ENVIRONMENT DESIGN GUIDE

APPLYING THE ADAPTIVE MODEL OF COMFORT

Dr Mark B Luther and Assoc Prof Richard de Dear

SUMMARY OF

ACTIONS TOWARDS SUSTAINABLE OUTCOMES

Environmental Issues/Principal Impacts

- The adaptive model of comfort is one which responds to external climatic conditions.
- In many Australian locations the climate is such that external outside air can be directly applied 40-60 per cent of the occupied building time.
- Optimisation of building control for energy, comfort and occupant productivity.
- Reduction of mechanical conditioning energy between 30-50 per cent.
- Reduction of environmental impacts through CO_2 reduction.
- Less operational costs.

Cutting EDGe Strategies

Application of the adaptive model of comfort is a cutting EDG strategy in itself. The purpose of this note is to demonstrate what is theoretically possible and could be considered for environmentally responsive buildings. The adaptive model of comfort involves:

- consideration of the monthly climatic data and the optimum indoor temperature set-point
- consideration of hybrid ventilation (mechanical together with natural passive systems) allowing for the *adaptive model* to be most effective
- consideration of ventilation strategies as a concept generator for a 'whole of building' design approach
- programming the HVAC (mechanical conditioning) control with the *adaptive model* as a thermostat
- downsizing of mechanical conditioning equipment.

Synergies and References

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APPLYING THE ADAPTIVE MODEL OF COMFORT

Dr Mark B Luther and Assoc Prof Richard de Dear

This note is directed to one major aspect of the comfort of building occupants – namely, thermal comfort. Even though it may be difficult to isolate thermal sensations from the whole of comfort itself, humans have a strong physiological connection with their thermal environment. Our thermal perceptions and sensations often vary greatly, especially between our indoor and outdoor environments. We may be totally comfortable lounging under a shade cloth on a 35°C day with a stiff breeze enveloping our body, but would never tolerate similar conditions indoors. Such divergent perceptions of the same thermal stimulus across differing contexts raise countless questions about just what the determinants of thermal comfort actually are, and how they may be managed against the demands for an environmentally responsive architecture.

1.0 WHAT IS COMFORT?

Very seldom when we experience comfort do we acknowledge it, but we regularly hear (or make) frequent complaints of *dis*comfort. It is often whilst experiencing discomfort that we articulate hypotheses about causal factors. We may claim that our lack of comfort is due to a cold draft, inappropriate clothing, radiant loads from an unshaded window, or insufficient air movement (stuffiness) as a result of a sealed window. To a large extent, our physiological state, along with perceptions and expectations of our environment, determine whether we will be comfortable or not.

For centuries humankind has striven to produce comfortable environments in architecture. Other industries, such as the automotive industry, are geared to providing comfort to their clientele through ergonomics, noise reduction, sound systems, direct air-conditioning, smooth acceleration, solid suspension and even interior smell. Perhaps such advancements in other built environments are the reason why today's architecture is increasingly judged, not necessarily for its aesthetic value, but more for its environmental performance and provision of comfort.

On a more abstract theoretical note, thermal comfort is obtained when our body temperature is kept in a 'state of balance' with our ambient environmental conditions, without taxing our autonomic thermoregulatory mechanisms too heavily (sweating, shivering, vasomotion etc). Although the control of body temperature is complex, there are two important sensors that are known to regulate it; our skin temperature and various deep core sensors throughout the central nervous system. The hypothalamus in the brain is the body's 'thermostat' which integrates incoming deep-body and peripheral thermoreceptor information, comparing them to the body's set-point, and triggering cooling responses above a 37°C body core temperature, or body warming responses when the core temperature drops below set-point. We can conclude that homeostasis of deep core body temperature is a necessary but insufficient physiological precondition for thermal comfort. Thermal comfort, or a sense of satisfaction with one's thermal environment, is also dependent on that homeostasis being maintained within reasonable tolerances of thermoregulatory effort. We can maintain constant body temperatures in a diverse range of environmental extremes, but doing so is anything but comfortable.

Defining just what those acceptable ranges or tolerances actually are for different sub-populations, and what factors might cause those tolerances to expand or contract, is precisely the core problem for thermal comfort researchers. In this paper we describe an empirical approach to this problem known as the 'adaptive model'. We then illustrate practical applications of this model in the field of building energy simulation, with particular focus on the considerable energy conservation potential that can be realised if we grant free reign to human adaptability under conditions of seasonally and geographically varying indoor climatic regimes.

2.0 PARAMETERS OF THERMAL COMFORT

We often mistakenly report our thermal environment through a single parameter; air temperature, yet, we know that there is much more involved than temperature alone. In 1962, Macpherson identified six factors that affect thermal sensation.

The physical and measurable parameters influencing thermal comfort are:

- air temperature (dry-bulb temperature)
- mean radiant temperature (MRT)[1]
- air velocity (wind speed, air movement)
- air humidity
- level of clothing (CLO)[2]
- metabolic rate (activity level).

[1] The mean radiant temperature (MRT) is an index measured at the location of the occupant in the room, and basically a function of room surface temperatures. It is defined as the temperature that would be received by a perfect radiation absorber and emitter (at occupant location) in absence of convective heat transfer.

[2] The level of clothing, the CLO factor, is derived from the actual pieces of clothing people are wearing as well as the furniture they may be sitting on.

These factors all affect our sense of thermal comfort, directly and interactively, and are responsible for bringing a building occupant into (or out of) the 'thermal comfort zone'.

3.0 OPTIMUM COMFORT RANGES

The American Society of Heating and Refrigeration and Air-conditioning Engineers (ASHRAE, 1992) define comfort zones via the psychrometric chart (Figure 1). This chart is confined to the thermal conditions of the air and its moisture content, and the radiative properties of the room. MRT is incorporated indirectly into the chart via the x-axis which is labelled operative temperature (an arithmetic average of air and mean radiant temperatures). Air velocity and metabolic activity (MET) value are not explicitly considered in the shaded zones of the chart. It is, however, expected that people will dress differently in winter (heavier) and summer (lighter), and therefore a seasonally differentiated 'zone shift' is observed on the standard chart.

The optimum settings for a HVAC system are given in the ASHRAE-Standard 55 and the European standard ISO 7730 for sedentary office workers (ASHRAE, 1992; ISO, 1993). In summer these standards recommend an *operative temperature* range of 23–26°C with seasonally adjusted upper humidity limits (wet bulb temperatures) and CLO values of 1.0 and 0.5 in winter and summer respectively (Figure 1).

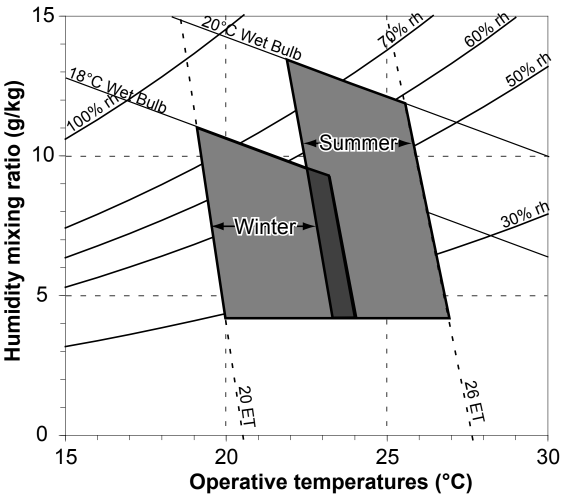

Figure 1. The 'comfort zone' according to ASHRAE Standard 55-92a Addendum: thermal environmental conditions for human occupancy (ASHRAE, 1992)

3.1 Operative temperature

Operative temperature is a weighted mean of convective (air) and MRT, with the weighting dependent upon the relative magnitude of convective and radiative heat transfer coefficients (*i.e.* a function of air velocity). For most intents and purposes it is satisfactory to arithmetically average the mean radiant and air temperatures to estimate operative temperature. The vertical boundaries of the summer and winter comfort zones are defined in terms of a thermal comfort index known as Effective Temperature (*ET*). In cool temperatures the ET isotherms on a psychrometric chart are perfectly vertical, reflecting the negligible effect of humidity on thermal comfort. However, under warmer temperatures the ET lines begin to slant away from the vertical, indicating that a fixed temperature will *feel* warmer if the humidity is high compared to low humidity conditions.

What is important to recognise here, is that comfort is not limited to a totally fixed set of thermal criteria. There are ranges within this six-dimensional space defined by the primary parameters of comfort, allowing for a vast number of combinations of thermal environmental conditions that can satisfy the requirements of comfort.

4.0 ENERGY IMPLICATIONS OF COMFORT

Given the fact that there is a *comfort zone*, permitting variations in any or all of its defining parameters, as demonstrated in the simplified three-dimensional ASHRAE chart (operative temperature, humidity and clothing in Figure 1), it is important to evaluate the implications of such variations with respect to the energy costs of delivering conditioned air to an internal space within a building. The content of energy in the air, in other words, moving from one state of thermal conditions to another, is called *enthalpy*. This brings us to a fundamental principle of environmental conservation running throughout this note on comfort:

> *If we can relax the energy input to the air being supplied within a building, yet still remaining within the boundaries of an acceptable range of comfort, energy conservation will result.*

This simple statement can be viewed as the foundation of a holistic energy conscious design approach. A permissible relaxation of thermostat setting can deliver:

- peak-load reduction in the mechanical system
- less capital cost of the equipment due to downsizing
- more useable floor area due to smaller equipment
- less operative costs throughout the year due to relaxed conditions
- life cycle cost savings.

It has been discovered through simulation, that a relaxed thermostat setting can provide substantial (30-40 per cent) energy savings to a building (Fuller and Luther, 2002). Morgan and de Dear estimated that a 1°C change in thermostat setting for cooling can contribute up to 10 per cent energy reduction (2003).

5.0 A BACKGROUND TO THERMAL COMFORT ASSESSMENT

As previously shown through the psychrometric chart, we expect to remain in comfort within a certain range of conditions, and the role of an HVAC system is to keep the indoor climate within these limits. Air conditioning engineers may recommend a set point of 24°C in summer and 21°C in winter; yet, we know that there is more to comfort than these limiting temperature set-points. To illustrate just how the full complexity of thermal comfort has unfolded in research, we will now briefly review the recent history of comfort models.

6.0 A STATIC MODEL OF COMFORT

Environments that are solely conditioned by a mechanical system, generally subscribe to a *static model* of comfort. As represented earlier on the psychrometric chart there are seasonal periods where a single-point thermostat setting prevails. In fact, often one setting of temperature is selected for a year-round constant indoor air temperature. Such control of indoor environments, often in the range of 22.5°C (+/- 1.5°C) subscribes to the ASHRAE-55 (1992) and the European ISO 7730 standard (ISO, 1994). These models are attributed to Fanger and Pharo Gagge's work, and although they are premised on the six primary comfort parameters outlined earlier in this paper – air temperature, MRT, air velocity, air humidity, CLO and metabolic rate (Fanger, 1970), they are often reduced to single operative temperature prescriptions.

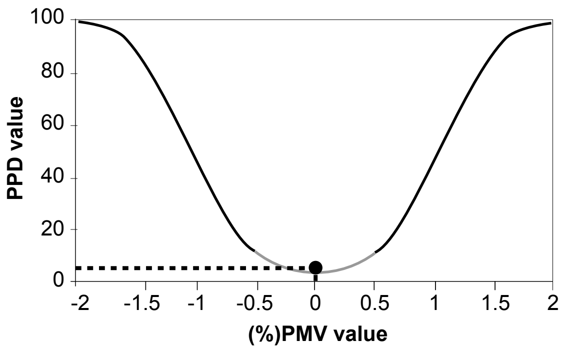

Figure 2. Fanger's per cent predicted dissatisfied and the predicted mean vote

The static (Fanger) model is most widely recognised and applied because of its particularly useful format of output, namely a Predicted Percentage Dissatisfied (PPD) and a Predicted Mean Vote (PMV) (Figure 2). PMV refers to the expected or predicted mean thermal sensation of a large sample of building occupants on a simple psychophysical linear scale ranging from *cold* (-3) through neutral (0) to hot (+3). PPD, based on an estimate of inter-individual variance within the population, refers to the number of people in that same large sample of building occupants who are expected to find themselves voting outside the acceptable central three categories on that seven point scale (*slightly cool, neutral and slightly warm*). Even when a theoretically optimal thermal environment is provided (with PMV=0) we still expect a minimum of 5 per cent PPD to occur, simply because of human variance – or paraphrased in street language, '*you can't please all of the people all of the time*'. Maintaining indoor climates within the prescriptions of these static standards can be very energy intensive since there is little tolerance with respect to temperature.

7.0 AN ADAPTIVE MODEL OF COMFORT

Until relatively recently, interior thermal comfort engineering has relied on these static models and their associated standards. Now the temperature band permitted under the ISO and ASHRAE standards are being challenged as being too limiting, especially for free-running buildings (Humphreys, 1981; de Dear & Brager, 2001). Recent *adaptive* thermal comfort models are beginning to propose a relationship of comfort that takes recognition of the external climatic environment.

Intuitively one suspects that local climatic context and occupant expectations are also important in thermal perception, every bit as much as the six primary parameters of comfort discussed above. But contextual and psychological dimensions have been largely overlooked in laboratory studies of comfort and the static models and standards that have been built upon them[3]. A major international collaboration on a world-wide comfort database, ASHRAE RP-884, suggests a modification of the ASHRAE 55 standard for specific applications in free-running buildings (de Dear 1998, de Dear & Brager 2001). That project suggested Equation 1 as a reliable predictor of the neutral temperature (T_n) to be used in free-running (naturally ventilated) buildings:

$$T_n = 17.8 + 0.31(Ta_{out})\ °C \qquad \textit{Equation (1)}$$

Ta_{out} is the monthly mean temperature °C

T_n is the neutral comfort temperature °C.

This yields a comfort standard directly tied to climate.

7.1 Principles behind the adaptive model

The adaptive model presented above in Equation (1) arose from an ASHRAE-sponsored research project in the late 1990's called RP-884 by de Dear and Brager (de Dear & Brager 1998, 2001). This model, depicted in Figure 3, came from a fundamentally different perspective than the PMV model (static approach) described above. The adaptive model was very much a field-based, empirical approach to thermal comfort, and was based on a database of over 21,000 questionnaires

[3] It is perhaps worth noting that to an extent Fanger's model is somewhat adaptive as it takes into account clothing worn and metabolic rate (although rarely is applied that way).

administered to the occupants of 160 buildings (mainly offices) across four different continents. In essence, the subjects in that database were asked to indicate their immediate thermal comfort and sensation status on a standardized questionnaire while their immediate environment at the time had a 'thermal snap-shot' taken by standardised indoor climate analysers. By pooling the subjective (questionnaire) and the objective (microclimatic) data sets within each building, it was possible to statistically identify the optimum comfort condition for that building's occupants, in that particular building, in that particular climatic/ geographic setting (de Dear & Brager 1998, 2001).

Having replicated this type of statistical analysis for all 160 buildings in the database, it was possible to discern some broad-brush relationships between the conditions that people were finding comfortable *inside* their buildings, and the general *outdoor* weather and climatic context of the building at the time of the building's survey. The regression (line of best fit) equation in Equation (1) succinctly summarises that relationship. It tells us that, in buildings that are free running, the optimum indoor comfort temperature is a linear function of the building's climate, as represented by the mean monthly outdoor temperature. The formal definition of the latter is that adopted in weather bureaus the world over; namely the average of daily maxima and daily minima across a particular calendar month. These statistics, typically based on long-term climatic records of 30 years or more, are readily available in most locations in the form of maps or tabulated climatic normals.

Having described the origins of the adaptive model, it is clearly a fundamental departure from the approach adopted by Fanger in his PMV model. But there is one similarity, as seen in Figure 3, namely the provision of two ranges of acceptable comfort; an 80 per cent and a 90 per cent satisfied temperature range.

- upper 80 per cent acceptable limit = 0.31 (outdoor air temperature) + 21.3
- upper 90 per cent acceptable limit = 0.31 (outdoor air temperature) + 20.3
- lower 80 per cent acceptable limit = 0.31 (outdoor air temperature) + 14.3
- lower 90 per cent acceptable limit = 0.31 (outdoor air temperature) + 15.3

To fully explain the way in which the adaptive model can be applied, it might be instructive to look at a worked example. A naturally ventilated building is proposed for a location with a fairly warm summer climate. The weather bureau advises that the warmest month for the hypothetical site is typically January, and that the long-term average (30 year) of daily maximum temperatures in January is 28.5°C, while the average daily minimum January temperature is 18°C. From these two items of data we can conclude that the long-term mean January temperature is 23.3°C, and this becomes the number we plug into the adaptive model depicted in Figure 3.

The optimum temperature inside a building in this location during January is predicted by the adaptive model to be 25°C ([0.31 x 23.3] + 17.8). The upper 80 per cent acceptable temperature limit for the

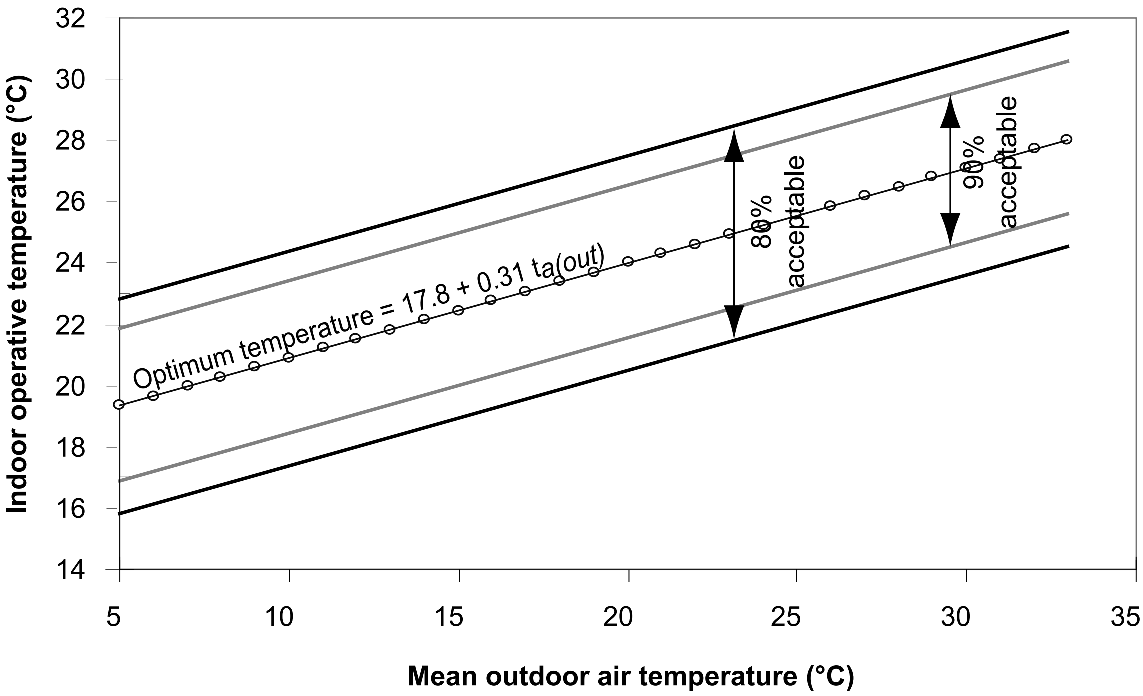

Figure 3. The adaptive model comfort chart (de Dear)

month of January = (0.31 x 23.3) + 21.3 which comes to 28.5°C, while the lower 80 per cent acceptable temperature limit for January = (0.31 x 23.3) + 14.3 = 21.5°C. So, if the building in question is going to be able to keep its indoor temperatures during January between 21.5°C and 28.5°C, then it is likely that 80 per cent of the occupants will regard the conditions as acceptable. If a higher satisfaction rating is desired (90 per cent as opposed to 80 per cent), then the band of acceptable January temperature needs to be tightened slightly (22.5–27.5°C).

These same results could have been generated simply by reference to the adaptive comfort chart in Figure 3. By plugging the mean January air temperature, 23.3°C, into the x-axis of the graph, projecting vertically up to the optimum temperature line, we can read a temperature of 25°C off the y-axis. Projecting from x=23.3 vertically up we can also read off the y-axis the 80 per cent and 90 per cent acceptability temperature limits as well.

7.2 What parameters define the adaptive model of comfort?

First the notion of ***optimal indoor comfort temperature*** needs to be defined. From the preceding discussion of how the adaptive model was generated, the optimal comfort temperature represents the operative temperature that is most likely to deliver thermal comfort or at least a satisfactory thermal condition for the occupants of a building. Like Fanger, we recognise that it is unlikely to satisfy all of the people all of the time, but the optimum temperature resulting from application of Equation (1) stands the best chance of maximising satisfaction. Departures away from the optimum are still acceptable, but the levels of satisfaction will taper off as things get warmer or cooler, until 90 per cent or 80 per cent satisfaction is achieved at the boundaries of the adaptive comfort chart for any particular outdoor mean temperature input on the x-axis of Figure 3.

As noted earlier in this paper, ***operative indoor temperature*** is simply a weighted average of mean radiant temperature and air temperature. The weighting in front of each temperature is proportional to the radiative and convective heat transfer coefficients respectively. However, for most practical intents and purposes, we can regard these weighting coefficients as 0.5 each, so operative temperature becomes a simple arithmetic average of air and radiant temperatures.

While the measurement of air temperature inside a building poses no major challenges, MRT is a little more complicated. A variety of 'off-the-shelf' instrumentation is commercially available, but it is invariably expensive. A perfectly workable alternative is based on the fabrication of a globe temperature from readily available components. Insertion of a thermometer, preferably a thermistor or RTD device with fairly fast time-constant, into the centre of a ping-pong ball (40mm diameter) that has been spray painted matt black (or grey) constitutes a perfectly valid instrument to measure globe temperature. The device usually takes about 10 to 15 minutes to reach equilibrium in any particular environment, but its reading, along with concurrent air temperature and air speed (preferably with hot-wire or hot-sphere anemometer, or something comparable) is all that is required to calculate MRT using the following equation from ASHRAE's *Handbook of Fundamentals* (ASHRAE 1993):

$$MRT = \left[(t_g + 273)^4 + \frac{1.10 \times 10^8 \, V^{0.6}}{\varepsilon \, D^{0.4}} (t_g - t_a) \right]^{1/4} - 273$$

where t_g is the globe thermometer temperature. V refers to the room air velocity (m/s) at the time of the globe thermometer reading, t_a refers to air temperature, D refers to the diameter of the globe thermometer (0.04m in the case of a ping-pong ball), and ε is the emissivity of the globe thermometer (assume 0.95 for a black or grey ping-pong globe).

The ***outdoor mean temperature*** input to Equation 1 is probably the least well understood parameter in adaptive models. In order to understand it more fully it is appropriate to first explain the theoretical purpose it serves. In adaptive comfort theory, the outdoor temperature used as the independent variable in predictive regression equations is supposed to represent the thermal history of the building occupants for whom the comfort prediction is being performed. The easiest solution is simply to consult the website of the relevant weather bureau and find out the current month's long-term average temperature. But there has been much discussion in the comfort research community about how accurately a 30-year climatic normal can represent the precise thermal milieu to which people have become adapted. Of course any particular month can be climatically anomalous (the hottest January on record etc), and so a preferable solution to the data input requirement posed by Equation (1) is to use actual concurrent meteorological records over the preceding month, if they are available from an automatic weather station or similar (which form an integral part of many building energy management systems these days). But even if on-site, contemporaneous meteorological observations are available, another question is whether the calendar month is the most accurate representation of the immediate thermal history of the building occupants?

A more realistic solution again would of course be to calculate the outdoor temperature as a *running* mean, and the optimum timescale for such calculations is probably shorter than a month. The limited extant empirical evidence on this issue so far (Morgan and de Dear, 2003) suggests that a running mean based on the preceding seven days optimally captures the adaptive climatic stimulus for the purposes of Equation (1).

8.0 ENVIRONMENTAL DESIGN AND THE ADAPTIVE MODEL

This section will attempt to illustrate how the adaptive comfort model can be applied into simulation as well as real case building measurements. It should be realised here that there are no satisfaction guaranteed solutions and that this work has come a long way in becoming marginally accepted by the industry. In the case studies provided, the major purpose is to demonstrate what is theoretically possible and could be considered for environmentally responsive buildings. Such buildings are generally those providing natural ventilation, relying on hybrid conditioning systems and allow users to take part in some control of their thermal environment. The final goal is the realisation that the *adaptive model* can provide genuine energy savings while maintaining acceptable occupant comfort.

8.1 Applying the adaptive model with building simulation

In a recent thermal study on high-rise apartment buildings in Hong Kong several set-point (conditioning dry-bulb) temperatures for a summer period were simulated using the TRNSYS computer program. This simulation program produces indoor operative temperatures as a result of room surface and dry-bulb (air) temperatures. There are two methods of operation considered in this study:

- First, where a set-point (control temperature) is fixed (static), yielding the energy required to maintain this set-point; and
- second, for each climatic data hour an interior operative temperature results, based on a limited *energy* supply into the room.

The following examples of simulation are expected to clarify these two conditions.

Figure 4 illustrates several static conditioning set-points with respect to the adaptive model comfort chart. Each of these fully conditioned set-points is represented by a horizontal line superimposed over the adaptive model chart. For each of the set-point temperatures (24°C, 26°C, 28°C) two air changes per hour (ACH) of ventilation air (external air) at a 50 per cent relative humidity level was supplied. Generally, a fully conditioned space will supply a total of 8-12 ACH, about 4/5 of this air is recirculated.

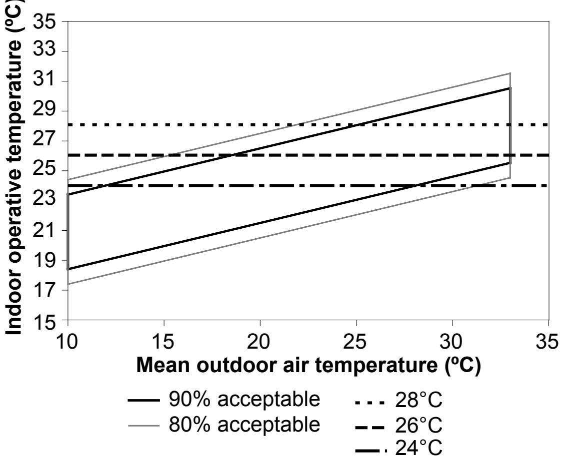

Figure 4. Static set-point conditioning with the adaptive model of comfort

It is important to note however, that if a static set-point were selected, a 26°C setting would provide the best comfort, in cooling periods, according to the adaptive model comfort bands.

Figure 5 illustrates the actual indoor operative air temperatures without any conditioning (free-running) into this space. The ventilation air consists of unconditioned infiltration air only and no fixed set of air exchange rate is provided. Note that there are numerous occupied hours external to the comfort bands. If the usefulness of the adaptive comfort model is to be explored in terms of energy efficiency it would be reasonable to consider an approach somewhere between the static (fixed) set-point and the free-running condition. The next approach is related to this idea, in that a limited (fixed) energy quantity will be supplied to the same space. Because the energy supply is limited, a varying set of indoor operative temperatures according to heat gains from occupants, solar exposure, appliances, and outdoor air infiltration results.

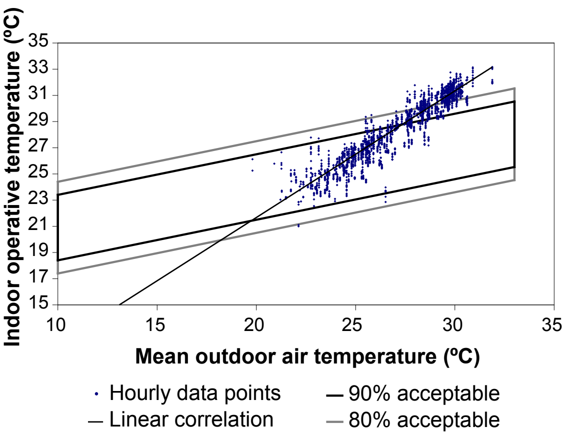

Figure 5. Free-running adaptive model comfort results

Figure 6 demonstrates the results of limiting the conditioning to the space with only two air changes per hour (ACH) of 100 per cent ventilation air treated to 16°C at 50 per cent RH. Note that the fixed set-points (Figure 4) also considered two ACH of ventilation air with their fully-conditioned mode of operation. Figure 6 supplies the ventilation air requirement only (two ACH), but at a lower temperature. Our results indicate that there are several marginally acceptable data points in the high temperature end of the chart (Figure 6). However, the results present an interesting point for consideration. The previously simulated static set-point cases also allowed for two ACH of fresh outside air. In Figure 6, only conditioned ventilation air at a limited energy capacity of two ACH is introduced into the space. The difference in energy savings from a fixed fully conditioned 24°C at 50 per cent RH set-point to that of Figure 6 is 58 per cent.

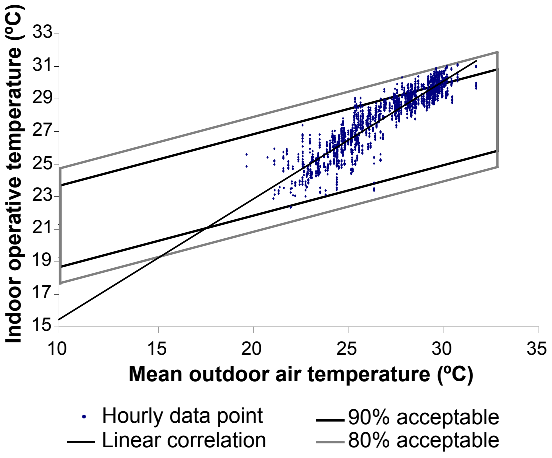

Figure 6. Limited conditioning adaptive model comfort results

Changing from a 24°C to a 26°C set-point represents energy savings of 25 per cent for the summer period of Hong Kong. Furthermore, changing from a 24°C to a 28°C set-point will yield a 44 per cent energy savings.

9.0 BUILDING CONTROL AND THE ADAPTIVE MODEL

The previous result is a very strong case for considering the benefits of regulated conditioning with respect to adopting the adaptive model of thermal comfort. Without a doubt, refinement in the control strategy and regulation of energy supply needs to be investigated further in relation to acceptable comfort ranges. However, it would appear, from the evidence so far, that it is quite feasible to expect up to a 50 per cent energy reduction from that of fully conditioned static control.

In a report on simulated energy savings for a university campus building, relaxed temperature set-points were demonstrated as the most effective strategy (Fuller and Luther, 2002). These findings place building control at a very high level of importance. If we are to depart from static set-point temperatures in favour of a dynamic energy supply and variable air humidity and temperature, then the requirement for such control is inevitable.

10.0 AUSTRALIAN EXAMPLES OF APPLICATION

Several examples of applying the adaptive model and its assessment to actual measurements of Australian buildings have occurred at the University of Newcastle (Dixon, 2002). In one particular study Dixon investigates a typical (air-conditioned) building, a passive (naturally ventilated) and a mixed-mode (hybrid) ventilated building. The findings from user surveys indicated that the fully air conditioned building (according to user surveys) performed only marginally better than the hybrid building. Yet, on average the hybrid (mixed mode) building was given a relatively high rating on overall temperature satisfaction whilst maintaining significant energy savings.

Figure 7 and 8 chart the actual measured performance of the naturally ventilated and the mixed mode building respectively on the adaptive comfort chart. The regression equation demonstrates the positive correlation between outdoor air temperature and the variance in indoor temperature for both buildings.

For each degree increase in outdoor temperature there is a 0.46°C indoor temperature rise for the naturally ventilated building. Similarly, for the hybrid ventilated building there is a 0.11°C temperature rise, indicating greater temperature stability due to thermostatically adaptive mechanical conditioning and controls and a greater adherence to the adaptive models prescribed 'optimum temperature' range (Dixon, 2002).

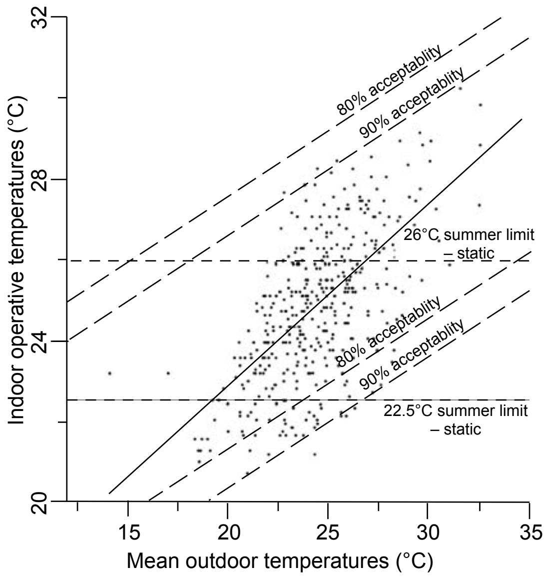

Figure 7. Naturally ventilated building – summer plot against adaptive comfort range and steady state indoor limits

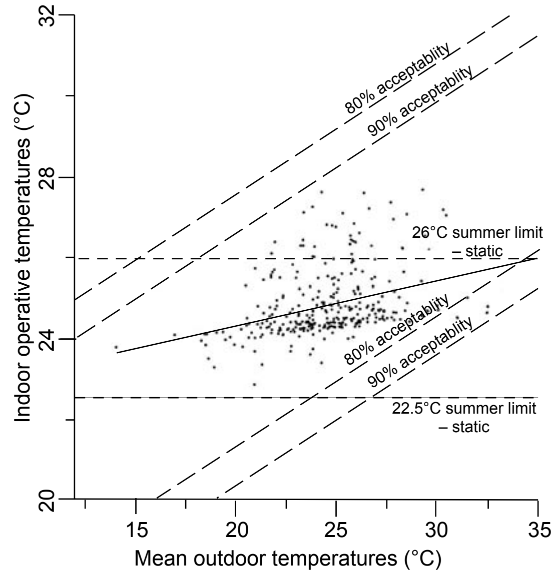

Figure 8. Mixed mode building – Summer plot against adaptive comfort range and steady state indoor limits

CONCLUSION

This paper has proposed a method of variable set-point temperature control based on the *adaptive model* of comfort. It has provided examples of its use in regards to user comfort and energy savings. The intention is to encourage the reader to accept and understand the adaptive model through various examples of its use.

In order to establish an understanding of the adaptive model we propose the following steps:

First, the calculation procedures of the various parameters as used in the adaptive model were presented and the adaptive comfort chart explained. Second, through the application of an hourly thermal simulation program (TRNSYS) it was demonstrated how a variable set-point temperature can be justified over static set-point temperature through tremendous energy savings while maintaining occupant comfort. Third, actual on-site measurements and user satisfaction surveys indicate support for the adaptive model as applied to an Australian hybrid building. In regards to this third point, Australians are demanding solutions of an environmentally responsive architecture. This architecture is one which will need to respond to dynamic set-point control as addressed by the adaptive model of comfort.

No doubt, we are in the early stages of understanding and applying the adaptive model of comfort for our buildings. Nevertheless, with respect to the potential energy savings and reduced delivered energy supply (of over 50 per cent) to our buildings, it seriously merits further study and investigation. We require more research evidence through actual building performance measurement together with occupant surveys. There is a huge potential to revisit and reprogram our existing building stock with an *adaptive comfort* set-point control. The authors of this paper would gratefully applaud those willing to undertake and support this task.

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Assoc Prof Richard de Dear worked on the adaptive comfort model for his PhD at the University of Queensland in the early 1980s. He had a two-year post-doctoral stint in Copenhagen (Technical University of Denmark) under Professor Fanger between 1985 and 1987. His first teaching post was at the National University of Singapore (1987–1991), and he has been on the teaching faculty in the Division of Environmental and Life Sciences at Sydney's Macquarie University since 1991. Richard has served the 'comfort committee' of ASHRAE throughout his career, including performance of several contract research projects, as well as serving on various committees. The adaptive model reported in the current BDP technical note is currently being incorporated into the latest revision of ASHRAE's influential thermal comfort standard (ASHRAE Standard 55).