Chapter 5
Thermal Comfort Inside and Outside Buildings

Richard de Dear and Jungsoo Kim

Abstract Engineers and architects are required to consider human occupants or pedestrians during the design process. The topic of human thermal comfort is often considered to be a long way from the traditional, hard science disciplines normally associated with engineering. Nevertheless there is a scientific basis for thermal comfort. The topic draws on several scientific disciplines, including physics (especially heat transfer and meteorology) and physiology. But most importantly of all, thermal comfort falls within the scope of psychology, since it is defined as 'that condition of mind that expresses satisfaction with the thermal environment'. Some general principles are relevant to the topic of thermal comfort both indoors and outdoors, but there are some very striking differences between the two settings as well, and these differences have significant implications for engineering of indoor and semi-outdoor climates.

Keywords Thermal comfort • PMV/PPD • HVAC • Adaptive comfort • Natural ventilation

5.1 Introduction: Thermal Comfort as a Design Consideration

Thermal comfort indoors has been the subject of scientific research ever since the ability to control indoor climate with air conditioning became commercially viable in the early decades of the twentieth century. There are six physical parameters that go into the comfort equation, comprising four environmental parameters (air temperature t_a, mean radiant temperature t_r, relative humidity *rh* and airspeed *v*) that affect heat transfers to or from the body and two personal parameters that describe the amount of heat being generated in the body and the resistance to that heat being lost to the environment (*met*, *clo*). From the designer's point of view, the four environmental parameters are affected by different elements of the built

---

R. de Dear (✉) • J. Kim
Faculty of Architecture, Design and Planning, University of Sydney, Sydney, NSW 2006, Australia
e-mail: richard.dedear@sydney.edu.au

Y. Tamura, R. Yoshie (eds.), *Advanced Environmental Wind Engineering*,
DOI 10.1007/978-4-431-55912-2_5

environment and are therefore amenable to deliberate control by both architectural elements and mechanical services. The easiest to control is air temperature, and the mechanism of direct control is heating, ventilation and air conditioning (HVAC). Relative humidity is also subjected to control by HVAC systems, sometimes, but because of the enormous amount of energy required to chill supply air below its dew point just to remove moisture, this capability of HVAC is not commonly exploited. Mean radiant temperature (t_r) refers to the average surface temperature of the enclosure, as 'seen' by the occupants, and it controls the thermal (infrared) radiation exchange with the human body. This includes wall, floor, ceiling and window temperatures, which are not commonly controlled parameters in building. However, with sufficient insulation it is possible to maintain wall, floor and ceiling temperatures close to the air temperature prevailing within the space. Glazing, however, is a bit more problematic, and the modern tendency for architects to use this material across large expanses of perimeter walls (facades) poses complex thermal comfort problems for the occupants. If single-pane glazing is used, there is a high risk that the internal surface of the window will have a low surface temperature whenever outdoor air temperatures are low, giving rise to undesirable local cooling of the occupants (termed 'radiant draught'). When glazing is directly irradiated by the sun, there is a risk of another local discomfort – high-temperature radiant heat from the direct solar radiation penetrating the glazing and also from the glazing itself after it has been heated by absorbed solar radiation. Airspeed is the fourth environmental control of the human body's heat balance and is a parameter that can be manipulated to varying degrees by intelligent design of the size, placement and configuration of openings in the walls or ceiling. By consideration of the outdoor meteorological and climatic conditions surrounding the building (site climate), air movement within the occupied zone can be exploited as a low-energy strategy for cooling building fabric and also the building's occupants in hot climates. For mechanically regulated indoor climates, airspeed is partially controllable by placement and sizing of air inlets relative to the occupants of the space and also the velocity of supply air as it enters the occupied zone. However, for most HVAC design systems in use today, airspeed within the occupied zone is not readily controlled, and so it is generally constrained to barely detectible speeds (<2 m/s) so as to avoid the risk of draught in cooler-than-neutral indoor climates. However, newer approaches to HVAC such as displacement ventilation rely on the delivery of very low-speed conditioned air to the space just above floor level where it accumulates and rises slowly due to thermal buoyancy as it becomes warmed by various heat sources within the occupied zone (occupants, computers, lighting, etc.).

The other two factors controlling the human body's heat balance are referred to as the personal comfort parameters – metabolic rate (*met*) and clothing insulation (*clo*). Since these two relate to the behaviour of the occupants of a building rather than the building itself, they are generally regarded as beyond the designer's control. By thoroughly understanding the nature of the occupancy of the building in question – learning about the dress codes or customs of the building's occupants and the types of activity levels they are likely to engage in within the building – the designer should be able to make reasonable estimates of *clo* and *met* values. This knowledge can then be used to optimise the design of the other four environmental comfort parameters so that occupant thermal comfort can be achieved.

Designing for comfort in *outdoor* settings is not as straightforward as the indoor scenario described above for the simple reason that these settings are not fully enclosed, and therefore, total control of the four environmental comfort parameters is not feasible. Whilst control of space temperature may not be a design option, the remaining three parameters can often be attenuated if not totally controlled. Air-speeds can be reduced by wind shelters or increased with deliberate design of 'wind catchers' or mechanical fans. Dehumidification may not be feasible in hot and humid outdoor settings, but humidification with sprays of droplets is one option in arid climate zones, with the added advantage of localised evaporative cooling. Radiant temperatures outdoors cannot be directly controlled, but solar shading is an essential strategy for keeping radiant loads within an acceptable range for the occupants of hot outdoor and semi-outdoor settings.

5.2 Thermal Comfort Indoors

ASHRAE Standard 55-2013 (ASHRAE 2013) currently recommends two distinct strategies for defining the indoor comfort zone, depending on whether the setting is (a) a mechanically air-conditioned building where occupants typically have little or no access to thermal controls or (b) a naturally ventilated building where occupants have access to operable windows. In relation to the former setting – centrally controlled air conditioning, the 'father of modern thermal comfort science', Professor P.O. Fanger (1970), subscribed to the adage that you 'can't please all of the people all of the time', so he devised an index (*PMV*/*PPD*) to maximise comfort for multiple occupants sharing the same indoor climatic conditions. Predicted Mean Vote (PMV) is an index that predicts the mean thermal sensation of a group of people, determined from thermal the six comfort parameters introduced earlier (i.e. t_a, t_r, *rh*, *v*, *met* and *clo*). The result is output on a seven-point scale ranging from −3 to +3 (−3 *cold*, −2 *cool*, −1 *slightly cool*, 0 *neutral*, +1 *slightly warm*, +2 *warm*, +3 *hot*). *PPD* (Predicted Percentage Dissatisfied) predicts the percentage of dissatisfied with thermal conditions and is derived directly from the *PMV* index. In ASHRAE Standard 55 (ASHRAE 2013), the acceptable thermal condition, so-called comfort zone , is defined as *PMV* values between ±0.5, corresponding to a *PPD* value of less than 10 %. By making an assumption that there will typically be an additional 10 % dissatisfied from local discomforts such as draught, radiant asymmetry and vertical air temperature stratification, the practising engineer can assume that an internal space with a PMV of ±0.5 will achieve a combined level of dissatisfaction below 20 %, commonly regarded as an industry benchmark. *PPD* reaches its minimum value (5 %) when *PMV* equals zero (i.e. *neutral*), then *PPD* starts to increase as *PMV* values deviates from neutrality in either the warm or cool direction.

The underlying concept of the *PMV*/*PPD* indices is Fanger's first prerequisite for thermal comfort – net heat balance for the human body. The simple heat equation identifies the state of thermal comfort as occurring when heat fluxes into the body by metabolism, convection, radiation and conduction are balanced by the fluxes out of the body via work, convection, radiation, evaporation and conduction. Fanger's second requirement for comfort was that mean skin temperature and evaporative heat loss from the skin are within their respective 'comfort ranges'. Comfort ranges for skin temperature and evaporative heat loss were defined empirically as functions of metabolic rate. The comfortable skin temperature is an inverse function of metabolic rate and the comfortable evaporative heat loss is a positive function of metabolic rate.

Referring back to the ASHRAE 55-2013 (ASHRAE 2013) comfort standard again, the second recommended approach is that for naturally ventilated spaces where there is no mechanical cooling available, but occupants have direct access to operable windows. In this setting, the ASHRAE standard prescribes de Dear and Bragers' (1998) adaptive approach to comfort, which differs fundamentally from Fanger's heat-balance approach in that it accepts non-heat-balance factors such as culture, thermal history, context and thermal expectation as exerting influence over thermal comfort outcomes. The adaptive model is based on extensive field studies of thermal comfort drawn from a wide spectrum of climate zones and 160 different buildings across the globe (de Dear 1998) and indicates that thermal comfort can be attained in warmer indoor temperatures if the outdoor climate is warm and cooler indoor temperatures when the outdoor climate is cold. In effect, the occupants of naturally ventilated buildings adapt to the conditions they are exposed to by a variety of mechanisms, including physiological (acclimatisation), behavioural (using operable windows) and psychological (adjusting comfort expectations). The major conceptual departure of the adaptive model is its reference to thermal history, expectations and attitudes, perceived control and availability of behavioural thermoregulatory options (sometimes referred to as 'adaptive opportunities'). Whilst the heat-balance model is able to account for some degree of behavioural adaptation, such as changing one's clothing or adjusting local air velocity, it ignores the psychological dimension of adaptation completely, which explains the inconstant predictive skill of PMV/PPD. Psychological dimensions of thermal adaptation may be particularly important in contexts where people's interactions with the environment (i.e. personal thermal control through adaptive opportunities), or diverse thermal experiences, may alter their expectations and, thus, their thermal sensation and satisfaction. Figure 5.1 shows the upper and lower operative temperature limits for 80 and 90 % acceptability, defined by adaptive model. The running 7-day mean outdoor air temperature ($T_{a(out)}$) is a basis used to define the adaptive driver for input to the adaptive comfort model, which is expressed as

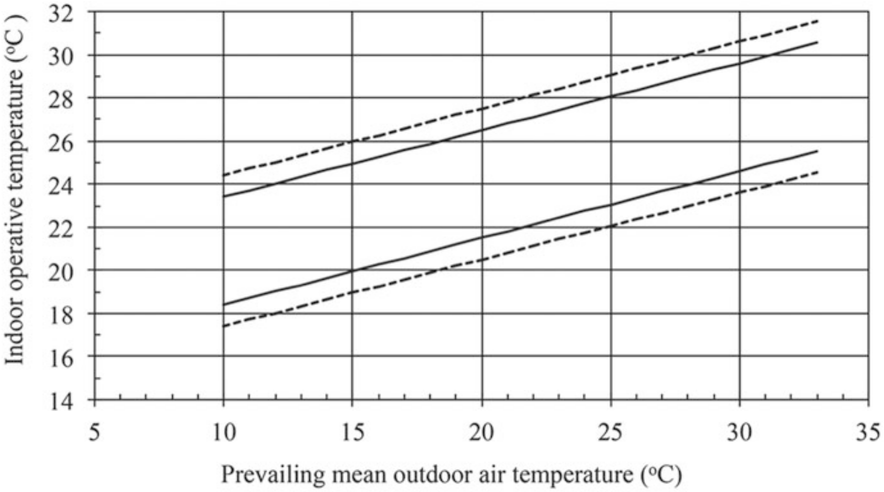

Fig. 5.1 Acceptable operative temperature (t_o) ranges for naturally conditioned spaces, *solid lines* and *dashed lines* represent 90 % and 80 % acceptability limits, respectively (ASHRAE 2013; de Dear and Brager 1998)

$$T_{a(out)} = 0.34T_{a(day\text{-}1)} + 0.23T_{a(day\text{-}2)} + 0.16T_{a(day\text{-}3)} + 0.11T_{a(day\text{-}4)} + 0.08T_{a(day\text{-}5)} + 0.05T_{a(day\text{-}6)} + 0.03T_{a(day\text{-}7)}$$

The 7-day running mean decay function signifies that the mean daily outdoor temperature yesterday is the most important driver of adaptive comfort (34 % weighting), followed by the day before yesterday (23 % weighting), then the day before that (16 % weighting) and so on back to 7 days ago which carries just 3 % weighting. These exponentially decaying weighting coefficients are based on empirical evidence provided by a clothing behaviour observational study (Morgan and de Dear 2003) in a shopping mall in Sydney, Australia. In that study, a detailed *clo* estimate was made for a random sample of about 50 subjects each day, continuously for a 6-month period. The daily mean *clo* value was then correlated with the mean outdoor temperature on the preceding day (day $x-1$). That correlation was repeated for *clo* on mean outdoor temperature on days $x-2$, $x-3$, $x-4$, $x-5$, $x-6$ and $x-7$. The relative sizes of those correlation coefficients formed the basis of the exponentially decaying weighting coefficients appearing in the above equation.

As implied by the adaptive model, psychosocial factors such as occupants' thermal history, expectations and adaptive behaviours can all play an important role in shaping their comfort zone inside buildings. Kim and de Dear (2012) explored differences between occupants in air-conditioned buildings and naturally ventilated buildings, focusing on their expectations of what indoor thermal environment should be like. The analysis was based on a large post-occupancy evaluation database ($n = 22{,}518$ from 137 office buildings) (Zagreus et al. 2004), and it suggested that people in air-conditioned buildings tended to have higher expectations for thermal uniformity inside their buildings, becoming highly critical whenever a building failed to meet those expectations (i.e. when indoor temperature deviates from the narrow temperature range they have come to expect). In contrast, occupants in naturally ventilated buildings reported relatively modest expectations of indoor thermal environment, tending to accept less-than-ideal thermal conditions. Therefore the researchers contended that thermal comfort in naturally ventilated buildings was regarded by their occupants as a 'bonus'. Such a building is 'forgiven' by occupants whenever it is thermally underperforming, but it can also be pleasantly surprising whenever it exceeds occupants' 'thermal expectations'. The air-conditioned subsample gave a different response – thermal comfort was perceived as 'basic' or minimum requirement of occupants of air-conditioned buildings.

In a centrally air-conditioned building, creating thermally uniform and imperceptible indoor environments (neither warm nor cool, i.e. neutral) based on *PMV/PPD* model has been the design objective for building services engineer since the invention of air conditioning. On the other hand, occupants in naturally ventilated buildings are exposed through operable windows to various unquantifiable or qualitative sensations (e.g. nice breeze, connection to outdoor weather rhythms, etc.), which can never be experienced in a sealed facade air-conditioned space. Whilst 'not being uncomfortable' is as good as it gets in air-conditioned buildings, a more dynamic and variable indoor climate, sometimes departing from neutrality in naturally ventilated buildings, may let occupants perceive thermal comfort transcending basic functional needs (Kim and de Dear 2012). According to the alliesthesia hypothesis, a dynamic indoor thermal climate offers the prospect of thermal pleasure, perhaps even thermal delight (Heschong 1979).

Since heating, ventilation and air conditioning (HVAC) typically account for about half of a commercial building's energy usage, the naturally ventilated approach is attracting renewed interest from architects and engineers who are keen to reduce the greenhouse gas footprint of the buildings they design. These designs can be fully naturally ventilated, or mixed-mode, depending on the severity of the external climatic environment. A mixed-mode building is one that is naturally ventilated for some of the time (weather permitting) using operable windows or vents whenever the external climate is favourable and air-conditioned whenever external atmospheric conditions are unable to deliver comfortable internal conditions. By intermittently flipping into natural ventilation mode, mixed-mode (or hybrid) ventilation buildings can dramatically reduce their energy use associated with HVAC systems whilst still maintaining the quality and acceptability of their indoor environment. Besides the impact of operating mode on energy consumption, there are differences in occupants' perception of thermal environment as well. According to a post-occupancy survey conducted in a mixed-mode building with accompanying physical measurements, the same occupants in the same building responded differently to the identical thermal environment, depending on the building's ventilation mode (Deuble and de Dear 2012). Within naturally ventilated mode, the occupants were more accepting of thermal conditions that were 'warmer than neutral', compared to when the building was operating under air-conditioned mode.

5.3 Thermal Comfort Outdoors

Thermal comfort research outdoors and in 'halfway' settings, sometimes called 'semi-outdoors', is usually based on the same four microclimatic parameters (t_a, t_r, rh and v) as indoor comfort research. However one of the key parameters, mean radiant temperature, is fundamentally different in the outdoor and semi-outdoor setting because there is a complex array of both short- and long-wave radiation fluxes impinging on the subject from all directions as a result of sunshine (which is generally not relevant indoors). A software tool by Matzarakis et al. (2010) estimates outdoor mean radiant temperature for practical applications.

Once the four microclimatic parameters (t_a, t_r, rh and v) have been directly measured or estimated in the outdoor or semi-outdoor setting, they are typically integrated together with estimates of clothing insulation (*clo*) and metabolic rates (*met*) into a heat-balance index of thermal comfort such as *OUT_SET*, *PT*, *PET* or, most recently, the Universal Thermal Climate Index (*UTCI*) (Hoeppe 2002). These indices integrate the effects of all six comfort parameters on the human thermal balance – giving a single number (environmental rating) that purport to represent a metric of subjective thermal comfort experienced by the 'average' person exposed to those outdoor environmental conditions.

Case studies of research in sports stadia were described by Bouyer et al. (2007). Wind environmental data in this study were estimated from wind tunnel simulations of scale model, whilst other comfort model inputs were estimated from meteorological records or dynamic thermal simulations of the structure's response to typical meteorological conditions.

A significant theoretical critique of this approach focuses on the presumption that 'neutral' or 'comfortable' means the same thing in physical or physiological terms in an *outdoor* context as it does indoors. There is no empirical basis for this extrapolation from indoor research to outdoors. As addressed in the earlier section, only a narrowband close to neutrality (i.e. $-0.5 < PMV < +0.5$) within boundaries of -3 (*cold*) and $+3$ (*hot*) is deemed as thermally acceptable range for air-conditioned spaces. However, outdoor climate conditions are expected to deviate more significantly from neutrality, covering a much wider range than typical indoor climates because the latter are commonly controlled or moderated by architectural or mechanical systems. Therefore the thermally acceptable range in outdoor spaces as well can be expected to stretch further from $PMV = 0$. Indeed, there are detailed outdoor and semi-outdoor comfort studies in Sydney (Spagnolo and de Dear 2003) and in Tokyo (Nakano and Tanabe 2004) indicating a discrepancy of up to 4 °C or 5 °C between optimum indoor and outdoor comfort conditions.

Using the classic thermal comfort field research design (the 'right-here-right-now' survey design), Spagnolo and de Dear (2003) conducted an outdoor comfort survey in various settings in subtropical Sydney with a purpose of developing thermal comfort instruments and protocols for (semi)-outdoor research. A mobile meteorological station was developed to measure outdoor microclimates including t_a, *rh*, *v*, *global short-wave radiation (k)*, *diffuse short-wave radiation (d)* and *long-wave radiation (l)*. A distinctive feature of this instrumentation was its alternative approach to measurement of mean radiant temperature (t_r). The sensors were installed on a hinged plate that could be inverted to record radiative fluxes from both hemispheres, one facing upwards and the other downwards (Fig. 5.2 left). Use of radiation sensors that integrate across 180° angle and two hemispheres provided a reliable average of the short- and long-wave radiation fluxes from all directions, which in turn simplified t_r calculation greatly. Their 'right-here-right-now' comfort survey carried out in diverse outdoor and semi-outdoor spaces with different surface types and human biometeorological conditions indicated that the comfort zone prescribed for indoor spaces is not directly applicable to outdoor contexts. The study reported a much larger range of comfort zone in outdoor settings than indoors, possibly because of the much great thermal variability of outdoor environment over space and time being factored into people's expectations.

A more recent study conducted in Japan took a completely different approach to the task of measuring human biometeorological urban climates. Instead of measuring at a single point in time and space, their focus was on the traverse of pedestrians through time and space. This required a new method of sensing the main comfort parameters and also the corresponding human physiological responses to those parameters. As illustrated in Fig. 5.2 (right panel), Nakayoshi et al. (2015) developed compact, wearable instrumentation that measures both meteorological variables (t_a, *rh*, *v*, *short-wave radiation s* and *long-wave radiation l*) and simultaneous physiological variables (t_{skin}, *pulse rate* and *body motion*). Whilst the subjects were walking through a series of urban outdoor settings, the microclimate enveloping the subject and the matching physiological states were simultaneously scanned into a logger worn by each subject. Some other physiological indices such as tympanic temperature and sweat rate were manually measured intermittently by the

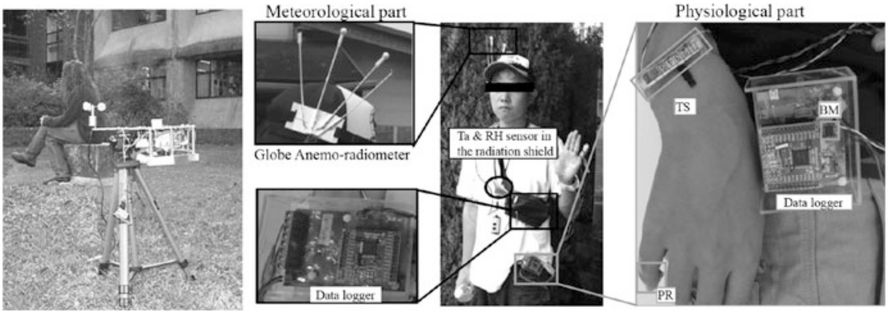

Fig. 5.2 Mobile meteorological station by Spagnolo and de Dear (*left*) (Spagnolo and de Dear 2003) and wearable thermal physiology measurement system by Nakayoshi et al. (*right*) (*TS* thermal sensation, *PR* pulse rate, *BM* body motion detected by accelerometers) (Nakayoshi et al. 2015)

researchers throughout the experiment (Nakayoshi et al. 2015). Given that thermal comfort studies in outdoor settings have previously been restricted by the difficulties of data collection, particularly if the environment is transient as is the case for pedestrians on the move, the instrumentation and protocol proposed by Nakayoshi et al. make a significant improvement in the practicality of characterising objective urban biometeorological environments and simultaneous subjective comfort responses of pedestrians moving through those environments.

Divergence between indoors and outdoor thermal comfort zones was highlighted by another *right-here-right-now* comfort survey carried out in humid tropical climate of Singapore (Yang et al. 2013). The naturally hot and humid climatic conditions of Singapore have been exacerbated in recent decades by an urban heat island resulting from rapid urbanisation. Thermal comfort perception and preference of people in various outdoor spaces (typically resting places) at various times of a day (morning, midday, afternoon and evening) were investigated matched against simultaneous measurements of the key microclimatic parameters (using an identical field method to that described earlier in Spagnolo and de Dear (2003)). The neutral operative temperature and preferred temperature based on 2036 sets of comfort questionnaires were estimated as 28.7 °C and 26.5 °C, respectively. In Singapore, the operative temperature range of 26–32 °C was found to be *acceptable* to people in outdoor spaces.

A consistent finding in all of these applications of the conventional *right-here-right-now* thermal comfort research method to outdoor settings is a discrepancy between the temperatures that indoor heat-balance models predict should be comfortable and what subjects in outdoor settings actually say is comfortable. This offset between indoor and outdoor comfort has usually been explained in terms of differences in comfort expectations (Spagnolo and de Dear 2003; Yang et al. 2013), but an alternative psychophysiological hypothesis has emerged in recent years (de Dear 2011) that gives a more thorough explanation of why positive feelings of comfort can be experienced in thermal situations that would not normally be regarded as comfortable were they to be encountered in indoor settings. Called 'alliesthesia', this hypothesis points, in a hot environmental context, to the effects of a cooling breeze on the skin and cutaneous cold thermoreceptors just beneath the skin surface. Even though the transient cooling may not be sufficient to fully restore skin temperature and skin latent heat loss to the values corresponding to 'neutral' for their metabolic rate (according to Fanger's indoor heat-balance comfort theory), the skin cooling is sufficient to trigger the impression that restoration of neutrality is on its way. Transient local cooling at skin surface in hot and humid thermal environments can be perceived as something more pleasant than a 'neutral' thermal sensation of the type encountered, for example, in a conventionally air-conditioned office environment. Alliesthesia also explains why a glass of water is being especially enjoyable when we are slightly dehydrated or why a meal tastes particularly delicious when we are hungry. The same meal taken when we are sated would taste ordinary by comparison – even though the meal itself is identical in both situations. The significance of alliesthesia in this chapter on thermal comfort is that indoor or outdoor thermal environments may not need to comply with the very narrow range prescribed by the *PMV*/*PPD* index in order to be acceptable. Indeed, warm indoor or outdoor environments can still be rated as acceptable by their occupants, as long as there is some relief provided by air movement around the body. That air movement can be mechanically generated by fans or it can result from the movement of a pedestrian *through* warm or even hot urban microclimates (Nakayoshi et al. 2015) – whenever localised cooling is detected on the skin surface, the alliesthesial response of thermal pleasure will be elicited in a pedestrian having a whole-body thermal sensation that is warmer than neutral.

5.4 Conclusions

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. It can be predicted in air-conditioned environments by the *PMV*/*PPD* index using just four environmental measurements and two personal parameters (*clo* and *met*). The goal of design in such contexts is to maintain *PMV* equal to or very close to zero (*neutral*) for as many of the occupied hours of the building's life as possible.

The range of thermal conditions required for comfort in naturally ventilated buildings is considerably wider than in air-conditioned buildings. The adaptive comfort theory describes an indoor comfort zone that drifts upwards in buildings located in hot climates and downwards in cold climate zones. This observation carries significant implications for the design and operation of low carbon-emitting buildings, and this represents one of our more promising avenues for mitigating humankind's impact on global climate.

Comfort in the outdoor and semi-outdoor climatic contexts is controlled by the same factors as described above for indoor settings, but cultural and contextual factors, including expectations, appear to widen the acceptable comfort zone even further. Rather than striving for static, neutral thermal conditions in outdoor settings, the designer should consider natural microclimatic dynamics as a positive attribute. In warm to hot microclimates, the key to creating comfort for the occupants seems to be the exploitation of wind (breeze) resources.

References

ASHRAE (2013) ANSI/ASHRAE standard 55-2013: thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta

Bouyer J, Vinet J, Delpeche P, Carre S (2007) Thermal comfort assessment in semi-outdoor environments: application to comfort study in stadia. J Wind Eng Ind Aerodyn 95:936–976

de Dear R (1998) A global database of thermal comfort field experiments. ASHRAE Trans 104 (1b):1141–1152 de Dear R (2011) Revisiting an old hypothesis of human thermal perception: alliesthesia. Build Res Inf 39(2):108–117

de Dear R, Brager G (1998) Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104(1):145–167

Deuble MP, de Dear R (2012) Mixed-mode buildings: a double standard in occupants' comfort expectations. Build Environ 54:53–60

Fanger PO (1970) Thermal comfort. Danish Technical Press, Copenhagen

Heschong L (1979) Thermal delight in architecture. MIT Press, Cambridge, MA

Hoeppe P (2002) Different aspects of assessing indoor and outdoor thermal comfort. Energy Build 34:661–665

Kim J, de Dear R (2012) Impact of different building ventilation modes on occupant expectations of the main IEQ factors. Build Environ 57:184–193

Matzarakis A, Rutz F, Mayer H (2010) Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. Int J Biometeorol 54(2):131–139

Morgan C, de Dear R (2003) Weather, clothing and the thermal adaptation to indoor climate. Clim Res 24(3):267–284

Nakano J, Tanabe S (2004) Thermal comfort and adaptation in semi-outdoor environments. ASHRAE Trans 110:543–553

Nakayoshi M, Kanda M, Shi R, de Dear R (2015) Outdoor thermal physiology along human pathways: a study using a wearable measurement system. Int J Biometeorol 59(5):503–515

Spagnolo J, de Dear R (2003) A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Build Environ 38(5):721–738

Yang W, Wong NH, Jusuf SK (2013) Thermal comfort in outdoor urban spaces in Singapore. Build Environ 59:426–435

Zagreus L, Huizenga C, Arens E, Lehrer D (2004) Listening to the occupants: a web-based indoor environmental quality survey. Indoor Air 14(8):65–74