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The adaptive model of thermal comfort and energy conservation in the built environment

Abstract Current thermal comfort standards and the models underpinning them purport to be equally applicable across all types of building, ventilation, occupancy pattern and climate zone. A recent research project sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, RP-884) critically evaluated these assumptions by statistically analysing a large database of research results in building comfort studies from all over the world (n=22,346). The results reported in this paper indicated a clear dependence of indoor comfort temperatures on outdoor air temperatures (instead of outdoor effective temperature ET* used in RP-884), especially in buildings that were free-running or naturally ventilated. These findings encourage significant revisions of ASHRAE's comfort standard in terms of climatically relevant prescriptions. The paper highlights the potential for reduced cooling energy requirements by designing for natural or hybrid ventilation in many moderate climate zones of the world.

Introduction

Indoor climate engineering represents the one of the largest energy-end uses in buildings, so the oil shocks of the 1970s prompted building engineers to closely examine building thermal insulation, air-tightness of building envelopes, and heat recovery to decrease energy consumption for heating, ventilating and air-conditioning (HVAC)

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in buildings. Buildings were rigidly isolated from the outdoor environment and their indoor environments were automatically controlled with artificial lighting, mechanical ventilation and heating and cooling systems (Heiselberg 1999). These developments necessitated some rational basis for engineering and management of indoor climate, to provide thermal comfort for building occupants, who, by the nature of their buildings, were denied any opportunity for decentralized, local thermal regulation. Thermal comfort standards have evolved to fulfil that need. The rationale of comfort standards is to optimise the thermal acceptability of indoor environments. The conventional "comfort wisdom" embodied in these standards (ASHRAE 1992, 1995; ISO 1994) prescribes an "envelope" or "comfort zone" of temperatures to be applied uniformly through space and time. In practice, however, engineers typically opt for a fixed set of design conditions – cool, still air – falling in the middle of the summer and winter comfort zones depicted in Fig. 1.

Standards like ASHRAE 55 (1992, 1995) and ISO 7730 (ISO 1994) are derived from a reductionist model of thermal comfort that views occupants as passive recipients of thermal stimuli. It is based upon extensive research conducted in climate chambers, using samples of subjects who were exposed to tightly controlled combinations of thermal environmental parameters such as temperature and humidity. The model evolving from this research methodology posits the subjective thermal state as a function of the physics of the body's thermal balance with its immediate environment, as mediated by autonomic physiological responses. These biophysical relationships have been assumed to be *universally applicable across all* building types, *all* climate zones, and *all* populations (Parsons 1994; Fanger 1970). But many thermal comfort researchers have been critically questioning the assumption of universality, arguing that it ignores important cultural, climatic, social and contextual dimensions of comfort, denying all processes of thermal adaptation, and ultimately leading to an exaggerated "need" for refrigerated cool, still air (Kempton and Lutzenhiser 1992; Prins 1992; Brager and de Dear 1998).
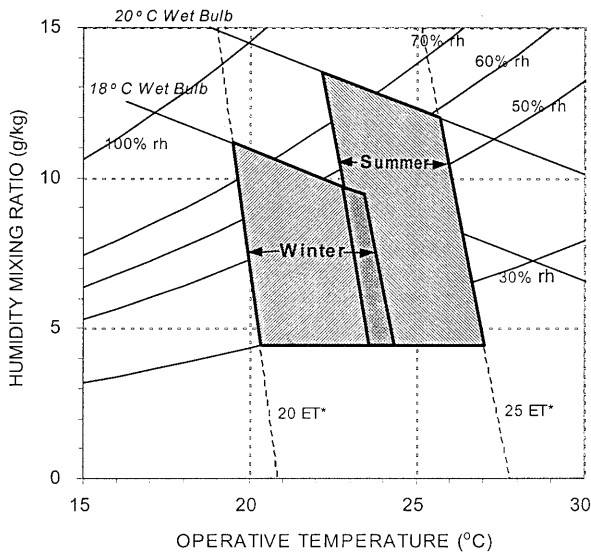
Fig. 1 The "comfort zone" according to American Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55–92 Addendum: Thermal environmental conditions for human occupancy (ASHRAE 1995). *ET** effective temperature

The dialectic between conventional and "adaptive" schools of thought in the thermal comfort literature has a long history going back to the 1970s and 1980s and it is not necessary to revisit it here. Not until the closing decade of the 20th century did we witness growing public disquiet over the prodigious energy inputs to buildings that slavishly implement the "static model" of thermal comfort. Of particular concern are the global environmental impacts such as greenhouse warming caused by mismanagement of energy resources within the built environment. The architectural and engineering responses to these concerns include optimal use of sustainable technologies such as passive solar gains and natural and hybrid ventilation – all falling under the heading of "bioclimatic design" (Szokolay 1998).

A recent innovation in the bioclimatic approach is known as hybrid ventilation. It is the current focus of the International Energy Agency Annex 35 and has been defined by Heiselberg (1999) as systems providing a comfortable internal environment using different features of both natural ventilation and mechanical air conditioning at different times of the day or season of the year. They have intelligent control systems that automatically switch between natural and mechanical mode in order to minimize energy consumption and maintain a satisfactory indoor environment. Perhaps the most famous example in the last decade is the Commerzbank in Frankfurt by the architect Sir Norman Foster. One of the tallest buildings in Europe deploys a hybrid ventilation system that uses natural ventilation for indoor air quality and thermal comfort control, resorting to mechanical ventilation for indoor air quality control and chilled ceilings for summer comfort control when necessary. Another example, the Liberty Tower of Meiji University, was recently described Chikamoto et al. (1999). Located in downtown Tokyo, Liberty Tower is a high-rise building with a "wind floor" located on an upper level that induces natural ventilation for the remaining floors with a stack effect through the building core. Other features included natural ventilation windows and air-conditioning plant integrated by a central building energy management system. Chikamoto et al. (1999) reported that the hybrid ventilation mode of Liberty Tower saved 35% on cooling energy consumption compared to a year-round air-conditioning mode.

However, the "environmentally responsible" ideals of bioclimatic design, such as natural and hybrid ventilation, with their dynamic indoor climatic conditions, are fundamentally inconsistent with conventional comfort wisdom (cool, still air). This has prompted calls for alternative design guidelines to supplement the current ASHRAE Standard 55 (1995). In particular, a variable indoor temperature standard would have direct relevance to naturally ventilated buildings, buildings with hybrid ventilation systems and other situations in which building occupants have some degree of indoor climatic control.

A variable temperature standard links indoor temperatures to the outdoor climatic context of the building and accounts for past thermal experiences and current thermal expectations of their occupants (Auliciems 1981). Because conventional comfort theory does not account for these contextual effects, such a standard has to be based on an alternative theory, termed the adaptive model of comfort, in which factors beyond fundamental physics and physiology interact with thermal perception. The basic tenet of the adaptive model is that building occupants are not simply *passive* recipients of their building's internal thermal environment, like climate chamber experimental subjects, but rather, they play an *active* role in creating their own thermal preferences. Contextual factors and past thermal history are believed to influence expectations and thermal preferences. Satisfaction with an indoor climate results from matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate *should* be like in that same context (Auliciems 1981, 1989; Nicol 1993; de Dear 1994). In short, satisfaction occurs through appropriate adaptation to the indoor climatic environment.
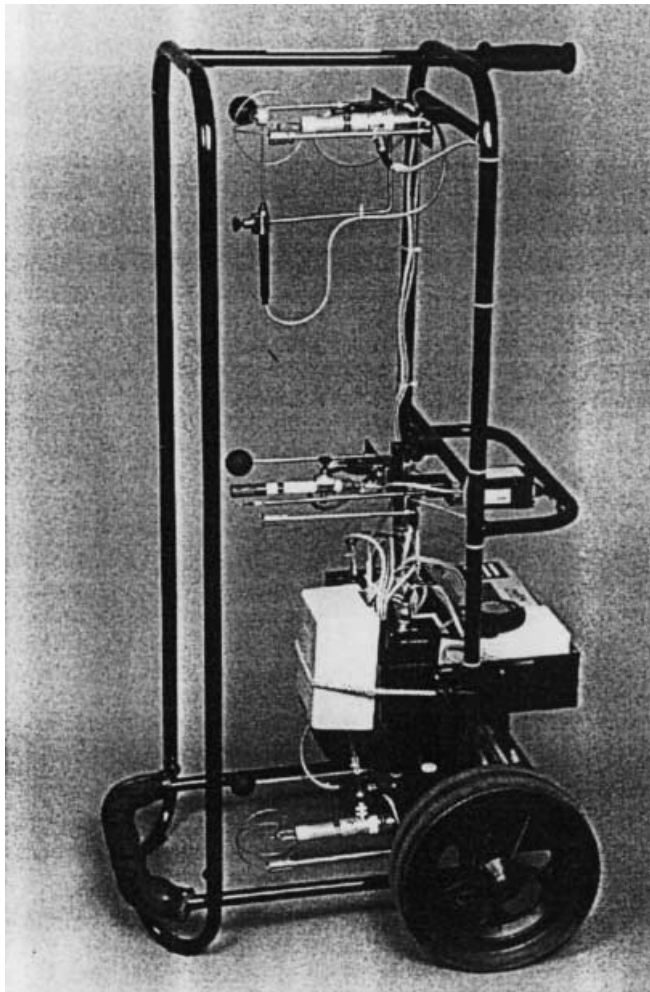
This paper reports and extends the results from the ASHRAE RP-884 project: Developing an adaptive model of thermal comfort and preference. The initial research was premised on the development and analysis of a quality-controlled, cumulative database of thermal-comfort field experiments worldwide (see de Dear 1998a for more details on the RP-884 database). Earlier analyses of the database (de Dear and Brager 1998) expressed the adaptive model in terms of outdoor effective temperature (ET*) but the complexities of calculating this index have rendered the model less accessible to practitioners than researchers. Therefore, apart from critically questioning the universality of conventional comfort wisdom embodied in current thermal comfort standards, the following re-analysis of the RP-884 database

sets out to express the adaptive model in more familiar meteorological terms – namely the mean outdoor air temperature, with an aim of developing an alternative adaptive comfort standard that is more conducive to energy conservation in buildings with natural and hybrid ventilation.

Materials and methods

ASHRAE recognises the narrow empirical bases of its comfort standard. Documents such as Standard 55 (ASHRAE 1995) were intended for routine use by HVAC engineers and facilities managers for both design and operational purposes, but these end-users often express concern about the validity of generalising from laboratory studies on small samples of college students to the global population of building occupants. In response to these concerns, ASHRAE's Technical Committee (TC 2.1) in charge of Standard 55 initiated a programme of field validation experiments in various climate zones ranging from Mediterranean, through hot-humid

Fig. 2 Modern thermal comfort field study instrumentation (Cena and de Dear 1999). Temperature and air speed are recorded at three heights within the occupied zone (0.1, 0.6 and 1.1 m above the floor) representing ankle, waist and neck for a seated subject. Samples are taken at a frequency of approx. 10 Hz for an interval of 5 min while the subject completes his or her thermal comfort questionnaire

and hot-dry zones to cold continental. To ensure consistency, the first in this series of field studies, ASHRAE RP-462 (Schiller et al. 1988), was charged with developing the standardized protocols for collecting physical and subjective data, which have since served as the models for the subsequent field studies. Mindful of the common criticisms levelled at research in the field, TC 2.1 specified laboratory-grade instrumentation and meticulous compliance with the procedures set out in Standard 55. An example of the type of indoor climatic instrumentation developed for this field programme is depicted in Fig. 2 (Cena and de Dear 1999). The bare essential sensors must measure air and radiant temperatures, humidity and air speed. Apart from standardized instruments, the ASHRAE programme defined a standard field questionnaire and protocol. This required, as a bare minimum, that thermal comfort questionnaires include the ASHRAE seven-point sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot), the McIntyre three-point preference scale (I want cooler, no change, warmer), a garment check-list (for estimation of ensemble clothing insulation), and a metabolic rate check-list, all to be administered at the same time as the indoor climatic instrumentation is being used. Using this standardized questionnaire, thousands of building occupants going about their normal day-to-day activities have volunteered their thermal perceptions of the environment inside their buildings.

Quality-controlled database of thermal comfort field research

Since its inception in the 1980 s, ASHRAE's field research programme has become the *de facto* methodological standard and numerous independent researchers have since adopted and applied it in their respective parts of the world. This led to the idea of assembling an internally consistent database of such results. The development of the database is fully documented elsewhere (de Dear 1998a). The purpose of this section is to outline briefly its contents and the basic steps taken to ensure its integrity.
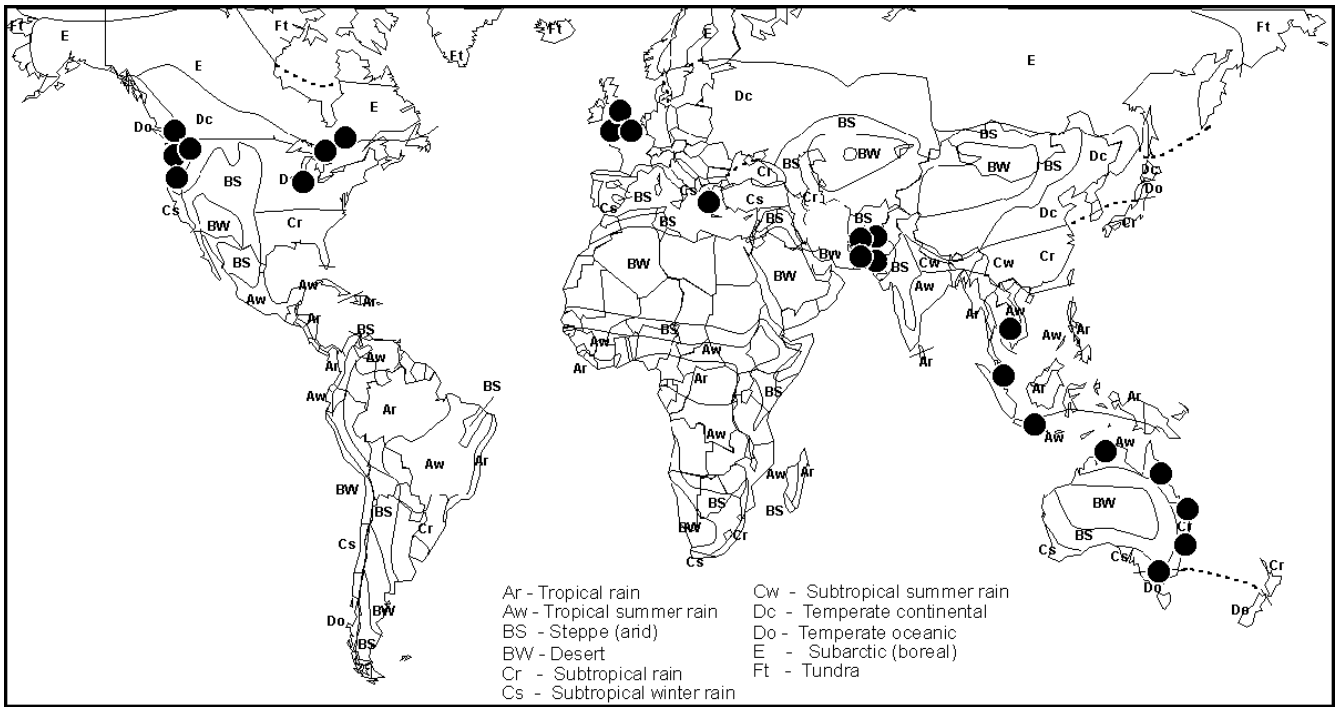
The process was initiated with a three-page questionnaire on field research methods, which was sent to more than 50 thermal comfort researchers currently or recently active in field research. On the basis of their returns, raw field data were requisitioned from researchers who met the following criteria:

1. Their measurement techniques, both physical and subjective, approximated "laboratory-grade."
2. Their data structures allowed each set of questionnaire responses to be linked to a concurrent set of indoor climatic and outdoor meteorological observations.
3. Their indoor climatic observations were comprehensive enough to enable conventional thermal comfort indices such as PMV and ET* to be calculated for each questionnaire respondent.

Apart from ensuring the quality of raw data inputs to the database, a secondary aim was to keep the internal consistency of the database as high as possible. If implemented together, these measures would pre-empt any subsequent criticism of this project's field-based comfort standard by proponents of the laboratory methods underpinning current comfort standards. To this end, raw field data were requisitioned instead of processed or published findings, enabling the uniform application of a variety of quality controls and standardised data processing techniques across the entire database.

Raw data in the RP-884 database came from four continents and a broad spectrum of climatic zones (Fig. 3). One hundred and sixty different buildings were included and approximately 22,000 sets of raw data were compiled from several locations in England and Wales, Bangkok Thailand, Indonesia, several Californian locations, Montreal and Ottawa in Canada, six cities across Australia, five cities in Pakistan, Athens in Greece, Singapore, and Grand Rapids in Michigan.

Each complete set of data was structured within the database using the template developed in previous ASHRAE-funded

even if it were practical there is no rational basis to suspect such a laborious procedure would have yielded a different result from the one achieved by the input-averaging method used here.

Parameters for the meta-database, defining the outdoor climatic environment of each building, were initially obtained by taking the mean daily minimum and mean daily maximum outdoor Stevenson screen temperature from the nearest meteorological records for the duration of the building's study. Relative humidities coinciding with the daily maximum and minimum temperatures were also recorded, enabling daily minimum and maximum outdoor effective temperatures (ET*) in the shade to be estimated (assuming mean indoor clothing insulation (clo) and met values calculated from that building's data) with the WinComf© software (Fountain and Huizenga 1996). Taking the arithmetic average of the minima and maxima gave the mean outdoor effective temperature that was used in the adaptive models reported in de Dear and Schiller Brager (1998). Subsequent discussions with the committee charged with revising ASHRAE Standard 55 (SSPC 55) have revealed that the practitioners whom we expect to be the end-users of the RP-884 adaptive models would be more likely to do so if the meteorological input data were expressed as air, not effective temperature. Therefore the final variable-temperature model proposed in the current paper has adopted this simplification.

Results and discussion

Indoor humidity limits for comfort

The effect of indoor humidity and whole-body thermal acceptability (as assessed with the seven-point thermal sensation scale) was assessed in the RP-884 database by
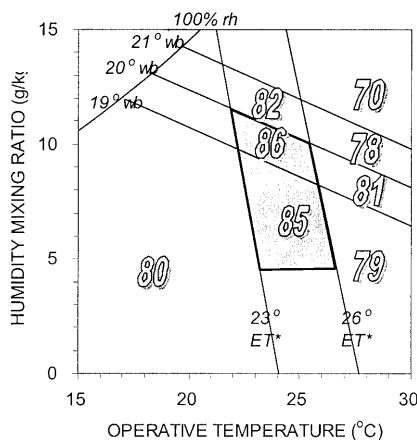
Fig. 4 Thermal acceptability ratings for summer studies in the RP-884 database. The ASHRAE Standard 55a (1995) comfort zone for summer is shaded grey. Numerical data on the chart represent percentages of thermally acceptable votes out of the total number of observations that fell within each region of the psychrometric chart

analysing the individual records, rather than by a building-by-building analysis. The indoor climate observations were first classified into 1 of 12 regions on the pyschrometric chart surrounding the summer comfort zone, as shown in Fig. 4. If the total number of cases in any particular region of the chart exceeded a reasonable sample size of 30, the percentage registering "satisfactory" or "acceptable" thermal sensations (i.e. thermal sensations between –1 and +1 on the seven-point scale) was calculated. Figure 4 presents only the summer results.

For the predominantly sedentary subjects being analysed in this chart it appears as if there is a negligible effect of increasing humidity (acceptability decreased 4% between 20°C and 21°C wet bulb temperature) as long as the effective temperature remained within the boundaries of ASHRAE's summer comfort zone. As might be expected on the warmer side of 26°C ET*, increasing humidity was associated with declining acceptability, particularly above 21°C wet bulb temperature.

Indoor air speed limits for comfort

The summer-time air speed data from the database were divided into three ET* categories: (a) cooler than the ASHRAE 55 comfort zone, (b) within the ASHRAE 55 comfort zone's ET* limits and (c) warmer than the ASHRAE 55 comfort zone. Observations within each of these three ET* zones were then further classified into five air speed (v) bands ranging from v<0.2 m s^{-1} to v≥ 0.8 m s^{-1} (see Table 1). We again regarded 30 observations as the minimum useful sample size, and for each cell of this matrix with more than 30 observations we calculated the percentage of cases registering "satisfactory" or "acceptable" thermal sensations (between –1 and +1). The results presented in Table 1 indicate that limiting air speeds to 0.2 m s^{-1} during summer is associated with improved thermal acceptability only in temperatures below 23°C ET* (i.e. below the cool-side limit of ASHRAE's summer comfort zone). At temperatures within or warmer than the ASHRAE summer comfort zone's ET* limits, air speeds elevated above 0.2 m s^{-1} were associated with improved thermal acceptability. It is conceded that these findings refer to general, whole-body acceptability because most of the original studies providing the data for Table 1 did not have questionnaire items dealing specifically with local thermal dissatisfaction. Nevertheless the overall pattern in Table 1 suggests that draft dissatisfaction is not as great an issue in warmer temperatures as it is in cool environments.

Table 1 Thermal acceptability ratings for the summer data in the RP-884 database. Data represent percentages of votes indicating that the conditions were thermally acceptable out of all observations at various combinations of ET* and air speed (n=cell sample size)

Air speed ranges	Votes indicating thermal acceptability (%)		
	ET* <23°C	23°C ≤ ET* ≤ 26°C	ET* >26°C
v ≥ 0.8 m s^{-1}			79 (n=322)
0.6 m s^{-1} ≤ v <0.8 m s^{-1}			78 (n=262)
0.4 m s^{-1} ≤ v <0.6 m s^{-1}		92 (n=48)	72 (n=554)
0.2 m s^{-1} ≤ v <0.4 m s^{-1}	72 (n=191)	83 (n=378)	76 (n=1875)
v < 0.2 m s^{-1}	80 (n=2390)	86 (n=4257)	72 (n=2482)

Fig. 5 Clothing insulation as adaptive thermoregulation (or lack of it) in heated, ventilated and air-conditioned (HVAC) buildings and naturally ventilated buildings. Each point represents a building mean (± SD) thermal insulation (clothes and chair) in relation to mean indoor operative temperature while the building was studied (after de Dear and Brager 1998)

buildings with centralized HVAC

$clo = 1.73 - 0.04 * t_o$
$R^2 = 0.18$, $p = 0.0001$

buildings with natural ventilation

$clo = 2.08 - 0.05 * t_o$
$R^2 = 0.66$, $p = 0.0001$
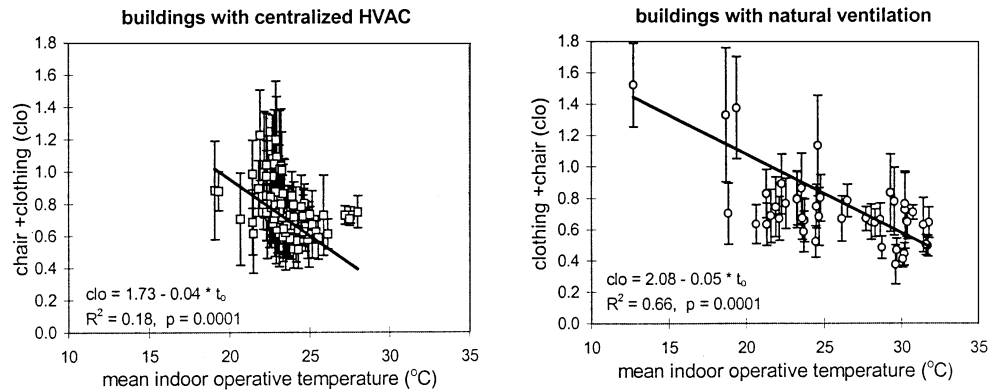
Fig. 6 Air velocity as an indicator of behavioral adaptation (or lack of it) in HVAC and naturally ventilated buildings (after de Dear and Brager)

buildings with centralized HVAC

$v = -0.56 + 0.03 * t_o$
$R^2 = 0.34$, $p = 0.0001$

buildings with natural ventilation

$v = 0.008 \, e^{0.117 * to}$
$R^2 = 0.53$, $p < 0.05$
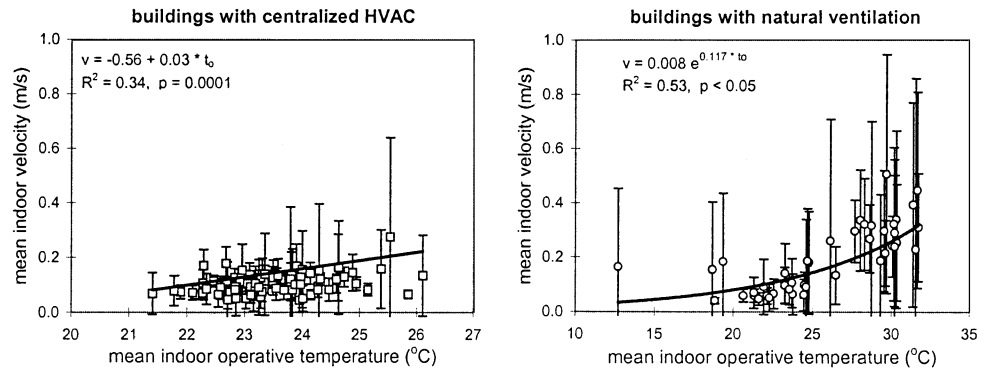
Behavioral adaptation to indoor climate

The first and most obvious manifestation of behaviorial adaptation to indoor climate by the occupants of a building is their selection of clothing for its thermal insulation, and this has been quantified in Fig. 5. The role of clothing in cancelling out inter-individual thermal differences within each building is amply demonstrated by the standard deviations around each building's mean clo value. As might be expected, the much narrower range of indoor temperatures between 21°C and 25°C found in the centrally air-conditioned (HVAC) part of the building database (left panel of Fig. 5) limited the range of clothing response in those contexts, which in turn deflated the correlation coefficient between temperature and clo value (explained variance = 18%). This point is amplified when comparisons are made with the naturally ventilated buildings (explained variance = 66%) on the right-hand side of Fig. 5.

Increasing air speed within a naturally ventilated space is another form of behavioural adaptation, where occupants modify environmental conditions. While this is one of the main ways for the occupants of a building to maintain acceptable thermal comfort in warm climates, the current comfort standards such as ASHRAE 55–92 (1992, 1995) limit indoor air speeds to 0.2 m s⁻¹. This permissible limit corresponds to the average air speeds measured in the naturally ventilated spaces (right-hand panel of Fig. 6) when the average indoor operative temperature was about 26°C. When temperatures in such buildings exceed 26°C, the average measured air speeds

would not be permissible under ASHRAE 55–92 unless each occupant had direct control over the air motion in their vicinity. For example, unless every occupant of an open-plan office environment at, say, 27°C had direct control over the operable windows on that space's perimeter, their building would not comply with ASHRAE Standard 55, even though they might all enjoy the benefits of the windows being open. It is safe to assume that warm temperatures (>26°C) combined with low air speeds (<0.2 m s⁻¹) would be uncomfortable for a majority of occupants. As a result, we see the strict interpretation of and compliance with ASHRAE 55–92 Standard (1992, 1995) leaves designers with no feasible alternative to the cool, still air approach to indoor climate engineering.

Adaptive model of thermal comfort

The preceding analyses of clothing and indoor air speed indicate that the occupants of naturally ventilated spaces are more responsive to their buildings' indoor climates than their counterparts in centralised HVAC buildings. This finding was also borne out in the analysis of subjective thermal comfort states such as thermal neutrality (de Dear and Brager 1998). It was noted that, particularly for the naturally ventilated buildings, the indoor temperatures found to be neutral (i.e. subjects voting zero on the seven-point thermal sensation scale) were significantly warmer in locations with warm outdoor climates than they were in cold climate zones. In other words, indoor
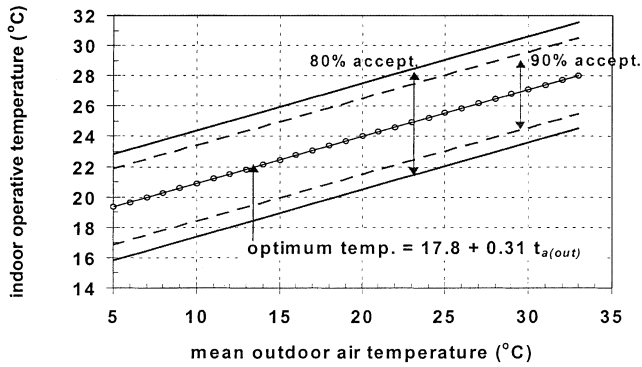
Fig. 7 The adaptive comfort standard (derived from temperature preferences) in naturally ventilated spaces as a function of prevailing outdoor air temperature. $t_{a(out)}$ is simply an arithmetic average of the mean monthly minimum and maximum daily air temperatures for the month in question

thermal neutralities and preferences tended to track the patterns of outdoor climate, but the analysis in de Dear and Brager (1998) demonstrated that this pattern could not be explained merely by differences in clothing levels.

More important than neutral sensation votes, perhaps, are expressions of thermal preference. The RP-884 analysis found the indoor temperatures that elicited a minimum number of requests for warmer or cooler conditions were, like thermal neutralities, a function of temperatures prevailing outside the building at the time of the survey. This main finding has been expressed as a linear relationship in Fig. 7. The gradient term of the highly significant regression model ($P<0.0001$) indicates that the preferred temperature *inside* a naturally ventilated building increases by approximately one degree for every three-degree increase in mean monthly *outdoor* air temperature. This finding comes remarkably close to Auliciems' earlier attempts at adaptive modelling (1983) despite the latter being based on a much more diverse set of building types, and less stringently quality-controlled data inputs. Despite these methodological differences, Auliciems' regression coefficient of 0.31 perfectly matches the coefficient found in the present study. Furthermore, in Auliciems' adaptive model the *y*-intercept of 17.6°C was a negligible 0.2°C cooler than the 17.8°C found in the current study. Such close agreement between two quite independent meta-analyses of two disparate field study databases is highly unlikely to be the result of chance alone.

Also depicted in Fig. 7 are the ranges of temperatures found to correspond with thermal acceptability ratings of 90% and 80%. It should be noted that these ratings were not derived from empirical acceptability questions in the project's database. Instead they came from a widely assumed relationship between the group mean thermal sensation vote (Fanger's PMV) and thermal dissatisfaction (Fanger's PPD). The relationship indicates that a large group of subjects expressing a mean thermal sensation

vote of ±0.5 could expect to have 10% of its members voting outside the central three categories on the sensation scale (i.e. assuming that such votes represent thermal dissatisfaction). The PMV/PPD relationship also indicates that a mean thermal sensation vote of ±0.85 would correspond to a 20% level of thermal dissatisfaction in the sample. Applying these 10% and 20% criteria to the mean thermal sensation (ASHRAE seven-point scale) recorded in the buildings of the RP-884 databases indicates that a latitude of 2.5°C either side the optimum temperature is consistent with 90% acceptability in these naturally ventilated buildings. For 80% acceptability the limits can be relaxed to 3.5°C either side the optimum temperature, as shown in Fig. 7. The questionnaires used in the field studies in the RP-884 database provide no opportunity to test empirically this relationship between mean thermal sensation and percentage dissatisfied because thermal dissatisfaction questionnaire items were used in only a small number of field studies. Nevertheless, since the assumed relationship has been accepted and adopted in thermal comfort standards such as ISO 7730 for many years (1984, 1994), it seems reasonable that it should extend to the adaptive comfort standard as well.

The linear equations for the optimum comfort model and acceptability limits, collectively known as the adaptive comfort standard and depicted in Fig. 7, can be written as:

Comfort temperature (°C) = 0.31 (mean outdoor monthly air temperature) + 17.8
Upper 80% acceptable limit (°C) = 0.31 (outdoor air temperature) + 21.3
Upper 90% acceptable limit (°C) = 0.31 (outdoor air temperature) + 20.3
Lower 80% acceptable limit (°C) = 0.31 (outdoor air temperature) + 14.3
Lower 90% acceptable limit (°C) = 0.31 (outdoor air temperature) + 15.3

It should be noted that these acceptability bands are assumed to account for local as well as whole-body thermal discomfort effects in typical buildings. Furthermore, this adaptive comfort standard already accounts for people's clothing adaptation in naturally conditioned spaces, so no special attempt need be made to estimate insulation from garment checklists when this standard is used. Other behavioural adaptations are also subsumed under this adaptive model, so neither humidity nor air speed limits need consideration when Fig. 7 is applied.

It is important to note that the model should be restricted to the outdoor temperature range depicted in Fig. 7. In extreme climate zones, where mean monthly temperatures go beyond that range, instead of simply extrapolating the linear models, one should adopt the relevant upper or lower comfort temperatures and acceptability limits from Fig. 7 (i.e. the linear function and its 80% and 90% acceptability limits should flatten out at mean monthly outdoor air temperatures warmer than 32°C or cooler than 5°C).

Conclusions

The analysis of the RP-884 database presented in this paper was based on many thousands of human subjects in building studies from around the world. It indicates that indoor temperatures falling outside ASHRAE's Standard 55–92 (1992, 1995) comfort zones (Fig. 1) may, in fact, be quite acceptable in buildings with natural or hybrid ventilation systems (the latter operating in their natural ventilation modes). The current prescription of a 20°C limit on wet-bulb temperatures had negligible relevance to thermal acceptability observed in these field experiments. Likewise, the database revealed that the risk of draft impacting on thermal acceptability was much less of a problem in warmer environments than in colder-than-neutral situations. Therefore the cool, still air philosophy of thermal comfort, which requires significant energy consumption for mechanical cooling, appears to be over-restrictive in these buildings and, as such, may not be the appropriate criterion when decisions are being made about whether or not to install centralised HVAC systems (Leaman et al. 1995). If a building design is predicted to achieve indoor temperatures within the much broader adaptive range depicted in Fig. 7, at the appropriate season, a *prima facie* case now exists for *not* resorting to conventional air-conditioning solutions, unless non-thermal factors (e.g. dampness, particulates, ocular discomfort etc.) dictate otherwise.

If nothing else, the adaptive comfort standard reported in this paper has confirmed a long-standing suspicion that, in their present form at least, Standard 55–92 (ASHRAE 1992, 1995) and its close relative, ISO 7730 (1994), may not be directly relevant to a large part of the building stock across a large swathe of moderate global climate zones. Therefore, existing standards need to have their scopes explicitly narrowed down to just those situations for which they were originally intended – namely, buildings with large numbers of occupants who have no individual control over their indoor climates. As demonstrated in the present paper, this does not include buildings with natural and hybrid ventilation operating in passive mode.

The adaptive comfort standard in this paper (Fig. 7) provides design guidance for naturally ventilated buildings in various climate zones. It indicates the optimum and acceptable indoor temperature ranges for different climate zones of the world (as defined by the mean monthly outdoor air temperature). Another application of the findings is in control algorithms for buildings with hybrid ventilation systems. As noted in the Introduction, hybrid ventilation refers to the practice of using a building's natural ventilation potential (and attendant energy conservation) during weather and seasons that are conducive, and then resorting to mechanical air-conditioning on occasions when natural ventilation is unlikely to deliver thermal comfort to occupants. An integral feature of hybrid ventilation systems is intelligent control through building management systems that switch between active and passive modes (Heiselberg 1999).

Combined with appropriate outdoor weather(temperature)-sensing capabilities (as initially proposed by Auliciems 1990) the adaptive model's 80% (or 90%) acceptability limit equations could be readily programmed into a hybrid building's management system as critical thresholds for switching the building between passive and active modes.

The earlier generation of adaptive models drew criticism in the comfort literature for being based on "low-grade" input data. In particular, attention has been drawn to the deficiencies of some of the instrumentation systems, or omission of clothing insulation or metabolic rates from the field observational protocols upon which earlier adaptive models such as Auliciems' (1981, 1983) were based. The up-dated adaptive model and adaptive comfort standard proposed in the current paper have removed this potential source of criticism. Besides, the fact that the present paper was able to generate an adaptive regression model almost exactly the same as an adaptive model from an earlier generation, despite being based on a completely different database, suggests that the instrumental errors in the earlier models were not really a problem after all.

Other criticisms of the variable-temperature indoor climate standard have highlighted problems of indoor air quality, particularly in relation to the role played by enthalpy in the perceived quality of indoor air (e.g. Fanger 1998; Fang et al. 1999). Laboratory studies indicate that perceived air quality ratings deteriorate in environments with elevated temperature, humidity or both. By direct inference, some argue that the uncontrolled, or at least partially deregulated indoor climates being advocated in this paper must, *ipso facto*, create lower perceived air quality than their air-conditioned counterparts, particularly in the warmer climate zones of the world. However, this indoor air aesthetics argument can be countered by reference to the sick building syndrome (SBS). Mendell's review (1993) of several very large SBS field studies found consistently *higher* symptom prevalence in conventionally air-conditioned than in naturally ventilated buildings. The more recent California Healthy Building Study also reiterated these findings, SBS symptoms being significantly less prevalent in naturally ventilated buildings (Mendell et al. 1997). The British research establishment (Raw 1992) also noted that the lowest SBS symptom prevalences in the UK were found in naturally ventilated buildings. "Mean levels [of SBS symptom prevalence] are clearly higher where there is cooling capacity in the ventilation system" (Raw 1992).

As is often the case in indoor air research, we have an apparent contradiction between large field-based observational databases and laboratory research, and a resolution of this conflict will hopefully be the focus of future research. Apart from scientific curiosity, a conclusion to this debate is well worth pursuing in view of demonstrable energy conservation in buildings with natural and hybrid ventilation operating under the adaptive comfort standard.

References

ASHRAE (1992) Standard 55. Thermal environmental conditions for human occupancy. ASHRAE, Atlanta

ASHRAE (1995) Addendum to Standard 55. Thermal environmental conditions for human occupancy. ASHRAE, Atlanta

Auliciems A (1981) Towards a psychophysiological model of thermal perception. Int J Biometeorology 25:109–122

Auliciems A (1983) Psychophysiological criteria for global thermal zones of building design. Int J Biometeorology 27:69–86

Auliciems A (1989) Thermal comfort. In: Ruck N (ed) Building design and human performance. Van Nostrand, New York, p 71–88

Auliciems A (1990) Airconditioning in Australia. III. Thermobile controls. Architect Sci Rev 33:43–48

Brager GS, de Dear RJ (1998) Thermal adaptation in the built environment: a literature review, energy and buildings. 27:83–96

Cena K, de Dear RJ (1999) Field study of occupant thermal comfort and office thermal environments in a hot, arid climate. ASHRAE Trans 105:204–217

Chikamoto T, Kato S, Ikaga T (1999) Hybrid air-conditioning at Liberty Tower of Meiji University Tokyo. In: Chen Z, Delsante A, Li Y, Rowe D (eds) Proceedings of HybVent Forum '99 – First international one-day forum on natural and hybrid ventilation CSIRO, U Sydney, International Energy Agency, Sydney, pp 1–10

de Dear RJ (1994) Outdoor climatic influences on indoor thermal comfort requirements. In: Oseland NA, Humphreys MA (eds) Thermal comfort: past present and future. BRE, Garston

de Dear RJ (1998a) A global database of thermal comfort field experiments. ASHRAE Trans 104:1141–1152

de Dear RJ (1998b) A global database of thermal comfort applied to questions of air speed and humidity limits in standards. In: ICHES98 Organising Committee (eds) Proceedings of the Second International Conference on Human-Environment System, Yokohama November 1998. The Organizing Committee for International Conference on Human-Environment System, Yokohama, pp 342–345

de Dear RJ, Brager GS (1998) Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104:145–167

Fang L, Wargocki P, Witterseh T, Clausen G, Fanger PO (1999) Field study on the impact of temperature, humidity and ventilation on perceived air quality. In: Raw G, Aizlewood C, Warren P (eds) Proceedings of Indoor Air'99, Edinburgh, Scotland, Vol 2, Indoor Air 99 Organising Committee, Edinburgh, pp 107–112

Fanger PO (1970) Thermal comfort – analysis and applications in environmental engineering. Danish Technical Press, Copenhagen

Fanger PO (1998) A moderate enthalpy and a low pollution load in healthy buildings. In: ICHES98 Organising Committee (eds) Proceedings of the Second International Conference on Human-Environment System, Yokohama November 1998, pp 608–613

Fountain ME, Huizenga C (1996) WinComf: A Windows 3.1 thermal sensation model. User's manual. Environmental Analytics, Berkeley

Heiselberg P (1999) Outline of HybVent. In: Chen Z, Delsante A, Li Y, Rowe D (eds) Proceedings of HybVent Forum '99 – First international one-day forum on natural and hybrid ventilation. CSIRO, U Sydney, International Energy Agency, Sydney, pp 1–10

Humphreys M, Nicol F (2000) Effects of measurement and formulation error on thermal comfort indices in the ASHRAE database of field studies. ASHRAE Trans 106:493–502

ISO (1984) International Standard 7730: Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions of thermal comfort, 1st edn. ISO, Geneva

ISO (1994) International Standard 7730: Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions of thermal comfort, 2nd edn. ISO, Geneva

Kempton W, Lutzenhiser L (1992) Introduction. Energy and Buildings 181:71–176

Leaman AJ, Cohen RR, Jackman PJ (1995) Ventilation of office buildings: deciding the appropriate system. Heat Air Condit J 68:90–101

Mendell MJ (1993) Non-specific symptoms in office workers: a review of the epidemiologic literature. Indoor Air 3:227–236

Mendell MJ, Fisk WJ, Deddens JA (1997) Elevated symptom prevalence associated with ventilation type in office buildings. Occup Health Ind Med 36:9

Nicol F (1993) Thermal comfort – a Handbook for field studies toward an adaptive model. University of East London, UK

Parsons K (1994) Thermal comfort standards: past, present and future, and open discussion that follows. In: Oseland NA, Humphreys MA (eds) Thermal comfort: past, present and future. BRE, Garston, pp 184–197

Prins G (1992) On condis and coolth. Energy and buildings 18: 251–258

Raw GJ (1992) Sick building syndrome: a review of the evidence on causes and solutions. HSE Report 42/1992. HMSO, London

Rudloff W (1981) World climates. Wissenschaftliche Verlagsgesellschaft, Stuttgart

Schiller G, Arens E, Bauman F, Benton C, Fountain M, Doherty T (1988) A field study of thermal environments and comfort in office buildings. ASHRAE Trans 94. Pt 2:280–308

Szokolay SV (1998) Bioclimatic architecture and solar energy. In: Auliciems A (ed) Advances in bioclimatology. Springer, Berlin Heidelberg New York, pp 111–131

Toftum J, Melikov AK, Rasmussen LW, Kuciel AA, Cinalska EA, Tynel A, Bruzda M, Fanger PO (2000) Human response to air movement. Part I. Preference and draft discomfort. DTU International Centre for Indoor Environment and Energy, Denmark