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Thermal comfort and building energy consumption implications – A review

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HIGHLIGHTS

- We review studies of thermal comfort and discuss building energy use implications.
- Adaptive comfort models tend to have a wider comfort temperature range.
- Higher indoor temperatures would lead to fewer cooling systems and less energy use.
- Socio-economic study and post-occupancy evaluation of built environment is desirable.
- Important to consider future climate scenarios in heating, cooling and power schemes.

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ABSTRACT

Buildings account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions. A large proportion of this energy is used for thermal comfort in buildings. This paper reviews thermal comfort research work and discusses the implications for building energy efficiency. Predicted mean vote works well in air-conditioned spaces but not naturally ventilated buildings, whereas adaptive models tend to have a broader comfort temperature ranges. Higher indoor temperatures in summertime conditions would lead to less prevalence of cooling systems as well as less cooling requirements. Raising summer set point temperature has good energy saving potential, in that it can be applied to both new and existing buildings. Further research and development work conducive to a better understanding of thermal comfort and energy conservation in buildings have been identified and discussed. These include (i) social-economic and cultural studies in general and post-occupancy evaluation of the built environment and the corresponding energy use in particular, and (ii) consideration of future climate scenarios in the analysis of co- and tri-generation schemes for HVAC applications, fuel mix and the associated energy planning/distribution systems in response to the expected changes in heating and cooling requirements due to climate change.

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1. Introduction

There is a growing concern about fossil energy use and its implications for the environment. The increasing threat of global warming and climate change has raised the awareness of the relationship between economic growth, energy use and the corresponding environmental pollutants. There is a statistically significant positive association between economic growth, energy use and carbon emissions (e.g. in the ASEAN countries [1], China [2,3] and among a total of 69 countries involving high, middle and low income groups [4]). There have been marked increases in energy use in developing countries, and it is envisaged that such trend will continue in the near future. For instance, during 1978–2010 China's total primary energy requirement (PER) increased from about 570 to just over 3200 Mtce (million tonnes of coal equivalent), an average annual growth of 5.6%. Although its energy use and carbon emissions per capita are low, China overtook the US and became the largest energy consuming and CO_2 emissions nation in 2009 [5–7]. In their work on technology and policy options for the transition to sustainable energy system in China, Chai and Zhang [8] estimated that China's PER would increase to 6200 Mtce in 2050, of which fossil fuels would account for more than 70% and the corresponding emissions could reach 10 $GtCO_2e$ (10×10^9 tonnes of CO_2 equivalent). It has been estimated that, by 2020 energy consumption in emerging economies in Southeast Asia, Middle East, South America and Africa will exceed that in the developed countries in North America, Western Europe, Japan, Australia and New Zealand [9].

The building sector is one of the largest energy end-use sectors, accounting for a larger proportion of the total energy consumption than both the industry and transportation in many developed countries. For example, in 2004 the building sector accounted for 40%, 39% and 37% of the total PER in USA, the UK and the European Union [9,10]. In China, building stocks accounted for about 24.1% in 1996 of total national energy use, rising to 27.5% in 2001, and was projected to increase to about 35% in 2020 [11,12]. Globally, buildings account for about 40% of the total PER and contribute to more than 30% of the CO_2 emissions [13]. This concern has led to a number of studies conducted worldwide to improve building energy efficiency: on the designs and construction of building envelopes (e.g. thermal insulation and reflective coatings [14–20], sensitivity and optimisation [21–23], and life-cycle analysis [24,25]); technical and economic analysis of energy-efficient measures for the renovation of existing buildings [26–31]; and the control of heating, ventilation and air conditioning (HVAC) installations and lighting systems [32–35]. A significant proportion of the increase in energy use was due to the spread of the HVAC installations in response to the growing demand for better thermal comfort within the built environment. In general, in developed countries HVAC is the largest energy end-use, accounting for about half of the total energy consumption in buildings especially non-domestic buildings [9,36–39]. A recent literature survey of indoor environmental conditions has found that thermal comfort is ranked by building occupants to be of greater importance compared with visual and acoustic comfort and indoor air quality [40]. This also affects the designs of the building envelope in general, and the windows and/or glazing systems in particular [41,42]. It is therefore important to have a good understanding of the past and recent development in thermal comfort and the implications for energy use in buildings. This paper presents a review of thermal comfort research and development work and discusses the implications for energy use in the built environment. The aim is not to conduct a detailed analysis of or comprehensive comparison between different thermal comfort models and studies (such analysis and comparison can be found in Refs. [43–46]), but rather highlight issues that are more pertinent to energy conservation in buildings. The objective is to examine the implications of thermal comfort for energy consumption in the built environment. It is hoped that this review can contribute to a better understanding of how thermal comfort is related to and affects the broader energy and environmental issues involving social-economic, fuel mix and climate change. Broadly speaking, there are two main categories of thermal comfort models – heat balance and adaptive. Heat balance models have been developed using data from extensive and rigorous experiments conducted in climate chambers, whereas adaptive models are mainly based on measured/surveyed data from field studies. Climate chambers tend to have consistent and reproducible results, but the disadvantage is the lack of realism of the day-to-day working or living environments that field studies can represent.

2. Heat balance models

Heat balance models assume that the human body's thermoregulatory system is to maintain an essentially constant internal body temperature. As such, the effects of the immediate thermal environment are mediated by the physics of heat and mass transfer between the body and the surrounding environment. To maintain a constant internal body temperature people will respond physiologically to any thermal imbalance with its thermal environment. It is assumed that people's thermal sensations (e.g. feeling hot or cold) are generally proportional to the magnitude of these responses measured in terms of mean skin temperature and latent heat loss

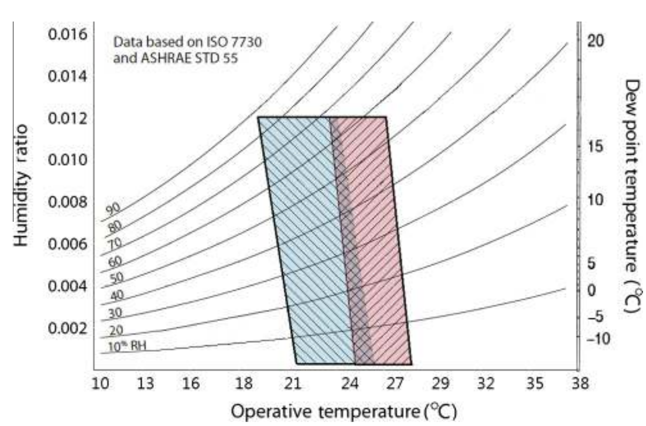

Fig. 1. Acceptable range of operative temperature and humidity for the thermal comfort zones (Ref. [49]).

or wittedness due to sweating. These form the basis for the development of heat balance thermal comfort models.

2.1. Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD)

In the 60s, Fanger [47] wanted to develop a method (an index), by which HVAC engineers would be able to predict whether a certain thermal environment would be acceptable to a large group of people. Through experimental work involving college-age participants in a climate chamber, linear relationships between (i) mean skin temperature and the activity level and (ii) sweat secretion and the activity level were established. These were then substituted into the heat balance equations to develop the comfort equation, which could predict the conditions that people would feel thermally neutral. To have practical applications, an index called the predicted mean vote (PMV) was derived by expanding the comfort equation to incorporate the seven-point ASHRAE thermal sensation scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot) and experimental studies involving 1396 subjects. Like the comfort equation, the PMV equation is rather complex, details of which can be found in Fanger [47]. Briefly, PMV is a function of the four environmental variables (air temperature (t_a in °C), mean radiant temperature (t_{mrt} in °C), relative air velocity (v in m/s) and air humidity (i.e. vapour pressure, p_a in kPa)), activity level (i.e. metabolic rate, M in W/m^2) and the clothing insulation (I_{cl} in clo). Thus:

$$\text{PMV} = f(t_a, t_{mrt}, v, p_a, M, I_{cl}) \quad (1)$$

PMV represents the mean thermal sensation vote on a standard scale for a group of building occupants for any given combination of the four environmental variables, prevailing activity level and clothing. People are not alike, and there will always be a certain variations in the thermal sensations of a large group of people. It is important to know the percentage of people who would be dissatisfied with the environment, because these are the ones who would most likely make complaints. Based on experimental studies in which participants voted on their thermal sensations, an empirical relationship between PMV and the predicted percentage of dissatisfied (PPD) was developed as follow:

$$\text{PPD} = 100 - 95 \times \exp(-0.03353 \times \text{PMV}^4 - 0.219 \times \text{PMV}^2) \quad (2)$$

Eq. (2) indicates that even at thermal neutrality (i.e. PMV = 0), about 5% of the people may still be dissatisfied. Instead of trying to achieve optimum thermal condition, design objective should therefore be exploring the range of thermal comfort. That is how cold or warm the thermal conditions could deviate from the optimum and what percentage of dissatisfied would be acceptable. This has important energy use implications because a wider range of thermal conditions tends to consume less heating/cooling energy than a narrow one [48]. The PMV–PPD model has been adopted by various national and international standards/guidelines (e.g. ASHRAE Standard 55 [49] and ISO 7730 [50]). Fig. 1 shows the range of operative temperatures outlined in the comfort zones of the ASHRAE Standard 55. This corresponds to thermal conditions that may be acceptable to 80% of the building occupants and is based on a PPD of 10% (i.e. −0.5 < PMV < +0.5) and an additional 10% dissatisfaction due to local (partial body) thermal discomfort. For an indoor relative humidity of 50%, the temperature range is approximately from 20 °C (lower limit of the winter zone) to just over 27 °C (upper limit of the summer zone).

2.2. Extension of predicted mean vote (PMV) model

Over the past four decades, the PMV model has been adopted by a number of researchers worldwide to assess indoor thermal environment [44]. In general, PMV model works well in built environment with HVAC systems. For naturally ventilated (or free-running) buildings, however, the indoor temperature considered most comfortable increases significantly in warmer climates, and decreases in colder climate regions [51,52]. This is not surprising given the fact that "Fanger was quite clear that his PMV model was intended for application by the heating, ventilation and air-conditioning (HVAC) industry in the creation of artificial climates in controlled spaces" [44]. In non-air-conditioned buildings in warm climates, people may sense the warmth as being less severe than that predicted by the PMV model due mainly to low expectations. To address this, PMV model was extended to include an expectance factor. The extended PMV model was tested against measured data from field studies in four cities (Athens, Bangkok, Brisbane and Singapore). It was found that both the measured and predicted results showed good agreement [53].

3. Adaptive models

3.1. Adaptive principle

The heat-balanced PMV model does allow the option of changing the level of activity (hence the corresponding metabolic rate) and clothing. The experimental works (upon which the PMV model is based), however, was conducted in climate chambers. Such arrangement did not give any indication of how the occupants would change these two parameters in an attempt to adapt to the surrounding environment. In practice, more often than not, assumptions have to be made about the on-going activity and clothing. This tends to limit the application of the PMV model to a more static thermal environment usually associated with air-conditioned spaces [54]. In general, people are not passive recipients of their immediate environment, but constantly interacting with and adapting to it. The return towards comfort is pleasurable. Therefore, if there is any discomfort due to changes in the thermal environment, people would tend to act to restore their thermal comfort. Broadly speaking, there are three different categories of adaptation – physiological, behavioural and psychological [55]. Physiological adaptation (in terms of acclimatisation) is not likely to play a major role in affecting occupants' thermal comfort for the moderate range of thermal conditions prevailing in the built environment. Psychological adaption refers to the effects of cognitive, social and cultural variables, and describes how and to what the extent habits and expectations might change people's perceptions of the thermal environment. Behavioural adaptation is by far

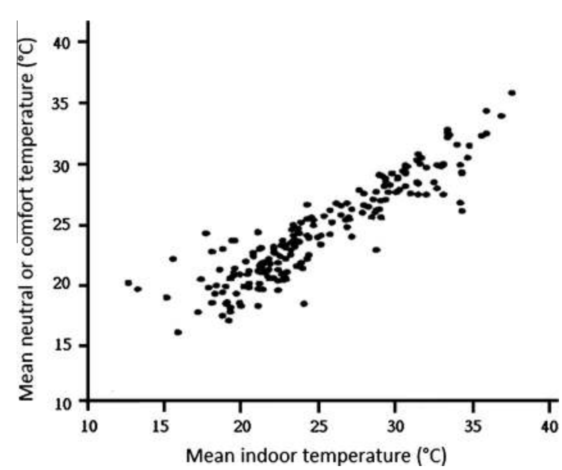

Fig. 2. Correlation between the comfort temperature and the mean indoor temperature (Ref. [56]).

the most dominant factor in offering people the opportunity to adjust the body's heat balance to maintain thermal comfort, such as changing the activity and clothing levels & opening/closing windows and switching on fans. A consequence of adaptive principle is that occupants try and hopefully become adjusted to their immediate thermal environment. Adaptive comfort studies should, therefore, be conducted in people's everyday routines at home or in the office. In other words, evidence of adaptation in the built environment should, ideally, be based on results from field studies. Fig. 2 shows a correlation between the neutral or comfort temperature and the mean measured indoor temperatures from a number of field studies [56,57]. Each point represents the results of a distinct population. It can be seen that the neutral temperature approximated closely the prevailing temperature measured indoor. This indicates that people tended to adapt/adjust to the thermal environment and felt comfortable at the different indoor temperatures. The presence of some outlying points indicates that there were incidences where adaptation was incomplete. These points were not confined to the two extremes (i.e. very hot/cold) suggests that such incompletion was due mainly to the social, psychological or economic circumstances rather than the thermal environment itself. The comfort temperature might be as low as 17 °C and as high as 30 °C.

3.2. Indoor neutral temperature and outdoor temperature relationships from field studies

One of the key findings from various field studies on adaptive thermal comfort is correlation between the indoor neutral temperature (T_n) and the corresponding mean outdoor temperature (T_o) for the months in question. The early work on worldwide thermal comfort data from the period during 1935–1975 by Humphreys [58] resulted in the following relationship for "free-running" building:

$$T_n = 11.9 + 0.534T_o \text{ (Coefficient of determination, } R^2 = 0.94) \quad (3)$$

More recently, similar adaptive model based on the mean effective outdoor temperature was developed by de Dear and Brager [51,59] using a global database of 21000 sets of thermal comfort results from 160 buildings. Subsequent revisions were made to raise the precision of the relationships and compare the correlations from these two databases [60]. For naturally ventilated or "free-running' buildings:

$$\text{(Humphreys) } T_n = 13.2 + 0.534T_o \text{ (Coefficient of determination, } R^2 = 0.94) \quad (4)$$

$$\text{(de Dear \& Brager) } T_n = 13.5 + 0.546T_o \text{ (Coefficient of determination, } R^2 = 0.91) \quad (5)$$

For HVAC, heated or cooled buildings:

$$\text{(Humphreys) } T_n = 20.1 + 0.0077T_o^2 \text{ (Coefficient of determination, } R^2 = 0.44) \quad (6)$$

$$\text{(de Dear \& Brager) } T_n = 22.2 + 0.003T_o^2 \text{ (Coefficient of determination, } R^2 = 0.49) \quad (7)$$

It can be seen that for naturally ventilated buildings Eqs. (4) and (5) are very similar. Both have strong correlation, indicating that more than 90% of the variations in the neutral temperature could be explained by the changes in the mean outdoor temperature. For climate-controlled buildings the relation is much looser. Nevertheless, this shows that when heating/cooling is in operation, the neutral temperature may vary within a fairly wide zone, with a modest but clear dependence on the prevailing external climate.

4. Energy savings implications

Findings from the field studies on adaptive models have important energy use implications. The acceptance of higher indoor temperatures in summertime conditions would lead to less prevalence of cooling systems. In situations/locations where air conditioning is unavoidable, a wider range of indoor thermal environment would mean less cooling requirements and hence less electricity consumption for the air conditioning systems [48]. There have been a number of studies investigating the energy use implications in the built environment. Broadly speaking, these can be grouped into two areas – case studies (HVAC, cooled or heated buildings) and implications for thermal comfort standards.

4.1. Case studies (HVAC, cooled or heated buildings)

Most of the case studies emphasised on either simply setting a higher summer set point temperature (SST) or implementing a wider/varying range of indoor design temperature for different time of the day and different outdoor conditions. Two major types of control techniques have been proposed for the heating and cooling systems. First type involves diverse thermostat strategies such as changes of the setback period, set point temperature and setback temperature [61]. Attempts have also been made to correlate cooling energy use with corresponding thermostat operation mode in an effort to have a better understanding of the trade-off between energy consumption and thermal comfort [62,63]. The second type deals with the dynamic control of the set point temperature based on adaptive comfort models [64,65]. Table 1 shows a summary of some of the case studies involving adaptive comfort models and/or raising the SST [66–73]. It can be seen that substantial energy savings could be achieved for both office and residential buildings, from 6% reduction in HVAC electricity consumption in Australian office buildings by raising 1 °C in the SST [72] to 33.6% reduction in total energy cost in hot desert area in Riyadh [71]. Apart from energy saving potential, raising the SST could also substantially reduce the peak electricity demand as demonstrated by the work on residential buildings in Las Vegas [73]. This could have significant energy policy implications as it helps alleviate and/or delay the need for new power plants to meet the expected increase in power demand due to economic and population growth.

4.2. Implications for thermal comfort standards

It has been shown from field studies that PMV model works pretty well in air-conditioned premises, but not in naturally ventilated buildings. PMV tends to over-predict the subjective warmth in the built environment, especially in warmer climates. Humphreys [74] argued that thermal comfort standard like the ISO 7730 based on PMV model was not entirely suitable for general applications. The use of ISO-PMV could lead to unnecessary cooling in warmer climates and unnecessary heating in cooler regions, and if applied in developing countries would have adverse economic and environmental penalty. Based on the analysis of 21000 sets of data from field studies in 160 buildings worldwide in different climate zones, the ASHRAE Standard 55 [49] was revised to include an adaptive model for naturally ventilated buildings. Fig. 3 shows the acceptable operative temperature ranges for naturally conditioned spaces. There have been a number of works on the implications to thermal comfort standards since early 2000s. Table 2 summaries some of the recent studies [52,55,75–83]. In general, these studies suggested that the

Table 1
Summary of energy savings in cooled buildings (in chronological order).

City (climate) (year)	Reference	Building	Measure	Energy savings
Hong Kong SAR (subtropical) (1992)	[66]	Office	Raise SST from 21.5 °C to 25.5 °C (SST = summer set point temperature).	Cooling energy reduced by 29%.
Montreal (humid continental) (1992)	[67]	Office	Raise SST from 24.6 °C to 25.2 °C (during 09:00–15:00) and up to 27 °C (during 15:00–18:00).	Chilled water consumption reduced by 34–40% and energy budget for HVAC by 11%.
Singapore (tropical) (1995)	[68]	Office	Raise SST from 23 °C to 26 °C.	Cooling energy reduced by 13%.
Islamabad (humid subtropical) and Karachi (arid) (1996)	[69]	Office	Change the 26 °C SST to a variable indoor design temperature ($T_c = 17 + 0.38T_o$; T_c = comfort temperature, T_o = mean monthly outdoor temperature).	Potential energy savings of 20–25%.
Hong Kong SAR (subtropical) (2003)	[70]	Office	Change SST from 24 °C (average) to adaptive comfort temperature ($T_c = 18.303 + 0.158T_o$).	Energy consumption by cooling coil reduced by 7%.
Riyadh (hot desert) (2008)	[71]	No specific building type	Change yearly-fixed Thermostat setting (21–24.1 °C) to optimised monthly fixed settings (20.1–26.2 °C).	Energy cost reduced by 26.8–33.6%.
Melbourne (oceanic), Sydney (temperate) and Brisbane (humid subtropical) (2011)	[72]	Office	Static (raise SST 1 °C higher) and dynamic (adjust SST in direct response to variations in ambient conditions).	HVAC electricity consumption reduced by 6% (static) and 6.3% (dynamic).
Las Vegas (subtropical desert) (2012)	[73]	Home	Raise SST from 23.9 °C to 26.1 °C (during 16:00–19:00).	Peak electrical energy demand reduced by 69%.

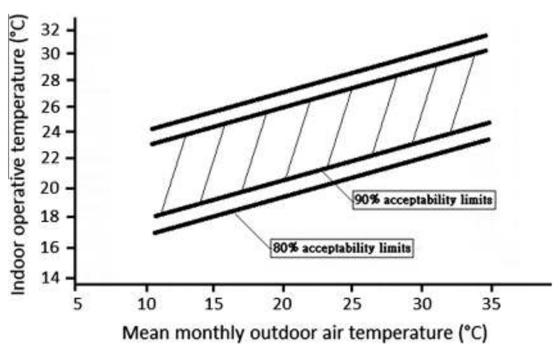

Fig. 3. Acceptable operative temperature ranges for naturally conditioned spaces (Ref. [49]).

adaptive model developed tended to be broader than the comfort temperature range stipulated in either the ASHRAE standard (e.g. in Chongqing, China [79]) or the local standard (e.g. in India [80]). In the interest of better building energy efficiency, the local standard should be revised and fine-tuned to better reflect the prevailing local situation. Consideration should also be given to other factors such as individual control/differences, climate context and carbon footprint, rather than simply the conventional thermal comfort and thermal neutrality [52,77,83].

5. Discussion and further research works

From the studies reviewed so far, it is not unreasonable to state that the static PMV model works well in air-conditioned buildings but not in naturally ventilated premises, where occupants could

Table 2
A summary of works on implications of adaptive models on thermal comfort standards (in chronological order).

Country/region (year)	Reference	Building	Key remarks/findings
Global (2002)	[52]	General	5 key issues: (i) Satisfaction and inter-individual differences, (ii) climate context, (iii) role of countries (especially personal/individual), (iv) beyond thermal neutrality, and (v) beyond thermal comfort.
Netherlands (2006)	[75]	Office	The 90% acceptability is allowed to exceed in 10% of the occupancy time (i.e. at least 90% satisfied for at least 90% of the time), and indoor temperature limits are given as a function of mean outdoor temperature.
Nigeria (2008)	[76]	Classrooms, studios and residential	The thermal comfort survey was underpinned by the adaptive thermal comfort paradigm, in which physiological and adaptive factors are equally important in the perception and interpretation of thermal comfort. The comfort range was 2–3 °C less than that suggested by the ASHRAE standard, probably due to higher relative humidity.
Global (2009)	[77]	General	New standards are needed that put the sustainable buildings at a premium, and the adaptive thermal comfort approach is conducive to defining conditions compatible with the low-carbon objective. Such standards will be building-based rather than environment-based, resulting in greater design freedom to achieve sustainability.
Europe (2010)	[78]	Office	The differences between European Standard EN 15251 and ASHRAE 55 were discussed. Suggested allowance in EN 15251 for air speed using fans can be applied to the equation for naturally ventilated buildings.
Global (2010)	[55]	General	New thermal comfort standards that allow occupants to choose and control their preferred temperature will be used. In future, buildings will be increasingly classified based on their energy use and carbon footprint.
China (2010)	[79]	University Classroom	The Chongqing adaptive comfort range is broader than that of the ASHRAE Standard 55-2004.
India (2010)	[80]	Residential	Temperature range based on adaptive model 26–32.5 °C, far higher than the Indian Standard 23–26 °C. This has far-reaching energy use implications for building and HVAC designs, and should be further developed to be included in the Indian Standard.
Portugal (2011)	[81]	Residential and "small services"	Based on an adaptive comfort protocol, the gain utilization factor was used to assess over-heating risks and cooling needs. The criterion of the percentage of hours above 28 °C is much more demanding than the adaptive comfort approach. Revised requirement (lower threshold values) would improve building thermal performance during summer.
Korea (2012)	[82]	Office	Occupants would feel comfortable even at 28 °C depending on the previous running mean outdoor temperature, 2 °C higher than the 26 °C stipulated in the Korean Standard.
Taiwan (2012)	[83]	School	Building envelope energy regulation had a significant impact on the level of thermal comfort in naturally ventilated buildings. Adaptive comfort model was developed and suggested to be integrated with other building design variables in the energy regulation.

interact with their surroundings to make themselves more comfortable through adaption. Adaptive models tend to have a wider range of comfort temperature, which could have significant energy savings in both air-conditioned and naturally ventilated buildings. Based on this, we believe there are three specific issues that need to be addressed and warrant further research and development work:

- Firstly, is the adoption of the PMV–PPD and Adaptive models mutually exclusive? Can one model complement the other?
- The second issue is about the socio-economic and cultural context. How will social norm (e.g. dress code) and environmental awareness/attitudes affect people's thermal acceptability of their immediate thermal environment?
- The third issue is about the responses to climate change in terms of mitigation and/or adaptation.

5.1. PMV–PPD versus adaptive models

The heat balance model is based on a fairly linear, deterministic logic, and has been tested with extensive and rigorous laboratory experiments yielding pretty consistent, reproducible results. But the direct cause-and-effect approach embodied in the two-equation PMV–PPD heat balance model is not so easily applied to the more complex environments within real buildings populated by real people as opposed to subjects. It has been suggested that the adaptive perspective complements rather than contradicts the static heat balance. The heat balance model is more correctly regarded as a partially adaptive model, since it acknowledges the effects of behavioural adjustments made by the occupants to the thermal parameters, clothing, and metabolic rate [43]. Based on linear regression technique, it has been demonstrated that PMV can be expressed as a function of temperature and relatively humidity for a wide range of clothing thermal insulation [84]. On the other hand, it is argued that the simple regression-based adaptive approach tends to produce varying results (in terms of the regression coefficients and predicted comfort temperature ranges) from different field studies. It is suggested that findings from various field studies should be employed to improve the performance and applicability of the PMV–PPD model. A recent survey of thermal comfort field studies in different climate zones worldwide has shown that individuals are likely to perceive the same environment differently and environments lacking adaptive means tend to receive poor comfort ratings [85]. More efforts are required to reconcile and unify the different adaptive models [86]. Besides, how can a combination of thermal and environmental parameters be considered unacceptable in a HVAC setting, and yet be regarded as acceptable in a naturally ventilated or mixed-mode situation? A new approach to thermal comfort modelling based on alliesthesia has been discussed [87]. The paradigm shift from the relatively simple, instrumentally assessable criteria towards a much more complex parameterization of spatial and temporal dimensions of alliesthesia is a significant challenge, but not insurmountable. More work is required especially on the multi-node physiological models to resolve the requisite alliesthesia [88].

5.2. Socio-economic and cultural issues

Energy is a key component in any overall sustainable development strategy, and it is important to monitor the effects of energy policy on thermal comfort in the social, economic and environmental dimensions [89–91]. It has been argued that a positive attitude towards energy and sustainability needs to be encouraged and maintained among the general public, and guiding households towards energy-conserving behaviours is considered a key energy policy option [92]. It has been found that people with ''pro-environmental'' attitude tend to be more ''forgiving'' in accepting their immediate indoor built environment in green buildings [93–95]. This could have far-reaching implications for energy savings in that the adaptive thermal comfort could be more widely adopted in both naturally ventilated and air-conditioned buildings if the general public are willing to tolerate a larger temperature range in buildings. Relaxing culturally-induced clothing norm and occupant expectations of closely controlled indoor environments could lead to significant progress in achieving a proper balance between thermal comfort, energy use and minimum environmental impact [96]. For instance in UK, habitual behaviours are important drivers of household energy consumption, and it has been suggested that social marketing programmes could be employed to promote the wide variation in thermostat settings as the foundation of a ''social norm'' campaign aimed at reducing temperatures and energy use in ''overheated'' homes [97,98]. Similarly, in Australia it has been shown that people's ability to respond to heat is shaped by the elements of prevailing cooling practices and it is possible to acclimatise ''air conditioning addicts'' to warmer indoor environment indoor environment without compromising their thermal acceptability [99,100]. However, not all climate variables have similar salience for human perception, and expectations, culture, religion, education and experience tend to mediate our perception of the thermal environment. Recent building surveys have indicated that the thermal environment within ''green buildings'' tends to be on the cold side in winter and on the hot side in summer [101,102]. More work in the socio-economic and cultural area is required, and post-occupancy evaluation of the built environment and the corresponding energy consumption would lead to a better understanding of the underlying issues affecting indoor thermal comfort and the corresponding energy use in the built environment [103].

5.3. Impact of climate change

It is generally agreed that our climate is changing and the temperature will rise gradually. This could have significant impact on the built environment [104] as well as the energy/power sector [105,106], especially that involves renewable power generation [107,108]. Recent studies on human bioclimates have found that heat stress shows an increasing trend and cold stress exhibits a decreasing trend in different climate zones during the 20th and 21st centuries [109–111]. A reduction in cold stress would lead to less space heating requirement in winter; whereas an increase in heat stress would increase the risk of summer overheating in naturally ventilated buildings. For air-conditioned buildings, this would result in more space cooling requirement during the hot summer months. Whether there is a net increase or decrease in the overall energy use for space conditioning depends on the prevailing climates, building types and mitigation/adaptation measures adopted. In severe cold climates (e.g. high latitude/altitude regions), reduction in energy use for heating would most likely outweigh the increase in cooling requirement. In mid-latitude areas where both heating and cooling requirements are significant, the magnitude of increase in cooling and reduction in heating could be comparable. The most obvious increase in energy use for space conditioning in the built environment would occur in low latitude regions with warmer climates [112]. More cooling requirement would mean more energy consumption, which in turn could exacerbate climate change. Mitigation measures are therefore needed to alleviate the envisaged impact. These measures can be explored in two specific aspects – increase in cooling requirement and the question of cooling versus heating:

- Increase in cooling requirement – Global warming would result in more cooling requirements, especially in cooling-dominated buildings in warmer climates. Greater attention should be paid to two particular mitigation measures. First, it has been found that adaptive comfort has great energy saving and mitigation potential, especially in warmer climates where building cooling load is the major design consideration [113]. More work is required to investigate how and to what extent would warmer weather conditions in future years affect the applicability of adaptive comfort models already established in different climate zones and regions around the world. Second, solar-powered cooling, though not yet widely adopted, has good energy-saving and mitigation potential especially in hot climates because building peak cooling load and maximum solar intensity tend to occur at about the same time [114–117]. More work is required particularly on the economic viability of active solar systems as compared with conventional electrical-driven vapour compression refrigeration plants.
- Heating versus cooling – Changes in the space heating and cooling requirements would vary from climates to climates and from one region to another. At the national or global energy policy level this could have serious implications. Firstly, in most large cities or developed economies, space heating is usually provided by oil- or gas-fired boiler plants, whereas air conditioning (space cooling) relies mainly on electricity. In terms of final/delivered energy use demand, there would certainly be a shift towards electrical power. This would put more pressure on the electrical power supply systems worldwide. Secondly, in terms of CO_2 emissions, this would increase even in severe cold climates where the reduction in heating outweighs the increase in cooling [112,113]. This is because of the much higher carbon footprint of electricity. For instance, in China the carbon footprint of electricity was 1.073 kg CO_2e per kWh based on about 80% coal in the fuel mix in 2007 as compared with an average of 0.184 kg CO_2e per kWh for natural gas [118]. This leads to the question about fuel mix and the role of renewable energy in the national and global energy policy. In terms of climate mitigation, it has been revealed that implementing energy savings, renewable energy and more energy conversion technologies can have positive socio-economic impacts, and 100% renewable energy systems will be technically feasible in the future [119]. It has also been shown that photovoltaic (PV) plays a key role in the development of zero energy buildings [120,121] and large scale integration of PVs in cities can produce 35% of the total electricity consumption in an entire district [122]. More work is required especially on a more integrated approach to solar energy utilization (i.e. PV, solar-powered cooling and solar thermal for heating purposes [123,124]). It has also been demonstrated that, from a global point of view, the application of high efficiency co- and tri-generation schemes for HVAC applications in buildings could result in great energy savings and CO_2 emissions reductions [125–127]. The operation mode of combined cooling, heating and power (CCHP) systems depends very much on the building thermal and electrical loads [128,129]. Much of these building loads tend to vary according to the outdoor ambient conditions. It is therefore important that analysis of CCHP systems and the corresponding operation strategies should take future climate scenarios into consideration to cater for the expected variations in cooling and heating requirements in different climate zones. Last but not least, the growing importance of distributed energy resources (renewable and otherwise) in the energy grids tends to result in a mismatch between supply and demand. More work on both the supply- and demand-side management in terms of urban energy planning is required [130,131]. Again, particular attention should be paid to the expected variations in cooling and heating demands due to global warming in the design and analysis of district heating [132,133] and/or cooling [134,135] systems for thermal comfort conditioning in the built environment.

6. Conclusions

We have reviewed a number of studies of thermal comfort in general and those pertinent to building energy efficiency in particular in different parts of the world. The emphasis is on the broader energy and environmental issues concerning social-economic, fuel mix and climate change. The conclusions are:

- The static PMV model works well in air-conditioned buildings but not in naturally ventilated premises, where occupants could interact with their surroundings to make themselves more comfortable through adaption. The regression-based adaptive approach tends to produce varying results (in terms of the regression coefficients and predicted comfort temperature ranges) from different field studies. More efforts are required to reconcile and unify the different adaptive models
- Adaptive comfort models tend to have a wider range of comfort temperature, which could have significant energy savings in both air-conditioned and naturally ventilated buildings. The acceptance of higher indoor temperatures in summertime conditions would lead to less prevalence of cooling systems. In situations/locations where air conditioning is unavoidable, a wider range of indoor thermal environment would mean less cooling requirements and hence less electricity consumption for the air conditioning systems. Apart from energy saving potential, raising the summer set point temperature could also substantially reduce the peak electricity demand. This could have significant energy and environmental policy implications as it helps alleviate and/or delay the need for new power plants to meet the expected increase in power demand due to economic.
- People with "pro-environmental" attitude tend to be more "forgiving" in accepting their immediate indoor built environment in green buildings. This could have far-reaching implications for energy savings in that the adaptive thermal comfort could be more widely adopted in both naturally ventilated and air-conditioned buildings if the general public are willing to tolerate a larger temperature range in buildings. Relaxing culturally-induced clothing norm and occupant expectations of closely controlled indoor environments could lead to significant progress in achieving a proper balance between thermal comfort, energy use and minimum environmental impact. However, not all climate variables have similar salience for human perception, and expectations, culture, religion, education and experience tend to mediate our perception of the thermal environment. More work in the socio-economic and cultural area is required, and post-occupancy evaluation of the built environment and the corresponding energy consumption would lead to a better understanding of the underlying issues affecting indoor thermal comfort and the corresponding energy use in the built environment and population growth.

- It is generally agreed that our climate is changing and the temperature will rise gradually. A reduction in cold stress would lead to less space heating requirement in winter; whereas an increase in heat stress would increase the risk of summer overheating in naturally ventilated buildings. For air-conditioned buildings, this would result in more space cooling requirement during the hot summer months. Changes in the space heating and cooling requirements would vary from climates to climates and from one region to another. At the national or global energy policy level this could have serious implications. Firstly, in most large cities or developed economies, space heating is usually provided by oil- or gas-fired boiler plants, whereas air conditioning (space cooling) relies mainly on electricity. In terms of final/delivered energy use demand, there would certainly be a shift towards electrical power. This would put more pressure on the electrical power supply systems worldwide. Secondly, CO_2 emissions would increase due to the much higher carbon footprint of electricity. In terms of climate mitigation, the application of high efficiency co- and tri-generation schemes for HVAC applications in buildings could result in great energy savings and CO_2 emissions reductions. The operation mode of combined cooling, heating and power (CCHP) systems depends very much on the building thermal and electrical loads, which tend to vary according to the outdoor ambient conditions. It is therefore important that analysis of CCHP systems, the corresponding operation strategies and the associated energy planning/distribution systems should take future climate scenarios into consideration to cater for the expected variations in cooling and heating requirements in different climate zones.

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