Faculty of Engineering and Information Sciences - Papers: Part A

Faculty of Engineering and Information Sciences

2017

# Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems

Xiang Deng
*University of Wollongong*, xd902@uowmail.edu.au

Georgios Kokogiannakis
*University of Wollongong*, gkg@uow.edu.au

Zhenjun Ma
*University of Wollongong*, zhenjun@uow.edu.au

Paul Cooper
*University of Wollongong*, pcooper@uow.edu.au

## Recommended Citation

Deng, Xiang; Kokogiannakis, Georgios; Ma, Zhenjun; and Cooper, Paul, "Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems" (2017). *Faculty of Engineering and Information Sciences - Papers: Part A*. 6642.
https://ro.uow.edu.au/eispapers/6642

# Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems

## Abstract

This study uses field monitoring and post occupancy evaluation (POE) surveys to investigate the indoor thermal comfort of an office building that is located in subtropical zone. The building is special as it combines advanced natural ventilation (ANV) strategies and underfloor air distribution (UFAD) systems. A comparison between a static thermal comfort model and a dynamic thermal comfort model is also conducted. The results show that the thermal comfort conditions in the case study building are satisfactory in summer while in winter there is evidence of thermal discomfort. For the case study building, the static thermal comfort model gives outputs that matched well with the responses of the occupants during the POE survey in winter while the dynamic model is more representative of the sensation of the occupants in summer.

## Keywords

systems, distribution, air, underfloor, comfort, ventilation, thermal, natural, advanced, building, office, ventilated, mode, mixed, evaluation

## Disciplines

Engineering | Science and Technology Studies

## Publication Details

Deng, X., Kokogiannakis, G., Ma, Z. & Cooper, P. (2017). Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems. Energy Procedia, 111 520-529. Turin, Italy 8th International Conference on Sustainability in Energy and Buildings

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 111 (2017) 520 – 529

Energy Procedia

8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, ITALY

# Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems

Xiang Deng[a,]*, Georgios Kokogiannakis[a], Zhenjun Ma[a], Paul Cooper[a]

[a]*Sustainable Buildings Research Centre, University of Wollongong, Wollongong 2522, NSW, Australia*

## Abstract

This study uses field monitoring and post occupancy evaluation (POE) surveys to investigate the indoor thermal comfort of an office building that is located in subtropical zone. The building is special as it combines advanced natural ventilation (ANV) strategies and underfloor air distribution (UFAD) systems. A comparison between a static thermal comfort model and a dynamic thermal comfort model is also conducted. The results show that the thermal comfort conditions in the case study building are satisfactory in summer while in winter there is evidence of thermal discomfort. For the case study building, the static thermal comfort model gives outputs that matched well with the responses of the occupants during the POE survey in winter while the dynamic model is more representative of the sensation of the occupants in summer,

Peer-review under responsibility of KES International.

*Keywords:* Mixed-mode ventilation; Thermal comfort; Post-occupancy evaluation (POE)

## 1. Introduction

The use of natural ventilation could reduce energy consumption and operating cost of air conditioning systems [1] and it is often more pleasant and acceptable to building occupants than using mechanical ventilation [2]. However, natural ventilation is often limited by the outdoor climate and it is therefore often necessary to employ mixed-mode ventilation strategies in buildings.

Previous studies have evaluated thermal comfort in mixed-mode ventilation buildings by using thermal comfort modelling techniques, e.g. [1]. Thermal comfort models were normally categorized into static models and dynamic

---

* Corresponding author. Tel.: +610415484106.
*E-mail address:* xd902@uowmail.edu.au

Peer-review under responsibility of KES International.
doi:10.1016/j.egypro.2017.03.214

models [3]. Static models make use of data collected from people within air-conditioned environmental chambers, while dynamic models are derived from field studies [4]. The details of both approaches have been well-documented in the literature, e.g. Ref [5].

It is worth noting that static and dynamic models are normally limited to mechanically ventilated buildings and pure naturally ventilated buildings, respectively [6]. Currently, there are no explicit standards declaring the most suitable thermal comfort model for buildings with mixed-mode ventilation systems. As a result, both static and dynamic thermal comfort models have been employed in research for mixed-mode ventilation (e.g., Ref [7-9] used a static model and Ref [10, 11] used a dynamic model). Comparisons between static and dynamic models have been reported in the literature [1, 12, 13] to identify the most suitable model for mixed-mode ventilated buildings. The general conclusion from these studies was that dynamic thermal comfort models are more applicable to mixed-mode ventilated buildings. However, this conclusion was drawn from mixed-mode ventilated buildings that use conventional fan coil units (FCU) and can not be generalized for mixed-mode ventilated buildings that use underfloor air distribution (UFAD) systems. UFAD, as a special mechanical ventilation method, supplies air into the space with an airflow velocity that is lower than conventional mechanical ventilation systems. Furthermore, the air is provided normally from swirl diffusers and can become well-mixed with the air in the occupied space. With UFAD systems, the conditioned air is supplied to locations close to the occupants and it therefore has a strong effect on the thermal sensation of occupants.

This study tries to expand existing research on indoor thermal comfort in mixed-mode ventilated buildings by investigating a case study office building where advanced natural ventilation strategies are combined with UFAD systems and the thermal perception of the occupants is evaluated by field measurements and POE survey. The performances of two types of thermal comfort models were evaluated to identify the most representative comfort model for the specific building.

## 2. Methods

Long-term monitoring of indoor thermal parameters was conducted in a case study building to analyse the indoor conditions and the associated ventilation control strategies. POE survey was also carried out to document the perception of the occupants on indoor conditions and correlate the responses with the monitoring data. Section 2.2.1 provides the details of the monitoring study and section 2.2.2 gives an overview of the POE survey.

### *2.1. Case study building and location*

The selected building is located at the University of Wollongong, Australia. Wollongong is on the eastern coast of Australia (34S, 151E) and experiences an oceanic climate with a mean summer daily maximum temperature of 25.9°C, a mean winter daily minimum temperature of 8.3°C and an annual mean daily maximum temperature of 21.7°C. The monthly average relative humidity ranges from 50% to 70% indicating that the air is usually dry and fresh. As the area is close to the ocean, the sea breeze lasts over the whole year and approximately 78% of the time the wind speed is between 1 and 8 m/s. Natural ventilation could therefore be a possible option in Wollongong due to the moderate climate and gentle sea breeze throughout the whole year.

The Sustainable Building Research Centre (SBRC) building is a two-storey building comprising of research laboratory spaces, meeting rooms and an open-plan office (Fig. 1). The open-plan office is 12 meters wide and 52 meters long, and it is occupied by about 39 staff and research students.

Fig. 1. A view of the case study building.

The building has a mixed mode ventilation system with automatically operated windows and mechanical ventilation using a UFAD system. The mechanical system is utilised when internal space temperatures can not be maintained by natural ventilation between 20 and 24°C. Outside these conditions the building uses mechanical ventilation with heating to maintain the space temperature above 19.5°C or cooling to maintain the space temperature below 24.5°C. A hysteresis region of 0.5°C has been placed between the operation modes to ensure there is not frequent toggling between different modes. The hysteresis also incorporates a switching delay time of 20 minutes. During natural ventilation, windows are fully open if the wind velocity is less than 15 km/h and the windows are modulated as a linear function of outdoor wind velocity when the wind velocity is between 15 and 30 km/h. The windows are fully closed if the wind velocity is greater than 30km/h. If the outside air temperature is less than 16°C or greater than 28°C, the windows are closed and the heating or cooling mode is activated. For the mechanical ventilation, the supply fans use a variable speed drive to maintain the AHU supply duct static pressure constant.

### 2.2. Field investigation

#### 2.2.1. Measurements

Fig. 2 shows how the sensors were divided and deployed in four groups (S1-S4). Indoor and outdoor air temperatures, wind speed and window opening percentage values and so on were recorded every 15 minutes over the whole year of 2015 and the first two months of 2016. Additional measurements were taken at different heights in the open plan space to evaluate if thermal stratification should be of a concern in winter and summer. Details and results for the thermal stratification analysis are given in section 3.2.

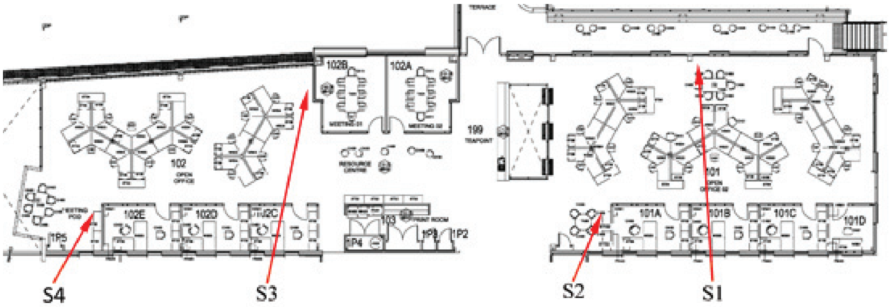

Fig. 2. Deployment of sensors.

#### 2.2.2. Post Occupancy Evaluation (POE) survey

POE surveys are defined as ‘the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time’ [14]. The Building Use Studies (BUS) questionnaire has been selected after a review of a number of standard surveys that are available in the public domain [15-18]. The BUS methodology is a free tool for evaluating occupant satisfaction and has been developed over the last 30 years. The BUS questionnaire is an established and tested way of benchmarking the levels of occupant satisfaction within buildings against a large database of results for similar buildings. For the research interest of this study, only results from survey questions related to indoor thermal comfort are presented. The selected survey questions cover questions on comfort with regards to summer and winter temperature, air quality, lighting, noise, and overall comfort. The answers are based on a 7-point scale evaluation system aiming at understanding occupants' subjective thermal perceptions in a quantitative way. The 'forgiveness factor' was introduced by BUS as a metric of comparison between overall comfort and individual comfort parameters and it is defined as follows [18]:

$$Forgiveness\_factor = Comfort\_overall / \left( \left( A_s + A_w + T_s + T_w + L + N \right) / 6 \right) \quad (1)$$

where *Comfort_overall* is the score of the building's overall comfort performance, $A_S$ and $A_W$ are average satisfaction scores for ventilation/air in summer and winter respectively, $T_S$ and $T_W$ are average satisfaction scores for temperature in summer and winter respectively, $L$ is the average score of satisfaction for lighting, and $N$ is the average satisfaction score for acoustics. BUS questionnaires were distributed to 39 occupants in June, 2015 for the winter case and a supplementary BUS survey was conducted in February, 2016 for the summer case.

## 3. Results analysis

### 3.1. Indoor thermal environment results

#### 3.1.1. Natural ventilation control over the whole year

As described in section 2.1, the case study building is equipped with windows which are operated automatically based on control logic that accounts for indoor and outdoor conditions. Fig. 3 presents the whole year's record of the average indoor temperature, outdoor temperature and window operation.

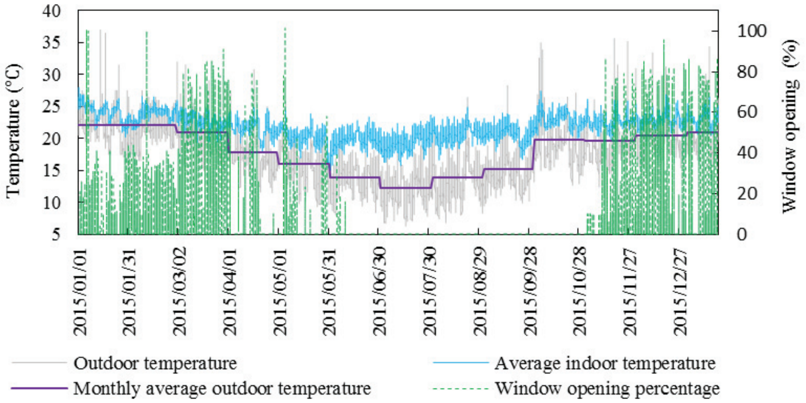

Fig. 3. Window control and average indoor temperature over the whole year.

Although the outdoor temperature fluctuated with the seasons, the average indoor temperature was mostly kept between 18 and 27°C. The building is often naturally ventilated during the summer and the transition seasons. Typical days in winter and summer were selected from the whole year's record to further analyse the control mode for the systems and the windows versus the corresponding average indoor air temperature (Fig. 4).

For the winter case in Fig. 4a, the outdoor temperature was always below 16°C and, as mentioned in section 2.1 these temperatures were below the maximum outdoor temperature threshold for considering the use of natural ventilation. Heating was therefore provided during working hours and the average indoor temperature was then maintained at 20±1°C.

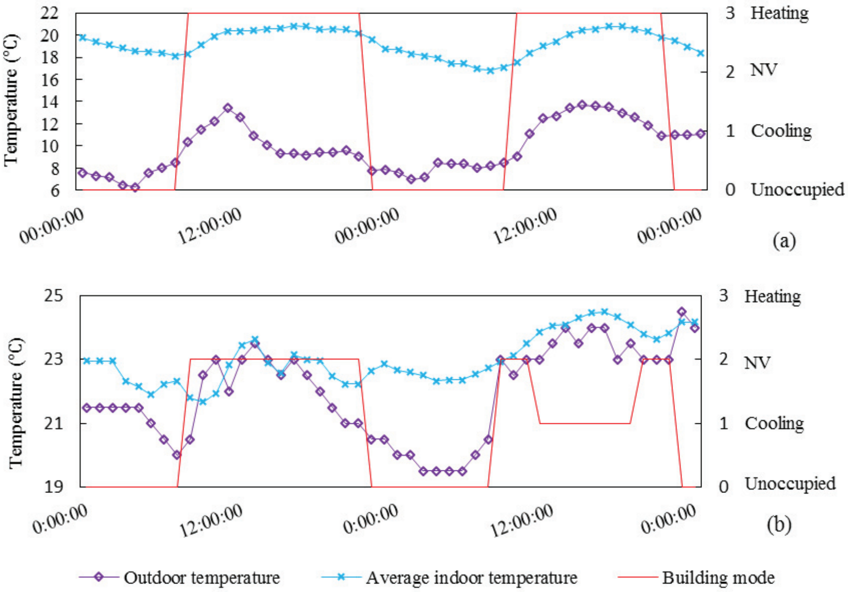

Fig. 4. Indoor temperature performance in different building modes: (a) winter (b) summer.

For the summer case in Fig. 4b, the outdoor temperature conditions could meet the requirements for natural ventilation and natural ventilation was therefore implemented over the whole first working day and at the start of the second working day. However, the average indoor air temperature kept increasing during the second day (Fig. 4b) as natural ventilation is not sufficient to provide required cooling to the building. The average indoor air temperature exceeded 24°C at 11am that was the upper limit of the indoor thermal comfort zone specified in section2.1, indicating that natural ventilation could not maintain the indoor thermal condition into the specific thermal comfort zone. Mechanical cooling was therefore activated to maintain the indoor temperature below the cooling setpoint of 24.5°C.

### *3.1.2. Temperature stratification measurements*

The vertical temperature difference between head and ankle could be of a concern and may cause thermal discomfort to the building occupants. The case study building has a high ceiling with an underfloor air displacement ventilation system that could result in thermal stratification.

To measure the vertical temperature, sensors were deployed at 0.3 m, 1.3 m (matching the head level at a sitting position) and 3.5 m above the floor level and on the north wall of the building (Fig. 5) and measurements were taken from 15 Jul 2015 to 15 Aug 2015 for the winter case and from 16 Jan 2016 to 16 Feb 2016 for the summer case. A sample of results is shown in Fig. 6 from a period in winter and summer.

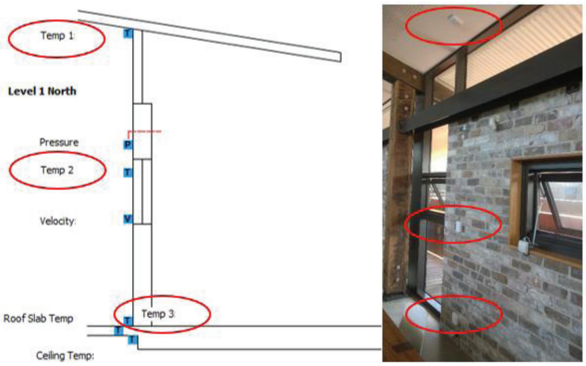

Fig. 5. Location of vertical temperature sensors.

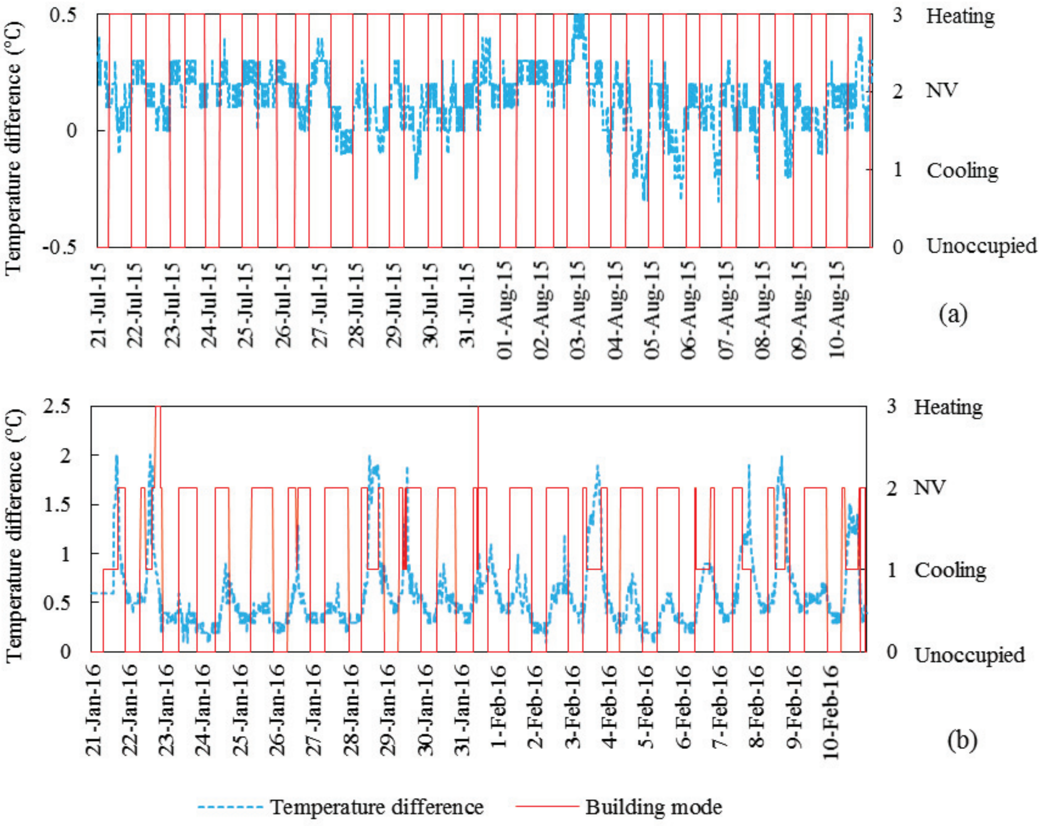

Fig. 6. Sample output of vertical temperature difference between head (1.3m) and ankle (0.3m) under different HVAC modes in (a) winter; (b) summer.

In winter, the heating mode dominated during the working days (Fig. 6a) and the heat supply from the underfloor distributors improved the indoor temperature at the ankle level and reduced the thermal stratification. The temperature difference between the two measurement heights ranged from -0.3 to 0.5°C. However, in summer, the temperature difference between head and ankle can reach up to 2.0°C as a result of cold air accumulation at lower levels of the space when the building is in the cooling mode. The thermal stratification phenomenon is alleviated when changing from mechanical cooling into natural ventilation.

### *3.1.3. POE analysis*

Fig. 8 presents the POE results for indoor thermal comfort based on a 7-point scale. The occupants in summer had a positive evaluation on overall comfort (Fig. 7b) whereas in winter the overall satisfaction result was neutral.

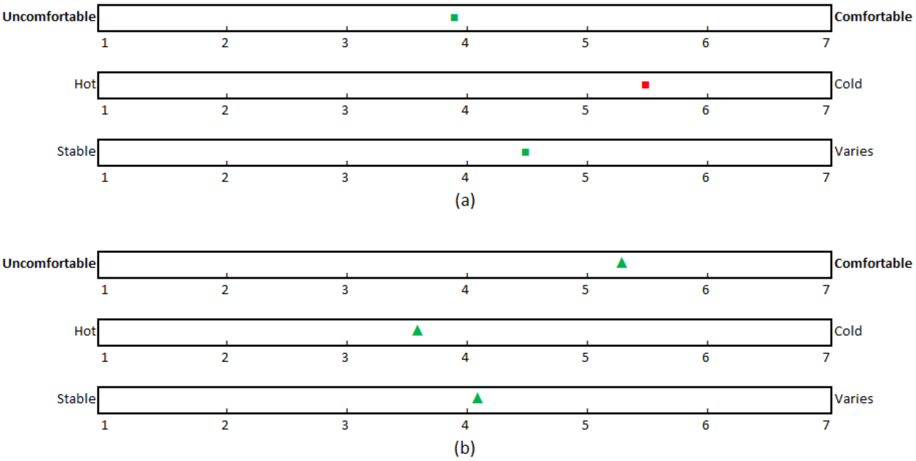

Fig. 8. A summary of POE satisfaction scores for indoor thermal comfort: (a) Winter; (b) Summer. The green marker indicates a better performance than BUS benchmark while the red marker denotes a worse performance than BUS benchmark.

The survey also revealed the issue of cool or cold indoor conditions in winter, which is consistent with the field measurement results presented in Fig. 4a where the indoor temperature was lower than the heating setpoint of 19.5°C at the start of the occupied period. The heating setpoint was 0.5°C lower than the lower limit of the recommended indoor design temperature ranges in winter (i.e., 20°C for ASHRAE [19] and ISO [20] Standards).

The ‘forgiveness factor’ from another mixed-mode ventilated office building which used conventional HVAC system [21] is also used for comparison purposes. The additional case study building is located in Sydney area and is therefore within the same climate as the case study building. The ‘forgiveness factor’ results are summarized in Table 1. The Australian BUS database for green buildings that use natural ventilation, advanced natural ventilation or mixed-mode ventilation [22] is used as a benchmark. ‘Forgiveness factor’ greater than 1 indicates a greater tolerance to the indoor conditions.

Table 1. Forgiveness factor.

| Study variable | Australian BUS database | Ref [21] | This study |
|---|---|---|---|
| Comfort overall | 4.18 | 3.69 | 4.68 |
| Forgiveness factor | 1.02 | 0.99 | 1.01 |

The “comfort overall” value of the building is 4.68 which is higher than the other building in Ref [21] and the Australian BUS benchmark. The high “comfort overall” result shows a better overall indoor comfort for the building. The ‘forgiveness factor’ matches the average value of the Australian BUS database. The forgiveness result also indicates the occupants in this case study building were slightly more tolerant to conditions than the occupants in Ref [21], albeit the tolerance difference is quite small.

### *3.2. Thermal comfort models comparison*

The Fanger's predicted mean vote (PMV) model [23] and the adaptive thermal comfort model from ASHRAE 55 [24] have been widely used and they were therefore applied to the case study building. Fig. 9 presents the evaluation results derived from the Building Management System (BMS) of the building during the working hours for winter (11th Jul 2015 – 11th Aug 2015) and summer (17th Dec 2015 – 17th Jan 2016).

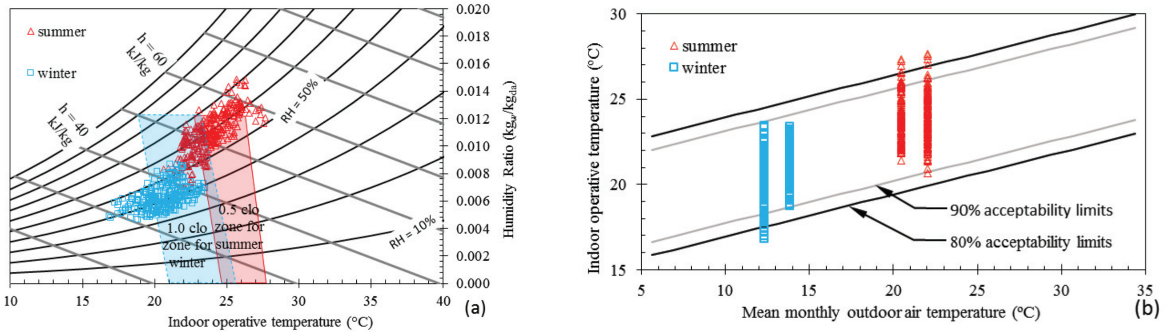

Fig. 9. Evaluation of the thermal responses of the occupants based on different models: (a) PMV model; (b) adaptive thermal comfort model.

Fig. 9a used the graphic comfort zone method from ASHRAE 55 to present the results produced by the PMV model. These results indicated a poor indoor thermal environment for both summer and winter. In winter, 40% of the data was distributed outside the thermal comfort zone and towards the cold side area of the psychrometric chart. In summer, 67% of the data was scattered out of both sides of the thermal comfort zone. However, the results of the adaptive model in Fig. 9b showed that most dots fall within the ASHRAE 55 80% acceptable ranges for both winter and summer cases.

The POE survey provided a thermal sensation vote (TSV) for the occupants to assess indoor thermal comfort conditions. The TSV results (Fig. 10) can serve as a reference to evaluate the reliability of the two thermal comfort models.

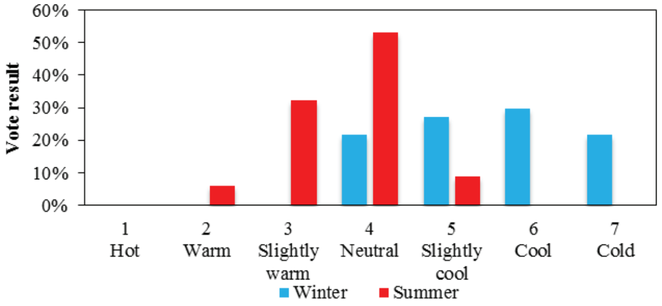

Fig. 10. Thermal sensation vote results (out of 39 participants).

According to the TSV results, 50% of the occupants in the building considered the indoor thermal conditions to be neutral or slightly cool and the rest as cool or cold in winter. In summer, 94% of occupants felt neutral, slightly warm or slightly cool, which indicated good thermal comfort conditions. The result from PMV model is therefore consistent with the TSV results in winter by reporting poor indoor thermal comfort conditions but its predictions did not match with the responses of occupants in summer. However, the ASHRAE 55 adaptive model reported acceptable thermal comfort conditions in summer, and this agrees with the TSV responses for the summer period.

## 4. Discussion

### 4.1. Indoor thermal comfort performance

The monitoring of window control and average indoor temperature over the whole year indicates the mild climate in Wollongong make the natural ventilation available to provide suitable and stable indoor temperature for most of the time in summer and transition seasons. Data from typical days further revealed that in winter natural ventilation was not applicable as a result of lower outdoor temperature and mechanical heating was necessary all the time during the work hours. In summer, mechanical cooling mostly happened in the afternoon if the outdoor temperature exceeded the upper limit for natural ventilation. However, it is worth noting the temperature between day and night was large in summer which implied a possibility of night ventilation to reduce the demand hours for mechanical cooling.

The thermal stratification is a common issue in the buildings with UFAD systems [25, 26]. ASHRAE Standard 55 [6] recommended that the vertical air temperature difference should not be greater than 3.0°C (i.e. associated with 5% of dissatisfaction). The findings from the field measurements showed that there was a thermal stratification in both winter and summer. The heat supply from the underfloor air distribution system in winter improved the indoor temperature at the ankle level, making the thermal stratification indifferent. Thermal stratification was enhanced by cold air from the underfloor air diffuser in summer but the temperature difference was still under the tolerance defined in ASHRAE Standard 55.

### 4.2. Suitability of thermal comfort models to mixed-mode ventilated buildings

In order to identify the optimal approach for the thermal comfort evaluation of occupants in the case building, two existing thermal comfort models were compared with the TSV results. The comparison results showed the PMV model was more suitable for winter whereas the ASHRAE 55 adaptive model was more consistent with the TSV results for the summer condition. The main reason for this is that mechanical heating was used in winter and the indoor conditions are closer to those emulated during the initial development of steady state comfort models. However, the frequent use of mixed-mode ventilation in summer makes the adaptive model more suitable in the case study building. Such results indicate that the terminal system for the mechanical ventilation does not affect significantly the comfort predictions of the adaptive model.

## 5. Conclusions

This study investigated the indoor thermal comfort conditions of an office building which uses advanced natural ventilation and underfloor air distribution systems in a subtropical area. Indoor thermal comfort factors were monitored and analysed and the thermal sensation of occupants was captured by a POE survey. The following could be concluded through this study:

- According to the POE surveys and field measurements, the Fanger’s PMV model is more applicable in winter for the case study building while the adaptive model predicts overall comfort better in summer.
- The high ceiling building with underfloor air distribution system experiences thermal stratification, however the measurements indicated that this did not have an impact on the thermal comfort of occupants.

Overall, there is a need to further investigate buildings that use advanced ventilation systems and identify representative thermal comfort models. The POE survey of this study showed that the building is still not commissioned in a way that occupant comfort is ensured at all times. This study has also shown that it is essential to combine different methodologies for evaluating thermal comfort, for example POE surveys will complement BMS data analysis and, if processed and analysed they could offer a useful understanding about the indoor environmental performance of a building.

## References

[1] Luo M, Cai B, Damines J, Lin B, Zhu Y. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. Building and Environment. 2015; 88:46-54.
[2] Ouyang Q, Dai W, Li H, Zhu Y. Study on dynamic characteristics of natural and mechanical wind in built environment using spectral analysis. Building and Environment. 2006;41(4):418-426.
[3] Carlucci S, Pagliano L. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. Energy and Buildings. 2012;53:194-205.
[4] Kwok AG, Rajkovich NB. Addressing climate change in comfort standards. Building and Environment. 2010; 45(1):18-22.
[5] Fanger PO, Toftum J. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy and Buildings. 2002; 34(6):533-536.
[6] ASHRAE. Standard 55-2013: Thermal Environmental Conditions for Human Occupancy. 2013.
[7] Song D, Kato S. Radiational panel cooling system with continuous natural cross ventilation for hot and humid regions. Energy and Buildings. 2004;36(12):1273-1280.
[8] Homod RZ, Sahari KSM. Energy savings by smart utilization of mechanical and natural ventilation for hybrid residential building model in passive climate. Energy and Buildings. 2013;60:310-329.
[9] May-Ostendorp P, Henze GP, Corbin CD, Rajagopalan B, Felsmann C. Model-predictive control of mixed-mode buildings with rule extraction. Building and Environment. 2011;46(2):428-437.
[10] Ezzeldin S, Rees SJ. The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. Energy and Buildings. 2013;65:368-381.
[11] Alan Short C, Lomas KJ. Exploiting a hybrid environmental design strategy in a US continental climate. Building Research and Information. 2007;35(2):119-143.
[12] Deuble MP, De Dear RJ. Mixed-mode buildings: A double standard in occupants' comfort expectations. Building and Environment. 2012;54(0):53-60.
[13] De dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. 1998.
[14] Preiser WF, Rabinowitz HZ, White ET.Post-occupancy evaluation. Van Nostrand Reinhold company. 1988.
[15] Oseland NA. A comparison of the predicted and reported thermal sensation vote in homes during winter and summer. Energy and Buildings. 1994;21(1):45-54.
[16] Huizenga C, Abbaszadeh S, Zagreus L, Arens E. Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey. Center for the Built Environment. 2006.
[17] Menezes AC, Cripps A, Bouchlaghem D, Buswell R. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. Applied Energy. 2012;97:355-364.
[18] Leaman A, Bordass B. Are users more tolerant of 'green'buildings? Building Research & Information. 2007;35(6):662-673.
[19] ASHRAE. HVAC applications. ASHRAE Inc., Atlanta, 2011.
[20] ISO. Ergonomics of the thermal environment: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 2006.
[21] Deuble MP, De dear RJ. Green occupants for green buildings: the missing link? Building and Environment. 2012;56:21-27.
[22] Leaman A, Thomas L, Vandenberg M. Green buildings: What Australian users are saying. 2007.
[23] Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering. 1970.
[24] De dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings. 2002;34(6):549-561.
[25] Alajmi A, El-Amer W. Saving energy by using underfloor-air-distribution (UFAD) system in commercial buildings. Energy Conversion and Management. 2010;51(8): 1637-1642.
[26] Kong Q, Yu B. Numerical study on temperature stratification in a room with underfloor air distribution system. Energy and Buildings. 2008;40(4):495-502.