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Assessing the Indoor Comfort and Carbon Dioxide Concentration in High-Rise Residential Buildings in Kuala Lumpur: The People's Housing Programme

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Abstract

The government of Malaysia has an ongoing People's Housing Programme (PPR) to construct one million affordable housing units across the country. It is trying to address the problem of squatters and housing woes of the low-income population, especially in densely populated areas. The first-generation design samples of these high-rise PPR are now being superseded by a new design for the second-generation of the construction of such buildings. After the occupation of the buildings, the users have generally installed air conditioned units, which indicates that the original design process of the buildings had not taken into consideration the environmental issues and the subsequent indoor comfort and air quality of the units. The main objective of this research is to investigate the actual indoor comfort and carbon dioxide level which could be found at three different zones in both PPR generations. The results for the first-generation of PPR showed that the average operative temperature at the different levels of the buildings surpass the CIBSE Guide A, ASHRAE Standard 55-2010 and Malaysian Standard 1525:2014 limits. For the second-generation, the gradually increasing operative temperature profile for the unobstructed facing zone has resulted from the gradient wind profile in the urban areas. The eddies and recirculation regions of the wind movement at the obstructed facing zone had reduced operative temperature at intermediate part of the building and the weaker stack effect happened in the enclosed facing zone decreased the operative temperature at higher part of the buildings. The outcomes of the research intend to inform future design of these buildings, so that they achieve indoor comfort and air quality for the occupants as well as the subsequent reduction in consumption of energy and resources.

Keywords Indoor Comfort, Carbon Dioxide, Residential High-Rise, People's Housing Programme, PPR, Kuala Lumpur, Environmental Design, Fieldwork

1.0 Introduction

The People's Housing Programme (PPR) is one of the Malaysian government initiatives to relocate squatters and solve the housing woes of low-income groups (1). In 2015, the government announced the construction of one million affordable housing units within the PPR programme, coordinated by the National Housing Department (NHD) of the Ministry of Urban Wellbeing, Housing and Local Government (UHLG) (2). According to the UHLG 2016 annual report, the government proposed 169 PPR projects all over the country with a total of 102,896 units. By December 2016, a total of 81,352 units had been build, regarding 115 different projects (3, 4). Kuala Lumpur has accommodated approximately 45% of the total PPR units so far and most of them are high-rise buildings (5, 6).

Since its creation in 1998, NHD has developed two generations of PPRs, with different designs: the first one extended from 1998 to 2008 and the second, was started in 2010 and it is still being implemented (7, 8). The main reason of the design change was to make improvements on shared facilities such as multi-purpose halls, chaplaincy, child nurseries, playgrounds and open areas (7). However, the designs did not seem to take full account of the actual indoor conditions of these residential units as the residents seem to confront several problems including indoor comfort and health issues (9, 10) and they had to add individual air conditioning units shortly after occupying the buildings. Some PPR buildings in Kuala Lumpur have been subject to several studies (8-10), but none of them have looked at indoor comfort and air quality so far even though these two factors are crucial for the quality of life in the buildings (8).

Malaysian building regulations set the requirements for key design elements such as openings, atriums and light-wells in high-rise residential buildings (11-13). Therefore, it is important to assess the suitability and effectiveness of the elements in providing comfort and health to the occupants. In addition, this study aims to investigate the actual indoor comfort and carbon dioxide (CO_2) level which could be found at three different zones (unobstructed facing zone, obstructed facing zone and enclosed facing zone) in both PPR generations. Next, this study will also suggest several scientific findings as basis for future research and solution.

2.0 Methodology for the evaluation of the thermal environment

Two case studies representing the first and second generation of PPR located in Kuala Lumpur have been selected to carry out fieldwork in order to gather the necessary data. The first case study (PPR Beringin) involved an occupied building meanwhile the second case study (PPR Seri Aman) included an unoccupied habitation building at the time when the fieldwork was carried out, between11th and 29th July 2017, when the Southwest Monsoon was active. This Monsoon runs from May to September every year and provokes a relatively dry weather, with an average prevailing wind (coming from the Southwest) speed, usually below 15 knots (7.7 m/s) (14). Carrying out the necessary fieldwork during this dry season is highly recommended due to the highest temperatures that usually occur in this period on every year (14).

All the selected bedrooms for the fieldwork were initially designed to be naturally ventilated. However, during the fieldwork study, a bedroom facing the atrium at level 10 of PPR Beringin was using air-conditioning system for several hours at night. All of these bedrooms were also supposed to be single sided ventilation but the occupants have installed curtains and blinds and thus, make the interior susceptible to external influences. Ceiling fans, in most cases, were periodically switched-on to provide air movement in these rooms. These changes are among regular additions and modifications made by the occupants after the occupation.

Following a review of the different methodologies, the evaluation of thermal environment in ASHRAE Standard 55-2010 – 'Thermal Environmental Conditions for Human Occupancy' was found to be the most suitable for this study as it is an internationally recognised standard which has been updated on a regular basis since its formulation back in 1966. The standard defines indoor comfort by addressing six primary criteria which have been segmented in two groups of factors: environmental factors (air temperature, radiant temperature, air speed and relative humidity) and human factors (metabolic rate and clothing insulation) (15). Concerning indoor air quality and selected pollutants, the guidelines of the World Health Organization (WHO), has listed nine harmful substances in indoor air, among them the CO_2 (16). Therefore, these criteria should be considered in this fieldwork study in order to achieve and ensure an indoor environment as a comfortable and healthy place to live. The methodology to be used in assessing comfort and health in indoor environments is as recommended in ASHRAE 55-2010 (Table 1).

Table 1 –Evaluation of Thermal Environment in accordance to ASHRAE 55-2010 (Thermal Environmental Conditions for Human Occupancy) (12)

Parameters	**ASHRAE 55-2010 Recommendations**
Measuring Device Criteria	Meet the requirements in ASHRAE Standard 70 or Standard 113 or ISO 7726
Measurement Positions	Location of Measurements: a. In occupied zones - where the occupants are known to spend their time, OR b. In unoccupied rooms – estimate of the most significant future occupant locations within the room, OR c. If occupancy distribution cannot be estimated – in the centre of the room
	Height Above Floor of Measurements: a. Operative temperature – at the 0.6 m level for seated occupants and 1.1 m level for standing occupants b. Air speed – 0.1, 0.6 and 1.1 m levels for sedentary occupants c. Humidity – shall be measured at 0.6 m level for seated occupants
Measuring Periods	a. Temperature – minimum 3 minutes to 15 minutes to average cyclic fluctuations b. Air Speed – for determining the average air speed at any location shall be three (3) minutes
Measuring Conditions	a. Test during the cooling period (summer conditions)

All the measuring instruments according to the standard should meet the ASHRAE Standard 70 or 113 or ISO 7726. It specifies the location of the instruments where in an occupied zone. The instrument should be located at the spot that the occupants are known to spend most of their time. For the unoccupied spaces, the location of the instrument should be at the centre of the room. In the cases of the PPR units, bedrooms are the best data gathering locations for occupied and unoccupied units since the majority of the occupants work during the day and spend most of their remaining time resting and sleeping.

According to ASHRAE 55-2010 recommendations; 0.6 m, 1.1 m and 0.6 m height from floor level could be the best height of measurements for seated activities in evaluating the operative temperature, air speed and humidity respectively (15). However this standard mentions indicates only the measuring period for operative temperature and air speed, which is three minutes as the most minimum time.

There are only two measuring conditions suggested in this regard. These could be identified during the heating periods (winter conditions) and cooling periods (summer conditions). For our study, the measuring conditions during cooling period have been preferred due to the local hot and humid climatic conditions.

3.0 Instrumentation

For the on-site data gathering, four types of equipment were used to measure the four environmental parameters selected, these have been operative temperature, relative humidity, air speed and CO_2. The instruments used were Tiny Tag Ultra 2, Fluke 975 Air Meter, Kimo AMI 310 and Aercus Instruments WS1093. The measuring ranges and recording methods for each of the equipment have been demonstrated in Table 2.

Table 2 – Measuring ranges and recording method for the equipment

Equipment	Parameter(s)	Measuring Ranges	Recording Method
TinyTag Ultra 2	Air temperature and Operative Temperature	-25℃ to +85℃	10-min log intervals
	Relative Humidity	0% to 95% RH	10-min log intervals
Fluke 975 AirMeter	Carbon Dioxide (CO_2)	0 to 5000 ppm	10-min log intervals
Kimo AMI 310	Internal Air Speed	-5 to 35 m/s	10-min log intervals
Aercus WS1093	Incoming Air Speed	0 to 44 m/s	10-min log intervals

4.0 Parameters, ranges and limits

During July 2017, when the fieldwork was carried out, Kuala Lumpur received an average outdoor air temperature of 29°C (14). Considering this and in accordance to the CIBSE Guide A (2015), using the formula '$\vartheta_{com} = 0.33\ \vartheta_{rm} + 18.8$', building designers and architects should aim for an indoor operative temperature (in naturally ventilated buildings) close to 28.4°C (17). Even though, the formula was developed using the data collected primarily in European office buildings, the indoor operative temperature suggested is in line with several studies done in Malaysia before (18-20). For relative humidity and air speed, the ranges provided by the standard are 40 to 70%RH and 0.15 to 0.50 m/s respectively (Table 3).

ASHRAE 55-2010 has also set different figures for the comfort criteria. For an acceptable operative temperature in naturally conditioned spaces, the suggested temperature range according to Kuala Lumpur's outdoor mean temperature is between 24°C and 29°C (15). For the relative humidity and air speed, the standard has been set below 65%RH and between 0.15 m/s to 0.80 m/s respectively (21) (Table 3). In Malaysia, at the moment, only Malaysian Standard (MS1525:2014) - 'Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings', set the indoor design conditions for air temperature (24°C to 26°C), relative humidity (50 to 70%RH) and air speed which are to be between (0.15 to 0.50 m/s). Unlike CIBSE and ASHRAE standards, these design conditions are for air conditioned spaces only (Table 3).

Table 3 – Parameters ranges and limits for fieldwork study

Parameters	CIBSE Guide A:2015	ASHRAE 55-2010	MS1525:2014
Recommended Comfort Criteria			
Operative Temperature	28.4°C (1)	24°C – 29°C (2)	24°C – 26°C (3)
Relative Humidity	40 – 70 %RH	<65 %RH	50 – 70 %RH
Air Speed	0.15 – 0.50 m/s	0.15–0.80 m/s	0.15 – 0.50 m/s
Recommended CO2 Limit			
Carbon Dioxide	5,000 ppm (4)	5,000 ppm (5)	1,000 ppm (6)

Notes:
(1) Limiting values for the operative temperature to avoid overheating in naturally ventilated buildings
(2) Acceptable operative temperature ranges for naturally conditioned spaces
(3) Recommended design dry bulb temperature for an air conditioned space for comfort cooling
(4) Indicated exposure limit for CO_2 in CIBSE Indoor Air Quality and Ventilation (KS17)
(5) Comparison of regulations and guidelines pertinent to indoor environment (ASHRAE 62.1-2007)
(6) List of indoor air contaminants and the acceptable limits - Industry Code of Practice on Indoor Air Quality (Department of Occupational Safety and Health, Malaysia, 2010)

In 2010, the Department of Occupational Safety and Health (DOSH), Malaysia, published the ‘Industry Code of Practice on Indoor Air Quality’ to ensure that occupants are protected from poor indoor air quality (18). This document establishes the acceptable limit for CO_2 in Malaysia, which should be less than 1,000 parts-per-million (ppm) (22) (Table3). The other international standards, CIBSE Indoor Air Quality and Ventilation (KS17) and ASHRAE 62.1-2007 (Ventilation for Acceptable Indoor Air Quality) have set a limit of 5,000 ppm for that substance.

5.0 Context and selection of case studies

5.1 Case study 1: PPR Beringin (first generation)

The two PPR complexes (Beringin and Seri Aman), are located at the Northern part of Kuala Lumpur with only 500 meters of distance between them. Due to this similar geographic location and surrounding environment, these two PPRs were selected as the most suitable and representative case studies for the fieldwork study.

The PPR Beringin, first occupied in 2004, consists of six blocks of 18 and 15 storey height, with 1,896 units in total (316 units per block). The design of each block includes two large open atriums in each block to provide natural lighting and ventilation into inward rooms and a row of residential units abutting to a corridor (Figure 1). The windows are composed by single-glazed glass louvers.

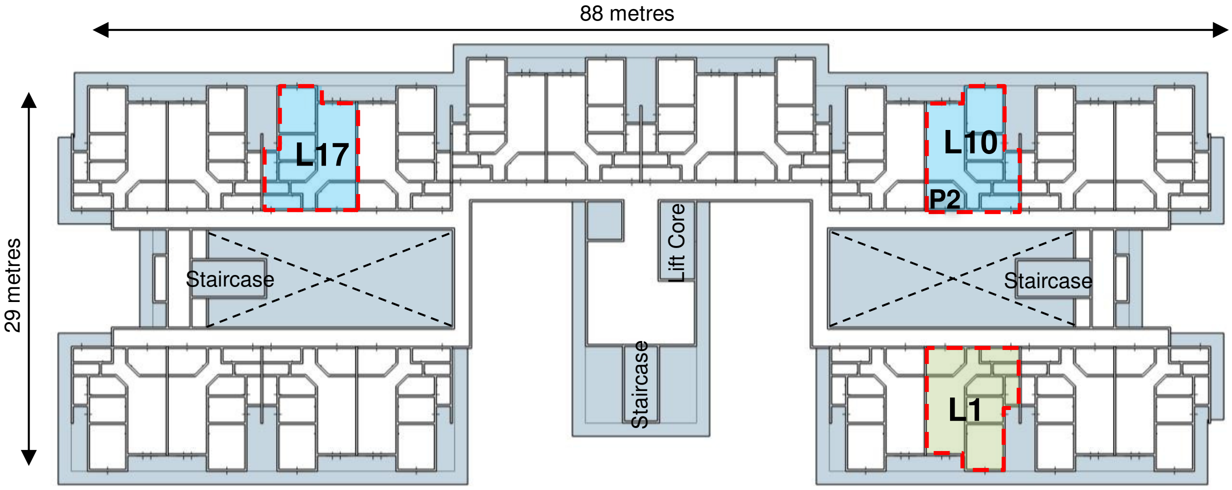

Figure 1 – Typical Floor Plan of PPR Beringin (First Generation)

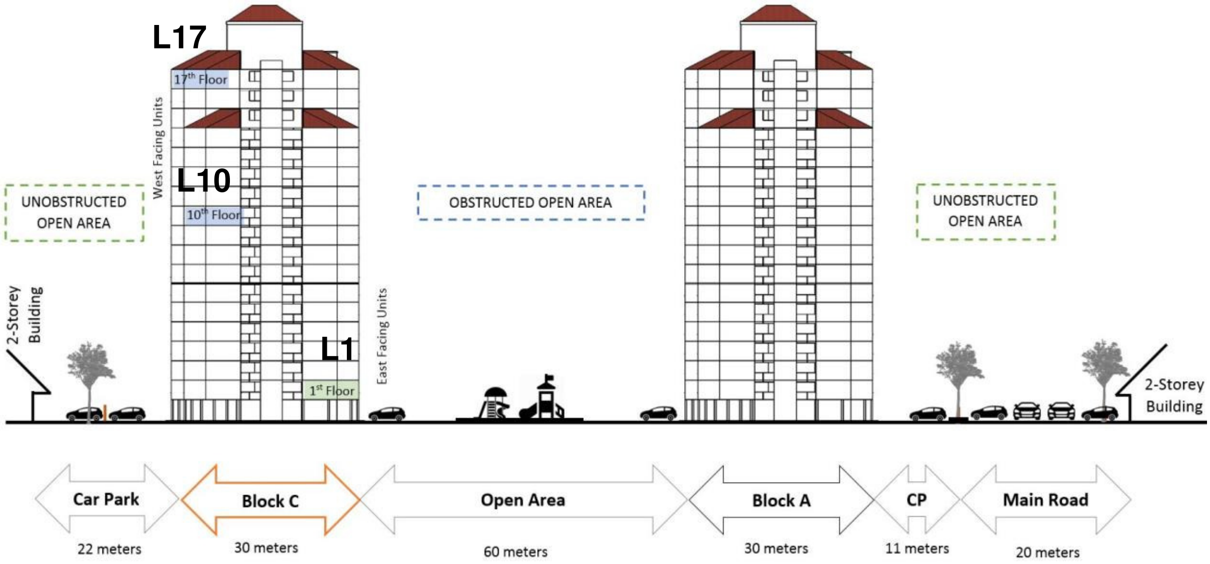

Figure 2 – Site Section of PPR Beringin

Three units within the block C (Figure 2) were selected which were located at level 1, level 10 and level 17 - representing lower, intermediate and upper parts of the block and different degree of obstruction. Two units at level 10 and level 17 have been facing an unobstructed open area and a unit at level 1 has been facing an obstructed open area (Figure 2).

5.2 Case study 2: PPR Seri Aman (second generation)

The PPR Seri Aman, the second generation of PPR, was completed in March 2017 and currently accommodates approximately 1,560 units in 4 blocks of 20 and 19 storey height. This second generation consists of two rows of residential units abutting to a corridor, with an enclosure setting environment compared to the previous design. In contrast to PPR Beringin, light-wells are the main source of natural lighting and ventilation for the bedrooms, kitchens and bathrooms facing towards the corridor (Figure 3). Single-glazed casement windows are used in this PPR second generation instead of the glass louvers of the previous design.

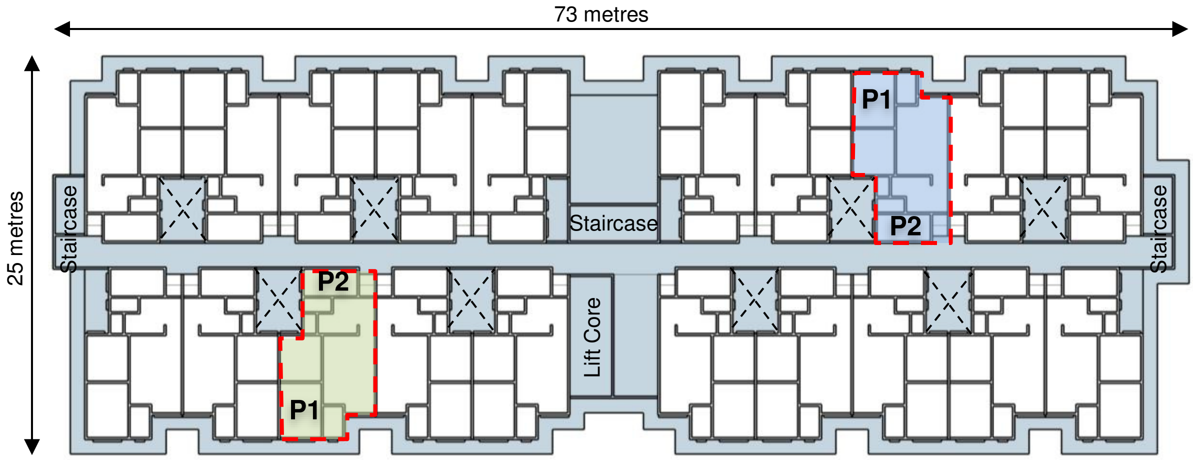

Figure 3 – Typical Floor Plan of PPR Seri Aman (Second Generation)

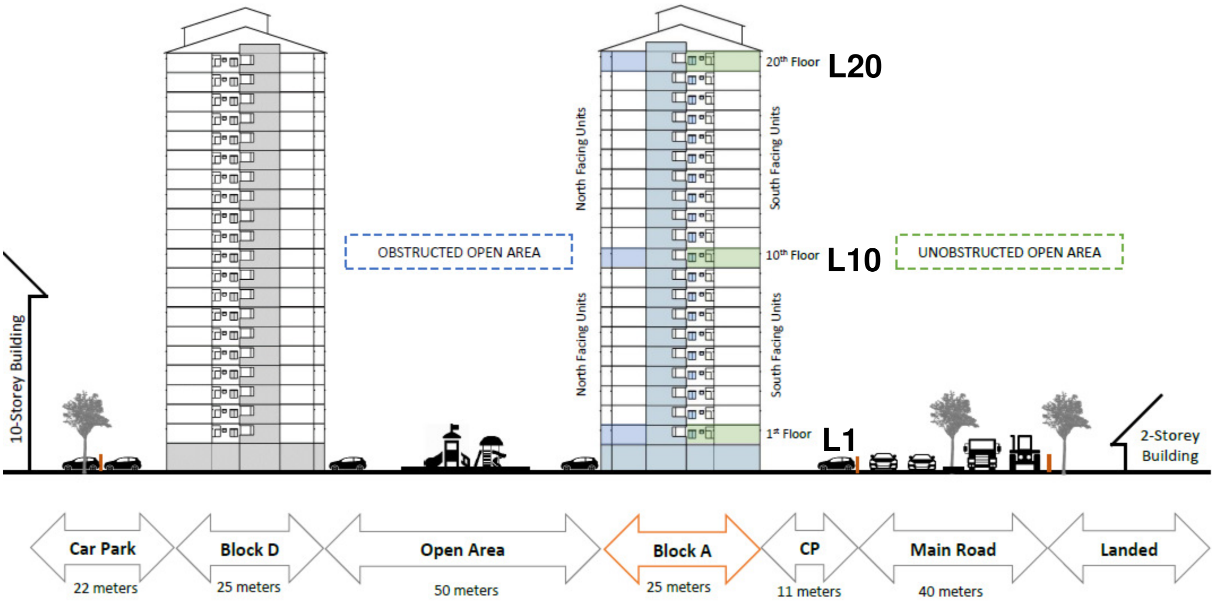

Figure 4– Site Section of PPR Seri Aman

Six house units were selected in block A, located at the same levels as in the PPR Beringin to represent the block’s lower, intermediate and upper zones. However, the highest floor in PPR Seri Aman is level 20, thus the level will represent the upper zone of the block. Three of the units have been facing unobstructed open areas and another three have been facing obstructed open area (Figure 4)

The buildings were still unoccupied during the fieldwork study, thereafter, there is no human activity, including smoking, respiration, perspiration as well as combustion processes for heating and cooking that can add water vapour and heat to its indoor atmosphere (23). Curtains or blinds that would cover the windows or openings were not fitted yet. Thus, the measurement recorded could be considered as a baseline of the buildings.

6.0 Measurement procedures

Two measurement campaigns were carried out within an 18-day period in PPR Seri Aman and a 4-day period in PPR Beringin. As mentioned before, in PPR Seri Aman, the three zones selected are unobstructed-facing area, obstructed-facing area and enclosed-facing area. Meanwhile, in PPR Beringin, the open area and open atrium zones were selected. As described before, two measurement points, located at the centre of the rooms were defined. The rooms are master bedroom (P1) and the third bedroom (P2) (Figure 5).

Figure 5 – Typical Unit Layouts for PPR Beringin & PPR Seri Aman and location of the equipment (P1 and P2)

Two units in level 1, level 10 and level 20 facing unobstructed and obstructed open area were selected, consisting of 12 measurement points in total (Table 4). Each point was measured for two days, starting with a continuous 24-hour period in an opened-environment (OP), i.e. with all the windows opened, and followed up by another continuous 24-hour period in a closed-environment (CL) where all the windows were closed during the measurement period. Measuring these two different environments are crucial to assess the effectiveness of windows in providing indoor comfort and air quality.

Due to the closed environment set-up and to know the set-up's actual effect on PPR Beringin, only operative temperature and relative humidity had been measured whereas, for PPR Seri Aman, the readings recorded were operative temperature, relative humidity, indoor and outdoor air speed and CO_2 (Table 4).

Table 4 – Allocated measurement periods for all points in both PPR

Parameters Measured	**Case Study 1: PPR Beringin (Level 1, 10 & 17)**		**Case Study 2: PPR Seri Aman (Level 1, 10 & 20)**					
	Open Area	**Open Atrium**	**Unobstructed Area**		**Obstructed Area**		**Enclosed Area**	
	P1	**P2**	**Ext.**	**P1**	**Ext.**	**P1**	**Ext.**	**P2**
Operative Temperature	4 days	4 days	2 days	2 days OP/CL	2 days	2 days OP/CL	2 days	2 days OP/CL
Relative Humidity	4 days	4 days	2 days	2 days OP/CL	2 days	2 days OP/CL	2 days	2 days OP/CL
Incoming Air Speed	-	-	2 days	-	2 days	-	2 days	-
Indoor Air Speed	-	-	-	2 days OP/CL	-	2 days OP/CL	-	2 days OP/CL
Carbon Dioxide (CO_2)	-	-	-	2 days OP/CL	-	2 days OP/CL	-	2 days OP/CL

*Note: OP = Opened Environment, CL = Closed Environment

7.0 Results

7.1 Operative temperature and relative humidity

As previously stated, in accordance with CIBSE Guide A, the recommended figure for operative temperature should be close to 28.4°C, and the relative humidity should be within 40 to 70%RH. The readings have surpassed the operative temperature limit set by the standard where all of the rooms at all levels recorded high operative temperature above 28℃ due to the presence of human activities and closed-environment setup (using curtains, blinds, etc.) (Figure 6). As expected the rooms with closed environments and poor ventilation could lead to trapping of heat within its indoor spaces.

Regardless of the height, the rooms had similar average readings of relative humidity, between 62% and 66%, which are within the CIBSE recommended limits (Table 3), demonstrating that humidity could be controlled in a closed environment condition. There was air-conditioning system for a few hours at night during the measurement period in room P2 at level 10, this is the reason why the recorded operative temperature was lower (Figure 6).

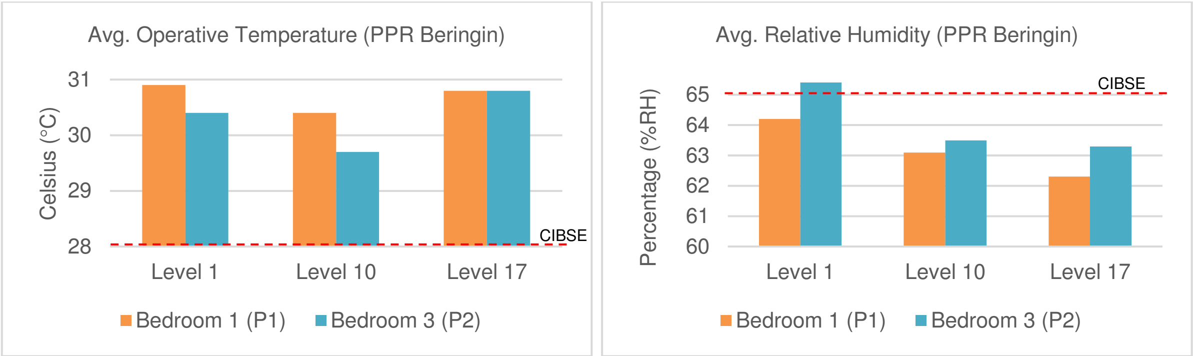

Figure 6 - Average Operative Temperature and Relative Humidity (PPR Beringin)

The average operative temperature and relative humidity for the units facing unobstructed area are shown in Figure 7. The average operative temperature in level 20 was the highest in both cases (OP and CL) followed by level 10 and level 1 due to hot-air-rises movement principle (24) and the gradient wind profile in the urban areas (25). The operative temperature readings in all cases surpassed the CIBSE limit. For relative humidity, the average readings for level 1 were significantly higher than level 10 and level 20 which above 70%RH in all cases. Due to that reason, it had the lowest operative temperature. Only relative humidity readings at level 10 and level 20 met the CIBSE standard of below 70%RH.

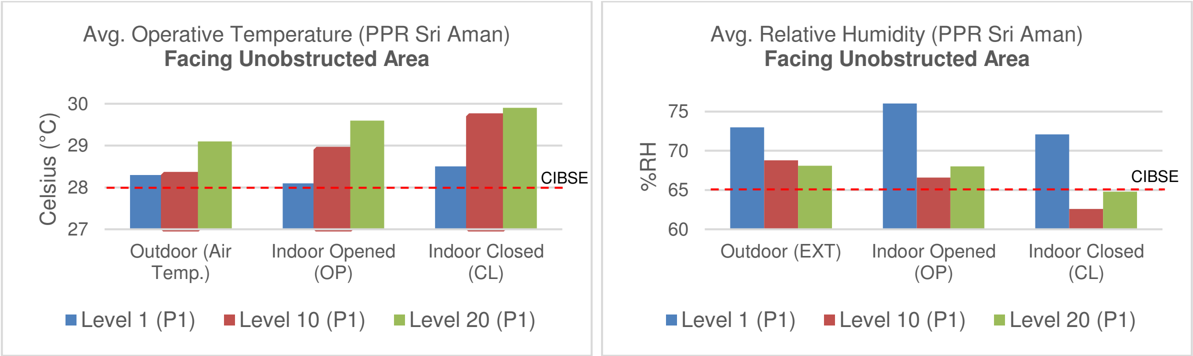

Figure 7 – Average AT and RH (unobstructed area) (Case Study 2: PPR Sri Aman)

The average operative temperature readings for the rooms facing obstructed area was significantly different compared to the rooms facing unobstructed area. Level 10 had consistently recorded lower operative temperature and higher humidity compared to level 1 and level 20. This scenario happened due to the wind movement effects at the windward section where eddies and recirculation regions of wind were formed (26, 27). All the operative temperature readings for the rooms facing obstructed area were above CIBSE recommended limit (Figure 8).

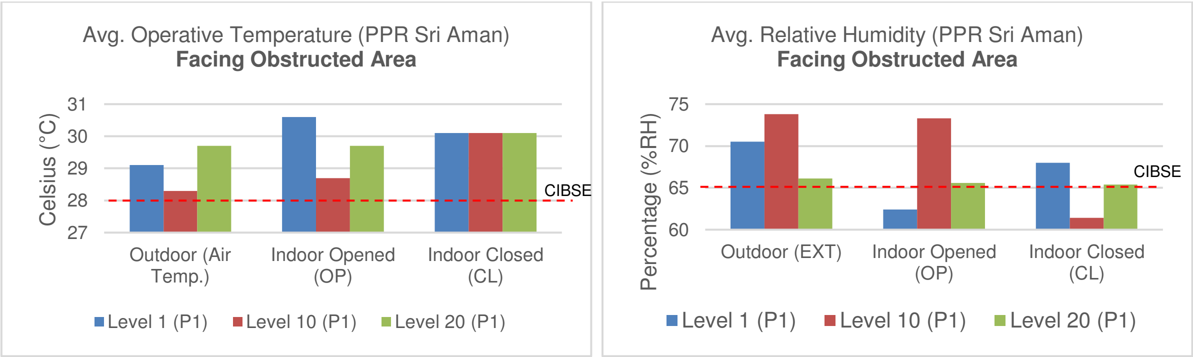

Figure 8 – Average AT and RH (obstructed area) (Case Study 2: PPR Sri Aman)

For the rooms facing the enclosed area (light-well), the operative temperature readings in level 1 were lower than the CIBSE recommended temperature and consistently lower than level 10 and level 20 readings (Figure 9). However, without a proper design, the hot-air-rising movement could be slowed down and accumulated at the upper part of the light-well (28). This scenario confirms that the stack effect can be employed using an architectural element such as light-well (29). For the relative humidity, the readings for level 1 were above CIBSE limits and significantly higher than in other levels due to the height of the light-well and enclosed environment at its bottom level (Figure 9).

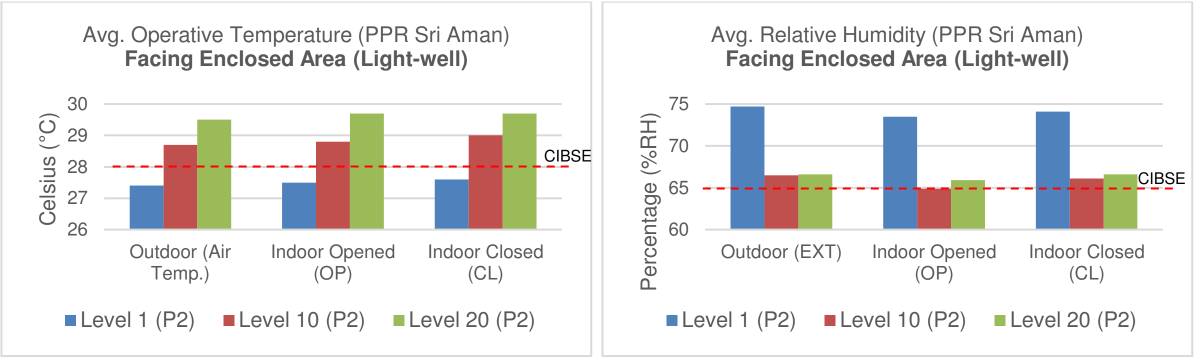

Figure 9 – Average AT and RH (enclosed area) (Case Study 2: PPR Sri Aman)

7.2 Incoming air speed and internal air speed

As mentioned in operative temperature results, external wind movement is the main factor for the temperature and humidity profiles. It also affects the maximum incoming air movement as shown in figure 10. The gradient wind profile in the urban areas makes the maximum air speed for the rooms facing unobstructed area gradually increasing from level 1 to level 20. For the rooms facing obstructed area, the highest air movement was at level 10 due to eddies and re-circulation regions of wind formed at the windward section of the sample block. For the rooms facing the enclosed area (light-well), the air speed recorded was lower at level 10 than level 1 and level 20 due to weaker stack effect at intermediate part of the light-well (Figure 10).

As a result, the average internal air speed in all cases had recorded 0.0 m/s and thus, do not meet the recommended limit set by CIBSE Guide A, which is 0.15 to 0.50 m/s (Figure 10). These results show that natural ventilation is inconsistent and unreliable for these type of high-rise buildings as previously outlined (12).

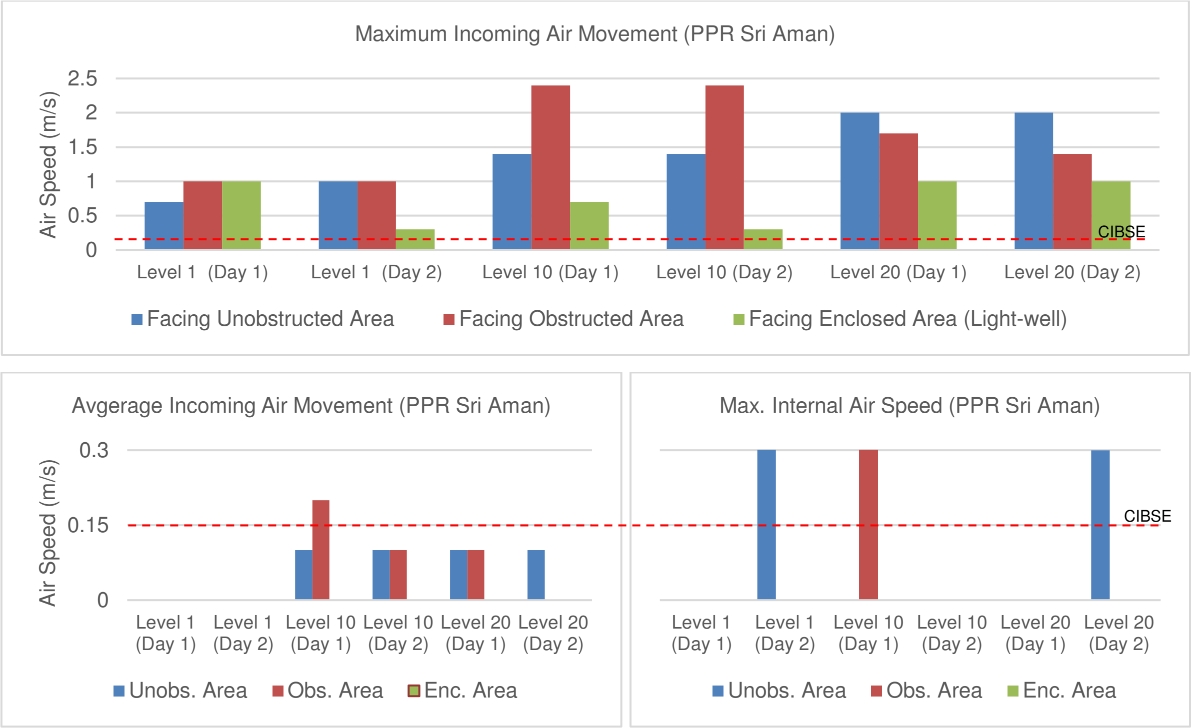

Figure 10–Maximum and average air speed in Case Study 2: PPR Seri Aman

7.3 Carbon dioxide (CO_2)

Our study has found that the average CO_2 level in Kuala Lumpur during the 19-day fieldwork study period was 420 ppm. A study done by Denli et al. (2017) has also suggested that the outdoor concentration of CO_2 could vary from 350 to 400 ppm or higher in a high traffic area (30).

Figure 11 shows the graphs for the CO_2 levels in PPR Seri Aman. The average CO_2 levels in opened environment for the rooms facing the unobstructed area, obstructed area and enclosed area have similar values, between 430 to 446 ppm. However, the average CO_2 in closed environment at level 1 facing unobstructed area was higher than level 10 and level 20. For the rooms facing the obstructed area, the average CO_2 at level 1 was the lowest among the other levels and for the enclosed area, the average CO_2 level at level 10 was significantly higher than level 20 and level 1 (Figure 11).

Figure 11 – CO_2 levels in PPR Seri Aman

It could be deduced that, in closed environment (CL) spaces, the CO_2 concentration levels are significantly different between the zones as follows:

a. Facing unobstructed area – decreasing pattern according to height,
b. Facing obstructed area – slightly increasing pattern, and
c. Facing enclosed area – high level of CO_2 in the middle of light-wells

This shows that the quality of air could be controlled by filtering the outside air through specific intakes and that a constant air speed is needed in indoor spaces to reduce the concentration level.

8.0 Analysis

As previously mentioned, the ASHRAE standard establishes that indoor operative temperature should not be beyond 29°C. Whereas, CIBSE Guide A has specified that the relative humidity should be between 40-70% RH and the indoor air speed has to be between 0.15-0.50 m/s; any reading outside these ranges are unacceptable. For CO_2, the Earth System Research Laboratory (ESRL) under National Oceanic and Atmospheric Administration of U.S. Department of Commerce has monitored that the global mean CO_2 level in August 2017 was 402.3 ppm (31). Thus, any reading surpass the 400 ppm are considered high (Table 5).

Table 5–Summary of the fieldwork study results

Location	***PPR Beringin (Post-Occupancy)**		**PPR Seri Aman (Pre-Occupancy)**		
	P1 (Open Area)	**P2 (OpenAtrium)**	**P1 (Unobstructed Area)**	**P1 (Obstructed Area)**	**P2 (Enclosed Area)**
AIR TEMPERATURE (AT)					
Level 1	High	High	Moderate	High	Low
Level 10	High	High	Moderate	Moderate	Moderate
Level 17/20	High	High	High	High	High
RELATIVE HUMIDITY (RH)					
Level 1	Moderate	Moderate	High	Moderate	High
Level 10	Moderate	Moderate	Moderate	High	Moderate
Level 17/20	Moderate	Moderate	Moderate	Moderate	Moderate
MAX. INCOMING AIR SPEED (MIAS)					
Level 1	-	-	Low	Low	Low
Level 10	-	-	Moderate	High	Low
Level 20	-	-	High	Moderate	Moderate
AVG. INCOMING AIR SPEED (AIAS)					
Level 1	-	-	Low	Low	Low
Level 10	-	-	Moderate	Moderate	Low
Level 20	-	-	Moderate	Moderate	Low
MAX. INTERNAL AIR SPEED (MIAS)					
Level 1	-	-	Low	Low	Low
Level 10	-	-	Low	Low	Low
Level 20	-	-	Low	Low	Low
AVG. INTERNAL AIR SPEED (AIAS)					
Level 1	-	-	Low	Low	Low
Level 10	-	-	Low	Low	Low
Level 20	-	-	Low	Low	Low
CARBON DIOXIDE (CO_2) – CLOSED ENVIRONMENT					
Level 1	-	-	High	High	Moderate
Level 10	-	-	Moderate	High	High
Level 20	-	-	Moderate	High	Low

Legend:

AT	: Low (<28°C)	Moderate (>28°C to 29°C)	High (>29°C)
RH	: Low (<40%RH)	Moderate (>40%RH to 70%RH)	High (>70%RH)
MIAS	: Low (<1.0 m/s)	Moderate (>1.1 m/s to 1.9 m/s)	High (>2.0 m/s)
AIAS	: Low (0.0 m/s)	Moderate (>0.1 to 0.5m/s)	High (>0.5 m/s)
CO2	: Low (>350 ppm)	Moderate (>351 to 400 ppm)	High (>401 ppm)

In summary, the fieldwork study has found three different zones for indoor comfort and air quality in PPR Seri Aman which are 'unobstructed facing zone', 'obstructed facing zone' and 'enclosed facing zone'. The study has also found that a different zone was created in PPR Beringin after the house units have been occupied. The environmental conditions of the first generation such as operative temperature and relative humidity show different profiles, which is uniform and similar regardless of levels and locations of the rooms (Figure 12). This is due to the closed-environment created by the occupants after curtains and blinds were installed. These items reduce the performance of natural ventilation and inhibit air exchange, resulting later in, heat (created from from solar radiation and human activities) accumulated and trapped within indoor spaces.

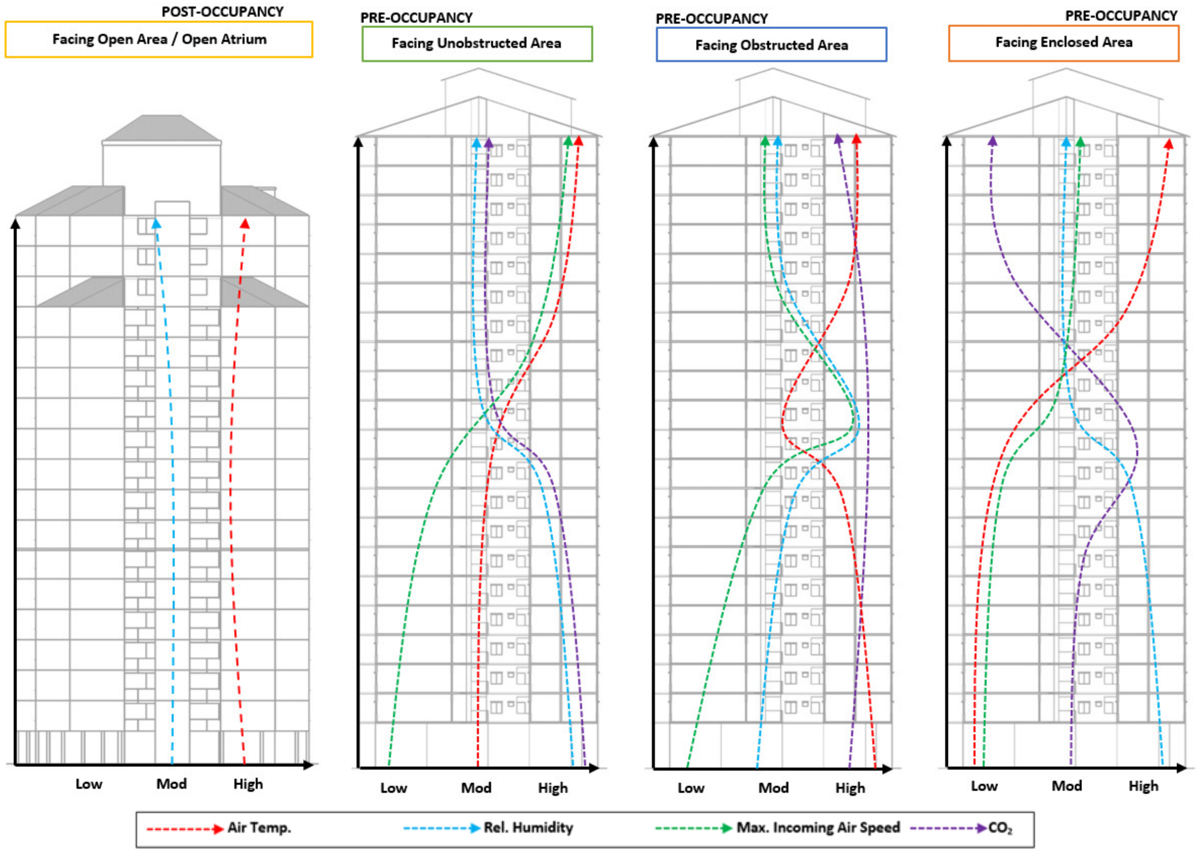

Figure 12 – The identified four different environmental conditions zones in PPR Seri Aman and PPR Beringin.

It could be deduced that the gradually increasing operative temperature profile for the unobstructed facing zone has resulted from the gradient wind profile in the urban areas (32). The eddies and recirculation regions of the wind movement at the obstructed facing zone had reduced operative temperature in level 10 (27) and the weaker stack effect happened in the enclosed facing zone decreased the operative temperature in level 20 (28). As a result, the different air speed profiles were the main factors for contributing to the variety of operative temperature, relative humidity and CO_2 values in these zones (Figure 12).

9.0 Conclusions and recommendations

Based on the findings of this study, it is recommended that PPR residential high-rise buildings in Kuala Lumpur requires a significant transformation. Light-wells, a compulsory element in PPR second generation for provisioning daylight and ventilation (11, 12), are typically designed as passive cores that serve the adjacent rooms through stack effect ventilation. However, as explained before, the passive stack effect in the case studies is ineffective for ventilation.

This study has also proved that the typical openings and designs of windows in the case studies, which is another compulsory element to provide views and ventilation for the occupants, do not provide at the moment, a healthy and adequate ventilation for the occupants of the buildings. The resulting three different environmental zones in the PPR Seri Aman, make the required clean, cool and constant air circulation almost impossible to achieve. Indoor environmental conditions should be taken into consideration while designing PPR high-rise buildings, so that they could achieve indoor comfort and air quality as well as the subsequent reduction in consumption of energy and resources. Optimum different strategy and design should be explored in order to provide an acceptable indoor comfort and air quality for all the zones.

A comfortable and healthy living environment can be achieved by architectural designs that could ensure constant air movement in indoor spaces and the filtering of external air pollution. Considering that natural ventilation strategies and designs have limitations such as poor external air quality, an integrated strategy for passive and low energy consumption should be explored in greater detail in considering the design of the openings and light-wells in more detail. An integrated strategy of hybrid light-well that can create negative pressure inside a building together with dynamic insulation that can filter air pollution, humidity and heat could be one of the suitable strategies to solve the problems highlighted. Further research will focus on this and it will involve capturing further on-site data of the actual indoor air quality in the same case studies and physical modelling of the new proposed design strategies.

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