

Adaptive thermal comfort standards in the hot–humid tropics

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Abstract

Field studies conducted in tropical climates have found that the International standard for indoor climate, ISO7730 based on Fanger's predicted mean vote (PMV/PPD) equations, does not adequately describe comfortable conditions. This paper presents some of the evidence and suggests ways in which International standards are failing and how they might be complemented using adaptive comfort standards derived from the results of local comfort surveys. In particular the implications of air movement and humidity for adaptive comfort standards are considered.

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1. Introduction

International standards to describe comfortable thermal environments indoors [1,2] are based on theoretical analyses of human heat exchange with the environment calibrated using the results from experiments in special climate-controlled laboratories or climate chambers. ISO 7730 uses the Fanger [3] predicted mean vote (PMV) formula which predicts a numerical value for the mean subjective response to the thermal environment on the ASHRAE scale (Table 1) from a knowledge of six thermal variables. These are the metabolic rate (M) and clothing insulation (I_{cl}) of the subjects, the temperature of the air (t_a) and surrounding surfaces (the radiant temperature, t_r), the water vapour pressure (p_a) and the relative velocity of the air (v_{ar}). The formula is based on the results of extensive work in the 1960s at Kansas State University and the Technical University of Denmark. Fanger was at pains to investigate the differences between groups including subjects who, though tested in Denmark, were straight from the tropics and so might have been physiologically adapted to the heat. He found no consistent difference between the 'tropical' and the 'non-tropical' subjects. Subsequent work by deDear et al. [4] in Singapore confirmed this finding in a tropical context, though later work has not always borne this out.

Surveys of thermal comfort in the field seem to bring these results in to question. Many surveys have been conducted using subjects in a tropical context and relate observed sensation on the ASHRAE scale (or the similar Bedford scale) to the physical environment. Examples are Webb [5], Nicol [6], Sharma and Ali [7], Busch [8], Matthews and Nicol [9], Taki et al. [10], Nicol et al. [11] and Bouden and Ghrab [12], many others are quoted in the literature e.g. in Humphreys [13] and deDear and Brager [14]. The results from these surveys give the subjects' responses in situations they normally experience and not the unfamiliar surroundings of the climate chamber. The conditions which they find comfortable (or vote = 0 on the ASHRAE scale) differ from the predictions of ISO7730 particularly when buildings are not mechanically heated or cooled [15]. ISO7730 overestimates the occupant response on the ASHRAE scale at high temperatures and underestimates it at low temperatures. As a result it predicts discomfort at temperatures which subjects in field surveys find comfortable and underestimates the range of temperatures which people find comfortable (Fig. 1).

Fanger and Toftum [16] have tried to explain the predictive errors in PMV partly as a result of the 'expectations' of the local population, in terms of how exposed they are to mechanical cooling (AC). deDear and Brager [15] propose a new thermal comfort standard for NV buildings, leaving PMV as the standard for AC buildings. This approach has been well received by ASHRAE and offers some help for architects committed to low-energy solutions. However Humphreys and Nicol [17] demonstrate that the errors in

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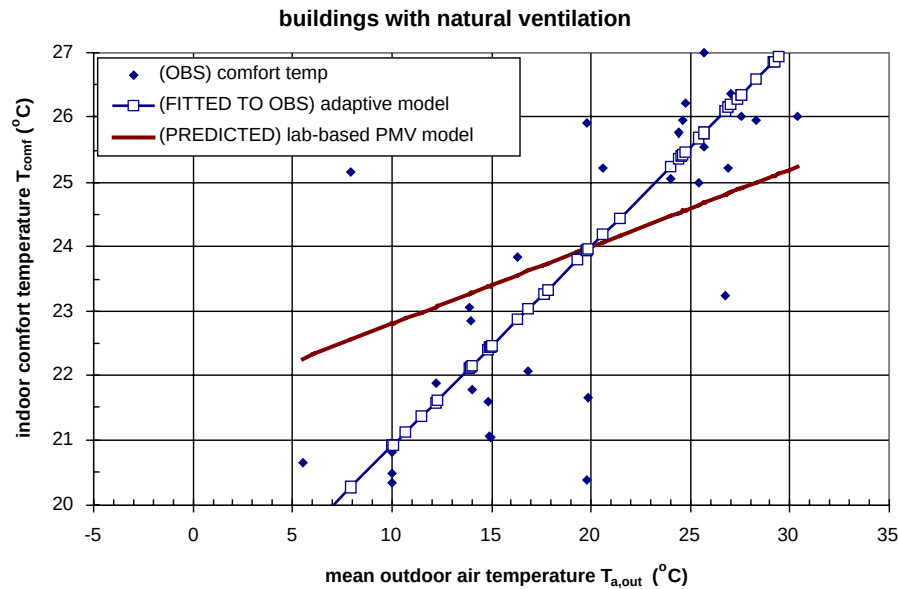


Fig. 1. Comfort temperatures in naturally ventilated buildings as predicted by the PMV model and actually measured in field surveys [15].

Table 1
The ASHRAE comfort scale

Description	Numerical value
Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	−1
Cool	−2
Cold	−3

PMV are not confined to NV buildings, they also occur in AC buildings but are masked by the narrow range of environments.

2. Why is the ISO7730 prediction wrong?

One problem for the prediction of comfort using ISO7730 in hot climates is the declared limitations to the applicability of the PMV, which are shown in Table 2. Air temperatures (t_a) above 30 °C and air velocities in excess of 1 m/s are not uncommon in buildings in tropical countries. Conditions are often such that the formula predicts PMV over 2. Yet many

field studies in hot climates have found that subjects can be comfortable at temperatures up to or even exceeding 30 °C especially if they are using a fan.

There are a number of theoretical [18] and practical reasons why the steady-state heat balance approach gives the wrong predictions of thermal sensation, particularly in the variable conditions that are found in naturally ventilated buildings in the tropics. If people are uncomfortable they will take actions such as changing their clothing or their activity or where possible using things like opening windows, closing blinds or switching on a fan so changing the environment to suit themselves. These changes will also take time to achieve and in addition the human body will take time to respond to a change in the heat balance. Time is an important element in thermal comfort which any prediction must take in to account.

There are other problems with the heat balance approach such as the way clothes are used—which varies from climate to climate. Most theoretical formulae see clothes as having a purely insulating function but in many climates they are used in more subtle ways to maintain an appropriate microclimate next to the skin (see e.g. [19]). Metabolic rate is usually calculated from a knowledge of the activity people are engaged in. This is assumed to be

Table 2
Limitations to the range of conditions over which PMV applies [1]

Variable	Symbol	Units	Lower limit	Upper limit
Metabolic rate	M	W/m ² (met)	46 (0.8)	232 (4)
Clothing insulation	I_{cl}	°C/W (clo)	0 (0)	0.310 (2)
Air temperature	t_a	°C	10	30
Radiant temperature	t_r	°C	10	40
Relative air velocity	v_{ar}	m/s	0	1.0
Water vapour pressure	p_a	Pa	0	2700
Predicted mean vote	PMV		−2	+2

independent of the temperature of the environment, yet people may be adjusting their activity to take account of the temperature. People also use changes in posture to affect heat balance by changing the surface area for convective and evaporative heat loss. None of these short-term changes are adequately accounted for in heat-balance models.

Each of these effects may be a minor source of error in itself, but taken together they can create significant errors in the theoretical relationship [20]. The sensation is the ‘trigger’ for subjects to change their own preferences to suit the environment, or to change the environment to suit themselves. Thus a number of measures may be taken at the same time. Even if all these could be accounted for, errors arising from such measures are often additive so small errors in estimating each can be significant in the overall prediction. A model which represents the thermal equilibrium as a heat balance at a point in time will not fully reflect thermal comfort in the field. Without full allowance for the dynamic nature of the human interaction with their surroundings, such a model is likely to have limited applicability. This is especially true in the conditions found in free-running buildings in hot climates.

The inappropriateness of the existing International standards poses problems for architects and engineers in tropical countries. How should they decide what temperatures to provide in their buildings?

3. Deciding what temperatures to provide: the field survey approach

Deciding what temperatures to provide in buildings is a complex problem. One way around this is to treat the process as a black box where the internal mechanisms of the relationship between comfort and the environment are less important than the outcomes. This is the approach taken by

those who use field surveys to investigate the problem. In the field all the variables are in action—people are free to change their clothes, their activity, their posture and when the building allows it, to change the temperature, air movement and even the humidity.

Nicol and Humphreys [20] presented the results of field studies in the UK, India, Iraq and Singapore. The result shows that mean comfort vote changes little with the mean temperature experienced. A similar figure including the results from many more studies world-wide is shown as Fig. 2. Each point represents the mean values of comfort vote (on the scale shown in Table 1) and the mean temperature the subjects experienced over a whole survey. Note that temperatures well above 30 °C are not considered uncomfortable in some cases.

Subsequent work by Humphreys [13] showed that the temperature which people find comfortable is closely related to the mean temperature they experience, Fig. 3 shows this effect for a wide range of different climates including Europe [21]. In other words people find ways in which to make themselves comfortable in the conditions they normally experience: they *adapt* to them behaviourally.

The effectiveness of these behavioural strategies is indicated in Fig. 4 which shows the proportion of people in Pakistani offices [11] who reported themselves comfortable at different indoor temperatures over a period of a year. Indoor temperatures between 20 and 30 °C caused little discomfort.

Free-running buildings are those which *at the time of the survey* are neither being heated nor cooled. In free-running buildings the mean indoor temperature tends to reflect the mean outdoor temperature. Because of the strong link between the comfort temperature and the mean indoor temperature (Fig. 3) the temperature which people find comfortable also tracks the outdoor temperature. In heated or cooled buildings the relationship is more complex because the indoor temperature is, to a certain extent, independent of the outdoor temperature. Humphreys [22] conducted a

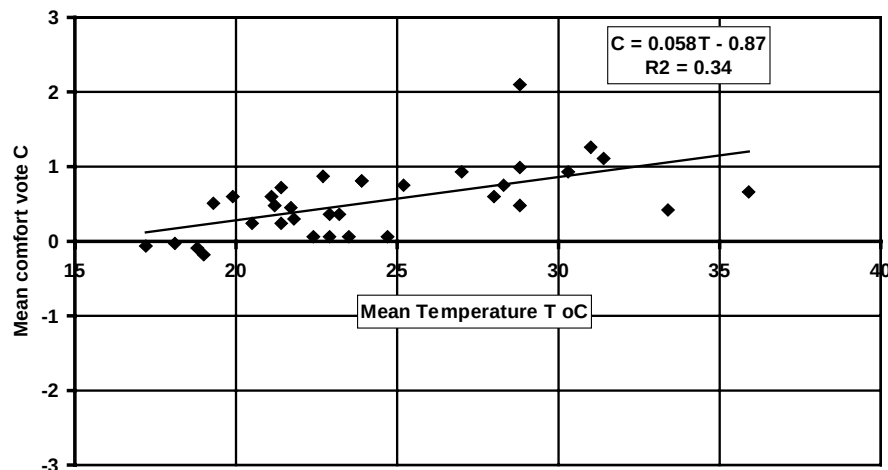


Fig. 2. Mean comfort vote on the ASHRAE comfort scale as a function of mean temperature experienced. Each point is the mean over a whole field survey.

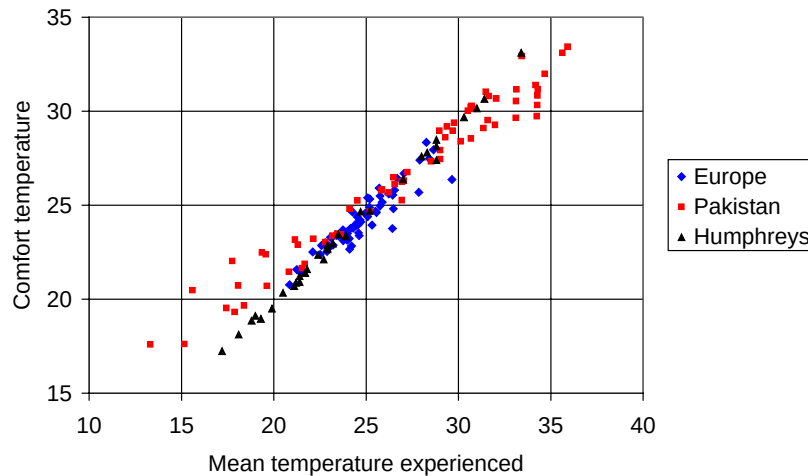


Fig. 3. The comfort temperature tends to follow the outdoor temperature. Data from Pakistan [11], Europe [21] and Humphreys [13].

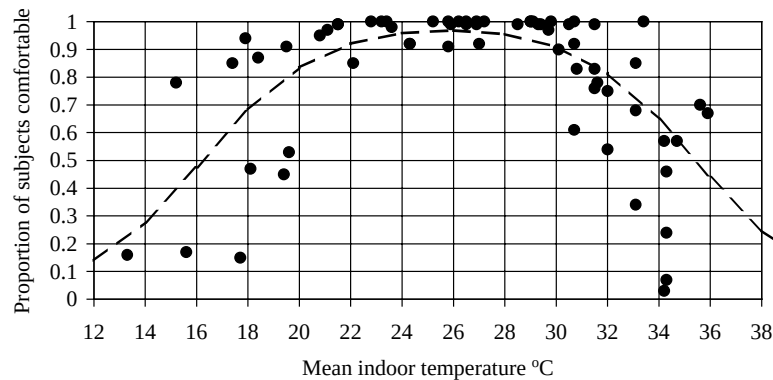


Fig. 4. The proportion of Pakistani office workers who felt uncomfortable plotted against the mean indoor temperature. Each point results from the votes of about 100 workers on the ASHRAE scale, comfort being defined as votes 1, 0 or –1 (Table 1) [11].

meta-analysis of the data from a large sample of comfort surveys world-wide and produced the relationships shown in Fig. 5.

The linear relationship which Humphreys derived between comfort temperature and mean outdoor temperature

for free-running buildings (the straight line in Fig. 5) is:

$$T_c = 0.534T_o + 12.9 \quad (1)$$

where T_c is the comfort temperature and T_o is the mean outdoor temperature. Recent work by Humphreys and Nicol

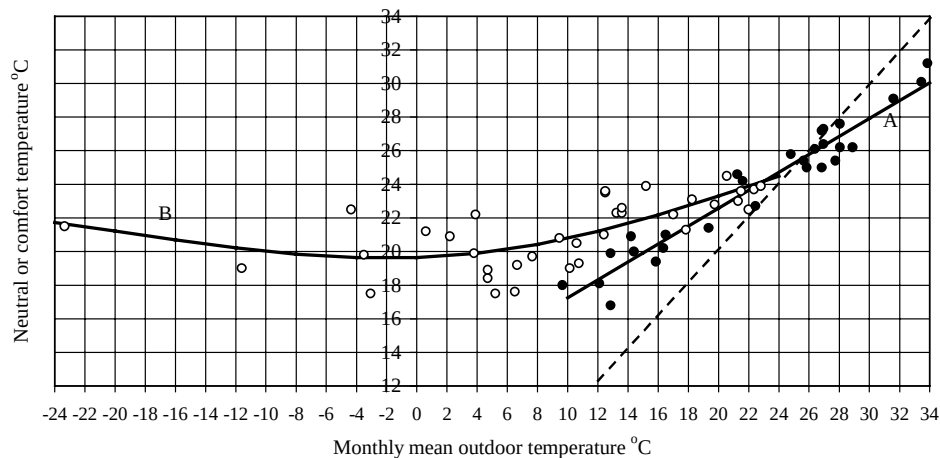


Fig. 5. The relationship between comfort temperature and monthly mean outdoor temperature. Filled points represent surveys conducted in free-running buildings and the open points those in buildings which were heated or cooled. The dashed line represents equality between comfort temperature and mean outdoor temperature.

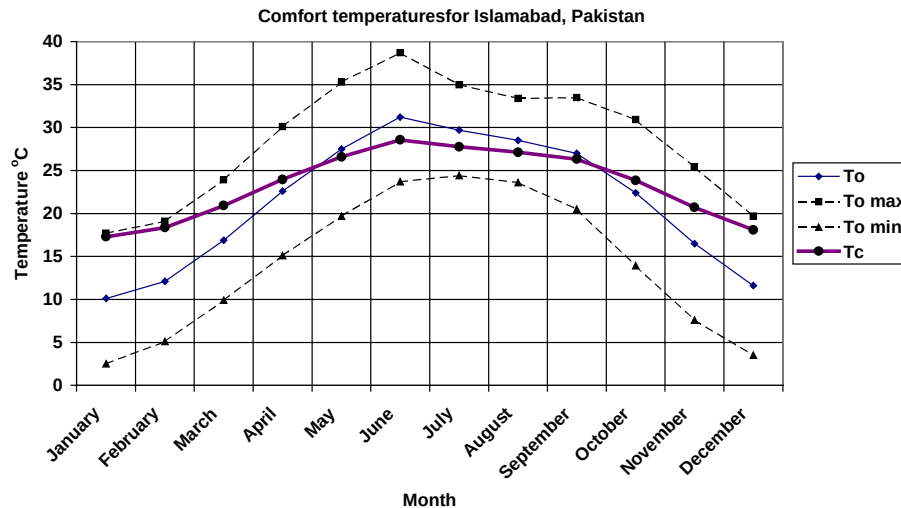


Fig. 6. Comfort temperature T_c for Islamabad Pakistan calculated from the outdoor temperature T_o using Eq. (1). T_o is calculated as the mean of the monthly mean maximum ($T_{o\max}$) and minimum ($T_{o\min}$).

[23] using data collected by deDear and Brager [14] shows that, taking account of differences in the calculation of comfort temperatures, almost exactly matches these earlier findings.

This relationship enables building professionals to predict the temperature which will be comfortable in free-running buildings by calculation from the monthly mean outdoor temperature given by meteorological records. Results for Islamabad, Pakistan are shown in Fig. 6. The figure shows the comfort temperature overlaid on the outdoor temperature to indicate the temperature differential which the building must achieve to remain comfortable indoors. In this case the building must be warmer than the outdoor mean in winter and cooler in summer, but by amounts which it might be possible to achieve by passive means (certainly in winter). A comfort zone within which temperatures are generally acceptable can be taken to extend some 2–3 °C either side of this optimum temperature.

4. Accounting for air movement and humidity

In this paper we try to show how air movement and humidity effect the comfort temperature as defined in Eq. (1) and Fig. 6 when we are considering comfort in hot, and in particular hot-humid (hh), climates. Because Eq. (1) is intended to give a target temperature, and not an instantaneous temperature, what we require is a simple set of rules which can be used to modify the predicted comfort temperature to account for air movement and high humidity enabling building designers to provide a comfortable environment. In the following analysis we will first look at the analytical and experimental predictions and then test them against results from field surveys. In developing the relationship in Eq. (1) Humphreys [22] attempted, where possible to give the relationship where air movement can be assumed to be

small (≤ 0.1 m/s) and relative humidity (RH) standardised at 50%.

Numerous studies of the effects of temperature, humidity and air movement on the human body in hot climates [24] have been undertaken. Much of this work in this area was to determine the relative effects of these factors on people's subjective response to heat. The effect of air movement and humidity are particularly important in hot climates where the heat lost by evaporation predominates.

One method of investigating the relative effects of the different elements of the thermal environment was to develop an 'index' of thermal comfort, often presented as an 'equivalent' temperature. This is defined as the temperature at a standard value of humidity and air velocity which will *feel* the same as the environment in question. One commonly used index of this sort is the effective temperature index (ET*) [25] resulting from extensive experimental studies. Such an index can also be derived from statistical analysis of a comfort survey in the field where the humidity and air movement have been measured. Two examples of empirical indices are Webb's Equatorial Comfort Index [5] developed in Singapore and Sharma and Ali's Tropical Summer Index [7] from hot-dry parts of India.

4.1. Air movement

In tropical climates air movement will be an important factor in determining comfort. A theoretical analysis [26] suggests that where the air velocity is above 0.1 m/s and fairly constant, this allowance can be equivalent to raising the comfort temperature by:

$$7 - \frac{50}{4 + 10v^{0.5}} \text{ °C} \quad (2)$$

There are assumptions built in to this equation, but the result is not particularly sensitive to the accuracy of

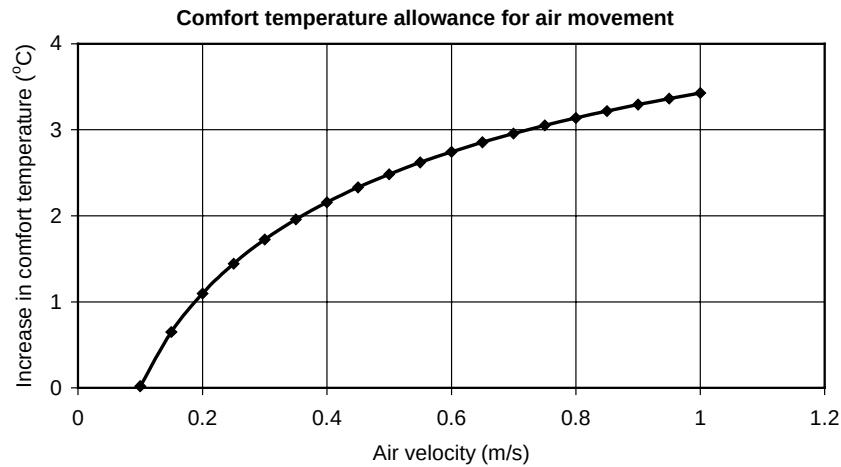


Fig. 7. The increase in comfort temperature for different air speeds.

these assumptions. This relationship is demonstrated in Fig. 7.

Nicol [6] showed that in the hot dry climates of Northern India and Iraq, the presence of air movement can be equivalent to a reduction in temperature of as much as 4°, and this is more or less in line with theoretical expectation. Sharma and Ali [7] found a similar effect. At hot times of year ceiling fans are used in almost all public buildings in the tropics, and this can be assumed to allow higher comfort temperature (T_c) than those given by Eq. (1).

Analysis of data from Pakistan [11] suggests that for indoor temperatures over 25°C, mean air velocity in rooms with fans is about 0.45 m/s, as opposed to about 0.1 m/s for those without fans running. Using Eq. (2) and Fig. 7 this suggests in dry conditions that normal use of fans will allow building occupants to be comfortable at a about 2°C above

the value suggested by Eq. (1). This effect is demonstrated in Fig. 8 which shows that fan use increases the comfort temperature by about 2°C over a wide range of outdoor temperatures.

4.2. Humidity

It is more difficult to account for the effect of humidity. Whilst humidity has been investigated in a number of field surveys in hot climates, and found to have a significant effect on comfort temperature, the size of the effect is generally small, and further research is needed. The first problem for the analysis of the effects of humidity is to decide how humidity should be measured. The relative humidity of the air is the best known measure and has been used in most studies of thermal comfort. RH is a *relative* measure and

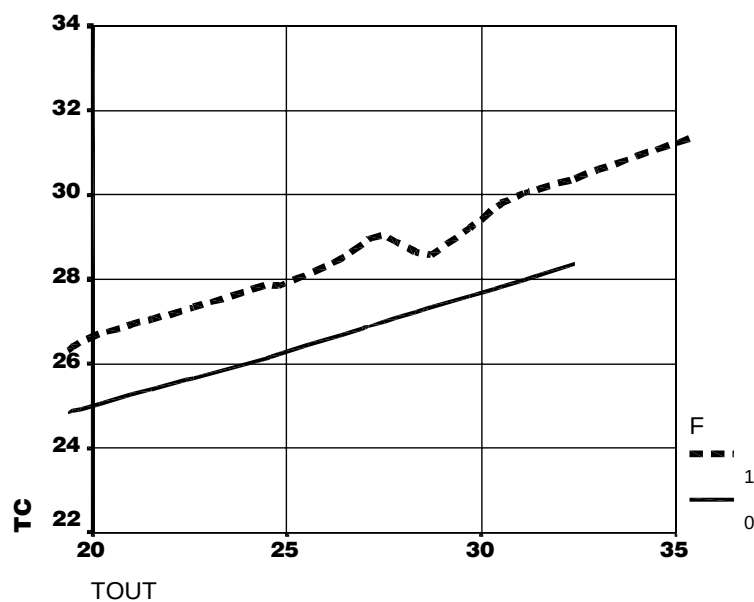


Fig. 8. Effect of fan use on comfort temperature (T_c) in offices in Pakistan. The dashed line shows the dependence of comfort temperature on outdoor temperature (T_{OUT}) when fans (F) are running (1), the solid line is for offices where fans are not running (0).

is therefore highly dependent on air temperature, especially at high temperatures. A more robust measure is the water vapour pressure (p_a) in the air. The driving force for heat loss by evaporation is the difference between the saturated water vapour pressure at the skin surface and p_a in the surrounding air. With the skin temperature remaining relatively constant, the saturated water vapour pressure at the skin surface is more or less constant. The p_a of the air should therefore be a good predictor of the evaporative heat loss, but has not always been recorded.

It is generally assumed that in hot conditions where loss of metabolic heat by convection and radiation decrease and the bulk of heat losses are via evaporation, increased humidity will increase discomfort. The barrier to evaporative heat loss caused by high humidity could, it is assumed, mean that people require a lower temperature for comfort.

deDear et al. [4] investigated the preferred temperature for seated subjects performing light activities and dressed in standard clothing (0.6clo) and in warm conditions (25–30 °C). The RH was set at two values: 70 and 35% and no significant difference was found in the preferred temperature between the two conditions. Ballantyne et al. [27] investigated the effect of water vapour pressure in thermal comfort data collected in the 60s at the Kansas State data on which Fanger's PMV was largely based. They found that the effect of p_a on the comfort votes of the subjects was small when the subjects were comfortable, but had a marked effect on the rate of change of comfort with temperature. In a moist environment people become uncomfortable with a smaller change in temperature than they do in a dry environment. The effect of activity on comfort is also more marked in a humid environment.

Reporting the results of two field studies of thermal comfort in hot dry conditions of Baghdad, Iraq and Northern India and with wvp in the region of 1.5–2.5 kPa and temperatures in the mid 30 s, Nicol [6] found a significant but small effect of wvp on thermal sensation. Webb [5] found that the water vapour pressure had a more marked effect on comfort in the cooler but more humid (mean wvp 3.3 kPa) conditions of Singapore. Other field studies in hot–humid climates [8,28,29] have unfortunately combined the effects of temperature and water vapour into the equivalent temperature index [25] which ‘accounts’ for the effect of humidity and they are unable to shed no light in the separate effect of humidity.

4.3. A meta-analysis of field studies

We have selected three sets of data to look at the relationship between comfort and humidity:

- the 1998 ASHRAE database [30];
- Humphreys' 1975 database [13] (used in Fig. 5 and the development of Eq. (1));
- data from Pakistan [11] which are not included in the ASHRAE database.

Table 3

Sites of thermal comfort field surveys where buildings were mostly free-running and their climate

Free-running buildings	Climate		
	hd	hh	Temp
Athens, Greece			6
Baghdad, Iraq	1		
Bangkok, Thailand		3	
Bay Area CA, USA			3
Birkenhead, UK			1
Brisbane, Australia			5
Calcutta, India		1	
Darwin, Australia		2	
Delhi, India	3		
Garston, UK			5
Islamabad, Pakistan	13		
Jakarta, Indonesia		2	
Karachi, Pakistan		6	
London, UK			2
Mapoon		1	
Melbourne, Australia			3
Merseyside, UK			4
Multan, Pakistan	11		
Oxford, UK			3
Peshawar, Pakistan	2		
Port Harcourt		1	
Port Moresby		4	
Quetta, Pakistan	9		
Rio, Brazil		2	
Saidu Sharif, Pakistan			12
Singapore		3	
Sydney, Australia			4
USSR (South)	1		
TOTALS	40	25	48

The sites are from the ASHRAE database [14] the Humphreys database [13] and the Pakistan database [11]. The table shows the number of separate field studies from each site. Climates are characterised as hot–dry (hd) hot–humid (hh) or temperate (temp).

All three studies have records of mean indoor and mean outdoor temperatures and estimates of the comfort temperature. Table 3 shows the locations and the rough climatic classification of the 113 comfort surveys from these databases where there was a large proportion of results from free-running buildings. Most also include records of mean outdoor relative humidity, though there are only 22 with records of mean p_a . The comfort temperature has been estimated for each survey. Where possible in the development of Eq. (1), Humphreys standardised his data, the actual values of the air movement and the humidity are not given. The papers from which he derived his data have been revisited and where possible the values of these variables have been extracted.

The surveys are all divided according to the climate at the site of the field study. These can then be classified according to climate as “hot–humid (hh)”, “hot–dry (hd)”, or “temperate (temp)”.

Fig. 9 shows the change of comfort temperature with mean outdoor temperature for data from different sites in the ASHRAE, Humphreys and Pakistan datasets where

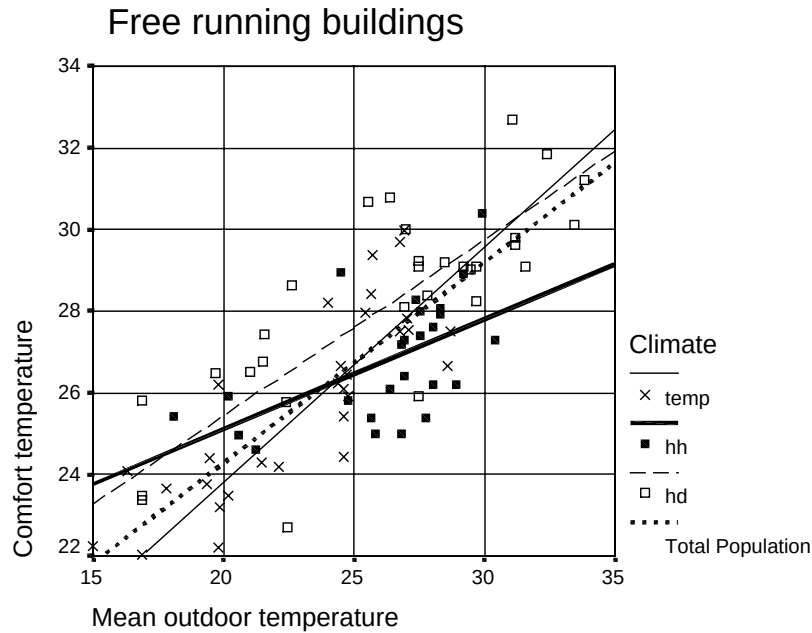


Fig. 9. The effect of climate type on comfort temperature at different values of outdoor mean temperature (T_{OUT}). Subjects in free-running buildings in a hot-humid climate (hh) desire a lower comfort temperature than those with a hot dry (hd) but the difference from the overall comfort temperature line is small climate for a given outdoor temperature.

buildings were free-running at the time of the survey. The continuous line hh shows the regression line of comfort temperature on outdoor temperature for locations with a hot-humid climate. The discontinuous line is the regression for all climates. Although the comfort line for hot-humid climates has a lower slope the actual comfort temperature

for hh climates is little different from the overall values for outdoor temperatures between about 20 and 30 °C.

In Fig. 10 a similar figure has been produced in which the comfort lines are shown for three grouped vales of mean outdoor relative humidity (RHO). The range of values contained in each group are shown in Table 4. In this case

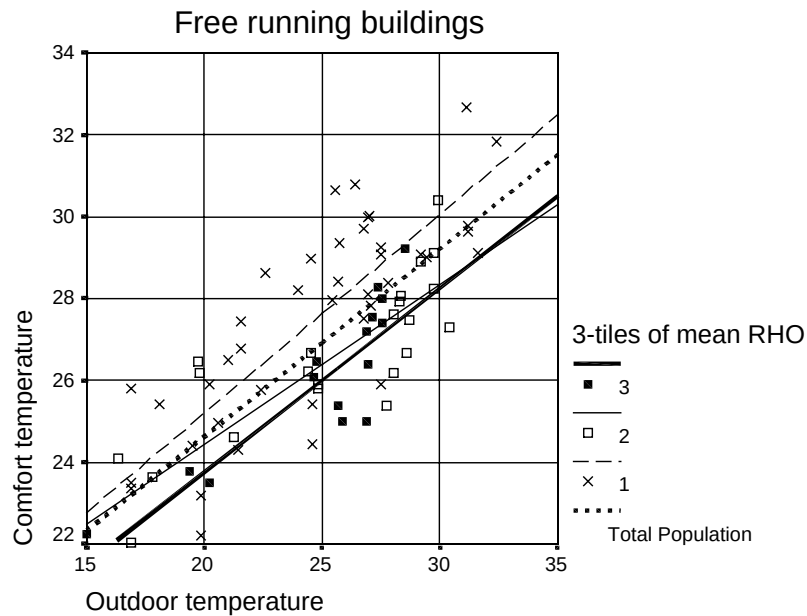


Fig. 10. The effect of mean outdoor relative humidity (RHO) on comfort temperature at different values of outdoor mean temperature. Subjects in free-running buildings in a warm climate desire a lower comfort temperature if the humidity is high (3, $RH > 75\%$) than if it is low (1, $RH < 64\%$) but the difference from the overall comfort temperature (total population) line is only about 1 °C.

Table 4

Range and mean value for the 3-tiles of outdoor relative humidity (RHO) and water vapour pressure (p_a)

N-TILE	Relative humidity (%)		Water vapour pressure, p_a (kPa)	
	Range	Mean	Range	mean
1	<63	53	<1.4	1.1
2	64–75	71	1.4–2.2	1.9
3	>75	81	>2.2	2.7

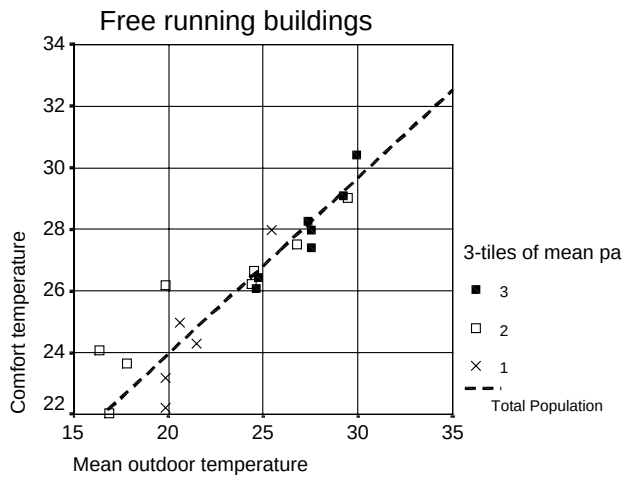


Fig. 11. The effect of mean water vapour pressure (p_a) on comfort temperature at different values of mean outdoor temperature. Subjects in free-running buildings in a warm climate show little change in their comfort temperature at different values of the water vapour pressure.

the regression lines for the overall condition and for the most humid third are more-or less parallel, with the higher humidity requiring a lower air temperature for comfort than the overall line by about 1 °C over the whole range of temperatures. The difference is just significant.

In view of the discussion above regarding the relative appropriateness of using p_a as a measure of humidity, a separate analysis was made of the results from the 22 surveys from free-running buildings where p_a was estimated. The result is shown in Fig. 11, and suggests that there is no difference in the comfort temperature for the three groups of values of p_a .

5. Conclusions

In theory at least the PMV should predict the temperature at which people are comfortable regardless of the local conditions. The equations on which it is based take account of changes in clothing and activity and so it should be able to predict thermal sensation irrespective of where it is used. In tropical conditions it fails to give accurate information about the temperatures which people will find comfortable.

It is particularly unfortunate that PMV predicts that people will feel hotter than they actually do and therefore tends

to encourage the use of more air conditioning than necessary. In addition, because ISO7730 does not provide information about what clothing people use in any particular circumstances, there is a tendency to assume a particular clothing level and the consequent need for a constant indoor temperature, thereby encouraging the use of mechanical cooling.

International standards which take account of the evidence from field studies in the tropics are urgently needed. ASHRAE have recently approved a new version of ASHRAE comfort standard 55 incorporating the information derived from field surveys [15]. Eventually it is to be hoped that these can be based on theory which has been successfully tested against wide-ranging empirical results. The cultural element and the allowance for time means that comfort surveys are needed in every area of the world, particularly in the tropics where current standards are weakest.

Meanwhile, the empirical findings of field surveys can be used as a guide for informing the design of buildings to provide comfortable conditions. In the first instance according to Eq. (1), which can be taken as an international generalisation of field studies throughout the world. Wherever possible this can be improved by the conduct of local field surveys to fully reflect local climate and culture.

Fig. 6 shows the way in which the results can be used to calculate the optimum comfort temperatures at different times of year. A comfort zone of 2–3° either side of the optimum can be taken as acceptable. If fans are available to building occupants another 2 °C can be added to the predicted comfort temperature in hot conditions. In a humid climate or in conditions when the relative humidity is high people may require temperatures that are about 1 °C lower to remain comfortable, but the main effect of a higher humidity (or water vapour pressure) is to reduce the width of the comfort zone.

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