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Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

Ergonomie des ambiances thermiques — Détermination analytique et interprétation du confort thermique par le calcul des indices PMV et PPD et par des critères de confort thermique local

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 7730 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*.

This third edition cancels and replaces the second edition (ISO 7730:1994), which has been technically revised. A method for long term evaluation has been added, as well as information on local thermal discomfort, non-steady-state conditions and adaptation, and an annex stating how thermal comfort requirements can be expressed in different categories.

Introduction

This International Standard covering the evaluation of moderate thermal environments was developed in parallel with the revised ASHRAE[1)] standard 55 and is one of a series of ISO documents specifying methods for the measurement and evaluation of the moderate and extreme thermal environments to which human beings are exposed (ISO 7243, ISO 7933 and ISO/TR 11079, all three dealing with extreme environmental conditions, are others in the series).

A human being's thermal sensation is mainly related to the thermal balance of his or her body as a whole. This balance is influenced by physical activity and clothing, as well as the environmental parameters: air temperature, mean radiant temperature, air velocity and air humidity. When these factors have been estimated or measured, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote (PMV). See Clause 4.

The predicted percentage dissatisfied (PPD) index provides information on thermal discomfort or thermal dissatisfaction by predicting the percentage of people likely to feel too warm or too cool in a given environment. The PPD can be obtained from the PMV. See Clause 5.

Thermal discomfort can also be caused by unwanted local cooling or heating of the body. The most common local discomfort factors are radiant temperature asymmetry (cold or warm surfaces), draught (defined as a local cooling of the body caused by air movement), vertical air temperature difference, and cold or warm floors. Clause 6 specifies how to predict the percentage dissatisfied owing to local discomfort parameters.

Dissatisfaction can be caused by hot or cold discomfort for the body as a whole. Comfort limits can in this case be expressed by the PMV and PPD indices. But thermal dissatisfaction can also be caused by local thermal discomfort parameters. Clause 7 deals with acceptable thermal environments for comfort.

Clauses 6 and 7 are based mainly on steady-state conditions. Means of evaluating non-steady-state conditions such as transients (temperature steps), cycling temperatures or temperature ramps are presented in Clause 8. The thermal environments in buildings or at workplaces will change over time and it might not always be possible to keep conditions within recommended limits. A method for long-term evaluation of thermal comfort is given in Clause 9.

Clause 10 gives recommendations on how to take into account the adaptation of people when evaluating and designing buildings and systems.

1) American Society of Heating, Refrigerating and Air-conditioning Engineers.

Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

1 Scope

This International Standard presents methods for predicting the general thermal sensation and degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. It enables the analytical determination and interpretation of thermal comfort using calculation of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) and local thermal comfort criteria, giving the environmental conditions considered acceptable for general thermal comfort as well as those representing local discomfort. It is applicable to healthy men and women exposed to indoor environments where thermal comfort is desirable, but where moderate deviations from thermal comfort occur, in the design of new environments or the assessment of existing ones. Although developed specifically for the work environment, it is applicable to other kinds of environment as well. It is intended to be used with reference to ISO/TS 14415:2005, 4.2, when considering persons with special requirements, such as those with physical disabilities. Ethnic, national or geographical differences need also to be taken into account when considering non-conditioned spaces.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13731, *Ergonomics of the thermal environment — Vocabulary and symbols*

ISO/TS 13732-2, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 2: Human contact with surfaces at moderate temperature*

ISO/TS 14415:2005, *Ergonomics of the thermal environment — Application of International Standards to people with special requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13731 and the following apply.

3.1
temperature cycle
variable temperature with a given amplitude and frequency

3.2
drift temperature
passive monotonic, steady, non-cyclic change in the operative temperature of an enclosed space

3.3
ramp temperature
actively controlled monotonic, steady, non-cyclic change in the operative temperature of an enclosed space

3.4
operative temperature
t_o
uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment

3.5
transient temperature
sudden change in the thermal conditions due to step change in temperature, humidity, activity or clothing

3.6
draught
unwanted local cooling of the body caused by air movement

4 Predicted mean vote (PMV)

4.1 Determination

The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (see Table 1), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate environment, the human thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance.

Table 1 — Seven-point thermal sensation scale

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
− 1	Slightly cool
−2	Cool
− 3	Cold

Calculate the PMV using Equations (1) to (4):

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028\right] \cdot \left\{ \begin{array}{l} (M-W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M-W) - p_a\right] - 0{,}42 \cdot \left[(M-W) - 58{,}15\right] \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}001\,4 \cdot M \cdot (34 - t_a) \\ -3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\} \quad (1)$$

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M-W) - I_{cl} \cdot \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl}+273)^4 - (\bar{t}_r+273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \begin{cases} 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases} \quad (3)$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290\, l_{cl} & \text{for } l_{cl} \leqslant 0{,}078 \text{ m}^2 \cdot \text{K/W} \\ 1{,}05 + 0{,}645\, l_{cl} & \text{for } l_{cl} > 0{,}078 \text{ m}^2 \cdot \text{K/W} \end{cases} \quad (4)$$

where

M is the metabolic rate, in watts per square metre (W/m^2);

W is the effective mechanical power, in watts per square metre (W/m^2);

I_{cl} is the clothing insulation, in square metres kelvin per watt (m^2 · K/W);

f_{cl} is the clothing surface area factor;

t_a is the air temperature, in degrees Celsius (°C);

$\bar{t}_r$ is the mean radiant temperature, in degrees Celsius (°C);

v_{ar} is the relative air velocity, in metres per second (m/s);

p_a is the water vapour partial pressure, in pascals (Pa);

h_c is the convective heat transfer coefficient, in watts per square metre kelvin [W/(m^2 · K)];

t_{cl} is the clothing surface temperature, in degrees Celsius (°C).

NOTE 1 metabolic unit = 1 met = 58,2 W/m^2; 1 clothing unit = 1 clo = 0,155 m^2 · °C/W.

PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity and air humidity (see ISO 7726). The equations for t_{cl} and h_c may be solved by iteration.

The PMV index is derived for steady-state conditions but can be applied with good approximation during minor fluctuations of one or more of the variables, provided that time-weighted averages of the variables during the previous 1 h period are applied.

The index should be used only for values of PMV between −2 and +2, and when the six main parameters are within the following intervals:

M 46 W/m^2 to 232 W/m^2 (0,8 met to 4 met);

I_{cl} 0 $m^2 \cdot K/W$ to 0,310 $m^2 \cdot K/W$ (0 clo to 2 clo);

t_a 10 °C to 30 °C;

$\bar{t}_r$ 10 °C to 40 °C;

v_{ar} 0 m/s to 1 m/s;

p_a 0 Pa to 2 700 Pa.

NOTE In respect of v_{ar}, during light, mainly sedentary, activity, a mean velocity within this range can be felt as a draught.

Estimate the metabolic rate using ISO 8996 or Annex B, taking into account the type of work. For varying metabolic rates, a time-weighted average should be estimated during the previous 1 h period. Estimate the thermal resistance of clothing and chair using ISO 9920 or Annex C, taking into account the time of year.

Determine the PMV in one of the following ways.

a) From Equation (1) using a digital computer. A BASIC program is given in Annex D for this purpose. For verification of other computer programs, Annex D provides example output.

b) Directly from Annex E, where tables of PMV values are given for different combinations of activity, clothing, operative temperature and relative velocity.

c) By direct measurement, using an integrating sensor (equivalent and operative temperatures).

The PMV values given in Annex E apply for a relative humidity of 50 %. The influence of humidity on thermal sensation is small at moderate temperatures close to comfort and may usually be disregarded when determining the PMV value (see Annex F).

4.2 Applications

The PMV can be used to check whether a given thermal environment complies with comfort criteria (see Clause 7 and Annex A), and to establish requirements for different levels of acceptability.

By setting PMV = 0, an equation is established which predicts combinations of activity, clothing and environmental parameters which on average will provide a thermally neutral sensation.

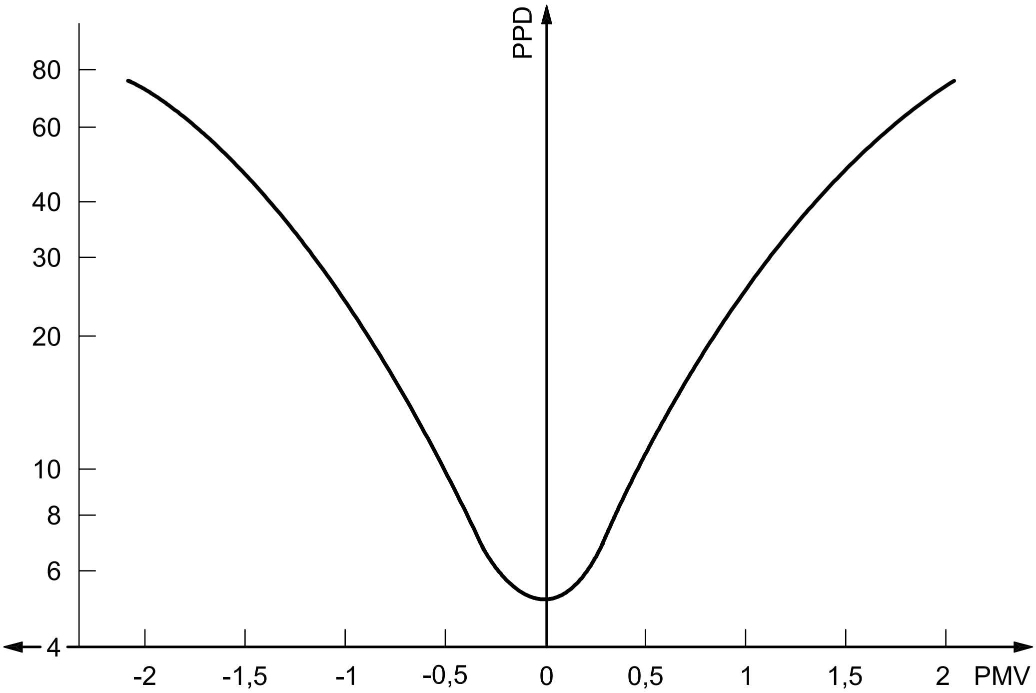
5 Predicted percentage dissatisfied (PPD)

The PMV predicts the mean value of the thermal votes of a large group of people exposed to the same environment. But individual votes are scattered around this mean value and it is useful to be able to predict the number of people likely to feel uncomfortably warm or cool.

The PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. For the purposes of this International Standard, thermally dissatisfied people are those who will vote *hot*, *warm*, *cool* or *cold* on the 7-point thermal sensation scale given in Table 1.

With the PMV value determined, calculate the PPD using Equation (5), see Figure 1:

$$PPD = 100 - 95 \cdot \exp(-0{,}033\,53 \cdot PMV^4 - 0{,}217\,9 \cdot PMV^2) \qquad (5)$$



Key

PMV predicted mean vote

PPD predicted percentage dissatisfied, %

Figure 1 — PPD as function of PMV

The PPD predicts the number of thermally dissatisfied persons among a large group of people. The rest of the group will feel thermally neutral, slightly warm or slightly cool. The predicted distribution of votes is given in Table 2.

Table 2 — Distribution of individual thermal sensation votes for different values of mean vote

PMV	PPD	Persons predicted to vote [a] %		
		0	−1, 0 or +1	−2, −1, 0, +1 or +2
+2	75	5	25	70
+1	25	30	75	95
+0,5	10	55	90	98
0	5	60	95	100
−0,5	10	55	90	98
−1	25	30	75	95
−2	75	5	25	70

[a] Based on experiments involving 1 300 subjects.

6 Local thermal discomfort

6.1 General

The PMV and PPD express warm and cold discomfort for the body as a whole. But thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the body. This is known as *local discomfort*. The most common cause of local discomfort is draught (6.2). But local discomfort can also be caused by an abnormally high vertical temperature difference between the head and ankles (6.3), by too warm or too cool a floor (6.4), or by too high a radiant temperature asymmetry (6.5). Annex A provides examples of local and overall thermal comfort requirements for different categories of environment and types of space.

It is mainly people at light sedentary activity who are sensitive to local discomfort. These will have a thermal sensation for the whole body close to neutral. At higher levels of activity, people are less thermally sensitive and consequently the risk of local discomfort is lower.

6.2 Draught

The discomfort due to draught may be expressed as the percentage of people predicted to be bothered by draught. Calculate the draught rate (DR) using Equation (6) (model of draught):

$$DR = \left(34 - t_{\mathrm{a,l}}\right)\left(\bar{v}_{\mathrm{a,l}} - 0{,}05\right)^{0{,}62}\left(0{,}37 \cdot \bar{v}_{\mathrm{a,l}} \cdot Tu + 3{,}14\right) \tag{6}$$

For $\bar{v}_{\mathrm{a,l}} < 0{,}05$ m/s: use $\bar{v}_{\mathrm{a,l}} = 0{,}05$ m/s

For $DR > 100$ %: use $DR = 100$ %

where

$t_{\mathrm{a,l}}$ is the local air temperature, in degrees Celsius, 20 °C to 26 °C;

$\bar{v}_{\mathrm{a,l}}$ is the local mean air velocity, in metres per second, $< 0{,}5$ m/s;

Tu is the local turbulence intensity, in percent, 10 % to 60 % (if unknown, 40 % may be used).

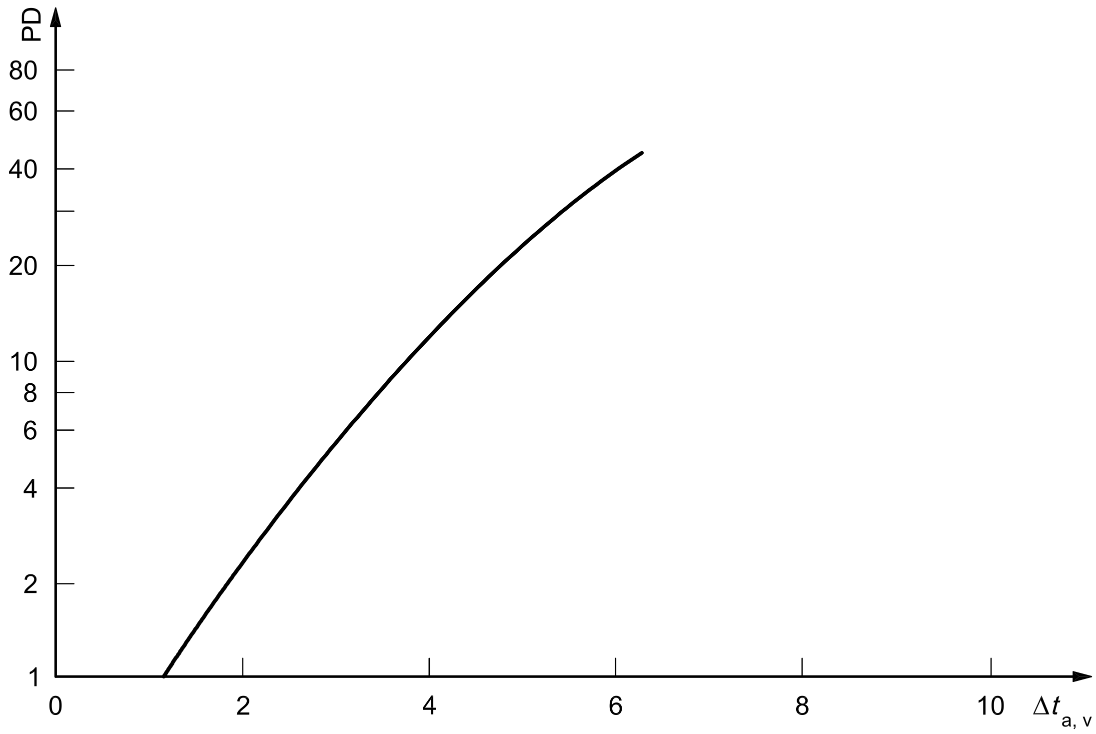
The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral and for prediction of draught at the neck. At the level of arms and feet, the model could overestimate the predicted draught rate. The sensation of draught is lower at activities higher than sedentary (> 1,2 met) and for people feeling warmer than neutral. Additional information on the effect of air velocity can be found in Annex G.

6.3 Vertical air temperature difference

A high vertical air temperature difference between head and ankles can cause discomfort. Figure 2 shows the percentage dissatisfied (PD) as a function of the vertical air temperature difference between head and ankles. The figure applies when the temperature increases upwards. People are less sensitive under decreasing temperatures. Determine the PD using Equation (7):

$$PD = \frac{100}{1 + \exp(5{,}76 - 0{,}856 \cdot \Delta t_{\mathrm{a,v}})} \tag{7}$$

Equation (7), derived from the original data using logistic regression analysis, should only be used at $\Delta t_{\mathrm{a,v}} < 8$ °C.



Key

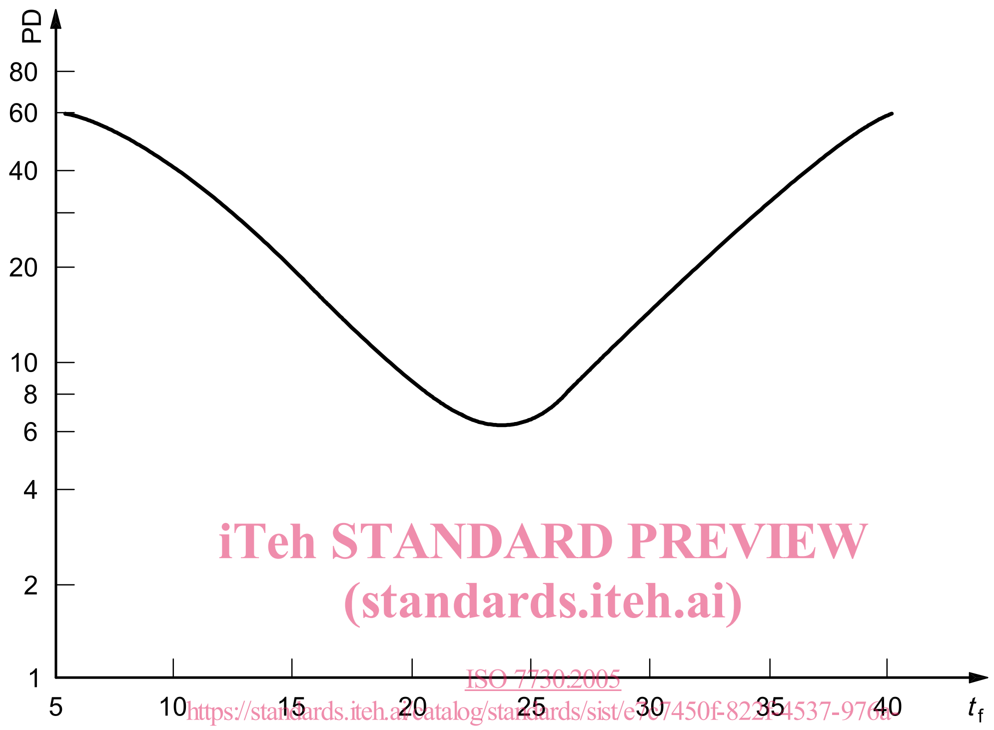
PD percentage dissatisfied, %

$\Delta t_{a,v}$ vertical air temperature difference between head and feet, °C

Figure 2 — Local discomfort caused by vertical air temperature difference

6.4 Warm and cool floors

If the floor is too warm or too cool, the occupants could feel uncomfortable owing to thermal sensation of their feet. For people wearing light indoor shoes, it is the temperature of the floor rather than the material of the floor covering which is important for comfort. Figure 3 shows the percentage dissatisfied as a function of the floor temperature, based on studies with standing and/or sedentary people.



Key

PD percentage dissatisfied, %

t_f floor temperature, °C

Figure 3 — Local thermal discomfort caused by warm or cold floors

For people sitting or lying on the floor, similar values may be used. Determine the PD using Equation (8), derived from the original data using non-linear regression analysis:

$$PD = 100 - 94 \cdot \exp(-1{,}387 + 0{,}118 \cdot t_f - 0{,}002\,5 \cdot t_f^2) \quad (8)$$

For longer occupancy the results are not valid for electrically heated floors.

NOTE By electrical heating, a certain heat input is provided independent of the surface temperature. A water-based heating system will not produce temperatures higher than the water temperature.

For spaces that people occupy with bare feet, see ISO/TS 13732-2.

6.5 Radiant asymmetry

Radiant asymmetry (Δt_{pr}) can also cause discomfort. People are most sensitive to radiant asymmetry caused by warm ceilings or cool walls (windows). Figure 4 shows the percentage dissatisfied as a function of the radiant temperature asymmetry caused by a warm ceiling, a cool wall, a cool ceiling or by a warm wall. For horizontal radiant asymmetry, Figure 4 applies from side-to-side (left/right or right/left) asymmetry, the curves providing a conservative estimate of the discomfort: no other positions of the body in relation to the surfaces (e.g. front/back) cause higher asymmetry discomfort. Determine the PD using Equations (9) to (12), as applicable.

a) Warm ceiling

$$PD = \frac{100}{1 + \exp(2{,}84 - 0{,}174 \cdot \Delta t_{pr})} - 5{,}5 \qquad (9)$$

$\Delta t_{pr} < 23$ °C

b) Cool wall

$$PD = \frac{100}{1 + \exp(6{,}61 - 0{,}345 \cdot \Delta t_{pr})} \qquad (10)$$

$\Delta t_{pr} < 15$ °C

c) Cool ceiling

$$PD = \frac{100}{1 + \exp(9{,}93 - 0{,}50 \cdot \Delta t_{pr})} \qquad (11)$$

$\Delta t_{pr} < 15$ °C

d) Warm wall

$$PD = \frac{100}{1 + \exp(3{,}72 - 0{,}052 \cdot \Delta t_{pr})} - 3{,}5 \qquad (12)$$

$\Delta t_{pr} < 35$ °C

Equations (9) to (12) were derived from the original data using logistic regression analysis, and should not be used beyond the ranges shown above. Those for a) (warm ceiling) and for d) (warm wall) have been adjusted to account for discomfort not caused by radiant asymmetry. See Figure 4.