor), 2_V (void on second floor), 3_V (void on third floor).

CO_2 concentration during the day is clustered similarly to night time (Figure 13). The average air velocity of each level from the bottom are 0.45 m/s, 0.19 m/s, and 0.27 m/s. The highest velocity at the pilotis can be attributed to the large opening ratio at the ground level, which had an average intake of 0.53 m/s. Pilotis acts as an opening which plays important role in determining the effectiveness of ventilation. Large windward opening ensures optimized airflow throughout the void space (Hakim et al., 2025). Meanwhile, the velocity at the top level was caused by the intake at the third level height (0.3 m/s) and the buoyancy caused by higher temperature.

Reaching peak air temperature of 39°C, the third level requires the highest Vc compared to any other position. While the air velocity at the pilotis exceeded Vc for 67% of the time, the second level air velocity only surpassed Vc for 38%, and even lower at the third level, which was 0.15 %.

Measured air velocity near the third level opening shows that there is a reduction of air velocity from the opening (0.23 m/s) into the void (0.07 m/s) by 30% (Figure 14). The decrease of air velocity in the void might be attributed to less buoyancy due to nighttime air temperature. However, the minimum Vc for the void area was also decreased during nighttime since air temperature and radiation dropped significantly. Average night time Vc for third level void and opening are each 0.22 m/s and 0.09 m/s, which are close to the average air velocity. For each position, V surpassed the required Vc for 46% and 44% of the time.

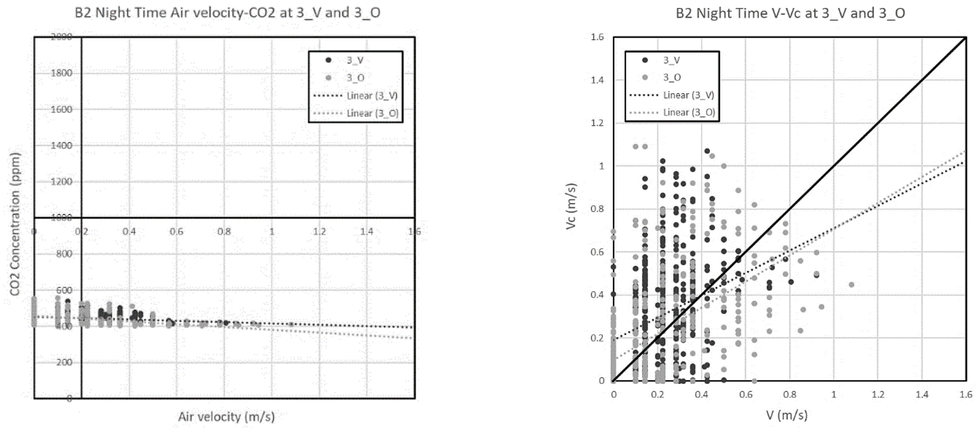


Figure 14. B2 night-time ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 3_V (void on the third floor), 3_O (third-floor front opening).

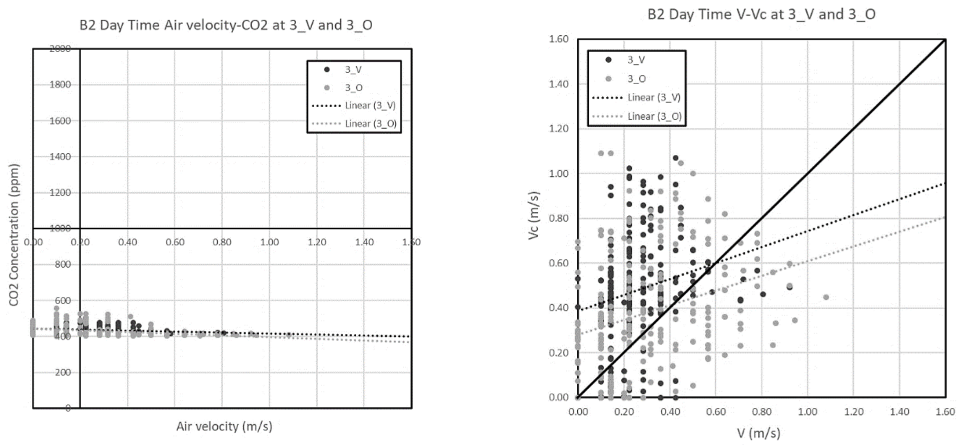


Figure 15. B2 daytime ventilation point-in-time air velocity evaluation based on CO2 concentration limit and physiological cooling requirement; 3_V (void on the third floor), 3_O (third-floor front opening).

During the day, similar average air velocity on third level void (0.27 m/s) and opening (0.3 m/s) were recorded. At night time, third-level void air velocity was at 0.24 m/s while the opening was 0.07 m/s (Figure 15). Relatively stable air velocity in the void might be attributed to the buoyancy caused by temperature, as the intake on the openings shows a significant decrease. Air temperature on the third level void was the highest at day (32.2 °C) and night (30.4 °C), compared to another level. This condition, possibly due to the thermal mass, maintains the upward air velocity regardless of decreasing air intake during nighttime.

At 0.50 m/s, the daytime Vc in the third level void is significantly higher than night time. This decreases the proportion of adequate air velocity for physiological cooling to 15%, indicating that natural ventilation at the third level is not sufficient for cooling. At the third level opening, the proportion is 56%, which is higher than night time. Daytime Vc at the opening is significantly higher (0.42 m/s) with an average air temperature of 34.6 °C compared to night time (0.09 m/s). However, the air velocity of opening intake is higher with an average of 1.08 m/s.

D. Effects of Void Design Variables Towards Air Velocity

Ventilation performance in the vertical void is determined by various design variables such as void-to-building ratio, void aspect ratio, and the size and position of openings. These factors play a crucial role in determining airflow patterns and ventilation effectiveness across different floors. The two boarding houses analyzed in this study differ notably in their void designs, with one featuring a centrally positioned void with a higher aspect ratio (B1) and the other utilizing an end-positioned void with a smaller void-to-building ratio (B2). These differences provide an opportunity to assess how specific design choices impact airflow distribution, air velocity, and the effectiveness of passive ventilation both during the day and night.

a) Night Time Ventilation

B1 have a larger void-to-building ratio (0.3) compared to B2 (0.06), and a larger void aspect ratio (0.49) compared to B2 (0.17). During the night time air velocity in the void decreased in buildings with higher void-to-building ratio and void aspect ratio on the second and third floor, while increased on the pilots (first floor) (Figure 16). At 0.1 void-to-building ratio, air velocity shows a slight increase with void aspect ratio but remains relatively consistent, clustering around 0.4–0.6 m/s. Air velocity slightly decreases as the void-to-building ratio and void aspect ratio increase, indicating diminishing returns in ventilation performance with wider voids at mid-level. At both cases, air velocity decreases as the void aspect ratio increases, since taller void with smaller W/H enhance stack effect better than wider void (Hakim et al., 2025). This trend is more pronounced at 0.3 void-to-building ratio, where wider voids reduce air velocity on the top floor.

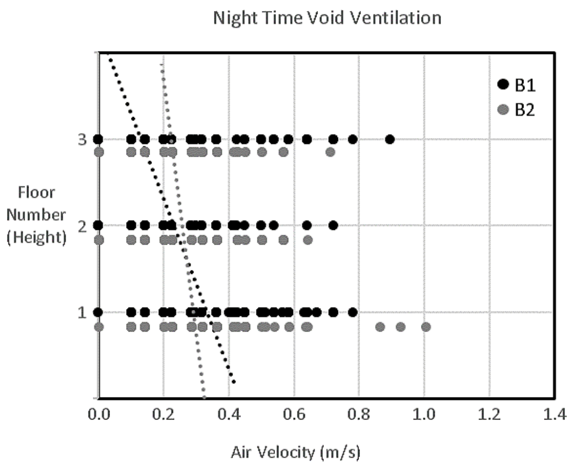


Figure 16. Night-time ventilation indicated by air velocity distribution on each void level to void-to-building ratio and void aspect ratio.

Consistently higher air velocity on the first floor might be an indication of the greater proportion of opening area compared to upper levels. The second level displays moderate air velocity, which indicates that the airflow is less sensitive to changes in void aspect ratio compared to the pilotis. This is also attributed to the corridor length as corridors can act as an interruption to the airflow (Kumar et al., 2023a). Void ventilation might benefit from the shorter distance between the opening and the void to maximize airflow induced by intake. The third level exhibits the lowest air velocities overall, particularly at larger void aspect ratios. This could be attributed to weaker air exchange and less effective upward airflow as distance from the ground increases. Due to the venturi effect, a void larger aspect ratio decreases wind pressure and air velocity moving through the void (Muhsin et al., 2017). A larger void-to-building ratio (0.3) and larger void aspect ratio (0.49) improve night time velocity for the first floor, while upper-level ventilation benefits from a smaller void-to-building ratio (0.1) and smaller void aspect ratio (0.17).

b) Daytime Ventilation

Daytime air velocity shows a different pattern to void-to-building ratio and void aspect ratio (Figure 17). Air velocity shows a negative relationship with the void aspect ratio and the void-to-building ratio at the first level. However, this relationship might also be attributed to the WWR ratio of the front opening, especially at the ground level. The building with a larger void aspect ratio and void-to-building ratio is B1, which has a smaller front WWR (0.23) compared to B2 (0.58). This may limit the airflow which lower the air velocity at 0.3 void-to-building ratio and 0.49 void aspect ratio.

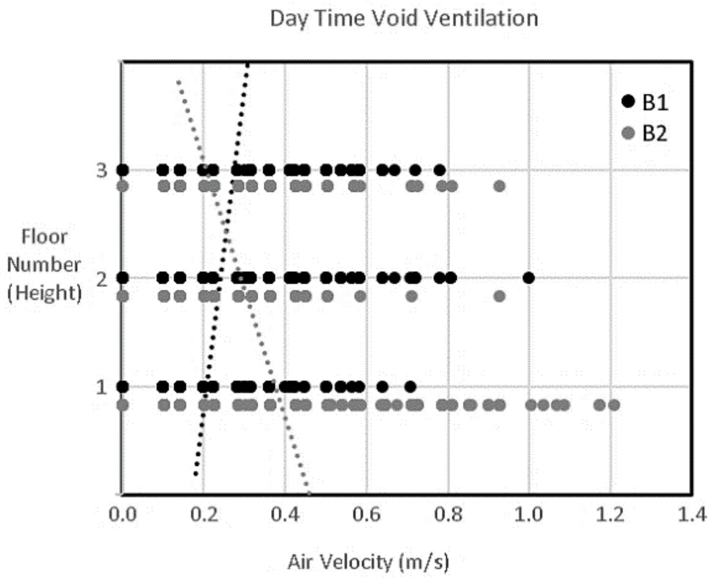


Figure 17. Daytime ventilation indicated by air velocity distribution on each void level to void-to-building ratio and void aspect ratio.

The first level exhibits the highest air velocities, especially B2, which has lower void aspect ratios (0.17) and a lower void-to-building ratio (0.06). Air velocity at the pilots is larger compared to another area as it is amplified by the venture effect (Kumar et al., 2023a). B2 shows higher air velocity since the pilots area is larger than B1. The second level void shows moderate and stable air velocity while the third floor shows a distribution of low air velocity, regardless of the void aspect ratios and the void-to-building ratio. It shows that day time ventilation performance is less affected by void design (void ratio and position) changes compared to night ventilation. Larger void aspect ratios (wider voids) reduce the airflow, leading to lower air velocities near the ground level. This is likely due to a reduction in the chimney effect, as wider voids disperse air velocity (Kumar et al., 2022). Compared to buildings with a smaller void aspect ratio, a larger void aspect ratio increases air velocity as shown in Figure 17. A smaller void ratio is expected to increase wind pressure, therefore it improves the upward airflow for better ventilation at upper levels. The difference between night and day performance shows that vertical void in the studied boarding houses mostly works by dispersing indoor air to the outdoor through upward airflow, instead of acting as the suction zone.

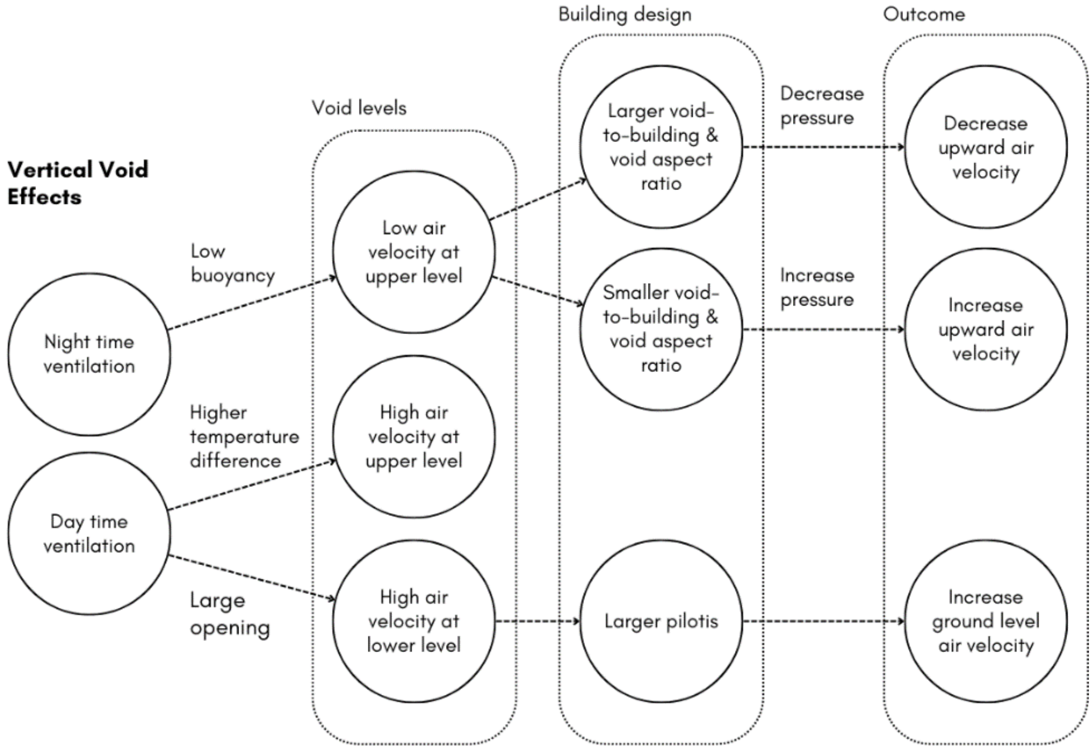


Figure 18. Suggested effects of void towards ventilation.

Different effects of vertical void on ventilation were observed during night and day (Figure 18). Ventilation in vertical void is more effective during the day than at night due to stronger thermal buoyancy and higher wind speed. The thermal buoyancy is especially higher since the temperature at upper levels is greater during the day. At night, weaker thermal and wind forces result in lower air velocity, particularly on upper levels. Larger void-to-building and aspect ratio are found to be decreasing upward air velocity by lowering pressure inside the void. Smaller ratios increase the indoor pressure, therefore increasing air velocity inside the vertical void. Air velocity is also affected by the pilots size, as boarding house with larger pilots shows higher air velocity at the ground level.

CONCLUSION

This study analyses the performance of vertical void ventilation regarding air quality, indicated by CO_2 concentration, and physiological cooling, indicated by air velocity. The results show that CO_2 concentration is not affected by the ventilation performance while the void-to-building ratio and void aspect ratio affect the condition of air velocity for physiological cooling. A descriptive analysis towards boarding house void ventilation performance reveals some insight into how void design can be adjusted to improve ventilation performance.

1. In both boarding houses, CO_2 concentrations remain clustered around 400–600 ppm, regardless of vertical void design and indoor air velocity. This level is acceptable for an indoor environment. While higher air velocities improve physiological cooling and ventilation comfort, the airflow patterns seem not to affect CO_2 concentration. However, this consistent CO_2 level may be attributed to the large volume of void and low level of occupancy. Although remediation regarding air quality is not necessary for common room, the condition of airflow for physiological cooling is more complicated especially due to the difference between day and night time conditions.
2. Day time ventilation is more effective across void levels compared to night ventilation. This is primarily due to enhanced thermal buoyancy and stronger wind velocity, as shown by the recorded air velocity at the openings. The increased solar radiation during the day generates greater temperature differentials, which amplify the stack effect, driving upward airflow through the vertical void. Besides stack effect, ventilation is also driven by typically higher daytime outdoor wind speeds. Ventilation performance is weaker at night, particularly on upper levels where the thermal buoyancy and wind speed are insufficient to drive significant airflow.
3. Night time ventilation at upper levels is characterized by lower air velocity. A larger void-to-building ratio (0.3) and larger void aspect ratio (0.49) enhance ventilation during the day by allowing greater interaction between the void and outdoor wind flow. However, this benefit diminishes at night, when the absence of strong thermal and wind forces limits the upward airflow. A narrower void with a lower void-to-building ratio (0.06) and lower aspect ratio (0.17) shows better airflow, especially during the night. Adjusting the void-to-building ratio and void aspect ratio on each level may enhance stack effect and improve ventilation performance and create stable upward airflow during night and day. Ventilation performance in multi-story residential buildings like boarding houses might be optimized by applying voids with floor height differences and size variations (void-to-floor-area ratio).

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