A model for the cooling effect of air movement

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Abstract: The importance of the cooling effect of air movement to thermal comfort in hot humid climates is widely acknowledged, however theoretical models of this effect have not been tested in a residential setting. An 11 month longitudinal comfort study of 20 houses in Darwin, Australia yielded 1360 thermal comfort vote responses with corresponding indoor climatic measurements, including air speed. A model to describe the cooling effect of air movement was developed using these data. This model allows for the benefits of natural ventilation and fan use to be accounted for when assessing the indoor thermal environments of climatically designed houses in hot humid conditions.

Keywords: Air movement; thermal comfort; cooling effect; residential.

1. Introduction

Traditional forms of tropical bio-climatic housing are designed to effectively capture and enhance air movement throughout the building, reducing or avoiding the need for air conditioning. The importance of air movement to thermal comfort is widely understood by the occupants of these buildings; however current theoretical models of this effect remain largely untested in residential settings. The aim of the research presented in this paper was to develop a model for the cooling effect of air movement using collected data and to compare it to existing models. This research is relevant because regulatory thermal simulation software in Australia, AccuRate, incorporates a theoretical model which may not adequately allow for the benefits of natural ventilation and fan use in houses in hot humid climates.

1.1 Air movement and thermal comfort

Early studies in hot humid climates emphasised the importance of air movement in achieving thermal comfort (Webb, 1957; McFarlane, 1958). Despite these findings, widely used thermal comfort standards developed in Europe and the United States (US) distinguish air movement as undesirable ‘draft risk’ (Fanger et al., 1988; ISO 7730, 2005). As these standards are increasingly applied worldwide in varying
climates, researchers are again seeking to recognise the beneficial contribution of air movement to thermal comfort in warm to hot conditions (Zhu et al., 2015; Rupp et al., 2015). The opportunities for providing thermally acceptable conditions through greater air movement is now of increasing interest, particularly in reference to the wider movement to reduce reliance on air conditioning appliances for comfort (Roaf et al., 2010; Brager et al., 2015). Recent studies have shown that there is often a strong demand for higher air velocities in warm and hot conditions (Yang et al., 2009; Cândido et al., 2011; Huang et al., 2013). Whilst much of the recent work incorporating some kind of assessment of air movement in relation to thermal comfort reports on the positive link between thermal sensation and air velocity, none attempt to describe this effect in a manner that can be incorporated into the future assessment of thermal environments. Similarly, very few studies are conducted in residential settings, despite the obvious opportunities for natural ventilation in dwellings. Supporting the need for further work in this area, Brager et al. (2005) conclude a review of contemporary thermal comfort research with;

A major theme has been indoor air movement, a long neglected resource for cooling and air quality, requiring new understanding, products and control approaches. (Brager et al., 2015, p286)

1.2. Measurement of air speed in thermal comfort field surveys

Air movement is one of the four environmental factors required to assess human thermal comfort conditions (ASHRAE, 2013); however it is not often measured in thermal comfort field research because of the expense, delicacy, accuracy and power consumption of anemometer sensors (Nicol et al., 2012). ASHRAE Standard 55-2013 (ASHRAE, 2013) presents stringent requirements for the range and accuracy of air speed measurement instrumentation; however historically methods used to determine air speed are far less precise. Early thermal comfort studies used the laborious Kata thermometer to estimate air speed (Nicol et al.; 2012; Bedford, 1963). More recent research employs thermal anemometers (Melikov et al., 2007), although their use often presents the same limitations as noted above (Nicol et al.; 2012). In cross-sectional thermal comfort surveys researchers are able to mount the monitoring equipment onto a portable base (Cândido et al., 2010); which largely overcomes many of the issues regarding expense and delicacy of sensors. In longitudinal studies where this approach is not appropriate a technique for estimating air speed based on window, fan and air-conditioning operation is commonly employed (Saman et al., 2013; Williamson et al., 1990). These solutions demonstrate the need to develop economical instrumentation for the measurement of air movement for thermal comfort research.


International thermal comfort standards facilitate some increase in the upper boundary of comfort in warm to hot conditions due to elevated air speeds. The effect of elevated air speed is incorporated within the equation of the analytical model for thermal comfort (i.e. PMV-PPD). This paper, however, will focus on adaptive models of thermal comfort which are likely to be more appropriate for application in residential settings (Peeters et al., 2009; Saman et al., 2013; Daniel et al., 2015). The upper boundary of the ASHRAE adaptive model can be extended incrementally by 1.2°C when the average air speed is 0.6m/s, 1.8°C at 0.9m/s and 2.2°C at 1.2m/s, when the prevailing mean outdoor temperature is greater than 25°C (ASHRAE, 2013). Similarly, the CEN adaptive model is able to be extended for air speeds above
0.2 m/s when the indoor operative temperature is above 25°C using a convex logarithmic function (CEN Standard 15251, 2007).

The key limitation of both of these models is that they are not dependent on humidity. Previous research (Givoni & Milne, 1981) suggests that the cooling effect of air movement decreases with increasing humidity. Therefore, in a hot humid climate where the conditions indoors are closely linked with outdoor weather, the recognition of humidity is vitally important.

1.4. Cooling effect of air movement in AccuRate

Within the regulatory building performance software, AccuRate, Szokolay’s theoretical model (2000) is used to account for the cooling effect of air movement (Delsante, 2005; Chen, 2011). This model was developed specifically for practical application in the assessment of tropical housing within Australia. The proposed function defined by Equation 1 is derived from the analysis of eight other models (ASHVE, 1932; Drysdale, 1952; Rohles et al., 1974; Arens et al., 1981; ASHRAE, 1985; Arens & Watanabe, 1986; Humphreys & Nicol, 1995). Again, despite the recognition that the cooling effect may diminish with increasing humidity, it is not included in the Szokolay equation. This paper explores a method for taking both air speed and humidity into account.

\[
\Delta T = 6v_e - 1.6v_e^2
\]

Where:
\(\Delta T\) = cooling effect (K), \(v\) = actual air speed (m/s), \(v_e\) = effective air speed = \(v - 0.2\) m/s

2. Methods

Twenty households located in Darwin, Australia, participated in an 11 month thermal comfort field study from June 2013 to May 2014. The households were chosen to participate in the study because the occupants operated their dwellings as partially or solely naturally ventilated. This fieldwork was conducted as part of a broader research project investigating occupant preferences and behaviour in dwellings of atypical construction within Australia (Daniel et al., 2015).

2.1. Climate

Darwin has the Köppen climate classification ‘BSh’; hot sub-tropical steppe. The climate has three main seasons; the build-up, the wet (monsoon) and the dry. Average annual rainfall recorded at the closest Bureau of Meteorology (BOM) weather station, Darwin Airport (Station number 014015, 12.42 °S, longitude 130.89 °E), is 1726.5mm. The majority of rainfall is received in the monsoon period through January, February and March. The driest period is through June, July and August where very low amounts of rainfall are recorded (1.9mm, 1.2mm and 5.0mm respectively). Mean daily maximum temperatures have a narrow range from 30.5°C in July (the dry) to 33.3°C in November (the build-up/the wet), while mean daily minimum temperatures have a similarly narrow range from 19.3°C in July to 25.3°C in November and December. Humidity is highest in the wet season with a mean 9am relatively humidity of 83% (February) and lowest in the dry season with a mean 3pm relatively humidity of 37% (July) (BOM, 2013).
2.2. Thermal comfort survey

A paper based comfort vote survey in booklet form was distributed to all households; residents above the age of 18 years old were invited to fill them out on a daily basis. Three widely used subjective measures of thermal comfort were included; sensation 1=Cold to 7=Hot (ASHRAE, 2013); preference 1=Cooler, 2=No change, 3=Warmer (McIntyre, 1982) and; comfort 1=Very uncomfortable to 6=Very comfortable (Brager et al., 1993). The survey also asked the respondents to report their clothing level, activity, and window, fan and artificial heating/cooling operation. A final question asked respondents to identify any source of discomfort not directly related to temperature (i.e. draft, stuffy, dry, humid sensation). Survey responses were collected at the mid-point and at the end of the monitoring period. Responses were manually entered into an Excel spreadsheet with the corresponding environmental measurements at or around the time the respondents completed their survey responses.

2.3. Equipment

Temperature, relative humidity and globe temperature were measured and recorded using the HOBO U12-013 data loggers. At the time of planning the fieldwork no existing systems for measuring and logging air speed were feasible to use. The data collection system needed to be relatively inexpensive, self-sufficient for power for at least six months, unobtrusive, robust and able to measure air movement to a sensitivity of 0.1m/s. In March and April 2013 an experimental system was developed that utilised the open source hardware and software system Arduino™ to connect an Accusense F900 Thermal Air Flow Sensor to the standard HOBO U12-013 logger. A full description of the system and development process was reported in (Daniel et al., 2014).

Two loggers were placed in each household; the logger incorporating the anemometer sensor was located in the household’s primary living area, while a secondary logger was placed either in a subsequent living area or the main bedroom. The loggers were located away from heat sources, out of direct sunlight and, where possible, in a central location within the room at approximately 1.1-1.7m above floor level. In general, data collection meets the requirements of a Class-II field study and the requirements of ASHRAE 55-2013 (ASHRAE, 2013) for data collection.

3. Results

During the monitoring period a total of 2535 thermal comfort vote surveys were completed by 56 subjects from the Darwin households. One thousand, three hundred and sixty of those surveys had corresponding air speed measurements, a basic statistical overview of these data are presented in Table 1. The conditions within the dwellings were predominantly warm to hot with high humidity (see Figure ) whilst the average air speed was relatively low (0.23m/s) at the time that votes were cast (see Table 1). Figure 2 demonstrates the range of air movement achieved within one of the dwellings during July 2013. Note that for the first half of the month the occupants were away and the house was closed up.
Table 1: Descriptive statistics for the thermal comfort votes surveys.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor operative temperature (°C)</td>
<td>1360</td>
<td>16.3</td>
<td>36.4</td>
<td>28.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>1360</td>
<td>0.01</td>
<td>2.01</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>1360</td>
<td>20.8</td>
<td>98.3</td>
<td>67.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Outdoors running mean temperature (°C)</td>
<td>1360</td>
<td>23.1</td>
<td>30.5</td>
<td>26.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Thermal sensation vote</td>
<td>1356</td>
<td>1</td>
<td>7</td>
<td>4.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Clothing insulation (clo)</td>
<td>1360</td>
<td>0.04</td>
<td>1.0</td>
<td>0.33</td>
<td>0.20</td>
</tr>
<tr>
<td>Metabolic rate (met)</td>
<td>1360</td>
<td>0.8</td>
<td>2.0</td>
<td>1.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 1: Psychrometric chart of the temperature and humidity at the time that “No change” thermal preference votes were recorded. (Note: dash lines indicate the acceptable range of operative temperature and humidity according to ANSI/ASHRAE 55-2013)

Figure 2: Hourly air speed measurements in a naturally ventilated Darwin dwelling in July 2013.
3.1. Development of the cooling effect model

The thermal comfort surveys that had corresponding air speed measurements were then used in the development of a model to describe the cooling effect of air movement. A model is proposed for the comfort effect of the form \( dT = f(v_e, \text{RH}) \). In order to identify the parameters of this function the surveys where occupants had elected a ‘no change’ preference vote were binned into <75% RH and >75% RH humidity groups. All data were used to represent a central or average humidity group. This approach was taken in order to attempt to account for the influence of humidity in the model.

These groups were then further disaggregated by binning the data by airspeed; <0.2m/s, 0.2-0.3m/s and >0.3m/s. The average operative temperature and air speed was attained for each of these bins. The temperature at 0.2m/s was determined using the equations derived from plotting the average temperature and average air speed at each bin. To get an effective air speed, the average air speed for each bin was subtracted by 0.2 following Szokolay’s methodology. The effective air speed was then plotted against the cooling effect; temperature at 0.2m/s subtracted from the average operative temperature at the 0.2-0.3m/s and >0.3m/s bins respectively, because by “definition” in the Szokolay method there is no cooling effect at zero effective air speed. Each plot in these cases is constrained to pass through the 0.0 point, see Figure 3. The coefficients derived from each humidity bin are presented in Table 2.

<table>
<thead>
<tr>
<th>Humidity bin</th>
<th>Average humidity</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>All RH values</td>
<td>67.1</td>
<td>2.99</td>
</tr>
<tr>
<td>&lt;75RH values</td>
<td>55.0</td>
<td>3.24</td>
</tr>
<tr>
<td>&gt;75RH values</td>
<td>85.4</td>
<td>2.38</td>
</tr>
</tbody>
</table>

The coefficient for each humidity group was then plotted against the average humidity for that group (Figure 4). This yields an equation by which the cooling effect of air movement can be calculated (Equation 2 & 3). The cooling effect for three different humidity levels is compared with Szokolay’s function in Figure 5.

\[
y = 4.86 - 0.029\text{RH} \tag{2}
\]

Where:
\[
\text{RH} = \text{relative humidity}
\]

\[
dT = v_e y \tag{3}
\]

Where:
\[
dT = \text{cooling effect (K) as a function of air speed (m/s)}, v_e = \text{effective velocity}
\]
Figure 3: Cooling effect & air speed for each humidity bin.

Figure 4: Coefficient & relative humidity.

Figure 5: Comparison of the calculated cooling effect of air movement with Szokolay’s function. (source: Szokolay, 2000, page 147)

4. Discussion

This model was developed specifically for application in the assessment of residential thermal environments within hot humid climates of Australia. Figure 6 demonstrates how the model could be applied to the ASHRAE adaptive model of thermal comfort. The extension is applied to the upper 80% limit at prevailing mean outdoor temperatures greater than 25.3°C, the temperature corresponding to the greatest proportion of ‘no change’ thermal preference votes. This corresponds well with the
temperature (25.0°C) that both the ASHRAE and CEN adaptive models allow the consideration of the cooling effect of elevated air speeds.

![Figure 6: Extension to adaptive upper 80% limit. (Note: the extensions are based on effective air speed at 67.6%RH, the average humidity at the time that comfort votes were recorded)](image)

Importantly, this model accounts for the influence of humidity levels in the cooling effect of air movement. At higher humidity levels, the cooling effect is reduced. For example, at 50%RH with an effective air speed of 1.0m/s the upper boundary of comfort could be raised by 3.4°C, while at 75%RH with the same air speed, it would be raised by 2.7°C. In ASHRAE 55-2013, the corresponding increase to the 80% upper limit of the adaptive model is just 2.2°C independent of humidity levels (ASHRAE, 2013).

Similarly, comparing Szokolay’s model, the cooling effect is greater than the proposed model at 1.0m/s but then is reduced at 1.5m/s and 2.0m/s. This example demonstrates that current allowances for the cooling effect of air movement may indeed under estimate the benefit afforded to thermal comfort.

5. Conclusions

In the assessment of the thermal performance of naturally ventilated houses in hot humid climates it is critical that the cooling effect of air movement be adequately accounted for when determining acceptable thermal conditions. The proposed model provides greater accuracy in assessing the effect of air movement than the current theoretical model incorporated within the regulatory thermal performance simulation software, AccuRate. The contribution of the research presented in this paper is to encourage more climatically appropriate responses to housing in tropical climates by acknowledging the influential role of natural ventilation in the thermal comfort of the occupants.

The results presented in this paper demonstrate the successful application of a relatively inexpensive experimental air movement sensor. With further development it offers a way by which air speed data can more readily be collected in longitudinal thermal comfort fieldwork studies.

The collection of this data enabled the development of a model to account for the cooling effect of air movement that also takes humidity into consideration. The use of this model allows the benefits of
natural ventilation and fan use to be acknowledged in the assessment of bio-climatically designed tropical housing.

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References


