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Thermal environments — Instruments and methods for measuring physical quantities

Ambiances thermiques — Appareils et méthodes de mesure des grandeurs physiques

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Foreword

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Thermal environments — Instruments and methods for measuring physical quantities

0 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.

In view of the increasing interest being shown in the problems raised by the exposure of man to thermal environments and the existence of few documents or national standards in this field, it seemed desirable to publish this International Standard without waiting for the complete series to be drafted.

Any measuring appliances which achieve the accuracy indicated in this International Standard, or even better improve 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.

1 Scope and field of application

This International Standard specifies the minimum characteristics of appliances 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 this index. Other International Standards give details of the methods making use of the information obtained in accordance with this document.

This International Standard shall be 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 study of hot, comfortable or cold environments in any place occupied by man.

2 Reference

ISO 7243, *Hot environments — Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature).*

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 (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 at present available.

3.2 Physical quantities characterizing the environment

The determination of overall indices of comfort or thermal stress requires knowledge of physical quantities connected

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with the environment. These quantities can be divided into two categories according to their degree of dependence on the environment.

3.2.1 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 man 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 ($\overline{T}_r$) or in degrees Celsius ($\bar{t}_r$) and radiant temperature asymmetry, expressed in kelvins or in degrees Celsius (Δt_{pr});

c) absolute humidity of the air (p_a), expressed in kilopascals. The absolute humidity can be measured by different means (see annex D). One of these means consists in measuring simultaneously the psychrometric temperature and the air temperature;

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

The connections between these four quantities and the various gains and losses of heat in relation to the organism are shown in table 1. This table 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 radiant temperature asymmetry.

3.2.2 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 directly without having recourse to a rational method for establishing the thermal balance of a man placed in a given thermal environment. The most commonly used derived quantities are the following :

a) natural wet bulb temperature (t_{nw}) which depends on the temperature, velocity and humidity of the air as well as the mean radiant temperature. This quantity must not be confused with the psychrometric wet temperature (t_w) used for calculations of humidity;

b) globe temperature (t_g) which depends on the mean radiant temperature and the air temperature and velocity. This quantity can be used as it stands to define an empirical index of thermal stress or as an intermediary quantity to calculate the mean radiant temperature;

c) wet bulb globe temperature *WBGT* depends on the temperature, the velocity and the humidity of the air as well as the mean radiant temperature. It is determined from the measurement of the natural wet bulb temperature (t_{nw}), the globe temperature (t_g) and, under the thermal effect of the sun, the temperature of the air. The weighting coefficients relating to these quantities are specified in ISO 7243;

d) wet globe temperature (t_{wg}) depends on the same quantities as the natural wet bulb temperature but the weightings are different. This quantity must not be confused with the *WBGT* thermal stress index.

All other things being equal, the sizes of the derived quantities are only meaningful for sensors of specified shape and dimensions.

4 Specifications relating to the measuring instruments

4.1 Measured quantities

4.1.1 Basic quantities

4.1.1.1 The air temperature is the temperature of the air around the human body. (See annex A.)

4.1.1.2 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 globe is a measuring instrument which is frequently used.

It permits an approximate value of the mean radiant temperature to be determined from the observed values of the globe temperature 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 case of a person in the upright position and for a person when seated.

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

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Table 1 — Main independent quantities involved in the analysis of a 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	Useful external work
Internal heat production, $M - W$							x	x
Heat transfer by radiation, R		x			x			
Heat transfer by convection, C*	x		x		x			
Heat losses through evaporation :								
— evaporation from the skin, E			x	x	x	x		
— evaporation by respiration, E_{res}				x			x	

* Heat transfer by convection is also influenced by body movements. The resultant air velocity at skin level is called relative air velocity (v_{ar}).

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

4.1.1.3 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 below).

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.

The plane radiant temperature (T_{pr} or t_{pr}) 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 plane radiant temperature is a quantity which describes the radiation in one direction.

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).

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.

4.1.1.4 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.

With regard to exchanges by evaporation between man and his environment, it is the absolute humidity of the air which should 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 etc.) (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 dry temperature of the air (t_a) and the psychrometric 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.

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

4.1.1.5 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 effective velocity of the air, i.e. the magnitude of the velocity vector of the flow at the measuring point considered (see annex E).

As a general rule, the air velocity can be determined

- either by the use of an omnidirectional probe which is directly sensitive to the magnitude of the velocity whatever its direction (hot bulb);

- or by the use of three directional sensors which allow the components of the air velocity to be measured along three perpendicular axes. If these three components are termed v_x, v_y and v_z, the effective velocity of the air can be expressed as follows :

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

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 flow can be discovered by carrying out smoke tests.

As air velocity usually fluctuates considerably it is recommended that these fluctuations be recorded in cold and comfortable environments. It is suggested that these fluctuations be expressed as the mean value and standard deviation. In a hot environment, it is sufficient to measure the mean value.

4.1.2 Derived quantity

4.1.2.1 The natural wet bulb temperature is the value indicated by a temperature sensor covered with a naturally ventilated wet wick, i.e. placed in the environment under consideration without any forced ventilation.

In the absence of additional information, the temperature sensor shall comply with the following characteristics :

a) Shape of the sensitive part of the sensor : cylindrical.

b) External diameter of the sensitive part of the sensor : 6 ± 1 mm

c) Minimum length of the sensor support : 3 cm (covered with the wet wick).

4.1.2.2 The globe temperature is the internal temperature of a naturally ventilated globe having the following characteristics :

a) Spectral emissivity : $\varepsilon = 0{,}95 \pm 0{,}05$

b) Diameter : 0,15 m

4.1.2.3 The wet bulb globe temperature *WBGT* is calculated from the following equations :

- In an internal environment (or external environment without the thermal effects of the sun)

$$WBGT = 0{,}7\ t_{nw} + 0{,}3\ t_g$$

- In an external environment (with the thermal effects of the sun)

$$WBGT = 0{,}7\ t_{nw} + 0{,}2\ t_g + 0{,}1\ t_a$$

The characteristics of sensors for measuring t_{nw} and t_g are as given above.

4.1.2.4 The wet globe temperature is the internal temperature of a sphere covered with a naturally ventilated, wet black fabric.

In the absence of any additional information, the diameter of the globe is taken to be 6 cm.

4.2 Characteristics of measuring instruments

4.2.1 Characteristics of instruments for measuring the basic and derived quantities

The measuring ranges, measuring accuracy and response times of the sensors for each of the basic and derived 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 an 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 62 % 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 τ. A 90 % response time is achieved after a period equal to 3,1 times the time constant.

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 sheath) 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.

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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 brackets in the table.

4.2.2 Characteristics of integrating types of measuring appliances

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

5 Specifications relating to measuring methods

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

5.1 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 indicated below does not exceed about ± 5 %. 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 points 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 4 shows the positions 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 positions to be used for the derived quantities shall preferably be chosen in conformity with the information supplied in table 4. 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 4 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 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).

5.2 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 to heat of the person 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 about ± 5 %.

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).

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Table 2 — Characteristics of measuring instruments

	Quantity	Symbol	Class C (comfort) Measuring range	Class C Accuracy	Class C Response time (90 %)	Class S (thermal stress) Measuring range	Class S Accuracy	Class S Response time	Comments
Basic quantities	Air temperature	t_a	10 to 30 °C	Required: ± 0,5 °C Desirable: ± 0,2 °C These levels shall be guaranteed at least for a deviation $\lvert \bar{t}_r - t_a \rvert$ equal to 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring appliance	− 40 to +120 °C	Required : − 40 to 0 °C: ± (0,5 + 0,01 $\lvert t_a \rvert$) °C > 0 to 50 °C: ± 0,5 °C > 50 to 120 °C: ± [0,5 + 0,04 (t_a − 50)] °C Desirable: $\frac{\text{required accuracy}}{2}$ These levels shall be guaranteed at least for a deviation $\lvert \bar{t}_r - t_a \rvert$ equal to 20 °C.	The shortest possible. Value to be specified as characteristic of the measuring appliance	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.
Basic quantities — Radiant temperature	Mean radiant temperature	$\bar{t}_r$	10 to 40 °C	Required : ± 2 °C Desirable : ± 0,2 °C These levels are difficult, or even impossible to achieve in certain cases with the equipment normally available. When they cannot be achieved, indicate the actual measuring precision.	The shortest possible. Value to be specified as characteristic of the measuring appliance	− 40 °C to + 150 °C	Required : − 40 to 0 °C: ± (5 + 0,02 $\lvert \bar{t}_r \rvert$) °C > 0 to 50 °C: ± 5 °C > 50 to 150 °C: ± [5 + 0,08 ($\bar{t}_r$ − 50)] °C Desirable : − 40 to 0 °C: ± (0,5 + 0,01 $\lvert \bar{t}_r \rvert$) °C > 0 to 50 °C: ± 0,5 °C > 50 to 150 °C: ± [0,5 + 0,04 ($\bar{t}_r$ − 50)] °C	The shortest possible. Value to be specified as characteristic of the measuring appliance	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.
Basic quantities — Radiant temperature	Radiant temperature asymmetry	Δt_{pr}	0 to 20 K	Required : ± 1 K Desirable : ± 0,5 K	The shortest possible. Value to be specified as characteristic of the measuring appliance	0 to 200 K	Required : 0 to 20 K : ± 2 K > 20 to 200 K : ± 0,1 Δt_{pr} Desirable : 0 to 20 K : ± 1 K > 20 to 200 K : ± 0,05 Δt_{pr}	The shortest possible. Value to be specified as characteristic of the measuring appliance	
Basic quantities	Air velocity	v_a	0,05 to 1 m/s	Required : ± $\lvert 0{,}05 + 0{,}05\, v_a \rvert$ m/s Desirable : ± $\lvert 0{,}02 + 0{,}07\, v_a \rvert$ m/s These levels shall be guaranteed whatever the direction of flow within a solid angle $\omega = 3\pi$ sr	Required : 1 s Desirable : 0,5 s	0,2 to 10 m/s	Required : ± $\lvert 0{,}1 + 0{,}05\, v_a \rvert$ m/s Desirable : ± $\lvert 0{,}05 + 0{,}05\, v_a \rvert$ m/s These levels shall be guaranteed whatever the direction of flow within a solid angle $\omega = 3\pi$ sr	The shortest possible. Value to be specified as characteristic of the measuring appliance.	Except in the case of a unidirectional air current, the air velocity sensor shall measure the effective velocity whatever the direction of the air. An indication of the mean value for a period of 3 min is also desirable. The degree of turbulence is an important parameter in the study of comfort problems. It is recommended that it be expressed as standard deviation of the velocity. In a cold environment it is recommended that class C instruments be used whatever the type analysis carried out (comfort or extreme thermal stress).

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

	Quantity	Symbol	Class C (comfort)			Class S (thermal stress)			Comments
			Measuring range	Accuracy	Response time (90 %)	Measuring range	Accuracy	Response time	
Basic quantities	Absolute humidity expressed as partial pressure of water vapour	p_a	0,5 to 2,5 kPa	± 0,15 kPa This level shall be guaranteed even for air and wall temperatures equal to or greater than 30 °C and for a difference $\lvert \bar{t}_r - t_a \rvert$ of at least 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring appliance	0,5 to 6,0 kPa	± 0,15 kPa This level shall be guaranteed even for air and wall temperatures equal to or greater than 30 °C and for a difference $\lvert \bar{t}_r - t_a \rvert$ of at least 10 °C.	The shortest possible. Value to be specified as characteristic of the measuring appliance	
Derived quantities	Natural wet bulb temperature	t_{nw}	Use not recommended			5 to 40 °C	± 0,5 °C	Value to be specified as characteristic of the measuring appliance.	Characteristics of the sensor prescribed
	Globe temperature	t_g	Use not recommended as comfort index			20 to 120 °C	20 to 50 °C: ± 0,5 °C > 50 to 120 °C: ± 1 °C	idem	Characteristics of the sensor prescribed. The globe temperature may also be used in the cold, moderate and hot temperature zone for estimating the mean radiant temperature.
	Wet globe temperature	t_{wg}	Use not recommended			0 to 80 °C	± 0,5 °C	idem	The measuring accuracy for the sphere temperature for determining $\bar{t}_r$ is not necessarily the same as that for measuring the globe temperature as a derived value. Characteristics of the sensor prescribed.

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

Measurement of the response time of sensors for \ Quantities of the standard environment	t_a	$\bar{t}_r$	p_a	v_a
Air temperature		$\approx t_a$	Any	< 0,25 m/s
Mean radiant temperature	$\approx \bar{t}_r$		Any	< 0,25 m/s
Absolute humidity	≈ 20 °C	$\approx t_a$		To be specified according to the measuring method
Air velocity	≈ 20 °C	$\approx t_a$	Any	

Table 4 — Measuring positions for the physical quantities of an environment

Positions of the sensors	Weighting coefficients for measurements for calculating 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

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Annex A

Measurement of air temperature

(This annex does not form part of this International Standard.)

A.0 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.1 Principle for measuring a temperature

A temperature is registered by measuring physical quantities which are continuous functions : lengths of solids, volumes of liquids, electrical resistance, electromotive force etc.

But 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.2 Precautions to be taken when using a temperature probe

A.2.1 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 an intermediate temperature between the air temperature and the mean radiant temperature.

Various means of reducing the effect of radiation on the probe are available as follows :

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 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 inmost 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).

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

A.2.2 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;

— 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.

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A.3 Types of temperature sensor

a) Expansion thermometers :

1) liquid expansion thermometer (mercury etc.);

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).

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Annex B

Measurement of the mean radiant temperature

(This annex does not form part of this International Standard.)

B.0 Introduction

The radiation received by the person in an enclosure can be determined directly from given dimensions, the thermal characteristics (temperature, coefficient of emission) and the position in relation to the person of the heat sources located in a room. 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. The black globe thermometer, compared diagrammatically with a physical model of a man, can also, however, subject to certain approximations, be used as a thermal stress index.

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B.1 Measurement of the mean radiant temperature using the black globe

B.1.1 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 15 cm, 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.1.2 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

$$q_r + q_c = 0 \qquad \ldots (1)$$

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 :

$$q_r = h_{rg} (\bar{T}_r^4 - T_g^4) \qquad \ldots (2)$$

where

$h_{rg} \simeq \sigma \varepsilon$ is the coefficient of radiation between the enclosure and the globe, in watts per square metre kelvin to the fourth power;

ε being the emissivity of the black globe (without dimension);

$\sigma = 5{,}67 \times 10^{-8}$ being the Stefan-Boltzmann constant, in watts per square metre kelvin to the fourth power;

$\bar{T}_r$ 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 :

$$q_c = h_{cg} (T_a - T_g) \qquad \ldots (3)$$

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 :

$$h_{rg} (\bar{T}_r^4 - T_g^4) + h_{cg} (T_a - T_g) = 0 \qquad \ldots (4)$$

The mean radiant temperature is given by

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

By natural convection, one obtains :

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

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

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

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By forced convection, one obtains :

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

or for the standard globe

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

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.

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

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

— in forced convection

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

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

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

$$\bar{t}_r = [(55 + 273)^4 + 2{,}5 \times 10^8 \times v_a^{0{,}6} (55 - 30)]^{1/4} - 273$$

$$\bar{t}_r = 74{,}7 \text{ °C}$$

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

$D = 0{,}1$ m

$\varepsilon = 0{,}95$

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

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

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

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

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B.1.3 Precautions to be taken when using a black globe thermometer

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 following precautions should be considered :

B.1.3.1 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 :

$\bar{t}_{r_1} = 25$ °C

$\bar{t}_{r_2} = 50$ °C

$\bar{t}_{r_3} = 40$ °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 :

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

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.1.3.2 The response time for a black globe thermometer is about 20 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.1.3.3 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.1.3.4 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 person.

An ellipsoid with projected area factors as shown in table 5 may be considered a closer approximation of the shape of the human body. Table 5 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.

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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.

Table 5 — 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.1.3.5 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 coefficient of emission 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.

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B.2 Other measuring methods

B.2.1 Two sphere radiometer

In this method two spheres with different emission coefficients (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, there is a difference in the heat supply to the two spheres and this is a measure for the radiation.

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

The mean radiant temperature is calculated from the equation :

$$\overline{T}_r^4 = T_s^4 + \frac{P_p - P_b}{\sigma\,(\varepsilon_b - \varepsilon_p)} \qquad \ldots (10)$$

where

$\overline{T}_r$ 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 emission coefficient of the polished sensor;

ε_b is the emission coefficient of the black sensor;

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

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

B.2.2 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) :

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

where

$\bar{T}_r$ 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 emittance of the sensor;

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

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B.3 Method for calculation of mean radiant temperature

B.3.1 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 emittance (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 :

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

where

$\bar{T}_r$ 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 1 to 4 in the case of rectangular surfaces but in general the determination of angle factors is more involved; the angle factor depending on the position of the person.

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

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

That is 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_{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.3.2 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 5 for the six directions: up (1), down (2), left (3), right (4), front (5), back (6).

For a standing person the mean radiant temperature may be estimated as

$$\bar{t}_r = \frac{0{,}08\,(t_{pr1} + t_{pr2}) + 0{,}28\,(t_{pr3} + t_{pr4}) + 0{,}35\,(t_{pr5} + t_{pr6})}{2\,(0{,}08 + 0{,}28 + 0{,}35)}$$

where t_{pr1} to t_{pr6} are the plane radiant temperatures in the six directions.

The mean radiant temperature for a seated person may be estimated in a similar manner.

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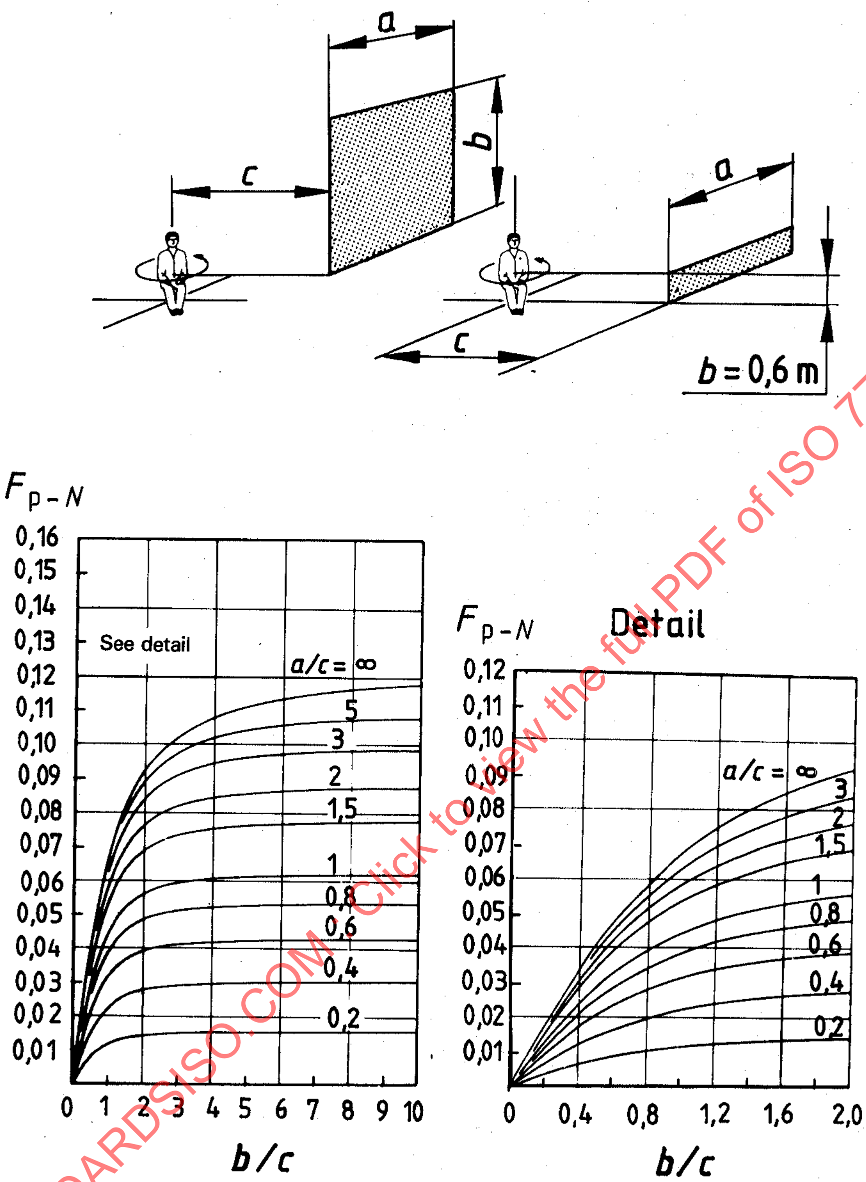

Figure 1 — Mean value of angle factor between a seated person and a vertical rectangle (above or below his centre) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

Example :

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

F_{p-a} = 0,029.

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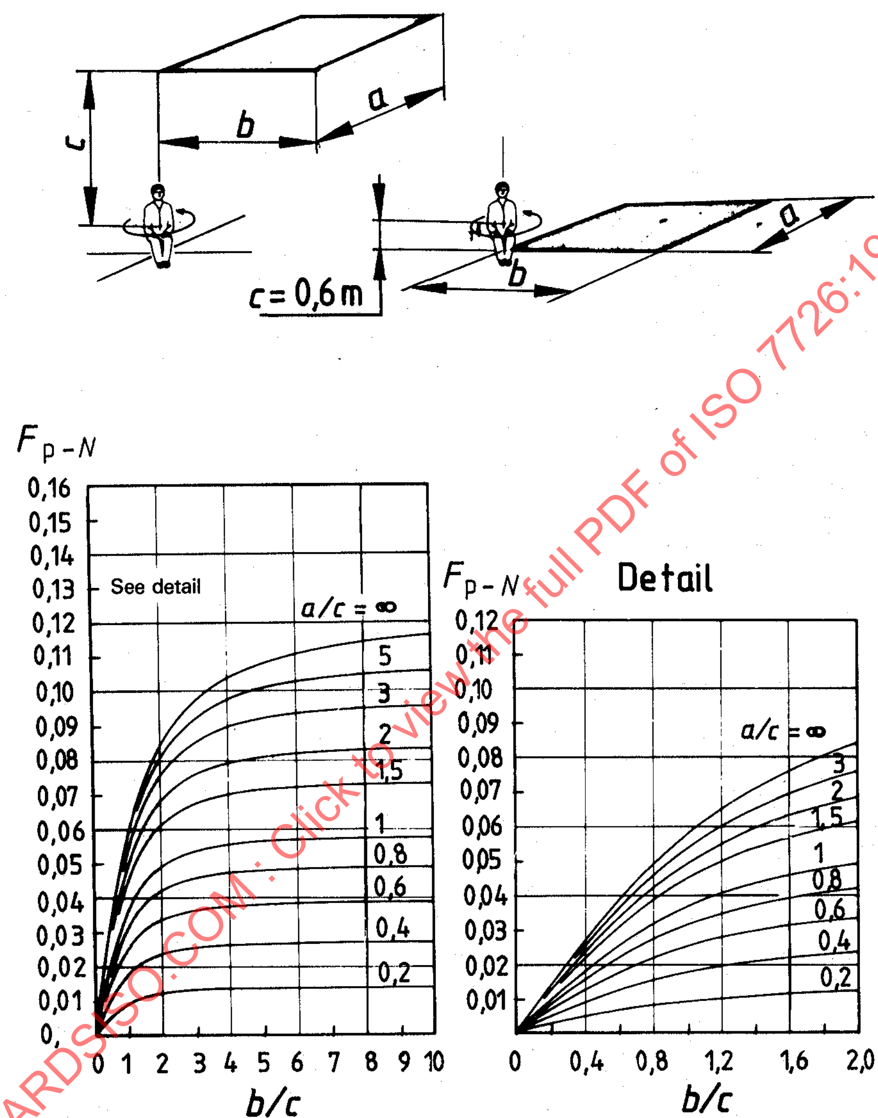

Figure 2 — Mean value of angle factor between a seated person and a horizontal rectangle (on the ceiling or on the floor) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

Example :

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

F_{p-a} = 0,067.

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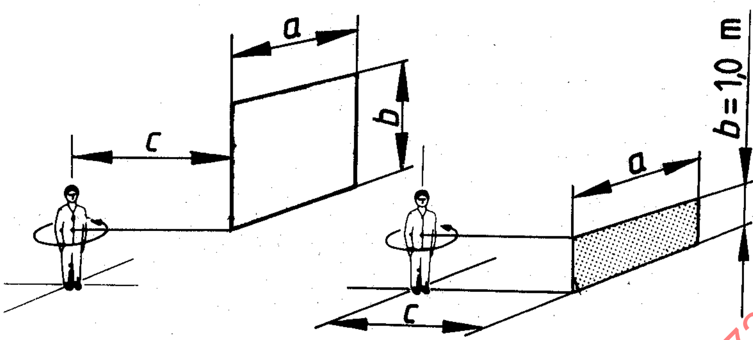

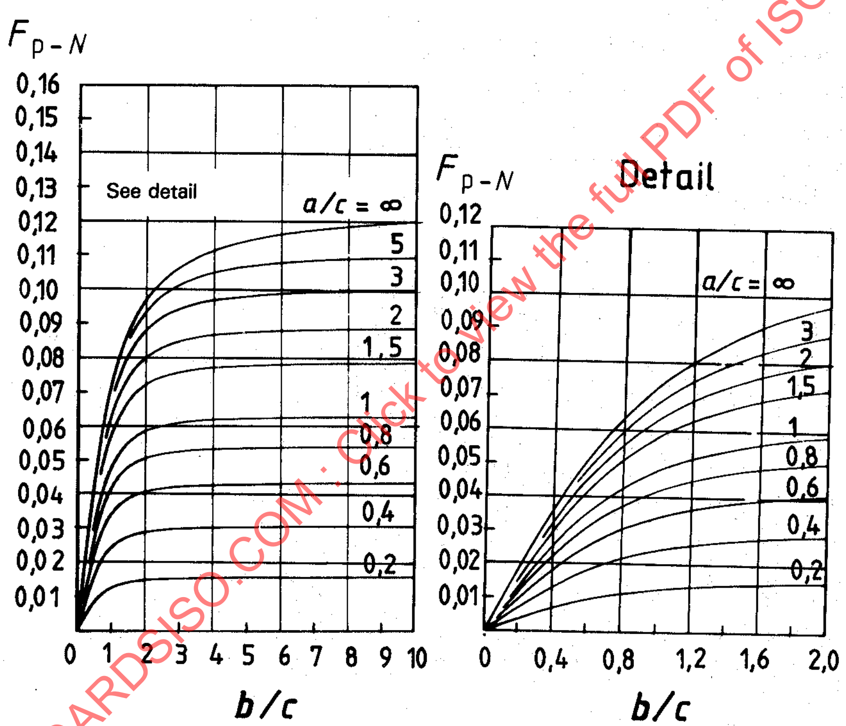

Figure 3 — Mean value of angle factor between a standing person and a vertical rectangle (above or below his centre) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

Example :

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

F_{p-a} = 0,047.

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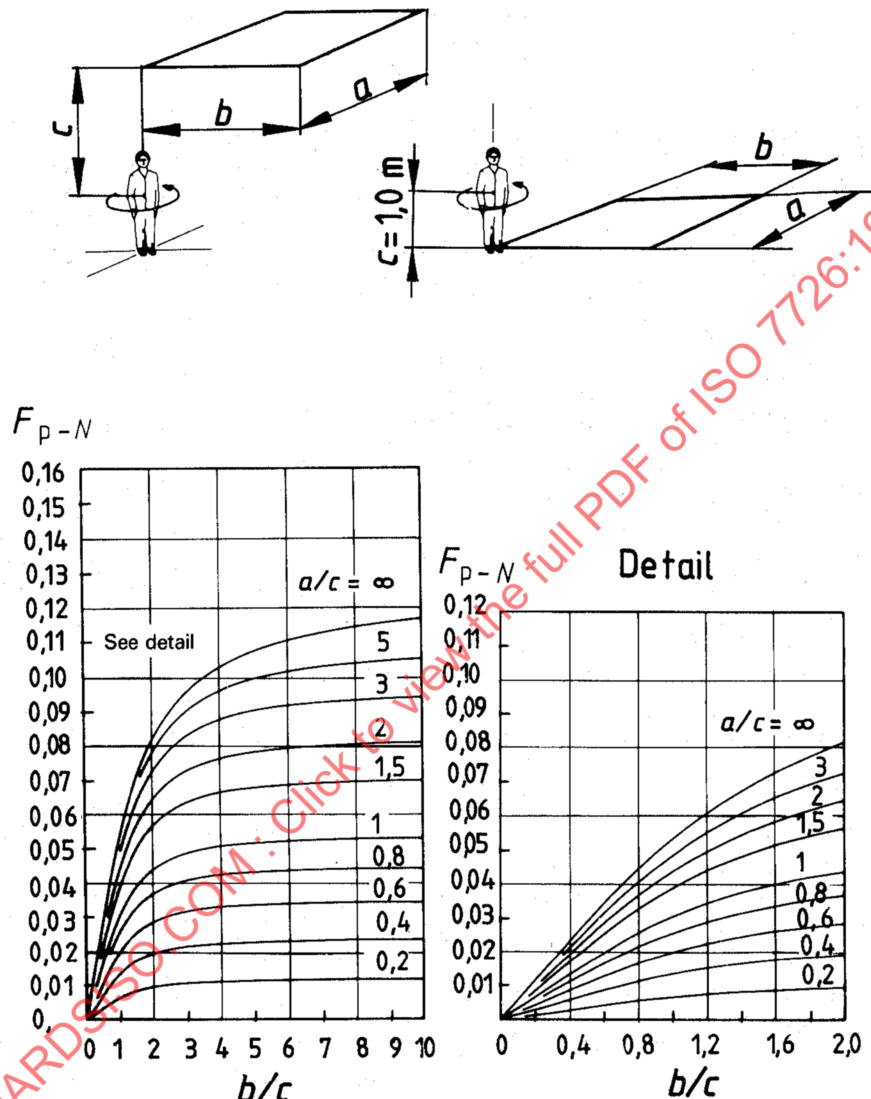

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Figure 4 — Mean value of angle factor between a standing person and a horizontal rectangle (on the ceiling or on the floor) when the person is rotated around a vertical axis. (To be used when the location but not the orientation of the person is known.)

Example :

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

F_{p-a} = 0,039.

Annex C

Measurement of radiant temperature asymmetry

(This annex does not form part of this International Standard.)

C.0 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 4.1.1.3).

In the present annex 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 the radiant temperature asymmetry.

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C.1 Measurement of radiant temperature asymmetry

C.1.1 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.1.2 Measuring

The net radiation is given by the following equation (14) :

$$P = \sigma (T_{pr1}^4 - T_{pr2}^4) \qquad \ldots (14)$$

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.

The radiant temperature asymmetry is equal to

$$\Delta t_{pr} = T_{pr1} - T_{pr2} \qquad \ldots (15)$$

where Δt_{pr} is the radiant temperature, in kelvins.

This quantity is not measured directly by a net radiometer but has to be calculated. Equation (14) can be written as

$$P = 4\sigma T_n^3 (T_{pr1} - T_{pr2}) \qquad \ldots (16)$$

In the linear radiant heat transfer coefficient ($4\sigma T_n^3$), $T_n = 0{,}5\,(T_{pr1} + T_{pr2})$ 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

$$\Delta t_{pr} = \frac{P}{4\sigma T_n^3} \qquad \ldots (17)$$

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

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/(m²·K) and for a temperature level equal to 50 °C the coefficient is equal to 7,6 W/(m²·K).

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

$$P_1 = \sigma T_{pr1}^4 - \sigma \varepsilon T_n^4 \qquad \ldots (18)$$

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 is the emittance of the sensor;

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

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

The plane radiant temperature is then equal to

$$T_{pr1} = \sqrt[4]{0{,}95\, T_n^4 + \frac{P_1}{\sigma}} \qquad \ldots (19)$$

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

C.2 Other methods of measuring

This clause outlines two other methods for measuring the 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 (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 (20)

$$T_{pr}^4 = T_s^4 + \frac{P_p - P_b}{\sigma (\varepsilon_b - \varepsilon_p)} \qquad \ldots (20)$$

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 emittance of the polished disc;

ε_b is the emittance of the black disc;

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

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C.2.2 Constant air temperature disc

In this method a small plane element is controlled at the same temperature as the surrounding air temperature. 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 (21)

$$T_{pr}^4 = T_s^4 - \frac{P_s}{\sigma \varepsilon_s} \qquad \ldots (21)$$

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 emittance of the disc;

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

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C.3 Method for calculation of radiant temperature asymmetry

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

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.

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

$$T_{pr}^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_N^4 F_{p-N} \qquad \ldots (22)$$

where

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

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

F_{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_{p-N}) can be estimated according to figures 5 and 6 or figures 7 and 8 in the case of rectangular surfaces but in general the determination of angle factors is more involved.

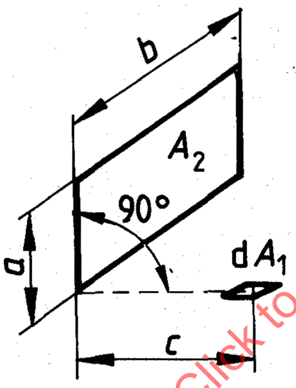
If there are only relatively small temperature differences between the surfaces of the enclosure equation (22) can be simplified to a linear form

$$T_{pr} = T_1 F_{p-1} + T_2 F_{p-2} + \ldots + T_N F_{p-N} \qquad \ldots (23)$$

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 ($F_{p-N} = 0,5$) has a temperature which is 10 K higher than the other half, the difference between the calculated mean radiant temperatures according to equation (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 the 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.

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

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

Figure 5 — Analytical formula relating to the calculation of the shape factor in the case of a small plane element perpendicular to a rectangular surface

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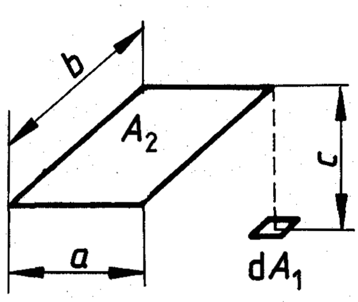

Element of a plane surface dA_1 and a rectangle in a plane parallel to it; the normal to the element passes through the corner of the rectangle.

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

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

Figure 6 — Analytical formula relating to the calculation of the shape factor in the case of a small plane element parallel to a rectangular surface

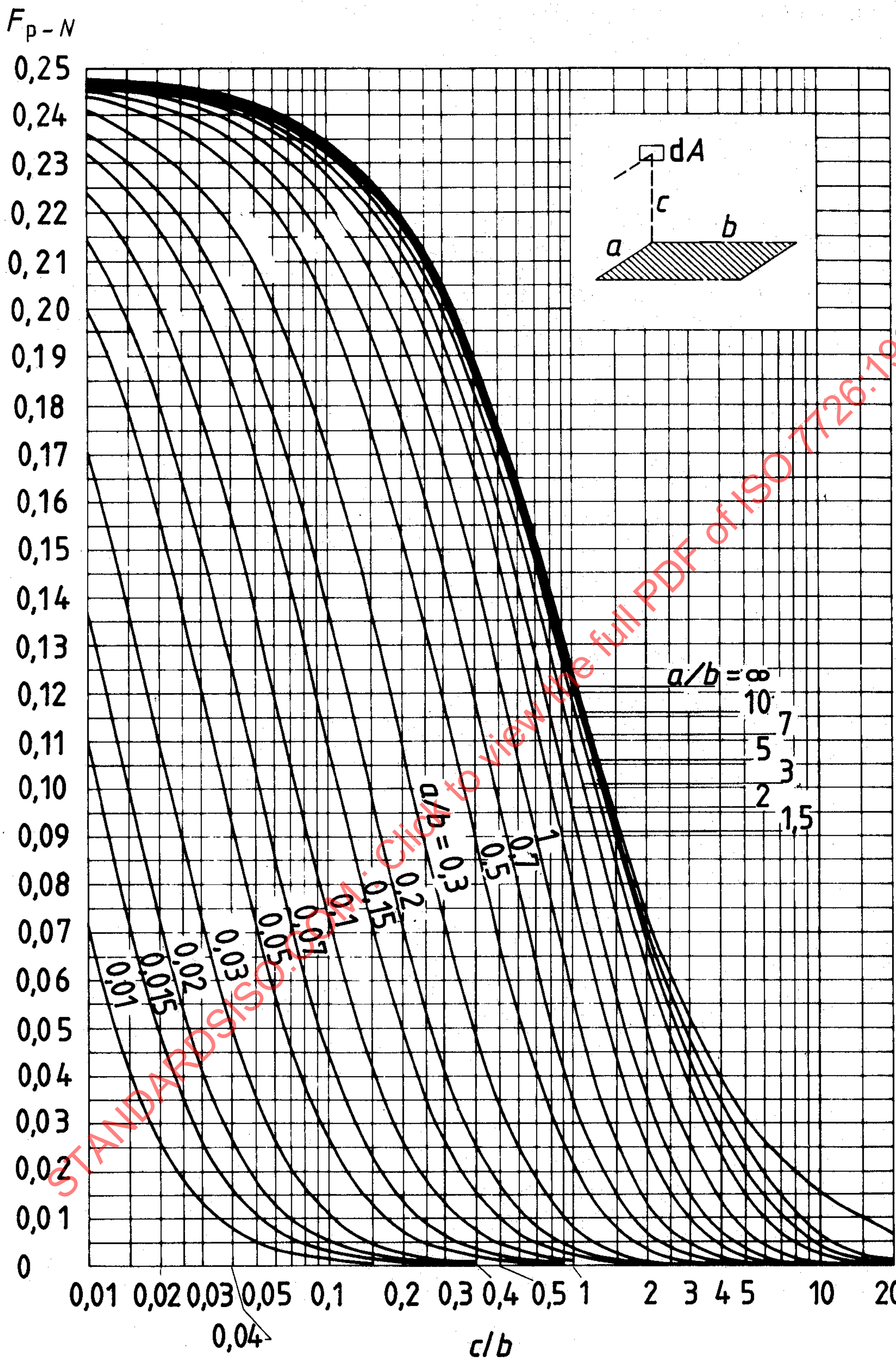

Figure 7 — Chart for the calculation of the shape factor in the case of a small plane element perpendicular to a rectangular surface

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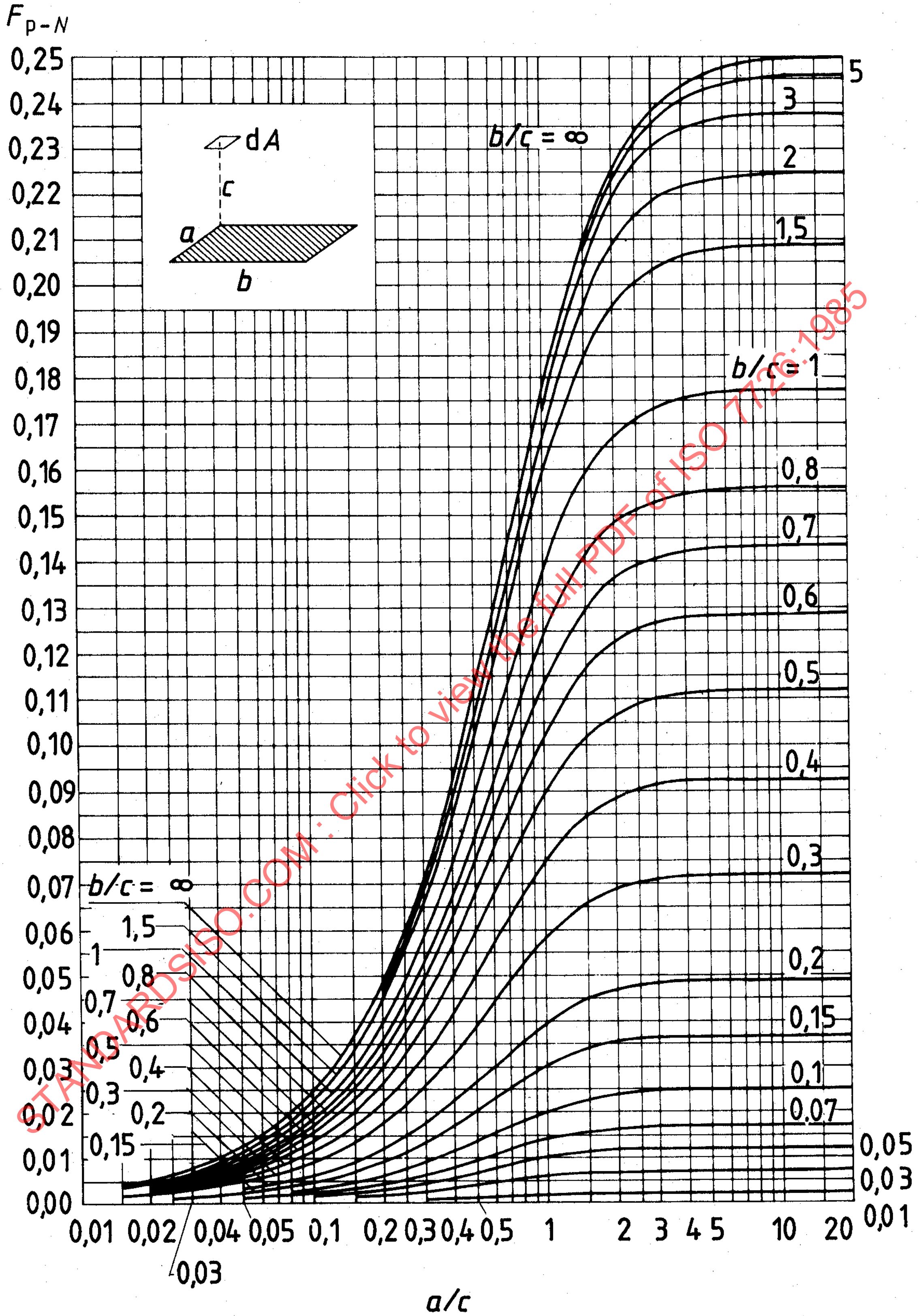

Figure 8 — Chart for the calculation of the shape factor in the case of a small plane element parallel to a rectangular surface

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Annex D

Measurement of the absolute humidity of the air

(This annex does not form part of this International Standard.)

D.0 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 resumé of the main characteristics of humid air.

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D.1 Thermo-hygrometric characteristics of humid air

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.1.1 Absolute humidity

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.1.1.1 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 :

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

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.1.1.2 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)

$$W_a = 0{,}612\,98 \frac{p_a}{p - p_a} \qquad \ldots (25)$$

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.1.2 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

$$e = \frac{p_a}{p_{as}} \qquad \ldots (26)$$

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

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.1.3 Direct determination of the thermo-hygrometric characteristics of humid air using a psychrometric chart

The main characteristics of humid air are usually grouped together in a chart known as a psychrometric chart (see figure 9). 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, right-hand side, the humidity ratio W_a;

c) on the y-axis, left-hand side, the partial pressure of water vapour p_a of the air expressed either in millimetres of mercury or 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 %.

The thermo-hygrometric characteristics given in the chart refer to an atmospheric pressure of 100 kPa, or 750 mmHg. Humidity measurements carried out at different pressures require the use of charts intended for these pressures.

Example :

Atmospheric pressure : 1 bar = 10^5 N/m^2 = 100 kPa.

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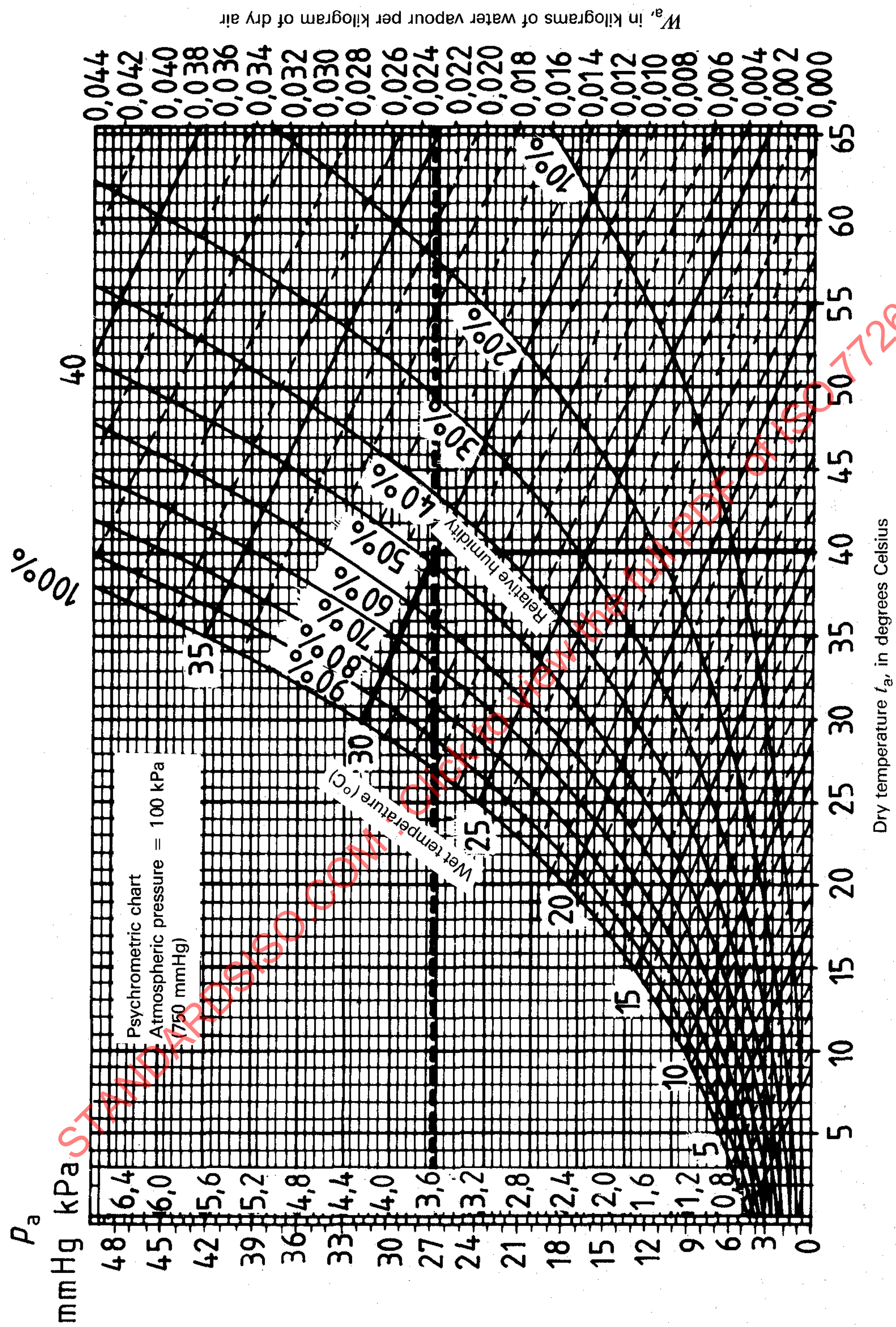

Figure 9 — Psychrometric chart — Example of the determination of the absolute humidity of the air

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