Thermal Environments

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INTRODUCTION

The main purpose for heating and air conditioning of work spaces is to provide an environment that is acceptable and does not impair the health and performance of the occupants. During production processes and external climate it may be necessary to work in unacceptable conditions for a limited time period. However, it must be ensured that these conditions do not impair the health of the employees. Light, noise, air quality and the thermal environment are all factors which will influence the acceptability and performance of the occupants. The present chapter will only deal with the thermal environment. Several standards dealing with methods for the evaluation of the thermal environment have been published by international standard organizations like ISO and CEN.

The present chapter deals with the ISO standards, which have been or are being prepared by ISO/TC159/SC5/Wg1 and CEN/TC122/WG11 "Ergonomics of the thermal environment". An overview of the standards issued and documents under preparation is given in Table 1. Furthermore a CEN Technical Report CR 1752 will be used in this chapter.

Several of these standards may be used as a basis for the design and evaluation of buildings, HVAC (heating, ventilation and air conditioning) systems, protective equipment (clothing) and optimization of work-rest schedules.

The basic philosophy has been to standardize evaluation methods, while recommended limit values for the different parameters or indices are listed in informative annexes. These or other values may then be adapted in national rules for the thermal environment.

THE THERMAL ENVIRONMENT

Existing methods for evaluation of the general thermal state of the body, both in comfort and in heat- or cold stress, are based on an analysis of the heat balance for the human body:

$$\mathbf{S = M - W - C - R - E_{sk} - C_{res} - E_{res} - K} \quad (1)$$

where:

S = heat storage in body;
M = metabolic heat production
W = external work;
C = heat loss by convection;
R = heat loss by radiation;
$\mathbf{E_{sk}}$ = evaporative heat loss from skin;
$\mathbf{C_{res}}$ = convective heat loss from respiration;
$\mathbf{E_{res}}$ = evaporative heat loss from respiration;
K = heat loss by conduction.

The factors influencing this heat balance are: activity level (metabolic rate, met or W/m^2); thermal resistance of clothing $\mathbf{I_{cl}}$ (clo or m^2 ^{o}C/W) evaporative resistance of clothing **Re**, clo (m^2 Pa/W); air temperature $\mathbf{t_a}$ (^{o}C); mean radiant temperature $\mathbf{t_r}$ (^{o}C); air speed $\mathbf{v_{ar}}$,(m/s); partial water vapor pressure $\mathbf{p_a}$ (Pa).

These parameters must be combined so that the thermal storage is 0 or else the working time has to be limited to avoid too much strain on the body. To provide comfort the mean skin temperature also has to be inside certain limits and the evaporative heat loss must be low. In existing standards, guidelines or handbooks, different methods are used to evaluate the general thermal state of the body in moderate environments, cold environments and hot environments; but all are based on the above heat balance and the listed factors.

Besides the general thermal state of the body, a person may find the thermal environment unacceptable or intolerable if local influences on the body from asymmetric radiation, air velocities, vertical air temperature differences or contact with hot or cold surfaces (floors, machinery, tools, etc.) are experienced.

MODERATE THERMAL ENVIRONMENTS

The main standards for comfortable thermal environment are ASHRAE 55-92 and ISO EN 7730. The research, which forms the basis for these two standards are mainly performed under environmental conditions similar to commercial and residential buildings, with activity levels, 1-2 met, normal indoor clothing (0.5 to 1.0 clo) and a limited range of the environmental parameters.

GENERAL THERMAL COMFORT

ISO EN 7730 standardizes the PMV-PPD index as the method for evaluation of moderate thermal environments. To quantify the degree comfort the PMV index gives a value on a 7-point thermal sensation scale: + 3 hot, + 2 warm, + 1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, - 3 cold. An equation in the standard calculates the PMV index based on the 6 factors (clothing, activity, air and mean radiant temperature, air speed, and humidity).

The PMV index can be determined when the activity (metabolic rate) and the clothing (thermal resistance) are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure (see ISO EN 7726).

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. Because the PMV index assumes that all evaporation from the skin is transported through the clothing to the environment, this method is not applicable for hot environments. It can be used within a range of PMV index of –2 to +2, i. e. thermal environments where sweating is minimal.

Furthermore it is recommended to use the PMV index when the six main parameters are inside the following intervals:

M = 46 to 232 W/m² (0,8 to 4 met);
I_{clo} = 0 to 0,310 m² · °C/W (0 to 2 clo);
t_a = 10 to 30 °C;
t_r = 10 to 40 °C;
v_{ar} = 0 to 1 m/s
p_a = 0 to 2 700 Pa

The metabolic rate can be estimated by ISO EN 9886 and the thermal resistance of clothing can be estimated by ISO EN 9920 taking into account the type of work and the time of year. For varying metabolic rates, it is recommended to estimate a time-weighted average during the previous 1 h period. For sedentary people the insulation of a chair must also be taken into account.

The PMV index can be used to check whether a given thermal environment complies with the comfort criteria specified in 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 will provide a thermally neutral sensation.

Figure 1 shows the optimal operative temperature as a function of activity and clothing for different levels of acceptability.

The PMV index 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 predict the number of people likely to feel uncomfortably warm or cool. The PPD-Index establishes a quantitative prediction of the number of thermally dissatisfied people. The PPD predicts the percentage of a large group of people likely to feel too warm or cool, i.e. voting hot (+3), warm (+2), cool (-2) or cold (-3) on the 7-point thermal sensation scale.

When the PMV-value has been determined, the PPD can be found from **Figure 2** or determined from the equation.

$$PPD = 100 - 95xe^{\left(-10,03353xxPMV^4 + 0,2179xPMV^2\right)} \quad (2)$$

LOCAL THERMAL DISCOMFORT

Besides the general thermal state of the body, a person may find the thermal environment unacceptable if local influences on the body from asymmetric temperature radiation, draught, vertical air temperature differences or contact with hot or cold surfaces (floors, machinery, tools, etc.) are experienced. The data for local thermal discomfort is mainly based on studies with people under low activity levels (1.2 met). For higher activities it can be expected that people are less sensitive to local thermal discomfort. The shown relations between dissatisfied and local discomfort parameters are from CR 1752.

Draught – Local Air Velocities

One of the most critical factors is draught. Many people at low activity level (seated-standing) are very sensitive to air velocities and therefore, draught is a very common cause for occupant complaints in ventilated and air conditioned spaces. Fluctuations of the air velocity have a significant influence on a person's sensation of draught. The fluctuations may either be expressed by the standard deviation of the air velocity or by the turbulence intensity Tu, which is equal to standard deviation (SDv_a) divides by the mean air velocity, v_a. The percentage of people feeling draught (draught rating, DR) may be estimated from the equation:

$$PD = (34 - t_a)\,(v_a - 0.05)^{0.62}\,(3.14 + 0.37 \cdot SDv_a) \quad (3)$$

where

v_a = mean air velocity (3 min) ms^{-1}
SDv_a = standard deviation of air velocity (3 min) ms^{-1}
t_a = air temperature, °C

For $v_a < 0.05$ ms^{-1} insert $v_a = 0.05$ ms^{-1}.

For DR > 100 % use DR = 100 %.

The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral. The sensation of draught is lower at activities higher than sedentary and for people feeling warmer than neutral.
For people at higher activity levels and/or at ambient temperatures above the comfort range an increased air velocity may improve the general thermal comfort. This influence is taken into account by using the PMV-equation. Also high local velocities (spoot cooling) may decrease discomfort from high activity and/or high ambient temperatures.

Vertical air temperature difference

A high vertical air temperature difference between head and ankles may cause discomfort. In **Figure 3** is shown the percentage of dissatisfied as a function of the vertical air temperature difference between head and ankles (1,1 and 0,1 m above the floor). The figure applies when the temperature increases upwards. People are less sensitive for decreasing temperature.

Warm and cool floors

If the floor is too warm or too cool, the occupants may feel uncomfortable due to warm or cool 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 the comfort. In **Figure 4** is shown the percentage of dissatisfied for seated or standing people as a function of the floor temperature.

Radiant Asymmetry

Radiant asymmetry may also cause discomfort. People are most sensitive to radiant asymmetry caused by warm ceilings or cool walls (windows). In **Figure 5** is shown the percentage of 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. These data apply for sedentary people and low ceiling height. A study with a high ceiling, 9 m, and asymmetry and ceiling mounted gasfired infrared heaters (Langkilde et. al. 1985) showed a higher acceptable temperature asymmetry. For seated and standing people a temperature asymmetry of 10 – 14 K resulted in less than 5 % dissatisfied.

TARGET VALUES FOR ACCEPTABLE THERMAL ENVIRONMENTS FOR COMFORT

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction may be caused by warm or cool discomfort of the body as a whole as expressed by the PMV and PPD indices or may be caused by an unwanted cooling (or heating) of one particular part of the body.
Due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody. There will always be a percentage of dissatisfied occupants. But it is possible to specify environments predicted to be acceptable by a certain percentage of the occupants.
Due to local or national priorities, technical developments and climatic regions in some cases a higher thermal quality (fewer dissatisfied) or lower quality (more dissatisfied) may be sufficient. In both cases the PMV and PPD indices, the model of draught and the relation between local thermal discomfort parameters (clause 6.3.3.2) and the expected percentage of dissatisfied people may be used to determine different ranges of environmental parameters for the evaluation and design of the thermal environment.

While some existing standards are only specifying one level of comfort (ISO EN 7730, ASHRAE 55-92) a CEN-report CR 1752 recommend three categories as shown in **Table 2.**

Each category prescribes a maximum percentage of dissatisfied for the body as a whole (PPD) and for each of the four types of local discomfort. Some requirements are hard to meet in practice while others are quite easily met. The different percentages express a balance struck between the aim of providing few dissatisfied and what is practically obtainable using existing technology.

The three categories in **Table 2** apply to spaces where persons are exposed to the same thermal environment. It is an advantage if some kind of individual control of the thermal environment can be established for each person in a space. Individual control of the local air temperature, mean radiant temperature or air velocity may contribute to balance the rather large differences between individual requirements and therefore provide fewer dissatisfied.
Modification of the clothing may also contribute to balance individual differences. The effect of adding (or removing) different garments on the optimum operative temperature is listed in **Table 14.**

Operative temperature range

For a given space there exists an optimum operative temperature corresponding to PMV = 0, depending on the activity and the clothing of the occupants. **Figure 1** shows the optimum operative temperature and the permissible temperature range as a function of clothing and activity for each of the three categories. The optimum operative temperature is the same for the three categories, while the permissible range around the optimum operative temperature varies.

The operative temperature at all locations within the occupied zone of a space should at all times be within the permissible range. This means that the permissible range should cover both spatial and temporary variations, including fluctuations caused by the control system.

Figure 1 applies for a relative humidity of 50%; however, in moderate environments the air humidity has only a modest impact on the thermal sensation. Typically a 10% higher relative humidity is felt equally warm as a 0,3°C higher operative temperature.
The number of dissatisfied persons in **Table 2** are not additive. Some of the same people experiencing general thermal comfort (PMV-PPD) may be the same as the people local thermal discomfort. In practice higher or lower number of dissatisfied persons may be found, when using subjective questionnaires in field investigations (ISO 10551).

Local Thermal discomfort

The following **Figure 6** and **Tables 3-5** give ranges for local thermal discomfort parameters for the three categories listed in
Table 2.
The mean air velocity is a function of local air temperature and turbulence intensity. The turbulence intensity may vary between 30% and 60% in spaces with mixing flow air distribution. In spaces with displacement ventilation or without mechanical ventilation, the turbulence intensity may be lower.

HOT ENVIRONMENTS

The ISO philosophy for the assessment of hot environments is to use a simple "fast" method for monitoring the environment, based on the Wet Bulb Globe Temperature (WBGT) index
(ISO 7243 (1989)). If the WBGT values exceed the provided 'reference' values or a more detailed analysis is required then ISO 7933 (1989) provides an analytical method of assessment.

Wet Bulb Globe Temperature (WBGT) heat stress index is calculated.

Inside buildings and outside buildings without solar load as:

$$WBGT = 0.7t_{nw} + 0.3t_g \quad (4)$$

Outside buildings with solar load as:

$$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a \quad (5)$$

where

t_{nw}	is the natural wet bulb temperature	°C
t_g	is the temperature at the center of a 150 mm diameter black globe thermometer	°C
t_a	is the air temperature	°C

The WBGT value of the hot environment is compared with a WGBT reference value, which is included in an informative Annex (Table 6).

The reference values have been established allowing for a maximum rectal temperature of 38 °C for the persons concerned. This corresponds to levels of exposure to which almost all individuals can be ordinarily exposed without any harmful effect, provided there are no pre-existing pathological conditions.

If the WBGT of the hot environment exceeds the WBGT reference value then the heat stress at the workplace needs to be reduces or a more detailed analysis made (i.e. using ISO 7933). The standard also includes a method to plan a work-rest schedule that will provide tolerable environments.

The method used in ISO 7933, Required Sweat Rate, $\mathbf{Sw_{req}}$, is based on the heat balance equation (1). Assuming that the heat storage is equal to 0, the necessary evaporation from the skin, $\mathbf{E_{req}}$, ensuring a heat balance, is calculated as follows:

$$\mathbf{E_{req} = M - W - C - R - E_{res} - C_{res}} \tag{6}$$

The maximum evaporation, $\mathbf{E_{max}}$, which can be absorbed by the environment, is estimated from the equation:

$$\mathbf{E_{max} = (p_{sk_s} - p_a)/R_{e_T}} \tag{7}$$

where:

$\mathbf{p_{sk_s}}$ = saturated water vapor pressure at skin;
$\mathbf{p_a}$ = water vapor pressure in the environment;
$\mathbf{R_{e_T}}$ = total evaporative resistance of clothing and boundary layer.

Based on the required evaporation and the maximum evaporation it is then possible to estimate the following factors:

Required skin wetness, $\mathbf{w_{req} = E_{req}/E_{max}}$ (8)

Sweating efficiency, $r = 1 - 0.5\, e^{-6.6\,(1 - w_{req})}$ (9)

Required Sweat Rate, $\mathbf{SW_{req} = E_{req}/r}$ (10)

These parameters are used to evaluate how stressful a given hot working environment is. Dependent on the physiological limitations for factors such as sweat rate, total sweat loss, heat storage and skin wetness, which are listed in the **Table 7**, it is possible to evaluate whether a given environment is acceptable for continuous work. The method also allows to calculate an acceptable working time. Detailed equations for the calculations can be found in the standard (ISO 7933).

The relation between the operative temperature and Sw_{req} for different combinations of activity and clothing is shown in **Table 8**.
A computer program is provided to allow ease of calculation and efficient use of the standard. this rational method of assessing hot environments allows identification of the relative importance of different components of the thermal environment, and hence can be used in environmental design. The WBGT index is an empirical index, which cannot be used to analyze the influence of the individual parameters. The required sweat rate (Sw_{req}) has this capability, but lack of data may make it difficult to estimate the benefits of protective clothing.

COLD ENVIRONMENTS

Many industrial work places are located in cold environments, such as cold storage, meat packing, work places located outdoors, etc. In cold environments, the clothing is the most important factor for obtaining an acceptable thermal environment. Based on the heat balance equation (1), an analytical method has been proposed by CEN ISO, Required Clothing Insulation, I_{req} , (ISO/TR ENV 11079). The method calculates the insulation of the clothing necessary to keep a heat balance in a given cold environment by knowing the activity level, air- and mean radiant temperature, air velocity and humidity according to the following equations:

$$I_{req} = \frac{t_{sk} - t_{cl}}{M - W - E_{sk} - C_{res} - E_{res}} \tag{11}$$

$$M - W - E_{sk} - C_{res} - E_{res} = C + R \tag{12}$$

The relationship between activity level ,operative temperature and Ireq may be calculated with this new method, which has not been widely used, and little experience is available. Therefore the method has been proposed in the form of a technical report, which in the future may be published as an ISO standard.
The index value may be used to select a clothing ensemble, which will provide the required insulation. The clothing insulation can according to **Table 9** be predicted either as a minimum, where some strain may be expected on the people, or as a neutral insulation, where people are expected to feel neutral. It is important when selecting the actual clothing (ISO 9920) to allow for individual adjustment of the clothing insulation. Also, the clothing insulation values listed in ISO 9920 are valid for people with standing and sedentary work. For people at higher activities, the clothing values from the tables in ISO 9920 should be reduced by approximately 20 %, owing to body movements (pumping effect).
If it is not possible to use or select a clothing ensemble with enough insulation, the method includes a procedure for calculation of a recommended exposure time. the basis for the calculations is the physiological requirements listed in **Table 9.**
For outdoor work there may be a risk for frostbite in wintertime. The report uses the wind chill temperature, WCI, calculated as

$$t_{ch} = \frac{33 - WCI}{25.5} \quad \text{°C} \qquad (13)$$

$$WCI = 1.16\left(10.45 + 10\sqrt{v_{ar}} - v_{ar}\right)\left(33 - t_a\right) \quad \text{W/m}^2 \qquad (14)$$

where t_a = outside air temperature, °C, WCI = wind chill index, W m^{-2}, v_{ar} = relative air velocity, m s^{-1}. **Table 10** shows the values depending on outside temperature and wind velocity and **Table 11** shows the expected effect.

SUPPORTING STANDARDS

The application of the above standards requires measurement or estimation of a number of parameters. The supporting and complementary standards described below provide information which is required for the application of standards for assessing thermal environments. They can also be used independently in ergonomics and other investigations.

METABOLIC RATE

All assessments of thermal environments require an estimate of metabolic heat production of the occupants. ISO EN 8996 presents three types of methods. The first is by use of tables, where estimates are provided based on a description of the activity. These range from a general description (e. g. light, heavy etc.) to methods of summating components of tasks (e. g. basal metabolic rate + posture component + movement component etc.). an example of activity levels is given in **Table 12.**

The second method is by the use of heart rate. The total heart rate is regarded as a sum of several components and in, general is linearly related to the metabolic heat production for heart rates above 120 beats per minute. Heat stress will, however, also increase the heat rate. The third method is to calculate the metabolic heat production from measures of oxygen consumption, and carbon dioxide production during activity and recovery.

CLOTHING

ISO EN 9920 provides a large database of thermal insulation values, which have been measured on a standing thermal manikin. One set of tables give the insulation values for a large number of ensembles (**Table 13).** Another set of tables give insulation values for individual garments (**Table 14**) , based on which the insulation for a whole ensemble can be estimated.

The insulation of an ensemble, I_{cl} , may be estimated as the sum of the individual garment insulation values, $I_{cl} = \Sigma I_{clu}$. The data on evaporative resistance are not so extensive. A few data are given in the standard, and a method to calculate the evaporative resistance based on the thermal insulation is also given. In the present standard no values are listed for the insulation of chairs, which may add 0.1-0.4 clo. Especially for the assessment of the level of heat stress, data for the evaporative resistance of clothing ensembles are important.

INSTRUMENTS AND MEASUREMTNS

ISO 7726 provides a description of the parameters which should be measured (air temperature, mean radiant temperature, plane radiant temperature, air velocity, humidity), together with methods of measurements and specifications for the instruments (accuracy, respond time, measuring range). Table 15 lists the accuracy required in the standard.

MEASUREMENS ON INDIVIDUALS

The methods listed above to evaluate the thermal environment assume an average person. As individuals often react very differently, both regarding acceptance of a given environment and regarding the strain that a given environment imposes, it may under certain circumstances be beneficial to take individual physiological and subjective measurements. Also, there may be a need for evaluation of an individual capability for performing a certain job under severe conditions in the field or in an ergonomics laboratory investigation.

Physiological Measurements

ISO EN 9886 presents the principles**,** methods and interpretation of measurement of relevant human physiological responses to hot, moderate and cold environments. The standard can be used independently or to compliment the use of other standards. Four physiological measures are considered; body core temperature, skin temperature, heart rates and body mass loss. Comments are also provides on the technical requirements, relevance, convenience, announce to the subject and cost, of each of the physiological measurements.
The use of ISO 9886 is mainly in extreme cases, where individuals are exposed to severe environments, or in laboratory investigations into the influence of the thermal environment on humans.

Subjective Measurements

Subject scales are useful in the measurement of subjective responses of persons exposed to thermal environments. They are particularly useful in moderate environments and can be used independently or to complement the use of objective methods (e.g. thermal indices) which were described in previously.
ISO EN 10551 presents the principles and methodology behind the construction and use of subjective scales and provides examples of scales that can be used to assess thermal environments.

The medical screening standard, ISO DIS 12894, provides advice to those concerned with the safety of human exposures to hot or cold thermal environments, about health screening and surveillance that may be appropriate prior to and during such exposures.

This guidance is applicable to both occupational and laboratory exposures to extreme environments. In either case an assessment should be made of the expected thermal stress on the individual, but the detailed arrangements for medical supervision may differ in the two situations. Control of occupation of exposures must also satisfy national health and safety legislation.
The laboratory or climatic chamber studies for which this standard will be relevant include those in which people may be exposed to high or low ambient conditions or local heating or cooling.

OTHER AND FUTURE STANDARDS

To help the user, an overview standard (ISO 11399) is being issued. this presents the different standards, and guides the user to which method and standard are applicable for the given situation. In addition, a standard has been prepared which lists all definitions, symbols and units (ISO 13731). Ongoing work is dealing with standards for contact with hot, cold and comfortable surfaces, application of the standards in vehicles, and precautions to take when assessing thermal environments for disabled, aged or other groups with special needs.

CONCLUSION

The series of standards presented in this paper provides a useful package for assessment and design of HVAC systems and protective equipment to be used in moderate, cold and hot environments. The standards may be used to estimate the optimal combination of the environmental thermal factors that will provide comfortable or tolerable and healthy working conditions. The standards may also be used to establish optimal workrest schedules for environments where the working time must be limited owing to strain on the human body.
Several of these standards are being adopted as national standards in several countries.
Some of the methods used in the standards are based on many years of research and validation, while others are relatively new and not validated to the same degree. It is therefore important to realize that a standard is not an everlasting document, but must be revised on a regular basis. These revisions take place at least each fifth year, where the experience with use and new knowledge are incorporated in the review process.

EXAMPLES

Table 16 show recommended operative temperatures and maximum mean air velocities for different type of spaces. The table is based on ISO EN 7730 and CR 1752.
Table 17 is showing the effect adding or removing garments will have on the preferred operative temperature. By individual adaption of the clothing it is possible to compensate for individual differences in prefferred temperature or for differences in activity level. The table is based on ISO EN 7730 and ISO EN 9920.

Bibliography

The relevant standards are listed in table 1.

Additional litterature is:

ASHRAE Standard 55-1992. Thermal environment conditions for human occupancy.
CR 1752, 1998. Ventilation for Buildings: Design Criteria for the Indoor Environment. CEN, Brussels
Langkilde, G., L. Gunnarsen, and N. Mortensen, 1985 Comfort limits during infrared radiant heating of industrial spaces. CLIMA 2000, Copenhagen.

Table 1: Ergonomics of the thermal environment: Development of International Standards

Aims of the standard	Title of the document	Status
General presentation of the set of standards in terms of principles and application	Ergonomics of the thermal environment: principles and application of international standards	ISO EN 11399
Standardization of quantities, symbols and units used in the standards	Ergonomics of the thermal environment: vocabulary and symbols	ISO 13731
Thermal stress evaluation in hotel environments Analytical method	Hot environments: analytical determination and interpretation of thermal stress using calculation of required sweat	ISO 7933 EN 12515
Diagnostic method	Hot environments: estimation of the heat stress on working man, based on the WBGT index (wet bulb globe temperature)	ISO EN 7243
Comfort evaluation in moderate environments	Moderate thermal environments: determination of the PMV and PPD index and specification of the conditions for thermal comfort	ISO EN 7730
Thermal stress evaluation in cold environments	Evaluation of cold environments: determination of required clothing insulation, I_{req}	ISOTRENV 11079 Technical report
Data collection standards Metabolic rate	Ergonomics: determination of metabolic heat production	ISO 8996 EN 28996
Requirements for measuring instruments	Thermal environments: instruments for measuring physical quantities	ISO 7726
Clothing insulation	Estimation of the thermal insulation and evaporative resistance of a clothing ensemble	ISO EN 9920
	Evaluation of thermal strain by physiological measurements	
Evaluation of thermal strain using physiological measures	Assessment of the influence of the thermal environment using subjective judgement scales	ISO EN 9886 ISO EN 10551
Subjective assessment of the thermal environment		
	Ergonomics of the thermal environment: medical supervision of individuals exposed to hot or cold environments	ISO DIS 12895
Selection of an appropriate system of medical supervision for different types of thermal exposure	Ergonomics of the thermal environment: methods for assessment of human responses to contact with surfaces	ISO CD 13732
Contact with hot, moderate and cold surfaces		
	Evaluation of the thermal environments in vehicles	
		NP 14505
Vehicle environments	Ergonomics of the thermal environment: the application of international standards for people with special requirements	ISO CD 14415
People with special requirements		
	Risk assessment	
		NP 15265
Assessment of risk in moderate, hot and cold environments		
		NP 15743
Work practice in cold environments		

Table 1 Developments of international standards for the ergonomics of the thermal environment.

Table 2 : Three categories of thermal environment

Category	Thermal state of the body as a whole		Local discomfort			
	Predicted Percentage of Dissatisfied PPD %	Predicted Mean Vote PMV	Percentage of dissatisfied due to draught DR %	Percentage of dissatisfied due to vertical air temperature difference %	Percentage of dis-satisfied due to warm or cool floor %	Percentage of dissatisfied due to radiant asymmetry %
A	< 6	-0,2<PMV<+0,2	< 15	< 3	< 10	< 5
B	< 10	-0,5<PMV<+0,5	< 20	< 5	< 10	< 5
C	< 15	-0,7<PMV<+0,7	< 25	< 10	< 15	< 10

Table 3: Vertical air temperature difference between head and ankles (1,1 and 0,1 m above the floor) for the three categories of the thermal environment

Category	Vertical air temperature difference °C
A	< 2
B	< 3
C	< 4

Table 4: Range of the floor temperature for the three categories of the thermal environment

Category	Range of surface temperature of the floor °C
A	19 - 29
B	19 - 29
C	17 - 31

Table 5: Radiant temperature asymmetry for the three categories of the thermal environment.

Category	Radiant temperature asymmetry °C			
	Warm ceiling	Cool wall	Cool ceiling	Warm wall
A	< 5	< 10	< 14	< 23
B	< 5	< 10	< 14	< 23
C	< 7	< 13	< 18	< 35

Table 6: Reference values of WBGT (ISO 7243)

	Metabolic rate, M		Reference value of WBGT			
Metabolic rate class	Related to a unit skinsurface area (Wm^{-2})	Total (for a mean skin surface area of 1.8 m^2) (W)	Person acclimatized to heat (°C)		Person not acclimatized to heat (°C)	
0 (resting)	M < 65	M < 117	33		32	
1	65< M < 130	117 < M < 234	30		29	
2	130 < M < 200	234 < M < 360	28		26	
3	200 < M < 260	360 < M < 468	No sensible air movement	Sensible air movement	No sensible air ovement	Sensible air movement
			25	26		23
4	M >260	M > 468	23	25		20

Note: The values given have been establish allowing for a maximum rectal temperature of 38 °C for the persons concerned.

Table 7: Reference Value for the different criteria of thermal stress and strain.

Criteria	Non-acclimatized subjects		Acclimatized subjects	
	Warning	Danger	Warning	Danger
Maximum skin wettedness w_{max}	0.85	0.85	1.0	1.0
Maximum sweat rate Rest: M < 65 W/m^2 SW_{max}, W/m^2 g/h Work: M > 65 W/m^2 SW_{max}, W/m^2 g/h	 100 260 200 520	 150 390 250 650	 200 520 300 780	 300 780 400 1040
Maximum heat storage Q_{max}, $W.h/m^2$	50	60	50	60
Maximum water loss D_{max}, $W.h/m^2$ g	1000 2600	1250 3250	1500 3900	2000 5200

Table 8: Required Sweat Rate index $\mathbf{SW_{req}}$, W/m^2 and wettednes ($\mathbf{w_{req}}$) as a function of clothing, temperature, air speed and humidity at the activity level **M** equal to 70 W/m^2.

Clothing I_{cl}, clo	Relative humidity, %	Operative Temperature, t_o, ^oC	Air Velocity V, m/s				
			< 0.1	0.2	0.5	1.0	2.0
0.5	20	25	10(.03)	8 (.02)	2(.01)		
		30	37(.13)	36 (.12)	33(.09)	29(.06)	24(.04)
		35	65(.24)	64 (.22)	64(.18)	63(.14)	62(.11)
		40	93(.37)	94 (.34)	95(.29)	98(.24)	101(.20)
		50	169(.78)	165 (.72)	165(.62)	171(.52)	182(.45)
		60	*(1.00)	*(1.00)	*(1.00)	*(1.00)	*(1.00)
	50	25	10(.04)	8 (.03)	2 (.01)		
		30	37(.17)	35 (.15)	33 (.12)	29(.08)	24(.05)
		35	65(.37)	65 (.34)	64 (.28)	63(.22)	62(.17)
		40	102(.74)	99 (.69)	98 (.57)	99(.47)	102(.39)
	80	30	37(.26)	36 (.23)	33 (.18)	29(.12)	24(.08)
		35	76(.82)	71(.75)	66 (.61)	64(.48)	63(.38)

Table 9: Suggested physiological cirteria for determination of IREQ, DLE and local cooling (ISO 7R 11079)

Type of cooling	Parameter		Minimal IREQ (high strain)	Neutral IREQ (low strain)
General	IREQ		30	35.7-0.0285 M
	t_{sk}	(°C)	0.06	0.0001 M
	w	(n.d.)		
	DLE			
	Q_{hm}	(Whm $^{-2}$)	-40	-40
Local	Hand temperature	(°C)	15	24
	WCI	(Wm $^{-2}$)	1600	-
	Respiratory tranct and eye temp.	(°C)	ta < -40	-

Table 10: Cooling power of wind on exposed flesh expressed as a chilling temperature, t_{ch}, under almost calm conditions. Bold types indicate risk of frostbite

	Actual thermometer reading										
Wind speed ($m\ s^{-1}$)	**0**	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**	**-35**	**-40**	**-45**	**-50**
1,8	0	-5	-10	-15	-20	-25	**-30**	**-35**	**-40**	**-45**	**-50**
2	-1	-6	-11	-16	-21	-27	**-32**	**-37**	**-42**	**-47**	**-52**
3	-4	-10	-15	-21	-27	**-32**	**-38**	**-44**	**-49**	**-55**	**-60**
5	-9	-15	-21	-28	**-34**	**-40**	**-47**	**-53**	**-59**	**-66**	**-72**
8	-13	-20	-27	**-34**	**-41**	**-48**	**-55**	**-62**	**-69**	**-76**	**-83**
11	-16	-23	**-31**	**-38**	**-46**	**-53**	**-60**	**-68**	**-75**	**-83**	**-90**
15	-18	-26	**-34**	**-42**	**-49**	**-57**	**-65**	**-73**	**-80**	**-88**	**-96**
20	-20	-28	**-36**	**-44**	**-52**	**-60**	**-68**	**-76**	**-84**	**-92**	**-100**

Table 11: Wind chill index, WCI, chilling temperature, t_{ch}, and effect on exposed flesh

WCI ($W\ m^{-2}$)	t_{ch} (°C)	Effect
1200	-14	Very cold
1400	-22	Bitterly cold
1600	-30	Exposed flesh freezes within 1 h
1800	-38	
2000	-45	Exposed flesh freezes within 1 min
2200	-53	
2400	-61	Esposed flesh freezes within 30 s
2600	-69	

Table 12: Metabolic rates

Activity	Metabolic rates	
	(W m^{-2})	met
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Standing light activity (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2.0
Walking on the level:	110	
2 km k^{-1}	140	1.9
3 km h^{-1}	165	2.4
4 km h^{-1}	200	2.8
5 km h^{-1}		3.4

Table 13: - Thermal insulation for typical clothing ensembles

Work clothing	I_{cl}		Daily wear clothing	I_{cl}	
	clo	m² · K /W		clo	m² · K /W
Underpants, boiler suit, socks, shoes	0.70	0.110	Panties, T-shirt, shorts, light socks, sandals	0.30	0.050
Underpants, shirt, boiler suit, socks, shoes	0.80	0.125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0.50	0.080
Underpants, shirt, trousers, smock, socks, shoes	0.90	0.140	Panties, petticoat, stockings, dress, shoes	0.70	0.105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1,00	0.155	Underwear, shirt, trousers, socks, shoes	0.70	0.110
Underwear with long legs and sleeves, thermo- jacket, socks, shoes	1.20	1.85	Panties, shirt, trousers, jacket, socks, shoes	1.00	0.155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1.40	0.220	Panties, stockings, blouse, long shirt, jacket, shoes	1.10	0.170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2.00	0.310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1.30	0.200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2.55	0.395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1.50	0.230

Table 14: Thermal insulation for individual garments

Garment description	Thermal insulation clo
Underwear	
Panties	0,03
Underpants with long legs	0,10
T-shirt	0,09
Shirts - Blouses	
Short sleeves	0,15
Normal, long sleeves	0,25
Trousers	
Shorts	0,06
Normal	0,25
Dresses - Skirts	
Light skirts (summer)	0,15
Heavy skirt (winter)	0,25
Winter dress, long sleeves	0,40
Sweaters	
Thin sweater	0,20
Thick sweater	0,35
Jackets	
Light, summer jacket	0,25
Jacket	0,35
High-insulative, fibre-pelt	
Boiler suit	0,90
Trousers	0,35
Jacket	0,40
Outdoor clothing	
Coat	0,60
Parka	0,70
Sundries	
Socks	0,02
Thick, long socks	0,10
Shoes (thick soled)	0,04
Boots	0,10

Table 15: - Characteristics of measuring instruments

		Class C (comfort)			Class S (thermal stress)			
Quantity	Symbol	Measuring range	Accuracy	Response time (90 %)	Measuring Range	Accuracy	Response time	Comments
Air temperature	t_a	10 to 40 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\mid t_r - t_a \mid$ equal to 10 °C	The shortest possible. Value to be specified as characteristic of the measuring instru-ment	- 40 to + 120 °C	Required: - 40 to 0 °C: ± $(0{,}5 + 0{,}01\mid t_a \mid)$ °C > 0 to 50 °C: ± 0,5 °C > 50 to 120 °C: ± $[0{,}5 + 0{,}04\,(t_a - 50)]$ °C Desirable: $\frac{\text{required accuracy}}{2}$ These levels shall be guaranteed at least for a deviation $\mid t_r - t_a \mid$ equal to 20 °C	The shortest possible. Value to be specified as characteristic of the measuring instrument	The air temperature sensor shall be effectively protected from any effects of the thermal radiation coming from hot or cold walls. An indication of the mean value over a period of 1 min is also desirable.
Mean radiant temperature	t_r	10 to 40 °C	Required: ± 2 °C Desirable: ± 0,2 °C These levels are difficult or even impossible to achieve in certain cases with the equipment normally available. When they cannot be achieved, indicate the actual measuring precision	The shortest possible. Value to be specified as characteristic of the measuring instru-ment	- 40 °C to + 150 °C	Required: - 40 to 0 °C: ± $(5 + 0{,}02\mid t_r \mid)$ °C > 0 to 50 °C: ± 5 °C >50 to 150 °C: ± $[5 + 0{,}08\,(t_r-50)]$ °C Desirable: - 40 to 0 °C: ± $(0{,}5 + 0{,}01\mid t_r \mid)$ °C > 0 to 50 °C: ± 0,5 °C > 50 to 150 °C: ± $[0{,}5 + 0{,}04\,(t_r-50)]$ °C	The shrtest possible. Value to be specified as characteristic of the measuring instrument	When the measurement is carried out with a black sphere, the inaccuracy relation to the mean radiant temperature can be as high as ± 5 °C for class C and ± 20 °C for class S according to the environment and the inaccuracy for v_a, t_a and t_g.

Plane radiant temperature	t_{pr}	0 to 50 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\lvert t_{pr} - t_a \rvert < 10$ °C	The shortest possible. Value to be specified as characteristic of the measuring instru- ment	0 to 200 °C	Required: - 60 to 0 °C : ± $(1+0,1 \lvert t_{pr} \rvert)$ °C 0 to 50 °C: ± 1 °C 50 to 200 °C: ± $[1+0,1 (t_{pr} - 50)]$ °C Desirable: $\frac{\text{required accuracy}}{2}$ These levels shall be guaranteed at least for a deviation $\lvert t_{pr} - t_a \rvert < 20$ °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	
Air velocity	v_a	0,05 to 1 m/s	Required: ± $(0,05 + 0,05\ v_a)$ m/s Desirable: ± $(0,02 + 0,07\ v_a)$ m/s These levels shall be guaranteed whatever the direction of flow within a solid angle $\omega = 3\ \pi$ sr	Required: 0,5 s Desirable: 0,2 s	0,2 to 20 m/s	Required: ± $(0,1 + 0,05\ v_a)$ m/s Desirable: ± $(0,05 + 0,05\ v_a)$ m/s These lavels shall be guaranteed whatever the direction of flow within a solid angle $\omega = 3\ \pi$ sr	The shortest possible. Value to be specified as characteristic of the measuring instrument.	Except in the case of a unidirectional air current, the air velocity sensor shall measure the velocity whatever the direction of the air. An indication of the mean value and standard deviation for a period of 3 min is also desirable.
Absolute humidity expressed as partial pressure of water vapour	pa	0,5 to 3,0 kPa	± 0,15 kPa This level shall be guaranteed even for air and wall temperatures equal to or greater than 30 °C and for a difference $\lvert t_r - t_a \rvert$ of at least 10 ° C	The shortest possible. Value to be specified as characteristic of the measuring instru- ment	0,5 to 6.0 kPa	± 0,15 kPa This level shall be guaranteed even for air and wall temperatures equal to or greater than 30 °C and for a difference $\lvert t_r - t_a \rvert$ of at least 20 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	

Surface temperature	t_s	0-50 °C	Required: ± 1 °C Desirable: + 0.5 °C	The shortest possible. Value to be specified as characteristic of the measuring instru-ment	- 40 to + 120 °C	Required: < - 10 °C: ± [1 + 0,05 ($-t_s$-10)] - 10 °C to 50 °C: ± 1 °C > 50 °C: ± [1 + 0.05 (t_s-50)] Desirable: $\frac{\text{required accuracy}}{2}$	The shortest possible. Value to be specified as characteristic of the measuring instrument.	

Table 16. Examples of recomended operative temperature and air velocity based on ISO EN 7730 and CR1752.

Type of building/ space	Clothing Cooling season (summer) clo	Clothing Heating season (winter) clo	Activity met	Category	Operative Temperature Cooling season (summer) °C	Operative Temperature Heating season (winter) °C	Mean Air Velocity Cooling season (summer) m/s	Mean Air Velocity Heating season (winter) m/s
Single office (cellular office)	0,5	1,0	1,2	A	24.5 ± 0.5	22.0 ± 1.0	0,18	0,15
				B	24.5 ± 1.5	22.0 ± 2.0	0,22	0,18
				C	24.5 ± 2.5	22.0 ± 3.0	0,25	0,21
Landscaped office	0,5	1,0	1,2	A	24.5 ± 0.5	22.0 ± 1.0	0,18	0,15
				B	24.5 ± 1.5	22.0 ± 2.0	0,22	0,18
				C	24.5 ± 2.5	22.0 ± 3.0	0,25	0,21
Conference Room	0,5	1,0	1,2	A	24.5 ± 0.5	22.0 ± 1.0	0,18	0,15
				B	24.5 ± 1.5	22.0 ± 2.0	0,22	0,18
				C	24.5 ± 2.5	22.0 ± 3.0	0,25	0,21
Auditorium	0,5	1,0	1,2	A	24.5 ± 0.5	22.0 ± 1.0	0,18	0,15
				B	24.5 ± 1.5	22.0 ± 2.0	0,22	0,18
				C	24.5 ± 2.5	22.0 ± 3.0	0,25	0,21
Cafeteria/ Restaurant	0,5	1,0	1,4	A	23.5 ± 1.0	20.0 ± 1.0	0,16	0,13
				B	23.5 ± 2.0	20.0 ± 2.5	0,20	0,16
				C	23.5 ± 2.5	20.0 ± 3.5	0,24	0,19
Classroom	0,5	1,0	1,2	A	24.5 ± 0.5	22.0 ± 1.0	0,18	0,15
				B	24.5 ± 1.5	22.0 ± 2.0	0,22	0,18
				C	24.5 ± 2.5	22.0 ± 3.0	0,25	0,21
Kindergarten	0,5	1,0	1,4	A	23.5 ± 1.0	20.0 ± 1.0	0,16	0,13
				B	23.5 ± 2.0	20.0 ± 2.5	0,2	0,16
				C	23.5 ± 2.5	20.0 ± 3.5	0,24	0,19
Department Store	0,5	1,0	1,6	A	23.0 ± 1.0	19.0 ± 1.5	0,16	0,13
				B	23.0 ± 2.0	19.0 ± 3.0	0,20	0,15
				C	23.0 ± 3.0	19.0 ± 4.0	0,23	0,18

Table 17. Examples of the relation between a change garment and the acceptable change in operative temperature.

Garment Description	Thermal Insulation clo	Change of Operative Temp. K
Panties	0,03	0,2
Underpants with long legs	0,10	0,6
T-shirt	0,09	0,6
Short sleeves shirt	0,15	0,9
Light shirt, long sleeves	0,20	1,3
Normal shirt, long sleeves	0,25	1,6
Shorts	0,06	0,4
Light-weight trousers	0,20	1,3
Normal trousers	0,25	1,6
Light skirts (summer)	0.15	0,9
Heavy skirt (winter)	0,25	1,6
Sleeveless vest	0,12	0,8
Thin sweater	0,20	1,3
Light, summer jacket	0,25	1,6
Normal jacket	0,35	2,2
Coat	0,60	3,7
Down jacket	0,55	3,4
Parka	0,70	4,3

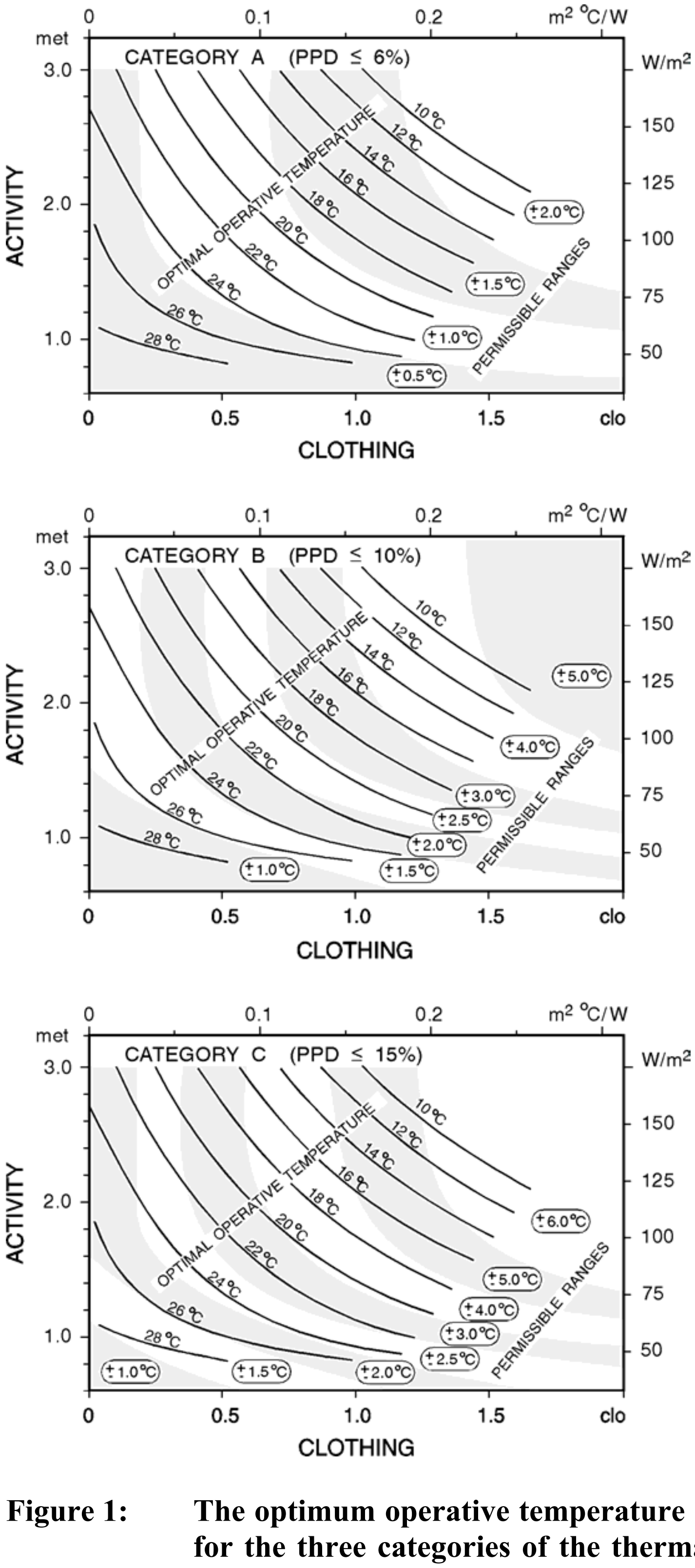
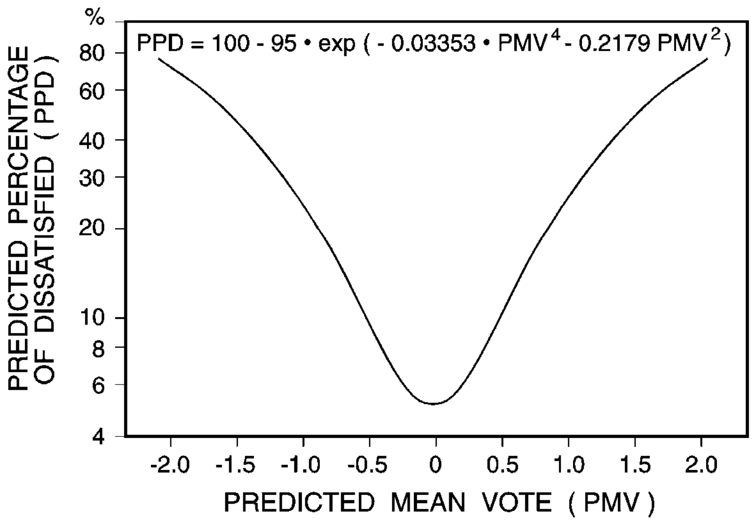


Figure 1: The optimum operative temperature as a function of clothing and activity for the three categories of the thermal environment. The three diagrams show also the range around the optimum temperature for the three categories.

The air velocity in the space is assumed < 0,1 m/s. The relative air velocity, v_{ar}, caused by body movement is estimated to be zero for a metabolic rate, M, less than 1 met and v_{ar} = 0,3 (M-1) for M > 1 met. The diagrams are determined for a relative humidity = 50%, but the humidity only has a slight influence on the optimum and permissible temperature ranges

Figure 2: Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV)



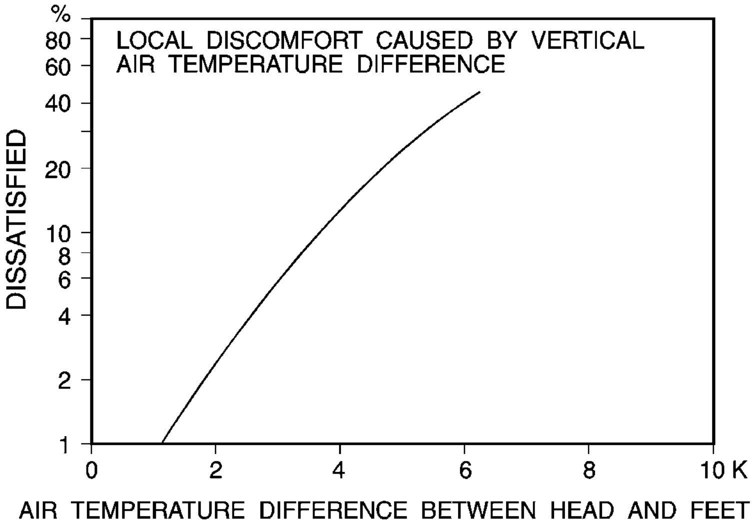


Figure 3: Local discomfort caused by vertical air temperature difference. Applies when the temperature increases upwards.

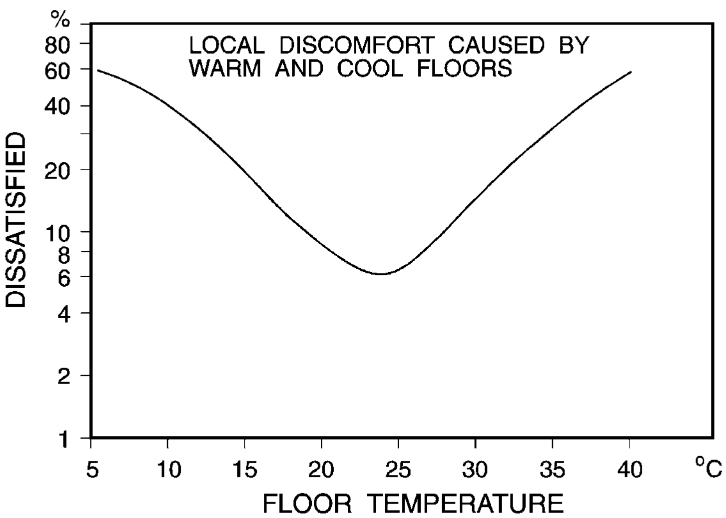
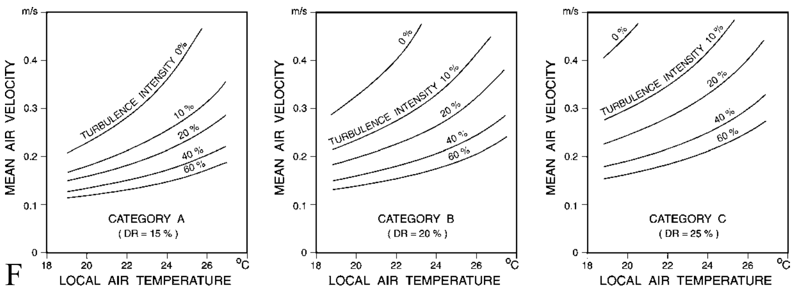


Figure 4: Local thermal discomfort caused by warm or cold floors.

Figure 5: Mean air velocity as a function of local air temperature and turbulence intensity for the three categories of the thermal environment.



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