1 THEORETICAL BACKGROUNDS ON ICQ

1.1 Indoor thermal quality

1.1.1 Introduction

Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment [C3; C5]. Thermal neutrality for a person is defined as the condition in which the person would prefer neither warmer nor cooler environment. Thermal neutrality is not always most preferred condition for comfort – for some people, thermal conditions that feel slightly cooler than thermal neutrality are most comfortable, and for others thermal conditions that feel slightly warmer than thermal neutrality are preferred. In practice when a group of people are subject to the same room environment it will not be possible to satisfy everyone because of the large physiological and psychological differences from person to person, as well as differences in activity and/or clothing. Therefore the first step in indoor environmental design is to create optimal comfort, including thermal comfort, for a highest possible percentage of occupants. More sophisticated design aims for a microenvironment at each workplace, i.e. providing occupants with opportunity to tailor the environment at their workplace to their personal preference. In this chapter the principles and relevant parameters and indices important for the design and assessment of overall room thermal environment are discussed.

1.1.2 Human body thermoregulation

Human beings have an average internal body temperature of approximately 37°C, though this can vary by more than ±1°C between people and time of day. The body's thermoregulation system maintains a constant core temperature by balancing the heat which is produced by the body and the heat which is lost to the environment. Increase of the core temperature above 43°C and decrease below 25°C is fatal.

The hypothalamus, located in the brain is the central control organ for body temperature. It receives signals from cold and warm thermal receptors located 0.2 – 0.5 mm under the skin. The cold receptors respond to a decrease of the skin temperature, and the warm receptors to an increase of the skin temperature. The thermal receptors have a static response to the level of constant skin temperature, and the dynamic response to the rate of change of the skin temperature [1].

The most important and often used physiological process for balancing body heat balance is the regulation the blood flow to the skin. When the body temperature increases the blood flow to the skin increases by vasodilatation of skin blood vessels, in order to carry internal body heat to the skin and transfer it to the environment; when body temperature falls blood flow to the skin is reduced (vasoconstriction) to conserve heat. Under extreme heat conditions the blood flow to the skin may increase 15 times when resting (from 1.7 mL/(s·m²) to 25 mL/(s·m²)). The effect of maximum vasoconstriction is equivalent to the insulation effect of a heavy sweater.

In a cold environment muscle tension increases to generate additional heat; shivering can increase resting heat production to 4.5 met. When the body temperature is raised, sweating is an efficient way of cooling the skin and increasing the heat loss from the body. At low relative humidity and elevated air movement the secretion from the sweat glands evaporates, and skin can remain dry at high sweat secretion. When conditions are less favourable the sweat spreads over the skin around the sweat glands thus increasing the area of sweat evaporation.

The fraction of the skin that is covered with sweat to account for the observed total evaporation rate is termed skin wettedness [2]. Skin wettedness is associated with uncomfortable warm conditions. It is rare for a sedentary or only slightly active person to be comfortable with a skin wettedness greater than 25%. Skin wettedness increases the friction between skin and fabrics, making clothing feel uncomfortable and fabrics rough. This may also occur when the skin is in contact with objects with smooth and non-hygroscopic surface. Average skin temperature is approx. 33°C with a variation of more than ±1°C between people. However the local skin temperature of different parts of the body can vary between 25 – 34°C and more. The skin temperature of the body extremities (feet, hands) is lower. The differences in the skin temperature decrease in a warm environment. The skin temperature of the extremities is a critical factor for comfort in a cooler environment: a hand skin temperature of approximately 20°C feels uncomfortably cold, 15°C extremely cold and at approximately 5°C painful.

1.1.3 Human body energy balance

At relatively extended exposure to a constant thermal environment, the body's core temperature remains constant on condition that there is a balance between heat production and heat loss. The heat balance for these conditions is (Figure 4.1):

$$S = M \pm W \pm R \pm C \pm K - E - RES \quad [\mathrm{W/m^2}] \quad (1)$$

Where S is the rate of heat storage, M is the rate of metabolic heat production, W is the rate of mechanical work accomplished. R is the rate of heat exchange by radiation, C is the rate of heat exchange by convection, K is the rate of heat exchange by conduction, E is the rate of heat exchange by evaporation and RES is the rate of heat exchange by respiration.

Heat balance is achieved when the rate of heat storage S=0.

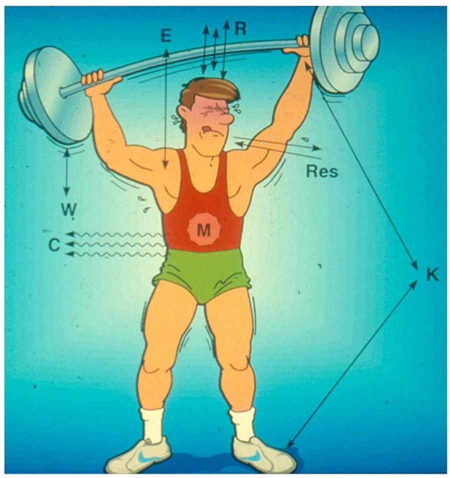

***Figure 4.1** Different modes of heat exchange between the human body and the surrounding environment.*

Equation 1 is modified to account for heat conduction through clothing, K_{cl}, of dressed person in state of heat balance:

$$M \pm W - E - RES = \pm K_{cl} = \pm R \pm C \quad [W/m^2] \quad (2)$$

The double equation (2) expresses that the heat conduction through the clothing is equal to the resultant metabolic heat production, the mechanical work accomplished, heat loss by evaporation and heat loss by respiration which is dissipated at the outer surface of the clothing by radiation and convection. The sign in equations 1 and 2 indicates that the body may loose or gain heat. Heat exchange due to conduction, e.g. contact between feet and floor, is not taken into account in the above equations because normally the amount of this heat exchange is insignificant compared to the total heat exchange. However heat exchange due to conduction may have significant influence on the local heat exchange for example at the fingers. Heat exchange due to conduction is significant for a person seated in an arm chair. In this case the chair is calculated as part of the clothing.

The metabolic heat production, required for body functioning, is the energy released by oxidation within the body. It may vary from an at rest value of 45 W/m² skin surface to more than 500 W/m² when running. The surface area of an average sized person is approximately 1.8 m². DuBois surface area, A_D=0.202$m^{0.425}l^{0.725}$ is the most often used measure of body surface area in m² (m = mass, kg and L=height, m). Metabolism is often given in unit “met”, 1 met= 58.15 W/m². Data on metabolic heat production rate at different activities are given in tables [C3; C5].

A portion of the body’s energy production may be expended through exercise and the excess heat is transferred to the environment by the modes of heat exchange defined above. The muscular effort for a given task is often expressed in terms of body’s mechanical efficiency, *W/M*. It is unusual *W/M* to be more than 0.05 – 0.10 since man is poor machine. For most activities it is close to zero.

The heat loss by evaporation is partly from water vapour diffusion through the skin and partly by evaporation of sweat on the skin surface. When evaporation takes place the water uses heat from the skin. The amount of water diffusion through the skin and the corresponding heat loss is the function of the difference between the of the saturated water vapour pressure on the skin and the water vapour pressure in the ambient air. Evaporation of sweat from the skin surface is one of the most effective ways by which the body keeps the internal temperature from increasing. The amount of sweat evaporation changes with the activity level, from 0 W/m² at rest up to 400 W/m² in a hot and dry environment when performing hard work.

During respiration, the body loses both sensible and latent heat by convection and evaporation of heat and water vapour from the respiratory tract to the inhaled air. A significant amount of heat exchange occurs due to respiration because air is inspired at ambient conditions and expired nearly saturated at a temperature only slightly cooler than the body core temperature. Respiratory heat loss is often expressed in terms of sensible and latent heat losses.

Heat exchange by radiation takes place between the body surface, including skin and clothing and the surrounding surfaces. Some clothing area exchanges heat due to radiation not with the surrounding surfaces but with other body parts, e.g. between arms and the body, etc. Therefore the effective radiant area is less than the total surface area. This is encountered with a factor which is approximately 0.71. Since the emittance from human skin is 1, and for most types of clothing is 0.95, a mean value of 0.97 is used for calculating the radiant heat loss. The mean radiant temperature needed calculating the heat loss due to radiation is defined as the uniform temperature of the surrounding surfaces which will result in the same heat exchange by radiation from the body as in the actual environment (Figure 4.2). Its determination estimated from the temperature of the surrounding surfaces is discussed later in this guidebook. Heat exchange by radiation plays an important role in the occupants' comfort.

Typically the surface temperature of the human body is higher than the temperature of the surrounding air. Thus the air in contact with the body will be heated and its density will become lower, i.e. it will be lighter than the surrounding air and will rise. This heat exchange is known as free convection. The free convection flow has a relatively low velocity and therefore an increased air temperature is often not sufficient for the body's heat balance. In this case, air is forced against the human's body, e.g. by a fan. This enhanced heat exchange is known as forced convection. While the free convection depends mainly on the difference between the body surface temperature and the air temperature, the forced convection also depends on the imposed velocity. In practice, depending on the conditions, either free or forced convection or both may play important role. For sedentary person in the comfortable range of room air temperature recommended in the standards, an airflow velocity of 0.2 – 0.3 m/s is needed for penetration of the free convection flow. When this occurs the forced convection starts to play major role for body cooling. Body heating by warm air, i.e. heat flow from air to body, is also used, though not as frequently.

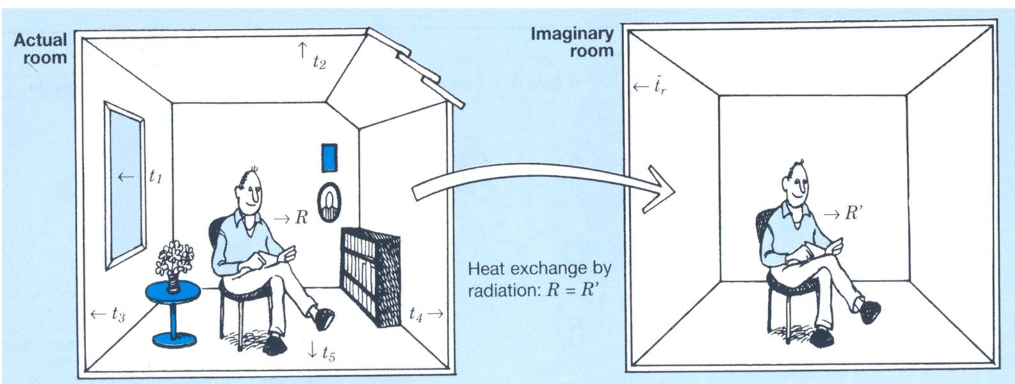

Figure 4.2 *Mean radiant temperature definition.*

Heat exchange through the clothing is a function of the mean skin temperature, clothing surface temperature and thermal insulation of clothing. In the present indoor climate standards the thermal insulation for different clothing designs and combinations is given in tables.

1.1.4 Conditions for thermal comfort

There are two personal factors, namely metabolic rate and clothing insulation, and four environmental parameters, air temperature, mean radiant temperature, air velocity and relative humidity, that must be addressed when defining the conditions for thermal comfort. Body heat balance may be achieved under different combinations of the personal factors and the environmental parameters. However only in a narrow range of environmental conditions, which are related to a narrow range of mean skin temperature and sweat loss, thermal comfort can be achieved (Figures 4.3 and 4.4). The individual differences existing between people can be seen in the figures.

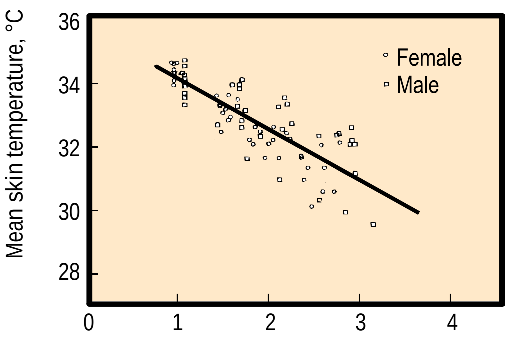

Figure 4.3 *Mean skin temperature as a function of activity level for a person in a state of thermal comfort. In order to maintain thermal comfort the air temperature is lower when the activity is higher [2].*

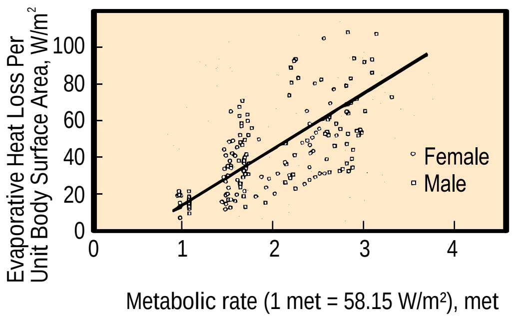

Figure 4.4 *Evaporative heat loss as a function of the activity level for human thermal comfort. In order to maintain thermal comfort the ambient temperature is lower than the activity level [2].*

The relationship between mean skin temperature and metabolic rate (Figure 4.3) and between evaporative heat loss and metabolic rate (Figure 4.4) was derived and incorporated in the double sided heat balance equation (2) in order to establish the well known comfort equation suggested by Fanger [2] which is included in the current standards ([1], [2]) and handbooks [3]. The comfort equation establishes those combinations of personal factors (activity and clothing insulation) and environmental factors (air temperature, mean radiant temperature, relative humidity, air velocity) which will provide thermal comfort. As already discussed large individual differences exist between people. Therefore the comfort equation predicts the thermal environmental conditions under which the largest percentage of people will be satisfied. Research has identified relatively small differences in the preferred comfort conditions from day to day and between males and females (often women prefer higher temperature than men mainly because of the lighter clothing worn). Under the same conditions (activity level, clothing, etc.) the preferred thermal environment of young and elderly people is rather much the same, though they may not be equally sensitive to cold or heat. Often elderly people keep room temperature high because their activity is low. People living in warm climates can more easily accept and work longer in hot environment than people from colder climates.

In order to simplify the assessment of thermal comfort conditions, different indices were introduced in an attempt to summarize the information about the various parameters (four of them environmental and two of them related to the person). The earliest indices only considered environmental conditions, but nowadays, the most sophisticated integrate all the relevant information.

The *operative temperature to*, introduced by Gagge [3] is defined as the uniform temperature of a imaginary black radiant enclosure, in which the occupants exchange the same amount of heat, by convection and radiation, as in an actual non-uniform environment.

$$T_o = (h_c\, t_{air} + h_r\, t_{rad})/(h_c + h_r) \qquad (3)$$

Mathematically, this corresponds to the average of the mean radiant and ambient air temperatures, weighted by their respective heat-transfer coefficients. In its calculation, three physical variables – air temperature, mean radiant temperature, and air velocity – are considered, the first two directly and the third one through its influence on the convective heat-transfer coefficient h_c. Simplified equations for the calculation of t_o are given in the standards [C3; C5].

Another index, Equivalent Temperature (T_{eq}) is defined as the uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiation and convection as in the actual non-uniform environment. A formula for calculating the equivalent temperature, in typical indoor conditions, was derived by Madsen *et al* [4]:

$$T_{eq} = 0.55t_a + 0.45t_r + 0.24 - 0.75\sqrt{v_a} + I_{cl} \times (36.5 - ta) \qquad (4)$$

Where t_a is the ambient air temperature (°C), t_r is the mean radiant temperature (°C), v_a is the air velocity (m/s), I_{cl} is the insulation index of the clothing (1 clo = 0.155m²°C/W).

A widely used index for the assessment of thermal comfort is PMV (predicted mean vote), introduced by Fanger (2). It uses the heat balance principles to relate the six key factors for thermal comfort to the average response of people on ASHRAE's thermal sensation scale. The 7-point ASHRAE thermal sensation scale, -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot, quantifies people's thermal sensation. In particular, a correlation model between the subjective human perception, expressed through the vote of comfort, and the difference between the heat generated and the heat released by the human body, was established, which corresponds to the following equation:

$$\mathrm{PMV} = (0{,}303 \times e^{-2{,}100 \times M} + 0{,}028) \times [(M - W) - H - E_c - C_{res} - E_{res}] \qquad (5)$$

Where M is the metabolic rate, W/m², W is the effective mechanical power, W/m², H is the sensitive heat losses, E_c is the heat exchange by evaporation on the skin, C_{res} is the heat exchange by convection in breathing, E_{res} is the the evaporative heat exchange in breathing.

This equation includes both the human perception model and the human body thermal balance. The transformation of the thermal balance value in the PMV index is made by multiplying the term inside the first brackets of the second member in equation (5), which corresponds to the human thermal perception modulation, when it is expressed in the so-called seven point scale.

Fanger concluded in his studies that the variation of PMV index can be approximated by an analytic expression that corresponds to a curve whose appearance is similar to an inverted Gaussian distribution:

$$PPD = 100 - 95 \times e^{-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)} \quad (6)$$

The PPD (predicted percentage of dissatisfied) index is related to the PMV as defined in Figure 4.5. It is based on the assumption that people voting +2, +3, -2, or -3 on the thermal sensation scale are dissatisfied, and the simplification that PPD is symmetric around a neutral PMV. As it can be seen from Figure 4.5, 10 percent of the people will be dissatisfied with the thermal environment for -0.5< PMV <0.5. The PMV-PPD indices are used in the present thermal comfort standards and are defined for different categories of thermal environment [C1; C3].

The different categories of thermal environment is defined in some of the present thermal comfort standards. For example ISO Standard 7730 (2005) [C3] defines three categories based on different ranges of PMV and PPD indices.

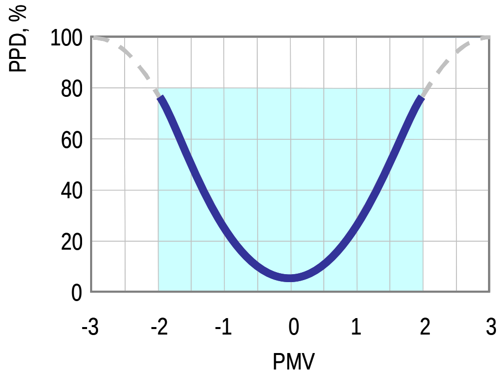

Figure 4.5 *Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV) [validity range: -2 < PMV < +2].*

For a given space an optimum operative temperature exists corresponding to PMV = 0 depending on the activity and the clothing of occupants. Figure 4.6 included in ISO Standard 7730 (2005) [C3] shows the optimal operative temperature as a function of the metabolic rate and clothing insulation together with the allowable ranges corresponding to Category B (PPD<10%).

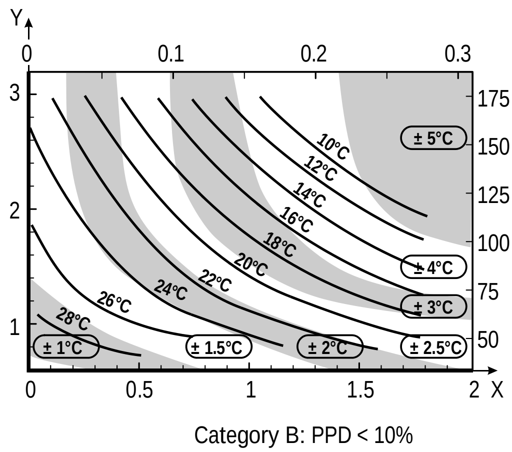

Figure 4.6 *Optimal operative temperature and allowable ranges around the optimal operative temperature.*

1.1.5 Local thermal discomfort

The PMV-PPD indices express thermal comfort for the body as a whole. However dissatisfaction can also be caused by unwanted local cooling or heating of one or more body parts. Most common local thermal discomfort is due to draught, but local thermal discomfort due to a high temperature difference between head and ankles, too warm or too cold floor, or too high radiant temperature asymmetry can also be the cause.

Draught is defined as unwanted local cooling of the body due to air movement. Air movement is characterised by mean velocity, turbulence intensity and air temperature. Mean velocity is obtained from instantaneous velocity when averaged in time; turbulence intensity is the ratio of the standard deviation (in time) of the velocity fluctuations around mean velocity divided by the mean velocity. The increase of the mean velocity and the turbulence intensity and the decrease of the air temperature increases the local heat loss at the particular body part and therefore the discomfort due to draught increases (Figure 4.7). The percentage of people bothered by draught can be predicted by the draught rating model:

$$DR = (34 - t_a)(v_{a,l} - 0{,}05)^{0.62}\ (0{,}37\ v_a\ T_u + 3{,}14) \qquad (7)$$

For $v_{a,l} < 0.05$ m/s, use $v_{a,l} = 0.05$ m/s
For $DR > 100\%$, use $DR = 100\%$

Where t_a is the local air temperature (in the range 20°C to 26°C), $v_{a,l}$ is the local mean air velocity (< 0.5 m/s), T_u is the is the local turbulence intensity (from 10% to 60%; if unknown, 40% may be used).

The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral and for prediction of draught at neck level. At the level of arms and feet, the model could overestimate the predicted draught rate. The sensation of draught is lower at activities higher than sedentary (>1.2 met) and for people feeling warmer than neutral. Figure 4.7 illustrates the combinations of air velocity, turbulence intensity and air temperature which will cause draught for 20% of occupants.

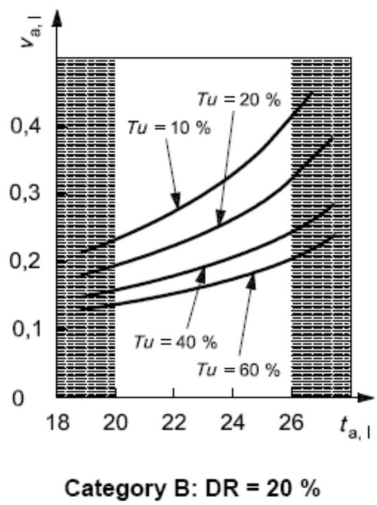

Figure 4.7 *Mean velocity as a function of air temperature and turbulence intensity which will cause 20% of dissatisfied occupants due to draught.*

Typically air temperature increases with the height of the room. When the difference in the air temperature at the head and at the ankles ($\Delta t_{a,v}$) becomes high, local thermal discomfort due to warm head and cold feet may occur. The percentage of dissatisfied occupants, PD (%), will increase with the increase of the temperature difference as shown in Figure 4.8 and can be determined by the equation (8):

$$PD = \frac{100}{1 + \exp(5.76 - 0.856 \times \Delta t_{a,v})} \qquad (8)$$

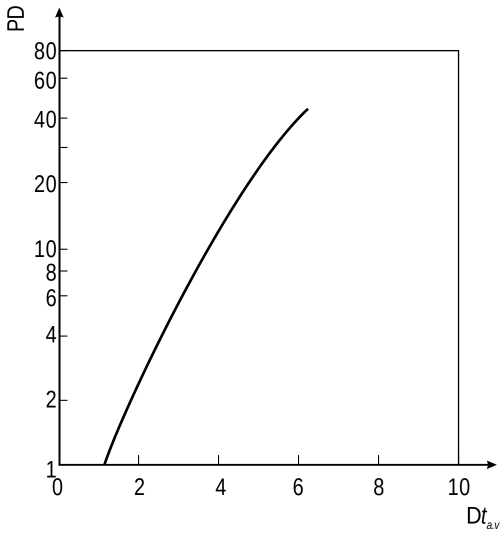

***Figure 4.8** Percentage of seated people dissatisfied as a function of the temperature difference at the head and the ankles.*

At head level an air temperature lower than the temperature at the ankle level is not critical.

Asymmetric thermal radiation may occur in rooms due to, for example cold/warm windows, ceiling heating, etc. People are more sensitive to asymmetry caused by an overhead warm surface than by a vertical cold surface. The influence of a cold ceiling or a vertical warm surface is much less (Figure 4.9). The local thermal discomfort due to radiant asymmetry is particularly important for the design of radiant heating/cooling. The percentage of dissatisfied, PD, due to different types of radiant asymmetry can be determined by the following equations:

<u>Warm ceiling:</u>

$$PD = \frac{100}{1 + \exp(2.84 - 0.174 \times \Delta t_{pr})} - 5{,}5 \qquad (9)$$

<u>Cool wall</u>:

$$PD = \frac{100}{1 + \exp(6.61 - 0.345 \times \Delta t_{pr})}; \quad (\Delta t_{pr} < 15°C) \qquad (10)$$

<u>Cool ceiling:</u>

$$PD = \frac{100}{1 + \exp(9.93 - 0.50 \times \Delta t_{pr})} \qquad (11)$$

<u>Warm wall:</u>

$$PD = \frac{100}{1 + \exp(3.72 - 0.052 \times \Delta t_{pr})} - 3{,}5; \quad (\Delta t_{pr} < 35°C) \qquad (12)$$

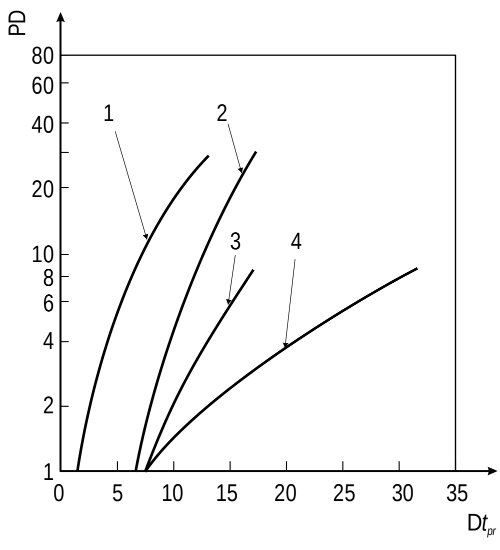

***Figure 4.9** Percentage dissatisfied, PD, due to radiant temperature asymmetry (1 – warm ceiling, 2 – cool wall, 3 – cool ceiling, 4 – warm wall).*

In rooms with cold/warm floor occupants may feel discomfort due to the thermal sensation at their feet. The percentage of dissatisfied occupants, PD, increases when the floor temperature, t_f, decreases/increases as shown in Figure 4.10 and can be calculated by the following equation:

$$PD = 100 - 94 \exp(-1.387 + 0.118\, t_f - 0.0025\, t_f^2) \quad (13)$$

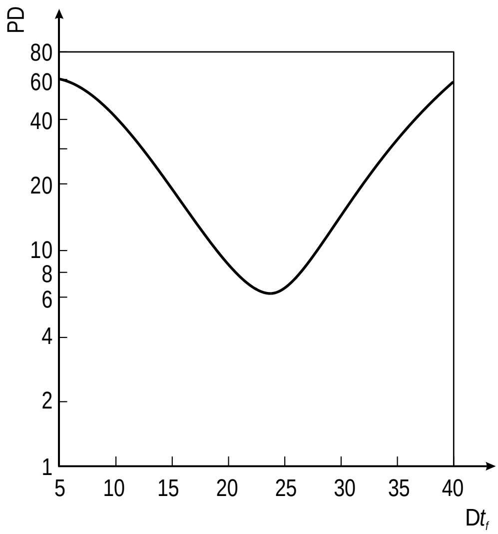

Figure 4.10 *Percentage dissatisfied, PD, due to floor temperature* t_f.

Non-steady-state thermal environments

The thermal comfort of occupants is not affected by temperature cycles with peak-to-peak variations of less than 1°C or temperature drifts and ramps with a rate lower than 2K/h. Step changes in the operative temperature are felt immediately. In the case of a step-up change in operative temperature the new thermal sensation can be predicted by the PMV–PPD indices. However during a step-down change in the operative temperature, the occupants' thermal sensation first overshoots, and then decreases below the thermal sensation predicted by the PMV-PPD indices achieved approximately 20 minutes after the change (Knudsen and Fanger 1996) [5].

1.1.6 Thermal comfort in buildings without mechanical cooling

In office buildings without mechanical cooling, and other buildings of a similar type used for human occupancy with mainly sedentary activities where there is easy access to openable windows and the occupants adapt their clothing to the indoor and/or outdoor thermal conditions the temperature ranges defined in Figure 4.11 can be applied. Field surveys have shown that in such buildings occupants' thermal responses depend in part on the outdoor climate, and differ from the thermal responses of occupants in buildings with HVAC systems because of the availability of control, shifts in occupants' expectations and other factors. In summer additional elevated air movement generated by for example fans and under individual control may be needed to achieve thermal comfort.

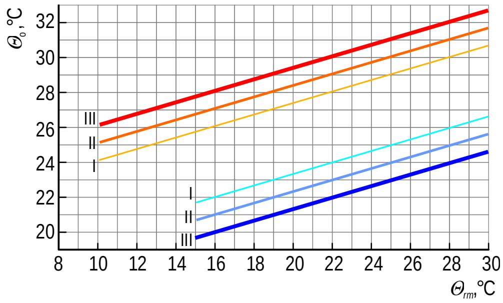

Figure 4.11 *Design values for the indoor operative temperature, Θ_o, for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature, Θ_{rm}.*

The allowable indoor operative temperatures of Figure 4.11 are plotted against the external running mean temperature Θ_{rm} which is defined as the exponentially weighted running mean of the daily outdoor temperature (EN 15251 2007) [C1]. The equations representing the lines in Figure 4.11 are:

· Category I:
upper limit: $\Theta_{i\ max} = 0.33\Theta_{rm} + 18.8 + 2$
lower limit: $\Theta_{i\ min} = 0.33\ \Theta_{rm} + 18.8 - 2$

· Category II:
upper limit: $\Theta_{i\ max} = 0.33\ \Theta_{rm} + 18.8 + 3$
lower limit: $\Theta_{i\ min} = 0.33\ \Theta_{rm} + 18.8 - 3$

· Category III:
upper limit: $\Theta_{i\ max} = 0.33\ \Theta_{rm} + 18.8 + 4$
lower limit: $\Theta_{i\ min} = 0.33\ \Theta_{rm} + 18.8 - 4$

Where Θ_i is limit value of indoor operative temperature, C; Θ_{rm} = running mean outdoor temperature. These limits apply when $10 < \Theta_{rm} < 30$°C for upper limit and $15 < \Theta_{rm} < 30$°C for lower limit. Above 25°C the graphs are based on a limited database. Detail instructions on the use of the Figure 4.11 are described in the document EN 15251 (2007) [C1].