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Ergonomics of the thermal environment — Instruments for measuring physical quantities

Ergonomie des ambiances thermiques — Appareils de mesure des grandeurs physiques

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Contents

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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.

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.

International Standard ISO 7726 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment.*

This second edition cancels and replaces the first edition (ISO 7726:1985), of which it constitutes a technical revision.

Annexes A to H of this International Standard are for information only.

Introduction

This document is one of a series of International Standards intended for use in the study of thermal environments.

This series of International Standards deals in particular with

- the finalization of definitions for the terms to be used in the methods of measurement, testing or interpretation, taking into account standards already in existence or in the process of being drafted;
- the laying down of specifications relating to the methods for measuring the physical quantities which characterize thermal environments;
- the selection of one or more methods for interpreting the parameters;
- the specification of recommended values or limits of exposure for the thermal environments coming within the comfort range and for extreme environments (both hot and cold);
- the specification of methods for measuring the efficiency of devices or processes for personal or collective protection from heat or cold.

Any measuring instrument which achieves the accuracy indicated in this International Standard, or even better improves on, may be used.

The description or listing of certain instruments in the annexes can only signify that they are "recommended", since characteristics of these instruments may vary according to the measuring principle, their construction and the way in which they are used. It is up to users to compare the quality of the instruments available on the market at any given moment and to check that they conform to the specifications contained in this International Standard.

Ergonomics of the thermal environment — Instruments for measuring physical quantities

1 Scope

This International Standard specifies the minimum characteristics of instruments for measuring physical quantities characterizing an environment as well as the methods for measuring the physical quantities of this environment.

It does not aim to define an overall index of comfort or thermal stress but simply to standardize the process of recording information leading to the determination of such indices. Other International Standards give details of the methods making use of the information obtained in accordance with this standard.

This International Standard is used as a reference when establishing

a) specifications for manufacturers and users of instruments for measuring the physical quantities of the environment;

b) a written contract between two parties for the measurement of these quantities.

It applies to the influence of hot, moderate, comfortable or cold environments on people.

2 Normative reference

The following standard contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 7730:1994, *Moderate thermal environments — Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.*

3 General

3.1 Comfort standard and stress standard

The specifications and methods contained in this International Standard have been divided into two classes according to the extent of the thermal annoyance to be assessed.

The type C specifications and methods relate to measurements carried out in moderate environments approaching comfort conditions (comfort standard).

The type S specifications and methods relate to measurements carried out in environments subject to a greater thermal stress or even environments of extreme thermal stress (heat stress standard).

The specifications and methods described for each of these classes have been determined bearing in mind the practical possibilities of *in situ* measurements and the performances of measuring instruments available at present.

3.2 Physical quantities characterizing the environment

3.2.1 Introduction

The determination of overall indices of comfort or thermal stress requires knowledge of physical quantities connected with the environment. These quantities can be divided into two categories according to their degree of dependence on the environment.

3.2.2 Basic physical quantities

Each of the basic physical quantities characterizes one of the factors of the environment independently of the others. They are often used to define the indices of comfort or thermal stress based on the rationalization of the establishment of the thermal balance of a person placed in a given thermal environment. These quantities are as follows:

a) air temperature, expressed in kelvins (T_a) or in degrees Celsius (t_a);

b) mean radiant temperature expressed in kelvins $\left(\bar{T}_r\right)$, or in degrees Celsius $\left(\bar{t}_r\right)$ plane radiant temperature expressed in kelvins (T_{pr}) or in degrees Celsius (t_{pr}) direct radiation expressed in watts per square metre;

c) absolute humidity of the air, expressed by partial vapour pressure (p_a) in kilopascals;

d) air velocity (v_a), expressed in metres per second;

e) surface temperature, expressed in kelvins (T_s), or in degrees Celsius (t_s).

The connections between these quantities and the various gains and losses of heat in relation to the human body are shown in table 1. Table 1 also gives four other quantities which, because they are usually estimated from data tables rather than measured, are not included in the remainder of this International Standard.

NOTE — The concept of mean radiant temperature allows the study of radiative exchanges between man and his environment. It presupposes that the effects on man of the actual environment which is generally heterogeneous and the virtual environment which is defined as homogeneous are identical. When this hypothesis is not valid, in particular in the case of asymmetric radiation, the radiation exchanges arising from thermally different regions and the extent of their effect on man should also be assessed using the concept of plane radiant temperature.

3.2.3 Derived physical quantities

The derived physical quantities characterize a group of factors of the environment, weighted according to the characteristics of the sensors used. They are often used to define an empirical index of comfort or thermal stress without having recourse to a rational method based on estimates of the various forms of heat exchanges between the human body and the thermal environments, and of the resulting thermal balance and physiological strain. Some derived quantities are described in the specific standards as they apply and where measuring requirements are included.

4 Measuring instruments

4.1 Measured quantities

4.1.1 The air temperature is the temperature of the air around the human body (see annex A).

4.1.2 The mean radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure.

The mean radiant temperature can be measured by instruments which allow the generally heterogeneous radiation from the walls of an actual enclosure to be "integrated" into a mean value (see annex B).

The black globe thermometer is a device frequently used in order to derive an approximate value of the mean radiant temperature from the observed simultaneous values of the globe temperature, t_g, and the temperature and the velocity of the air surrounding the globe.

The accuracy of measurement of the mean radiant temperature obtained using this appliance varies considerably according to the type of environment being considered and the accuracy of measurement of the temperatures of the globe and the air and the velocity of the air. The actual measuring accuracy shall be indicated wherever it exceeds the tolerances specified in this International Standard.

The mean radiant temperature is defined in relation to the human body. The spherical shape of the globe thermometer can give a reasonable approximation of the shape of the body in the case of a seated person. An ellipsoid-shaped sensor gives a closer approximation to the human shape both in the upright position and the seated position.

The mean radiant temperature can also be calculated from measured values of the temperature of the surrounding walls and the size of these walls and their position in relation to a person (calculation of geometrical shape factors). (See annex B.)

The mean radiant temperature may also be estimated for the plane radiant temperature in six opposite directions weighted according to the projected area factors for a person. Similarly, it can be estimated from the measurement of the radiant flux from different directions.

Any other measuring device or calculation method which allows the mean radiant temperature to be determined with the accuracy specified in the following subclauses may be used.

4.1.3 The plane radiant temperature is the uniform temperature of an enclosure where the radiance on one side of a small plane element is the same as in the non-uniform actual environment.

The so-called "net" radiometer is an instrument which is often used to measure this quantity (see annex C). With this it is possible to determine the plane radiant temperature from the net radiation exchanged between the environment and the surface element and the surface temperature of the radiometer.

A radiometer with a sensor consisting of a reflective disc (polished) and an absorbent disc (painted black) can also be used.

The plane radiant temperature can also be calculated from the surface temperatures of the environment and the shape factors between the surfaces and the plane element (see annex C).

The radiant temperature asymmetry is the difference between the plane radiant temperature of the two opposite sides of a small plane element (see definition of the plane radiant temperature).

The concept of radiant temperature asymmetry is used when the mean radiant temperature does not completely describe the radiative environment, for instance when the radiation is coming from opposite parts of the space with appreciable thermal heterogeneities.

The asymmetric radiant field is defined in relation to the position of the plane element used as a reference. It is, however, necessary to specify exactly the position of the latter by means of the direction of the normal to this element.

The radiant temperature asymmetry is measured or calculated from the measured value of the plane radiant temperature in the two opposing directions.

Any other device or method which allows the radiant temperature asymmetry or the plane radiant temperature to be measured or calculated with the same accuracy as indicated below may be used.

4.1.4 The absolute humidity of the air characterizes any quantity related to the actual amount of water vapour contained in the air as opposed to quantities such as the relative humidity or the saturation level, which gives the amount of water vapour in the air in relation to the maximum amount that it can contain at a given temperature and pressure.

With regard to exchanges by evaporation between a person and the environment, it is the absolute humidity of the air which shall be taken into account. This is often expressed in the form of partial pressure of water vapour.

The partial pressure of water vapour of a mixture of humid air is the pressure which the water vapour contained in this mixture would exert if it alone occupied the volume occupied by the humid air at the same temperature.

The absolute humidity can be determined directly (dew-point instruments, electrolytic instruments) or indirectly by the measurement of several quantities simultaneously (relative humidity and temperature of the air; psychrometric wet temperature and temperature of the air) (see annex D).

The psychrometer is an appliance which is frequently used for measuring humidity. It allows the absolute humidity of the air to be determined from a measured value of the air temperature (t_a) and the psychometric wet temperature (t_w). The accuracy of measurement is likely to be in accordance with the specifications of this International Standard only if the appliance is well designed and the precautions to be taken during use closely adhered to.

Any device which allows the absolute humidity of the air to be measured with the accuracy indicated in the following subclauses may be used.

4.1.5 The air velocity is a quantity defined by its magnitude and direction. The quantity to be considered in the case of thermal environments is the speed of the air, i.e. the magnitude of the velocity vector of the flow at the measuring point considered (see annex E).

The air velocity, v_a, at any point in a space fluctuates with time and it is recommended that the velocity fluctuations be recorded. An air flow can be described by the mean velocity, v_a, which is defined as the average of the velocity over an interval of time (measuring period) and by the standard deviation of the velocity, SD, given by the equation:

$$\mathrm{SD} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(v_{a_i} - v_a\right)^2}$$

where

v_{a_i} is the velocity at the time "i" of the measuring period.

The turbulence intensity, TU, of the airflow is defined as the standard deviation divided by the mean velocity and is usually expressed in percent,

$$\mathrm{TU} = \frac{\mathrm{SD}}{v_a} \times 100$$

4.1.6 Surface temperature is the temperature of a given surface. This is used to evaluate the radiant heat exchange between the human body by means of the mean radiant and/or the plane radiant temperature. It is also used to evaluate the effect of direct contact between the body and a given surface. The surface temperature can be measured by the method given in annex F, including:

- contact thermometer, where the sensor is in direct contact with the surface. The sensor may change the heat flow at the measuring point and then influence the result.
- infrared sensor, where the radiant heat flux from the surface is measured and converted to a temperature. This may be influenced by the emissivity of surface.

4.2 Characteristics of measuring instruments

4.2.1 Characteristics of instruments for measuring the basic quantities

The measuring ranges, measuring accuracy and 90 % response times of the sensors for each of the basic quantities are summarized in table 2. These characteristics shall be considered to be minimum requirements. According to needs and technical manufacturing possibilities, it is always possible to specify more exact characteristics. Thus, for certain quantities, very precise thermal stress measurements may require the use of appliances with measuring ranges in class S and accuracy of class C.

For the purposes of this International Standard, the time constant of a sensor is considered to be numerically equal to the time taken for the output of the sensor, in response to a step change in the environmental quantity being measured, to reach 63 % of its final change in steady-state value without overshoot. The response time, which is in practice the time after which the quantity being measured (for example: temperature of the thermometer) can be considered to be sufficiently close to the exact figure for the quantity to be measured (for example: temperature of the air), can be calculated from the time constant. A 90 % response time is achieved after a period equal to 2,3 times the time constant. It is necessary to wait, as a minimum, for a time equivalent to the response time before a measurement is taken.

As the time constant and hence the response time of a sensor does not depend solely on the sensor (mass, surface area, presence of a protective shield) but also on the environment, and hence on factors connected with a given measurement (air velocity, radiation, etc.), it is necessary to indicate the conditions under which these values were obtained. The standard environmental conditions are specified in table 3 (classes C and S). They shall be used as a reference except where this contradicts the principle for measuring the quantities under consideration.

In addition, the accuracy of measurement for air temperatures, mean radiant temperature, radiant temperature asymmetry, air velocity and humidity also depends on the effect of other quantities. Consequently, the accuracy specified in table 2 shall be achieved for the environmental conditions specified in the table.

4.2.2 Characteristics of integrating types of measuring instruments

Any measuring instrument integrating the measurement of several variables shall have a measuring interval, a response time and an accuracy equal to or better than those of the corresponding individual variables.

5 Specifications relating to measuring methods

5.1 General

The methods for measuring the physical characteristics of the environment shall take account of the fact that these characteristics vary in location and time.

The thermal environment may vary with the horizontal location, and then account has to be taken of how long a time a person is working at the different locations. The environment may also vary in the vertical direction, as shown in 5.2.

5.2 Specifications relating to variations in the physical quantities within the space surrounding the subject

An environment may be considered to be "homogeneous" from the bio-climatical point of view if, at a given moment, air temperature, radiation, air velocity and humidity can be considered to be practically uniform around the subject, i.e. when the deviations between each of these quantities and their mean spatial value calculated as a mean of the locations does not exceed the values obtained by multiplying the required measuring accuracy from table 2 by the corresponding factor X listed in table 4. This condition is frequently met in the case of air temperature, air velocity and humidity, but more rarely in the case of radiation.

When the environment is too heterogeneous, the physical quantities shall be measured at several locations at or around the subject and account taken of the partial results obtained in order to determine the mean value of the quantities to be considered in assessing the comfort or the thermal stress. Previous analyses of the thermal stress of the work places being studied or of work places of a similar type may provide information which is of interest in determining whether certain of the quantities are distributed in a homogeneous way. It is usual in the case of poorly defined rooms or work places to consider only a limited zone of occupancy where the criteria of comfort or thermal stress shall be respected. In case of dispute in the interpretation of data, measurements carried out presuming the environment to be heterogeneous shall be used as a reference.

Table 5 shows the heights to be used for measuring the basic quantities and the weighting coefficients to be used for calculating the mean values for these quantities according to the type of environment considered and the class of measurement specifications.

The heights to be used for the derived quantities shall preferably be chosen in conformity with the information supplied in table 5. Plane radiant temperature, mean radiant temperature and absolute humidity are normally only measured at the centre height. Reference, however, shall be made to the general standard which defines the stress indices or thermal comfort indices and which takes precedence over this International Standard.

The different sensors shall be placed at the heights indicated in table 5 where the person normally carries out his activity. When it is impossible to interrupt the activity in progress, it is necessary to place the sensors in positions such as that the thermal exchanges are more or less identical to those to which the person is exposed (this measurement detail shall be mentioned in the results).

5.3 Specifications relating to the variations in the physical quantities with time

The physical quantities in the space surrounding the person can change as a function of time, for the following two reasons:

a) for a given activity, the quantities can vary as a function of external incidents such as those which accompany a manufacturing process in the case of an industrial activity;

b) the quantities can also vary as a result of the movements of the person in different environments (for example, a warm environment close to a machine and a comfortable rest environment).

An environment is said to be stationary in relation to the subject when the physical quantities used to describe the level of exposure are practically independent of the time, i.e. for instance when the fluctuations in these parameters in relation to their mean temporal value do not exceed the values obtained by multiplying the required measuring accuracy from table 2 by the corresponding factor X listed in table 4.

It should be noted that the other quantities used to describe the level of exposure to heat (metabolism, energy efficiency, insulation of clothing) can also depend on time.

When an environment cannot be considered as stationary in relation to the subject, note should be taken of the main variations in its physical quantities as a function of time (this information will be used in other standards in this series in order to determine an overall comfort or thermal stress index). The measuring time and interpretation of the data will depend on which comfort or thermal stress index is being used. This information shall be found by reference to the appropriate standards.

Table 1 — Main independent quantities involved in the analysis of the thermal balance between man and the thermal environment

Elements in the thermal balance	Quantities							
	t_a	$\bar{t}_r$	v_a	p_a	I_{cl}	R_{cl}	M	W
	Air temperature	Mean radiant temperature	Air velocity	Absolute humidity of the air (partial pressure of water vapour)	Insulation of clothing	Evaporative resistance of clothing	Metabolism	External work
Internal heat production, $M - W$							x	x
Heat transfer by radiation, R		x			x			
Heat transfer by convection, C 1)	x		x		x			
Heat losses through evaporation:								
— evaporation from the skin, E			x	x		x		
— evaporation by respiration, E_{res}				x			x	
Convection by respiration C_{res}	x						x	

1) Heat transfer by convection is also influenced by body movements. The resultant air velocity at skin level is called relative air velocity (v_{ar}). Heat conduction (surface temperature) has only a limited influence on the total heat balance.

Table 2 — Characteristics of measuring instruments

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Air temperature	t_a	10 °C to 40 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\lvert t_r - t_a \rvert$ equal to 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring instrument.	− 40 °C to + 120 °C	Required: − 40 °C to 0 °C: ± (0,5 + 0,01 $\lvert t_a \rvert$) °C > 0 °C to 50 °C: ± 0,5 °C > 50 °C 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 $\lvert t_r - t_a \rvert$ 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	$\bar{t}_r$	10 °C 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 instrument.	− 40 °C to + 150 °C	Required: − 40 °C to 0 °C: ± (5 + 0,02 $\lvert t_a \rvert$) °C > 0 °C to 50 °C: ± 5 °C > 50 °C to 150 °C: ± [5 + 0,08 (t_r−50)] °C Desirable: − 40 °C to 0 °C: ± (0,5 + 0,01 $\lvert t_r \rvert$) °C > 0 °C to 50 °C: ± 5 °C > 50 °C to 150 °C: ± [0,5 + 0,04 (t_r−50)] °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	When the measurement is carried out with a black sphere, the inaccuracy relating 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.

Table 2 — Characteristics of measuring instruments *(continued)*

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Plane radiant temperature	t_{pr}	0 °C 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 instrument.	0 °C to 200 °C	Required: – 60 °C to 0 °C: ± $(1 + 0{,}1 \lvert t_{pr} \rvert)$ °C 0 °C to 50 °C: ± 1 °C 50 °C 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 m/s 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 $(:) = 3\pi$ sr	Required: 0,5 s Desirable: 0,2 s	0,2 m/s to 20 m/s	Required: ± $(0{,}1 + 0{,}05\, v_a)$ m/s Desirable: ± $(0{,}05 + 0{,}05\, v_a)$ m/s These levels shall be guaranteed whatever the direction of flow within a solid angle $(:) = 3\pi$ sr	The shortest possible. Value to be specified as characteristic of the measuring instrument. For measuring the degree of turbulence a small response time is needed.	Except in the case of a undirectional 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.

Table 2 — Characteristics of measuring instruments (*concluded*)

Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
		Measuring range	Accuracy	Response time (90%)	Measuring range	Accuracy	Response time (90 %)	
Absolute humidity expressed as partial pressure of water vapour	p_a	0,5 kPa to 3,0 kPa	± 0,15 kPa This level shall be guaranteed 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 instrument.	0,5 kPa to 6,0 kPa	± 0,15 kPa This level shall be guaranteed 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 °C to 50 °C	Required: ± 1 °C Desirable: ± 0,5 °C	The shortest possible. Value to be specified as characteristic of the measuring instrument.	− 40 °C to + 120 °C	Required: < -10 °C: $\pm [1 + 0{,}05\,(-t_s - 10)]$ − 10 °C to 50 °C: ± 1 °C > 50 °C: $\pm [1 + 0{,}05\,(t_s - 50)]$ Desirable: $\dfrac{\text{required accuracy}}{2}$	The shortest possible. Value to be specified as characteristic of the measuring instrument.	
Radiation directional	r_d	From − 35 W/m² to + 35 W/m²	± 5 W/m²	Required: 1,0 s Desirable: 0,5 s	From − 300 to + 100 °C From 100 °C to 1000 °C From 1000 W/m² to 2500 W/m²	± 5 W/m² ± 10 W/m² ± 15 W/m²	Required: 1,0 s Desirable: 0,5 s	

NOTE — At some work places in hot environments (steel, coal, glass industries) there may be a need to measure plane radiant and surface temperatures at higher levels than the range in this table. The manufacturers of instruments are required to state the accuracy for an extended range.

Table 3 — Standard environmental conditions for the determination of time constants of sensors

Quantities of the standard environment Measurement of the response time of sensors for	t_a	$\bar{t}_r$	p_a	v_a
Air temperature		$= t_a$	Any	$<$ 0,15 m/s
Mean radiant temperature	$= t_r$		Any	$<$ 0,15 m/s
Absolute humidity	= 20 °C	$= t_a$		To be specified according to the measuring method
Air velocity	= 20 °C	$= t_a$	Any	
Plane radiant temperature	= 20 °C	$= t_a$	Any	$<$ 0,15 m/s
Surface temperature	= 20 °C	$= t_a$	Any	$<$ 0,15 m/s

Table 4 — Criteria for a homogeneous and steady-state environment

Quantity	Class C (comfort) Factor X	Class S (thermal stress) Factor X
Air temperature	3	4
Mean radiant temperature	2	2
Radiant temperature asymmetry	2	3
Mean air velocity	2	3
Vapour pressure	2	3
NOTE — Deviation between each individual quantity and their mean value shall be less than that obtained by multiplying the required measuring accuracy (table 2) by the appropriate factor X from this table.		

Table 5 — Measuring heights for the physical quantities of an environment

Locations of the sensors	Weighting coefficients for measurements for calculation mean values				Recommended heights (for guidance only)	
	Homogeneous environment		Heterogeneous environment		Sitting	Standing
	Class C	Class S	Class C	Class S		
Head level			1	1	1,1 m	1,7 m
Abdomen level	1	1	1	2	0,6 m	1,1 m
Ankle level			1	1	0,1 m	0,1 m

Annex A
(informative)

Measurement of air temperature

A.1 Introduction

The air temperature shall be taken into account when determining heat transfer by convection at the level of the person. The measurement of this quantity, while often considered simple, can in fact lead to considerable errors if a number of precautions are not taken.

A.2 Principle for measuring a temperature

Temperature is obtained by measuring physical quantities which are its continuous functions: lengths of solids, volumes of liquids, electrical resistance, electromotive force.

Whatever the physical quantity measured, a sensor can only measure the temperature at which it finds itself and this temperature may differ from the temperature of the fluid (air for instance) to be measured.

A.3 Precautions to be taken when using a temperature probe

A.3.1 Reduction of the effect of radiation

Care should be taken to prevent the probe from being subjected to radiation from neighbouring heat sources as the temperature measured in such a case would not be the actual temperature of the air but a temperature intermediate between the air temperature, and the mean radiant temperature.

Various means of reducing the effect of radiation on the probe are available, such as the following:

a) Reduction of the emission factor of the sensor, by the use of a polished sensor when the latter is made of metal or a sensor covered with a reflective paint when it is of the insulating type.

b) Reduction in the difference in temperature between the sensor and the adjacent walls. Since it is not possible to modify the temperature of the walls of the enclosure, one or more reflective screens are used, arranged between the sensor and the enclosure. Thus the sensor "views" a wall, the temperature of which gradually approaches that of the sensor as the number of screens increases. This method of protecting the sensor is effective and easy to install.

   The screens can in practice be made from thin (0,1 mm or 0,2 mm) sheets of reflective metal (for example aluminium). When the screens are used on their own, i.e. without forced ventilation, the inner screen shall be separated from the sensor by an air space large enough to allow air to circulate inside by natural convection.

c) Increasing the coefficient of heat transfer by convection, by an increase in the air velocity around the sensor by forced ventilation (mechanical or electrical ventilator) and by a reduction in the size of the sensor (thermistor, thermocouple).

Figure A.1 shows the relation between the air velocity, sensor size and relative influence of air and radiant temperature on an unshielded air temperature sensor. The measured temperature can be expressed as $X.t_a + (1 - X).t_r$ where X is the relative influence of air temperature. Figure A.1 shows a significant influence of both sensor size (diameter) and air velocity. The figure is based on the heat exchange calculations for a sphere (see annex B). It is assumed that the emissivity of the sensor is 0,95.

EXAMPLE:

If the sensor is 1 mm in diameter and air velocity = 0,15 m/s, the temperature of the sensor

$= 0{,}85\ t_a + 0{,}15\ t_r$.

The figure is only for information purposes and should not be used to correct a measurement.

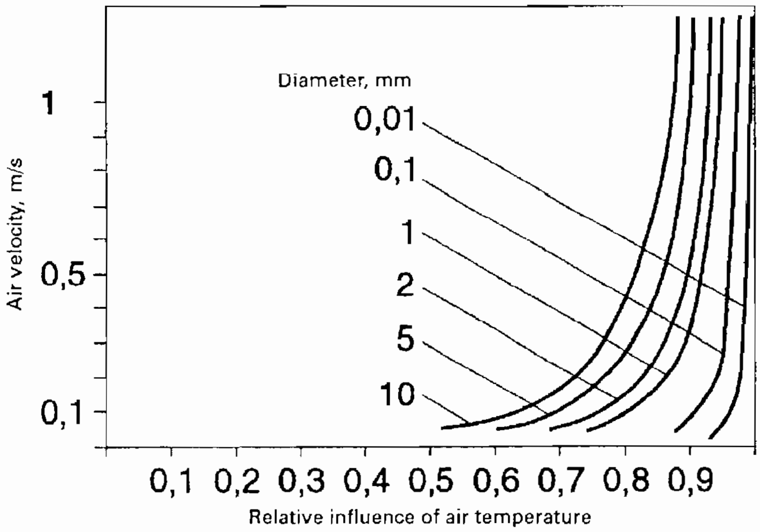


Figure A.1 — The relative influence of air temperature on sensor temperature for different air velocities and sensor diameters (For larger diameters see figure B.1)

Certain devices use the three means of protection mentioned above simultaneously, which results in small measuring errors.

A.3.2 Thermal inertia of the sensor

A thermometer placed in a given environment does not indicate the air temperature instantaneously. It requires a certain period to reach equilibrium.

A measurement should not be made before a period has elapsed equal to at least 1,5 times the response time (90 %) of the probe.

A thermometer will respond more rapidly:

— the smaller and lighter the temperature sensor is and the lower its specific heat capacity;

— the better the thermal exchanges with the environment. With regard to this, increasing the coefficient of heat transfer by convection at the level of the sensor, already an advantage as far as the established conditions are concerned, also improves the response of the thermometer during transitional conditions.

A.4 Types of temperature sensor

a) Expansion thermometers:

  1) liquid expansion thermometer (mercury);

  2) solid expansion thermometer.

b) Electrical thermometers:

  1) variable resistance thermometer

    — platinum resistor;

    — thermistor;

  2) thermometer based on the generation of an electromotive force (thermocouple).

c) Thermomanometers (variation in the pressure of a liquid as a function of temperature).

Annex B
(informative)

Measurement of the mean radiant temperature

B.1 Introduction

The net amount of radiant heat lost or received by the human body is the algebraic sum of all radiant fluxes exchanged by its exposed parts with the various surrounding heat sources. Each of these fluxes can be calculated knowing the dimensions, locations and thermal characteristics (surface temperature and emissivity) of the source and of the exposed body or clothing part. This method however, soon becomes complex and time consuming to put into effect once the number of sources becomes large or the sources have elaborate shapes.

The aim of this annex is

— to describe a method for determining the mean radiant temperature from the measurement of the temperature of the black globe and the air temperature and air velocity at the level of this globe;

— to summarize other methods for measuring the mean radiant temperature;

— to indicate the principle for calculating the mean radiant temperature using angle factors.

The black-globe thermometer will be used in this annex as an instrument for measuring a physical value, namely the mean radiant temperature.

B.2 Measurement of the mean radiant temperature using the black globe

B.2.1 Description of the black-globe thermometer

The black-globe thermometer consists of a black globe in the centre of which is placed a temperature sensor such as the bulb of a mercury thermometer, a thermocouple or a resistance probe.

The globe can in theory have any diameter but as the formulae used in the calculation of the mean radiant temperature depend on the diameter of the globe, a diameter of 0,15 m, specified for use with these formulae, is generally recommended.

It should be noted that the smaller the diameter of the globe, the greater the effect of the air temperature and air velocity, thus causing a reduction in the accuracy of the measurement of the mean radiant temperature.

So that the external surface of the globe absorbs the radiation from the walls of the enclosure, the surface of the globe shall be darkened, either by means of an electro-chemical coating or, more generally, by means of a layer of matt black paint.

B.2.2 Principle of the measurement

The black globe shall be placed in the actual enclosure where the mean radiant temperature $\overline{T}_r$, is to be measured. The globe tends towards a thermal balance under the effect of the exchanges due to the radiation coming from the different heat sources of the enclosure and under the effect of the exchanges by convection.

The temperature of the globe at the thermal balance allows $\overline{T}_r$ to be determined.

The temperature sensor placed inside the globe allows the mean temperature of the latter to be measured. In fact, the temperature of the inner surface of the globe (thin) and the temperature of the air outside the globe (closed space) are practically equal to the mean external temperature of the globe.

NOTE — Throughout the remaining part of this International Standard, the expressions temperature of the globe and temperature of the sensor placed inside the globe will be identical.

The balance of the thermal exchanges between the globe and the environment is given by the equation

$$q_r + q_c = 0 \tag{1}$$

where

q_r is the heat exchange by radiation between the walls of the enclosure and the globe, in watts per square metre;

q_c is the heat exchange by convection between the air and the globe, in watts per square metre.

The heat transfer by radiation between the walls of the enclosure, characterized by the mean radiant temperature, and the globe is expressed as follows:

$$q_r = \varepsilon_g \, \sigma \left(\overline{T}_r^4 - T_g^4 \right) \tag{2}$$

where

ε_g is the emissivity of the black globe (without dimension);

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power; [$\sigma = 5{,}67 \times 10^{-8}$ W/(m^2 · K^4)];

$\overline{T}_r$ is the mean radiant temperature, in kelvins;

T_g is the temperature of the black globe, in kelvins.

The heat transfer by convection between the air contained in the enclosure and the globe is given by the equation:

$$q_c = h_{cg} \left(T_a - T_g \right) \tag{3}$$

where

h_{cg} is the coefficient of heat transfer by convection at the level of the globe, in watts per square metre kelvin.

In the case of natural convection

$$h_{cg} = 1{,}4 \left(\frac{\Delta T}{D} \right)^{1/4}$$

and in the case of forced convection

$$h_{cg} = 6{,}3 \frac{v_a^{0{,}6}}{D^{0{,}4}}$$

where

D is the diameter of the globe, in metres;

v_a is the air velocity at the level of the globe, in metres per second.

In a type C environment, the coefficient of heat transfer by convection to be adopted is the one giving the highest value. In a type S environment, it is possible either to adopt the same method as previously or, more simply, to adopt the coefficient of heat transfer in forced convection directly.

The thermal balance of the black globe is expressed as follows:

$$\varepsilon_g \, \sigma \left(\overline{T}_r^4 - T_g^4 \right) + h_{cg} \left(T_a - T_g \right) = 0 \tag{4}$$

The mean radiant temperature is given by

$$\bar{T}_r = \sqrt[4]{T_g^4 + \frac{h_{cg}}{\varepsilon_g \sigma}\left(T_g - T_a\right)} \qquad (5)$$

By natural convection, one obtains:

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + \frac{0{,}25 \times 10^8}{\varepsilon_g}\left(\frac{\left|t_g - t_a\right|}{D}\right)^{1/4} \times \left(t_g - t_a\right)\right]^{1/4} - 273 \qquad (6)$$

In the case of the standard globe $D = 0{,}15$ m, $\varepsilon_g = 0{,}95$ (matt black paint) and equation (6) becomes

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 0{,}4 \times 10^8 \left|t_g - t_a\right|^{1/4} \times \left(t_g - t_a\right)\right]^{1/4} - 273 \qquad (7)$$

By forced convection, one obtains

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + \frac{1{,}1 \times 10^8 \times v_a^{0{,}6}}{\varepsilon_g \times D^{0{,}4}}\left(t_g - t_a\right)\right]^{1/4} - 273 \qquad (8)$$

or for the standard globe

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 2{,}5 \times 10^8 \times v_a^{0{,}6}\left(t_g - t_a\right)\right]^{1/4} - 273 \qquad (9)$$

In practice, it is this expression which will be most frequently used to calculate the mean radiant temperature. It is valid only for a standard globe by forced convection.

The relative influence of air temperature and mean radiant temperature on a globe is shown in figure B.1.

EXAMPLE:

For a 100 mm globe at an air velocity of 0,35 m/s, the globe temperature, $t_g = 0{,}6\, t_a + 0{,}4\, \bar{t}_r$.

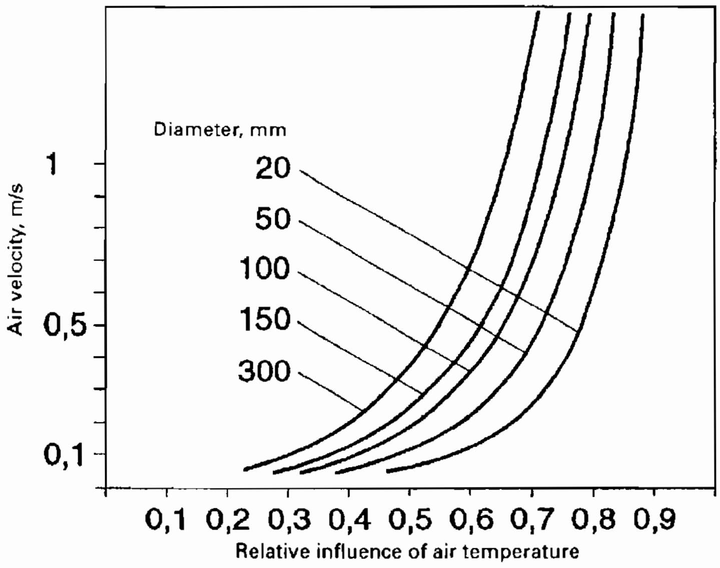


Figure B.1 — Relative influence of air temperature, t_a, and mean radiant temperature, $\bar{t}_r$, on the globe temperature for different air velocities and globe diameters

EXAMPLES:

The following results were obtained in an environment using a standard globe:

$t_g = 55$ °C

$t_a = 30$ °C

$v_a = 0{,}3$ m/s

The coefficient of exchange at the level of the globe is calculated as follows:

— in natural convection

$$h_{cg} = 1{,}4\left(\frac{\Delta T}{D}\right)^{1/4} = 1{,}4\left(\frac{55-30}{0{,}15}\right)^{0{,}25} = 5\,\mathrm{W}/\left(m^2\cdot K\right)$$

— in forced convection

$$h_{cg} = 6{,}3\left(\frac{v_a^{0{,}6}}{D^{0{,}4}}\right) = 6{,}3\times\frac{(0{,}3)^{0{,}6}}{(0{,}15)^{0{,}4}} = 6{,}5\,\mathrm{W}/\left(m^2\cdot K\right)$$

The coefficient of exchange in forced convection will therefore be used.

The mean radiant temperature is calculated according to equation (9):

$$\bar{t}_r = \left[(55+273)^4 + 2{,}5\times10^8\times v_a^{0{,}6}\,(55-30)\right]^{1/4} - 273$$

$$\bar{t}_r = 74{,}7\ °\mathrm{C}$$

If the measurement is carried out with a globe with the following characteristics:

$D = 0{,}1$ m

$\varepsilon_g = 0{,}95$

the temperature measured for the black globe is 53,2 °C.

The mean radiant temperature is then calculated according to equation (8):

$$\bar{t}_r = \left[(53{,}2+273)^4 + \frac{1{,}1\left(0{,}3^{0{,}6}\right)}{0{,}95\left(0{,}10^{0{,}4}\right)}(53{,}2-30)\right]^{1/4} - 273 = 74{,}7\,°\mathrm{C}$$

The figure for the mean radiant temperature characteristic of the environment considered is thus obtained.

B.2.3 Precautions to be taken when using a black-globe thermometer

B.2.3.1 As the radiation of an enclosure is frequently one of the main factors in the thermal stress of an environment, an incorrect determination of the mean radiant temperature can lead to large errors in the overall assessment of this stress. The precautions in B.2.3.2 to B.2.3.6 should be considered:

B.2.3.2 In the case of heterogeneous radiation it is necessary to use three black globes. When the radiation is heterogeneous, the measurement of a black-globe temperature carried out at a single point is not representative of the overall radiative field received by the subject. It is, therefore, necessary to place the black globes at the levels defined in this International Standard and in such a way that the radiation received by each of the globes is very close to the radiation received by each part of the body located at the same level. The mean radiant temperature is equal to the mean, weighted according to the coefficients defined in this International Standard, of the measurements at the specified levels.

EXAMPLE:

The temperature measurements for three globes located at the level of the head, the abdomen and the ankles of a person lead respectively to the calculation of the following three mean radiant temperatures:

$\bar{t}_{r1} = 25$ °C

$\bar{t}_{r2} = 50$ °C

$\bar{t}_{r3} = 40$ °C

The environment is heterogeneous with regard to radiation and high thermal stress. The mean radiant temperature is calculated by applying the weighting coefficients of table 4 as follows:

$$\bar{t}_r = \frac{1 \times 25 + 2 \times 50 + 1 \times 40}{4} = 41\,^\circ\mathrm{C}$$

However, if the measurement had been carried out using a single black globe placed at the level of the abdomen, the measuring error would have been of the order of 9 °C.

B.2.3.3 The response time for a black-globe thermometer is about 20 min to 30 min according to the physical characteristics of the globe and the environmental conditions.

Successive readings of this temperature will allow the thermal balance to be registered easily.

Because of its high inertia, the black globe thermometer cannot be used to determine the radiant temperature of environments which vary rapidly.

B.2.3.4 The accuracy of measuring the mean radiant temperature using a black globe can vary to a great extent according to the values for the other characteristics of the environment.

In each case, a check should be carried out to determine whether the accuracy achieved is in conformity with the value indicated in this International Standard and if it is not, to indicate the actual accuracy.

B.2.3.5 The use of a black globe thermometer for the assessment of the mean radiant temperature is an approximation due to the difference in shape between a person and a globe. In particular, the radiation coming from a ceiling or a floor will be over-estimated by the globe in relation to that received by a standing or seated person.

An ellipsoid with projected area factors as shown in table B.1 may be considered a closer approximation of the shape of the human body. Table B.1 shows the projected area factors for a person, an ellipsoid and a sphere. The projected area factor is estimated as A_{pr}/A_r, where A_{pr} is the surface area projected on one direction and A_r is the total radiant surface area. This factor is related to the shape of a person or a sensor and indicates the relative importance of the radiation from different directions.

The inclination of the axis of the ellipsoid depends on the position of the subject: standing, axis vertical; seated, axis inclined at 30°; lying, axis horizontal.

B.2.3.6 The use of a globe thermometer in the case of exposure to short-wave radiation (for example the sun) requires the use of a paint on the globe (for example medium grey) with approximately the same absorptivity for short wave radiation as the outer surface of clothed persons (except for the measurement of the WBGT where this factor is taken into account in the weighting formula between the different quantities). The emissivity for the paint should be approximately 0,95 for long-wave radiation. An alternative is to use the black globe and calculate the mean radiant temperature taking into account the absorptivity of the clothing worn.

Table B.1 — Projected area factors

		Up/down	Left/right	Front/back
Standing	Person	0,08	0,23	0,35
	Ellipsoid	0,08	0,28	0,28
	Sphere	0,25	0,25	0,25
Seated	Person	0,18	0,22	0,30
	Ellipsoid	0,18	0,22	0,28
	Sphere	0,25	0,25	0,25

B.3 Other measuring methods

B.3.1 Two-sphere radiometer

In this method, two spheres with different emissivities (one black and one polished) are used. As the two spheres are heated to the same temperature, they will be exposed to the same convective heat loss. As the emittance of the black sphere is higher than the polished one, there is a difference in the heat supply to the two spheres and this is a measure of the radiation.

To estimate the mean radiant temperature, the emissivity and temperature of the sensors are required.

The mean radiant temperature is calculated from the equation:

$$\bar{T}_r^4 = T_s^4 + \frac{P_p - P_b}{\sigma\left(\varepsilon_b - \varepsilon_p\right)} \qquad (10)$$

where

$\bar{T}_r$ is the mean radiant temperature, in kelvins;

T_s is the sensor temperature, in kelvins;

P_p is the heat supply to the polished sensor, in watts per square metre;

P_b is the heat supply to the black sensor, in watts per square metre;

ε_p is the emissivity of the polished sensor;

ε_b is the emissivity of the black sensor;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4)].

Instead of a sphere, an ellipsoid shaped sensor, which is closer to the shape of the human body, can be used.

B.3.2 Constant-air-temperature sensor

In this method, a sensor (sphere, ellipsoid) is controlled at the same temperature as the surrounding air temperature; there being no convection heat loss and the necessary heat supply (cooling supply) to the sensor being equal to the radiant heat loss (or gain).

The mean radiant temperature is calculated by equation (11):

$$\overline{T}_r^4 = T_s^4 - \frac{P_s}{\sigma \varepsilon_s} \qquad (11)$$

where

$\overline{T}_r$ is the mean radiant temperature, in kelvins;

T_s is the sensor temperature, in kelvins;

P_s is the heat supply (cooling supply) to the sensor, in watts per square metre;

ε_s is the emissivity of the sensor;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power.

B.4 Method for calculation of mean radiant temperature

B.4.1 Calculation from the temperature of the surrounding surfaces

The mean radiant temperature can be calculated from

- the surface temperature of the surrounding surfaces;
- the angle factor between a person and the surrounding surfaces, a function of the shape, the size and the relative positions of the surface in relation to the person.

As most building materials have a high emissivity (ε), it is possible to disregard the reflection i.e. to assume that all the surfaces in the room are black.

The following equation (12) is then used:

$$\overline{T}_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots T_N^4 \ F_{p-N} \qquad (12)$$

where

$\overline{T}_r$ is the mean radiant temperature, in kelvins;

T_N is the surface temperature of surface N, in kelvins;

F_{p-N} is the angle factor between a person and surface N.

As the sum of the angle factors is unity, the fourth power of mean radiant temperature will be seen to be equal to the mean value of the surrounding surface temperatures to the fourth power, weighted according to the size of the respective angle factors.

The angle factors (F_{p-N}) can be estimated according to figures B.2 to B.5 in the case of rectangular surfaces. The angle factors may also be calculated from the equation in figure B.6 where AC is a/c and BC is b/c on figures B.2 to B.5. Figures B.2 to B.5 assume a certain distance between a surface and a person. For floors or other surfaces, where the person is close, figures B.2 to B.5 underestimate the angle factor to these surfaces. For typical indoor environments, the effect on the mean radiant temperature will be less than 1 K.

If there are only relatively small temperature differences between the surfaces of the enclosure, equation (12) can be simplified to the following linear form:

$$\overline{T}_r = T_1 \ F_{p-1} + T_2 \ F_{p-2} + \cdots + T_N \ F_{p-N} \qquad (13)$$

In other words, the mean radiant temperature is calculated as the mean value of the surrounding temperatures weighted according to the magnitude of the respective angle factors. Equation (13) will always give a slightly lower mean radiant temperature than equation (12), but in many cases the difference is small. If, for example, half of the surroundings ($F_{\mathrm{p-N}} = 0{,}5$) has a temperature which is 10 K higher than the other half, the difference between the calculated mean radiant temperatures according to equation (12) and equation (13) will be only 0,2 °C. If, however, there are large differences in temperature between the surfaces, the error in using equation (13) can be considerable. If the temperature difference in the example above is 100 K, the mean radiant temperature will, according to formula (13), be calculated approximately 10 K too low.

B.4.2 Calculation from the plane radiant temperature

The mean radiant temperature may be calculated from

- the plane radiant temperature, t_{pr}, in six directions (see annex C);
- the projected area factors for a person in the same six directions.

The projected area factors for a seated or standing person are given in table B.1 for the six directions: up (1), down (2), left (3), right (4), front (5), back (6).

The mean radiant temperature can then be calculated by multiplying the six measured values by the relevant projection factors given in table B.1 adding the resultant data and dividing the result by the sum of the projected area factors, i.e. for a seated person:

$$\bar{t}_{\mathrm{r}} = \frac{0{,}18\left(t_{\mathrm{pr}}[\mathrm{up}] + t_{\mathrm{pr}}[\mathrm{down}]\right) + 0.22\left(t_{\mathrm{pr}}[\mathrm{right}] + t_{\mathrm{pr}}[\mathrm{left}]\right) + 0{,}30\left(t_{\mathrm{pr}}[\mathrm{front}] + t_{\mathrm{pr}}[\mathrm{back}]\right)}{2\,(0{,}18 + 0{,}22 + 0{,}30)}$$

and for a standing person:

$$\bar{t}_{\mathrm{r}} = \frac{0{,}08\left(t_{\mathrm{pr}}[\mathrm{up}] + t_{\mathrm{pr}}[\mathrm{down}]\right) + 0{,}23\left(t_{\mathrm{pr}}[\mathrm{right}] + t_{\mathrm{pr}}[\mathrm{left}]\right) + 0{,}35\left(t_{\mathrm{pr}}[\mathrm{front}] + t_{\mathrm{pr}}[\mathrm{back}]\right)}{2\,(0{,}08 + 0{,}23 + 0{,}35)}$$

where

$\bar{t}_{\mathrm{r}}$ is the mean radiant temperature;

t_{pr} is the plane radiant temperature.

Where the orientation of the person is not fixed, the average of the Right/Left and Front/Back projected area factors is used.

The equations are then simplified to:

$$\text{Sitting } \bar{t}_{\mathrm{r}} = 0{,}13\left(t_{\mathrm{pr}}[\mathrm{up}] + t_{\mathrm{pr}}[\mathrm{down}]\right) + 0{,}185\left(t_{\mathrm{pr}}[\mathrm{right}] + t_{\mathrm{pr}}[\mathrm{left}] + t_{\mathrm{pr}}[\mathrm{front}] + t_{\mathrm{pr}}[\mathrm{back}]\right)$$

$$\text{Standing } \bar{t}_{\mathrm{r}} = 0{,}06\left(t_{\mathrm{pr}}[\mathrm{up}] + t_{\mathrm{pr}}[\mathrm{down}]\right) + 0{,}220\left(t_{\mathrm{pr}}[\mathrm{right}] + t_{\mathrm{pr}}[\mathrm{left}] + t_{\mathrm{pr}}[\mathrm{front}] + t_{\mathrm{pr}}[\mathrm{back}]\right)$$

B.5 Other radiant heat flow quantities

B.5.1 General

Some instruments measure the radiation in watts per square metre. This clause shows how this may be converted into mean radiant or plane radiant temperature. To describe the radiant heat flow through a defined plane by radiant sources in the steel and glass industries, gas heating systems in cold storage, and solar radiation in buildings, the heat flow is measured using the quantity of directional radiation ($\mathrm{W \cdot m^2}$).

B.5.2 Absolute radiant heat flow

The absolute radiant heat flow is the basic physical quantity for energy emission by radiation.

The rate of thermal energy emitted by a surface depends on its absolute temperature. The absolute radiant heat flow is defined as the total rate of energy emitted in one direction per unit area of surface and is given by:

$$E_{\text{abs}} = \sigma \varepsilon_{\text{s}} T^4$$

where

ε_{s} is the emissivity of the surface (without dimension);

σ is the Stefan-Bolzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4)];

T is the temperature of the surface in kelvins.

B.5.3 Effective radiant heat flow

A commonly used quantity for measuring and describing the radiation received by a person in a given enclosure is the effective radiant heat flow (e_{eff}). It is given in watts per square metre of surface area (W/m^2).

The effective radiant heat flow is defined as the heat exchange by radiation between the walls of the enclosure and the human body. The mean temperature of the body surface is set to 32 °C and the emissivity of the human body is set to 0,95.

With these values, the mean radiant temperature can be calculated from:

$$\bar{t}_{\text{r}} = \left(t_{\text{b}} + 273\right)\left(1 + 2{,}146 \times 10^{-3} \times E_{\text{eff}}\right)^{0{,}25} - 273$$

where

$\bar{t}_{\text{r}}$ is the mean radiant temperature, in degrees Celsius;

t_{b} is the reference body temperature, in degrees Celsius;

E_{eff} is the mean effective radiant heat flow, in watts per square metre of surface area, measured in all six directions.

By using this equation, the effective radiant flow can also be converted to other body surface temperatures.

Similarly to this, the plane radiant temperature t_{pr} can be calculated from the effective radiant heat flow, measured in one direction:

$$t_{\text{pr}} = \left(t_{\text{b}} + 273\right) \times \left(1 + 2{,}146 \times 10^{-3} \times E_{\text{eff}}\right)^{0{,}25} - 273$$

where

t_{pr} is the plane radiant temperature, in degrees Celsius;

t_{b} is the reference body temperature, in degrees Celsius;

E_{eff} is the effective radiant heat flow, in watts per square metre of surface area, measured in one direction.

If the mean radiant temperature or plane radiant temperature are known, the corresponding effective radiant heat flow may be calculated using the above equations.

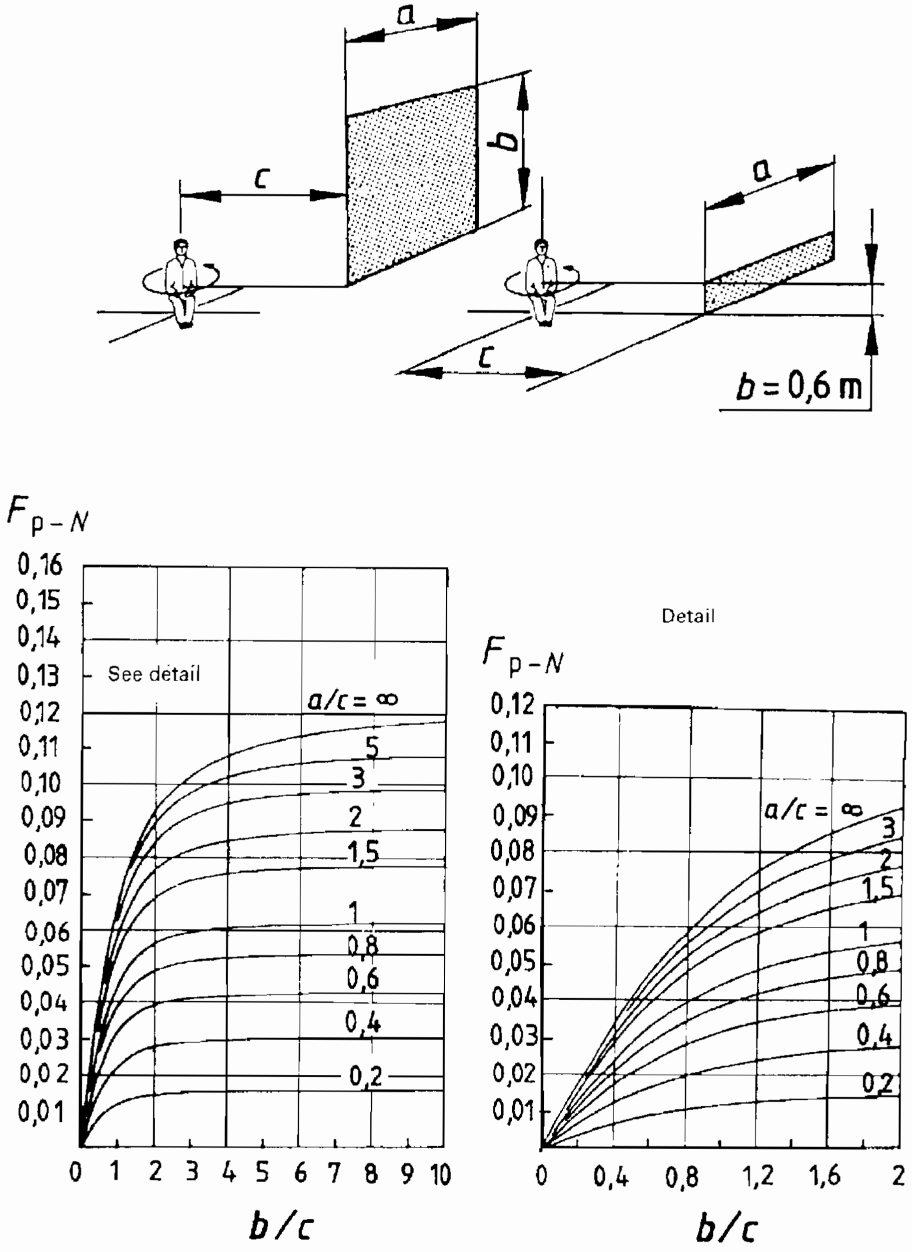


Figure B.2 — Mean value of angle factor between a seated person and a vertical rectangle (above or below his centre) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known).

EXAMPLE:

a = 4 m; b = 3 m; c = 5 m; b/c = 0,6; a/c = 0,8;

F_{p-a} = 0,029.

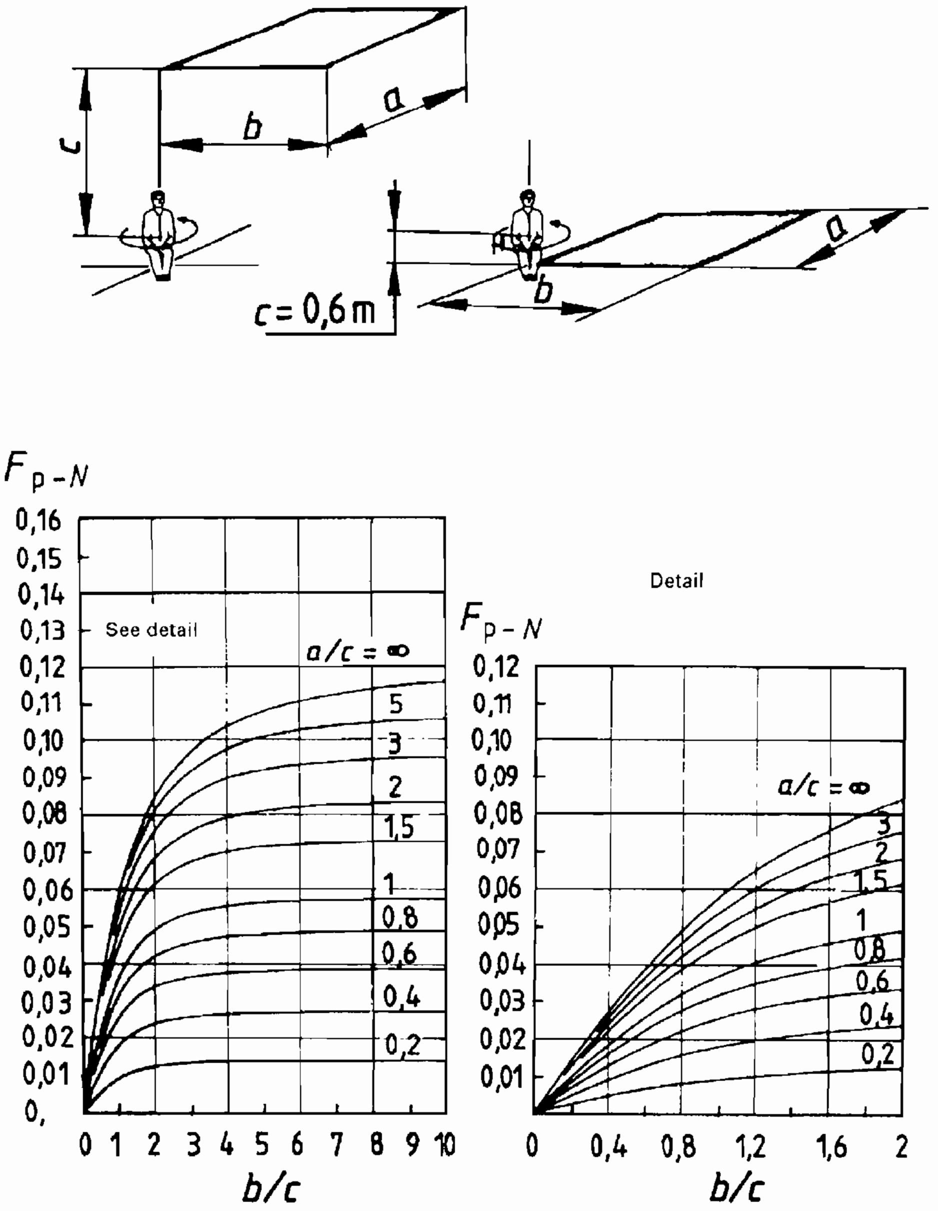


Figure B.3 — Mean value of angle factor between a seated person and a horizontal rectangle (on the ceiling or on the floor) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

EXAMPLE:

a = 3 m; b = 6 m; c = 2 m; b/c = 3,0; a/c = 1,5;

F_{p-a} = 0,067.

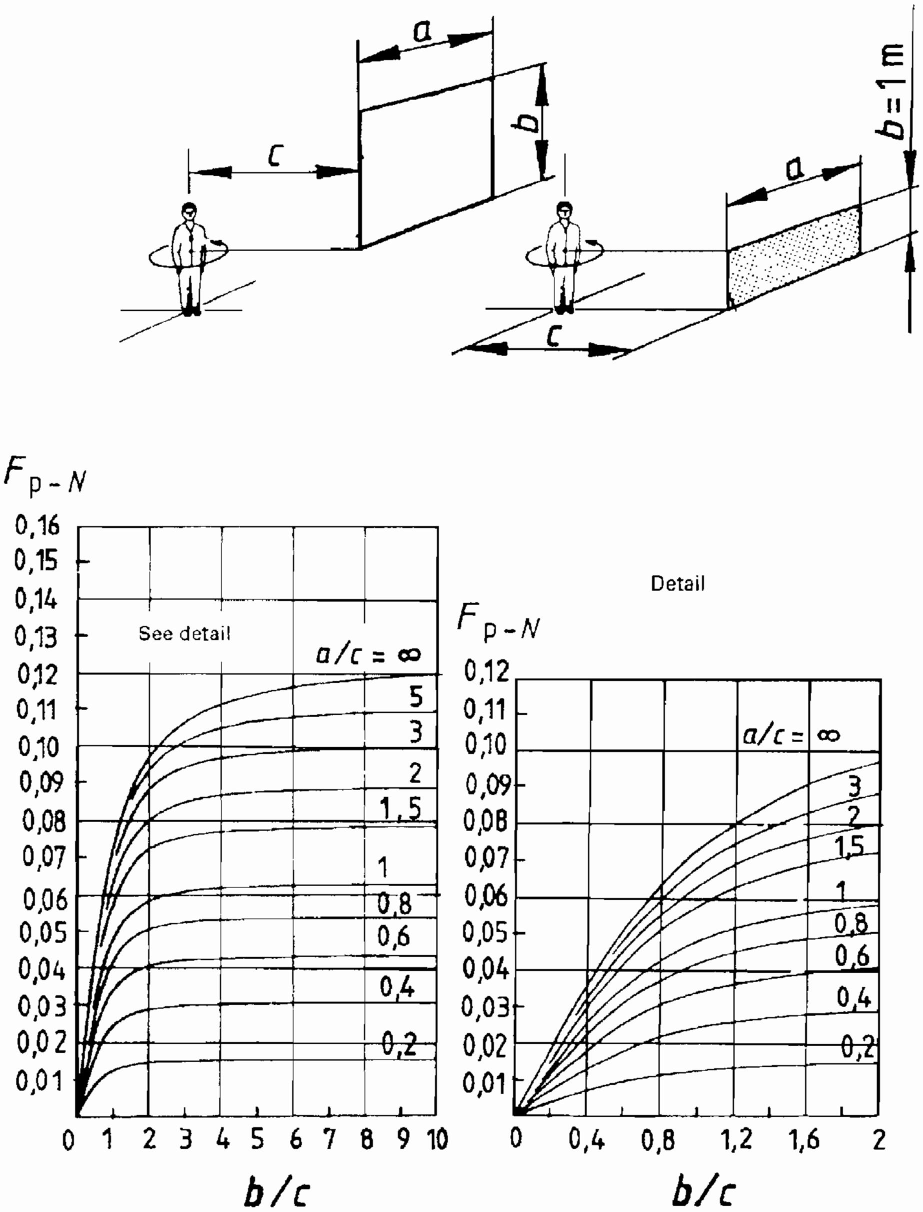


Figure B.4 — Mean value of angle factor between a standing person and a vertical rectangle (above or below his centre) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

EXAMPLE:

a = 4,5 m; b = 2,0 m; c = 3,0 m; b/c = 0,67; a/c = 1,5;

$F_{\mathrm{p-a}}$ = 0,047.

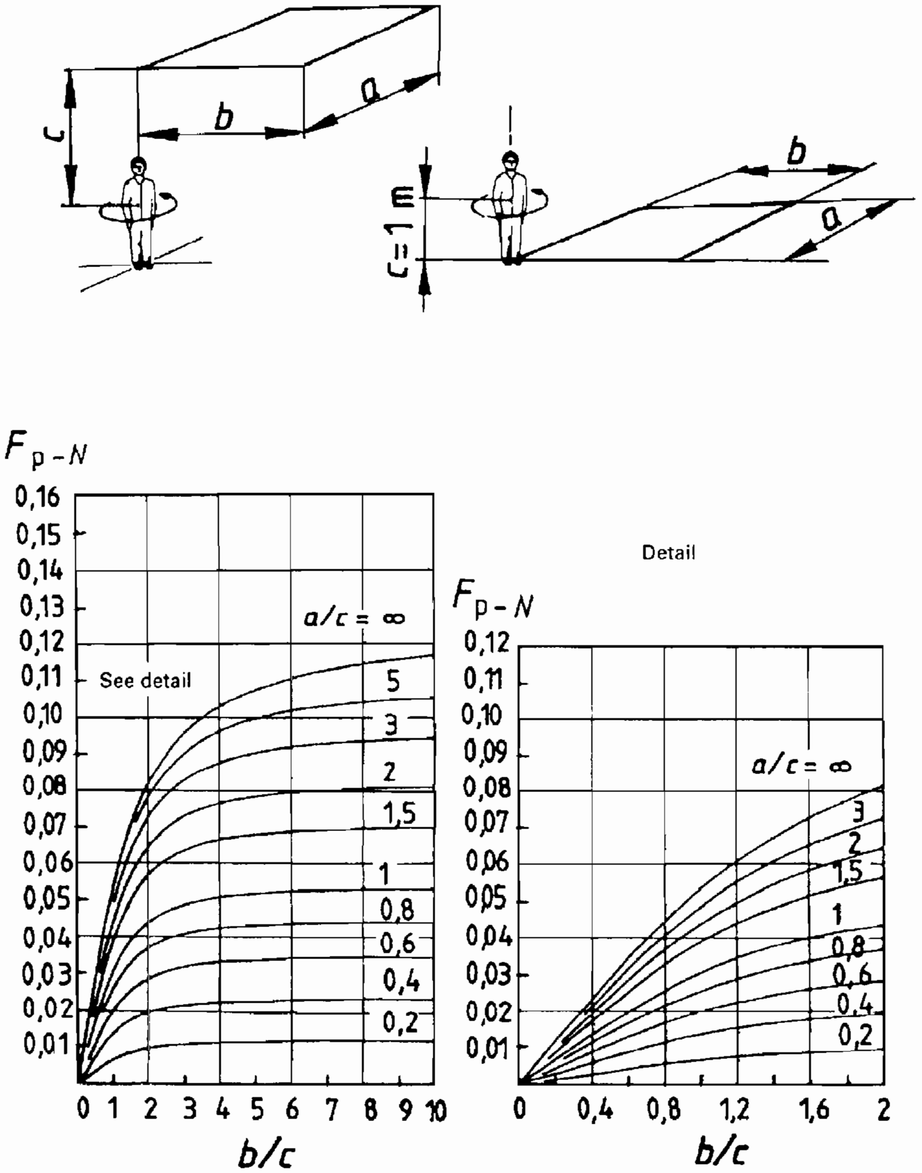


Figure B.5 — Mean value of angle factor between a standing person and a horizontal rectangle (on the ceiling or on the floor) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

EXAMPLE:

a = 1,0 m; b = 15 m; c = 1,5 m; b/c = 10; a/c = 0,67;

F_{p-a} = 0,039.

ANGLE FACTOR $= F_{\max} \left(1 - e^{-(a/c)/\tau}\right) \left(1 - e^{-(b/c)/\gamma}\right)$

where

$$\tau = A + B\,(a/c)$$

$$\gamma = C + D\,(b/c) + E\,(a/c)$$

	$F_{\max}$	A	B	C	D	E
SEATED PERSON, figure B.2 Vertical surfaces: Wall, Window	0,118	1,216	0,169	0,717	0,087	0,052
SEATED PERSON, figure B.3 Horizontal surfaces: Floor, Ceiling	0,116	1,396	0,130	0,951	0,080	0,055
STANDING PERSON, figure B.4 Vertical surfaces: Wall, Window	0,120	1,242	0,167	0,616	0,082	0,051
STANDING PERSON, figure B.5 Horizontal surfaces: Floor, Ceiling	0,116	1,595	0,128	1,226	0,046	0,044

Figure B.6 — Equations for calculations of the angle factors

Annex C
(informative)

Measurement of plane radiant temperature

C.1 Introduction

The human being can be exposed to asymmetric thermal radiation in various environments. To evaluate the asymmetry, the concept of radiant temperature asymmetry (Δt_{pr}) is used. This quantity is the difference between the plane radiant temperature (t_{pr}) on two opposite sides of a small plane element (see 4.1.3).

A method is described for measuring the plane radiant temperature and radiant temperature asymmetry by means of a net radiometer. Two other methods of measuring are also presented as well as a method for calculating plane radiant temperature and the radiant temperature asymmetry.

C.2 Measurement of plane radiant temperature

C.2.1 Heated sensor consisting of a reflective disc, and an absorbing disc

The plane radiant temperature can be measured by a heated sensor consisting of a reflective (gold-plated) disc and an absorbing (matt black painted) disc. The gold-plated disc will lose heat almost entirely by convection whereas the black painted disc will lose heat both by convection and radiation. If both discs are heated to the same temperature, the difference in heat supply to the two discs is equal to the heat transfer by radiation between the painted disc and the environment.

The plane radiant temperature is thus calculated from equation (14)

$$T_{pr}^4 = T_s^4 + \frac{P_p - P_b}{\sigma\left(\varepsilon_b - \varepsilon_p\right)} \tag{14}$$

where

T_{pr} is the radiant temperature, in kelvins;

T_s is the disc temperature, in kelvins;

P_p is the heat supply to the polished disc, in watts per square metre;

P_b is the heat supply to the black disc, in watts per square metre;

ε_p is the emissivity of the polished disc;

ε_b is the emissivity of the black disc;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4)].

C.2.2 Constant air temperature disc

In this method, a small plane element is controlled at the same temperature as the surrounding air. There is no convection heat loss and the necessary heat supply (cooling supply) to the element is equal to the radiation heat exchange (cooling exchange).

The plane radiant temperature is thus calculated from equation (15)

$$T_{pr}^4 = T_s^4 + \frac{P_s}{\sigma \varepsilon_s} \qquad (15)$$

where

T_{pr} is the plane radiant temperature, in kelvins;

T_s is the disc temperature, in kelvins;

P_s is the heat supply (cooling supply) to the disc, in watts per square metre;

ε_s is the emissivity of the disc;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4)].

C.3 Method for measuring plane radiant temperature and asymmetry with a net radiometer

C.3.1 Description of the net radiometer

The net radiometer consists of a small black plane element with a heat flow meter (thermopile) between the two sides of the element. The net heat flow between the two sides is equal to the difference between the radiant heat transfer at the level of the two sides of the element.

The measuring elements are usually covered by a thin polyethylene sphere to decrease the effect of air velocity.

Occasionally the net radiometer is equipped with an adaptor for unidirectional measurement.

C.3.2 Measurement

The net radiation is given by the following equation (16):

$$P = \sigma \left(T_{pr1}^4 - T_{pr2}^4 \right) \qquad (16)$$

where

P is the net radiation measured, in watts per square metre;

T_{pr1} is the plane radiant temperature, side 1, in kelvins;

T_{pr2} is the plane radiant temperature, side 2, in kelvins;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m$^2 \cdot$ K^4)].

The radiant temperature asymmetry is equal to:

$$\Delta t_{pr} = T_{pr1} - T_{pr2}$$

where

Δt_{pr} is the radiant temperature asymmetry, in kelvins. (17)

This quantity is not measured directly by a net radiometer but has to be calculated.

Equation (16) can be written as:

$$P = 4\,\sigma\,T_n^3\left(T_{pr1} - T_{pr2}\right) \tag{18}$$

In the linear radiant heat transfer coefficient $\left(4\,\sigma\,T_n^3\right)$, $T_n = 0{,}5\,(T_{pr1} + T_{pr2})$ or with a closer approximation equal to the temperature of the net radiometer. On most net radiometers, T_n is easily measured.

Thus the radiant temperature asymmetry is equal to:

$$\Delta t_{pr} = \frac{P}{4\,\sigma\,T_n^3} \tag{19}$$

where

Δt_{pr} is the radiant temperature asymmetry, in kelvin.

The linear radiant heat transfer coefficient is influenced by the temperature level given by T_n. At a temperature level equal to 20 °C the coefficient is equal to 5,7 W/(m^2 · K) and for a temperature level equal to 50 °C the coefficient is equal to 7,6 W/(m^2 · K).

The following equation is valid only when the radiation heat transfer on one side of the net radiometer (P_1) is measured.

$$P_1 = \sigma\,T_{pr1}^4 - \sigma\varepsilon_s T_n^4 \tag{20}$$

where

P_1 is the radiation measured at side 1, in watts per square metre;

T_{pr1} is the plane radiant temperature, side 1, in kelvins;

T_n is the temperature of the net radiometer, in kelvins;

ε_s is the emissivity of the sensor;

σ is the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power [$\sigma = 5{,}67 \times 10^{-8}$ W/(m^2 · K^4)].

For a black painted surface, the emissivity may be estimated to approximately 0,95.

The plane radiant temperature is then equal to

$$T_{pr1} = \sqrt[4]{0{,}95\,T_n^4 + \frac{P_1}{\sigma}} \tag{21}$$

To determine the radiant temperature asymmetry, it is also necessary to measure in the opposite direction and calculate the corresponding plane radiant temperature.

C.4 Method for calculation of plane radiant temperature

The plane radiant temperature can be calculated from

— the surface temperature of the surrounding surfaces;

— the angle factor between a small plane element and the surrounding surfaces, a function of the shape, the size and the relative position of the surface in relation to a person.

The radiant temperature asymmetry is estimated as the difference between the plane radiant temperature in two opposite directions.

As most building materials have a high emittance (ε), it is possible to disregard the reflections, i.e. to assume that all the surfaces in the room are black.

The following equation (22) is then used

$$T_{\mathrm{pr}}^4 = T_1^4\, F_{\mathrm{p-1}} + T_2^4\, F_{\mathrm{p-2}} + \cdots + T_{\mathrm{N}}^4\, F_{\mathrm{p-N}} \tag{22}$$

where

T_{pr} is the plane radiant temperature, in kelvins;

T_{N} is the surface temperature of surface N, in kelvins;

$F_{\mathrm{p-N}}$ is the angle factor between a small plane element and surface N.

As the sum of the angle factors is unity, the fourth power of the plane radiant temperature will be seen to be equal to the mean value of the surface temperature of the hemisphere to the fourth power, weighted according to the size of the respective angle factors.

The angle factors ($F_{\mathrm{p-N}}$) can be estimated according to figures C.1 and C.2 or figures C.3 and C.4 in the case of rectangular surfaces but in general the determination of angle factors is more involved.

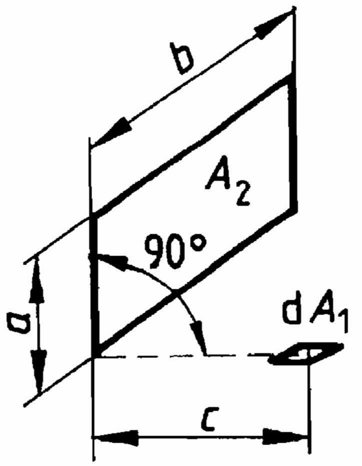
If there are only relatively small temperature differences between the surfaces of the enclosure, equation (22) can be simplified to a linear form

$$T_{\mathrm{pr}} = T_1\, F_{\mathrm{p-1}} + T_2\, F_{\mathrm{p-2}} + \ldots + T_{\mathrm{N}}\, F_{\mathrm{p-N}} \tag{23}$$

That is, the plane radiant temperature is calculated as the mean value of the surface temperatures weighted according to the magnitude of the respective angle factors.

Equation (23) will always give a slightly lower plane radiant temperature than equation (22), but in many cases the difference is small. If, for example, half of the surroundings (N = 0,5) has a temperature which is 10 K higher than the other half, the difference, between the calculated mean radiant temperatures according to equation (22) and equation (23) will be only 0,2 °C. If, however, there are large differences in temperature between the surfaces, the error by using equation (23) can be considerable. If the temperature difference in the example above is 100 K, the plane radiant temperature will, according to equation (23), be calculated approximately 10 K too low.

The radiant temperature asymmetry is then calculated as the difference between the plane radiant temperature on the two opposite sides of the small plane element.

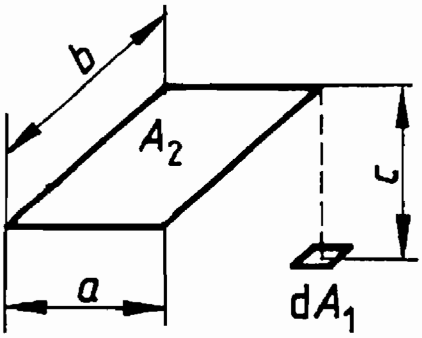


Element of a plane surface dA_1 and a rectangle in a plane perpendicular to the plane of the element

$$X = \frac{a}{b} \quad Y = \frac{c}{b}$$

$$F_{d1-2} = \frac{1}{2\pi}\left(\tan^{-1}\frac{1}{Y} - \frac{Y}{\sqrt{X^2+Y^2}}\tan^{-1}\frac{1}{\sqrt{X^2+Y^2}} \right)$$

Figure C.1 — Analytical formula relating to the calculation of the shape factor in the case of a small plane element perpendicular to a rectangular surface



Element of a plane surface dA_1 and a rectangle in a plane parallel to it; the normal to the element passes through the corner of the rectangle

$$X = \frac{a}{c} \quad Y = \frac{b}{c}$$

$$F_{d1-2} = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}} \right)$$

Figure C.2 — Analytical formula relating to the calculation of the shape factor in the case of a small plane element parallel to a rectangular surface

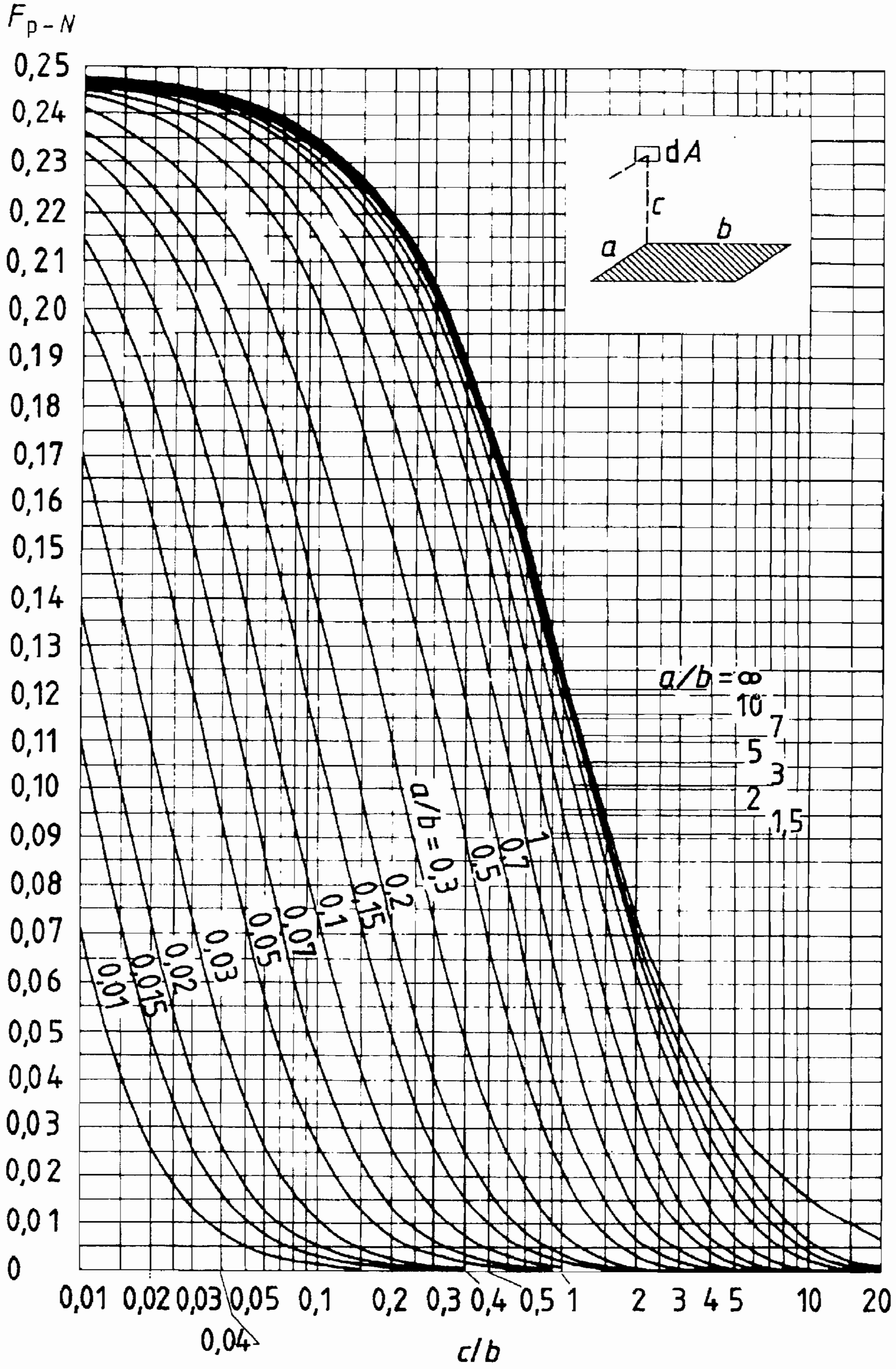


Figure C.3 — Chart for the calculation of the shape factor in the case of a small plane element perpendicular to a rectangular surface

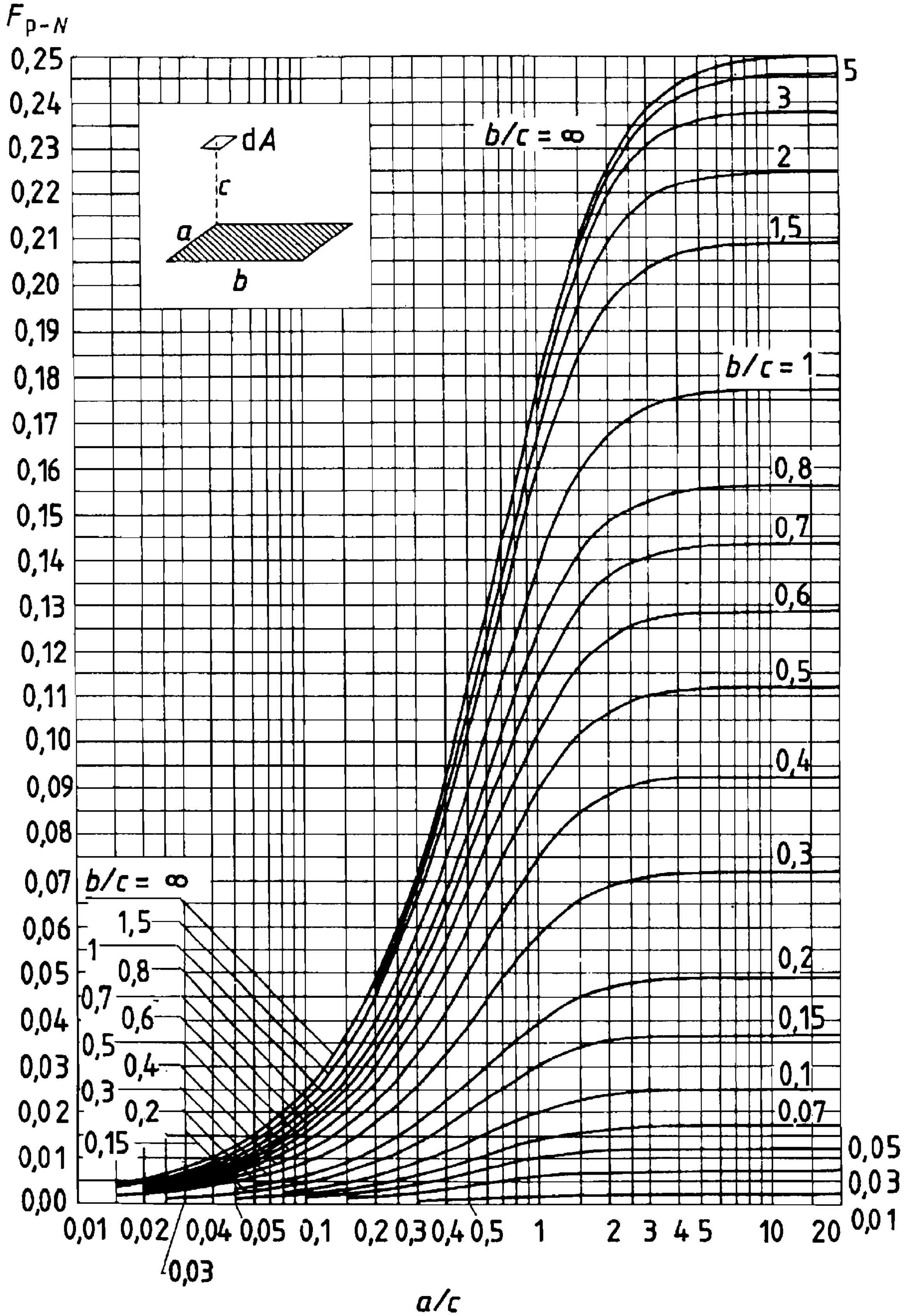


Figure C.4 — Chart for the calculation of the shape factor in the case of a small plane element parallel to a rectangular surface

Annex D
(informative)

Measurement of the absolute humidity of the air

D.1 Introduction

The absolute humidity of the air is taken into account when determining the transfer of heat by evaporation from a subject. A high air humidity reduces evaporation of sweat and thus constitutes a thermal stress for the subject.

This annex describes the principles of and the precautions to be taken when using the following two types of appliance:

— psychrometer;

— lithium chloride hygrometer.

It also gives a brief resume of the main characteristics of humid air.

D.2 Thermo-hygrometric characteristics of humid air

D.2.1 General

Humid air is a mixture of several gases which can be divided into two groups:

— the gases which make up dry air (oxygen, nitrogen, etc.); and

— water vapour.

At any given temperature, air cannot hold more than a certain amount of water vapour. Beyond that amount, the water vapour condenses. As the temperature of the air increases, so does the maximum amount of water vapour it can hold.

D.2.2 Absolute humidity

D.2.2.1 Introduction

The values connected with the actual quantity of water vapour contained in the air characterize the absolute humidity of the environment.

Two values are generally used to characterize the absolute humidity of the air: the humidity ratio and the partial pressure of water vapour.

D.2.2.2 Humidity ratio

The humidity ratio W_a, for a given sample of moist air, is the ratio of the mass of water vapour in the sample to the mass of dry air in the sample:

$$W_a = \frac{M_v}{M_a} \qquad (24)$$

where

W_a is the humidity ratio;

M_v is the mass of the water vapour;

M_a is the mass of dry air in a given sample of humid air.

D.2.2.3 Partial pressure

The partial pressure of water vapour p_a of the humid air is the pressure which the water vapour would exert if it alone occupied the volume occupied by the humid air at the same temperature.

These two values (W_a and p_a) are connected by the relationship (presuming the gases to be perfect)

$$W_a = 0{,}6220 \frac{p_a}{p - p_a} \tag{25}$$

where

W_a is the humidity ratio;

p_a is the partial pressure of water vapour;

p is the total atmospheric pressure.

At saturation point, these two values are known as the humidity ratio at saturation W_{as} and the saturation pressure or saturated vapour pressure p_{as}.

The saturated vapour pressure p_{as} is connected to the absolute temperature T of the humid air mixture by a one-to-one relationship.

D.2.3 Relative humidity

The values giving the composition of the air in terms of water vapour in relation to the maximum amount it can hold at a given temperature characterize the relative humidity of the environment.

The relative humidity e is the ratio between the partial pressure of water vapour p_a, in humid air and the water vapour saturation pressure p_{as} at the same temperature and the same total pressure

$$e = \frac{p_a}{p_{as}} \tag{26}$$

The relative humidity is often expressed as a percentage in accordance with the following relationship:

$$\text{RH} = 100\, e$$

With regard to the heat transfer between man and his environment by evaporation, it is the absolute humidity of the air which has to be taken into account.

D.2.4 Direct determination of the thermo-hygrometric characteristics of humid air using a psychometric chart

The main characteristics of humid air are usually grouped together in a chart known as a psychometric chart (see figure D.1). The coordinates of this chart are as follows:

a) on the x-axis, the air temperature t_a, in degrees Celsius;

b) on the y-axis, the partial pressure of water vapour p_a of the air, expressed in kilopascals.

A given sample of humid air is represented by a point on the chart. It should be noted, however, that at a given temperature, the absolute humidity of the air cannot exceed a maximum amount which corresponds to a relative humidity of 100 %, called saturation.

The thermo-hygrometric characteristics given in the chart refer to an atmospheric pressure of 101,3 kPa. Humidity measurements carried out at different pressures require the use of charts intended for these pressures.

EXAMPLE:

Atmospheric pressure: 1 bar = 10^5 Nm^{-2} = 100 kPa.

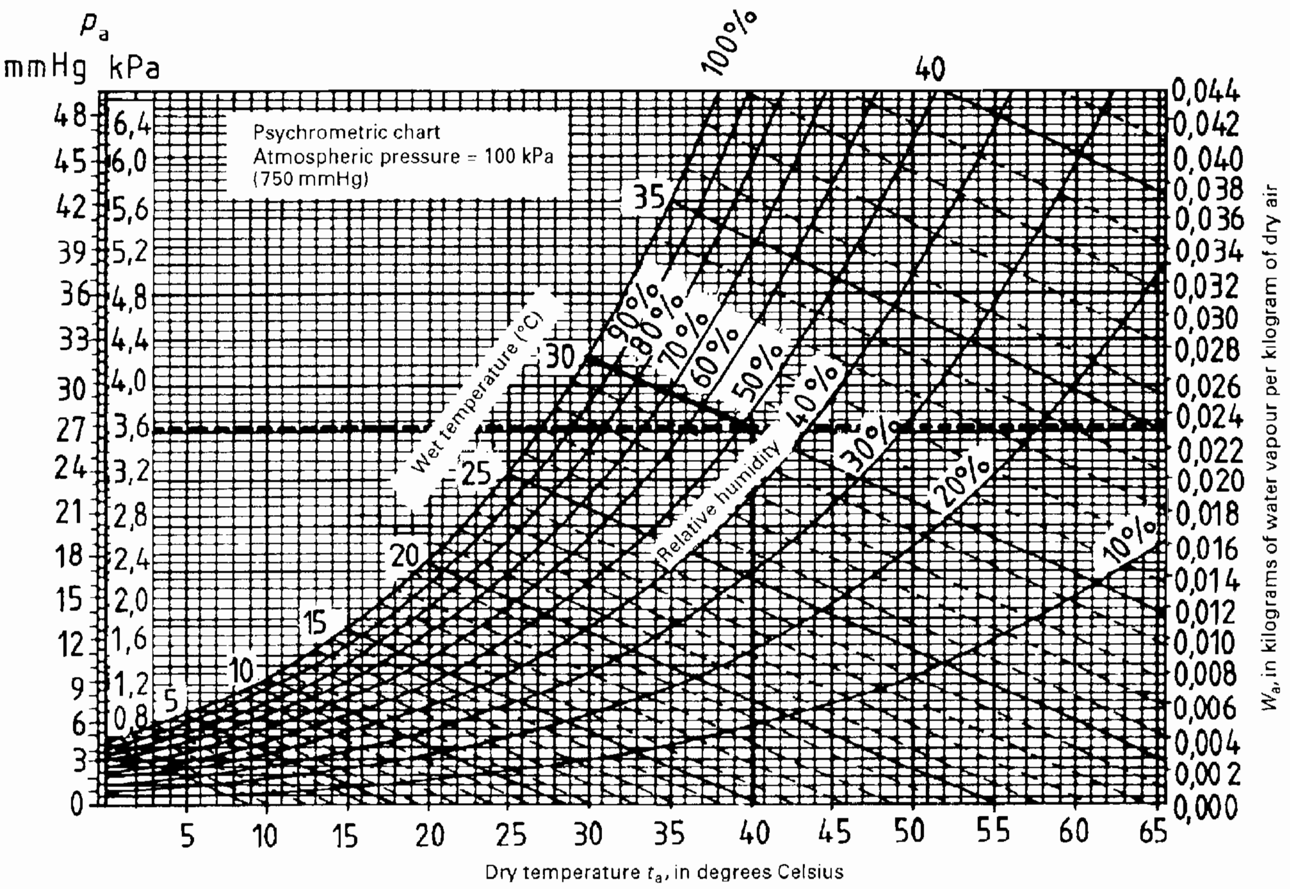


Figure D.1 — Psychrometric chart

Consider a sample of humid air which corresponds to the point of intersection of the heavy lines of the psychometric chart. The thermo-hygrometric characteristics of this sample will be as follows:

- air temperature: t_a = 40 °C
- partial pressure of water vapour: p_a = 3,6 kPa
- saturated vapour pressure p_{as} = 7,4 kPa
- relative humidity: e = 0,49 or RH = 49 %; or $e = \frac{p_a}{p_{as}} = \frac{3,6}{7,4} = 0,49$

D.3 Hygrometer types

D.3.1 Dew-point hygrometers — Principle

Condensation of the water vapour contained in the air on a mirror cooled to the dew-point of the mixture.

D.3.2 Electrical conductivity variation hygrometer

D.3.2.1 Lithium chloride hygrometer (to measure the absolute humidity) — Principle

Determination of the absolute humidity by measuring the variation in temperature due to the variation in electrical conductivity of the sensor (see clause D.5).

D.3.2.2 Capacitance hygrometer (to measure the relative humidity) — Principle

Determination of the relative humidity by measuring the variation in electrical capacity of the sensor.

D.3.3 Absorption hygrometer (hair type) — Principle

Deformation or elongation of certain organic materials caused by the surface tension of liquid water in the pores of these porous materials. Determination of the relative humidity.

This type of hygrometer should be calibrated frequently.

D.3.4 Psychrometer — Principle

Cooling of a wet thermometer in a current of air by evaporation (see clause D.4).

The most common humidity conversion equations are summarized in table D.1.

D.4 Measurement of the absolute humidity using psychrometry

D.4.1 Description and principle of operation

A psychrometer consists of two thermometers and a device to ensure ventilation of the thermometers at a minimum air velocity (see figure D.2). By thermometer is meant any temperature sensor such as a mercury thermometer, thermocouple, resistance probe, etc.

The first thermometer is an ordinary thermometer indicating the air temperature t_a. This will be referred to as the "dry" temperature of the air as opposed to the "wet" temperature indicated by the second thermometer.

The latter consists of a thermometer surrounded by a wet wick generally made from close-meshed cotton. The end of the wick lies in a container of water. The water is raised by capillary attraction from the container to the thermometer and then evaporates at a rate dependent upon the humidity of the air. This results in a greater cooling of the thermometer the drier the air (this cooling is limited by the heat transfer due to air convection). The temperature indicated by the thermometer surrounded by the wet wick is referred to as the wet temperature (psychometric) t_w.

The observed dry temperature and wet temperature are used in the determination of the absolute humidity of the air.

Table D.1 — Humidity conversion equations

Parameter	Equation	No.	Unit
p_{as}	$= 0{,}611 \times \exp\left(\dfrac{17{,}27\, t_a}{t_a + 237{,}3}\right)$	* (1)	kPa
	$= 100 \dfrac{p_a}{\mathrm{RH}}$	(2)	kPa
p_a	$= p_{as\,w} - 6{,}27 \times 10^{-4} \times (t_a - t_w)$	* (3)	kPa
	$= 0{,}01 \times p_{as} \times \mathrm{RH}$	(4)	kPa
	$= \dfrac{p}{\dfrac{0{,}6220}{W_a} + 1}$	(5)	kPa
t_d	$= 38 \times \lg\left(\dfrac{1000\, W_a}{4{,}8}\right)$	* (6)	°C
	$= 237{,}3 \dfrac{\ln\left(\dfrac{p_a}{0{,}611}\right)}{17{,}27 - \ln\left(\dfrac{p_a}{0{,}611}\right)}$	* (7)	°C
W_a**	$= 4{,}8 \times 10^{-3} \times 10^{\frac{t_d}{38}}$	* (8)	kg/kg
	$= 0{,}6220 \dfrac{p_a}{p - p_a}$	(9)	kg/kg
RH	$= 100 \times \dfrac{p_a}{p_{as}}$	(10)	%

* Approximated equations p = atmospheric pressure

** The ratio of two masses, W_a, is a dimensionless value. However, in order to determine the correct order of the values, it is often followed by the words "kg of water/kg of dry air" to signify that the sample contains W_a kg of water per kg of dry air.

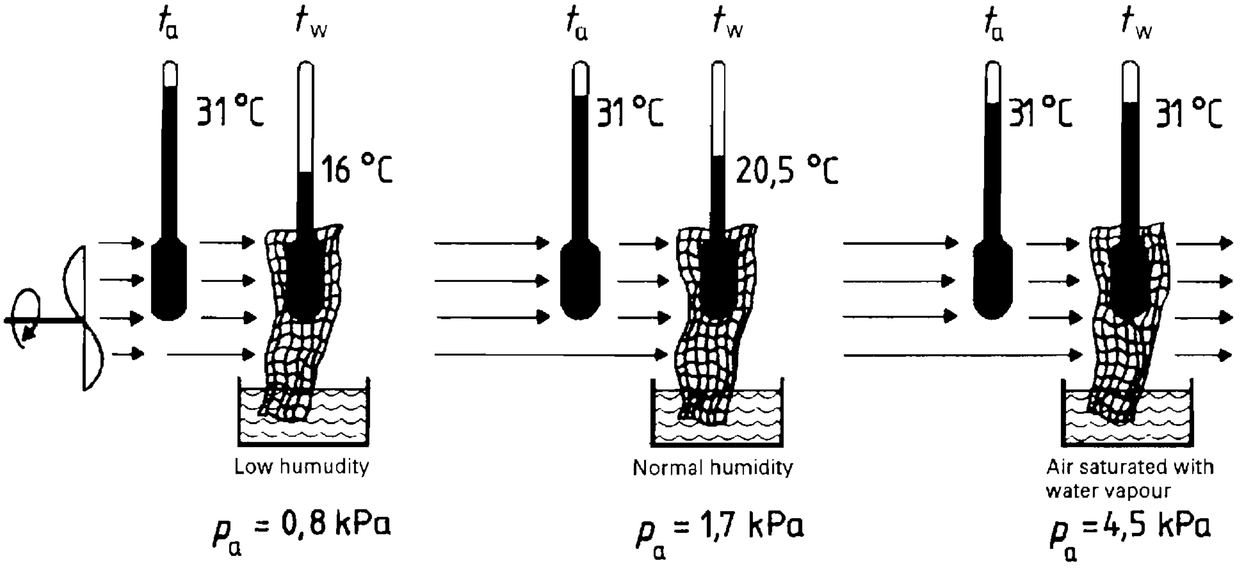


Figure D.2 — Principle of operation of a psychrometer

D.4.2 Direct determination of the absolute humidity of the air using a psychrometric chart

The absolute humidity of the air, expressed in terms of partial pressure of water vapour, is linked to the wet thermodynamic temperature by a relationship of the following form:

$$p_a = p_{as,w} - Ap\left(t_a - t_w\right) \tag{27}$$

where

p_a is the partial pressure of the water vapour in the air, in the same units as $p_{as,w}$ and p;

t_a is the air temperature, in degrees Celsius;

t_w is the psychrometric wet temperature, in degrees Celsius;

p is the total atmospheric pressure, in kilopascals;

$p_{as,w}$ is the saturated vapour pressure determined at the wet temperature t_w, in kilopascals;

A is the psychrometric coefficient, in degrees Celsius to the power of minus one.

It is recommended to use $A = 6{,}67 \times 10^{-4}\ °C^{-1}$.

This expression can also be written:

$$p_a = -Apt_a + Apt_w + p_{as,w} \tag{28}$$

or

$$p_a = -Apt_a + f(t_w) \tag{29}$$

Thus in a psychrometric chart, presuming the psychrometric coefficient A to be more or less constant, the equal wet temperature curves are parallel straight lines of slope ($-Ap$).

The intersection of the wet temperature t_w straight line with the vertical line drawn to the air temperature t_a gives a point representative of the humid air considered.

p_a is then read directly on the y-axis.

EXAMPLE:

Taking the previous example

$p = 1$ bar $= 10^5$ Pa;

$t_a = 40$ °C;

$t_w = 30$ °C;

the use of the psychrometric chart leads to the following value:

$p_a \approx 3{,}6$ kPa

D.4.3 Precautions to be taken

D.4.3.1 General

The simplicity of the principle and the use of a psychrometer should not cause one to forget the precautions to be taken during its use which, if not followed, can lead to very considerable measuring errors.

D.4.3.2 The wet thermometer should be ventilated at a sufficient velocity generally at least 4 m/s to 5 m/s.

The air may be renewed either by rapidly moving the wet thermometer manually in the environment (whirling psychrometer), or by sucking air with a microturbine or a small ventilator driven by an electrical or mechanical motor. As a general rule, small sized temperature sensors require lower minimum air velocities.

The psychometric wet temperature should not be confused with the natural wet temperature which is measured using a naturally ventilated sensor with a wet wick.

D.4.3.3 The dry and wet thermometers should be protected from radiation by a screen.

When the mean radiant temperature is higher or lower than the air temperature, the air temperature sensor should be protected by using one or more screens.

As the wet temperature may also be different from the mean radiant temperature, it is important that the wet thermometer be protected.

D.4.3.4 The wick around the wet thermometer should extend beyond the sensitive part of the sensor in order to eliminate errors due to thermal conduction in the thermometer.

If this precaution is not taken, the sensitive part of the sensor cooled by evaporation is at the wet temperature, whereas the non-sensitive part, not being cooled, is at the air temperature. This results in a transfer of heat by conduction between the two parts and consequently in an error in the measurement of the wet temperature.

The wet wick should therefore extend sufficiently far along the thermometer to cool the thermometer beyond the sensitive part.

Table D.2 indicates the wick lengths which have been recommended for different types of thermometer.

Table D.2 — Wet Thermometer — Length of thermometer covered by the wet wick

Dimensions in millimetres

Type	Diameter	Wick length
Mercury thermometer	All	20 above the bulb
Thermocouple	1,2	60
	0,45	30
	0,12	10

D.4.3.5 The water wetting the wick should be distilled water, since the water vapour pressure in the case of saline solutions is less than that in the case of pure water.

D.4.3.6 The wick of the wet thermometer should allow the water to circulate easily by capillary attraction, particularly when the absolute humidity of the air is low.

In these latter conditions, the increased evaporation of water at the thermometer requires the water to rise quickly from its reservoir. Replace the wick if soiled.

D.4.3.7 It is necessary to measure the barometric pressure when this deviates perceptibly (2 %) from 101,3 kPa.

As the phenomenon of evaporation depends on the atmospheric pressure (variable in particular as a function of the altitude), it is necessary to use charts corresponding to the barometric pressure measured.

D.5 Measurement of humidity using a lithium chloride hygrometer

D.5.1 Description and principle of operation

The measurement of humidity using lithium chloride (LiCl) hygrometers is based on two phenomena.

a) The saturation pressure above saturated hygroscopic saline solutions and in particular lithium chloride solutions is less than that above water at the same temperature (see figure D.3).

b) The electrical conductivity of a lithium chloride solution is much higher than that of the solid salt.

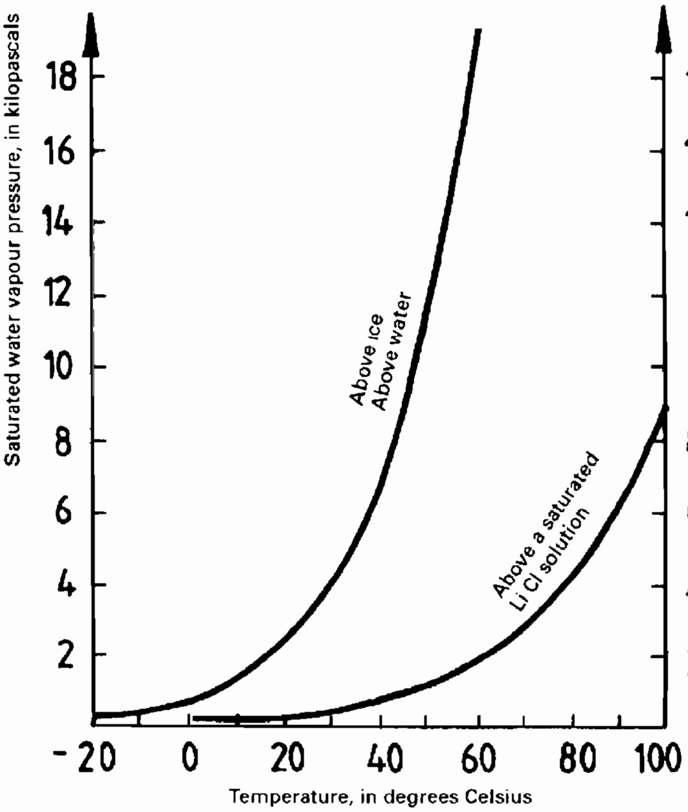


Figure D.3 — Saturated water vapour pressure above water and above a standard lithium chloride solution, as a function of the temperature

As a result of the first phenomenon, the dew-point above a saturated lithium chloride solution, corresponding to the steam pressure, is located within a wide range above the ambient temperature, and can therefore be achieved by heating the solution.

As a result of the second phenomenon, the heating operation and the adjustment of the heating power can be achieved by simple means.

Figure D.4 shows the absolute humidity measurement range for lithium chloride hygrometers.

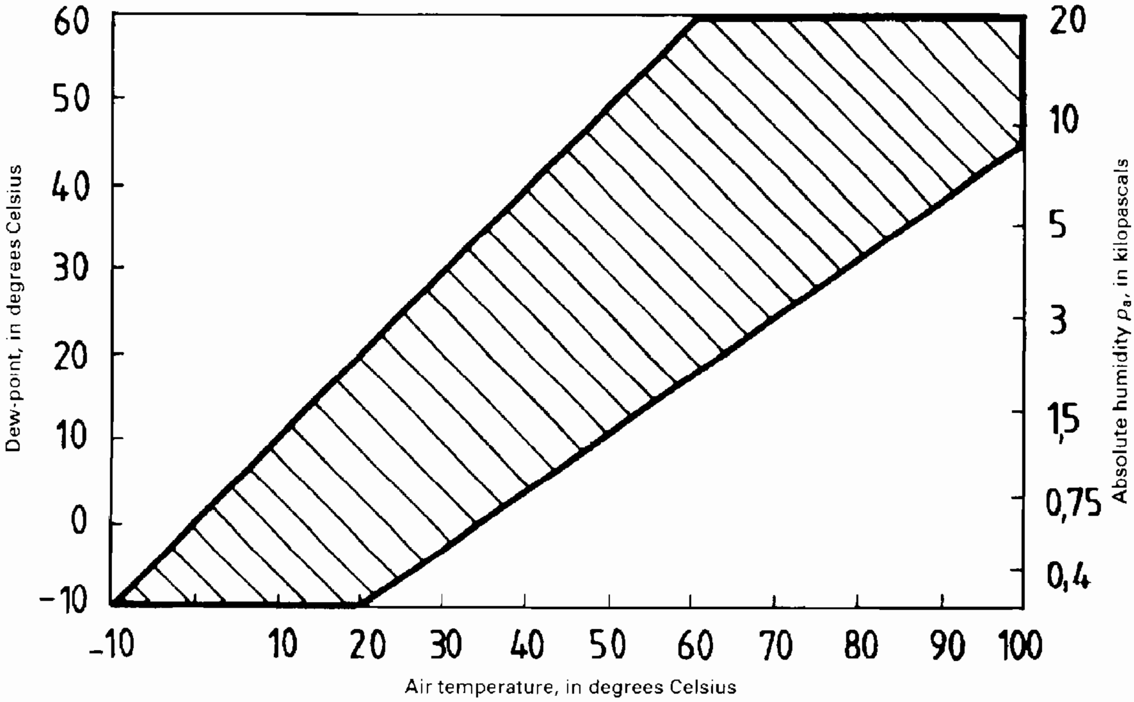
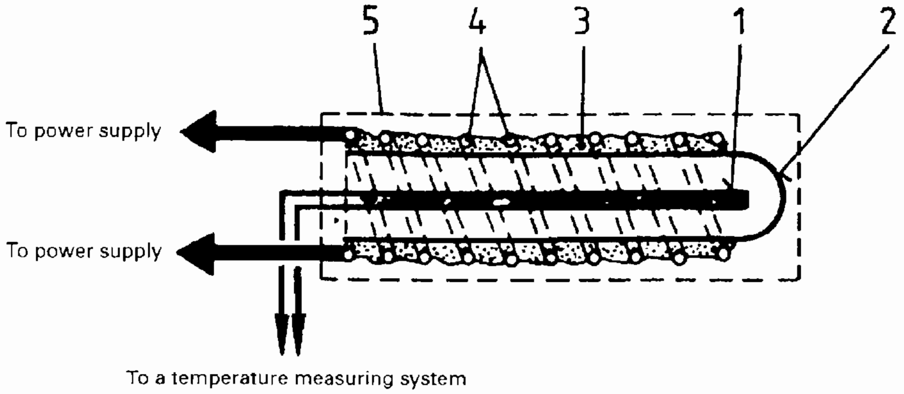


Figure D.4 — Range of measurement of absolute humidity for lithium chloride hygrometers

The active part of a sensor (see figure D.5) generally consists of a thin insulating tube covered with muslin glass, impregnated with lithium chloride solution. Two precious metal electrodes are arranged side by side in a spiral on the muslin cover and the whole is protected by a perforated protective sheath. The two electrodes are connected to a low voltage alternating power supply. The resulting current causes the lithium chloride solution to heat up and the previously absorbed water to evaporate. Once the water has evaporated, the solution crystallizes. The electrical conductivity, and the intensity between the two electrodes, is considerably reduced and the temperature falls once more.



Key

1 Resistance thermometer

2 Glass tube

3 Lithium chloride impregnated glass wool

4 Electrodes

5 Perforated protective sheath

Figure D.5 — Diagram of the principle of a lithium chloride humidity detector

The lithium chloride solution can then absorb the water vapour contained in the air which has the effect of increasing its electrical conductivity. The current increases and causes the water to evaporate once more.

A balance is quickly established between the water vapour content of the air, the heating power and the temperature of the detector. This equilibrium temperature, which is measured using a thermometer, depends solely on the water vapour pressure of the air. It gives a direct measurement of the dew-point or the absolute humidity; this being just one of the advantages of lithium chloride hygrometers.

D.5.2 Precautions to be taken during use

D.5.2.1 The velocity of the air onto the detector should not exceed a certain value according to the type of screen used to protect the sensor. Beyond this value, the readings of the hygrometer are too low. In order to obtain accurate readings, it is necessary to conform to the manufacturer's instructions.

D.5.2.2 The electrical supply should be constant once the hygrometer has been brought into use. If the detector is disconnected, the lithium chloride absorbs water vapour from the air which may cause stress in the electrodes when starting up again.

D.5.2.3 Deposits of conductive impurities (dust etc.) on the sensitive part of the sensor can distort the readings of the appliance.

D.5.2.4 The lithium chloride solution should be renewed periodically having ensured that the detector is first cleaned.

D.5.2.5 The reading should only be taken following thermal stabilization of the sensor. The response time of a lithium chloride probe is in the order of 6 min.

Annex E
(informative)

Measurement of air velocity

E.1 Introduction

The air velocity should be taken into account when determining heat transfer by convection and evaporation at the position of a person. It is generally difficult to perform accurate velocity measurements in spaces, because typically airflow is turbulent, i.e. the air velocity fluctuates randomly and most often changes its direction as well. In the case of thermal environments, the speed of the air, i.e. the magnitude of the velocity vector of the flow at the measuring point, is considered. Although studies show that a person is differently sensitive to airflow from front, back, side, above and below, the use of the air speed is justified because the air velocity changes its direction in a relatively small spatial angle.

Three characteristics of instruments for measuring the air velocity should be considered:

- the sensitivity to the direction of airflow;
- the sensitivity to the velocity fluctuations;
- the possibility of obtaining a mean velocity and a standard deviation of the velocity over a certain measuring period.

E.2 Accuracy of the velocity measurements

The following important factors have to be considered for accurate velocity measurements:

a) the calibration of the instrument;

b) the response time of the sensor and the instrument;

c) the measuring period.

The accurate measurement of the mean velocity depends on the calibration of the instrument. The accuracy of measuring the standard deviations, i.e. the turbulence intensity, depends on the response time. An instrument with a long response time will not measure fast velocity fluctuations. Measurements in an airflow with a high turbulence intensity and low frequency of the velocity fluctuations will require a longer measuring period than measurements in an airflow with a low turbulence intensity and a high frequency of the velocity fluctuations.

E.3 Types of anemometers

As a general rule the air velocity, v_a, can be determined

- either by the use of an omnidirectional probe which is sensitive to the magnitude of the velocity whatever its direction (hot-sphere sensor);
- or by the use of three directional sensors which allow the components of the air velocity to be measured along three perpendicular axis (cosine law). If these three components are termed v_x, v_y and v_z the speed of the air, v_a, can be expressed as follows:

$$v_a = \sqrt{v_x^2 + v_y^2 + v_z^2}$$

In practice it is very difficult to measure accurately in one direction.

In those cases where the air flow is unidirectional, it is possible to use a probe which is sensitive to this one air direction (blade anemometer, hot-wire anemometer, etc.)

The main direction of the air flow can be discovered by carrying out smoke tests.

Examples of anemometers used for measurements in spaces are:

a) Vane and cup anemometers (directional appliance).

b) Hot-wire anemometer (directional appliance).

c) Pulsed wire anemometer (insensitive to flow direction).

d) Hot-sphere and thermistor anemometer (insensitive to flow direction).

e) Ultrasonic anemometer (insensitive to flow direction).

f) Laser-doppler anemometer (insensitive to flow direction).

E.4 Anemometer with a hot-sphere type sensor

E.4.1 General

The anemometer with a hot-sphere type sensor is most used in practice for velocity measurements in spaces.

E.4.2 Description and principle of operation

Like all heated sensors for measuring air velocity, the anemometer with a hot-sphere type sensor is based on the measurement of the transfer of heat between a hot solid and the ambient air, which depends on the aerodynamic characteristics of the air. Calibration of the instrument beforehand allows this transfer of heat to be converted to air velocity.

The anemometer consists of a sphere heated electrically to a temperature higher than the air temperature. The hot element loses heat to its surroundings mainly by convection.

The thermal balance of the element is expressed as follows:

$$C_p = h_c \, (t_c - t_a)$$

where

C_p is the heating power received by the element;

h_c is the coefficient of exchange by convection between the element and the air, as a function of the air speed;

t_c is the temperature of the element;

t_a is the air temperature.

The heating characteristics of the element, the temperature of the element and that of the air allows the air velocity to be determined through the use of the coefficient of heat transfer by convection.

The anemometer should therefore have two temperature sensors, one to measure the temperature of the hot element and another to measure the air temperature. Simplified instruments without an air temperature sensor are able to operate only at the air temperature for which they have been calibrated.

E.4.3 Precautions to be taken during use

The main characteristic of the hot-sphere type sensor is to have reduced sensitivity to the direction of the airflow except for a small solid angle around the support of the sensor (see figure E.1). However, a hot-wire anemometer has a high sensitivity to the direction of air flow (see figure E.2).

Design of the sensor should not affect the airflow. Protection around the sensor against damage may generate additional turbulence in the flow or damp the velocity fluctuations.

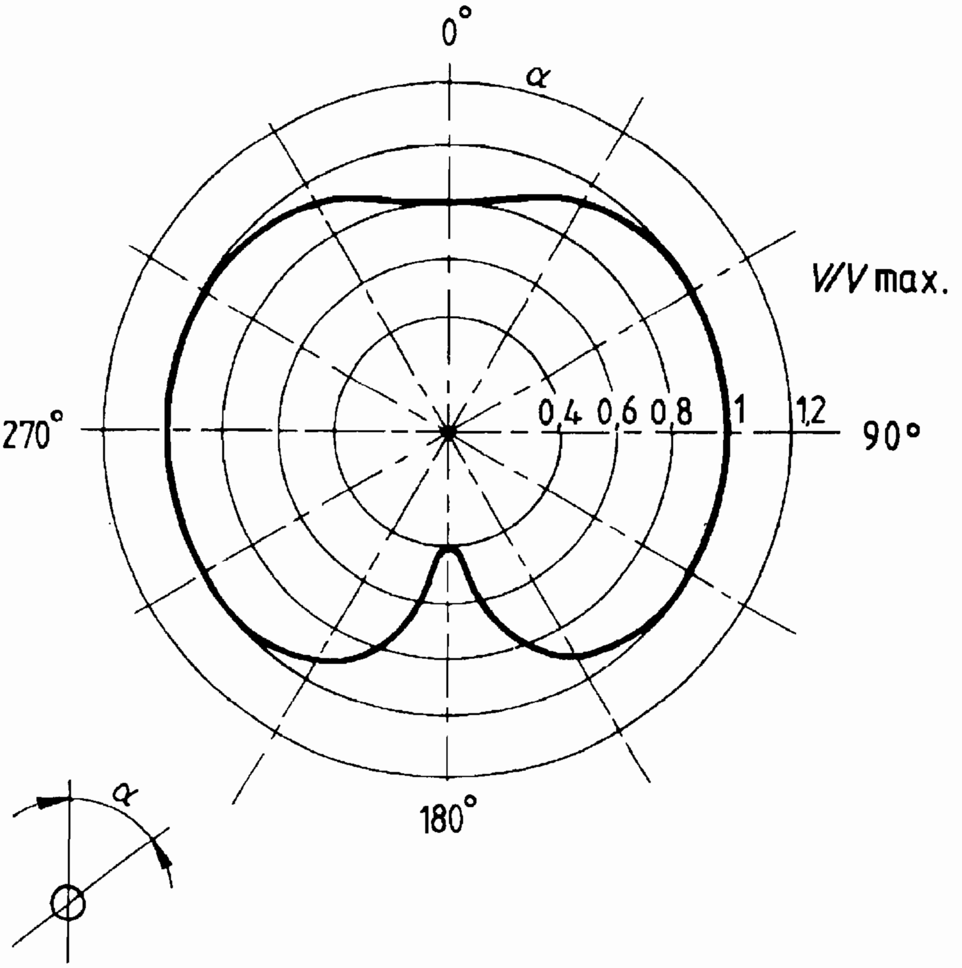


Figure E.1 — Hot-sphere anemometer — Example showing the effect of the direction of movement of the air on the measurement of the air velocity

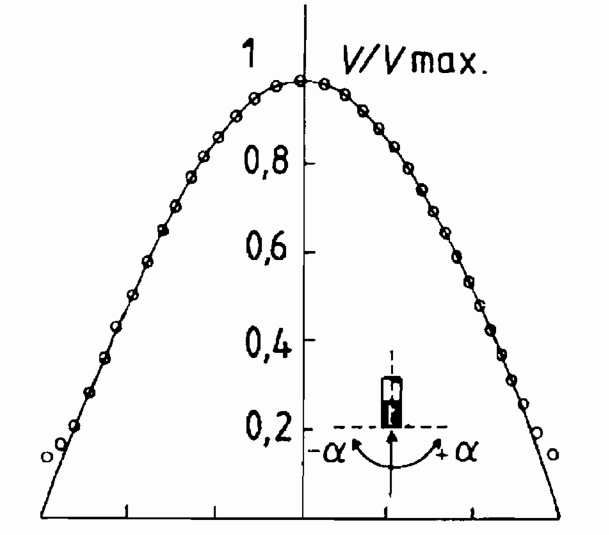


Figure E.2 — Hot-wire anemometer — Example showing the effect of the direction of movement of the air on the measurement of the air velocity

Annex F
(informative)

Measurement of surface temperature

F.1 Introduction

Surface temperature is the temperature of a given surface. This is used to evaluate the radiant heat exchange between the human body by means of the mean radiant and/or the plane radiant temperature. It is also used to evaluate the effect of direct contact between the body and a given surface.

The surface temperature may be measured by a sensor in contact with the surface (contact thermometer) or by an infrared sensor. Using a contact thermometer will change the heat exchange between the surface and the environment. This is especially a problem on surfaces with a low thermal conductivity.

Measurements with infrared sensors are influenced by the emissivity of the surface.

Instruments for measuring surface temperatures are

a) contact thermometers (resistance, thermocouples);

b) infrared sensors.

F.2 Contact thermometers

A contact thermometer consists of a temperature sensor, which can be brought into contact with a surface. It is important that the heat exchange between the sensor and the surface is significantly higher than the heat exchange between the sensor and the environment. This is obtained by increasing the contact through large contact surface pressure, heat conductive paste or other means, and insulating the sensor towards the environment.

The contact between sensor and surface will influence the heat exchange between surface and environment and then the measured surface temperature. On surfaces with low thermal conductivity (especially) this may result in false measurements.

F.3 Infrared radiometers

Infrared radiometers (also called remote temperature sensors) permit non-contact measurement of surface temperature over a wide range. Most are passive systems and require that the observed object be illuminated with infrared radiation. Point and scanning radiometers are available; the latter is able to display temperature variation over an area. In all passive radiometers, radiant energy from the observed object is focused by an optical system onto an infrared detector that sends an output signal, proportional to the incident radiation, to a meter or display unit.

Radiometers are usually classified according to the detector used, either thermal or photon. In thermal detectors, a change in electrical property is caused by the heating effect of the incident radiation. Examples of thermal detectors are the thermocouple, thermophile, and metallic and semiconductor bolometers. In photon detectors, a change in electrical property is caused by the surface absorption of incident photons. Because these detectors do not require an increase in temperature for activation, their response time is much shorter than that of thermal detectors. Scanning radiometers usually use photon detectors.

A radiometer only measures the energy level of the radiation incident on the detector, and this incident radiation includes radiation emitted by the object and radiation reflected from the surface of the object. An accurate measurement of surface temperature, therefore, requires knowledge of the long-wave emissivity of the object and the radiant field surrounding the object. An internal or external reference temperature is required to make absolute surface temperature measurements.

Temperature resolution of radiometers decreases as object temperature decreases. For example, radiometers that detect temperature differences under 0,3 °C on an object at 20 °C may only detect a difference of about 1 °C on an object at − 20 °C.

Annex G
(informative)

Measurement of operative temperature

G.1 Introduction

Operative temperature (t_o) is defined as the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the existing non-uniform environment.

The exact equation for the operative temperature is:

$$t_o = \frac{h_c \cdot t_a + \bar{h}_r \ \bar{t}_r}{h_c + h_r}$$

where

t_a is the air temperature;

$\bar{t}_r$ is the mean radiant temperature;

h_c is the heat-transfer coefficient by convection;

h_r is the heat-transfer coefficient by radiation.

This may also be written as

$$t_o = a \cdot t_a + (1 - a) \cdot \bar{t}_r$$

where

$$a = h_c/(h_c + h_r) = 1/(1 + h_r/h_c)$$

G.2 Direct measurement of the operative temperature

One requirement for a sensor for direct measurement of operative temperature is that the relation between the radiant and convective heat loss coefficient is the same as for a person. Using the equation for the convective heat loss coefficient, h_c, given by ISO 7730 it is possible to estimate the diameter of a sensor which will have the same relation h_c/h_r as for a person. This is shown in figure G.1. The optimal diameter of a sensor depends on the air velocity and is around 0,04 m – 0,1 m. A standard globe of 0,16 m diameter will overestimate the influence of the mean radiant temperature.

The same precautions as listed in B.2.3 for the measurement of mean radiant temperature using a black-globe thermometer is valid when measuring the operative temperature. Shape of the sensor (see B.2.3.5) is important in non-uniform radiant environments and colour of the sensor (see B.2.3.6) is important by exposure to short-wave radiation.

G.3 Calculation of the operative temperature based on air temperature and mean radiant temperature

In most practical cases where the relative velocity is small (< 0,2 m/s) or where the difference between mean radiant and air temperature is small (< 4 °C), the operative temperature can be calculated with sufficient approximation as the mean value of air and mean radiant temperature.

For higher precision and other environments, the following formula may be used:

$$t_o = At_a + (1 - A)\bar{t}_r$$

where the value of A can be found from the values below as a function of the relative air velocity, v_{ar}, in metres per second.

v_{ar}	$< 0,2$	0,2 to 0,6	0,6 to 1,0
A	0,5	0,6	0,7

The operative temperature may also be calculated as:

$$t_o = \frac{t_a \cdot \sqrt{10 \cdot v_a} + \bar{t}_r}{1 + \sqrt{10 \cdot v_a}}$$

where

v_a is the air velocity, in metres per second;

$\bar{t}_r$ is the mean radiant temperature, in degrees Celsius.

Annex H
(informative)

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