Maximum temperatures in buildings to avoid heat discomfort

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ABSTRACT

This paper looks at the ways in which summer overheating can be avoided in European - and in particular UK - office buildings. Starting with the results from field surveys expressed in adaptive comfort theory the paper defines comfortable conditions and the range of acceptable temperature around these in both free running buildings and those which are heated or cooled. Data from the EU project SCATs and other surveys is used to explore how an upper envelope of acceptable temperatures might be defined.

1. INTRODUCTION

The use of results from field studies of thermal comfort is widely accepted as a means to predict what temperatures will be found comfortable in buildings. This 'adaptive approach' is now a part of ASSI/ASHRAE standard 55/2005 for predicting comfort temperatures in naturally ventilated buildings and will almost certainly soon be accepted into European and International standards.

The prediction of maximum acceptable temperatures in buildings is more difficult involving a prediction of the distribution of comfort levels about the 'optimum' represented by the 'comfort temperature', and may also require a judgement of the frequency of discomfort which will be acceptable to building occupants.

With the rise of highly-glazed, light-weight buildings in the mid-20th century the problem of summer overheating of buildings became increasingly important even in countries like the UK which are not noted for their high summertime temperatures. The UK Health and Safety Executive (HSE) reports that the most frequent enquiry they get from industry is for guidance on avoiding summer overheating in workplaces.

The development by the Building Research Establishment of the 'admittance' method for calculating indoor temperatures was largely driven by this problem (Loudon, 1968). The approach was to provide a prediction of the indoor temperatures resulting from a given building configuration, in sunny weather, both as an expected mean temperature and a temperature 'swing' about it. More sophisticated and accurate calculation methods have followed, but the problem remains: what is an acceptable indoor temperature? Even with a method for calculating temperatures there will be a need to interpret this in terms of how much discomfort would be caused and how this will translate into dissatisfaction with the building.

The HSE guidance publication, Thermal Comfort in the Workplace, (HSE, 1999) seeks to define thermal comfort, and states:

> An acceptable zone of thermal comfort for most people in the UK lies roughly between 13°C (56°F) and 30°C (86°F), with acceptable temperatures for more strenuous work activities concentrated towards the bottom end of the range, and more sedentary activities towards the higher end.

The Chartered Institution of Building Services Engineers (CIBSE) in their Guide A (CIBSE, 1986) is rather more cautious and recommends that:

> (in Naturally ventilated buildings the temperature will be acceptable if) for sedentary areas such as offices an inside dry re-

sultant temperature of 25°C is not exceeded for more than 5% of the annual occupied period (typically 125 hours).

Engineers and consultants have found the CIBSE limitation increasingly difficult to fulfil without air conditioning. At the same time, Based on surveys in real offices adaptive theory (Humphreys and Nicol, 1998) tells us that the temperatures that people find comfortable will vary with the outdoor conditions. We can assume that the maximum permissible temperature must do the same.

We can assume that the further the indoor temperature is from the 'comfort temperature' the more likely it is that people will be uncomfortable. But just how much temperature can differ from the comfort temperature before discomfort becomes a problem depends on the building context.

Baker and Standeven (1995) gave an explanation in terms of the 'adaptive opportunity' available. This is a measure of the opportunity the building offers for the occupants to make themselves comfortable. Figure 1 illustrates the concept, showing how an increasingly wide range of temperatures is permissible as the adaptive opportunity is increased.

Fanger (1970) gives an estimate of potential discomfort in terms of his Predicted Mean Vote (PMV) index which called Predicted Percentage Dissatisfied (PPD). PPD was calibrated with subjects in laboratory conditions and therefore excludes the effect of adaptive opportunity. A standard based on Fanger's work may be more prescriptive than one based on a real setting (see Fig. 1). Humphreys and Nicol (2002) have

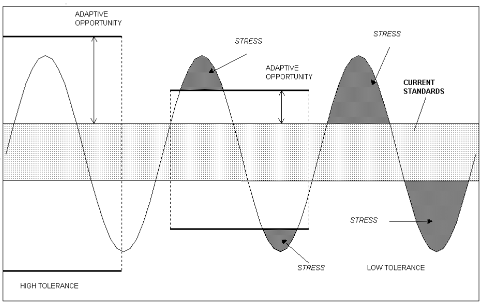

Figure 1: Effect of adaptive opportunity: the greater the opportunity to control the environment - or the occupants' requirements - the less likelihood of thermal stress (signified by the darker shaded areas) (Adapted from Baker and Standeven, 1995).

shown this to be so.

This paper uses the information gathered from field studies in European offices in the SCATS project (McCartney and Nicol, 2002) to explore the range of temperature around the 'adaptive comfort temperature' in order to suggest what range of temperatures around a 'comfort zone' might be considered acceptable by building occupants.

2. THE SCATS PROJECT

The project 'Smart Controls and Thermal Comfort (SCATs)' was funded by the European Union in 1997-2000. It involved the measurement of conditions in 26 offices in 5 European Countries (France, Greece, Portugal, Sweden and the UK). Subjects were visited on a monthly basis over a period of a year and asked about their thermal comfort on the ASHRAE comfort scale (scale a in Table 1) and a five point preference scale (scale b).

At the same time physical measurements were taken using precision instruments housed on a 'trolley' which was placed near the desk of the subject. The thermal environment was represented by the air temperature, globe temperature, relative humidity, and air movement. As well as the comfort votes a note was made of the activity of the subject over the past hour and of the insulation of the clothing they were wearing. In addition measurements were made of the CO_2 concentration, the noise level and the illuminance on subjects' desks. The outdoor temperature and relative humidity were obtained from nearby meteorological stations. In all 4655 full sets of comfort data were collected.

The data collected were used to calculate a value for the comfort temperature using a stan-

Table 1: Wording of a) the ASHRAE thermal comfort scale and b) the five-point preference scale used in the SCATs surveys (these were translated in to each language).

a. How do you feel?	b. How would you prefer to feel?
7 Hot	
6 Warm	5 Much cooler
5 Slightly warm	4 A bit cooler
4 Neutral	3 No change
3 Slightly cool	2 A bit warmer
2 Cool	1 Much warmer
1 Cold	

dardised relationship between temperature and comfort of two degrees per scale point (Humphreys and Nicol, 2000). This was related to the running mean of the outdoor temperature (Fig. 2). The methodology is described by Nicol and McCartney (2001) and McCartney and Nicol (2002).

The relationship between comfort temperature and running mean outdoor temperature was investigated using regression analysis. Figure 2 shows the predicted comfort temperatures related to the outdoor running mean temperature, for all buildings. It will be noted that the rate of change of comfort temperature is much greater as the outdoor temperature rises above 10^{o}C. Below 10^{o}C nearly all buildings are heated and this is reflected in the independence of the indoor comfort temperature from outdoor conditions. Above 10^{o}C increasingly the temperature in naturally ventilated buildings is affected by the outdoor temperature and occupants find ways to adjust to this through changes in clothing and other mechanisms (see Humphreys and Nicol, 1998).

The difference between the indoor temperature and the comfort temperature (T_{diff}) was calculated for each set of data from the indoor globe temperature T_g and the comfort temperature T_{comf}

$$T_{diff} = T_g - T_{comf} \quad (1)$$

T_{diff} is positive when the indoor temperature is above the comfort temperature and negative when it is below. The numbers of subjects reporting discomfort could then be plotted against T_{diff}. Most workers have defined 'comfort' on

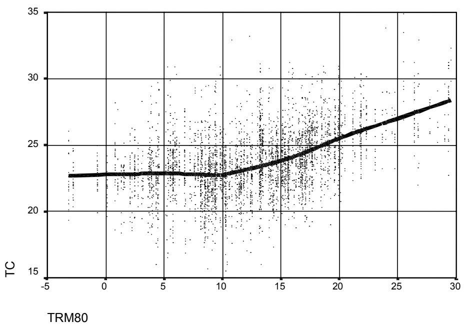

Figure 2: The value of the comfort temperature (Tcomf labelled TC) plotted against the running mean of the outdoor temperature (all cases) from McCartney and Nicol 2002.

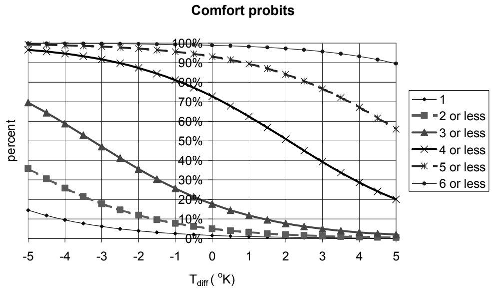

Figure 3: Probit lines for comfort vote against temperature offset T_{diff} from the predicted comfort temperature. Results from the SCATs data for all buildings and countries. The points are the measured values in each category for 20 bins of T_{diff}.

the ASHRAE scale (table 1a) as those people voting 'slightly warm (5), 'neutral' (4) or 'slightly cool' (3). On the preference scale (table1b) it is possible to define those who are comfortable as voting 'no change' (3). By categorising the whole database into 20 'bins' of roughly equal numbers of data sets according to the value of T_{diff} it was possible to work out how many people in each T_{diff} bin recorded each comfort vote.

Probit analysis was used to develop the predictive curves shown in Figure 3 which show the proportion of subjects who voted less than a certain value of comfort vote (Table 1) (for more on this method see Webb (1959)). Note that the number voting, say, 4 will be the difference between those voting 4 or less and those voting 3 or less. It is now possible to produce a curve showing the proportion who were comfortable according to the two definitions given above (see Figs. 4 and 5)

Figure 4 shows the changes in the number of

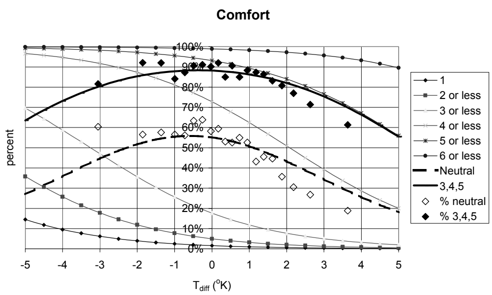

Figure 4: Showing the proportion of subjects voting Neutral (open symbols, dashed line) or between slightly cool and slightly warm on the ASHRAE scale (%3,4,5, filled symbols, continuous line).

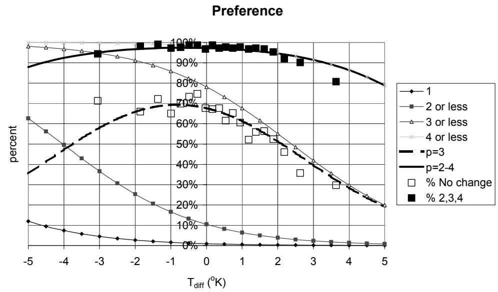

Figure 5: Proportions of subjects who want no change (open symbols, dashed line) or 'a bit warmer or cooler (solid symbols, continuous line) as a function of temperature offset from comfort.

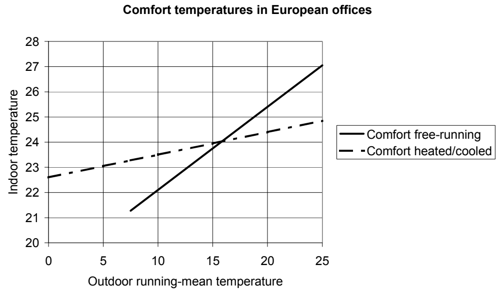

Figure 6: Regression lines for dependence of comfort temperature on outdoor running mean temperature for free-running (solid line) and air conditioned (dashed) buildings.

people voting comfortable (continuous line) or Neutral (dashed line) with the value of T_{diff}. The graph indicates that for temperature up to 2°K above comfort temperate over 80% of subjects are comfortable, and up to half of them are neutral on the comfort scale.

Figure 5 shows the proportion of subjects wanting 'No change' in the temperature (dashed line) or a 'bit warmer' or a 'bit cooler' (continuous line). At a temperature 2°K above the comfort temperature, 50% of subject are still wanting 'no change' and less that 10% want the temperature to be 'much cooler'.

3. COMFORT AND AIR CONDITIONING

The comfort temperature of occupants has been shown by a number of researchers to depend on whether or not the building is being heated or cooled (e.g. Humphreys, 1978). A building which is not being heated or cooled is described as 'free-running'. In both fully air-conditioned and in free-running office buildings the comfort temperature increases with rising outdoor temperature, indicating that the occupants accept higher indoor temperatures during hot spells. The slope is greater in free running buildings giving the following equation for comfort temperature (T_{comf}) as a function of the running mean of the outdoor temperature (T_{rm}).

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad (2)$$

This line may be used to indicate probable optimum comfort-temperatures in the free-running condition (typically for naturally ventilated buildings in summer). For buildings which are being heated or cooled the comfort temperature changes much more slowly compared with that outdoors and the equivalent relationship is:

$$T_{comf} = 0.093T_{rm} + 22.6 \qquad (3)$$

These relationships are illustrated in Figure 6, Note that the two lines cross at a mean outdoor temperature in the region of 15°C. At a T_{rm} above 15°C most European county's naturally ventilated buildings are free running and below about 10°C most are heated.

Figure 7 shows the proportion of subjects neutral or comfortable as a function of T_{diff}. The proportion of people who consider themselves comfortable at any given value of T_{diff} is almost independent of whether the building is heated or cooled (dashed line) or free-running (continuous line).

The graph of preference and Tdiff (Fig. 8) is less symmetrical. In free-running buildings preference for 'no change' is highest when the indoor temperature is about 1°K less than the comfort temperature. For heated or cooled buildings the graph is more symmetrical, though

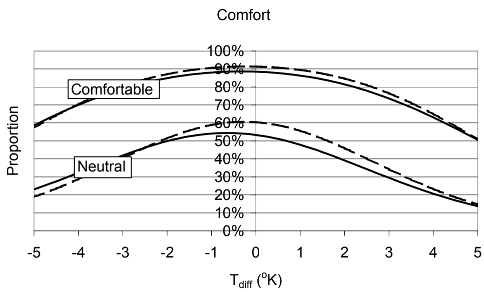

Figure 7: Comfort and T_{diff} for air conditioned buildings (dashed lines) and free running buildings (continuous lines).

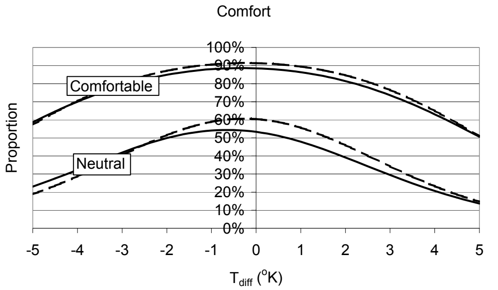

Figure 8: Preference and T_{diff} for air conditioned buildings (dashed lines) and free running buildings (continuous lines).

it should be remembered that the comfort temperature will in most cases be lower.

4. DISCUSSION OF RESULTS

It is in the nature of thermal comfort research that no definite boundary between comfort and discomfort is produced. This means that a degree of judgement is required to interpret the results. When the indoor temperature is at the comfort temperature about 10% of subjects are uncomfortable and this proportion has increased to almost 20% when the temperature is 2^oK above the comfort temperature. For greater values of T_{diff} the proportion of building occupants increases more quickly. The proportion of building occupants who experience discomfort will approximately double to 40% by the time T_{diff} reaches 4.5^oK.

How this translates into dissatisfaction with the indoor climate of the building is difficult to determine, but it seems likely that a value of Tdiff of 2^oK or less will be accepted as ‘normal’ particularly in hot weather. Above this the degree of discomfort is likely to increase more markedly and may be considered unacceptable. Whether there is a time limit to the degree of acceptability as is implied in the CIBSE guide definition recommendation quoted in section 1 above is beyond the scope of our investigation.

Figure 7 shows that the difference between free-running and heated or cooled buildings is in the definition of the comfort temperature, and not in the degree of difference from the appropriate comfort temperature.

Figure 5 shows that when T_{diff} is zero about 70% of subjects will express a preference for ‘no change’. Of the 30% who want a change, about twice as many want to be ‘a bit cooler’ than want to be ‘a bit warmer’

In defining his Predicted Percentage Dissatisfied Fanger presents a graph of PPD as a function of Predicted Mean Vote (PMV). This curve is shown in Figure 9 as the continuous curve. The minimum PPD when PMV is zero is 5% (Fanger 1970). It might be argued that the PPD is predicting a lower minimum discomfort, and that this implies that PMV is a more precise method of predicting a comfort temperature. PMV/PPD was calibrated using data from climate chamber experiments. Humphreys and Nicol (2002) explored the relationship between PMV and actual discomfort in Field studies using the ASHRAE database of field studies (de Dear, 1998). The results of the analysis are shown by the points in Figure 9. Clearly in the circumstances of a field survey, PMV/PPD loses the ability to predict precise circumstances for avoiding discomfort.

5. CONCLUSIONS

This paper establishes that for offices in Europe the level of discomfort is a function of the difference between the prevailing indoor temperature and the comfort temperature

The comfort temperature can be calculated from the running mean of the outdoor temperature. For free-running buildings equation (2) should be used when the running mean of the outdoor temperature is between 10^oC and 27^oC. The comfort temperature for heated or cooled buildings can be calculated from equation (3).

There is no temperature at which everyone

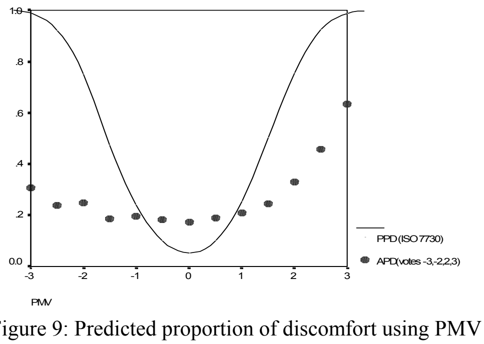

Figure 9: Predicted proportion of discomfort using PMV to predict PPD (continuous line) and actual discomfort recorded by subjects from the ASHRAE database (from Humphreys and Nicol 2002).

will feel comfortable, or would not sometimes prefer indoor temperatures to be warmer or cooler.

The range of temperatures at which minimum discomfort will be experienced is within about 2°K of the comfort temperature. If the difference between the indoor temperature and the comfort temperature is more than 2°K there will be an increase in the likelihood of discomfort.

ACKNOWLEDGEMENT

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REFERENCES

ASHRAE, 2004. Standard 55-04 Thermal Environmental Conditions for Human Occupancy. Atlanta, American Society of Heating, Refrigerating and Air-conditioning Engineers.

Baker, N.V. and M.A. Standeven, 1995. A behavioural approach to thermal comfort assessment in naturally ventilated buildings. Proceedings CIBSE National Conference, Eastbourne, pp76-84 London, Chartered Institution of Building Services Engineers.

CIBSE, 1986. Cibse Guide, Volume A. London, Chartered Institution of Building Services Engineers.

de Dear, R.J., 1998. A global database of thermal comfort field experiments. ASHRAE Transactions, Vol. 104(1), 1998).

Fanger, P.O., 1970. Thermal Comfort. Copenhagen, Danish Technical Press.

HSE, 1999. Thermal comfort in the workplace guidance for employers. Health and Safety Executive HSG 194, Health and Safety Executive Books.

Humphreys, M.A., 1978. Outdoor temperatures and comfort indoors. Building Research and Practice (J CIB), 6(2) pp 92-105.

Humphreys, M.A. and J.F. Nicol, 1998. Understanding the Adaptive Approach to Thermal Comfort, ASHRAE Transactions 104 (1) pp 991-1004.

Humphreys, M.A. and J.F. Nicol, 2000. Outdoor temperature and indoor thermal comfort: raising the precision of the relationship for the 1998 ASHRAE database of field studies. ASHRAE Transactions 206(2) pp 485-492.

Humphreys, M.A. and J.F. Nicol, 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings 34(6) pp 667-684.

Loudon, A.G., 1968. Window design criteria to avoid overheating by excessive solar gains, Building Research Current Paper 4/68, Garston. Building Research Establishment.

McCartney, K.J. and J.F. Nicol, 2002. Developing an Adaptive Control Algorithm for Europe: Results of the SCATs Project. Energy and Buildings 34(6) pp 623-635.

Nicol, F. and K. McCartney, 2001. Final report (Public) Smart Controls and Thermal Comfort (SCATs) (also subsidiary reports to Tasks 2 [comfort surveys] and 3) [developing an adaptive algorithm] Report to the European Commission of the Smart Controls and Thermal Comfort project (Contract JOE3-CT97-0066) Oxford, Oxford Brookes University.

Webb, C.G., 1959. An analysis of some observations of thermal comfort in an equatorial climate, British Journal of Industrial Medicine, 16(3) 297-310.