The effects of microclimate and air-infiltration on energy and long-term thermal comfort in high-rise buildings in tropical climate

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Abstract. An increase in the number of high-rise buildings in most developing cities affects the surrounding microclimate. In this study, the influence of microclimate due to height variations and air infiltration were investigated for a building’s energy and long-term thermal comfort performances. A 20-storey high-rise office building with full glass façade in a hot and humid climate of Malaysia was studied using EnergyPlus to simulate the energy performance and RStudio programme for thermal comfort performance analysis. It was found that the building energy consumption reduced up to 2% when the air infiltration was removed from the building. However, the effect of microclimate showed insignificant reduction in energy consumption, but it had a significant difference in discomfort hours up to 17%. Air infiltration had less effect on thermal comfort with only 3% reduction in discomfort hours. Microclimate should be considered to accurately evaluate the building performances in the densely built with high-rise buildings area. Removal of air infiltration from space helped in providing comfort and at the same time reduced the building energy consumption.

1. Introduction
Numerous high-rise buildings have been constructed in urban areas to accommodate the population due to rapid urbanization. This has caused changes in the topology of surrounding area which further contribute to an urban microclimate. The consequences from the formation of microclimate in the past decades has become a concern, which has resulted in the focus on urban heat island (UHI) [1–7] and building energy performance [8–12] by most researchers in these subject matters. The influence of building morphology on urban climate was also explored during the past decades [13–15], nevertheless the exploration was only based on a typical single urban microclimate data and limited to low-rise buildings. The results showed a significant difference in building performance compared to the one dependent on meteorology data from weather stations. Thus, it was suggested that the specific location of climate data (microclimate data) should be used to evaluate the building performance in urban areas [12].

A study by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) [16] showed a variation in air temperature and wind speed along the building height for different site locations including large cities, urban, suburban, open terrain and flat on unobstructed areas, depending on the density and building height in that surrounding area. Rode et al.[3] reported...
that the area that is surrounded by numerous high-rise buildings helps in improving the energy
efficiency in the building [3]. Most of the studies evaluated the effect of urban microclimate on the
overall building energy consumption by only considering the average environmental parameters at
pedestrian level. However, there are only a few studies on the variation of microclimate along with
building height, thus this needs to be further investigated [17–19]. The real-life studies on the effect
of urban microclimate at different building height are inefficient due to equipment limitation,
different arrangement of the building and parameter variation, which led to the contradiction and
inaccuracy in research findings. Previous researches suggested an alternative in evaluating this effect
through simulation study where the studied parameters can be controlled.

The trend of applying glass façade in construction industry has become another concern as most of
newly constructed high-rise buildings in the city area, especially in Malaysia, use it at high proportion.
However, its application in the hot and humid climate of Malaysia is still in doubt in term of energy
consumption and thermal comfort. Previous studies on glass façade only limited to medium window-
to wall ratio (WWR), medium-rise buildings and associated to other than hot and humid climate [20–
24]. Further researches on glass façade high-rise buildings are necessary to study the behaviour of
building performance especially when the air-infiltration through façade needs to be controlled for the
purpose of maintaining the air tightness of the building.

This study aims to investigate the variation in building performances at different building heights
when exposed to the urban microclimate. Behaviour of the building with air infiltration through its
façade is another element explored. A series of simulations were conducted on a full glass high-rise
office building with air-conditioning operating systems to evaluate the building energy and thermal
comfort performances.

2. Methodology

An annual simulation study was performed by using the EnergyPlus software. The development of
base case model was made using the SketchUp software while the OpenStudio plug-in was used to set
the construction data, materials and internal heat gains settings. The annual energy data and hourly
thermal comfort simulation were gathered to study the building performance. Besides, the RStudio
software was used to calculate the long-term thermal comfort performance.

2.1. Weather data

Weather data of Kuala Lumpur with latitude and longitude of 3.12 °N, 101.55 °E provided by
EnergyPlus was used [25]. Figure 1 shows the mean, maximum and minimum monthly dry bulb
temperature for the year 2016. The highest and lowest mean monthly air temperature were recorded in
June (27.9°C) and December (26.4°C) respectively, while the maximum monthly temperature of
29.7°C was recorded in June.

![Figure 1. Monthly dry bulb temperature in Kuala Lumpur, Malaysia for 2016 [25].](image-url)
2.2. Base case model
The base case model was developed from the building inventory study conducted in Kuala Lumpur city centre. The results show 97% of the buildings are high-rise buildings, thus Kuala Lumpur is categorised under large cities according to ASHRAE’s definition [16]. The definition specifies that at least 50% of the buildings in that area are higher than 21.3 m. A 20-storey open space layout office building with dimension of 10 m × 10 m, floor-to-floor height of 4 m and a total height of 80 m was developed from the inventory study. A full glass façade (WWR = 100%) in the South direction was applied in order to evaluate the optimum performance. The thermal zones were divided according to building levels; hence each zone was representing the building height. For example, Zone 10 represented level 10 with 38 m (at the centroid of the zone) height from the ground.

2.3. Simulation setting
Table 1 shows the building material properties and building operation setting used in this study. The whole year simulation was done by assuming all days as working days in order to consider all possibility of extreme days. The clo value and metabolic rate were set based on summer clothing and office working activities respectively as recommended in ASHRAE Standard 55 [26].

| Table 1. Building materials properties and building operation setting. |
|---------------------------------------------|
| **Materials Properties**                    |
| External wall insulation                    | U-Value: 0.987 W/m²·K |
| Roof insulation                             | U-Value: 0.274 W/m²·K |
| Glazing type                                | Low E glass, 3 mm, U-value: 6.424, SHGC: 0.237, TVIS: 0.252 |

| **Building Operation Details**               |
| HVAC system type                             | Fan coil systems with chillers |
| Cooling and heating                          | Chilled Water Loop |
| Temperature set point                        | 24 °C |
| Fresh air supply rate                        | 0.00944 m³/s-person |
| Type of lighting                             | 10.66 W/m² (ASHRAE 198.1) |
| Office equipment gain                        | 7.64 W/m² (ASHRAE 198.1) |
| Occupancy density                            | 0.25 person/m² (ASHRAE 198.1) |
| Operation schedule                           | All days: 08:00 – 17:00 |
| Thermal comfort parameters                   | 0.5 clo (Clothing); 1.1 met (Metabolic rate) |

Table 2 shows four different building cases and parameters studied in this paper. Two sets of weather data profiles were studied to determine the effects of different microclimates. Single weather station (WS) data and large cities microclimate (LC) data with variation along building height were used. Further exploration by removing the influence of air infiltration through building facade was studied for both weather data profiles, denoted as WSNI and LCNI in the table.

| Table 2. Building cases and parameters.      |
|---------------------------------------------|
| Building Air Infiltration rate (m³/s·m²)     |
| Temperature gradient (°K/m)                  |
| Wind speed profile exponent                  |
| Wind speed boundary layer thickness (m)      |
| WS   | 0.0003 | 0.0000  | 0.14 | 270 |
| LC   | 0.0003 | 0.0065  | 0.33 | 460 |
| WSN | 0.0000 | 0.0000  | 0.14 | 270 |
| LCNI | 0.0000 | 0.0065  | 0.33 | 460 |

2.4. Energy and long-term thermal comfort calculation
The thermal comfort output parameters from EnergyPlus were imported into RStudio algorithm to calculate the long-term thermal comfort indices. Four long-term thermal comfort indices were
evaluated based on the Predicted Mean Value (PMV) and Percentage of Dissatisfaction (PPD) values according to ISO 7730 (2005) [27]. The indices studied were percentage of PMV outside comfort range (Index 1), number of PMV hours exceeding the comfort range as a function of PPD (Index 2), average of PPD (Index 3) and total of PPD (Index 4). The equations for calculated indices are as shown in Equation 1 to Equation 4.

\[
\text{Index 1} = \sum_{i=1}^{n} \left\{ \begin{array}{ll}
0 & \text{for } -0.5 < PMV < +0.5 \\
1 & \text{for } -0.5 > PMV > +0.5 \\
\end{array} \right\} \times 100 \tag{1}
\]

\[
\text{Index 2} = \sum_{j=1}^{n} w_f \times t \times \left\{ \begin{array}{ll}
0 & \text{for } -0.5 < PMV < +0.5 \\
1 & \text{for } PMV = PMV_{\text{limit}} \\
\end{array} \right\} \\
\frac{PPD_{\text{actual}}}{PPD_{\text{PMVlimit}}} \text{ for } -0.5 > PMV > +0.5 \tag{2}
\]

\[
\text{Index 3} = \sum_{i=1}^{n} \frac{PPD_i}{n} \tag{3}
\]

\[
\text{Index 4} = \sum_{i=1}^{n} PPD \tag{4}
\]

3. Results and discussions

3.1. Outdoor environmental parameters pattern
In order to investigate the trends of indoor, outdoor and thermal comfort parameters, the dataset based on maximum dry bulb temperature recorded on 6\textsuperscript{th} July were used. The trends for the influence of different building cases on outdoor environmental parameters at different zones are shown in Figure 2. The dry bulb temperature (DBT) for weather station data at different height is represented by the single line (AllZone_WS) as there is no variation in temperature at different building heights (Figure 2(a)). From the plot, the outdoor temperature for LC increases with the increase of occupied hours. The minor difference in temperature for both climate data is less than 0.5° C. In comparison, WS dry bulb temperature is higher than LC, in which the outdoor temperature in the latter is slightly reduced with the increase in building height (Figure 2(b)).
The wind profile shows an increase in speed with time in all cases. It can be clearly seen that wind speed for WS is higher than that of LC. The low wind speed in LC was due to obstruction caused by the high number of tall buildings. For both climates, the wind speed increases with the increase in building height. This is due to the gradient height factor, in which the wind is not affected by friction due to obstruction at location higher than the gradient height. This finding compares well with others studies which reveal that denser cities have a higher gradient height [18,28].

3.2. Indoor parameters at selected building height

Figure 3 shows the indoor thermal parameters (i.e. mean radiant temperature - MRT and relative humidity - RH) and thermal comfort performance parameters (PMV and PPD) for different building cases in zones 5, 10 and 15. In general, there is no significant change in WS climate for all parameters as the building height changes. This is due to the utilization of single weather data with no temperature variation in height but varies in wind speed. This result shows that the WS variation in outdoor wind speed does not affect the indoor environmental performance at different building heights.

The MRT in LC (Figure 3(a)) shows a decrease with the increase in building height. As MRT is influenced by the surrounding surface temperature due to solar radiation and outdoor air temperature, the decrease in outdoor air temperature in LC lowers the radiant temperature as the height increases. Meanwhile the results show that the buildings with air infiltration (WS and LC) have a higher RH (Figure 3(b)) than the buildings without air infiltration (WSNI and LCNI). The RH for LC increases with building height due to a higher wind pressure at a higher level.

PMV and PPD also decrease when the building height increases, which indicates that there is a reduction in discomfort due to the decrease in outdoor temperature and MRT (Figure 3(c) and Figure 3(d)). However, overall results show that the increase in RH has less influence in the decrease in PMV and PPD. This is in agreement with ASHRAE Standard 55: 2014 [26] which recommends that 10% higher in humidity causes a warmer sensation equals to the increase of 0.3 °C. In this study, the increment of RH is less than 1% (Figure 3(b)), hence the influence of relative humidity is insignificant which agrees with a study done by Silva et al. [29].
Figure 3. Indoor thermal parameters and thermal comfort performance at selected building zones (height).

3.3. Building energy performance

The annual end use and cooling energy for different building cases are presented in Figure 4. More than 70% of the annual end use energy is for cooling purpose. Energy consumption of buildings in LC and LCNI are lower than the ones with weather station data (WS and WSNI). This is due to the reduction in air temperature when height variation is applied, as discussed in the previous sections. However, less than 1% energy reduction occurs upon consideration of LC with height variation.

Figure 4. Annual end uses energy and cooling energy.

The results show that WS and LC consume more energy than the ones without infiltration (WSNI and LCNI). By removing the air infiltration effect, building energy consumption can be reduced up to 2%. Infiltration of air increases RH within the space, thus more energy is required in order to cool and remove the moisture. The effect of air infiltration seems to be higher than the effect of microclimate based on the reduction in energy consumption. Further exploration on the effect of height variation in
LC and air infiltration on thermal comfort performance needs to be investigated in order to observe
the overall influence of these two factors on building performances.

3.4. Thermal comfort performance

3.4.1. Classification of thermal comfort category. The categories of thermal comfort based on BS EN
15251: 2007 [30] and the results of percentage of PMV outside comfort limit (Index 1) are shown in
Table 3. The percentage of PMV falls outside the comfort range is higher for WS and WSNI as
compared to LC and LCNI. The results clearly show that all the building cases meet category II (-0.5<
PMV<+0.5) i.e. normal level of comfort for a normal new building with less than 3 % PMV outside
range as stated in BS EN 15251:2007.

| Category | PPD (%) | Predicted Mean Vote | WS | LC | WSNI | LCNI |
|----------|---------|---------------------|----|----|------|------|
| I        | < 6     | -0.2 < PMV < + 0.2  | 67.7 | 67.1 | 67.2 | 66.6 |
| II       | < 10    | -0.5 < PMV < + 0.5  | 0.7 | 0.6 | 0.7 | 0.6 |
| III      | < 15    | -0.7 < PMV < + 0.7  | 0.0 | 0.0 | 0.0 | 0.0 |
| IV       | > 15    | PMV < -0.7 or +0.7 < PMV | 0.0 | 0.0 | 0.0 | 0.0 |

3.4.2. Long-term thermal comfort indices. Further investigation on thermal comfort based on category
II was evaluated and is presented in Table 4. PMV outside range (Index 1) for all cases is less than 3
% as stated by the Standard. As for PMV exceedance hours (Index 2), all building cases shows
exceedance hours less than 3 % (2190 hours). The PPD average (Index 3) shows that all the building
cases having the same value of 7%.

The variation in long-term thermal comfort indices match with the energy performance, where
buildings exposed to large cities microclimate and without air-infiltration perform better than the
others. Indices based on PMV values (Index 1 and Index 2) are based on comfort classes and more
accurate in predicting the conditions compared to the PPD basis. Averaged PPD (Index 3) is the direct
response on occupants’ comfort compared to summation of PPD (Index 4) which is unable to measure
the actual severity of the building cases due to summing up and averaging the PPD [31].

| Building Cases | PMV_{out} (%) | PMV_{EH} (hr) | PPD_{avg} (%) | PPD_{sum} |
|----------------|---------------|---------------|---------------|-----------|
| WS             | 0.7           | 575.3         | 7             | 496321    |
| LC             | 0.6           | 480.4         | 7             | 490960    |
| WSNI           | 0.7           | 564.4         | 7             | 494517    |
| LCNI           | 0.6           | 458.7         | 7             | 489160    |

Based on PMV exceedance hours (Index 2), the averages of reduction in discomfort due to
microclimate consideration and removal of air infiltration are 17% and 3%, respectively.
Contradictory to the building energy performance, microclimate shows a higher effect on thermal
comfort performance as compared to air infiltration. In thermal comfort, the influence of radiant
temperature is more significant than the relative humidity. A clear understanding on thermal comfort
performance at different building height (zones) is discussed next using Index 2.

3.4.3. Detailed of PMV exceedance hours in all zones. The exceedance hours of PMV falls outside
range at different building heights is shown in Figure 5. The exceedance hours increase from zone 1
to zone 2 and almost plateaued from zone 3 to zone 19. Meanwhile, zone 20 shows the maximum exceedance hours. A slight difference in exceedance hours is found in large cities microclimate due to the influence of height variation. Small reduction in exceedance hours in zone 3 to zone 19 for building with large cities microclimate (LC and LCNI), while a constant exceedance hour is found in normal microclimate.

![Figure 5. PMV exceedance hours for all zones.](image)

The small amount of exceedance hours in zone 1 to zone 2 is due low indoor air temperature caused by the huge amount of heat absorbed by the earth. Meanwhile the temperature rises to the maximum at zone 20 is influenced by the solar radiation absorbed by the roof. A similar trend is also found in the previous studies in which the air temperature increases with building height in a high-rise building [17–19]. However, the findings are based on the selected height at low, middle and top floors. In this study, thermal comfort performance was evaluated by neglecting the ground and top floor to avoid the effect of heat absorbed from earth mass and solar radiation. Hence, the different in all building cases are compared in the range of zone 3 to zone 19.

In zone 3 to 19, the exceedance hours in WS and WSNI show small difference in values along the height due to no variation in outdoor air temperature. Though there is variation in wind speed and relative humidity, the influence on thermal comfort performance is insignificant. Buildings exposed to large cities microclimate (LC and LCNI) show the exceedance hours decrease with the increase of building height. This matches with the trend of the outdoor and indoor temperature as presented in Fig. 3. BS 15251: 2007 [30] sets a limitation for PMV exceedance hours to be less than 3 % (109 hours) during occupied hours annually. From the results, all zones do not exceed and still within the comfort zone.

4. Conclusion
This study evaluated the influence of large cities microclimate and air infiltration on building energy and thermal comfort performances in a high-rise office building with full glass façade design. EnergyPlus was used to perform a whole year simulation while the total annual energy consumption and long-term thermal comfort indices were used to assess the optimum building condition. This study concludes the following:

1. High density of high-rise buildings in large cities microclimate cause the pattern in outdoor air temperature to decrease with the increase of building height. The outdoor wind speed increases along the building height but is found to be lower than the weather station climate.
2. Buildings exposed to microclimate and no air infiltration effect (LCNI) is found to be lower in energy consumption and thermal discomfort compared to other building cases.
3. The effect of air infiltration on building energy performance is found to be higher than the effect of microclimate. However, both show a small reduction in energy consumption (less than 2 %).
4. In the aspect of thermal comfort, considering microclimate and removing the air infiltration show a reduction in discomfort hours of 17% and 3% respectively. In summary, microclimate should be considered in assessing the building performances in large cities area full of high-rise buildings. Removing the air infiltration from building helps in improving the building energy in full glass façade buildings.

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