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Thermal comfort evaluation of natural ventilation mode: case study of a high-rise residential building

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Abstract: Natural ventilation can be used as a low-cost alternative to mechanical ventilation. Bearing in mind that ventilation mode plays an important role in natural ventilation performance, the current study investigates the effectiveness of two major natural ventilation modes (i.e. single-sided and cross ventilation) in providing thermal comfort for occupants of high-rise residential buildings in cooling dominant climates. Measurements of air velocity, temperature and relative humidity were carried out in a unit located in a high-rise residential building in Brisbane, Australia. Both single-sided and cross ventilation settings were examined in two consecutive days in summer. The extended Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) were calculated and results showed a considerably better performance of cross ventilation over single-sided ventilation. Cross ventilation could provide thermal comfort in a typical hot summer day for most of the day (greater than 70% of the time), while, for single-sided ventilation the thermal conditions of internal spaces was comfortable for only 1% of the time.

Keywords: Natural ventilation; ventilation mode; thermal comfort; high-rise residential.

1. Introduction

In cooling dominant climates, weather conditions mostly lie outside the comfort range, especially during summer. Therefore, air-conditioners are widely used for space cooling and providing a thermally comfortable environment. Air-conditioners are energy intensive and consume a large portion of the energy delivered to buildings (Pérez-Lombard *et al.*, 2008). Natural ventilation as a passive cooling strategy, on the other hand, is a low-cost alternative to air conditioners. Natural ventilation not only contributes to thermal comfort but also can improve indoor air quality.

There are a number of parameters that affect natural ventilation performance and can be addressed through building design such as building orientation, shape and size of openings, and ventilation mode. Among these design related parameters, ventilation mode has the most impact on ventilation performance (Fung and Lee, 2014).

There are two major ventilation modes namely: single-sided ventilation and cross ventilation (Jiang and Chen, 2001). In single-sided ventilation, air enters and exits from openings at one side of the space while in cross ventilation, air flow enters and leaves through separate openings at different sides of the space (Liddament, 1996). Air movement in single-sided ventilation is mainly due to temperature difference between inside and outside and the consequent buoyancy forces and pressure difference (Linden, 1999). In cross ventilated spaces, on the other hand, the pressure difference produced by the wind at inlet and outlet is the main driving force (Liddament, 1996). As far as pressure difference goes, wind produces a much larger force compared to buoyancy and temperature difference. Therefore, a space with cross ventilation normally experiences a higher airspeed and ventilation rate (Evola and Popov, 2006).

Although cross ventilation performs better than single-sided ventilation, it is not always possible to design buildings with cross ventilation. Sometimes site restrictions dictate single-sided ventilation as the only possible option especially in high-rise buildings in dense urban areas. Despite the importance of this subject matter, effectiveness of ventilation modes in providing a thermally comfortable environment is yet to be thoroughly investigated.

The current study investigates the effectiveness of the two major ventilation modes (single-sided and cross ventilation) in providing thermal comfort for a high-rise residential building in a cooling dominant climate. Air velocity, temperature and Relative Humidity (RH) data were collected for two hot summer days in a residential apartment in a high-rise building located in Brisbane, Australia. The collected data were used in calculating a thermal comfort index applicable to naturally ventilated buildings. Finally, thermal conditions inside the case study for both cases of cross ventilation and single-sided ventilation were evaluated and compared.

1.1. Climate condition of Brisbane

Brisbane is located in 27.4° S latitude and 153° E longitude. Brisbane's climate is subtropical with warm and humid summers and mild to cool winters. Monthly mean temperature ranges from 10°C in July to 30°C in January and mean relative humidity is relatively high most of the time, laying in the range of 50% to 70% on average. The annual mean wind speed is 3.6 m/s and is predominantly blowing from south and south-west in the mornings and from east and north-east in the afternoons (Australian Government Bureau of Meteorology, 2016). The graph below shows mean monthly temperature and wind speed in Brisbane.

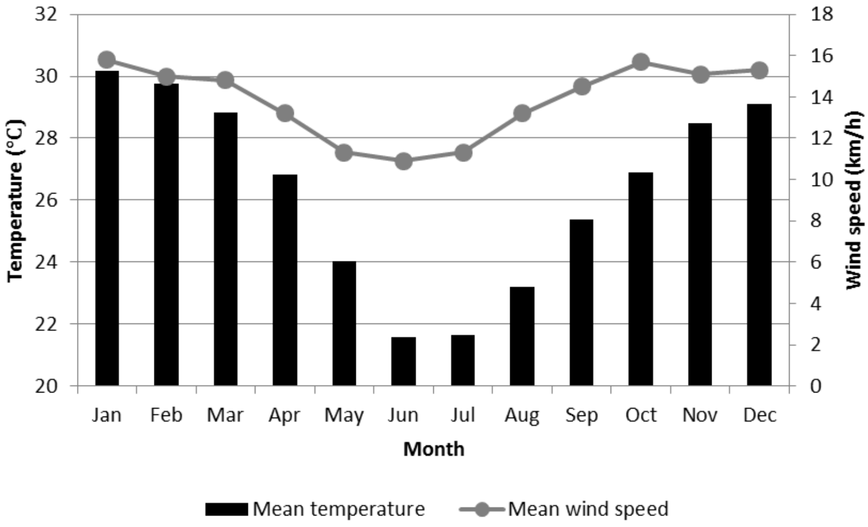

Figure 1: Brisbane's mean monthly temperature and wind speed

2. Methodology

This study investigates the effectiveness of single-sided and cross ventilation in proving thermal comfort for building occupants using full-scale on-site measurements. Air velocity, temperature and RH were measured in a high-rise residential apartment for both single-sided and cross ventilation. The collected data was used for thermal comfort evaluation by adopting extended PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfaction) as criteria.

2.1. Full-scale measurements

Data collection for the current study was carried out in a residential unit located at level five of a 36-storey residential building situated in Brisbane, Australia. The case study's layout with two balconies at two opposite sides of the living area allowed measurements for both single-sided and cross ventilation. Both balcony doors were kept fully open (1.16m*2.5m=2.9 m^2 operable area each) for the cross ventilation setting. For the single-sided ventilation setting, the northern balcony door was shut and the southern door was kept fully open for the duration of the experiment. Figure 2 represents the location of the case study within the whole building (left) and the measurement point on the case study's plan (right). As can be seen, the case study is a two bedroom apartment; however, all the measurements were only carried out in the living area. Therefore, doors and windows to the bedrooms were kept closed for the duration of the data collection.

The data collection was conducted in summer (January 13th and 14th) to examine the possible worst case scenario. In Brisbane, January is the hottest month of year (Figure 1) and the most critical time in terms of cooling energy requirements. Therefore, if a naturally conditioned building is thermally comfortable in the hottest time of year, it may not need mechanical cooling for the rest of the year.

Temperature, RH and air velocity were measured inside the living area of the case study (Figure 2) for single-sided and cross ventilation during 24 hours for each setting. Considering the fluctuating nature of wind, temperature change and solar radiation pattern, 24 hours might be long enough to cover typical weather condition variations. Measurements were carried out on days with clear sky when no precipitation occurred.

Instrumentations that were used in the data collection included a velocity transducer (8475 series, TSI), and temperature and RH sensors (iBotton, Maxim integrated). The velocity transducer logged air speed at a sampling rate of 5 Hz, temperature and RH data were recorded at one-minute intervals. All the sensors were installed at a height of 1.2 m which represents the head level of a sitting occupant.

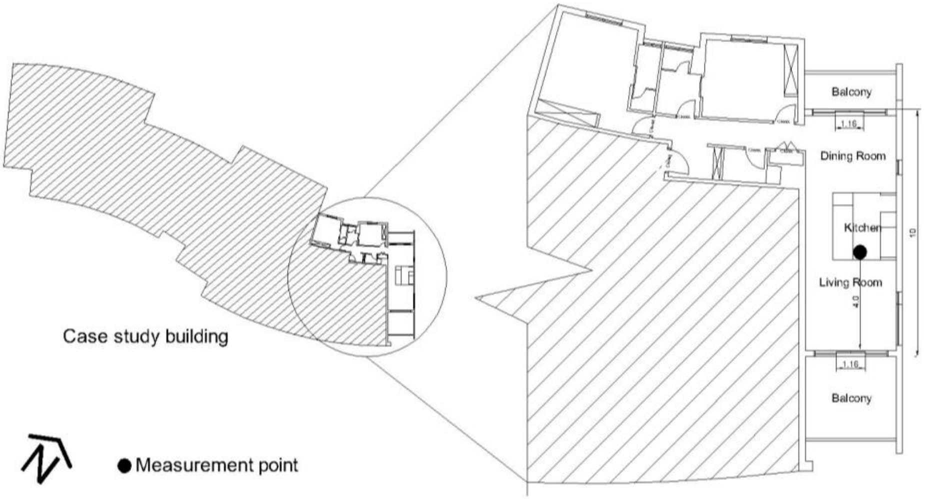

Figure 2: Case study location within the building (left) and plan and measurement point (right)

2.2. Evaluation criteria

One of the main purposes of natural ventilation is to provide occupants with a thermally comfortable environment. To this end, thermal comfort was chosen as the criteria for assessment of ventilation modes. Hence, an appropriate comfort model needed to be adopted for this study. In the last few decades, a number of comfort models have been developed with the aim of predicting an environment's thermal condition for its occupants.

One of the first comfort models was the PMV developed by Fanger (Fanger, 1970). PMV is an index for human body thermal sensation and ranges from -3 to +3 where -3 refers to cold, 0 shows neutrality and +3 indicates hot sensation of the environment. ASHRAE standard (ASHRAE, 2013) considers an environment thermally comfortable when at least 80% of its occupants are satisfied with the thermal condition of their environment which can be translated to $-0.5<PMV>0.5$. Parameters such as air temperature, radiant temperature, air velocity, RH, metabolic rate and clothing are taken into consideration in PMV calculations. PPD can also be calculated based on PMV. The PMV model is proven to underestimate thermal comfort for naturally ventilated buildings (Croome *et al.*, 1993). De Dear and Brager (1998) explain this shortcoming with regards to the steady-state assumption of thermal comfort in the PMV model, as well as neglecting physiological (acclimatisation), psychological and, behavioral effects. The adaptive comfort model, therefore, was developed by De Dear and Brager (1998) based on an extensive field study to predict thermal comfort in naturally ventilated buildings. The adaptive model represents the acceptable limits of indoor operative temperature as a function of mean outdoor temperature. Although considered in the model development process, there is no direct input for air velocity in the adaptive comfort model. Therefore, it was not a suitable model for the current study. Subsequently, Fanger and Toftum (2002) introduced the extended PMV model by adding two correction factors to the traditional PMV model. One is expectancy factor (e) which should be multiplied by the traditional PMV. The expectancy factor considers thermal expectation of occupants based on their experience and varies between 0.5 and 1. The other parameter considered in the extended PMV model is the activity level. People tend to reduce their activity level unconsciously when feeling warm. This reduction is 6.7% by every scale unit increase in PMV index above the neutral point. Therefore, for PMV values above zero, a new metabolic rate needs to be obtained and considered in recalculation of the traditional PMV. Accordingly, PPD can be calculated based on the obtained extended PMV value. The extended PMV model could predict thermal sensation votes for free-running buildings in warm climates reasonably well (Fanger and Toftum, 2002). The extended PMV model, therefore, was chosen for thermal comfort evaluation in the current study.

The source code of the CBE thermal comfort tool (Hoyt *et al.*, 2013) provided by the developers were used for calculating PMV using the R statistical software (Team, 2014). The expectancy factor and adjusted activity level were then applied to the obtained PMV values and extended PMV was calculated.

To assess thermal comfort performance of single-sided and cross ventilation using the extended PMV model some assumptions needed to be made. Occupants were assumed to be involved in sedentary activities. Metabolic rate therefore, was set to 1.2 met. Considering measurements were carried out in summer, typical light clothing insulation value equal to 0.5 clo was taken for PMV calculations. The expectancy factor for Brisbane was set to 0.9 based on Fanger and Toftum's (2002) suggestion. Activity level reduction was also taken into consideration.

3. Results and discussion

3.1 Cross ventilation

The experimental measurements for cross ventilation setting were carried out on January 13th for 24 hours. A summary of external weather conditions and measured values are presented in Table 1. A narrower temperature range is evident inside the case study compared to the external weather temperature while the internal average temperature is slightly higher yet very close to the external weather mean temperature (ΔT_{mean}=0.6).

Table 1: weather condition and measured values summary for the cross ventilation setting

	External weather condition			Internal measured values		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Temperature (°C)	26.25	31	20.3	26.85	29.4	25.1
RH (%)	65.8	92	47	63.5	72	54.5
Wind speed (m/s)	1.8	5	0	0.64	2	0

The extended PMV values and corresponding PPD for the experiment duration are plotted against the time of day in Figure 3. The lowest and highest values for PMV are -0.64 and 0.98 respectively. Average PMV and PPD are 0.23 and 8.9% correspondingly demonstrating a predominantly comfortable environment for the cross ventilation setting. PMV exceeds ASHRAE upper limit (0.5) for 28% of the experiment time and it is mainly from around 11:30 am to 4 pm when the outside temperature is high.

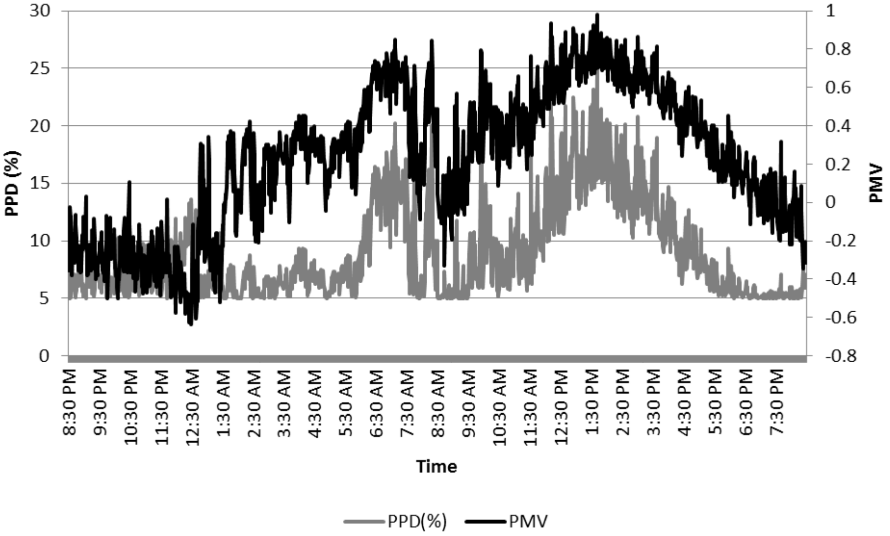

Figure 3: extended PMV and PPD results for the cross ventilation setting

3.2. Single-sided ventilation

Physical measurements were conducted on January 14th in the same case study building with single-sided ventilation setting. All the opening conditions were kept the same as cross ventilation setting except that the northern balcony door was fully closed during the measurements. Outside weather and internal conditions presented in Table 2 show higher temperatures inside the case study with average value difference of about 2 °C (ΔT_{mean}=2.02). In addition, internal temperature changes in a relatively limited range compared to the outside temperature variations.

Table 2: weather condition and measured values summary for the single-sided ventilation setting

	External weather condition			Internal measured values		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Temperature (°C)	26.28	31.7	21	28.3	30.2	26.1
RH (%)	66	84	46	62.2	68.3	54.5
Wind speed (m/s)	2.14	7	0	0.1	0.5	0

PMV and PPD were calculated and rendered in Figure 4. Average PMV of 1 and average PPD of 28% highlight a dominant warm internal thermal condition. PMV results also confirm an uncomfortable internal condition for the single-sided ventilation setting as PMV exceeds the 0.5 limit for 99% of a time. PMV reaches its highest range (1.2-1.6) from around 11 am to 4:30 pm which can be due to high external temperature and solar radiation.

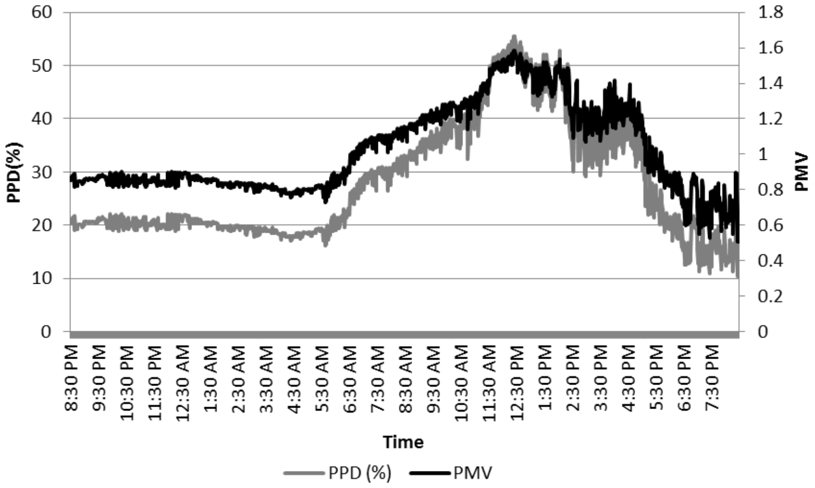

Figure 4: extended PMV and PPD results for the single-sided ventilation setting

3.3. Discussion

The experimental measurements for single-sided and cross ventilation cases were carried out on two consecutive days in summer under relatively similar weather conditions to allow fair comparison of ventilation mode performance and its effect on thermal comfort in a hot summer day when cooling is needed most. All the influential and controllable variables such as size of the openings, sensors height and location were kept the same in both measurement settings. Results reported in section 3.1 and 3.2 revealed a significant difference between single-sided and cross ventilation performance in terms of thermal comfort. PMV values from both settings are also displayed in Figure 5 for better interpretation and comparison between the two cases. ⍰

Single-sided ventilation failed to provide thermal comfort in a hot summer day since PMV value was within the comfort zone for only 1% of time. On the other hand, cross ventilation could provide a comfortable thermal environment for more than 70% of time. Average PMV values for single-sided ventilation was more than four times higher than that of the cross ventilated case. The difference between these two ventilation modes becomes even more apparent when considering that in the cross ventilation setting, the PMV values were under the lower limit of thermal comfort (-0.5) representing cool thermal sensation for about 1% of time which happened around midnight. Given that occupants have control on the openings, the cool sensation that would result from high airspeed can be eliminated by the occupants in such instances.

Looking at Figure 5, both cases have experienced their highest PMV range from around noon to 4:30 pm which should be related to temperature rise as a result of solar radiation. In addition, both graphs follow a consistent trend while more fluctuations of PMV values are evident in the cross ventilation graph. This can be explained by the fluctuating nature of wind and the fact that the cross ventilation case has experienced higher indoor airspeeds.

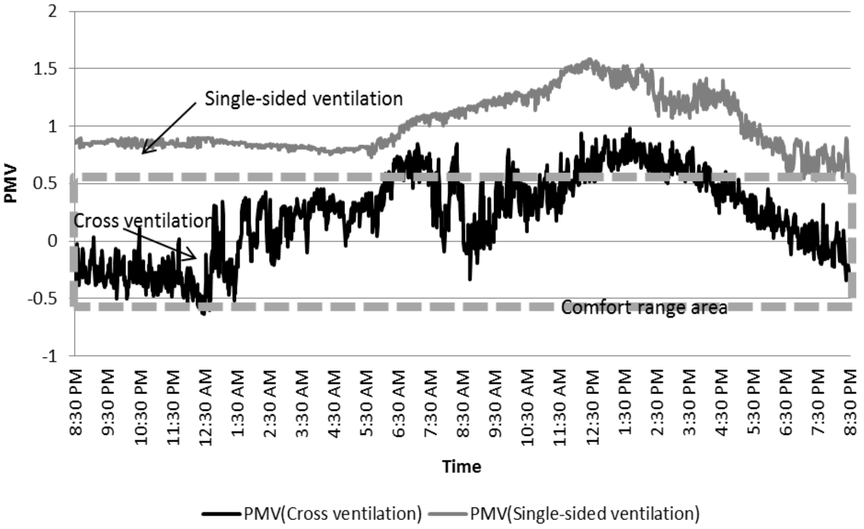

Figure 5: extended PMV results for the single-sided ventilation setting

In summary, cross ventilation performed considerably better than single-sided ventilation in terms of thermal comfort as could be expected. However, the major result is the significant difference which puts the two ventilation modes almost at two ends of the spectrum. While single-sided ventilation totally failed in providing thermal comfort, cross ventilation offered desirable thermal conditions for more than 70% of time. Considering all the influential parameters except for ventilation mode were similar in both cases, this extreme difference can be explained by natural ventilation driving forces in each case.

The potential reduction in air conditioning equipment cost versus the possible increased cost of designing for cross ventilation needs to be studied.

4. Conclusion

This study evaluated the performance of two major ventilation modes, namely single-sided and cross ventilation, in providing thermal comfort for occupants of a high-rise residential building situated in Brisbane, Australia. Full-scale measurements of airspeed, temperature and RH were carried out in a residential unit of the building. Measurements were conducted in summer to allow assessment for the expected worst case scenarios. Two experimental arrangements of single-sided and cross ventilation were examined during two consecutive days in the same case study unit. Extended PMV and PPD were adopted as thermal comfort assessment criteria. It was found that cross ventilation could provide thermal comfort for more than 70% of the day while in the case with single-sided ventilation thermal comfort was achieved for only 1% of time. This suggests that in case of applying cross ventilation the need for air conditioning for space cooling can be reduced significantly.

It needs to be noted that this study was conducted at a case study unit at fifth floor. Considering that wind magnitude increases with the increase in height, higher airspeeds can be expected at upper floors and vice versa. Therefore, higher floors could potentially experience acceptable thermal conditions for longer periods compared to the tested case study. Finally, regardless of building's height, natural cross ventilation is a much more effective solution than single-sided ventilation in providing thermal comfort.

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