Building and Environment 82 (2014) 171–179

Contents lists available at ScienceDirect

Building and Environment

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

Bayesian thermal comfort model

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ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form
13 August 2014
Accepted 14 August 2014
Available online 24 August 2014

Keywords:
Bayesian thermal comfort model
Predicted mean vote
Predicted percentage dissatisfied
Thermal sensation vote

ABSTRACT

Thermal comfort assessment is a prime measure in indoor environment design to evaluate occupant satisfaction. Fanger's thermal comfort model using heat balance theory conducted by chamber test has been widely adopted for thermal environment design criteria. However, rising numbers of thermal comfort field studies show that Fanger's model is not a good predictor of actual thermal sensation and many field measurements were statistically insignificant. This study proposes a Bayesian approach to update our current beliefs about thermal comfort and shows that the maximum likelihood of posterior estimates is close to the actual percentage dissatisfied (APD) obtained from large sample field surveys. For small sample sizes, the Bayesian estimation is close to Fanger's prediction and gives a solution for the discrepancy of Fanger's model. Congruence between Fanger's model prediction and contemporary field survey data is quantified. This quantitative assessment on the belief in newly yielded thermal comfort data can be a solution to the choice of thermal comfort criteria in future thermal environment designs.

1. Introduction

Thermal comfort, a key indoor environmental quality concern for homes, offices and classrooms, is closely related to energy use, occupant productivity and student learning performance [1–3]. Thermal comfort models for predicting occupant satisfaction and for designing an acceptable thermal environment can be found in literature; the 225-node finite element model [4], predicted mean vote (PMV) model [5], 25-node basic heat flow model [6], 2-node basic heat flow model [7] and 2-node with transient response model [8] are a few examples.

Developed by Fanger using chamber test results under steady state conditions, the PMV model uses six key parameters, namely, air temperature (T_a), mean radiant temperature (T_r), air velocity (v_a), relative humidity (R_h), occupant metabolic rate (M_e) and clothing value (C_L), to get the predicted percentage dissatisfied (PPD) under given thermal conditions. Despite the fact that it is widely used for designing indoor thermal environments [9], a number of discrepancies between actual percentage dissatisfied (APD) related to thermal sensation vote (TSV) and predicted percentage dissatisfied (PPD) determined from predicted mean vote (PMV) have been revealed [10,11]. These discrepancies can be grouped into two major categories: (i) PMV against TSV as presented in Table 1; and (ii) PPD against APD as presented in Table 2. Moreover, the usefulness of extrapolated PMV-TSV regressions has received criticism as extreme thermal conditions are rare in many field studies (Table 1).

Using the values of intercept (C_0) and slope (C_1) reported in the literature (Table 1), linear regressions for category (i) are described by the following equation:

$$\mathrm{TSV} = C_1 \times \mathrm{PMV} + C_0 \tag{1}$$

Two phenomena were observed in this category. First, a steep slope ($C_1 > 1$) was generally found in air-conditioned (AC) buildings and a flat slope ($C_1 < 1$) in naturally ventilated (NV) buildings during summer. In other words, occupants in AC buildings, especially in offices and classrooms where they have limited control over the thermal environmental settings, were more sensitive to the perception of thermal comfort than occupants in NV buildings and had higher expectations in a narrow thermal comfort range [28,29]. Fanger and Tofum confirmed this phenomenon and extended the PMV model to minimize the discrepancies [30]. Although occupants in the studies by Fato et al. and Han et al. might have higher expectations for heating during winter in NV buildings [16,22], rural residents (i.e. with lower socioeconomic status) in different climate zones were reported to have high levels of tolerance to climatic conditions [28]. Second, occupants in NV buildings were found to be adapting to a cooler environment ($+C_0$) in winter and a warmer environment ($-C_0$) in summer for thermal neutrality (TSV = 0). This can be explained by the adaptive approach to outdoor environment [31]. Occupants in AC or mixed-mode buildings,

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http://dx.doi.org/10.1016/j.buildenv.2014.08.018

Nomenclature

A, B	events
AC	air-conditioned
APD	actual percentage dissatisfied
abs	of absolute
C_0	y – intercept of predicted mean vote (PMV) – thermal sensation vote (TSV) plot
C_1	slope of PMV–TSV plot
C_L	clothing value (clo)
F	distribution function
k	dissatisfaction cases reported for each vote
n	number of cases surveyed for each vote
n_2	target sample size
M_e	occupant metabolic rate (Met)
NV	naturally ventilated
P	probability function
PMV	predicted mean vote
p	p-value of a statistical test
R_h	relative humidity (%)
SD	standard deviation
T_a	air temperature (°C)
T_r	mean radiant temperature (°C)
TSV	thermal sensation vote
v_a	air velocity (ms^{-1})
x	dummy variable
φ	predicted percentage dissatisfied (*PPD*)
σ	shape factor
ε	Error
Σn	total sample size
Σk	total dissatisfied sample
Superscript	
$\bar{}$	of mean value
$'$	of posterior estimate
Subscript	
1, 2	of conditions 1, 2
i	of the ith item
max	of maximum
rms	of root-mean-square

Table 1
Occupants' thermal sensation votes (TSV) in various studies.

Ref.	Location	Building	Type of ventilation	Season	Total sample size, Σn	C_1	C_0	TSV						
								−3	−2	−1	0	1	2	3
[12]	Italy	Classroom	Mixed	Mixed	959	0.76	−0.51	–	–	–	–	–	–	–
[13]	Taiwan	Classroom	Mixed	Winter	1294	0.50	0.13	18	95	282	623	188	44	44
[14]	China	Residential	Mixed	Summer	110	1.69	−2.60	1	3	4	54	30	13	5
[15]	Australia	Office	AC	Mixed	1234	3.10	−0.49	–	–	–	–	–	–	–
[2]	Hong Kong	Office	AC	Mixed	1273	3.08	2.97	48	100	307	606	174	28	10
[2]	Hong Kong	Classroom	AC	Winter/Spring	312	5.76	2.54	5	19	92	146	36	10	4
[16]	Bari (Italy)	–	AC	Winter	133	1.93	0.51	0	1	5	47	56	22	2
[16]	Bari (Italy)	–	AC	Summer	250	2.04	−0.97	0	0	9	96	98	41	6
[17]	Brazil	–	NV	Mixed	1150	0.56	−0.01	–	–	–	–	–	–	–
[16]	Bari (Italy)	–	NV	Summer	423	0.99	−0.30	0	0	16	119	128	118	42
[18]	Ilam (Iran)	Residential	NV	Summer	513	0.69	−0.74	–	–	–	–	–	–	–
[19]	India	Residential	NV	Summer	294	0.70	−1.04	0	0	11	107	100	50	26
[20]	Singapore	Residential	NV	Mixed	538	0.81	−0.48	–	–	–	–	–	–	–
[21]	Indonesia	Residential	NV	Mixed	525	1.33	−1.61	28	83	78	82	97	26	131
[16]	Bari (Italy)	–	NV	Winter	1034	1.61	0.70	37	93	324	367	162	43	8
[22]	Hunan (China)	Residential (Urban)	NV	Winter	53	1.24	0.06	1	9	12	30	1	0	0
[22]	Hunan (China)	Residential (Rural)	NV	Winter	50	0.48	−0.54	3	5	16	24	1	1	0
[23]	Hunan (China)	Classroom	NV	Spring	1273	0.39	0.15	5	8	122	993	120	21	4

'–' indicates the TSV values are not available in the corresponding studies.

Table 2
Review of actual percentage dissatisfied (APD; %) in various studies.

Ref.	Location	Ventilation	Season	Total sample size, Σn	TSV						
					−3	−2	−1	0	1	2	3
[24]	Israel	Heating	Winter	189	100	64	50	9	19	14	14
[24]	Israel	NV	Summer	205	–	33	36	18	86	83	100
[25]	Taiwan	AC	Summer	600	–	5	5	6	10	18	57
[25]	Taiwan	NV	Summer	619	28	32	6	7	21	54	65
[10]	Ngaoundere	NV	Harmattan	119	100	20	22	13	25	50	100
[10]	Kousseri	NV	Harmattan	95	100	84	20	20	18	–	100
[26]	Taiwan	AC	N/A	27	90	49	22	20	41	80	95
[27]	Harbin	NV	Winter	120	100	100	43	12	27	25	50
					PMV						
					−3	−2	−1	0	1	2	3
Predicted percentage dissatisfied (PPD) in Fanger's model [5]					99	75	25	5	25	75	99