Building and Environment 44 (2009) 948–960

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal comfort in residential buildings – Failure to predict by Standard model

R. Becker [a,*], M. Paciuk [b]

[a] Faculty of Civil & Environmental Engineering, Technion – Israel Institute of Technology, Rabin Building, Technion City, Haifa 32000, Israel
[b] National Building Research Institute, Technion – IIT, Haifa 32000, Israel

ARTICLE INFO

Article history:
Received 19 February 2008
Received in revised form 17 June 2008
Accepted 18 June 2008

Keywords:
Thermal sensation
Thermal comfort
Predicted mean vote
Dwellings
Field survey

ABSTRACT

A field study, conducted in 189 dwellings in winter and 205 dwellings in summer, included measurement of hygro-thermal conditions and documentation of occupant responses and behavior patterns. Both samples included both passive and actively space-conditioned dwellings. Predicted mean votes (PMV) computed using Fanger's model yielded significantly lower-than-reported thermal sensation (TS) values, especially for the winter heated and summer air-conditioned groups. The basic model assumption of a proportional relationship between thermal response and thermal load proved to be inadequate, with actual thermal comfort achieved at substantially lower loads than predicted. Survey results also refuted the model's second assumption that symmetrical responses in the negative and positive directions of the scale represent similar comfort levels. Results showed that the model's curve of predicted percentage of dissatisfied (PPD) substantially overestimated the actual percentage of dissatisfied within the partial group of respondents who voted $TS > 0$ in winter as well as within the partial group of respondents who voted $TS < 0$ in summer. Analyses of sensitivity to possible survey-related inaccuracy factors (metabolic rate, clothing thermal resistance) did not explain the systematic discrepancies. These discrepancies highlight the role of contextual variables (local climate, expectations, available control) in thermal adaptation in actual settings. Collected data was analyzed statistically to establish baseline data for local standardized thermal and energy calculations. A 90% satisfaction criterion yielded 19.5 °C and 26 °C as limit values for passive winter and summer design conditions, respectively, while during active conditioning periods, set-point temperatures of 21.5 °C and 23 °C should be assumed for winter and summer, respectively.

1. Introduction

Fanger's method [1–3] for calculating the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) is used world wide for estimating the thermal comfort level achieved under a given combination of hygro-thermal conditions (T_a – air temperature; MRT – mean radiant temperature; v – air velocity; P_a – partial vapor pressure), and occupant's personal data (M – metabolic rate; η – mechanical efficiency; I_{cl} – clothing's thermal resistance). According to this model, which is henceforth denoted the Standard model, the PMV is given on the ASHRAE [2] thermal sensation (TS) scale, shown in Table 1, and is correlated to the personal thermal load (TL) by

$$\mathrm{PMV} = \left(\alpha \times \mathrm{e}^{-\beta \times M} + \gamma\right) \times \mathrm{TL}/A_{du} \quad (1)$$

where $\alpha = 0.303$, $\beta = -0.036$, and $\gamma = 0.028$ are statistically derived parameters, obtained by Fanger [1] from the thermal sensation votes recorded in climate chamber experiments with 1396 college-age respondents dressed in standardized clothing and subjected to a range of controlled environmental conditions. A_{du} is the body's surface area (m^2), M is the metabolic rate (W m^{-2}), and TL denotes the heat accumulated in the body or withdrawn from it and is given by [1–3]

$$\mathrm{TL} = M \times (1-\eta) \times A_{du} - [L + E_{re} + (E_d - E_{sw}) \times A_{du}] - (C+R) \times f_{cl} \times A_{du} \quad (2)$$

where L and E_{re} are the rates of sensible and latent heat removal by respiration, respectively, E_d is the rate of heat removal by vapor diffusion through the skin, E_{sw} is the rate of latent heat removal by sweat evaporation, and C and R are the rates of heat removal from the clothing surface by convection and radiation, respectively. The values of these terms can be calculated from the combination of the ambient hygro-thermal conditions, the personal data, and the clothing surface temperature, T_{cl}, which is obtained by solving the following equation:

$$\frac{T_s - T_{cl}}{I_{cl}} = C + R \quad (3)$$

where T_s is the skin temperature and is a function of M and η [1].

* Corresponding author. Tel.: +972 4 8292248; fax: +972 4 8295697.
E-mail address: becker@tx.technion.ac.il (R. Becker).

0360-1323/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2008.06.011

Table 1
Thermal response scales used in the field study

TS	Thermal sensation Scale	Cold −3	Cool −2	Slightly cool −1	Neutral 0	Slightly warm +1	Warm +2	Hot +3
TP	Thermal preference Scale	Much cooler −3	Cooler −2	Slightly cooler −1	No change 0	Slightly warmer +1	Warmer +2	Much warmer +3
TC	Thermal comfort Scale	Comfortable 1	Slightly uncomfortable 2	Uncomfortable 3	Very uncomfortable 4	Unbearable 5		

The main assumption of the model is that a positive or negative heat load implies a thermal sensation and a response on the positive or negative side of the grading scale, respectively, while a virtually zero load implies a neutral response, $TS = 0$, representing optimal comfort that is reinforced by the response "no need to lower or increase the ambient temperature". The assumption is reflected in Eq. (1) by the proportionality of PMV to TL.

In addition, the model assumes that thermal satisfaction is identified with a PMV response that is within the range of −1 to +1, and yields the following equation for predicting PPD:

$$PPD = 100 - 95 \times \exp\left[-\left(\delta \times PMV^4 + \zeta \times PMV^2\right)\right] \quad (4)$$

where $\delta = 0.03353$ and $\zeta = 0.2179$ are statistically derived parameters obtained by Fanger [1].

Population type, climatic background, cultural and social habits, expectations and available control over thermal conditions in actual building settings may differ greatly from those encountered in climate chamber experiments. Thus, although Fanger's formulations were based on a sound physical model, the general validity of the statistically derived parameters is doubtful. Unsurprisingly, thermal responses from occupants recorded in different countries displayed disagreement with predictions [4–9]. Deviation trends were not identical in all studies. Despite these disagreements, Humphreys showed [9] that a world wide data set of 16,762 respondents in various settings agrees quite well with the predictions. Consequently, although no general conclusions for local settings could be drawn from the studies performed to date, the strong physical basis of the model made it an attractive option for use in Israel as well.

The intention to adopt the Standard model to derive local baseline data for energy-related building design triggered an investigation of the model's suitability for the specification of thermal comfort conditions in local Israeli dwellings. The research program was performed during one winter and two summer seasons, from 1999 to 2003, and included both passively reacting dwellings as well as actively space-conditioned dwellings. The study was initially based on the assumption that it would be best to accept the model and check its suitability for local conditions in real-life residential settings, identifying factors that may affect its applicability, such as space conditioning category, sex, age, and years of residence in Israel.

The paper first challenges the model's two inherent assumptions, which state: (1) a linear proportional relationship exists between thermal sensation and thermal load, with a zero load eliciting a zero mean vote; and (2) both thermal sensation vote ranges, $TS < 0$ and $TS > 0$, imply an equal level of thermal dissatisfaction throughout the year. It then checks whether local discrepancies between recorded TS and calculated PMV match Fanger's argument that in warm climates PMV overestimates TS. The paper then examines whether statistically derived modifications may be used to adjust the Standard model to local conditions. Consequently, the paper shows how data collected in dwellings can be used to derive interim local thermal comfort baselines for the design of residential buildings, without the aid of the Standard model.

2. Investigation procedure, methods and samples

The survey was conducted in the summers of 1999 and 2002 in 205 owner-occupied dwellings sampled from six multi-story buildings, and in the winter of 2003 in 189 owner-occupied dwellings sampled from seven multi-story buildings. Two of the buildings were visited both in summer and in winter. All buildings were located in and around the city of Haifa, representing typical Israeli urban locations. Each dwelling was visited for a period of approximately 30 min, between 16:00 and 20:00. Measurements included continuous monitoring of air and globe temperatures, relative humidity and air speed at the 0.1 m, 0.6 m and 1.1 m levels at close proximity to a seated household member ($M = 58\ W\,m^{-2}$) recording his or her responses on questionnaire sheets. Fig. 1 shows the measuring cart.

Temperatures were measured using calibrated platinum PT100 probes, with a calibrated accuracy of ±0.2 °C. Horizontal air speed was measured using Kurz Instruments hot wire anemometers, with a range of 0–0.508 $m\,s^{-1}$ and ±0.015 $m\,s^{-1}$ accuracy. Three anemometers measured horizontal air speed at the three standard levels in the plane of the seated person. A fourth anemometer

Fig. 1. Measuring cart.