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Indoor Environmental Quality assessment of mixed-mode ventilation with ceiling fans in the tropics

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Abstract. Mixed-mode ventilation in buildings has a potential for significant energy savings. However, previous attempts in the tropics were unsuccessful due to the hot and humid weather. Indeed, there is little to no natural ventilation potential in tropical climates if conventional air conditioning systems are used. Additionally, existing studies typically do not consider the noise and air quality constraints while the performance of mixed-mode buildings is susceptible to outdoor conditions. Using elevated air movement has proven to be an effective strategy to offset the rise in the room temperature setpoint without sacrificing occupants' thermal comfort as it helps dissipate body heat through the convective cooling effect. Hence, this study aims at investigating the total indoor environment quality (IEQ) performance of mixed-mode ventilation operations with various air speeds based on tropically acclimatized subjects. To this end, a testbed was designed and constructed in Singapore, consisting of a variable air volume (VAV) system, ceiling fans with continuous speed control, personal ventilation (PV) desks, and plenum acoustic windows. Five operating modes have been tested: fully air-conditioned (AC) mode using VAV alone, hybrid air conditioned (AC+PV) mode using VAV and PV desks, concurrent ventilation (CV) mode using PV desks with the windows partially opened, natural ventilation (NV) mode with the windows fully opened, and acoustic natural ventilation (Acoustic NV) mode with the windows partially opened. 57 subjects were invited to the experiment and asked to complete a comprehensive IEQ survey under 16 different indoor conditions, which are combinations of these operating modes and air speeds ranging from 0.10 to 1.15 m/s. Experiment results show that NV and CV in Singapore can achieve more than 90% thermal acceptability with adequate air movement. More importantly, the median standard effective temperature (SET*) for thermal neutrality is approximately 3°C higher when operating in NV as compared to AC+PV or CV modes, indicating adaptation even when the modes switches are within the same day.

1 Introduction

Natural ventilation has the potential to significantly reduce building operating costs. However, due to the hot and humid climate year-round, tropical cities have almost zero natural ventilation hour if no mechanical cooling method is used [1]. Ceiling fans with elevated indoor air temperature could extend the thermal comfort zone and this strategy has been successfully implemented in tropical buildings [2, 3]. To take the advantage of free cooling from the outdoor air as often as possible, ceiling fans have also been used for mixed-mode ventilation such as in [4]. More specifically, experimental results have revealed that occupants feel comfortable in indoor environments up to 29 °C if increased air movement is provided [5-7]. Furthermore, studies have shown that occupants in naturally ventilated buildings were much less sensitive to the temperature changes than those in air-conditioned buildings [8]. Therefore, the combined use of natural ventilation and ceiling fans is a promising strategy for energy efficiency in tropical climates.

Although natural ventilation has great potentials for reducing building energy and improving occupant comfort and indoor air quality, outdoor disturbances are often not considered in previous research on mixed-mode ventilation [9]. In fact, outdoor noise and air pollution are major public issues that negatively impact human comfort, health and well-being [10]. Lee et al. surveyed 105 schools in Singapore on their external noise and concluded that only about 6% of the schools met the recommended noise performance requirements [11], resulting in natural ventilation being unsuitable most of the time. Song et al. estimated that the loss of annual natural ventilation saving potentials in London due to the noise and air pollution were 8 kwh/m^2 and 9 kwh/m^2, respectively [12]. Tong et al. found that the loss of natural ventilation hours due to air quality problems in China was as high as 1,655 hours [13]. Therefore, considering such outdoor disturbances is essential for operating mixed-mode buildings.

Personal ventilation systems attempt to improve the inhaled air quality and thermal comfort by supplying unpolluted air directly to occupants' breathing zone [14]. Compared with conventional mixing ventilation, it can achieve up to 80% reduction in the pollutant level in inhaled air [15]. Additionally, studies have shown that lowered inhaled air temperature and humidity would lead to improved perceived air quality [15, 16]. Besides, since PV is capable to the control microclimate,

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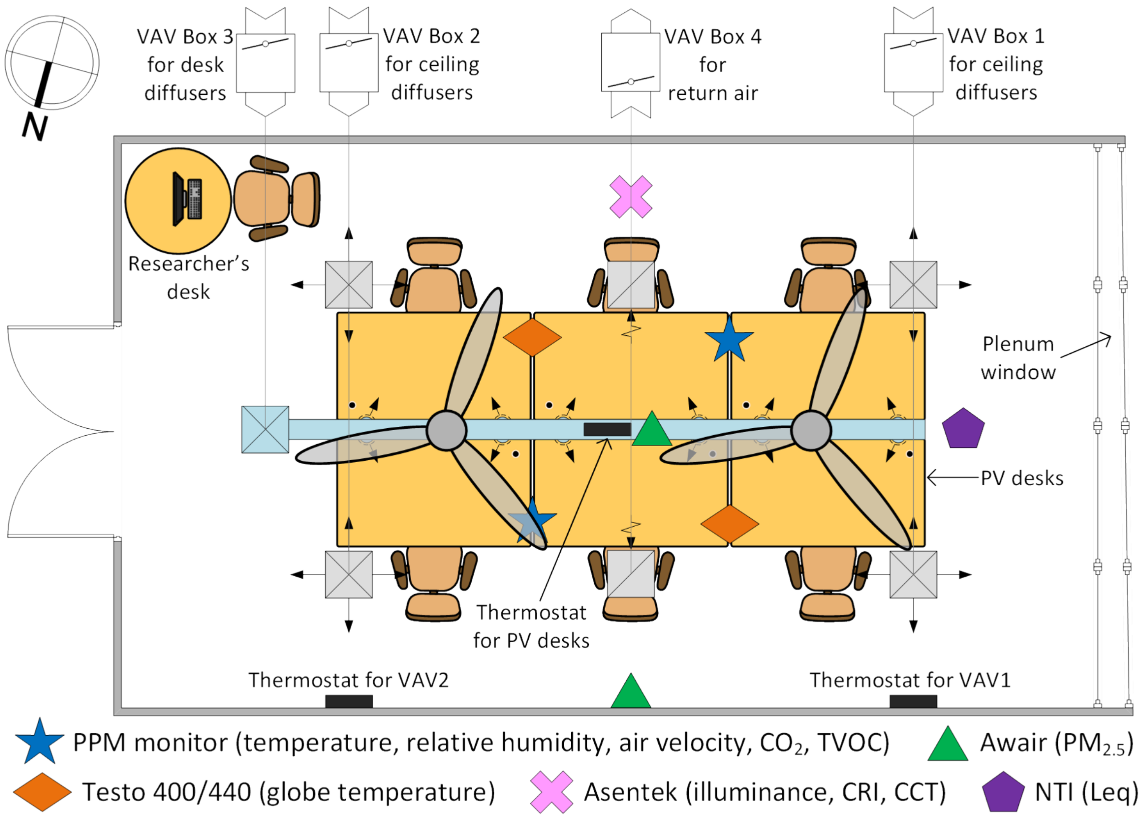

Fig. 1. Floor plan and measurement plan of the testbed

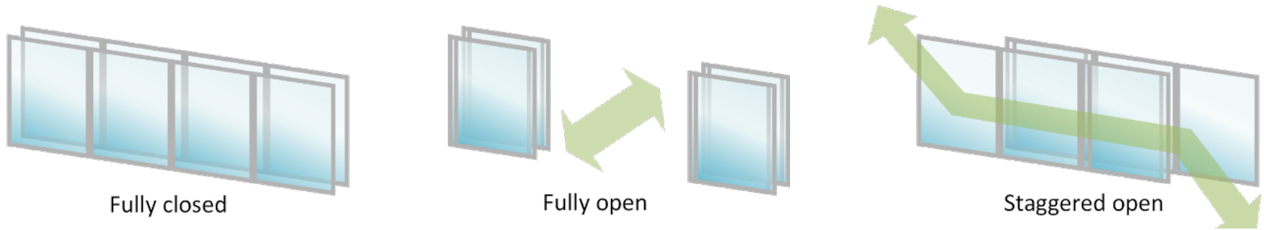

Fig. 2. Illustration of plenum window states

significant energy savings can be achieved by allowing increased room ambient temperature, which is especially suitable for hot and humid climates [17]. On the other hand, using plenum windows is an effective way to achieve sound insulation and natural ventilation at the same time, which composes of double glazing with staggered openings. Compared to standard windows, the sound reduction from plenum windows is between 7.1 and 9.5 dBA [18], making them the promising solution to outdoor noise problems during natural ventilation in compact cities [19].

According to the literature, two knowledge gaps have been identified. First, very little is currently known about the integration of PV, ceiling fans, and plenum windows, as they would provide a different indoor environment than using a conventional air conditioning system with openable windows. In fact, current standards only provide a conservative upper air speed limit to protect occupants who are sensitive to air movement [20]. Second, most mixed-mode ventilation control studies consider only thermal constraints, such as the predicted mean vote (PMV) or temperature bands. However, far too little attention has been paid to address other IEQ requirements such as acoustic and air quality performance. Therefore, the objective of this study is to investigate the total IEQ performance of mixed-mode ventilation operations using PV and plenum windows at various air speeds.

2 Experimental design

2.1 Experiment setup

To systematically assess the IEQ performance, an occupant comfort experiment was conducted to acquire both subjective and objective measurement data under various mixed-mode ventilation conditions. A 50 m^2 testbed (9m (L) * 5.6m (W) * 2.8m (H)) was constructed on the 3rd level of the Building and Construction Authority Academy (BCAA) building in Singapore. The floor plan is illustrated in Fig. 1, which consists of six personal ventilation (PV) desks, a researcher's desk, and a plenum window. In particular, the specially designed window can operate as a conventional ventilation window or as an acoustic window (staggered opening), the latter of which allowed a certain degree of natural ventilation while attenuating noise from the outdoor. Meanwhile, a dedicated air handling unit was responsible for supplying conditioned air to four VAV

Table 1. Summary of operational conditions tested in the experiment

Mode	Description	Temperature setpoint	Ceiling fan speed
AC	Supply air via ceiling diffusers, plenum window closed	24 °C and 26 °C	Off, low, medium
AC+PV	Supply air via both ceiling and desk diffusers, plenum window closed	26 °C	Off, low, medium
CV	Supply air via desk diffusers, plenum window staggered-open	26 °C and 28 °C	Off, low, medium, high
NV	Plenum window fully-open	Free floating	Off, low, medium, high
Acoustic NV	Plenum window staggered-open	Free floating	Off, low, medium, high

boxes. Specifically, VAV box #1 and #2 connected to the ceiling diffusers for ambient temperature control, while VAV box #3 connected to diffusers located at the PV desks serving the occupied area. The participants were allowed to toggle the desk diffusers to make them comfortable. Moreover, elevated air movement was provided through two ceiling fans with 4-level speed controls (Off: ~0.15 m/s, Low: ~0.45 m/s, Medium: ~0.90 m/s, High: ~1.15 m/s).

This experiment considered five mixed-mode ventilation modes as shown in Table 1. The corresponding plenum window opening status is illustrated in Fig 2. In each mode, combinations of various room temperature setpoints and ceiling fan speeds were tested, resulting in 23 different operating conditions. Approved by the Institutional Review Board (NUS-IRB-2021-325), the experiment was conducted over ten executive working days from 20th June to 1st July in 2022 with 57 tropically acclimatized subjects (28 males and 29 females). All participants were between 21 and 60 years old, with an average age of 33 years old. Participants were asked to perform their regular office activities in the testbed for 8-hour in a single day. Throughout the experiment, indoor operating conditions were changed every 30 minutes in a randomized order. Hence, every participant experienced 16 unique operating conditions. At the 25th minute of each condition, a standard post-occupancy evaluation survey was carried out online, which consisted of 15 questions related to occupants' thermal, air quality, acoustic and visual comfort.

Since the surveys were only conducted at the end of each condition, this study evaludated the occupants' IEQ satisfaction in steady-steady conditions in the the AC, AC+PV, and CV modes with fixed temperature setpoints. Although the indoor temperature was free-floating in both NV and acoustic NV modes, the testbed was considered to have reached a steady-state temperature and humidity at the time of the survey due to the relatively stable daytime outdoor climate in Singapore. Furthermore, when the air handling unit was on, the outdoor air damper was manually adjusted to maintain an 8-hour average CO_2 concentration between 600 and 700 ppm.

2.2 Data collection and processing

For the objective measurement, indoor environment variables in the testbed were continuously monitored at 1-minute intervals at the desk height (0.8m). The locations of measurement instruments are depicted in Fig. 1. The measured indoor environment variables and the sensor specifications are summarized in Table 2. After collecting the raw data, we removed the outliers for data points that were more than three standard deviations from their mean to avoid bias due to sensor errors. Since most of the environment variables were monitored at two separated locations in the room, we calculated their mean values as the representations of average indoor conditions. The subjective survey responses were also manually verified by checking for duplicate or incomplete survey responses. We rectified erroneous inputs and retained only the most recent submission responses. Finally, for every comfort survey response, we considered the environmental variables measured at the same time as the participants submitted the survey as the corresponding objective measurement data. Based on the these processing steps, the cleaned dataset consisted of 905 valid instances.

Table 2. Indoor environment variables and instrument

IEQ aspect	Variable	Unit	Sensor brand	Accuracy
Thermal	Air temperature	°C	PPM	±0.3 °C
	Relative humidity	%		±1.8%
	Air velocity	m/s		±0.1 m/s
	Globe temperature	°C	Testo	±0.2 °C
Indoor air	CO_2	ppm	PPM	±75 ppm
	TVOC	ppm		±10%
	PM2.5	μg/m^3	Awair	±15 μg/m^3
Acoustic	Leq	dBA	NTI	±0.5%
Visual	Illuminance	Lux	Asentek	±3%
	CRI	%		±2%
	CCT	K		±2%

3 Results and discussion

3.1 Overall IEQ performance

The overall thermal, IAQ, acoustic and visual comfort performance in the five modes are illustrated in Fig. 3, Fig. 4, Fig. 5, and Fig. 6, respectively. The AC+PV mode received the most "clearly acceptable" votes, while the total thermal acceptability rate, which is the sum of "clearly acceptable" and "just acceptable" rates, was the same as the AC mode. The NV and Acoustic NV mode only achieved about 70% total thermal acceptability, which is expected as occupants may experience discomfort when it is hot outside and there is

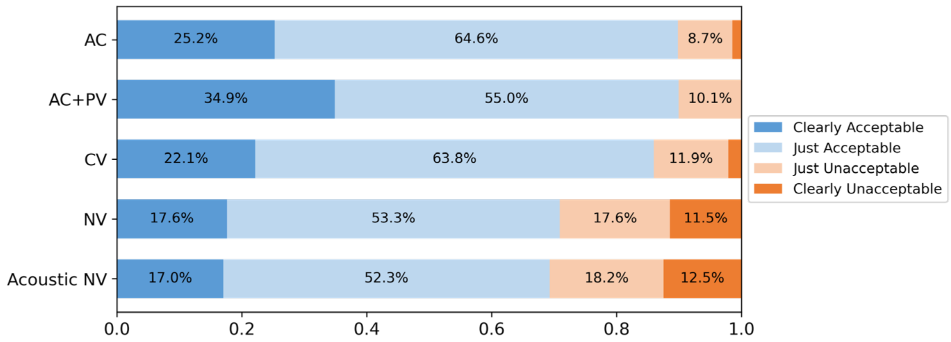

Fig. 3. Thermal acceptability for various modes

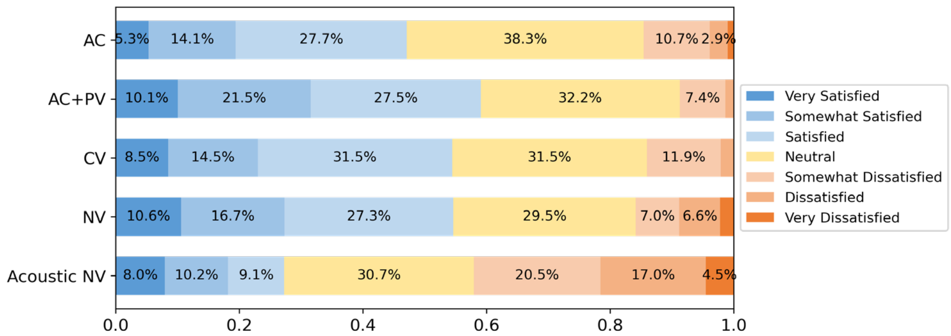

Fig. 4. Air freshness satisfaction for various modes

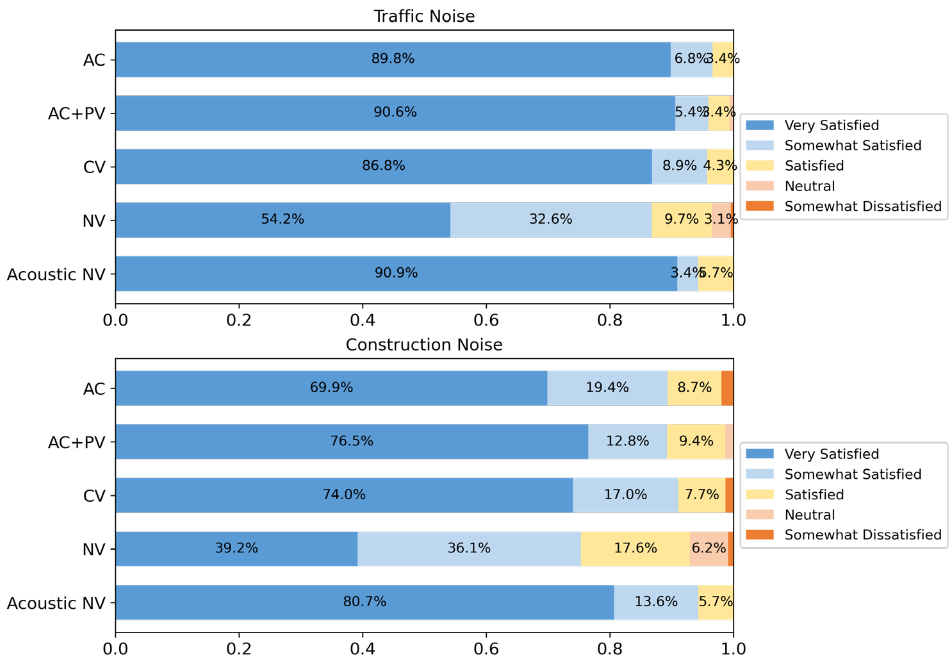

Fig. 5. Acoustic annoyance from traffic (top) and construction (bottom) for various modes

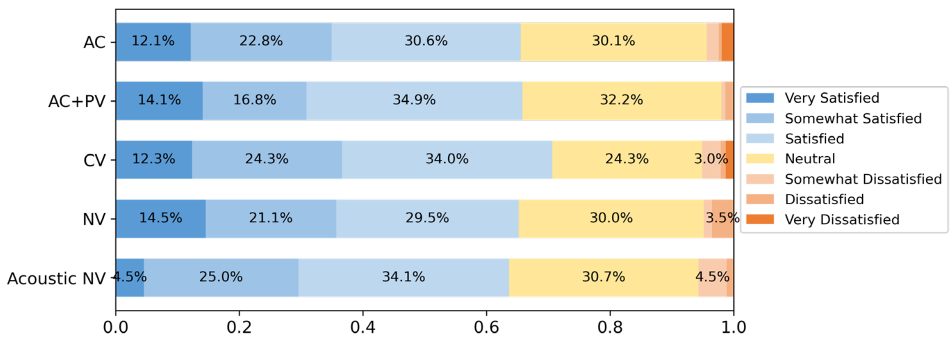

Fig. 6. Daylight or natural light satisfaction for various modes

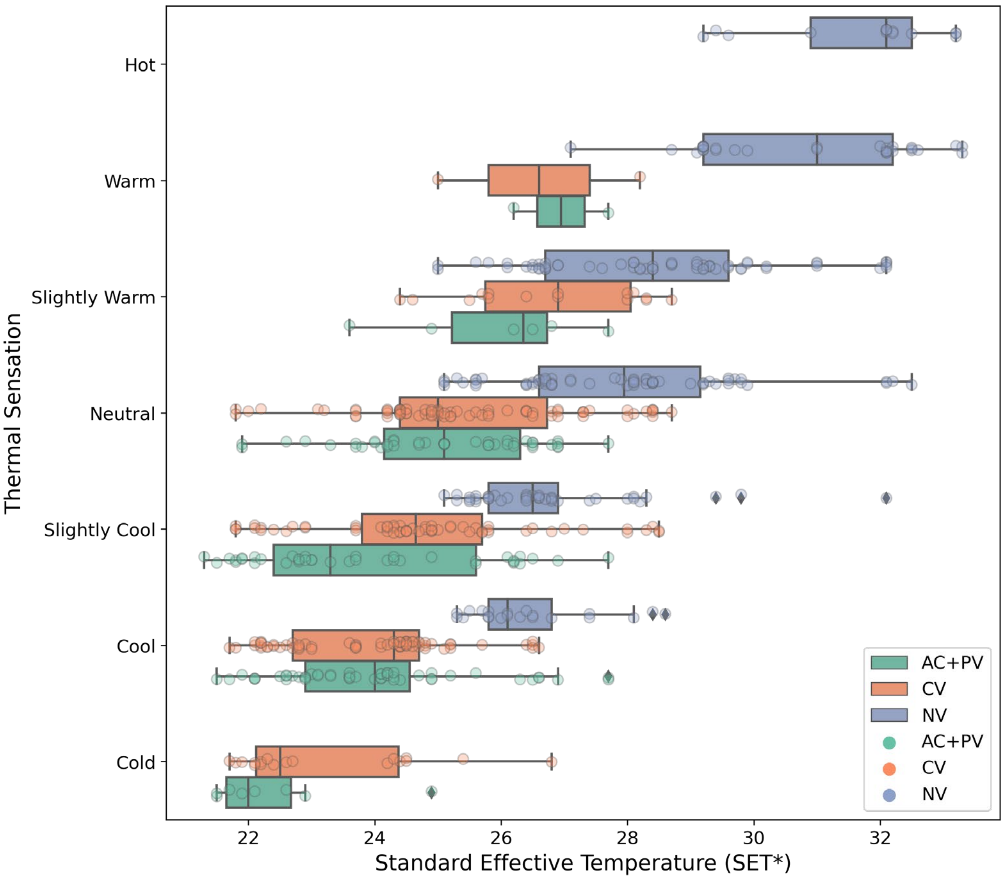

Fig. 7. Thermal sensation vote and SET*

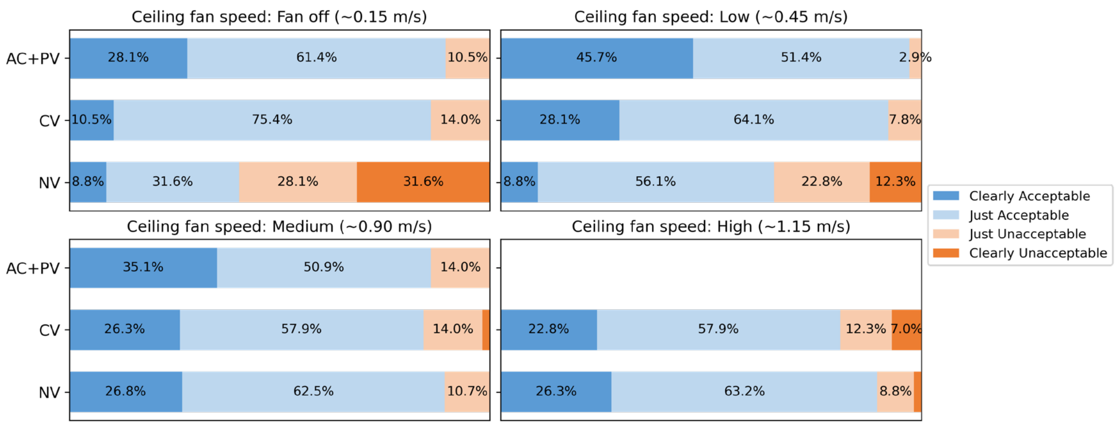

Fig. 8. Thermal acceptability vote at different ceiling fan speeds.

insufficient air movement. The total thermal acceptability was 16% higher in the CV mode than in the Acoustic NV mode, indicating the spot cooling strategy improved thermal comfort in tropical climates.

The IAQ dissatisfaction rates were similar for all modes except the Acoustic NV mode, ranging from 9% to 16%. Since the effectiveness of natural ventilation is highly dependent on climatic conditions, insufficient window openings can lead to poor indoor air quality. In this experiment, the plenum window was designed to prioritize noise reduction requirement (R'w = 29 dB), and the opening size was very limited in the staggered-open operation. Consequently, the median and max CO_2 concentration measured in the Acoustic NV mode was 950 ppm and 1346 ppm, respectively, which was significantly higher than that in the modes with mechanical ventilation (616 to 724 ppm). On the other hand, the median CO_2 concentration in NV mode (664 ppm) was only slightly higher than that in AC+PV and AC modes, indicating that natural ventilation alone was sufficient to meet the ventilation requirements in the testbed setup.

The testbed was about 50 meters away from a construction site and faced a parking lot, so it was affected by both traffic noise and construction noise. Results showed that occupants were more disturbed by the construction noise than the traffic noise. Not surprisingly, for 46% and 60% of the time in NV mode, occupants were disturbed by the traffic noise and construction noise, respectively. In contrast, the acoustic comfort votes were similar when the plenum window was fully closed or staggered-open. The measured mean

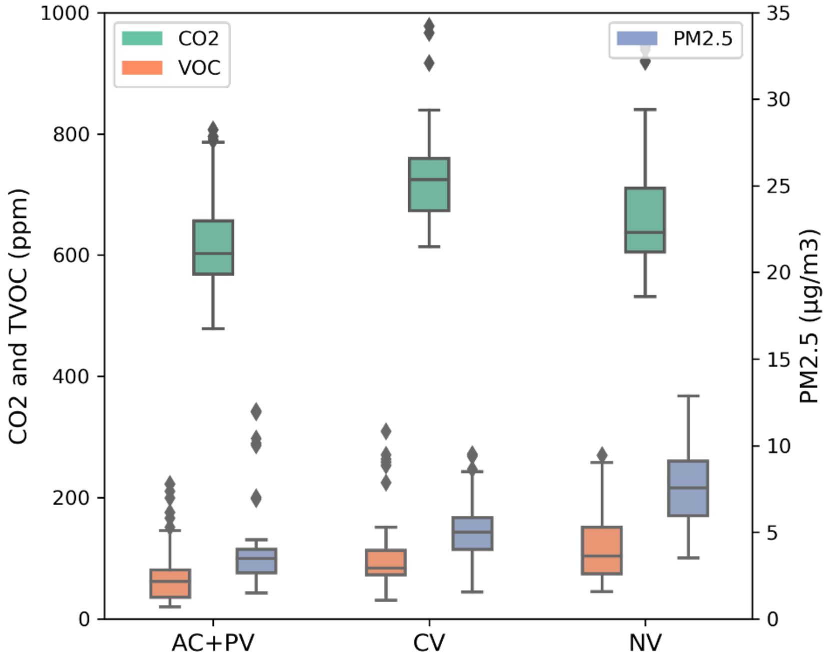

Fig. 9. Comparison of measured CO2, TVOC and PM2.5 in different modes

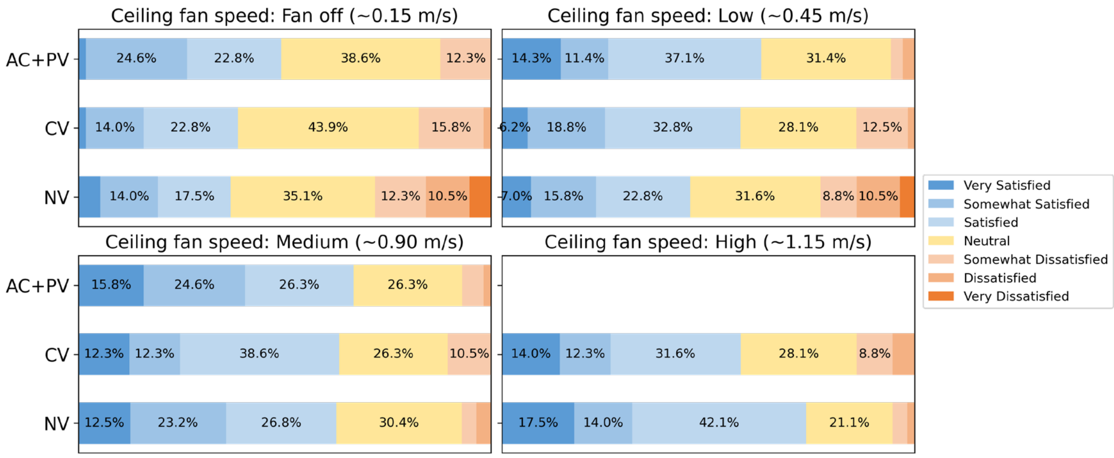

Fig. 10. Air freshness satisfaction at different ceiling fan speeds.

indoor noise level was 45.6 dB $LA_{eq,1\text{-}min}$ in the NV and 37 to 39 dB $LA_{eq,1\text{-}min}$ in the other modes, suggesting that the proposed plenum window design achieved a similar level of acoustic performance as a closed window while providing natural ventilation. Hence, in compact cities, acoustic disturbances must be carefully considered when designing naturally ventilated spaces, as indoor noise levels can easily exceed those measured in this experiment.

The occupants' satisfaction with the amount of daylight or natural light was similar across different modes, probably because the existing artificial lighting was good enough to provide visual comfort. Based on the light meter, there was no significant difference in the mean illuminance level, CCT, and CRI of the different modes.

According to the IEQ assessment results, the AC+PV mode achieved the best overall performance. It outperformed the AC mode in terms of thermal and IAQ comfort due to the capability to allow individuals to control their micro-environment. The Acoustic NV mode cannot provide a satisfactory IAQ due to the limited window opening size for natural ventilation. The integration of PV and staggered-open plenum window leads to the spot cooling strategy (i.e., the CV mode), providing similar IEQ comfort to the conventional AC mode, while saving building energy through raising the ambient temperature [21]. Hence, the AC+PV, CV, and NV modes are recommended based on this testbed configuration, and the analysis in the following sections mainly focuses on these three modes.

3.2 Same-day thermal adaptation for tropically acclimatized subjects

Fig. 7 compares the relationship between thermal sensation votes and the corresponding Standard Effective Temperature (SET*). The median SET* for thermal neutrality is approximately 3°C higher when operating in the NV as compared to the AC+PV or CV mode, indicating adaptation even when the mode switching is within the same day. Because of the longitudinal experiment design, this finding suggests that tropically acclimatized subjects in naturally ventilated buildings would be more tolerant of warmer indoor environment than in air-conditioned buildings. Consequently, to maximize occupant thermal satisfaction, it is important to account for differences in thermal comfort when switching modes in mixed-mode ventilated buildings. Results from this experiment also agreed with the ASHRAE Comfort Database II [22, 23] that the building neutral temperatures were 1–2°C higher in Asian countries than in Western countries.

3.3 Importance of air movement

As shown in Fig. 8, the AC+PV, CV and NV modes can achieve over 90% total thermal acceptability with adequate air movement. Specifically, the highest percentage of thermal acceptability was provided with a low ceiling fan speed (around 0.45 m/s) for the AC+PV and CV mode and with a high ceiling fan speed (around 1.15 m/s) for the NV mode. Furthermore, compared with the environment with no air movement, a low ceiling fan speed at around 0.45 m/s improved the thermal acceptability by 7% in the AC+PV and CV modes. Therefore, it is essential to optimize the ceiling fan speed to maximize occupant comfort.

In this experiment, occupants were found to be more sensitive to the airflow in the NV mode than in the other modes due to the greater variation in thermal acceptability rate (from 40% to 90%). However, this outcome seems to be contrary to that of Rupp et al. [8] who found that occupants in naturally ventilated buildings were less thermal sensitive than occupants in the air-conditioned buildings. This inconsistency may be explained by the fact that thermal sensitivity is typically estimated as the occupant's change in thermal sensation per unit indoor temperature change, with the key assumption being that the air speed is constant [24]. However, changes in air movement and air temperature may have different effects on occupant thermal sensitivity. Another possible explanation is that the indoor temperature range in the NV mode (27.6–30.8 °C) has little overlap with those in the other modes (24.1–28.3 °C).

3.4 The perceived air freshness

All three modes maintained good indoor air quality, which was well below the existing thresholds (Fig. 9). Interestingly, it can be seen from the data in Fig. 10 that higher air movement generally led to better-perceived air freshness even though the measured IAQ metrics were similar. Since an additional form of airflow is provided through the desktop diffusers in the AC+PV mode, this finding possibly explains why this mode provided the highest air quality satisfaction.

4 Conclusions

A comprehensive longitudinal IEQ assessment for five mixed-mode ventilation modes with elevated air movement was conducted in a testbed in Singapore. Both subjective measurements from 57 tropically acclimatized subjects and objective measurements via IEQ sensors were collected and analyzed. The experiment results showed that even in the hot and humid climate, natural ventilation or spot cooling strategy could achieve over 90% total thermal acceptability with adequate air movement. Moreover, the PV desks could improve occupant thermal and IAQ satisfaction as it allows for personal control of the airflow. In the NV mode, the occupants were susceptible to the noise annoyance, and the plenum window is an effective approach to alleviate the acoustic disturbance. More importantly, the same-day thermal adaptation was observed, suggesting that it is important to account for differences in thermal comfort when switching modes in mixed-mode ventilated buildings. Although the current study is based on a small sample of participants, the findings provide valuable insights into future design and operation of mixed-mode buildings in the tropics.

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