5. Important aspects of human thermal comfort in nZEB

5.1. Introduction

As technology has advanced, the increasing pressure on energy usage reduction and expectations of consumers regarding comfort have made the requirements posed on clothing and control of the indoor climate more demanding. The contemporary trends, such as flexible open plan or multi-use office and industrial spaces, entail the development of new concepts of heating, ventilation and air conditioning systems (HVAC) and new protective and functional apparel to ensure health and safety, while maintaining energy efficiency of the buildings and vehicles, and the well-being, thermal comfort and productivity of occupants. These goals, in turn, require advanced and reliable analytical methods that can faithfully relate to the human thermal behaviour and sensational perception.

5.2. Thermal manikins as nowadays instrument to improve HVAC systems;

Thermal manikins are the most realistic devices widely used for the assessment of heat and mass transfer from the human body to the environment. Their anatomic shape and ability to sweat and move provide experimental conditions that are closer to the real human. The presence of homogeneous and heterogeneous thickness of the air layers within the clothing system as well as the contact area influences noticeably the local heat, vapour and liquid exchange. They are able to measure not only thermal insulation and evaporative resistance of clothing systems but also provide information on dynamic changes in the clothing system, for example, due to presence of moisture, limb movements or thermally complex environments. [1] (see **Figure 5.1** The heat and mass transfer within the clothing system is a composition of a number of physical processes)

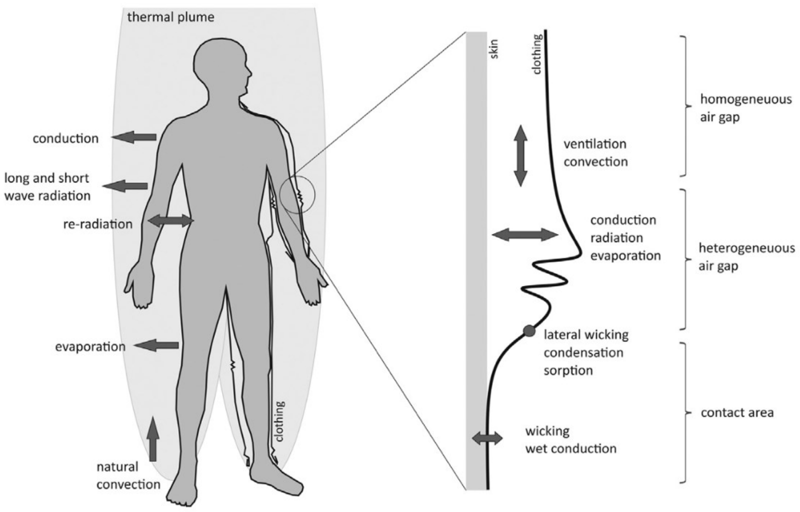

Figure 5.1 *The heat and mass transfer within the clothing system is a composition of a number of physical processes [1]*

Thermal manikins have proved to be helpful to assess the indoor air quality, the spread of airborne particles, and also to calculate the human environment heat transfer coefficients used in numerical simulations of indoor spaces with occupants. The role of the thermal manikin is to measure the resultant influence of the environmental conditions including radiant asymmetries, temporal and spatial changes of the local air movement around the manikin body, ambient temperature and its shifts as well as heat transfer through surface contact, e.g. with seat, furniture, floor or other objects. Depending on the choice of the coupling method either the surface temperature or the heat flux from the manikin are used as input parameters to the model. The measurement quality of these parameters depends on the calibration method as well as on the construction of the manikin. Surface temperature accuracy is related to the accuracy of the used reference sensors and their placement if the climatic chamber has a tendency to temperature stratification. To evaluate the quality of the new conditioning solution in terms of occupant satisfaction the thermal sensation and thermal comfort indices are being used. These models can be used at the design stage of the building and enable the assessment of the indoor environment for thermal sensation and comfort already at this early stage. [2]

The control of the manikin parameters used in this type of analysis is typically based on the so-called ‘comfort mode', in which the surface temperature of the manikin is determined based on its heat loss according to the equation derived based on Fanger 's comfort criteria:

$$Tskin = 36.4 - 0.054 \times Qt,$$

where Tskin is a resultant mean manikin surface (skin) temperature under thermal neutrality (°C) and Qt is the sensible heat loss from the manikin (W/m2). This method is a certain simplification and does not allow a full analysis of thermal dynamics occurring in the human body that is adjusting skin blood flow, metabolic heat production and sweating to maintain optimal body core temperature. [1,2]

For example, there is experiment report’s data below, that would give impression of manikin’s utility. Applications of equivalent temperature based on the thermal manikin for an underfloor air distribution system were shown. Equivalent temperature based on the thermal manikin was shown to be a useful tool with whichto detect the effects of asymmetriesin heat sources and airflow.

The nude thermal manikin in the sitting posture was exposed in the climatic chamberunder three operative temperatures. Heat losses from the whole body were 91.2 W/m2 at an operative temperature of 19.8°C, 2 2 64.4 W/m at 24.8°C, and 37.7 W/m at 29.7°C. Heat losses at the feet and hands were slightly greater than those at other parts. The combined heat transfer coefficient for the nude and sitting manikin was not affected by the exposure temperatures. The meanof the combinedheat transfer coefficients for the wholebody in the nude was 7.9 W/m°C. Whenthe radiative heat transfer coefficient for the humanbody (hr) was assumed to be 4.7 W/m2.°C, the convective heat transfer coefficient (hc) was estimated to be 3.2 W/m2. o C. The manikin was exposed in the climatic chamber in sitting and standing postures with clothing. Theheat losses from the whole body were 48.2 W/m2 for the sitting posture and 45.3 W/m2 for the standing posture. The total thermal resistance for the whole body was 0.189 m2C°/W (1.22 clo) for the sitting posture and 0.205 m2.°C/W(1.32 clo) for the standing posture. Thebasic clothing insulation value of the tested clothing ensemblein the sitting (Icl) posture wascalculated to be 0.55 clo. [2]

5.3. Thermal comfort

5.3.1. Comfort zones for indoor occupants

ASHRAE Standard 55 recommends comfort zones of 20-24 C° for winter clothing (1 clo) and ~23.5-27 C° for summer clothing (0.5 clo) (0.1 m/s air velocity). Recommendations from EN15251 and ISO7730 are of similar nature. Enhanced air speeds can stretch the summer limits to ~30 C°. Since at typical indoor heating temperatures, air flow would just enhance heat loss from skin, convective heating is a lot less desirable and cannot extend winter comfort.

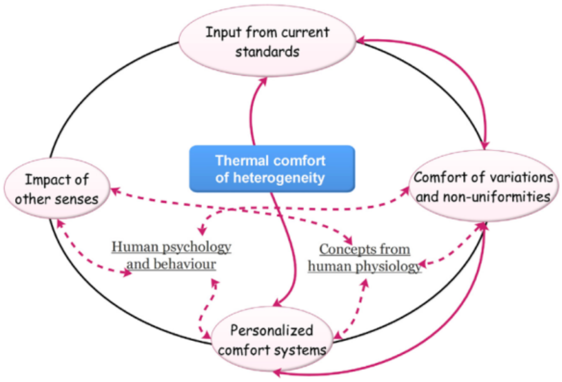

Figure 5.2 *A representation of the interconnection between different sections*

A reduction of clothing resistance by 0.1 clo corresponds to an increase of 0.8 C in operative temperature and vice versa. Unlike other similar options (having fans, windows, blinds, radiant heaters etc.), flexibility in occupant clothing is probably the only true ‘0’ cost option. Impact of prior exposure/ activity levels may last up to 1 h. Requirements presented regarding local thermal discomforts, from causes like draft, thermal asymmetry etc., are for occupants with clothing insulation less than 0.7 clo and activity level less than 1.3 met. Above these levels, no local discomfort limits are prescribed. (see Figure 5.2 A representation of the interconnection between different sections)

Draft sensitivity is greatest for portions of body without clothing head region (head, neck, and shoulders) and leg region (ankles, feet, and legs). At operative temperatures below 22.5 C, average air speed caused by building, fenestrations, and HVAC system should not exceed 0.2 m/s. Requirements for thermal stratification are for situations where head is warmer than feet. Temperature differences in the other direction are rare and are also perceived favourably by occupants. Floor temperatures need to limited between 19 and 29 C. Around the comfort temperature determined on a particular day, for 80% occupant acceptability, a comfort zone width of ±3.5 or ±3 is allowed. [2,3]

The human brain is more sensible to raise of the temperatures than any other core organ. Face sweating was maintained even for dehydrated individuals so that the induced cooling can maintain brain temperature below deep body temperature. Under slightly warm conditions, facial cooling is a welcome relief while facial warming is perceived as a distress. The preference for a cooler brain may be used to justify the advantage of personalised comfort measures. By cooling just the face/head, the upper limit of comfort temperature can be pushed to 30C and exercise work rate and duration can be improved, that explains why cool ceiling asymmetry can be much more than cool floor asymmetry. But excessive cooling of breathing zone must also be avoided.

5.3.2. Spatial transients and thermoreception

Types of temperature requirements, based on allowed breadth of indoor temperature variations, do not produce appreciably different results for occupant comfort and acceptability. They found that tighter control did not give appreciably better satisfaction, while being 12-30% more energy intensive. Average limits of occupant discontent in conditioned buildings is 19-26 C° and for free running buildings with ceiling fans is 19.5-28 C°. Within these limits, occupant acceptability is more or less unvarying, though dropping off sharply beyond the limits. So, there is no particular advantage in HVAC systems targeting a single “optimum” temperature. Indoor conditions maintained within narrow zones could gradually atrophy thermoregulatory ability and adaptive capacity of the occupants.

Under static conditions, error signals from core temperature and mean skin temperature drive any thermoregulatory action while during transient episodes, the rate of change of skin temperature also plays a role. Latest researches showed Cold receptors are more abundant in the skin, while warm receptors are more numerous in the body core, making all cutaneous regions more sensitive to cool than warmth. Cutaneous cold receptors are closer to the skin surface and conduct information faster than the cutaneous warm receptors. When subjected to a sequence of different thermal conditions, the response of people to a particular ambient significantly differed depending on the sequence of previous environments they had experienced. Thermal sensation and comfort ratings, during spatial transitions, often have an anticipatory effect and lead physiological responses.

Some observations have shown that cooling overshoots may occur only for strong cooling steps (~5 C°), while overshoots for upsteps can occur for sudden changes of moderate step size (~3 C°). The initial overshoot in sensation could just be the perceived/ anticipated relief in thermal stress. Moving from a hot to a warm room or a cold to a cool room may thus induce a neutral sensation. In a similar vein, people working in a location are likely to be less satisfied with their prevalent thermal environment, and have narrower thermal comfort zones, than people who are passing through, for example, staff vs passengers in an airport.

Occupant adaptations have been categorized as physiological, behavioural, and psychological. Head, chest, back, and calf are most sensitive to step-changes in temperature. In addition to depending on direction of the transition (even when the magnitude is similar), responses also depend on magnitude of the step change and magnitude of the starting temperature [4].

Down-steps may result in greater changes in sensation than up-steps. The subjective ratings of comfort and sensation also stabilise faster than physiological parameters (like skin temperature or skin blood flow). Certain physiological responses like skin temperature and heart rate variability (HRV) can be more sensitive to down steps. [5]

During activity, blood flow to skeletal muscles rises as activity level increases. But when the activity has to come to a sudden halt, blood flow levels fall off quickly leaving the heat trapped in these large muscles, which are slow-responding thermal masses. This has implications regarding local cooling requirements (focusing on limbs, where most of the large skeletal muscles are concentrated) for individuals who come to work by cycling/ walking.

During transition time of 20-30 min, the individual is adjusting to the new conditions, both physiologically and mentally. Spaces through which transitions last shorter than this duration, could do with relaxed set-point controls. (see Figure 5.3 Relaxed thermal comfort requirements for transition spaces) Areas like lobbies, hallways etc., in typical commercial buildings, are examples of such transitional spaces. Having transition spaces at an intermediate temperature can also help reduce the physical distress of transiting directly between a conditioned building and the outdoors. To avoid overwhelming burdening of thermoregulatory system, the magnitude of step changes from main area to transition spaces may be limited to ±3C°.

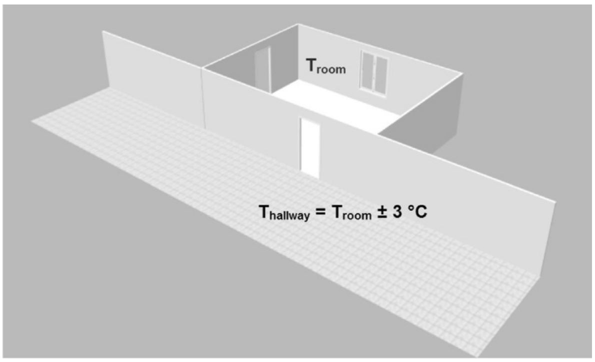

Figure 5.3 *Relaxed thermal comfort requirements for transition spaces*

The range of cyclic temperature deviation perceived as tolerable by occupants reduces with the frequency of those cycles. Cyclic variations are acceptable where air temperature variations are 3.3 K/hour or smaller and the peak to peak variation magnitude is less than 3.3 K. Greater variations are unacceptable even when within the comfort zone. For temperature change rates of 4 K/hour, have reported only non-significant changes in such physiological parameters as blood pressure, heart rate, and core temperature. One of the methods suggested for energy savings in intermittent occupancy situations like offices is to let the cooling set point temperature drift towards end of occupancy period. It was found that allowing the space temperature to drift to 27 C° after 3 p.m. does not adversely affect occupant comfort. Small drifts of temperature towards day end may not be noticed by occupants for around 4 h. Before occupants respond to such drifts, if the HVAC system initiates a corrective drift back to neutral conditions, a positive comfort response could be elicited from occupants. Such positive response may be attributed to a feeling of spatial alliesthesia [6].

5.3.3. Circadian rhythm

Circadian rhythm of core temperature in human beings is internalized and heat generation in the body coacts with heat loss mechanisms to ensure this rhythm, even without variations in activity level due to sleep-wake cycle. Mean oral temperature of human beings is close to 36.8 C with diurnal variations of 1C°, a nadir around 4 a.m. and the zenith between 4 and 6 p.m. in the evening. During periods of declining core temperature, average skin temperature increases to aid heat loss. Circadian rhythm of heat production, core temperature, and heat loss are out of phase with each other and this helps with sustaining the diurnal variation, with primary contribution coming from heat loss rhythm.

The core temperature increases while heat production is more than heat loss, and vice-versa. Building occupants are thus in a “heat gain” mode in the morning (as the core temperature climbs) and in a “heat loss” mode in the evening. Subjective thermal sensations and behavioural responses have also been reported to have a circadian rhythm with minima pre-noon and maxima during late evening. This can lead to an warmer preferred ambient temperature during afternoon, compared to morning (by about 1.5C°) , minimally dressed subjects choosing to dress quicker and in thicker clothing during morning than in evening etc. The temperature in immediate vicinity of occupants can be 0.5-1.5 C° lower than the room's average temperature. This would impact individual evaluation of a common work place. Local non-uniformities can also result from occupant posture and clothing ensemble. As radiant heat transfer is dependent on orientation and view factors, spatial arrangement of heat sources impacts the performance of radiant systems . Similar magnitudes of radiant asymmetry have a greater impact on thermal sensation when frontal in nature than when side wise. [5]

Taking of food or drinks is a ‘non-gadget’ means of personal control. Consuming hot or cool food items/drinks can have a considerable impact on body temperature, especially as the impact on core temperature can be direct. Digesting food increases metabolism to an extent such that core temperature can rise by ~0.01 C per ~160 kcal of food consumed. This is apart from the effect of the food's own temperature. Consuming an ice cream or a can of cold-drink can have an average cooling effect of ~12-14 W over an hour and a portion of soup could have a warming effect of ~13 W over an hour. For a person engaged in standard office activity, this could mean nearly 10% of their metabolic rate. It has been reported that ingestion cool food/drink in intermittent steps can have better efficacy than one time bulk consumption. As conditions get warmer/cooler, occupants may increase their consumption rate of such food/drinks to retain their comfort levels. Availability of occupant control forms an intricate linkage between personalised comfort systems and human psychology.

5.3.4. Non-uniformities of the human body

Relative contributions of different portions of the body to thermoregulatory effect is often debated. As a gross estimate, skin surface, deep abdominal and thoracic tissues, spinal cord, hypothalamus, and other portions of the brain each contribute roughly 20% to control of autonomic thermoregulatory defences while behavioural defences may have a much higher contribution from value of skin temperature. Skin temperature contribution to thermoregulation is usually expressed in terms of a weighted mean skin temperature. Due to the differential distribution of receptors, the thermal sensitivity of different body parts, as fraction of whole-body sensation were documented to be: 0.21 for face, 0.21 for chest and back, 0.17 for abdomen, 0.15 for upper legs, 0.08 for lower legs, 0.12 for upper arms, and 0.06 for lower arms.

In a thermally neutral ambient, preferred local skin temperatures and width of comfort zone vary with body parts, for both genders, with width being wider for males. Certain body parts are particularly suited for exchanging heat with the ambient and this may be inferred from their structure: high surface-to-volume ratio, lack of hair, high density of cutaneous blood vessels, presence of arteriovenous anastomoses. Our limbs, for example, account for nearly 50% of body's skin surface area.

One of the arguments in favour of personalised thermal comfort arrangements is the wide variations in individual physiology. Oral, rectal, tympanic, and mean skin temperature can vary by as much as 0.5, 0.8 and 1ºC, respectively, across individuals. The influential individual parameters are: fat mass, body surface area (BSA) to body mass ratio, maxVO2 consumption, sweat rates, and heart rate. It is a common observation that the ability to thermoregulate reduces with age and reduced fitness; increase of illness and disabilities may be an important reason for this. The elderly have reduced responses in terms of sweat output, skin blood flow, and cardiac output volume to heat stress, reduced muscle mass and oxygen consumption, leading to lowering of basal metabolic rate (BMR), thermoreceptor sensitivity, and compromised ability to discriminate temperature sensations. If the effects of fitness level, body compositions, and chronic diseases are accounted for, it would seem that heat tolerance is minimally affected by just the chronological age. Reduced functionality of autonomic thermoregulation in face of cold exposure may lead the elderly to rely more on behavioural defences, like, seeking higher heating set points. Such behaviour may account for higher heating energy consumption in residences elderly residents. In terms of physiological differences, women have lower body mass, lower BSA, a lower BMR/BSA ratio and higher BSA/body mass ratio (implying a lower heat generation to heat loss surface area ratio), thicker subcutaneous fat, a slightly higher normal temperature, higher sweating and vasomotion thresholds, lower sweat rates, a higher core set-point during luteal phase, greater insulation when vasoconstricted, and lower exercise capacity. In warmer and more humid environments, female subjects prefer higher air velocity than their male counterparts. Females prefer higher room temperatures, by about 1.2-3

Cº.Among a population of office workers, up to 9% could have neutral temperatures differing by 2 Cº from the mean value and about 40% could have differences of 1 Cº. These differences continue to be a major argument in favour of more personalised thermal comfort design for indoors.[6]

5.3.5. Alliesthesia

Alliesthesia, as a term, was coined by Michel Cabanac, using the Greek words esthesia (meaning 'sensation') and allios (meaning 'changed'). Any thermal environment has a descriptive part (sensation, intensity) and an affective part (pleasure, comfort), which are independent of each other. While the descriptive part remains unchanged, the affective part depends on the ability of a stimulus to help the body to return to its 'normal' thermal state. Both these parts can be important for the decision-making process. They are processed in different parts of the brain and are processed simultaneously. Being processed in different parts of the brain leads to the advantage that while a certain sensation (warmth or coolth) may not be pleasurable for the being at the very instant, there is significant advantage in remembering what the stimulus is, especially if it may be used later, e.g., warm/cool parts of a residence. [4,7]

The preferred thermal sensation depends on mean skin temperature and core temperature. As an example in the Figure 5.4. see Preferred thermal sensation, dependent upon body conditions , the comfort and warmth perception of warm, hand-held electronic devices differs with the ambient conditions. [4]

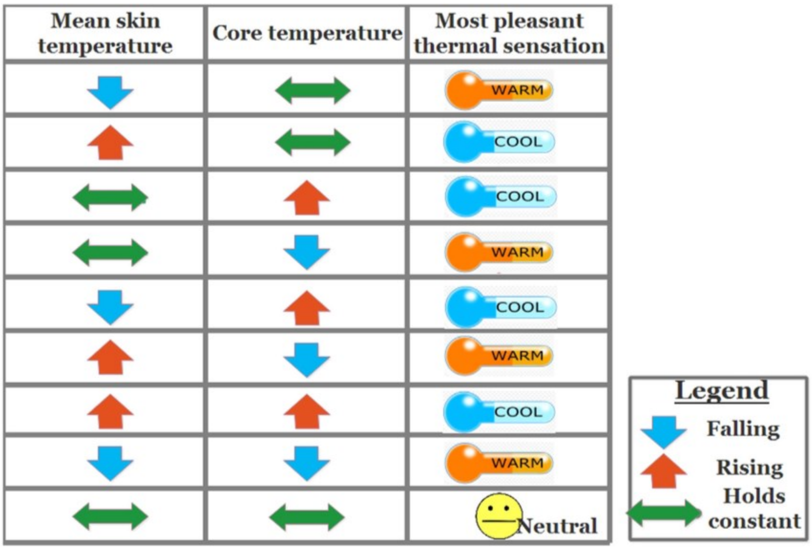

Figure 5.4. *Preferred thermal sensation, dependent upon body conditions [3]*

Alliesthesia helps explain certain aspects of comfort under transient conditions, like the anticipatory effect on sensation and comfort following moving from one set of thermal conditions to another. It also provides pointers regarding indoor conditions and operational strategy that can be more comfortable to occupants, like the corrective drift from HVAC systems. [3, 7]

5.3.6. Trend for green buildings

The better understanding of human thermal comfort requirements, can assist and drive the progress of comfortable buildings, with better occupant satisfaction and yet lower energy consumption. The potential for creating an indoor environment with greater diversity in its character, that could enhance subjective acceptance of occupants and help save energy. There are also aspects of differences in individual physiology which would advocate for more personalised environments and more personal control to extend the realm of thermal comfort to all. Control options improve thermal comfort, visual comfort, overall satisfaction, productivity, and can even reduce incidences of SBS/building related illness symptoms in offices. Environments where occupants believe they have more control, have better comfort ratings under similar temperatures d homes better than offices and offices better than climatic chambers. Just the awareness of having control options/adaptive avenues, can aid psychological adaptation and improve satisfaction. Adjustments at a personal level to clothing or just accepting the condition d is often preferred by office occupants over adjusting the thermostat, even when such an option is available. People who are frequently having to resort to environmental controls may be the most dissatisfied with the thermal environment's state. But they do want the idea of control d to be used when BMS is not functioning properly or some discomfort turns up. It could be most beneficial to have the automated building systems playing the role of an observer, who allows for manual manipulations but also has the capability of set-back, in small steps. While providing occupants with personalised systems, it also makes sense to have some form of communication between these personal systems and the overall conditioning system of the building.

This would let the two mechanisms work in synergy, towards improving comfort and saving energy, instead of working against each other and increasing energy needs.

Conclusions

The contemporary trends, such as flexible open plan or multi-use office and industrial spaces, entail the development of new concepts of heating, ventilation and air conditioning systems (HVAC) and new protective and functional apparel to ensure health and safety, while maintaining energy efficiency of the buildings and vehicles, and the well-being, thermal comfort and productivity of occupants.

Thermal manikins are the most realistic devices widely used for the assessment of heat and mass transfer from the human body to the environment. Thermal manikins have proved to be helpful to assess the indoor air quality, the spread of airborne particles, and also to calculate the human environment heat transfer coefficients used in numerical simulations of indoor spaces with occupants.

One of the arguments in favour of personalised thermal comfort arrangements is the wide variations in individual physiology. The influential individual parameters are: fat mass, body surface area (BSA) to body mass ratio, maxVO2 consumption, sweat rates, and heart rate. It is a common observation that the ability to thermoregulate reduces with age and reduced fitness; increase of illness and disabilities may be an important reason for this.

The elderly have reduced responses in terms of sweat output, skin blood flow, and cardiac output volume to heat stress, reduced muscle mass and oxygen consumption, leading to lowering of basal metabolic rate (BMR), thermoreceptor sensitivity, and compromised ability to discriminate temperature sensations.

Among a population of office workers, in warmer and more humid environments, female subjects prefer higher air velocity than their male counterparts. Females prefer higher room temperatures, by about 1.2-3 Cº; up to 9% could have neutral temperatures differing by 2 Cº from the mean value and about 40% could have differences of 1 Cº.

During activity, blood flow to skeletal muscles rises as activity level increases. But when the activity has to come to a sudden halt, blood flow levels fall off quickly leaving the heat trapped in these large muscles, which are slow-responding thermal masses. During transition time of 20-30 min, the individual is adjusting to the new conditions, both physiologically and mentally. Spaces through which transitions last shorter than this duration, could do with relaxed set-point controls, to avoid overwhelming burdening of thermoregulatory system, the magnitude of step changes from main area to transition spaces may be limited to ±3C°.

The range of cyclic temperature deviation perceived as tolerable by occupants reduces with the frequency of those cycles. One of the methods suggested for energy savings in intermittent occupancy situations like offices is to let the cooling set point temperature drift towards end of occupancy period.

References

1. A.Psikuta, J.Allegrini, B. Koelblen, A. Bogda, S. Annahei, N.Martínez, D.Derome, J.Carmeliet, René M. Thermal manikins controlled by human thermoregulation models for energy efficiency and thermal comfort research – A review; Rossi˙ Renewable and Sustainable Energy Reviews 78 (2017) 1315–1330; https://www.sciencedirect.com/science/article/pii/S1364032117306202?via%3Dihub

2. Tanabe, S. Arens, Edward A Bauman, Fred et al. Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature; https://escholarship.org/uc/item/22k424vp

6. A.K. Mishra *, M.G.L.C. Loomans, J.L.M. Hensen Thermal comfort of heterogeneous and dynamic indoor conditions d An overview

7. K. Nagano, A. Takaki, M. Hirakawa, Y. Tochihara, Effect of ambient temperature steps on thermal comfort requirements. Int. J. Biometeo rol. 50 (1) (2005) 33-39

8. J. Xiong, Z. Lian, X. Zhou, Y. Lin. Effects of temperature steps on human health and thermal comfort. Build. Envir. 94 (2015) 144-154

9. T. Parkinson, R. de Dear. Thermal pleasure in built environments. Spatial alliesthesia from contact heating. Build. Res. Inf. 44 (3) (2016) 248-262

10. M. Cabanac. Physiological role of pleasure. Sience 173 (4002) (1971) (1103-1107)