Ventilation mode effect on thermal comfort in a mixed mode building

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Abstract. Between 2017 and 2018, we conducted a longitudinal field experiment in a mixed-mode ventilation building located in Wollongong Australia, with a particular focus on occupant thermal comfort and adaptive behaviour. This study investigated how different building operation modes i.e. air-conditioning (AC) and natural ventilation (NV), can have an impact on occupant perception of thermal comfort. Time-and-place matching of objective (physically measured indoor climate parameters, outdoor meteorological data, and building operational information) and subjective data (i.e. occupant survey questionnaires) enabled empirical investigation of the relationships between those parameters. The result of the analysis revealed that subjective perception of indoor thermal environment can be affected by different modes of building operation. Occupants were found to be more tolerant of, or adaptive to, the indoor thermal conditions when the building was in the NV mode of operation compared to the AC operational mode. The applicability of the adaptive comfort standard to the mixed-mode ventilation context was also discussed.

1. Introduction

The mixed-mode (MM) building operation, which integrates both natural and mechanical ventilation strategies, is deemed as an alternative to the centralised HVAC approach for both comfort [1] and energy efficiency [2]. By employing appropriate design and operation strategy, MM buildings can improve comfort and energy performance especially in an appropriate climate like Sydney, Australia. Despite of the clear benefits that the MM approach can offer, there is ambiguity about which thermal comfort targets to use under the two different modes of operation in such buildings. For example, the European standard EN15251 [3] permits the adaptive comfort model to be applied to MM buildings operating under NV (or free-running) mode. In contrast, the current version of ASHRAE Standard 55 [4] limits the use of the adaptive comfort model exclusively to NV spaces, wherein no mechanical cooling system is installed. This means that MM buildings should be treated as AC buildings, and be operated as per the comfort zone defined by the PMV-PPD model even when a building is naturally-ventilated. Since its inclusion in ASHRAE Standard 55 (from the 2004 version), a relaxed thermal comfort zone promoted by the adaptive model has permitted design and operational approaches to rely more on passive strategies, contributing to the reduction of energy used for space heating and cooling in the building sector. Despite its profound energy implications, ASHRAE Standard 55's explicit restriction on the adaptive model's scope of application may discourage energy-efficient design and operation approaches. Previous research in this domain finds that the mode of operation can affect users' comfort responses [5], and also suggests that the adaptive model is applicable during NV operation of MM buildings [6,7]. To be able to reach a consensus in terms of which comfort model to be applied to different operational modes, more research is necessary to better understand how the mode of operation influence occupant thermal comfort. This paper attempts to address how the mode of operation (i.e. AC and NV) in a mixed-mode building can affect indoor environmental conditions, and occupants' perception of thermal comfort and their adaptive behaviours.

2. Methods

The case-study building for this research, the Sustainable Buildings Research Centre (SBRC) at University of Wollongong, is a net-zero energy and Six-Star GreenStar (Australian green building rating tool) accredited building. The Building Management System (BMS) in the case-study building automatically controls its mixed-mode ventilation system as a function of both the indoor and the outdoor air temperatures. Natural ventilation is utilised through the use of operable windows, while the mechanical ventilation is provided via an Under Floor Air Distribution (UFAD) system. In the SBRC building, various adaptive actions can be practiced by its occupants (e.g. adjustable floor vents, personal fans and operable windows). We made longitudinal field observations between June 2017 (winter) and April 2018 (spring) in the SBRC building. The aim was to capture the building's indoor environmental performance and the occupants' evaluation of its performance across different seasons. In terms of instrumental measurements, autonomous monitoring stations known as SAMBA [8,9] were installed at various sampling points across different occupied zones of the building. SAMBA units monitored and averaged indoor thermal comfort parameters every 5 minutes, then transmitted data through the cellular network to the University of Sydney IEQ Lab's file-server. Hourly outdoor climate data were obtained from the closest weather station (Bellambi Bureau of Meteorology station). Time-stamped building operational status details including HVAC and NV modes, occupancy schedules and window status were downloaded from the building's BMS.

Table1. The structure of online questionnaire

Question	Answer
Are you currently in your building?	Yes; No (survey terminates)
Where are you right now?	Open office, east; Open office, west; Cubicle, east; Cubicle, west; Flexi office
How do you feel, right here right now?	Cold; Cool; Slightly cool; Neutral; Slightly warm; Warm; Hot
Here and now, would you prefer to be	Cooler; No change; Warmer
Is the thermal environment acceptable?	Yes; No
Which comfort strategies are in use, here and now?	Adjust clothing; Use personal fan; Use personal heating; Adjust floor diffuser; Consume hot/cold beverages or food; Override BMS to open window
Which best describes your clothing right now?	Very light (0.4 *clo*); Light (0.5 *clo*); Slightly light (0.6 *clo*); Slightly heavy (0.9 *clo*); Heavy (1.0 *clo*); Very heavy (1.4 *clo*)
Which best describes your activity during the preceding half hour?	Relaxing, seated (1.0 *met*); Working, seated (1.1 *met*); Working, standing (1.4 *met*); Walking about (1.7 *met*); Exercising (3.0 *met*)

A right-here-right-now (RHRN) survey was employed to collect subjective comfort evaluations from the building occupants throughout the 11-month monitoring period. 31 occupants (out of a total of approximately 50 staff) agreed to participate in the study. The researchers sent SMS messages containing a link to an online occupant survey questionnaire 1~3 times per week, during normal office hours. The participants returned their responses to our online comfort survey on multiple occasions over the 11-month longitudinal monitoring period. This simple questionnaire addressed the following questions; (1) if the participant is in the building, (2) the participant's location in the building at the time of the survey, (3) thermal sensation, preference and acceptability, (4) which adaptive comfort strategies were practiced, and (5) simple classification of activity (i.e. metabolic rate) and clothing type being worn (i.e. *clo*-value). Each of the returned questionnaires was time-stamped the completion time. Table 1 summarises the structure of the smartphone questionnaire. All the information collected throughout the longitudinal field investigation (i.e. indoor/outdoor climate observations, BMS data, survey responses) was matched together for the subsequent quantitative analysis. A total of 909 samples were logged and used for the present analysis.

3. Results & Discussion

Table 2 presents descriptive statistics of the key indoor climatic and comfort indices (measured or calculated) at the time when each online questionnaire was completed. During the monitoring period, the indoor operative temperature T_o varied between 18.5 and 29.9°C. According to *clo*-value (0.4~1.4 *clo* range) reported by the occupants, they seemed to be flexible in selecting what to wear to work. Mean metabolic rate (*met*) of the participants was estimated to be 1.3, which corresponds to sedentary typical office activities. The average Predicted Mean Vote (PMV) was 0 (neutral), and the accompanying Predicted Percentage of Dissatisfied (PPD) indicated that 10.6% of the participants would be dissatisfied with the given indoor thermal environmental conditions. The mean value of actual thermal sensation (Thermal Sensation Vote, TSV of 0.1) of the occupants was well aligned with the predicted value (PMV = 0).

Table 2. Descriptive statistics of indoor climate and thermal comfort indices recorded at survey times

Indices	Min.	Max.	Mean	Std. Deviation
T_o (°C)	18.5	29.9	23.9	1.7
RH (%)	17	78	53	13
V_{air} (m/s)	0.01	0.56	0.08	0.05
clo	0.4	1.4	0.6	0.2
met	1.0	3.0	1.3	0.2
PMV	-1.9	+2.4	0.0	0.6
PPD	5.0	89.7	11.6	10.6
TSV	-3	+3	0.1	1.0

Table 3 presents proportions of the participants' thermal comfort perception recorded via online occupant surveys. PMV values calculated for each sample were rounded off to the closet point on the 7-point thermal sensation scale. For comparative purposes, the distribution of PMV values was added into this table. The middle three categories of the 7-point thermal sensation scale ('slightly cool', 'neutral' and 'slightly warm') are typically regarded as expression of thermal satisfaction [10]. Based on this assumption, 86.7% of the occupants were satisfied with the indoor thermal environment. This high rate of thermal satisfaction was also closely aligned with the direct thermal acceptability (88.9%). On the other hand, about 12% discrepancy between the actual (86.7%, according to the TSV distribution) and the predicted value (98.6% according to the PMV distribution) was detected, which will be further explored in the later sections of this paper. In general, the case-study building exceeded the 80% acceptability target typically used by industry. The results indicated that the building successfully delivered 'satisfactory' thermal environment to its occupants.

Table 3. Summary of indoor climate and thermal comfort indices recorded at survey times

Comfort indices	Rating scale	Percent
Thermal Sensation Vote (TSV)	- Cold (-3)	1.2%
	- Cool (-2)	1.9%
	- Slightly cool (-1)	15.4%
	- Neutral (0)	56.3%
	- Slightly warm (+1)	14.0%
	- Warm (+2)	5.5%
	- Hot (+3)	2.4%
Thermal Preference (TP)	- Cooler	16.4%
	- No change	66.7%
	- Warmer	16.9%
Thermal Acceptability (TA)	- Acceptable	88.9%
	- Unacceptable	11.1%
Predicted Mean Vote (PMV)	- Cold (-3)	0%
	- Cool (-2)	0.2%
	- Slightly cool (-1)	19.6%
	- Neutral (0)	64.9%
	- Slightly warm (+1)	14.1%
	- Warm (+2)	1.2%
	- Hot (+3)	0%

We further investigated the 12% discrepancy between TSV and PMV observed in Table 3, by performing a regression analysis between the two. The previous studies reports that in mixed-mode buildings the mode of ventilation (i.e. AC vs. NV) can influence occupant perception of thermal comfort [6,7]. In order to further explore this question, our sample was divided into two groups according to the operational mode of the building at the time each questionnaire was completed – i.e. AC mode (n = 416) and NV mode (n = 461). The relationship between TSV and PMV defined by the regression analysis is expressed in Equations 1 and 2. In the air-conditioning mode, the participants' TSV values conformed to the PMV values relatively well, by achieving a regression coefficient of 0.85. However, a relatively large discrepancy was found when the building was naturally ventilating. Equation 2 indicates that a shift of one unit in PMV corresponds to only 0.59 unit change in TSV. In other words, the occupants' actual thermal sensations changed about 40% less than predicted by the PMV. The current result highlights discrepancies between the actual and predicted comfort level of occupants in mixed-mode buildings especially during natural ventilation operation phase. Our results therefore reinforce earlier findings [6,7].

$$TSV = 0.85 \times PMV + 0.15 \text{ (AC mode; n = 416; } R^2 = 0.26\text{; regression coefficient } p<0.001) \quad (1)$$

$$TSV = 0.59 \times PMV + 0.02 \text{ (NV mode; n = 461; } R^2 = 0.12\text{; regression coefficient } p<0.001) \quad (2)$$

The analysis above misses out on thermal adaptation processes that could potentially have played a role in forming the occupants' perceived comfort over the period of our longitudinal field monitoring. The fundamental concept of the adaptive comfort model suggests that the perception of thermal comfort is affected by the occupant's past and current thermal experiences [11]. Provided that the current study was conducted across different seasons, it is rational to take into account adaptive processes could have been in play across the longitudinal monitoring period. Thus in the following analysis, a relative temperature scale (Temperature offset from neutrality, T_{diff}) was used to adjust for adaptive processes within each of the samples [12]. The temperature difference between indoor operative temperature T_o and neutral temperature T_n (estimated by ASHRAE 55 adaptive comfort model: $T_n = 0.31 \times$ prevailing mean outdoor temperature + 17.8) was calculated for each of our samples (i.e. $T_{diff} = T_o - T_n$). On this relative scale, positive values of T_{diff} represent indoor thermal condition in which T_o was warmer than the adaptive model's neutrality, whereas negative values indicate T_o was cooler than T_n. A linear regression was fitted between TSVs and T_{diff} in order to examine how the participants' thermal sensations changed according to indoor temperature variations.

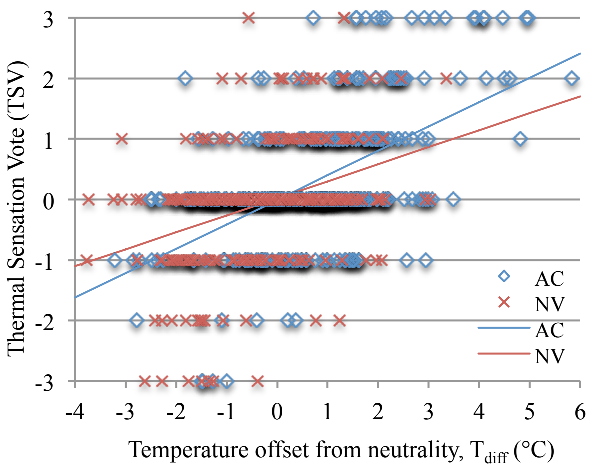

Figure 1. Thermal Sensation Votes (TSV) regressed on temperature offset from neutrality T_{diff}, by building operation mode (AC vs. NV)

$$TSV = 0.39 \times T_{diff} - 0.01 \text{ (AC mode; n = 416; } R^2 = 0.29\text{; } p<0.001) \quad (3)$$

$$TSV = 0.28 \times T_{diff} + 0.02 \text{ (NV mode; n = 461; } R^2 = 0.15\text{; } p<0.001) \quad (4)$$

The regression model performed separately on the two sub-samples (AC and NV samples) is illustrated in Figure 1, and also reported in Equations 3 and 4. By examining the point of intersections between the regression lines and TSV of 0 in Figure 1, it can be seen that the adaptive model prescribed in ASHRAE 55 almost perfectly estimated the neutrality of our participants. The slope of the regression line is typically translated as thermal sensitivity of occupants. The regression slopes in Figure 1 indicate that our participants were more tolerant of indoor temperature changes when the building was operated in NV mode than in AC mode. According to Equation 3, a change of temperature of 2.6 degrees accounts for one unit change of thermal sensation in AC mode. In contrast, when the building was in NV mode, it requires 3.6 degrees of temperature change to shift up/down occupant thermal sensation by one unit (Equation 4). The results indicate that the occupants were about 38% more sensitive to thermal conditions during AC operation period than during NV operation period. In this analysis, the 80% acceptability range can be defined by a mean TSV = ±0.85. This is because PPD value reaches 20% when the mean thermal sensation, i.e. PMV, equals ±0.85. Using Equations 3 and 4, the temperature range corresponding to a group mean TSV was derived to be 4K for the AC group and 6K for the NV group. The NV sample group's regression coefficient of 0.28 was found to be almost identical to the mean regression gradient of 0.27 estimated for the NV building samples of the ASHRAE RP-884 project [13], which later became the basis of the current ASHRAE 55 adaptive model. The AC sample group's regression coefficient of 0.39 was smaller than that of 0.51 observed in the AC building samples of the ASHRAE RP-884 project [13]. In the current ASHRAE Standard 55 [4] the application of the adaptive comfort model is constrained to exclusive naturally ventilated spaces where no mechanical system is equipped. This means that MM buildings are excluded from the scope of the adaptive comfort standard even during the NV operation period. However, the empirical evidences provided in this paper strongly support that, from the perspective of occupant thermal comfort, MM buildings can be classified as NV at least during the NV operation period.

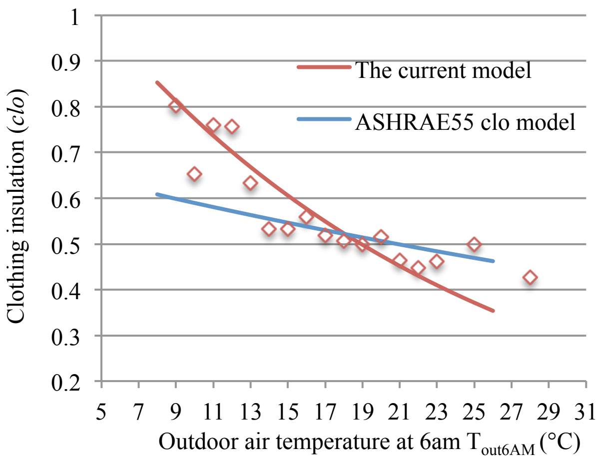

Figure 2. Clothing behaviour observed in the current study compared against the ASHRAE55 dynamic clothing insulation model as a function of outdoor temperature at 6AM

The ASHRAE Standard 55 [4] prescribes the dynamic clothing insulation (*clo*) prediction model based on outdoor air temperature at 6AM (T_{out6AM}), following work by Schiavon and Lee [14]. According to this predictive model, the clothing insulation of a representative occupant for a day in which T_{out6AM} falls between 5 and 26°C is determined as: $clo = 10^{(-0.1635-0.0066Tout6AM)}$, which also can be described as: $clo = 0.6863e^{-0.0152Tout6AM}$. The clothing insulation data collected via questionnaires in the present study (Table 1) was then compared against the ASHRAE *clo* model. During the survey period, T_{out6AM} in Wollongong always fell within the range of 5 and 26°C. The observed *clo*-values were related to T_{out6AM}, and plotted against the ASHRAE *clo* model in Figure 2. It was found that the ASHRAE *clo* model underestimated the *clo* value when T_{out6AM} was below 18°C, and overestimated the *clo* value when T_{out6AM} was over 18°C. The resulting model based on the present study data is defined as:

$$\text{For } 5°C \leq T_{out6AM} < 26°C,\ clo = 1.262e^{-0.0489Tout6AM}\ (R^2 = 0.33) \qquad (5)$$

The current analysis used T_{out6AM} as the predictor to maintain directly comparability with the ASHRAE model. Outdoor air temperature at 6AM (T_{out6AM}) is deemed as a good approximation of the daily minimum air temperature (T_{outMIN}). However, we have observed up to a few degrees (°C) of discrepancy between T_{out6AM} and T_{outMIN} in our sample. When we used daily minimum air temperature, the predictive model improved with an increased R^2 value, which is described in Equation (6) below.

$$\text{For } 5°C \leq T_{outMIN} < 26°C,\ clo = 1.24e^{-0.0501 ToutMIN} \quad (R^2 = 0.37) \qquad (6)$$

4. Conclusion

A longitudinal thermal comfort field study was conducted in Australia's mixed-mode ventilation context. We found that the occupants' response to indoor thermal environments differed between the two modes of building operation – i.e. air-conditioning (AC) and natural ventilation (NV). The occupants were more tolerant of, or adaptive to indoor temperature variations in their office space during the NV operation period than the AC period. Our findings suggested that the adaptive comfort standard is suitable to mixed-mode buildings especially during the NV operation period. The study also found that the occupants in the studied mixed-mode building were more active in adjusting their clothing insulation than that predicted by the ASHRAE 55 dynamic clothing model.

Acknowledgements

This study was conducted within the framework of the International Energy Agency – Energy in Buildings and Communities Program (IEA-EBC) Annex 69 - *Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings*. The authors thank all occupants of the SBRC building for participating in this study.

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