Applied Energy 104 (2013) 117–127

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

HVAC systems testing and check: A simplified model to predict thermal comfort conditions in moderate environments

C. Buratti [a,*], P. Ricciardi [b,1], M. Vergoni [a,2]

[a] Dipartimento di Ingegneria Industriale, Università di Perugia, via G. Duranti 67, 06125 Perugia, Italy
[b] Dipartimento di Ingegneria Idraulica e Ambientale, Università di Pavia, via Ferrata 1, 27100 Pavia, Italy

HIGHLIGHTS

- ▶ New tool for testing thermal comfort in HVAC systems only measuring *T* and RH.
- ▶ Diagrams PMV vs. temperature for different values of relative humidity are traced.
- ▶ Diagrams are valid in moderate environments.
- ▶ Diagrams are valid in the 0.25–1.65 clo range of clothing thermal insulation.
- ▶ A mean error in estimate PMV of ±0.22 was found, good for applications.

ARTICLE INFO

Article history:
Received 5 July 2012
Received in revised form 30 October 2012
Accepted 6 November 2012

Keywords:
Thermal-hygrometry comfort
Simple correlations
Moderate environments
Simplified evaluation model
Clothing thermal insulation influence

ABSTRACT

An interesting tool for testing and check phases of HVAC systems was developed, in order to evaluate thermal comfort parameters only measuring temperature and relative humidity in moderate environments, for a wide range of clothing thermal insulation. A simplified approach to thermal comfort was developed in the seventies by Rohles, who found a correlation between PMV, air temperature and relative humidity, for sedentary activity and clothing thermal insulation equal to 0.6 clo. An improvement of Rohles model is proposed, aiming to extend results in a wider range of clothing thermal insulation (0.25–1.65 clo). Data from experimental campaigns in moderate environments were used to implement a function PMV = PMV(*T*, RH) and diagrams PMV vs. temperature, for different values of relative humidity, were traced (nine equations and diagrams for male, female, and both sexes, and for three ranges of I_{cl}). Standard deviation between measured and calculated data was evaluated and a mean error on PMV of ±0.22 was found; a T-Student test was also performed and results were significant. Mean Radiant Temperature data were used to calculate Operative Temperature and to correlate to PMV and to Neutral Temperature, corresponding to thermal comfort, by means of linear regression method.

1. Introduction

Nowadays the thermal comfort concept follows two different methods: the heat balance approach and the adaptive approach. The first one, also known as rational approach, is basically used to handle climate chamber data, while the second one is generally connected with field studies. Fanger's model [1] is the milestone of the first group; the comfort is determined by a whole body satisfaction and local discomfort by means of six factors and the main indexes are Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). An equation depending on different environmental and physiological parameters was found, by combining results of different research groups. This equation associated thermal conditions to the seven-point ASHRAE thermal sensation scale (PMV index). Fanger also related PPD to PMV. This approach allowed to establish a given PPD maximum value (i.e. 10%) and to define the corresponding PMV range of acceptability [2]. Afterwards Gagge proposed the Pierce two-node model, wherein body is divided into two concentric cylinders: the two models are accurate for subjects in sedentary activity and steady conditions [3].

A wide number of parameters are needed for the calculation of PMV such as air temperature, air Relative Humidity, air velocity, Mean Radiant Temperature, clothing thermal insulation, and activity level (metabolism). All these data are not always available,

* Corresponding author. Tel.:+39 075 5853993; fax: +39 075 5853916.
E-mail addresses: cburatti@unipg.it (C. Buratti), riccia@unipv.it (P. Ricciardi), vergoni.unipg@ciriaf.it (M. Vergoni).
[1] Tel.: +39 0382 985723; fax: +39 0382 985589.
[2] Tel.: +39 075 5853694; fax: +39 075 5853697.

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http://dx.doi.org/10.1016/j.apenergy.2012.11.015

Nomenclature

F	female
I_{cl}	clothing thermal insulation (clo, m^2 K/W)
M	male
MV	mean value
PPD	Predicted Percentage of Dissatisfied (%)
PMV	Predicted Mean Vote
P	probability from T-Student test (%)
P_v	water vapor pressure (kPa)
RH	Relative Humidity (%)
SD	standard deviation
T	temperature (°C)
v_a	air velocity (m/s)

Subscripts

a	air, dry bulb
ank	ankle
calc	data calculated with the new model
g	globothermometer
meas	measured
mr	mean radiant
n	neutral
o	operative
quest	questionnaire
Ro	data calculated with Rohles model
u	wet bulb

especially in conventional buildings, where only temperature and relative humidity are often monitored by means of simple measurement instrumentations, such as hygrothermographs.

A simplified approach was developed in 1971 by Rohles (Institute of Environmental Research of the State University of Kansas) [4], with the aim of obtaining a model to express PMV in terms of parameters easily sampled in the environment: air temperature and relative humidity. The Rohles model had a limit: it was only referred to sedentary activity (metabolic rate = 1.2 met) and to a fixed range of clothing thermal insulation (I_{cl} = 0.6 clo).

Rohles [4] tried to simplify the model by measuring simple environmental parameters to predict thermal comfort with PMV. Even if these approaches represented a strong effort to reduce a large number of input variables and to obtain information about comfort parameters through a single index, one of their limits is that all the studies took place in laboratory and in steady state conditions, while the real conditions are extremely dynamic. In the ASHRAE Transactions, McIntyre put in evidence a comparison between Fanger's climate chamber studies vs. Humphreys field studies. Oseland's research highlighted the gap that occur between the Predicted Mean Votes (PMVs) and the Actual Mean Votes (AMVs) obtained in actual conditions, such as home or offices, with climate chamber studies attributing the differences to the background and adaptation effects [3].

Since the 2000 and until today, a new approach has been developed based on adaptive models. PMV-and-PPD were both measured and surveyed by means of questionnaires provided to the occupants; the comparison often showed a weak correlation [2,5–8]. This meant an impulse to new adaptation field studies, which aim to evaluate real indoor room conditions: De Dear summarized up the three typical subjects' adjustments, other authors (Jannot) tried to link thermal comfort to outdoor conditions and meteorological data [3].

Applications were tested in different buildings, from the first studies on the adaptive models [9,10], also related to the International Standards [11] and to the buildings energy performance [12], and in different parts of the world [13–21]. Chu and Jong combined the thermal comfort with the theory of enthalpy, while Shukuya focused on control systems. Many others dedicated their efforts to develop thermal comfort theory by means of CFD codes [3]. Also, commercial calculation codes [22,23] are in fact now able to predict PMV and PPD values, which must be verified after the building is constructed.

A simplified approach to the thermal comfort evaluation is nevertheless necessary due to the growing interest in the energy performance of buildings, related to the envelope characteristics and to the occupants comfort. The advantage of a simplified model is to enforce a link between the steady state heat balance approach and the adaptive approach: the measured parameters are reduced, instruments are less invasive and it is also possible to check the comfort conditions provided by HVAC systems in field studies, in order to comply with the occupants behavior and habit.

Therefore, a simplified model for the PMV calculation based only on air temperature and relative humidity measurements could be very useful in the plant final test. The idea is to develop the model, originally conceived by Rohles [4] for only fixed activity and clothing insulation, in order to test its reliability with a wider range of clothing thermal insulation and metabolic rate values.

In the present paper, data available at the University of Perugia and of Pavia and referred to buildings with HVAC systems in different seasons were used to implement a simplified model for the PMV calculation, based only on air temperature and relative humidity measurement. A wide range of data were available from experimental campaigns carried out in classrooms and open space offices, where occupants could be considered in sedentary conditions. A variability of the clothing thermal insulation of the occupants (distinguished in M = male and F = female) in the 0.25–1.65 clo range was registered and data were collected in different seasons. Over 450 instrumental measurements and over 1100 questionnaire results were available. Measured data were elaborated to implement the new model by means of a function PMV = PMV(T, RH) and to trace diagrams of PMV vs. temperature for different values of relative humidity. The equations and the diagrams obtained are an interesting tool in the testing and check phases of HVAC systems in moderate environments, allowing to predict thermal comfort parameters only measuring temperature and relative humidity, in a wide range of clothing thermal insulation. The added value of the new method consists in providing a simple tool, in compliance with the Rohles approach, but covering all seasons for the values assumed by the clothing thermal insulation I_{cl} and therefore useful in summer and winter plant operating mode.

Overall PMV is affected by several human factors such as body mass index, culture, body fat percentage, climate condition of a test, human subject location (internal or boarding position in the wide space of a room), and so on. But in this study, a simplified approach to the PMV calculation was tried in order to give a first evaluation of the comfort conditions by means of easily-measurable parameters. Nevertheless a more thorough approach is possible by the use of the Operative Temperature T_o when data of the Mean Radiant Temperature T_{mr} could be easily measured. Therefore, a correlation between PMV and the Operative Temperature was found, such as proposed in other studies [24]. Also, the Neutral Temperature T_n, corresponding to thermal comfort, was calculated and correlated to the Operative Temperature by means of linear regression method.