Chapter 3
Ventilative Cooling and Comfort Models

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Abstract This chapter focuses on the description of comfort models for Ventilative Cooling. In particular, the adaptive comfort approach is described in full practical detail with an eye to related standards and regulations and designing buildings which will allow occupants to make themselves comfortable.

3.1 Chapter Introduction and Methodology

Thermal comfort in most standards and guidance is defined as *That **state of mind** that expresses satisfaction with the thermal environment (author emphasis),* but comfort is most often investigated as if it arises largely from a heat balance between metabolic heat production, and heat loss from the body surface. It is, of course, necessary to balance metabolic heat production and the heat loss, from the body over time, but the experience of comfort is also heavily influenced by other psychological, social and behavioural factors that impinge on a 'state of mind'.

Temperature is the physical measure which most clearly relates to thermal comfort, and the sensation involves both the temperature of the air (T_a) surrounding the body, and the radiant temperature in the occupied space (T_r). The operative temperature (T_{op}) is an index which combines the air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two temperatures, the weighting depending on the heat transfer coefficients by convection (h_c) and by radiation (h_r) at the clothed surface of the occupant. It is often used to express the overall temperature in a space. Thus in both the ASHRAE 55 [1] and the BSI/CEN EN15251 [2] international standards, the neutral (or comfort) temperature in the adaptive section is expressed in terms of the operative temperature (see Nicol et al. [3], Chap. 5)

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The operative temperature is defined as:

$$T_{op} = H \cdot T_a + (1 - H) \cdot T_r \tag{3.1}$$

where H is the ratio $h_c/(h_c + h_r)$. Researchers have differed in their estimates of the values of these heat transfer coefficients, and hence of the value of H. In the CIBSE Guide A [4] the value $\surd(10\ v)$, is used for the ratio of h_c to h_r where v is the air speed, and so:

$$T_{op} = \frac{T_a \cdot \sqrt{10v} + T_r}{1 + \sqrt{10v}} \tag{3.2}$$

So the relative importance of radiant temperature and air temperature in the value of T_{op} is a function of the air velocity, At higher values of v, the operative temperature tends towards the value of the air temperature. At indoor air speeds below 0.1 m/s, natural convection around the human body is assumed to approach 0.1 m/s so T_{op} approximates to

$$T_{op} \approx 1\big/2\ T_a + 1\big/2\ T_r \tag{3.3}$$

Operative temperature is a theoretical and not an empirical measure and therefore cannot be measured directly, but in practice it approximates to the temperature of a 40 mm diameter globe thermometer.

Although the equations for the evaluation of Fanger's (1970) PMV/PPD (Predicted Percentage of Dissatisfied) [5] index do not use the operative temperature as a variable, the basic physical relationships shown in Eqs. (3.2) and (3.3) will apply in any indoor space, as will an approximation of the relationships shown in Eq. (3.2) and the role of air movement in them.

Evaporative heat loss is also determined partly by the air movement. The equations for evaporative heat loss are

$$E = wh_e(p_{ssk} - p_a) \tag{3.4}$$

where E is the rate of evaporative heat flow per square metre of body surface, w is the 'skin wettedness' (a measure of the proportion of the skin which is wet with sweat in the thermal, conditions) [6], h_e is the evaporative heat transfer coefficient (see below), p_{ssk} the saturated water vapour pressure at skin temperature (kPa), and $_{pa}$ the water vapour pressure of the air (kPa).

$$h_e = 16.5h_c\ (\mathrm{W/m^2kPa}) \tag{3.5}$$

The cooling effect of air movement on wetted skin is clearly considerably greater than that on dry skin—an effect which will be familiar to anyone who has used a blown air hand-dryer. The driving force for the heat loss is therefore related to the difference between the water vapour pressure at the temperature of the skin (or other wetted surface), and the water vapour pressure of the surrounding air, making the total heat loss from the body a combination of convective heat loss, radiative heat loss and evaporative heat loss.

So air movement is clearly an important factor in the thermal relationship between humans and their environment. Air movement influences both the heat loss from the surface of the body, and also the relative importance of radiant and convective heat exchange. Models of thermal comfort were based on achieving a heat balance between building occupants and their immediate environment. Many theoretical, or empirical, comfort models were developed to enable air conditioning engineers to design their cooling systems. At first the model assumed that the resulting indoor conditions were comfortable and air movement was a source of discomfort or draught. With increased interest in natural ventilation and adaptive behaviour, air movement is now also seen as a useful, free, source of comfort cooling. Although in cool conditions an increase in ventilative cooling can increase cold discomfort, and have a negative effect, in warm environments where it is heat that is causing discomfort, the cooling effect of air movement will help This can break down at extremely high environmental temperatures where heating by radiant and convective transfer becomes greater than the cooling by evaporation.

The cooling effect of air movement is influenced not only by the mean air speed but also by its variability through turbulence [7]. It is possible to apply dynamic airflows in work areas in warm conditions through proper dynamic air supply devices. Compared to constant mechanical airflow, dynamic airflows can act like real or simulated natural wind and can achieve stronger cooling effects and better thermal comfort sensations without negatively impacting occupants' work performance [8]. The effectiveness of fans for cooling can also be increased by incorporating evaporative cooling systems [9].

3.2 Principles of Adaptive Thermal Comfort

Based on observations in field surveys, the ***Adaptive Principal*** states that *If an environment is uncomfortable people will take actions to restore their comfort*. In the adaptive approach these actions can be physiological, and possibly psychological, but are principally behavioural. Analysis of the results of international comfort surveys in the field show that this results in a strong relationship between neutral temperature of a group of people, and the mean indoor temperature they are experiencing. In naturally ventilated buildings in 'free running' mode (i.e. without heating or cooling), the indoor temperature will follow the outdoor temperature as modified by the building's form and physical character. These two relationships imply a relationship between the indoor comfort temperature, and the outdoor temperature. This is the relationship which is most widely used in international 'adaptive' comfort standards.

3.2.1 Adaptive Comfort in Free-Running Naturally Ventilated Buildings

The neutral (or comfort) temperature is the temperature which at which a vote of 'neutral' (0) is most likely to be cast by the subjects in a field survey. Actual comfort temperatures can only be found from the results of comfort surveys in which the comfort votes are collected. Comfort votes can be named +3 Hot, +2Warm, +1 Slightly warm, 0 Neutral, −1 Slightly cool, −2 Cool, −3 Cold. This scale is known as the ASHRAE scale and is used in most comfort surveys. Figure 3.1 shows the result of plotting the neutral temperature against the prevailing outdoor temperature for a wide range of buildings in free-running mode. The 'outdoor prevailing temperature' is the typical outdoor temperature at the time of the survey. In the ASHRAE and CEN standards this is the running mean of the daily mean outdoor temperature or a weighted mean of the daily mean outdoor temperature over the last few days. All buildings in the survey are in free-running mode at the time of the survey.

In Fig. 3.1 each dot on the graph gives the mean neutral temperature and the concurrent mean outdoor temperature from a whole survey, including in some cases, hundreds of sets (and none <20) of individual votes and measurements of environmental variables (temperature indoors and out, humidity, air movement etc.). In some surveys the actions of building occupants have taken to make themselves comfortable have also been recorded.

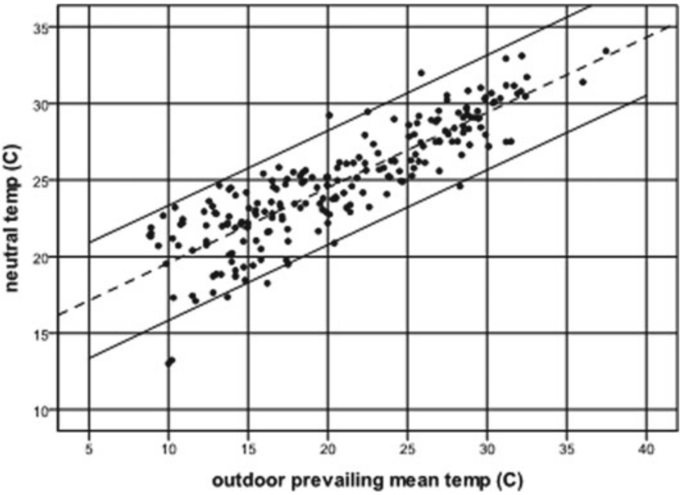


Fig. 3.1 The relationship between the temperature at which building occupants will be most likely to vote 'neutral' on the ASHRAE comfort scale and the outdoor temperature. In this graph all the buildings are in 'free-running' mode meaning that no mechanical heating or cooling is in operation at the time of the survey

The mean neutral temperature in Fig. 3.1 is 24.9 °C (s.d. 3.9 K) at the mean prevailing outdoor temperature of 21.3 °C (s.d. 8.5 K). The correlation coefficient between the neutral temperatures and the outdoor prevailing mean is 0.89, and the equation of the regression-line is:

$$T_n = 13.8 + 0.53(\pm 0.02)T_o \quad \text{(Humphreys et al. [12], Chap.29)} \tag{3.6}$$

Where T_n is the neutral indoor operative temperature, and T_o the prevailing mean outdoor temperature.

The scatter of the points about the line (the residual s.d.) is 1.8 K. The standard error associated with the estimate of a neutral temperature based on 20 observations was some 0.4 K. This is very much smaller than the observed scatter. It follows that the scatter of the points about the line is not attributable chiefly to random error, but represents real differences among the neutral temperatures of the various groups of people at any prevailing mean outdoor temperature. It is therefore better to represent the data not by a line, but by a band. The band drawn on the figure includes 95% of the observed neutral temperatures. The neutral temperatures in all the surveys selected (N $\geq$ 20) from the SCATs database [10], and from the ASHRAE RP-884 database [11], fall within the band (Fig. 3.1). The regression line should be interpreted as giving the most probable neutral temperature, rather than the only possible neutral temperature.

3.2.2 Adaptive Comfort in Conditioned Buildings

In international comfort standards [1, 2], and for much of the advice [4] given by the Heating, Ventilating and Air Conditioning (HVAC) industry, it is assumed that adaptative behaviour does not occur in buildings which are heated or cooled (conditioned), because the HVAC system provides 'comfort', making such behaviour unnecessary.

In fact, although the indoor temperatures in buildings which are conditioned (filled circles in Fig. 3.2) exhibit a smaller range, there is still a strong correlation between neutral temperature and mean indoor temperature. This suggests that even in conditioned indoor conditions building occupants adapt to be comfortable at temperatures close to the mean indoor temperature. As with free-running buildings, the occupant are effectively adjusting themselves to the conditions provided by the building, and its conditioning systems.

It is noticeable that in Fig. 3.2 that a large proportion of conditioned buildings (heated or cooled) have indoor temperatures (and neutral temperatures) in the range 20–25 °C (roughly the temperature range suggested for conditioned offices and homes in existing, non-adaptive, standards). In conditioned buildings the air-conditioning or other temperature control mechanisms will have been set to this temperature range. In Fig. 3.2 the mean indoor temperature in conditioned buildings is 23.8 °C (s.d. 1.7 K), and in naturally ventilated free running buildings 24.7 °C (s.d.

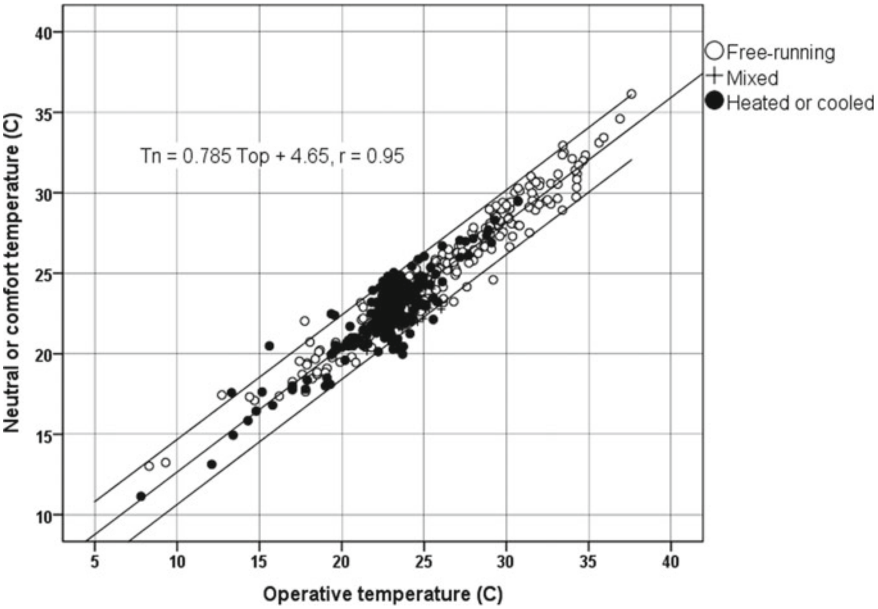


Fig. 3.2 The variation of comfort or neutral temperature (T_n) with the mean indoor operative temperature (T_{op}) in a large number of survey results (from Humphreys et al. [12])

5.0 K). Notice also that the neutral temperature is slightly below the mean operative temperature at high mean temperatures (i.e. they would prefer it to be a bit cooler) and slightly above it at low mean operative temperatures (they would prefer it to be a bit warmer), but the overall correlation between Operative and Neutral temperatures is 0.94 and the equation of the regression line is

$$T_n = 0.783 \cdot (\pm 0.011) \cdot T_{op} + 4.5 \quad \text{(Humphreys et al. [12], Chap.28)} \qquad (3.7)$$

3.3 Air Movement as an Adaptive Opportunity in Buildings

Adaptive thermal comfort assumes that people who are uncomfortable are motivated to take the *opportunities which are available to them* to make themselves comfortable i.e. those which the building, its services and the culture of the building's occupants have made available to them. Culture can be hugely important in driving or limiting actions and culture here might refer to the cultural practices of the local population, or the building management, or the group around the occupant in question. Some of these *adaptive opportunities* enable people to use the effect of air movement (either mechanically created or through the thermal or pressure driven sources) to enable building occupants to adapt their indoor environment to their liking, or to influence their own neutral temperature to move towards the conditions in the building, by for instance taking off or putting on clothes, changing postures, activities or locations in a room or building.

Many of the technologies used rely on the provision of air movement. Air movement is relatively quick and easy to control and is often readily available through simple mechanical devices such as fans and windows. The use of fans in hot conditions to increase air movement is almost universal at certain temperatures.

3.3.1 Fans

A fan does not typically change the air temperature in a space, but it simply does two things:

(a) Increases or decreases air movement to enhance comfort by increasing convective and/or evaporative heat losses from the skin or reducing them. This function is commonly used in homes, offices and public spaces.

(b) Mixes the room air to change temperatures by drawing down warmer, more buoyant air to increase comfort nearer the floor in cooler spaces. This feature can be exploited with large ceiling fans in high industrial spaces and office atria to enhance the comfort of workers on the floor [7].

(c) If the fan pushes air over, or through a water body or moisturised air then its temperature will be lowered by evaporative cooling, a feature exploited in some new cool towers where the effect can be enhanced using micronized water jets spray droplets into the air at the top of a shaft, cooling the air that then drops, often assisted by a fan, to cool people at the base of the tower [9].

Pakistan is a country with a wide range of warm and cool climates from the typical south-asian composite climate in Islamabad to the cold desert of Quetta on the border of Afghanistan, and Saidu Sharif in the Himalayas or Multan in the hot desert of the Punjab and Karachi's warm humid coastal climate. Figure 3.3 illustrates the varying use of fans in these various cities in Pakistan and shows that fans are used across a very wide range of conditions, from as low as 18 up to 35 °C with differences in practice visible between the cooler climates to the very hot climates.

The use of Fans in European offices and other cooler climates will only be significant in warmer season. Their use in Quetta as shown in Fig. 3.3 illustrates the difference. Fans begin to be used at a similar temperature to hotter climates but then rises less steeply. This is often caused by there being some places where fans are not available, and consequently fewer being available for use.

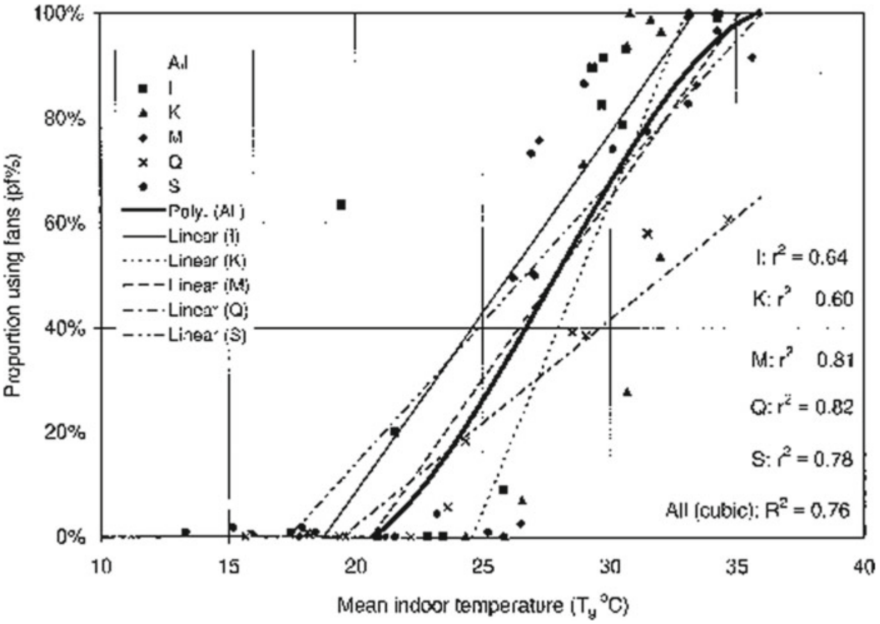


Fig. 3.3 Fans are widely used in hot climates to help offset the effects of high temperature (Date from offices in Pakistan. Nicol et al. [14]). The initial letters signify the city where the data were collected I = Islamabad, K = Karachi, M = Multan, Q = Quetta and S = Saidu Sharif

3.3.2 *Windows*

The opening of a window can change the indoor temperature, and it can also encourage indoor air movement which will modify the heat exchange at the body surface of the occupants so that their desired temperature is also changed.

The opening of a window will have a cooling effect, for any individual, at a temperature which might be called the 'warm trigger temperature' (t_{warm}, Fig. 3.4a).

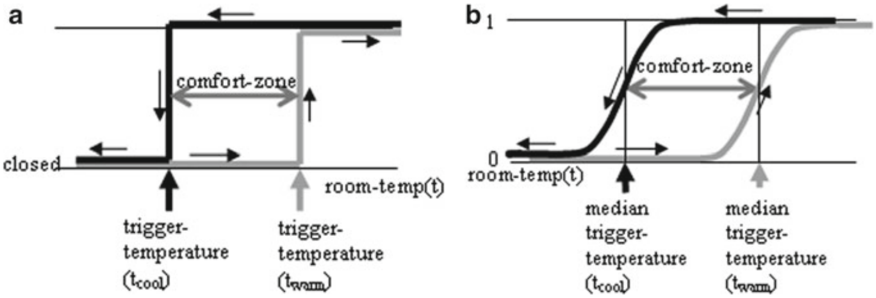


Fig. 3.4 **a** Showing the basic model for an individual, **b** the overall model for a group

The assumption is that opening the window will (a) allow cooler outdoor air to cool the interior, (b) increase air movement (the effect of outdoor wind or of thermal pressure). The overall cooling effect can be increased by air movement. Even if the outdoor air coming in through the window is at a higher temperature than the indoor air the increased loss of heat through evaporation can mean the indoor temperature feels cooler. Likewise, if the room becomes too cool and the window is open, the individual will close the window at a 'cool trigger temperature' (t_{cool} in Fig. 3.4a).

Figure 3.4b shows how this might apply to a group of people in a single room. Each will have a different pair of trigger temperatures and this will be expressed by a horizontal distribution. The median values of the trigger temperatures t_{warm} and t_{cool} are suggested. As temperatures vary within the room the likelihood of windows being open or closed will change but in general there will be a tendency for the windows to be open more often within a limiting envelope.

Figure 3.5 shown the distribution of the likely number of open windows in buildings at different indoor temperatures. Such a distribution curve can be used to estimate energy use and comfort in a group of buildings with opening windows [13]. The air movement measured in any building tends to rise as the temperature increases as a result of the adaptive behaviour of occupants in opening windows and using fans.

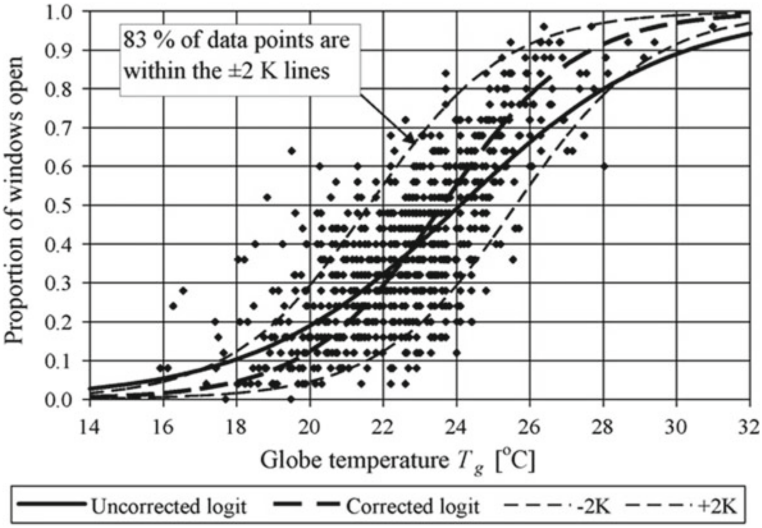


Fig. 3.5 The shape of the window open distribution in data collected from a number of buildings in the UK (Oxford and Aberdeen) over a year. Each point is the proportion of windows open from 25 occasions with the same indoor temperature (*Source* Rijal et al. [13])

3.3.3 Air Movement in Buildings

That air movement is used as a tool to cool the interior is amply illustrated by the two graphs in Fig. 3.6 which show the mean air speed in buildings as a function of indoor temperature in offices in Europe and Pakistan. Note the air speed is represented by its square root in these graphs because the square root best represents the cooling effect of air movement. Note also that the minimum air speed is represented by 0.3 $(\text{m/s})^{1/2}$ ($\approx 0.1\ \text{ms}^{-1}$) which is the speed of air caused by convective heat lost at the skin. Note that air velocities are higher in the warmer climate but that in both the increase starts at about 26 °C.

The cooling effect of air movement through windows can be enhanced by encouraging cross ventilation between one opening and another. Air movement is managed in buildings not just through windows but that other pathways are also widely used. The opening of doors can create effective cooling, or warming, air pathways through a building, driven by temperature differences between spaces and wind pressure between openings. In a wide survey in the UK, Raja et al. [15] investigated the effect of having both door and window open and found temperature of the average room with cross ventilation was lower by about 1 °K than in those with one-sided ventilation at the same outdoor temperature.

Spaces such as atria, sunspaces and conservatories can act to 'pump' warmed, expanded, air through a building. Stair wells and vertical shafts can work to push warmer air upwards by buoyancy during warm spells, or draw cooler air downwards in cooler ones. Good designers can anticipate and use the form of the building and knowledge of the local climate to design internal comfort conditioning systems using such thermal and pressure driven air systems.

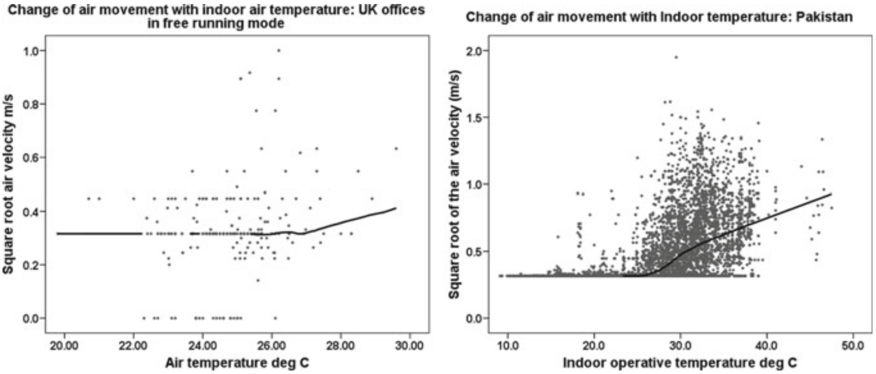


Fig. 3.6 Mean air movement measured at different indoor temperatures in (left) free-running European offices (data from France, Greece, Portugal and UK in the SCATs project) and (right) Pakistani offices (from various towns [14])

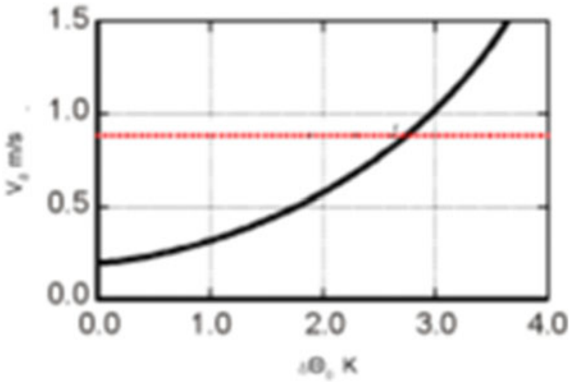


Fig. 3.7 Equivalence between air velocity and temperature as proposed by ASHRAE 55 [1] and BSI [2]

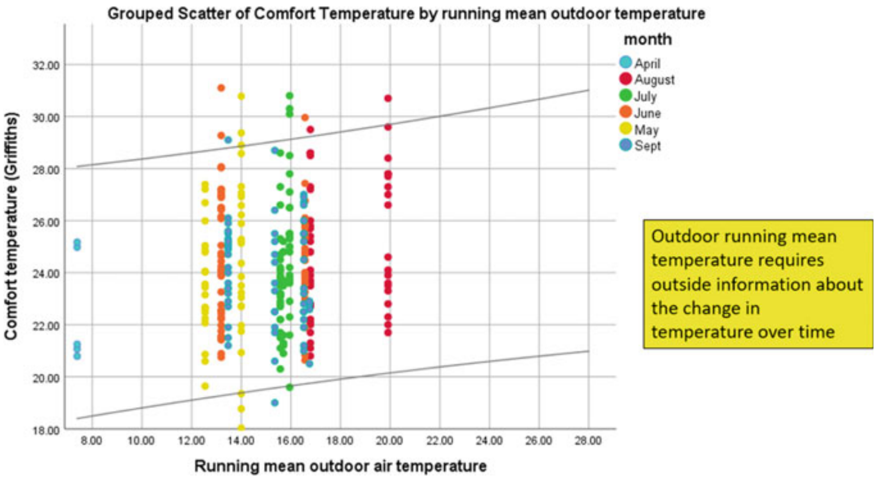
3.3.4 Air Movement in International Standards and Adaptation

As far as possible the indoor environment in a building should naturally fall within usual local comfort limits. This can be achieved not only with mechanical ventilation, but also in a more environmentally friendly and low energy way by using passive means to control temperatures indoors. These can use, for instance, permanent or temporary shading, thermal mass, orientation, window size, the diurnal and seasonal harvesting or dumping of heat with windows utilising local micro-climates, and so on. The building should allow occupants to control their environment with a range of adaptive opportunities including opening windows, adjustable shades to keep sun out, fans for increased air movement and different climate spaces around the building.

International Standards recognise the importance of air movement through a rough ‘equivalence’ between air movement and temperature reduction (Fig. 3.7). There is a growing imperative to mitigate climate change by reducing carbon dioxide emissions, hence reducing energy use in buildings and limiting the use of refrigerant gasses, particularly those with a high global warming potential. Thus the use of mechanical heating and/or cooling should be kept to a minimum by using careful building design which takes account of the regional climate and importantly local micro-climates around a building.

3.4 Building Occupants and Changing Temperatures

Nicol [16] found that in dwellings the range of indoor temperatures is often larger in buildings when they are heated or cooled than when they are free-running. This is not predicted by comfort standards where buildings with mechanical conditioning are



Outdoor running mean temperature requires outside information about the change in temperature over time

Fig. 3.8 Showing the wide range of indoor neutral (comfort) temperatures at monthly intervals

expected to be using the conditioning keep their temperature constant at a calculated neutral temperature. This unexpected result suggests that heating and cooling systems are in reality being used to suit the indoor temperature to the variable requirements of building occupants.

It is important to stress that there is evidence that acclimatised populations in their own homes find a wide range of temperatures, between 10 and 35 °C [17] are acceptable, to occupy during their habitual diurnal, or annual, lifestyle pathways through the familiar thermal landscapes of the spaces and places.

Figure 3.8 shows that acceptable temperatures in homes and offices vary not only by day and year but by month as well. These broad limits for acceptable comfort are demonstrated for adapted populations, who have to hand a functional range of adaptive opportunities that enable them to adapt themselves and their environments to achieve the goal of creating adequately comfortable conditions.

The control of air movement and clothing will influence the indoor environment which is found comfortable by the occupants. So where possible occupants should also feel free to adjust clothing, move to more comfortable places etc. This implies that it is not just the physical environment which is important but also the culture of the local population.

These considerations will also vary according to the purpose of the building so that a dwelling will be used differently than a workplace, and the level of operable adaptive opportunity may vary enormously, not only between buildings, but also between the mind-sets and cultural constraints of building owners, operators, managers, personalities and occupants (so management need to be aware of the ‘cost’ of a ‘dress code’).The financial responsibility for energy use can also change behaviours, driven by the desire to reduce or increase reliance on passive conditioning of buildings, as can the growing awareness of the environmental impacts of energy use in a heating world. Both of these factors influence the current move back towards designing buildings that can rely for as much of the day or year as possible using natural ventilation, and only relying on heating and cooling to condition buildings when needed.

3.5 Humidity and Comfort

There is a popular conception that humidity plays an important role in the thermal comfort of people. If humidity is measured as relative humidity (RH) it can appear important but that is because RH includes temperature in its definition, and this is reflected in the statistics. If instead of RH, the water vapour pressure is used to measure the effect of humidity the it is found to be small (Humphreys et al. [12], pp. 179–180). At the temperatures we are assuming within a warm building (say 30 °C) a difference in water vapour pressure from 0 kPa (zero humidity) to 4 kPa (about the maximum for air at this temperature) the difference in PMV is about 1. In reality the inside of an occupied room is unlikely to have anything like this range of humidity.

3.6 Conclusions

Ventilation is a key element of how people use, and appreciate, buildings. It is not just a matter of having enough air of the right quality, speed and temperature, but the air which moves through a building is an essential part of the deep and unspoken relationship between the building, its thermal landscapes and its occupants. The theory of thermal comfort allows for the estimation of the effect of moving air, and the ways in which its heat transfer properties are used by building occupants to make their dwellings, workplaces and lifestyles comfortable enough within the cultural and economic constraints of their own cultures, and personal circumstances.

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