HOW AIR MOVEMENT SAVES ENERGY IN INDOOR ENVIRONMENTS

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ABSTRACT

A caution is given against using the lesser thermal comfort expectations of occupants, in naturally conditioned space, in design for occupants of air conditioned space. Temperature offsets for cooling from local air movement of up to 4.4K are indicated for air speeds of 1.6 m/s from ASHRAE Standard 55-2004 in air conditioned spaces. Temperature offsets for local air movement of up to 9.5K for air speeds of 3.0 m/s to enhance thermal comfort in naturally conditioned spaces are indicated by Khedari et al, 2000. Graphs indicate the influence of relative humidity on temperature offsets in air conditioned and naturally conditioned space. A cooling energy savings rate of 6%/K is suggested for the combined effects of temperature offsets and local air flow from circulating fans in air conditioned spaces. During cooler months in sub-tropical regions, de-stratification with large ceiling fans can save approximately 10% of heating energy for each 3 m of floor to ceiling height in spaces with ceiling heights over 7 m.

Keywords: thermal comfort, temperature offsets, natural ventilation, destratification

1. Introduction

This paper explores the benefits of air movement in buildings in tropical and sub-tropical climates. It compares the expectations of thermal comfort of occupants in naturally conditioned and air conditioned spaces. While air movement does not cool air, it can cause a cooling sensation as it passes over occupants' skin. Design data on this effect is presented as temperature offsets. It is important during design to recognise the difference in expectations between occupants in air conditioned space, to the expectations of occupants of naturally conditioned space. Air movement can increase occupant satisfaction and improve energy efficiency. Energy savings can also be gained by de-stratifying air in heated spaces with high ceilings during cooler months.

2. Adaptive thermal comfort

Adaptive thermal comfort represents occupants' expectations of thermal sensation in naturally conditioned commercial and industrial spaces. It is not an opportunity to change people's expectations of thermal comfort in air conditioned space. If adaptive thermal comfort criteria are used in design for air conditioned commercial and industrial spaces, occupants will have thermal comfort expectations of a cooler environment and are likely to adjust thermostats to lower temperature settings than those used in the design. This behavior can result in the designed cooling plant capacity being inadequate and the occupants being dissatisfied with the performance of the air conditioning system.

2.1 Operative temperature

For the first time, the ASHRAE Standard 55-2004[1] included a graph indicating the ranges of indoor operative temperature that should satisfy 80% of occupants in naturally conditioned commercial or industrial spaces, based on mean monthly outdoor air temperature (Figure 1). Operative temperature, t_o, is defined in ASHRAE Standard 55-2004 as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

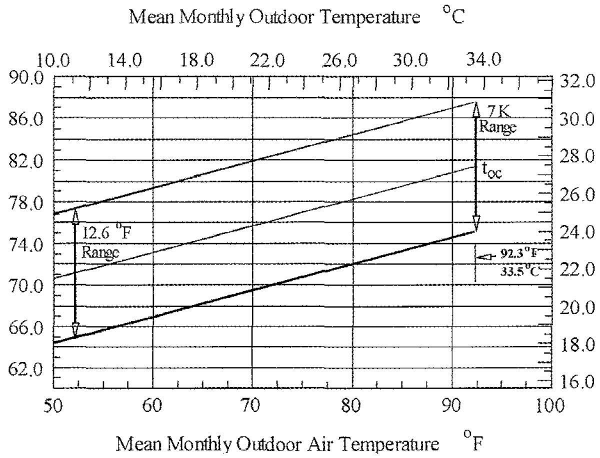

Figure 1 – operative temperature ranges to satisfy 80% of occupants in naturally-conditioned space

With a mean monthly outdoor dry bulb air temperature of 24.9°C in Brisbane in January, the operative comfort temperature can be calculated using the equation provided by ASHRAE[2]:

$$t_{oc} = 18.9 + 0.255\,(t_{out}) \qquad (1)$$

where t_{oc}, is the operative comfort temperature, and t_{out}, is the mean monthly outdoor dry bulb air temperature.

$$t_{oc} = 18.9 + 0.255(24.9) = 25.3°C$$

Similarly, with a mean monthly outdoor dry bulb air temperature of 27.6°C in Townsville, during January, t_{oc} is 25.9 °C. From long term climate data[3] the January difference between t_{oc} for Brisbane in January and the 86 percentile maximum monthly dry bulb air temperature at the Brisbane Regional Office of the Bureau of Meteorology is 31.7 °C – 25.3 °C or 6.4 K.

Similarly from Townsville Meteorological Office climate records in January the difference between the t_{oc} and the 86 percentile maximum daily temperature for January, typically the hottest month, is 32.9 °C – 25.9 °C or 7 K.

These differences represent the cooling effects from air flow needed to restore thermal comfort for about 80% of the climatically-adapted population in naturally conditioned space. It will be shown later in this paper (Figure 7) that a 7K temperature offset can be achieved by an air speed of 1.5 m/s when RH is 50%.

2.2 Thermal comfort zone

There is significant individual variation in individual human thermal response. Researchers[4] have shown that this variation in thermal response can be accommodated by defining a thermal comfort zone, CZ_{80} that satisfies 80% of occupants in naturally conditioned space.

$$CZ_{80} = t_{oc} +/- 3.5 \qquad (2)$$

For Brisbane in January, the CZ_{80} for January centered around the toc of 25.3°C, is 25.3 +/- 3.5 or 21.8°C to 28.7°C. Similarly for Townsville in January the CZ_{80} centered around the t_{oc} of 25.9°C, is 25.9 +/- 3.5 or 22.4°C to 29.4°C.

3. Comfort in air conditioned space

The most convenient method to determine thermal comfort in air conditioned space is to use the ASHRAE Thermal Comfort Tool software[5]. If we assume in air conditioned space that:

- RH is controlled to around 50%,
- Air movement is <0.2 m/s,
- Occupants are wearing typical summer dress (0.5 clo)
- Occupants have a sedentary metabolic activity of 1 met,

Then the range of temperature to satisfy 80% of occupants (±0.5 PMV) according to ASHRAE Standard 55-2004 (anywhere on earth) is 24.7°C to 27.5°C (2.8 K).

4. Different comfort expectations

It is important to appreciate the difference between the occupants' expectations in air conditioned space in contrast to naturally conditioned space.

For air conditioned space in sub-tropical Brisbane in January it is 24.7°C to 27.5°C (2.8 K), in naturally conditioned space in Brisbane in January it is 21.8°C to 28.8°C (7 K).

For air conditioned space in tropical Townsville in January it is 24.7°C to 27.5°C (2.8 K), in naturally conditioned space in Townsville in January it is 22.4°C to 29.4°C (7 K).

5. Cooling effect of air movement

There are many sources indicating the cooling effect of air movement on people. The one that covers the widest range of wind speed, 0 to 10.3 m/s, is the Manual of Naval Preventive Medicine[6]. The graph in the manual is not particularly useful for design purposes because it relates to relative cooling effect and does not indicate relevant variables pertaining to the study.

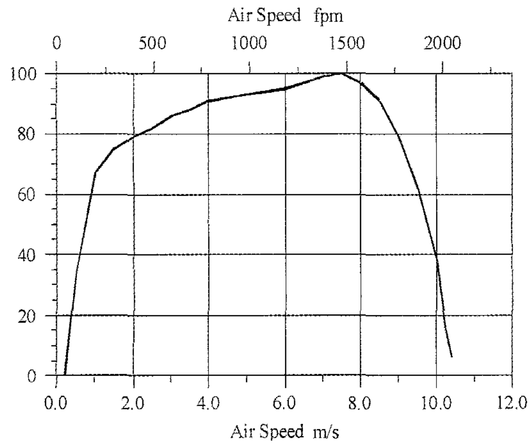

Figure 2 – relative cooling effect of air speed (after[6])

5.1 Graphical temperature offsets for elevated air speeds

From the HVAC design viewpoint, the temperature offsets for elevated air speed provided in Figure 5.2.3 of the ANSI/ASHRAE Standard 55-2004 (shown as Figure 3) are more useful.

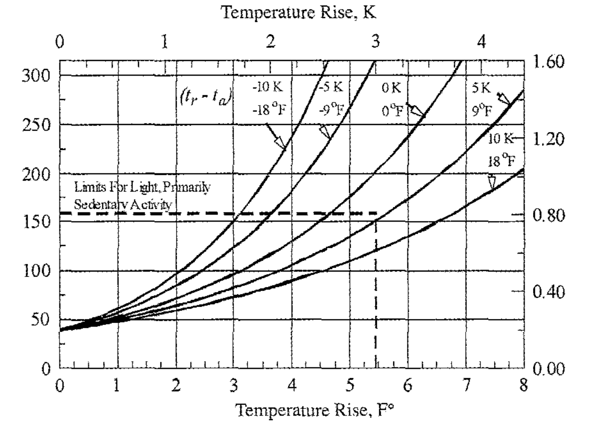

Figure 3 – temperature offsets from ASHRAE Standard 55-2004

5.2 Temperature offsets from ASHRAE Thermal Comfort Tool

Another source is the ASHRAE Thermal Comfort Tool software [5]. This software allows adjustment of all thermal comfort input variables:

- Dry bulb air temperature
- Mean radiant temperature
- Air velocity
- Humidity
- Metabolic rate, and
- Clothing insulation

The relevant output from this software is the predicted mean vote (PMV). Thermal comfort to satisfy 80% of occupants under this Standard is defined as a PMVA between -0.5 and +0.5. This software was principally developed for assessing thermal comfort in air conditioned space. The algorithms for cooling effect of air velocity are based on sensible heat transfer. Temperature offsets from elevated air speed can be obtained by setting the air temperature to 25°C. The other reference settings for the software are: relative humidity to 50%; metabolic rate to 1 met; clothing to 0.5 clo; and air speed to 0.1 m/s.

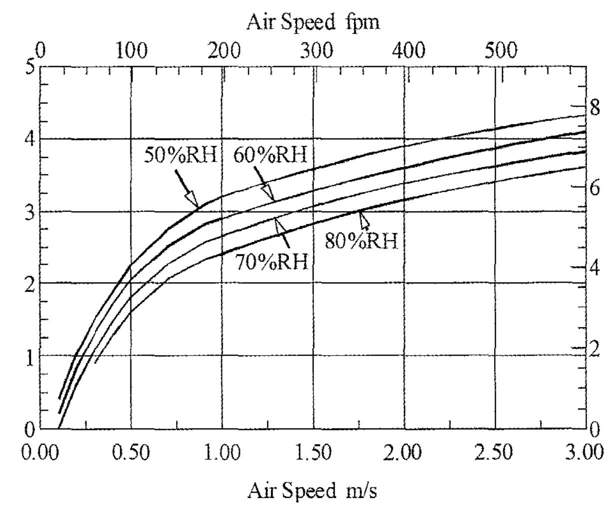

Figure 4 – temperature offsets for air speed at 50% to 80% RH from the ASHRAE Thermal Comfort Tool

The dry bulb air temperature setting is then increased until the PMV is +0.5, the upper limit of the comfort zone to satisfy 80% of occupants. The difference between the 25°C and the temperature setting at PMV = +0.5 is the temperature offset for that air speed setting. Offsets for other air speed settings are found by setting the air speed at a higher value and increasing the dry bulb air temperature until PMV = +0.5.

The ASHRAE Thermal Comfort Tool is valuable in that it provides an opportunity to evaluate the relative influence of other variables such as elevated metabolic rates on air speed temperature offsets in air conditioned space that are otherwise difficult to determine.

6. Air movement in air conditioned environments

Where air movement is provided for individuals, it should be controllable in speed and direction by that individual. This has been recognised by automobile and aircraft designers for decades. HVAC engineers are only now starting to recognise this. At least two manufacturers in the USA have user-controlled task ambient air supply devices (above or below desk) that operate from sub-floor supply systems. Evaluations of such systems have been performed [7, 8].

6.1 Estimating cooling energy savings from temperature offsets

ANSI/ASHRAE Standard 55-2004 shows that increased air speed in air conditioned space, when mean radiant temperature equals air temperature, can offset a temperature increase of 2.5K with a local air speed of 0.8 m/s in Figure 5.2.3 of that Standard. A 7.3 m diameter ceiling fan, operating at a speed of 20 rpm using 0.14 kW of electricity can provide a mean air speed of 0.8 m/s near floor level over an area of 600 m^2 (0.2 W/m^2).

Facility maintenance engineers at Travis Air Force Base [9] in California claim that raising the thermostats on air conditioning equipment at the base by 1.1 K saves 8% of cooling operating costs (7.3%/K). Using a savings rate of say 6%/K to allow for energy used by the fans on the 2.5 K temperature offset, gives a net saving of 15%. ASHRAE Standard 55-2004 allows for cooling effects of air movement up to 3.0 K, when $t_a - t_r >$ 5 K for sedentary activity. Using the 6%/K savings rate gives a net saving of 18% for a temperature offset of 3.0 K.

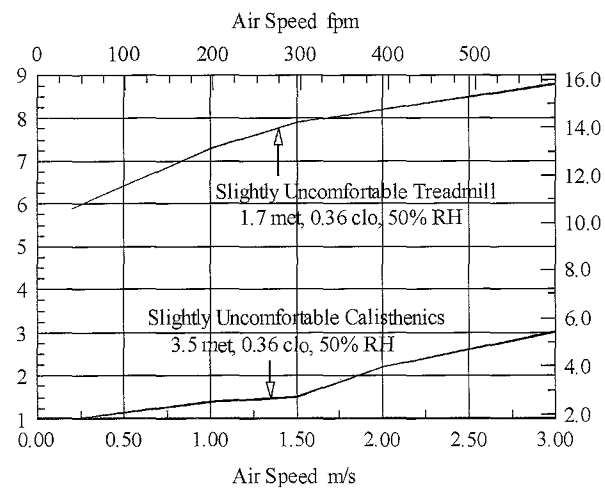

Figure 5 – temperature offsets for air speed at elevated metabolism and reduced clo.

In non-sedentary spaces such as gymnasia, ANSI/ASHRAE Standard 55-2004 allows for elevated air speeds up to 1.6 m/s. When $T_r = T_a$, the temperature offset for 1.6 m/s is 3.8 K. The potential energy savings from a 3.8 K offset using a savings rate of 6%/K would be 22.8%. A 7.3 m diameter ceiling fan, operating at a speed of 30 rpm using 0.63 kW of electricity can provide a mean air speed of 1.6 m/s near floor level over an area of 729 m^2 (0.9 W/m^2)

7. Khedari et al study in Bangkok, Thailand

Wind is a naturally available source for air flow through buildings particularly in sub-tropical and tropical coastal regions of Queensland. Khedari et al [10] conducted a study of the influence of air speed and humidity on thermal comfort in Bangkok, Thailand. This study surveyed 288 college aged subjects (183 males and 105 females in sedentary activity).

All subjects wore normal clothing (0.54 – 0.55 clo) and six desk fans were located behind the subjects. The thermal sensation scale used in the study ranged from Cool (-2), Slightly cool (-1), Neutral (0 [27.17°C at 0.2m/s]), Slightly warm (1), Warm (2), Hot (3), Very Hot (4). Maximum thermal neutrality was 36.3°C at 50% RH and 3 m/s.

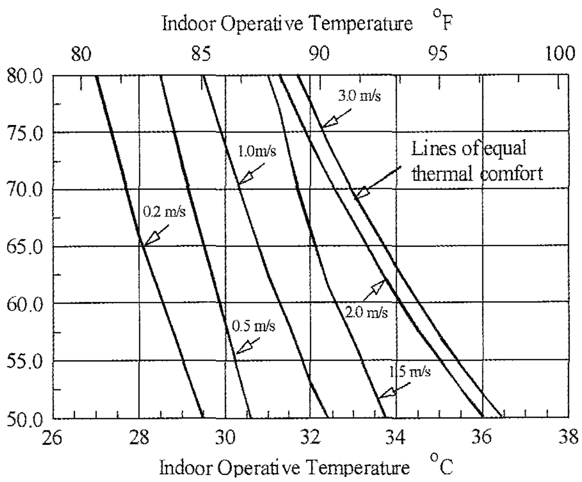

Figure 6 – lines of equal thermal comfort developed by Khedari et al [9]

7.1 Khedari temperature offsets for air speed

Given that the Khedari study was conducted in naturally conditioned space in Thailand, a humid tropical climate location, the data separation into responses over a range of relative humidity levels makes it a very useful tool in accounting for the influence of humidity.

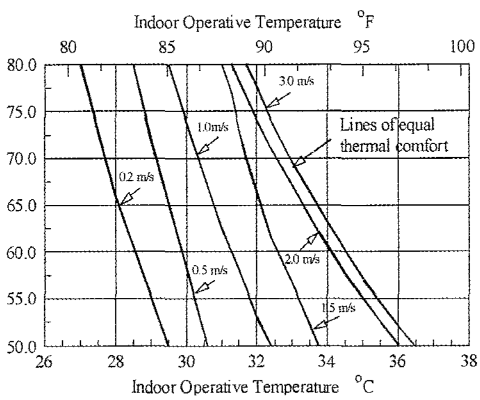

Figure 7 – temperature offsets for air speed at RH from 50 to 80%

Temperature offset curves were obtained by plotting the points along selected relative humidity lines at each equivalent comfort line.

7.2 Comparison of ATCT and Khedari temperature offset curves

If the temperature offset curves derived from the ASHRAE Thermal Comfort Tool are compared with those derived from the Khedari study, it can be seen, Figure 8, that the curves for 80% RH are similar shape showing a difference at an air speed of 1.5 m/s is about 1.3 K, and at an air speed of 3.0 m/s about 1 K. The curves for 50% RH show a much larger difference at 1.5 m/s of about 3 K and at 3.0 m/s the difference is 5 K. Obviously people in the humid tropical location experienced a much greater cooling effect from airflow exceeding 1.5 m/s with 50%RH than predicted by the ASHRAE Thermal Comfort Tool.

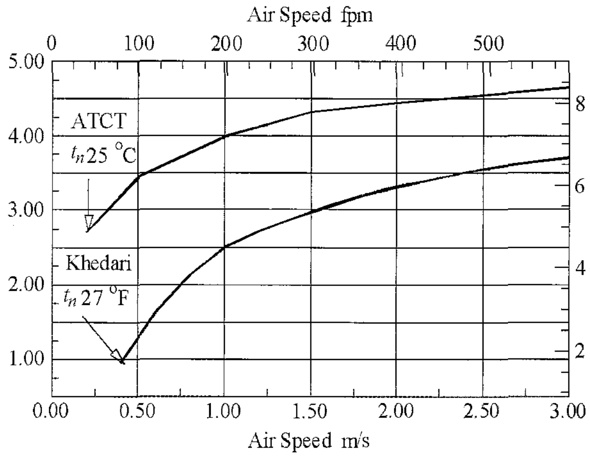

Figure 8 – comparison of temperature offsets for air speed from the ASHRAE Thermal Comfort Tool and the Khedari study at 80% RH

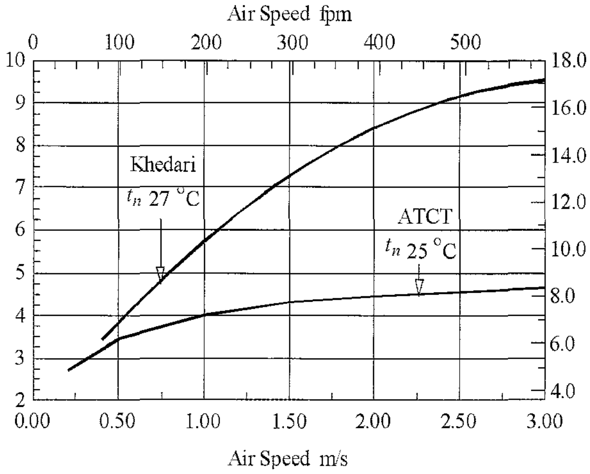

Figure 9 – comparison of air speed temperature offsets for ASHRAE Thermal Comfort Tool and Khedari at 50% RH

These differences in human response to thermal environments between the ASHRAE Thermal Comfort Tool, and the survey data by Khedari et al, are due to the strong differences in human expectations with respect to air conditioned spaces compared to non-air conditioned spaces. It is important that designers respect these differences and not try to achieve illusionary cooling energy savings by applying Khedari thermal comfort data in air conditioned space.

8. De-stratification savings during cooler months

When spaces are heated during cooler months in sub-tropical and temperate climate regions, the hotter air in a space rises toward the ceiling under gravity forces, stratifying with a significant temperature gradient, typically 1.25 K/m, from floor to ceiling. In taller spaces, over 2 m high, the heat energy in air above head height is wasted in that it does not contribute to occupant thermal comfort in the occupied zone near the floor. Thorough mixing of this hotter air with the cooler air in the space (de-stratification) will result in a uniform air temperature throughout the space. When this is achieved, heat provided to the space is better utilised [11]. Typically 10% of heating energy is saved for each 3m of floor to ceiling heights greater than 7m.

Large ceiling fans can provide substantial winter energy savings from de-stratification. Large fans are needed to achieve large air circulation rates without exceeding 0.2 m/s at head height (threshold of winter "draft" complaints). Approximately half the volume of air in a space needs to be circulated each hour for effective de-stratification. Large 7.3 m diameter fans at low speed (6.9 rpm) offer much greater aerodynamic efficiencies (up to 316 L/s.W) delivering 46.7 m^3/s compared to smaller 1.8m diameter fans operating at 300 rpm with an efficiency of fans (142 L/s.W) delivering 20.6 m^3/s.

8.1 De-stratification in air conditioned space

While architects revel in the spatial drama achieved by atria in air conditioned space, HVAC engineers have a difficult time balancing the air conditioning system due to the gravity forces unleashed by temperature difference and high ceilings. Large ceiling fans can mix the air in atria to a uniform temperature and eliminate system balancing problems.

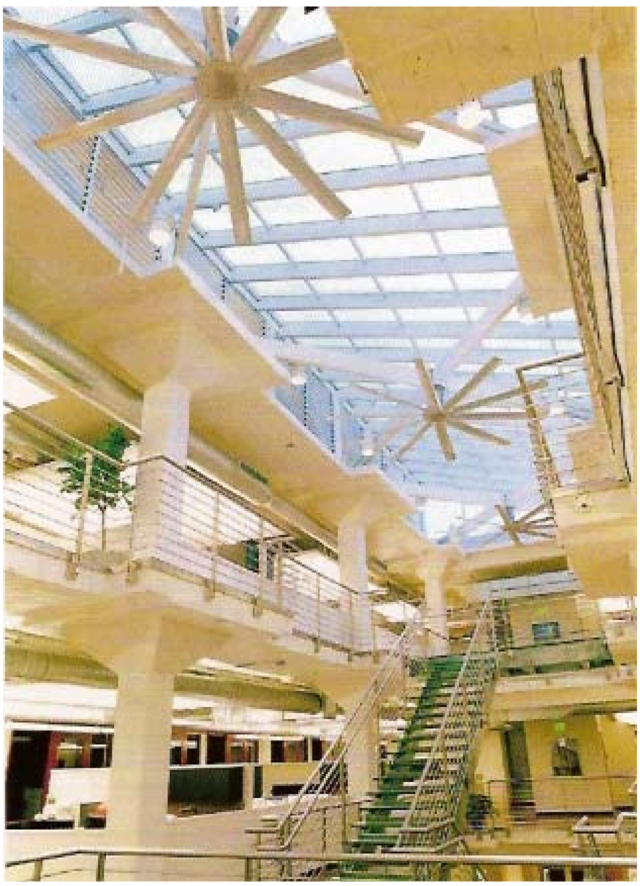

Figure 10 – de-stratification fans in air conditioned atria space

9. Conclusions

Air movement can save space heating and cooling energy in a number of ways, but care should be taken not to be confused by the widely different expectations of occupants in air conditioned and naturally conditioned spaces

In warm climates where air conditioning is not provided, air movement from natural ventilation or fans can provide a temperature offset of up to 9K to occupants. Indications of the degree of this cooling effect can be gained from the Khedari [10] study in Thailand. The effectiveness of this cooling will be influenced by the air speed, the air temperature, the mean radiant temperature, the humidity, the amount of clothing worn, and the intensity of physical activity of occupants.

In warm climates where air conditioning is provided, air movement from fans can provide a cooling effect of up to 2.5K to sedentary occupants when $t_r = t_a$, and 3.8K for non-sedentary occupants. When mean radiant temperature exceeds air temperature by more than 5K, the cooling effect on sedentary occupants can be up to 3K and 4.4K for non-sedentary occupants.

Indications of the temperature offsets from air speed in air conditioned space can be gained using the ASHRAE Thermal Comfort Tool software [5]. The value of this temperature offset is influenced by the air speed, the air temperature, the mean radiant temperature, the humidity, the amount of clothing worn, and the intensity of physical activity of occupants.

A study of facilities at the US Air Force base in Travis, California [9] showed raising thermostats by 1.1 K in summer, reduced cooling energy by 8% costs (7.3% /K).

Air movement can be used to offset such increases in set point temperatures as indicated in Figure 5.2.3 of ASHRAE Standard 55-2004 [5]. For commercial buildings the writer suggests a conservative energy savings rate of 6%/K which includes a deduction for the operation of fans to balance the increase in thermostat temperature set point.

When thermally stratified air in heated commercial or industrial spaces is de-stratified using ceiling fans, heat is better utilised [11] and typically 10% of heating energy is saved for each 3m of ceiling height. Larger, slower-moving ceiling fans can be more than twice as energy-efficient (316 L/s.W) when compared to using smaller faster ceiling fans. ■

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During his academic career he has been a consultant to federal and state governments in the USA, Australia, and New Zealand on thermal performance, energy efficiency, natural ventilation, and wind effects on buildings. He was also wind effects consultant on major building projects by architect Ken Yeang in Malaysia and Singapore. He has served on a variety of building-related standards committees in Australia, USA and New Zealand since 1975 including the committee maintaining ANSI/ASHRAE Standard 55.

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