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Air Infiltration and Ventilation Centre

Adaptive Thermal Comfort and Ventilation

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1 Introduction

Thermal comfort standards determine indoor conditions in buildings as well as the energy consumption for heating and cooling purposes. Existing comfort standards are based on steady state thermal conditions and according to recent research can not describe well comfort conditions in non air conditioned buildings.

Field comfort studies carried out around the world have shown that the so called adaptive approach describes comfort conditions in non air conditioned buildings better. The fundamental assumption of the adaptive approach is expressed by the 'adaptive principle' that stipulates:

"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Humphreys and Nicol 1998).

Most of the surveys have verified that the comfort temperature is very closely related to the mean indoor temperature (Humphreys 1975). It was subsequently found that in free-running buildings the optimum comfort temperature is a linear function of the outdoor temperature, and may be predicted from the mean outdoor temperature.

Based on these results and the data of de Dear and Brager (2002) a new adaptive thermal comfort for naturally ventilated buildings has been integrated in the 2004 update of ASHRAE – 55 Standard.

The present VIP aims to inform on the main progress on comfort research, to present the proposed adaptive standards, to investigate the impact of ventilation on comfort and in parallel to evaluate the possible energy gains when adaptive comfort standards are used in place of steady state models.

2 Existing Thermal Comfort Methods

Existing thermal comfort standards and methods cover mainly thermal comfort conditions under steady state conditions. Most of the thermal comfort studies have been carried in laboratories and are based on evaluations of the heat transfer between the human beings and their environment and of the required physiological conditions for thermal comfort.

The most well known and widely accepted methods are the PMV 'Comfort Index' proposed by Fanger, (Fanger 1972), and the J.B. Pierce two node model of human thermoregulation, (Gagge 1973 and Gagge et al. 1986). Based on these models several steady state thermal comfort standards have been established. (ISO 1994, ASHRAE 1992, Jokl 1987).

Given the thermal interaction between the building envelope, the occupants and the heating and cooling system, it is very rare to encounter steady state conditions in real buildings, and it is evident that the temperature in free running buildings is far less likely to be steady. Monitoring of passive solar buildings with constant set point, has shown that there are important indoor fluctuations raising between 0.5 and 3.9 °C, as an effect of the control system (Madsen 1987). Basic research on thermal comfort has concluded that there is an important discrepancy between steady-state models and those where no mechanical conditioning is applied (Humphreys 1976). As mentioned, this is mainly due to the temporal and spatial variation of the physical parameters in the building (Baker 1993). Thus, knowledge of thermal comfort under transient conditions is necessary.

Recent experimental comfort surveys have concluded that there are significant discrepancies between thermal comfort in real buildings conditions versus laboratory conditions. As mentioned by Nicol and Humphreys (1973), this discrepancy could be the result *"… of a feedback between the thermal sensation of subjects and their behaviour and that they consequently 'adapted' to the climatic conditions in which the field study was conducted"*. According to thermal comfort experts, occupants living permanently in air conditioned buildings develop expectations for low temperatures and homogeneity and are critical when indoor conditions deviate from the comfort zone they are used to. On the other hand, occupants living in non air conditioned buildings are usually better able to control their environment and they become used to climate variability and thermal diversity. Thus, their thermal preferences extend to a wider range of temperatures or air speeds.

According to Humphreys and Nicol (2002), data from recent field surveys show that steady state methods, like the PMV one, do not accurately predict the actual votes cast on the ASHRAE scale, overestimating discomfort by an unacceptable margin especially in variable conditions. Humpherys and Nicol (2002) and Parsons et al. (1997) have provided some explanations for the discrepancies in the PMV theory. It is reported that, as PMV is a steady state model there is a theoretical contradiction between the basic assumptions of the model and the imbalance assumed if the body is not comfortable. A second reason is related to the uncertainty and the fuzziness to calculate exactly the metabolic heat and the clothing insulation.

Other possible explanations for the found discrepancies are given by Nicol (2003).

3 The Adaptive Approach

The principle of the adaptation to the thermal environment has been extensively studied and documented (Nicol et al. 1995, Brager and de Dear 1998, 2000, de Dear 1998, de Dear and Brager 1998, Rijal et al. 2002).

The fundamental assumption of the adaptive approach is expressed by the adaptive principle mentioned in §1. This principle codifies the behaviour of building occupants which takes two basic forms:

- Adjustments to the optimal comfort temperature by changes in clothing, activity, posture, etc. so that the occupants are comfortable in prevailing conditions
- Adjustment of indoor conditions by the use of controls such as windows, blinds, fans and in certain conditions mechanical heating or cooling. Occupants may also migrate around the room to find improved conditions

It is as a result of these adaptive behaviours that field surveys have verified that the comfort temperature is very closely related to the mean indoor temperature (Nicol et al. 1999, McCartney and Nicol 2002). Nicol and Humphreys (1973) suggested that such an effect could be seen as the result of feedback between the thermal sensation of subjects and their behaviour as part of the processes by which thermostasis (the maintenance of body temperature) is preserved.

Based on data collected in many field studies, Humphreys and Nicol (1998) proposed an adaptive comfort model. They demonstrated that for a group of people the comfort temperature is close to the average temperature they experience.

In parallel, very important research has been carried out in order to develop an international adaptive comfort standard. Analysis of the data included in the ASHRAE RP-884 database involving data of comfort surveys around the world (de Dear and Brager 2002) has shown that "*occupants of naturally ventilated buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns*", while PMV predictions fit very well with the preference of occupants in HVAC buildings (Figure 1).

The same conclusions have been reported from various old and recent comfort field studies (Webb 1959, Nicol 1973, Humphreys 1975, Busch 1992, Nicol and Roaf 1994, Matthews and Nicol 1995, Taki et al. 1999, Nicol et al. 1999, Bouden and Ghrab 2001). As a result of the field studies, it was found that the optimum comfort temperature in naturally ventilated buildings is a function of the outdoor temperature, and may be predicted by linear equations of the following form, (Humphreys 1978, Auliciems and de Dear 1986, Nicol and Raja 1995) :

$$T_{comf} = a\ T_{a,out} + b$$

where $T_{a,out}$ is the mean outdoor air temperature.

de Dear and Brager (2002), have proposed the following expression :

$$T_{comf} = 0.31T_{a,out} + 17.8$$

While Humpreys (1978), Humphreys and Nicol (2000) and Nicol (2002) have proposed a similar expression for free-running buildings (which includes most naturally ventilated buildings outside the heating season):

$$T_{comf} = 0.534T_{a,out} + 11.9$$

Based on these results a new adaptive thermal comfort for naturally ventilated buildings has been integrated in ASHRAE – 55 Standard, (Figure 2). McCartney and Nicol (2002) have suggested that a running mean of the outdoor temperature is a better predictor of indoor comfort temperature than the monthly means used by Humphreys (1978) and later by de Dear and Brager (2002), and at the same time allows for deviations of the weather from long term average conditions which may occur from time to time, especially with climate change.

As close analysis by Humphreys and Nicol (2000) suggests that there is a remarkable agreement between their work on free-running buildings and the 1998 ASHRAE database (Humphreys 1978, de Dear 1998) (Figure 3). It is also found that the relationship between the two databases for air conditioned buildings is more complex, showing a 2^{o}C difference in indoor comfort temperatures between the results of Humphreys in 1978 and those of de Dear in 1998.

Results from the PASCOOL research project have verified the adaptive principle. Based on the previous works, the comfort group of the European research project PASCOOL coordinated by N. Baker, (Baker 1993, Baker and Standeven 1994), carried out field measurements in various countries, to understand the mechanisms by which people make themselves comfortable at higher temperatures. It is found that people are comfortable at much higher temperatures than expected in hot conditions. It was observed that people make a number of adaptive actions to make themselves comfortable including moving to cooler parts of the room. 273 adjustments to building controls and 62 alterations to clothing were observed during 864 monitored hours.

Various other research studies have verified the adaptive comfort approach. Klitsikas et al. (1995) performed comfort studies in office buildings in Athens, Greece, during the summer period. It has been found that almost always the theoretical PMV value is higher or equal than the measured thermal sensation vote, and the subjects felt more comfortable than predicted by the PMV theory. Lin Borong et al. (2003) have performed comfort studies in Chinese naturally ventilated buildings. It is concluded that the thermal sensation of people has a larger range than that at a stable environment. Comparisons have been performed against the PMV scale and it is concluded that the PMV model needs correction when used to evaluate people response to unstable or natural thermal environments.

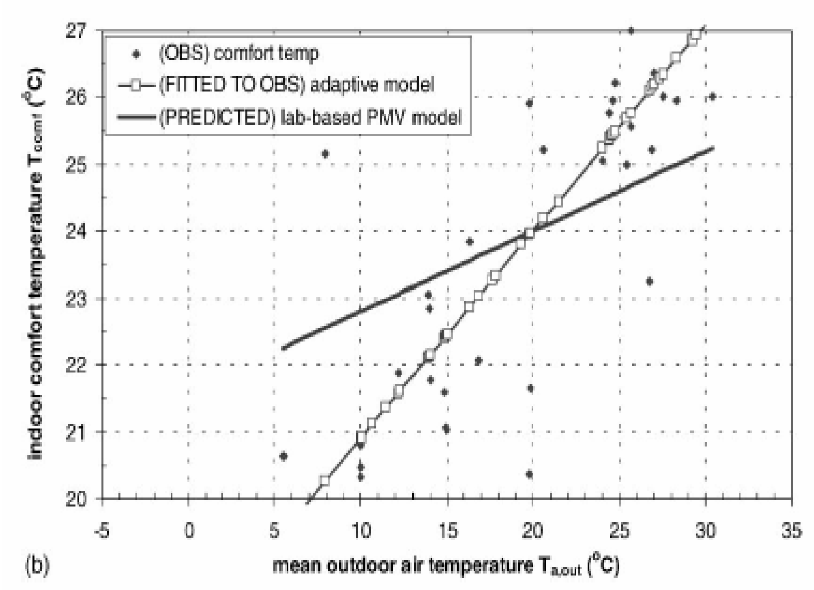

Figure 1 : Observed (OBS) and predicted indoor comfort temperatures from RP-884 database, for naturally ventilated buildings, (from De Dear and Brager 2002)

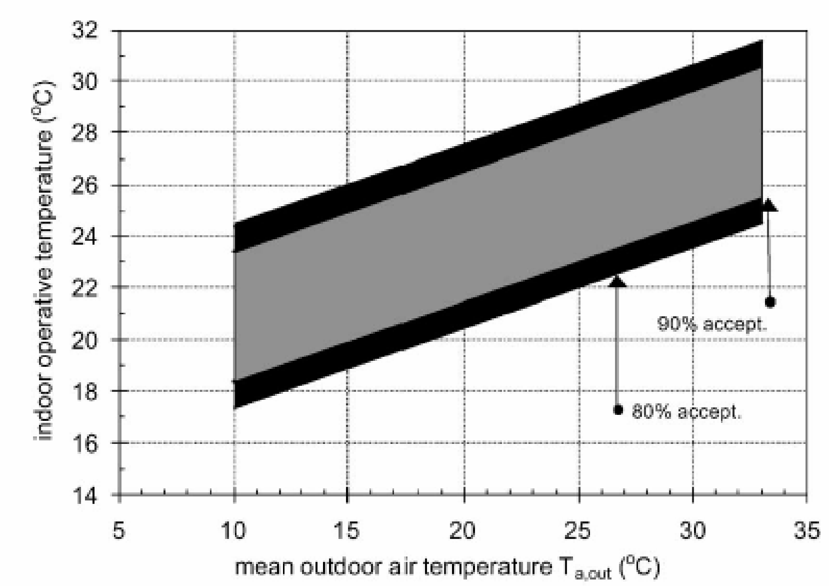

Figure 2 : Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings, (from De Dear and Brager 2002)

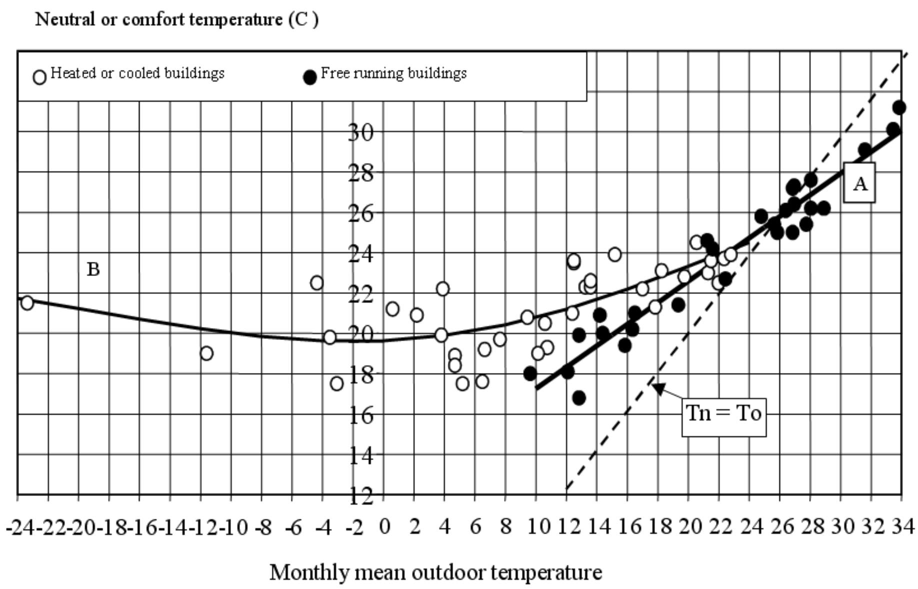

Figure 3 : The change in comfort temperature with monthly mean outdoor temperature for free floating and air conditioning buildings, (From Nicols 2003)

Similar results have been found during a comfort survey under hot and arid conditions in Israel (Becker et al., 2003), in Singapore (Hien and Tanamas 2002), in Indonesia (Feriadi 2002), in Algeria (Belayat et al. 2002) and in Bangladesh (Mallick 1994).

4 Thermal Comfort and Air Speeds

The air speed has a big effect on comfort conditions in buildings. Although many research projects are devoted to this issue, it is still an open area of scientific research (Tanabe and Kimura 1994, Arens et al. 1984, 1986).

Air velocity affects both convective and evaporative losses and thus determines thermal comfort conditions. Steady state comfort methods accept a relatively low indoor air speed. However, recent, studies performed mainly in tropical climates, (de Dear 1991, Mallick 1996, Hien and Tanamas 2002), confirm that the increase in air velocities, especially at higher temperature enhances the thermal comfort conditions. According to Kukreja (1978), indoor air speed in warm climates should be set at 1.00–1.50 m/s. Hardiman (1992) proposes an air speed between 0.2–1.5 m/s for light activity.

Similar results are also reported for research outside tropical climates. Results from a recent Danish climatic chamber research (Toffum et al. 2000) show that the subjects preferred 28°C when are permitted to select their own preferred airspeed and 26°C with a fixed air speed of 0.2 m/sec. Nicol (2004) in an analysis of results from Pakistan, found that temperatures considered comfortable with fans running were 2K higher than those without over a wide range of indoor temperatures.

Other studies propose much higher air speeds. As it is reported (Hien and Tanamas 2002), undesirable effects of high air movements of above 3 m/sec have been observed.

5 The Impact of Comfort Standards on the Energy Consumption of Buildings

Analysis from various researchers has shown that when variable indoor temperature comfort standards based on adaptive theory are used in air conditioned buildings remarkable energy savings may occur (Auliciems 1990, Hensen and Centrenova 2001). The expected energy saving in European buildings is more than 18% over that from using a constant indoor temperature as reported by Stoops et al. (2000), while the corresponding energy savings for UK conditions have been estimated close to 10 % (Milne 1995, Wilkins 1995).

In parallel, when variable indoor temperature comfort standards are applied, the use of natural ventilation in buildings becomes much easier because narrow temperature limits are not needed so long as the occupants have a good measure of control, and thus the energy consumption for cooling is reduced.

Research by Kolokotroni et al. (1996) has shown that naturally ventilated buildings consume less than half of the energy of air conditioned ones. At the same time it is evident that indoor temperatures in free floating buildings are constantly changing so that a variable indoor temperature standard which reflects this variability will help save energy by encouraging the use of naturally ventilated buildings

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