Available online at www.sciencedirect.com
ScienceDirect
Building and Environment 42 (2007) 699–706
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

Neutral temperature in subtropical climates—A field survey in air-conditioned offices

K.W. Mui*, L.T. Wong

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

Received 21 January 2005; received in revised form 24 October 2005; accepted 26 October 2005

Abstract

The thermal environment for air-conditioned offices in subtropical climates is examined from the prospect of maintaining an optimum operative temperature for the occupants. In this study, the optimum neutral temperature is evaluated from 422 occupants' responses towards the perceiving thermal environment in 61 air-conditioned offices and 186 complaints of thermal discomfort in an air-conditioned office building on an electronic questionnaire, using a semantic differential evaluation scale and a dichotomous assessment scale. In particular, physical parameters for the thermal comfort study were measured by an indoor environmental quality (IEQ) logger, and the operative temperature was correlated with the occupants' thermal responses. The probability of accepting an operative temperature for the thermal comfort of the occupants was correlated with logistic regression curves; the optimum operative temperature was derived in order to maximize the probability of thermal comfort expressed by the occupants. The results showed that the thermal neutral temperatures for air-conditioned offices in subtropical climates were 23.6 and 21.4 °C in summer and winter, respectively. The preferred thermal environment in Hong Kong should be slightly cool, corresponding to about 1 °C below the neutral temperature, in order to satisfy most of the occupants in the office space.

Keywords: Air-conditioned office; Thermal comfort; Neutral temperature; Office occupant response; Field survey

1. Introduction

Literature discussing thermal comfort can be found from as early as the 1850s. Perhaps the most influential standards have been the ones developed by ASHRAE, the International Standardization Organization (ISO) and the European Committee for Standardization (CEN) [1–3]. According to the ASHRAE standard 55 [1], thermal comfort is defined in terms of the perception of satisfaction when a subject experiences in a given thermal environment. It is found to be dependent on a number of environmental and physical parameters: air temperature, radiant temperature, air speed, air humidity and the metabolic rate and clothing level of an occupant [4,5]. A thermal comfort model using the predicted mean vote (PMV) derived from the steady-state heat balance of a human body with empirical constants was determined from chamber studies for thermal sensation [2,5]. A PPD index, first established based on the PMV, was a quantitative predication of the number of thermally dissatisfied persons among a large group of people. Applicability of that index was confirmed by later studies, and various thermal comfort indices were proposed [2,6,7]. A Pierce two node model was developed to simulate the human thermoregulatory system minute-by-minute within a specified time period [8,9], in which a human body was simulated by two concentric cylinders (a core cylinder and a thin skin cylinder surrounding it) with clothing evenly covering its skin surface. The adaptive thermal comfort temperature and the associated thermal comfort indices in transitional spaces of a building, automobiles, airplanes and trains were studied [10–16]. Thermal comfort models with the consideration of external climate, physiological and thermal expectations were proposed [15,16].

In a typical office space, the steady-state thermal sensation would be correlated with the PMV or observed

*Corresponding author.
E-mail addresses: behorace@polyu.edu.hk (K.W. Mui), beltw@polyu.edu.hk (L.T. Wong).

0360-1323/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2005.10.021

mean vote (OMV) against the operative temperature or the effective temperature. A neutral temperature can be obtained at the intercept of a linear regression line with the temperature axis [17,18]. This is the temperature perceived by an occupant in a space that offers a 'neutral feeling of thermal sensation' and the occupant would vote for neither the 'warm' nor the 'cool' side. A semantic differential scale of evaluation on thermal sensation has been widely adopted in many thermal comfort studies, with the results being used in development design criteria for indoor air-conditioned spaces [1–5,19]. These design criteria have been widely adopted in many air-conditioned office buildings in Hong Kong [20,21].

Thermal discomfort was reported in some indoor air-conditioned spaces [21–24]. Indeed, differences in neutral temperature between test chamber studies and field surveys were also reported [18,21–24]. Measured thermal comfort PMV values found were approximately 0.33 lower than the calculated ones [23]. It was reported that the predictive indices underestimated thermal sensations by up to 1.0 unit for warmer regions, and the neutral temperatures reported in some office buildings were lower than those predicted from the laboratory-based comfort models by 1.4–2.4 °C [24,25].

In this study, a neutral temperature was evaluated from the occupants' responses towards the perceiving thermal environment in 61 air-conditioned offices, and from complaints about thermal discomfort in an air-conditioned office building in Hong Kong. A semantic differential scale and a dichotomous scale have been adopted in many engineering applications to assess attitudes or values of this kind [2,25–27]. In the study, the neutral temperature was evaluated by the frequency distribution of the subject responses, using a semantic differential assessment scale for indirect acceptability and a dichotomous assessment scale for direct acceptability of an occupant. Results obtained from different samples using the two assessment scales were studied and mathematical expressions using logistic regression model were proposed.

2. Assessment scales

The thermal dissatisfaction refers to an occupant who feels either hot or cold, and votes for it on a semantic differential evaluation scale for thermal sensation [1,2,18,26,27]. The scale is used to measure an individual's feelings of the thermal environment being perceived based on a continuum that extends between two extremes, 'Cold' and 'Hot'. In this study, a seven-point semantic differential scale r_1, shown in Fig. 1, was constructed on an indoor environmental quality (IEQ) logger with a seven-way selection switch from (-3) to $(+3)$, where a '$-$' represented the feeling of cold and a '$+$' the feeling of hot; thus, $(+3)$ was 'hot', $(+2)$ 'warm', $(+1)$ 'slightly warm', (0) 'neutral', (-1) 'slightly cool', (-2) 'cool', and (-3) 'cold' [18]. The occupant's acceptance of the perceived indoor thermal comfort was also studied with a two-point dichotomous assessment scale r_2, shown in the same figure. This scale was used for a direct feedback or acceptability with the question 'Is the thermal environment being perceived in the office environment acceptable to you?' being asked. The ranks '(1) Yes, acceptable' and '(0) No, not acceptable' were self-explanatory.

Both scales were easily understandable and, therefore, rapid responses could be made during the survey. In order to confirm the validity of those responses, each respondent had to use both scales for the subjective assessment.

In the study, an occupant vote on the perceived thermal environment at an operative temperature T (°C) using one of the scales i, is expressed by

$$r_i = k_i = f(T); \quad i = 1, 2, \tag{1}$$

$$T = C_1 T_{\mathrm{a}} + (1 - C_1) T_{\mathrm{r}}, \tag{2}$$

where k_i is the occupant vote; T_{a} (°C) and T_{r} (°C) are the air temperature and the mean radiant temperature; C_1 is a weighing factor accounting for the convective and radiant heat transfer coefficients and is determined by air speed v_{a} (m s^{-1}) [2],

$$C_1 = \begin{cases} 0.5 \\ 0.6; \\ 0.7 \end{cases} \begin{cases} v_{\mathrm{a}} < 0.2, \\ 0.2 \leqslant v_{\mathrm{a}} < 0.6, \\ 0.6 \leqslant v_{\mathrm{a}} < 1. \end{cases} \tag{3}$$

In a field study, thermal sensation votes on the thermal comfort by a population of N occupants in an indoor environment would be recorded. For a particular vote i using the two scales, the corresponding operative temperature would be described by a distribution

$$\hat{T}_i = \int_{T_{\mathrm{a}}}^{T_{\mathrm{b}}} f(T_i)\, \mathrm{d}T_i; \quad \begin{cases} r_i = k_i, \\ T_{\mathrm{a}} \leqslant T_i \leqslant T_{\mathrm{b}}. \end{cases} \tag{4}$$

It is assumed that an occupant prefers a 'neutral' thermal sensation for a comfortable environment, i.e. $r_1 = 0$, and the 'overall acceptance' r_2 is related to the absolute value of r_1:

$$1 - r_2 = f(|r_1|), \tag{5}$$

where the neutral thermal sensation is indicated by $1 - r_2 = 0$.

The association between the ranked assessment results in Eq. (5) of the two scales can be examined by the Spearman's rank correlation R_{s} [28]:

$$R_{\mathrm{s}} = 1 - \frac{6\sum_{i=1}^{N} d_i}{N(N^2 - 1)}, \tag{6}$$

where d_i is the pair-wise differences of the ranks of the assessment results; N is the number of pairs of observations.

The criterion for accepting the significance of a correlation is determined by a statistic t-test at a certain