Longitudinal field study of thermal comfort in a low energy mixed-mode building

Jungsoo Kim
IEQ Lab, University of Sydney, Sydney, Australia
jungsoo.kim@sydney.edu.au

Richard de Dear
IEQ Lab, University of Sydney, Sydney, Australia
richard.dedear@sydney.edu.au

Thomas Parkinson
Center for the Built Environment, University of California, Berkeley, USA
tom.parkinson@berkeley.edu

Federico Tartarini
Sustainable Buildings Research Centre, University of Wollongong, Wollongong, Australia
federico@uow.edu.au

Paul Cooper
Sustainable Buildings Research Centre, University of Wollongong, Wollongong, Australia
pcooper@uow.edu.au

Abstract: It is commonly assumed that high levels of occupant comfort and energy efficiency are mutually exclusive. To challenge this misconception and to demonstrate that it is possible to maintain comfort without increasing energy use, a case study was carried out in an exemplary low energy building in Australia. This study was performed under the umbrella of the International Energy Agency’s Energy in Buildings and Community Programme (IEA-EBC) Annex 69 – Strategy and practice of adaptive thermal comfort in low energy buildings. Longitudinal field observations were made for eleven months between 2017 and 2018, through instrumental indoor climate measurements (temperature, humidity and airspeed) and the collection of building operational data (operation of HVAC and windows), coupled with right-here-right-now occupant comfort surveys delivered to the participant’s smartphones. Time-and-place matching of the collected objective and subjective data enabled the quantitative analysis of the relationship between building operational decisions, climatic factors, and occupants’ perception of comfort.

Keywords: Thermal comfort; mixed-mode; PMV; continuous monitoring

1. INTRODUCTION

The advancement of Heating, Ventilation and Air-Conditioning (HVAC) technologies made it possible to tightly regulate indoor climate so that it varies little over diurnal or seasonal timescales. However, this created a problem in the enormous amounts of energy spent to guarantee a narrow band of thermal environments indoors irrespective of the prevailing outdoor conditions. The greatest proportion of building energy use is attributed to the provision of building services during the operational phase. For example, in the Australian commercial property sector, HVAC is the largest end-use of energy, responsible for typically more than half of commercial building energy use (DCCEE, 2012). In a typical sealed office building, a centralised HVAC is programmed to maintain indoor temperatures within a very narrow range, oftentimes narrower than even the relevant authorities and standards recommend. For example, Mendell and Mirer (2009) reported that in US office buildings indoor temperatures in summer were cooler than the comfort thresholds prescribed in the relevant international standards (e.g. ASHRAE, 2017; ISO, 2005), and paradoxically, were even cooler than in winter. Likewise in Australia, a very narrow range of indoor air temperature (22.5 ± 1.5°C in summer) is written into typical commercial office building leases (Roussac et al., 2011), despite ample empirical evidence from around the world indicating that tight and energy-intensive control of indoor temperatures does not translate into high occupant satisfaction (Arens et al., 2010; Hoyt et al., 2015).

While many building operators have been focusing on maintaining a steady and tight indoor temperature all year round, the research literature on adaptive thermal comfort suggests that the acceptable range of indoor temperatures drifts in sync with the outdoor seasonal cycle (e.g. de Dear and Brager, 1998; Humphreys, 1978). According to the adaptive comfort concept, the indoor comfort zone tracks prevailing outdoor weather – shifting up in warm weather and down in cool weather. The important implication is that, as long as indoor temperature is maintained within the acceptable range appropriate to the season, it is possible for people to achieve comfort. This means there is no need to always maintain a steady indoor thermal
environment. Accommodating this natural adaptability of occupants within the building’s HVAC operation strategy can have very positive implications for energy efficiency, because an accepted engineering rule of thumb equates 1°C difference in the set-point temperature with 10% energy HVAC energy (e.g. Roaf et al., 2010).

The international research community has been focusing on this fundamental question of how to better understand the mechanisms of adaptive thermal comfort in buildings. Since 2015, researchers from fourteen different countries have been working together under the International Energy Agency’s Energy in Buildings and Community Programme (IEA-EBC) Annex 69 – “Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings”. The ultimate objective of the Annex is to reduce energy use in buildings by the application of the thermal adaptation concept in design, evaluation and control of indoor built environments. One of the key research activities of Annex 69 is to conduct case studies of office buildings in participating countries, focusing on the best practices of building performance in both occupant comfort and energy efficiency. The case studies are specifically aimed to present compelling evidence that low-energy buildings can deliver high standards of comfort to their occupants, dispelling the “hair shirt” myth about sustainable built environments. As of 2018, a total of eleven low-energy buildings in eight different Annex participating countries are being studied. This paper presents preliminary results of a case study conducted in Australia.

2. METHODS

Sustainable Buildings Research Centre (SBRC) at University of Wollongong was selected as the Australian case study building. The SBRC is a net zero energy, 6 Star Green Star (GBCA, 2018) accredited building, representing ‘World Leadership’ in environmentally sustainable design practices. The SBRC is a two-storey building comprising offices and laboratories, however, in the present study research data were only collected in office areas. The building uses a mixed-mode ventilation system, which is automatically controlled by the Building Management System (BMS). Natural ventilation is achieved through the use of operable windows, while the mechanical ventilation uses an under-floor air distribution system. The building ventilation mode is automatically controlled as a function of both the indoor and the outdoor dry-bulb air temperatures. Windows can be used only if the outdoor wind velocity does not exceed 30 km/h.

The building hosts university academics, professional staff and postgraduate research personnel and it offers various adaptive opportunities to its occupants (e.g. adjustable floor vents and operable windows). Furthermore, occupants are not required to follow a strict dress code and are encouraged to adapt their clothing insulation as function of the indoor and outdoor conditions.

Between June 2017 and April 2018, longitudinal field observations were made in the SBRC building, monitoring the building’s indoor environmental performance in winter, swing and summer seasons. During the monitoring period, autonomous monitoring stations, SAMBA (de Dear et al., 2016), were placed at various sampling points throughout the occupied zones of the building. SAMBA units sensed indoor thermal comfort parameters (air and globe temperatures, humidity and air speed) at 5-minute intervals (time-stamped), then transmitted data through the cellular network to the University of Sydney IEQ Lab’s server. Hourly outdoor climate observations were acquired from the Bureau of Meteorology’s weather station closest to the sample building. Building operational data such as details of HVAC modes, occupancy schedules and window operation status were retrieved from the Building Management System (BMS).

A total of 31 occupants of the building were recruited for the study. Being a longitudinal research design, the participants were required to respond to our online comfort survey on multiple occasions over the 11-month monitoring period. Throughout the field observation period, SMS messages containing a link to an online comfort questionnaire were periodically (1~3 times per week, during normal office hours) sent to the participants. The questionnaire was designed to require less than one minute to complete (Parkinson et al., 2013), addressing simple questions; (1) whether or not the participant is in the building, (2) the participant’s location in the building at the time of the survey, (3) thermal comfort perception (i.e. sensation, preference and acceptability), (4) the kinds of adaptive comfort strategies in use, and (5) simple classification of activity
and clothing type being worn. Each of the survey responses was time-stamped at the point when the questionnaire was completed. The structure of the smartphone questionnaire used in the study is summarised in Table 1.

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 became the basis for our analysis.

Table 1: Summary of the online questionnaire

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
</table>
| 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  
- Light  
- Slightly light  
- Slightly heavy  
- Heavy  
- Very heavy |
| Which best describes your activity during the preceding half hour? | - Relaxing, seated  
- Working, seated  
- Working, standing  
- Walking about  
- Exercising |

3. RESULTS & DISCUSSION

Wollongong, the city where the sample building is located, has characteristics of coastal climate with humid, subtropical summers and mild, temperate winters. Figure 2 depicts daily outdoor temperature changes across the entire field-monitoring period. Based on daily minimum and maximum temperature records obtained from the closest Bureau of Meteorology station, daily mean temperatures and 7-day running mean temperatures were calculated and illustrated in this figure. The average of daily mean outdoor temperatures in winter and in summer during the monitoring period were 14.3 and 22.2°C respectively. As can be seen in Figure 2, the outdoor maximum temperature occasionally exceeded 35°C across the summer monitoring period.

The SBRC, from its first year of operation, has always been consistently meeting its net zero energy target. In particular, between 2015 and 2017 the building photovoltaic system generated annually on average 233 MWh (SD 6 MWh) of energy, while the average overall building energy consumption was 123 MWh (SD 16 MWh).
Table 2 briefly describes the key indoor climatic and comfort indices measured/calculated at the time when each smartphone questionnaire was completed. Descriptive statistics including the range, mean, and standard deviation of each comfort parameter are listed in this table. The indoor operative temperature $T_o$ fell within the range of 18.5 and 29.9°C during the study period. The range of self-reported clo-value (0.4–1.4 clo) indicated that our participants were flexible in choosing their clothing. Mean metabolic rate ($\text{met}$) of the participants was 1.3, indicating that most of the participants were sedentary and engaged in typical office activities at survey times. On average, the Predicted Mean Vote (PMV) was 0 (neutral), and the Predicted Percentage of Dissatisfied (PPD) estimated that just over 11% of the participants would be dissatisfied with the indoor thermal environment. The actual thermal sensation (Thermal Sensation Vote TSV) of the participants was well aligned (mean = 0.1) with the predicted value (PMV = 0).

Figure 2: Daily outdoor temperatures (°C) of Wollongong during the field study period (data obtained from Bureau of Meteorology)

Table 2: Summary of indoor climate and thermal comfort indices recorded at survey times (n=909)

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

Percentage breakdowns of the participants’ thermal comfort perception recorded via smartphone surveys are summarized in Table 3. PMV values calculated for each sample were rounded up/down to the closet point on the 7-point thermal sensation scale, and then the distribution was added into this table for comparative purposes. It is typically assumed that votes in the middle three categories of the 7-point thermal sensation scale are expression of thermal satisfaction (i.e. slightly cool -1, neutral 0, slightly warm +1) (Fanger, 1972). Applying this assumption to the current subjective data, 86.7% of the occupants expressed satisfaction with the building’s thermal condition. This satisfaction rate was also well aligned with the thermal acceptability (88.9%) as registered directly in the comfort questionnaire (Table 1). However, there was about 12% discrepancy between the actual (86.7%, according to the TSV distribution) and the predicted value (98.6% according to the PMV distribution), which will be further looked into in the subsequent section of this paper. Overall, the results indicated that the building was successful in delivering ‘satisfactory’ thermal conditions to its occupants by well exceeding the typically used 80% acceptability target (ASHRAE, 2017).
Table 3: Summary of indoor climate and thermal comfort indices recorded at survey times (n=909)

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

The discrepancy between the actual (TSV) and predicted (PMV) thermal sensations observed in Table 3 was further investigated by fitting a linear regression between the two variables. It is well known that in mixed-mode buildings the mode of operation (i.e. air-conditioning AC vs. natural ventilation NV) can affect occupant subjective perception of indoor thermal environment (Deuble and de Dear, 2012). For the current analysis, the entire data set was grouped according to the operational mode of the building at the time each questionnaire was completed; AC mode (n = 416) and NV mode (n = 461). The relationship between TSV and PMV is shown in Figure 3, and the results of regression analysis are given in Equations 1 and 2.

When the building was in AC mode, the participants’ TSV conformed to the PMV values relatively well (regression coefficient of 0.89). However, a large discrepancy was observed during NV mode of building operation. According to Equation 2, 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 model during this mixed-mode building’s NV operations. The current result highlights discrepancies between the actual and predicted comfort level of occupants in mixed-mode buildings (especially during NV mode), reinforcing earlier findings by Deuble and de Dear (2012).

Figure 3: Thermal Sensation Votes (TSV) regressed on Predicted Mean Votes (PMV) by building operation mode (AC vs. NV)

TSV = 0.89 × TSV + 0.18 (AC mode; n = 416; $R^2 = 0.26$; regression coefficient $p<0.001$) (1)

TSV = 0.59 × TSV + 0.02 (NV mode; n = 461; $R^2 = 0.12$; regression coefficient $p<0.001$) (2)
The previous analysis (Figure 3) ignores thermal adaptation processes that might have played a role in shaping the participants’ perception of comfort over the period of the field monitoring. According to the fundamental concept of the adaptive model, the perception of thermal comfort is affected by past and current thermal experiences (Brager and de Dear, 1998). Given that the current study was conducted across different seasons, it was reasonable to assume that adaptive processes were in play within our longitudinal field observations. In the next analysis, a relative temperature scale (Temperature offset from neutrality, $T_{\text{diff}}$) was used to adjust for adaptive processes within each of the samples. The temperature difference between indoor operative temperature $T_o$ and neutral temperature $T_n$ (calculated by ASHRAE 55 adaptive model: $T_n = 0.31 \times \text{prevailing mean outdoor temperature} + 17.8$) was calculated for each of our samples (i.e. $T_{\text{diff}} = T_o - T_n$). Therefore, positive values of $T_{\text{diff}}$ 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 $T_n$. In order to investigate how the participants’ thermal sensations changed across different indoor temperature conditions, a linear regression was fitted between TSVs and $T_{\text{diff}}$. The regression model performed separately on the two sample groups (AC and NV mode) were presented in Figure 4 and Equations 3 and 4. The slope of the regression line can be interpreted as thermal sensitivity of occupants. For example, a steep slope represents those who are sensitive to temperature variations, whereas a gentle slope represents those who are highly adaptive (or tolerant) to changes in thermal conditions. Figure 4 implies that our participants were more tolerant of indoor temperature variations when the building was operated in naturally-ventilated mode than in air-conditioned mode. According to Equation 3, 2.5 degrees of temperature change accounts for one unit change of thermal sensation during AC mode. On the other hand, during NV mode, it requires 3.6 degrees of temperature change to shift up/down thermal sensation by one unit (Equation 4). The results indicate that the occupants were about 40% more sensitive to thermal conditions during AC mode than during NV mode. The NV sample group’s regression coefficient of 0.28 was almost identical to the mean regression gradient of 0.27 observed in the NV building samples of the ASHRAE RP-884 project (de Dear and Brager, 1998), which later became the basis of the current ASHRAE 55 adaptive model. The AC sample group’s regression coefficient of 0.40 was smaller than that of 0.51 observed in the AC building samples of the ASHRAE RP-884 project (de Dear and Brager, 1998). The ASHRAE 55 adaptive model almost perfectly estimated the neutrality of our participants (by examining the point of intersections between the regression lines and TSV of 0 in Figure 4).

![Figure 4: Thermal Sensation Votes (TSV) regressed on Predicted Mean Votes (PMV) by building operation mode (AC vs. NV)](image)

$$TSV = 0.40 \times TSV - 0.01 \quad (AC \ mode; \ n = 416; \ R^2 = 0.29; \ p<0.001) \quad (3)$$

$$TSV = 0.28 \times TSV + 0.02 \quad (NV \ mode; \ n = 461; \ R^2 = 0.15; \ p<0.001) \quad (4)$$
4. CONCLUSION

As part of IEA-EBC Annex 69, a longitudinal field study was conducted focusing on thermal comfort in an exemplary low energy building. Time-and-place matching of multi-dimensional data (i.e. smartphone survey responses, instrumentally measured indoor climate parameters, outdoor meteorological observations, and building operational information) enabled quantitative analysis of the relationships between those parameters. This Australian case study conducted in the SBRC building challenged a misconception that occupant comfort and energy consumption are mutually exclusive, and the result of our analysis clearly demonstrated that it is possible to achieve high level of occupant comfort without spending copious energy in HVAC operations. The results also indicated that subjective perception of indoor thermal environment can be influenced by different modes of building operation (i.e. AC or NV). Further investigation into this topic is suggested for future research.

ACKNOWLEDGEMENTS

This study was conducted as part of IEA-EBC Annex 69 - Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings. The authors thank Sustainable Buildings Research Centre (SBRC) and all occupants of the building for participating in this study.

References


