Applied Thermal Engineering 76 (2015) 283–291

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

A study of adaptive thermal comfort in a well-controlled climate chamber

Yu Yang [a, b], Baizhan Li [a, b, *], Hong Liu [a, b], Meilan Tan [a, b], Runming Yao [c, **]

[a] Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, China
[b] National Centre for International Research of Low-carbon and Green Buildings, Ministry of Science and Technology, Chongqing University, Chongqing 400045, China
[c] School of Construction Management and Engineering, University of Reading, UK

HIGHLIGHTS

- The discrepancy between the PMV and AMV in a well-controlled environment was observed.
- People's long-term living experience in the hot-humid climate accustoms thermal sensation to warm.
- Habituations neutralises thermal sensation due to moderated thermal sensibility of the skin.
- A revised PMV_a are proposed as $PMV_a = 0.22PMV^2 + 0.45PMV - 0.1$.
- PMV_a contributes to the thermal engineering solutions in terms of energy efficiency of an air-conditioning system.

ARTICLE INFO

Article history:
Received 4 July 2014
Accepted 4 November 2014
Available online 12 November 2014

Keywords:
Thermal comfort
Adaptation
PMV
Skin temperature
Hot-humid region
Air-conditioned environment

ABSTRACT

This paper aims to critically examine the application of Predicted Mean Vote (PMV) in an air-conditioned environment in the hot-humid climate region. Experimental studies have been conducted in a climate chamber in Chongqing, China, from 2008 to 2010. A total of 440 thermal responses from participants were obtained. Data analysis reveals that the PMV overestimates occupants' mean thermal sensation in the warm environment (PMV > 0) with a mean bias of 0.296 in accordance with the ASHRAE thermal sensation scales. The Bland–Altman method has been applied to assess the agreement of the PMV and Actual Mean Vote (AMV) and reveals a lack of agreement between them. It is identified that habituation due to the past thermal experience of a long-term living in a specific region could stimulate psychological adaptation. The psychological adaptation can neutralize occupants' actual thermal sensation by moderating the thermal sensibility of the skin. A thermal sensation empirical model and a PMV-revised index are introduced for air-conditioned indoor environments in hot-humid regions. As a result of habituation, the upper limit effective thermal comfort temperature SET* can be increased by 1.6 °C in a warm season based on the existing international standard. As a result, a great potential for energy saving from the air-conditioning system in summer could be achieved.

1. Introduction

The Predicted Mean Vote (PMV) developed by Fanger is a commonly used index to assess occupants' thermal comfort which has been referenced in international standards including ISO 7730 [1], ASHRAE 55 Standard [2], EN 15215 [3] and Chinese Standard [4]. It is based on the principle of steady-state heat balance and predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (1), warm (2), hot (3)) by six inputs (air temperature, mean radiant temperature, air speed, humidity, metabolic rate and the insulation of the clothing) [5]. In the HVAC engineering design practice, PMV is expected within ±0.5 to meet 90% occupant satisfaction criteria for indoor thermal environment [1–4]. However the PMV has been challenged by the adaptive thermal comfort principle from field studies and has been criticized as over/under estimating occupants' actual thermal sensation, i.e.

* Corresponding author. Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, China. Tel.: +86 023 65127531.
** Corresponding author.
E-mail addresses: baizhanli09@gmail.com (B. Li), r.yao@reading.ac.uk (R. Yao).

http://dx.doi.org/10.1016/j.applthermaleng.2014.11.004
1359-4311/

Acronyms

AMV	actual mean vote
ANOVA	analysis of variance
MST	mean skin temperature (°C)
P	probability in Hypothesis Testing
PMV	predicted mean vote
SET*	standard effective temperature (°C)

Abbreviations

A	body surface area (m^2)
C	heat lost by convection (W/m^2)
c_b	specific heat of blood [J/(kg·°C)]
c_c	specific heat of core [J/(kg·°C)]
c_s	specific heat of skin [J/(kg·°C)]
E_{dif}	heat of vaporized water diffusing through the skin (W/m^2)
E_{res}	heat loss by respiration (W/m^2)
E_{rsw}	heat loss by regulatory sweating (W/m^2)
K	heat conductance of skin tissue [$W/(m^2·°C)$]
M	metabolic rate (W/m^2)
m_c	mass of core (kg)
m_s	mass of skin (kg)
M_{shi}	metabolic heat by shivering (W/m^2)
PMV_a	adaptive predicted mean vote
R	heat or lost by radiation (W/m^2)
T_{back}	skin temperature of back (°C)
T_c	core temperature (°C)
T_c/dt	rate of change in core temperature (°C/s)
T_{calf}	skin temperature of calf (°C)
T_{chest}	skin temperature of chest (°C)
$T_{forehead}$	skin temperature of forehead (°C)
T_{hand}	skin temperature of dorsal hand (°C)
$T_{lower\ arm}$	skin temperature of lower arm (°C)
T_s	skin temperature (°C)
T_s/dt	rate of change in skin temperature (°C/s)
T_{thigh}	skin temperature of thigh (°C)
$T_{upper\ arm}$	skin temperature of upper arm (°C)
V_b	rate of skin blood flow [$kg/(m^2·s)$]

Actual Mean Vote (AMV) [6,7]. Research into adaptive thermal comfort first began following the oil crisis in the mid-70's [8] and has increased dramatically in recent years due to the concerns over climate change and energy efficiency.

It has been concluded that behavioural, physiological and psychological adaptation processes are the three types of presumed causes of the discrepancies between the PMV and AMV [6,9]. However, besides giving a statistical approximation of the general effect of such adaptive processes on the thermal perception vote, little is known about the individual contributions of the three types of adaptive processes to the effect [10]. Liu et al. [11] conducted a subjective survey research and introduced a method of quantifying the portions of the adaptation processes by weighting the contribution of these three adaptation categories to the thermal adaptation using the analytic hierarchy process (AHP). However, the specific quantitative identification of each category still remains uncertain.

Principles of adaptive thermal comfort were mainly studied in free-running buildings through field surveys [12–17]. A review of the previous studies reveals that there is little research on the topic of adaptive thermal comfort in air-conditioned environments. For example, de Dear [6] statistically analyzed discrepancies between the PMV and the AMV in air-conditioned environments from the ASHRAE RP-884, a quality-controlled global database. He concluded that 'adaptation is at work in buildings with central HVAC, but only at the biophysical (behavioural) level of clothing and air speed adjustments'; 'PMV appears to have been remarkably successful at predicting comfort temperatures in the HVAC buildings of RP-884's database'. In contrast, Humphrey [18] analyzed the *vote bias*, PMV minus AMV, using the same database. He argued that the possible origins of the bias may be caused by physical, psychological or physiological factors. Humphreys argued that 'PMV can be seriously misleading when used to predict the mean comfort votes of groups of people in everyday conditions in buildings, particularly in warm environments'. The research leaves open two questions: i) can the PMV predict thermal comfort accurately in air-conditioned buildings and ii), if not, what factors are involved and how do they impact on actual thermal sensation in addition to the behavioural adaptation?

The occupant acceptable indoor temperature is considered as one of the design criteria of an air-conditioning system, which is one of the key factors with impacts on the operation of air-conditioning and therefore the energy consumption of buildings [19,20]. Currently the international and national standard for design and operation temperatures of an air-conditioning system is based on the PMV/PPD method [1–4]. The aim of this research is to observe and examine the discrepancies between the PMV and AMV in an air-conditioned environment through a laboratory study, and identify the factors contributing to such discrepancies, consequently provide optimal design basis for the engineering solutions to a creation of thermal environment in hot-humid region.

2. Research methods

Quantifying the specific factors contributing to the vote bias between the PMV and AMV poses considerable challenges because the factors such as physical environmental parameters, occupant adaptive behaviourbehaviour and their previous thermal experience, and occupant thermal comfort expectations are all variables in real buildings. However, these challenges could be solved in a laboratory study by limiting variables and focussing on one variable in each experimental case. The research methods applied in this study include experimental measurement, a subject questionnaire survey and statistical data analysis. Previous field studies in free-running buildings indicated that occupants demonstrated a strong adaptability, particularly in the hot-humid tropics [6,21–24]. We carried out laboratory experiments in Chongqing, the region with typical hot and humid climatic characteristics in summer. The typical summer climate condition in Chongqing is listed in Table 1 [25]. The average air temperature in summer is 26.9 °C and the average relative humidity is 78%. The climate chamber can provide the required indoor physical environmental parameters including air temperature, relative humidity and air velocity constantly during the experiment. In order to identify the contribution of the physiological and psychological

Table 1
Typical climate condition in the summer in Chongqing [25].

Month	Air temperature (°C)		Relative humidity (%)
	Monthly mean	Maximum	Monthly mean
June	25.2	34.9	81.2
July	28.0	36.6	77.1
August	27.6	37.7	75.7