Chapter 14
Development of an Adaptive Thermal Comfort Equation for Naturally Ventilated Buildings in Hot and Humid Climates

Doris Hooi Chyee Toe

Abstract The objective of this study was to develop an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates. The study employed statistical meta-analysis of the ASHRAE RP-884 database, which covered several climatic zones. The data were carefully sorted into three climate groups including hot-humid, hot-dry, and moderate and were analysed separately. The results revealed that the adaptive equations for hot-humid and hot-dry climates were analogous with approximate regression coefficients of 0.6, which were nearly twice those of ASHRAE Standard 55 and EN15251, respectively. Acceptable comfort ranges showed asymmetry and leaned towards operative temperatures below thermal neutrality for all climates. In the hot-humid climate, a lower comfort limit was not observed for naturally ventilated buildings, and the adaptive equation was influenced by indoor air speed rather than indoor relative humidity. The new equation developed in this study can be applied to tropical climates and hot-humid summer seasons of temperate climates.

Keywords Thermal comfort · Adaptive model · Hot-humid climate · Natural ventilation · ASHRAE RP-884

14.1 Introduction

The adaptive model of thermal comfort is used in ASHRAE Standard 55 [1] as the code for naturally conditioned spaces and in EN15251 [2] for buildings without mechanical cooling systems. The adaptive model investigates the dynamic relationship between occupants and their general environments based on the principle that *if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort* [3]. Such adaptation encompasses physiological, psychological, and behavioural adjustments simultaneously. Therefore, the adaptive model provides greater flexibility in matching optimal indoor temperatures with outdoor climate,

D. H. C. Toe (✉)
Faculty of Built Environment, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

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Table 14.1 Classification of the ASHRAE RP-884 database for naturally ventilated buildings according to climate

Climate	Number of observations	
	Original database	Refined database
Hot-humid	1682	1673
Hot-dry	4339	2776
Moderate	4044	3213
All	10,065	7662

particularly in naturally ventilated buildings [4, 5]. Adaptive models are thus considered more appropriate for supporting comfort in low-energy buildings [4, 6].

Because climatic context is a primary consideration in the adaptive model, it is imperative to evaluate the comfort requirements of people worldwide, particularly in tropical regions that lack comprehensive standards [7, 8]. This study examines the thermal adaptation of occupants and develops an adaptive thermal comfort equation to be used as a standard for naturally ventilated buildings in the hot-humid climate [9]. It employs statistical meta-analysis of the ASHRAE RP-884 database [10, 11]. It is hypothesized that reanalysis of the ASHRAE RP-884 database according to climate would clarify any differences in thermal adaptation among climates.

14.2 Meta-analysis Method

The data files supplied in the ASHRAE RP-884 database [10] were classified into one of three climate groups including hot-humid, hot-dry, and moderate according to survey locations and seasons. Table 14.1 shows that of the 10,065 observations for naturally ventilated buildings in the database, 1682 represent hot-humid climate while 4339 represent hot-dry climate. The remaining 4044 observations apply to moderate climate. Both residential buildings and offices were surveyed in each climate. In the hot-humid climate, 583 observations were gathered from subjects in residential buildings and 1099 observations were from offices. Overall, the database contained 2209 observations in residential buildings and 3657 observations in offices solely, while the other 4199 observations followed subjects in their houses and offices and were a mix of both building types [11]. The latter involved the hot-dry and moderate climates.

The classified data were then checked for the consistency of each variable and refined where necessary. In particular, the outdoor temperatures for all observations were standardized by using the daily (24-h) mean outdoor air temperature for each exact survey date and station in the survey location. These data were obtained from Global Surface Summary of Day Data Version 7 by NOAA [12]. The final refined database for analysis consisted of 7662 observations (Table 14.1).

Linear and probit regressions using the least-squares method were employed in the data analysis. Analyses of both regression models were conducted at the individual observation level with raw data used as a single unit. All transverse and longitudinal surveys in the database were treated similarly. A complete outline of the method is detailed in [9].

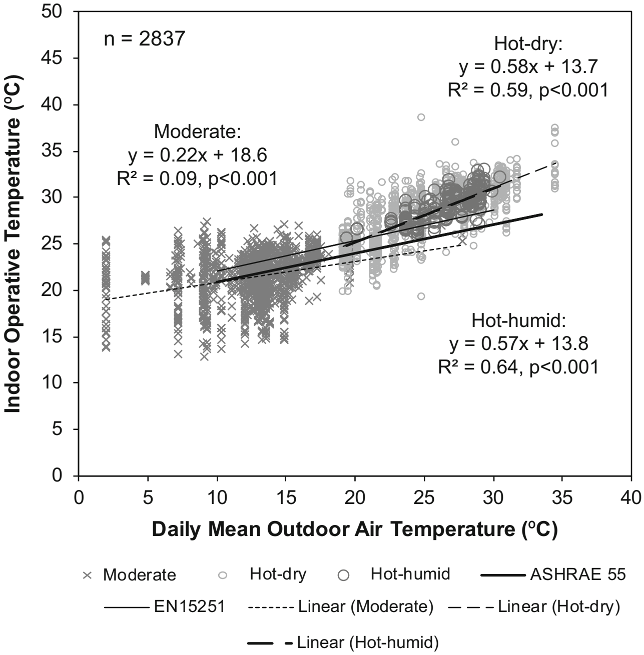


Fig. 14.1 Scatter diagram of indoor operative temperatures at thermal neutrality and the daily mean outdoor air temperatures. The discontinuous lines are linear regression models of this study and represent adaptive equations for predicting neutral temperatures (Source from [9])

14.3 Results and Discussion

14.3.1 Adaptive Thermal Comfort Equation

Figure 14.1 presents a scatter diagram of observed indoor operative temperatures at thermal neutrality and the corresponding daily mean outdoor air temperatures together with the adaptive thermal comfort equations (linear regression lines). It is clear that data for each climate have a distinguishable range of daily mean outdoor air temperatures. It is noteworthy that the adaptive comfort equations underlying ASHRAE [1] and EN15251 [2] standards are

$$T_{\text{comfop}} = 0.31\,T_{\text{outpm}} + 17.8, \tag{14.1}$$
$$T_{\text{comfop}} = 0.33\,T_{\text{outrm}} + 18.8, \tag{14.2}$$

respectively, where T_{comfop} is indoor comfort operative temperature (°C), T_{outpm} is prevailing mean outdoor air temperature (°C), and T_{outrm} is running mean outdoor air temperature (°C).

The regression lines for hot-humid, hot-dry, and moderate climates are defined by the following equations, respectively:

$$T_{neutop} = 0.57\,T_{outdm} + 13.8 \tag{14.3}$$
$$T_{neutop} = 0.58\,T_{outdm} + 13.7 \tag{14.4}$$
$$T_{neutop} = 0.22\,T_{outdm} + 18.6 \tag{14.5}$$

where T_{neutop} is indoor neutral operative temperature (°C) and T_{outdm} is daily mean outdoor air temperature (°C). All regression coefficients are significant at the 0.1% level. As indicated, these regression lines differ among themselves and from those of the standards in terms of their gradients and the outdoor temperature ranges (Fig. 14.1). Compared with the ASHRAE adaptive equation, the regression lines for hot-humid and hot-dry climates are nearly twice as steep with regression coefficients close to 0.6.

This result supports our hypothesis such that climate is a major influence on the thermal adaptation of occupants in naturally ventilated buildings. It also implies that people living in hot climates, particularly regions with daily mean outdoor air temperatures higher than 20 °C, adapt to a wider and higher range of indoor operative temperatures relative to the same magnitude of outdoor air temperature increases than those living in colder climates.

Further, when the outdoor air temperature in Eq. (14.3) is characterized as monthly mean, prevailing mean [1], and running mean [5], respectively, similar neutral operative temperatures are predicted for hot-humid climate. The adaptive equation based on the daily mean shows the highest coefficient of determination (R^2) and predicts at least 10% more variability in the neutral operative temperature compared with the other outdoor temperature characterizations [9]. The result implies the above climate classification that considers season sufficiently distinguishes the data to explain adaptation to thermal history in this climate even without considering the previous outdoor temperatures. The dependence on the previous days' outdoor temperatures, hence acclimatization in the time frames of a month or a week, in the hot-humid climate is likely negligible due to the small changes in its daily outdoor weather conditions over the entire year.

14.3.2 Acceptable Comfort Limits

An acceptable range of temperature deviation from the predicted neutral operative temperature (Eqs. (14.3, 14.4 and 14.5)) for each climate is analysed in Fig. 14.2 by using probit models in consideration of the thermal sensation votes. Figure 14.2a shows that the proportion of occupants voting "neutral" does not exceed 30% and peaks at 0.7 °C lower than the neutral operative temperature for hot-humid climate. The probit line for "comfortable" thermal sensation, which includes "slightly cool," "neutral," and "slightly warm," or −1, 0, +1, respectively, is one-tailed and has no symmetry within the observed temperature range (Fig. 14.2a). The proportion of

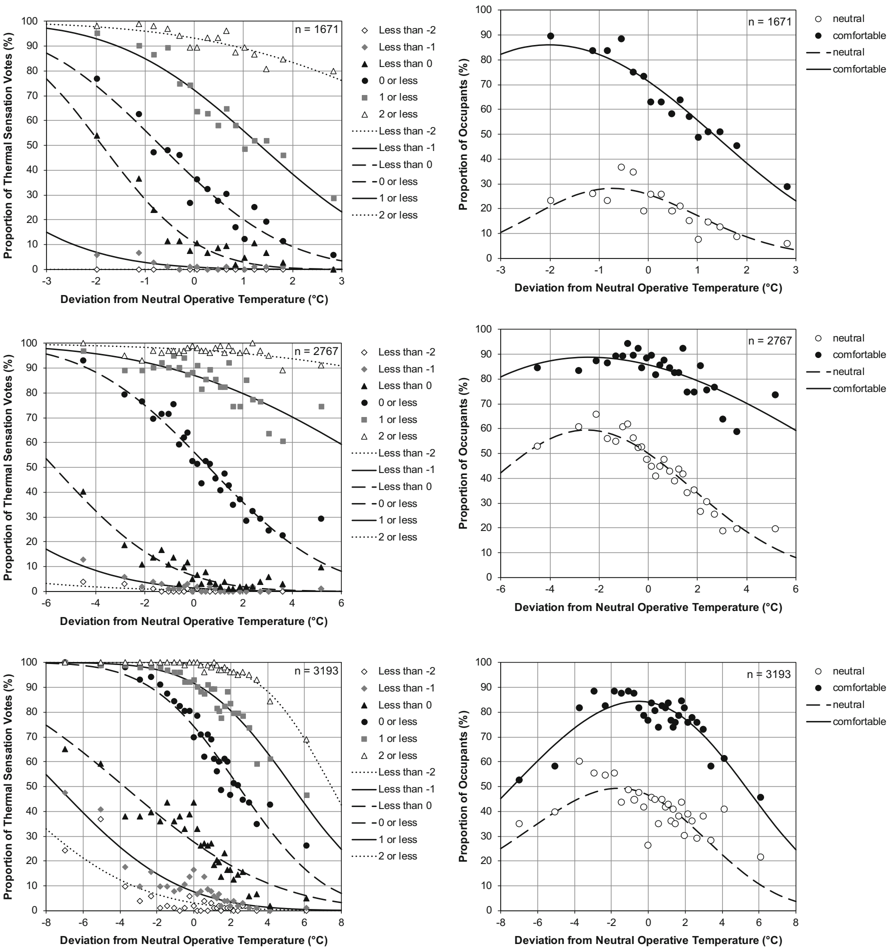


Fig. 14.2 Proportion of thermal sensation votes (left) and proportion of occupants voting “neutral” (0) and “comfortable” (±1) (right) as a function of deviation from the predicted neutral operative temperature. (**a**) Hot-humid climate; (**b**) hot-dry climate; (**c**) moderate climate. Lines indicate probability predicted by probit regression models. Points represent observed values for equal bins of the temperature deviation (102–105 data per bin). In the left figure, dashed lines and black points represent “neutral” votes (0); continuous lines and grey points represent “comfortable” votes (±1) (Source from [9])

occupants who voted “comfortable” increases from 30% at 2.5 °C higher than the predicted neutral temperature to 86% at 2 °C below the predicted neutral temperature. Eighty percent “comfortable” votes are predicted at 0.7 °C less than the neutral temperature for hot-humid climate.

In comparison, at least 80% of the occupants voting “comfortable” appear within temperature deviations of approximately 2 °C above and 6 °C below the predicted neutral temperature for hot-dry climate (Fig. 14.2b) and approximately 1.5 °C above and 2.5 °C below that for moderate climate (Fig. 14.2c). The comfortable temperature range is largest for hot-dry climate, at 8 °C for 80% of "comfortable" votes, likely because adapting to a wider temperature range is easier when humidity is low.

The analysis implies the upper and lower comfort limits must be considered separately for each climate, as determined in Fig. 14.2 for the respective percentages of "comfortable" votes. In particular, a lower comfort limit is not observed for naturally ventilated buildings in hot-humid climate. The upper comfort limit for this climate is recommended to not exceed 0.7 °C below the predicted neutral operative temperature so that at least 80% of the occupants would be in comfort.

14.3.3 Effects of Indoor Air Speed and Humidity

As discussed in Sect. 14.3.1, the adaptive thermal comfort equations for hot-humid and hot-dry climates are steeper than that for moderate climate. The indoor air speed and indoor humidity levels are two possible factors affecting the thermal adaptation in hot-humid and hot-dry climates.

The effects of indoor air speed on the adaptive equations are analysed in Fig. 14.3. In the figure, the data are categorized into three groups of indoor air speeds including low (<0.3 m/s), moderate (0.3 to <0.65 m/s), and high (≥0.65 m/s). Figure 14.3a shows similar linear regression lines for low and moderate air speeds that maintain regression coefficients at 0.57 and 0.54, respectively, for hot-humid climate. These regression lines predict that moderate air speed has little to no effect on neutral temperatures compared with low air speed. Still air conditions do not generally occur in naturally ventilated buildings in hot-humid climate. The regression line for high air speed (0.80) is steeper and higher than that for low air speed (0.57) by up to approximately 2 °C at 29 °C daily mean outdoor air temperature. The analysis of variance reveals a significant mean difference of $F\ (2,\ 309) = 4.52$, $p < 0.05$. These results imply that air movement is likely a possible factor for increasing the gradient of the adaptive equation for hot-humid climate.

For hot-dry climate, the regression lines predict no constant increase in indoor neutral operative temperature at moderate and high air speeds when compared with low air speed (Fig. 14.3b). The thermal adaptation processes of occupants in dry air conditions differ in humid air conditions at high temperatures. Increased air speed allowance is not applicable to hot-dry climate.

In terms of humidity, the regression line for low relative humidity (<60%) predicts higher neutral operative temperatures than for high relative humidity (≥60%) by 0.6–1.7 °C for hot-dry climate (Fig. 14.4b). The analysis of variance shows a significant mean difference at $F\ (1,\ 1045) = 9.29$, $p < 0.01$. The indoor relative humidity likely accounts for the effect of water vapour pressure on evaporation indirectly. A similar effect is not apparent in the regression lines for hot-humid climate (Fig. 14.4a). Indoor relative humidity is high (≥60%) more than 75% of the time in hot-humid climate. This result indicates that humidity influences the predicted neutral temperature in hot-dry climate but not in hot-humid climate.

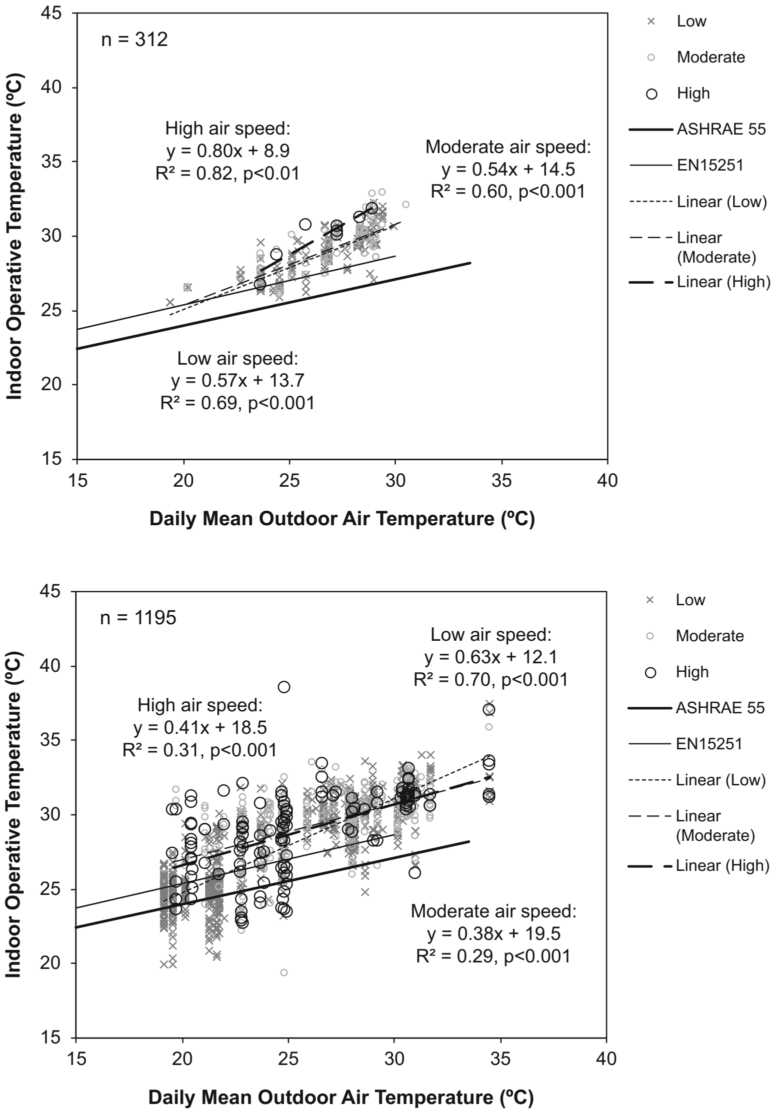
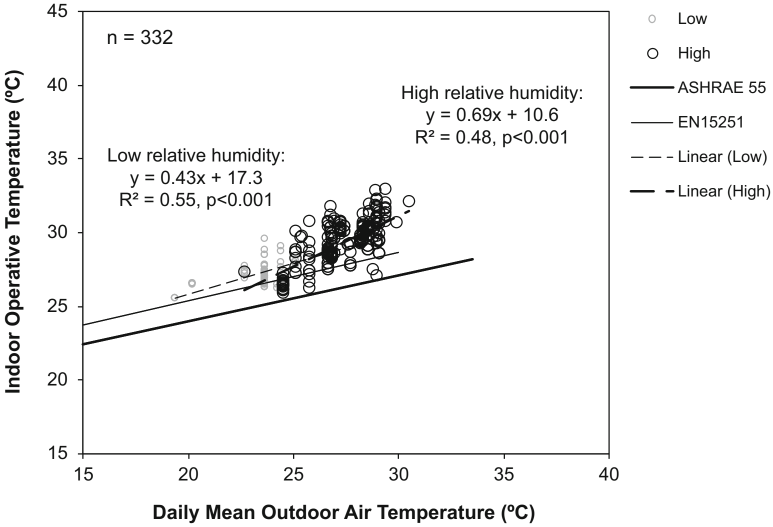


Fig. 14.3 Scatter diagram of indoor operative temperatures at thermal neutrality and the daily mean outdoor air temperatures at different indoor air speeds. (**a**) Hot-humid climate; (**b**) hot-dry climate (Source from [9])

14.4 Conclusion: Future Direction

This study highlights several key differences in the thermal adaptation of occupants in naturally ventilated buildings among climates and the existing standards [1, 2]. A basic set of adaptive thermal comfort criteria for naturally ventilated buildings in



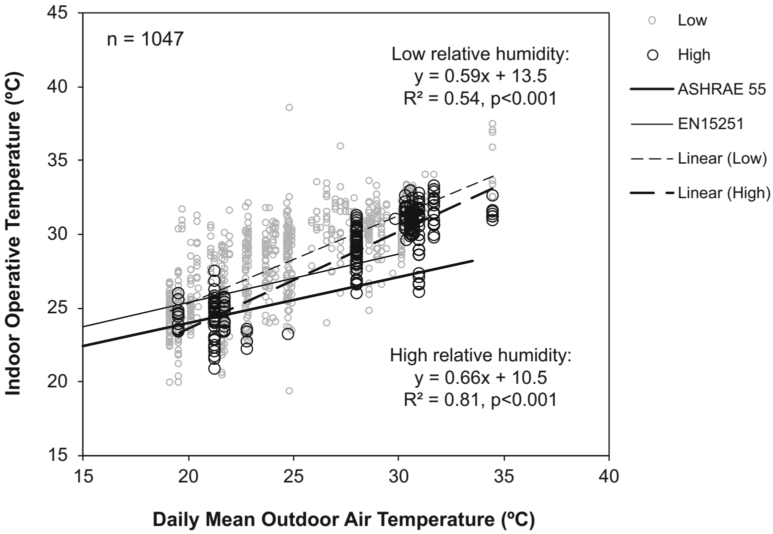


Fig. 14.4 Scatter diagram of indoor operative temperatures at thermal neutrality and the daily mean outdoor air temperatures at different indoor relative humidity. (**a**) Hot-humid climate; (**b**) hot-dry climate (Source from [9])

hot-humid climate is thus proposed in Table 14.2 based on the findings. It is anticipated that the new criteria can be incorporated as thermal comfort standards in hot-humid regions for better applicability (and saving energy).

One of the critical areas of future studies would be to develop an increased air speed allowance for hot-humid climate. Occupants in this climate likely adapt to

Table 14.2 Proposed adaptive thermal comfort equation and related criteria for naturally ventilated buildings in hot-humid climate

No.	Aspect	Criterion	Note
(i)	Climate type	All A climate types and summer season of Cfa climate type	Climate type refers to the Köppen-Geiger climate classification system
(ii)	Neutral operative temperature, T_{neutop} (°C)	$T_{neutop} = 0.57\ T_{outdm} + 13.8$	T_{outdm} is daily mean outdoor air temperature (°C), i.e. the 24-hour arithmetic mean for the day in question
(iii)	Daily mean outdoor air temperature, T_{outdm} (°C)	Range from 19.4 to 30.5	Recommended applicable range for criterion no. (ii)
(iv)	Lower comfort operative temperature limit, T_{lower} (°C)	No required limit	–
(v)	Upper comfort operative temperature limit, T_{upper} (°C)	$T_{upper} = T_{neutop} - 0.7$ for 80% comfortable thermal sensation votes	Graphical representation can be referred in Fig. 14.2a (continuous line in the right figure) for a different percentage of comfortable thermal sensation votes
(vi)	Indoor air speed, v (m/s)	<0.65 at and below neutral operative temperature; ≥ 0.65 above neutral operative temperature	Recommended to provide non-still air and occupants' control to adjust the indoor air speeds according to their preferences
(vii)	Indoor humidity, RH (%)	No required limit	–

Source from [9]

neutral temperatures by making use of air movement to aid evaporative heat loss in indoor high-humidity conditions. This can be seen in how cooling techniques have been implemented traditionally since the past, for example, in the Malay house (see Chap. 3) and the Chinese shophouse (see Chap. 37). It would be interesting to pay attention to a possible trade-off in thermal adaptation between securing lower indoor temperature by reducing ventilation rate with the outdoors (when the outdoor temperature is higher than the indoors) and increasing indoor air speed for sweat evaporation by improving natural ventilation while allowing temperature increase.

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