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Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble

Ergonomie des ambiances thermiques — Détermination de l'isolement thermique et de la résistance à l'évaporation d'une tenue vestimentaire

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Foreword

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

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

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

ISO 9920 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 9920:1995), which has been technically revised. It includes major changes to the sections on clothing vapour resistance as well as those dealing with the effects of air movement and body motion on clothing insulation and vapour resistance.

This corrected version of ISO 9920:2007 incorporates the following corrections.

— A value and a symbol missing from Equation (38) have been reinstated.

— In Equation (15), the multiplication symbol has been substituted for an (incorrect) asterisk.

— In Figure A.1, traditional Korean garments erroneously captioned “China” and “Sokchina” have been corrected to read *Chima* and *Sokchima*.

— In Equation (F.8), the subscript of the second representation of “I_{cl}” has been changed to I_{cli}.

— In the description of symbol H given with Equation (F.1), the minus sign missing from the superscript attached to the unit W·m^{-2} has been inserted.

— “Mean skin temperature”, given as the description for $\bar{t}_{\text{cl}}$ with Equation (G.6), has been corrected to “mean outer clothing surface temperature”.

— In a number of instances, “weight” has been changed to the accepted ISO term, *mass*.

— Values in Table A.2, No. 134 for I_{cl} and I_{T} have been corrected.

— Introductory text similar to that present in the first edition has been reinstated in Annex A, and a new introductory text has been added to Annex C.

— Some minor editorial corrections and additions have been made.

Introduction

This International Standard is one of a series of International Standards intended for use in the study of thermal environments. It is a basic document for evaluation of the thermal characteristics of a clothing ensemble (thermal insulation and water vapour resistance). It is necessary to know these values when evaluating the thermal stress or degree of comfort provided by the physical environment according to standardized methods. The thermal characteristics determined in this International Standard are values for steady-state conditions. Properties like “buffering”, adsorption of water and similar are not dealt with.

The emphasis in this International Standard is on the estimation of the thermal characteristics. The heat and vapour resistance may also be measured directly, and this is discussed in the annexes.

This International Standard does not deal with the local thermal insulation on different body parts, nor the discomfort due to a non-uniform distribution of the clothing on the body.

Man’s thermal balance in neutral, cold and warm environments is influenced by the clothing worn. For evaluating the thermal stress on human beings in the cold (IREQ, see ISO/TR 11079, insulation index), neutral environments (PMV-PPD, see ISO 7730, indices) and the heat (predicted heat strain, see ISO 7933, index), it is necessary to know the thermal characteristics of the clothing ensemble, i.e. the thermal insulation and the water vapour resistance.

Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble

1 Scope

This International Standard specifies methods for estimating the thermal characteristics (resistance to dry heat loss and evaporative heat loss) in steady-state conditions for a clothing ensemble based on values for known garments, ensembles and textiles. It examines the influence of body movement and air penetration on the thermal insulation and water vapour resistance.

This International Standard does not

— deal with other effects of clothing, such as adsorption of water, buffering or tactile comfort,

— take into account the influence of rain and snow on the thermal characteristics,

— consider special protective clothing (water-cooled suits, ventilated suits, heated clothing), or

— deal with the separate insulation on different parts of the body and discomfort due to the asymmetry of a clothing ensemble.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
thermal insulation
I
resistance to dry heat loss between two surfaces, expressed in square metres Kelvin per watt ($m^2 \cdot K \cdot W^{-1}$)

NOTE 1 In this International Standard it is considered as the *equivalent uniform thermal resistance*, or thermal insulation, on a human body. This is the clothing *heat resistance* (thermal insulation) that, when uniformly covering the whole body surface (including hands, face, etc.), would result in the same heat loss as the actual, possibly non-uniform, clothing heat resistance. This heat resistance is the quotient of the temperature gradient between the surfaces (the driving force) over the dry heat loss per unit of body surface area (the flux):

$$I = \frac{\text{temperature gradient}}{\text{heat loss per unit of body surface area}} \quad (1)$$

For the human body, this resistance can be divided into specific layers, as illustrated in Figure 1 (see also Annex F).

NOTE 2 Because of the special definition of thermal insulation in this International Standard, it is usually expressed in clo, the unit of thermal insulation of clothing. Although it can be converted into SI units in similar fashion to the thermal insulation of, for example, textile samples [symbol: R_{ct}; 1 clo = 0,155 ($m^2 \cdot K \cdot W^{-1}$)], the meaning is not the same.

2.1.1
total insulation
I_T
thermal insulation from the body surface to the environment (including all clothing, enclosed air layers and boundary air layer) under reference conditions, static

See Figure 1.

NOTE Based on Equation (1), it is expressed as:

$$I_T = \frac{\bar{t}_{sk} - t_o}{H} \quad (2)$$

where

$\bar{t}_{sk}$ is the mean skin surface temperature, in degrees Celsius;

t_o is the operative temperature, in degrees Celsius (in most cases equal to the air temperature, t_a);

H is the dry heat loss per square metre of skin, in watts per square metre.

2.1.2
basic insulation
intrinsic insulation
I_{cl}
thermal insulation from the skin surface to the outer clothing surface (including enclosed air layers) under reference conditions, static

See Figure 1.

NOTE Based on Equation (1), it is expressed as:

$$I_{cl} = \frac{\bar{t}_{sk} - t_{cl}}{H} \quad (3)$$

where $\bar{t}_{cl}$ is the mean outer clothing surface temperature, in degrees Celsius.

2.1.3
air insulation
I_a
thermal insulation of the boundary (surface) air layer around the outer clothing or, when nude, around the skin surface

See Figure 1.

NOTE 1 Based on Equation (1), it is expressed as

$$I_a = \frac{\bar{t}_{cl} - t_o}{H} \quad (4)$$

NOTE 2 The dry heat loss is composed of radiant and convective heat loss (see Annex G). These heat transfers through the clothing layers are not considered separately in this International Standard; for the air layer, they can be considered separately. The alternative representation is then:

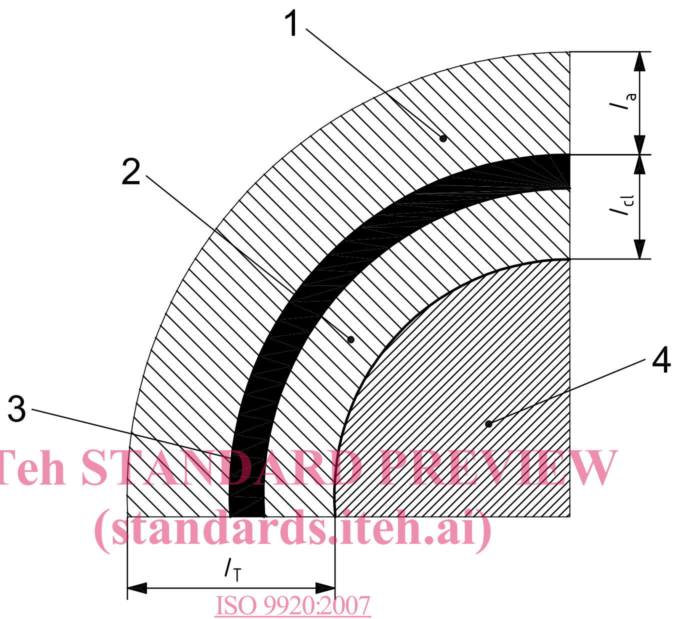
$$I_a = \frac{1}{h_c + h_r} \quad (5)$$

where

h_c is the convective heat transfer coefficient, in watts per square metre Kelvin ($W \cdot m^{-2} \cdot K^{-1}$);

h_r is the radiative heat transfer coefficient, in watts per square metre Kelvin ($W \cdot m^{-2} \cdot K^{-1}$).

NOTE 3 Such values are defined for standardized conditions (static body, wind still, i.e. speed $< 0,2\ m \cdot s^{-1}$). When air movement is present, or when the body moves, this will affect the insulation (typically lowering it), in which case, it is referred to as *resultant* or *dynamic heat resistance*.



Key

1 surface (or boundary) air layer

2 enclosed air layer

3 clothing

4 body

Figure 1 — Schematic representation of total, basic and air insulations

2.1.4
clothing area factor
f_{cl}
ratio of the outer surface area of the clothed body to the surface area of the nude body

NOTE 1 The outer surface area of a clothed person, A_{cl}, is greater than the surface area of a nude body, A_{Du}. Their ratio is therefore larger than 1:

$$f_{cl} = \frac{A_{cl}}{A_{Du}} \quad (6)$$

NOTE 2 Basic and air insulation do not simply add up to total insulation. This is explained by the difference in surface area between the outer clothing surface and the skin surface. Owing to this higher surface area, the insulative effect for the body of the air insulation is reduced the thicker the clothing (the larger the outer clothing surface area):

$$I_T = I_{cl} + \frac{I_a}{f_{cl}} \quad (7)$$

2.1.5
resultant total insulation
dynamic total insulation
$I_{T,r}$
actual thermal insulation from the body surface to the environment (including all clothing, enclosed air layers and boundary air layers) under given environmental conditions and activities

NOTE It is the total insulation (I_T) value in actual situations (as opposed to reference conditions), including the effects of movements and wind. Values for I_T given in this International Standard and in most of the literature are obtained on a thermal manikin which remains static in a low wind condition, and such values need to be corrected for wind and movement effects.

2.1.6
resultant basic insulation
dynamic basic insulation
$I_{cl,r}$
actual thermal insulation from the body surface to the outer clothing surface (including enclosed air layers) under given environmental conditions and activities

NOTE It is the basic (intrinsic) insulation (I_{cl}) value in actual situations (as opposed to reference conditions), including the effects of movements and wind.

2.1.7
effective insulation
I_{clu}
increase in insulation provided to a thermal manikin by a single garment compared to the nude manikin insulation

NOTE For insulation of individual garments, the term *effective thermal insulation* is used (I_{clu}). The effective thermal insulation of individual garments making up the ensemble (see Table B.2) is determined on a manikin wearing only that single garment as:

$$I_{clu} = I_T - I_a = \frac{\bar{t}_{sk} - t_o}{H} - I_a \quad (8)$$

where

I_T is the total thermal insulation of the garment, in square metres Kelvin per watt ($m^2 \cdot K \cdot W^{-1}$) or in clo;

t_o is the operative temperature, in degrees Celsius (equal to the air temperature, t_a, for most measuring conditions in climatic chambers).

2.2
water vapour resistance
evaporative resistance
R_e
resistance to water vapour transfer between two surfaces, expressed in square metres kilopascal per watt

NOTE 1 In this International Standard it is considered as the *equivalent uniform* vapour resistance. This is the resistance that, when uniformly covering the whole body surface (including hands, face, etc.), would result in the same heat loss through evaporation as the actual, possibly non-uniform, vapour resistance. This resistance is the quotient of the vapour pressure gradient between the surfaces (the driving force) over the evaporative heat loss per unit of body surface area:

$$R_e = \frac{\text{vapour pressure gradient}}{\text{evaporative heat loss per unit of body surface area}} \quad (9)$$

NOTE 2 Similarly to heat resistance, it is divided into specific layers.

2.2.1
total water vapour resistance
$R_{e,T}$
vapour resistance from the body surface to the environment (including all clothing, enclosed air layers and boundary air layers) under reference conditions, static

2.2.2
basic water vapour resistance
$R_{e,cl}$
vapour resistance from the body surface to the outer clothing surface (including enclosed air layers) under reference conditions, static

2.2.3
air water vapour resistance
$R_{e,a}$
vapour resistance of the boundary (surface) air layer around the outer clothing or, when nude, around the skin surface

NOTE In analogy to heat resistance:

$$R_{e,T} = R_{e,cl} + \frac{R_{e,a}}{f_{cl}} \tag{10}$$

2.2.4
resultant total water vapour resistance
dynamic total water vapour resistance
$R_{e,T,r}$
vapour resistance from the body surface to the environment (including all clothing, enclosed air layers and boundary air layers) under given environmental conditions and activities

NOTE 1 It is the total water vapour resistance ($R_{e,T}$) value in actual situations (as opposed to reference conditions), including the effects of movements and wind.

NOTE 2 Values of $R_{e,T}$ are defined for standardized conditions (static body, wind still, i.e. speed $< 0{,}2\ \mathrm{m \cdot s^{-1}}$). When air movement is present, or when the body moves, this will affect the vapour resistance (typically lowering it), in which case it is referred to as the *resultant* or *dynamic* total water vapour resistance.

2.2.5
resultant basic water vapour resistance
dynamic basic water vapour resistance
$R_{e,cl,r}$
vapour resistance from the body surface to the outer clothing surface (including enclosed air layers) under given environmental conditions and activities

NOTE 1 It is the basic water vapour resistance ($R_{e,cl}$) value in actual situations (as opposed to reference conditions), including the effects of movements and wind.

NOTE 2 Values of $R_{e,cl}$ are defined for standardized conditions (static body, wind still, i.e. speed $< 0{,}2\ \mathrm{m \cdot s^{-1}}$). When air movement is present, or when the body moves, this will affect the vapour resistance (typically lowering it), in which case it is referred to as the *resultant* or *dynamic* basic water vapour resistance.

3 Application of this International Standard

Where possible, the insulation and vapour resistance values of a clothing ensemble should be measured using equipment such as thermal (wetted or sweating) manikins, or by performing experiments involving human subjects. Test procedures for the measurement of heat and vapour resistance are outlined in Annexes D and E. However, given the cost and the need for specialized equipment, actual measurement will most likely be beyond the reach of most users of this International Standard. In that case, the insulation and vapour resistance shall be estimated using the methods specified in the following clauses and Annexes A, B and C.

For guidance, the stepwise approach is schematically represented in the flowcharts of Figure 2, for the determination of heat resistance, and Figure 3, for the determination of vapour resistance. The various options are described.

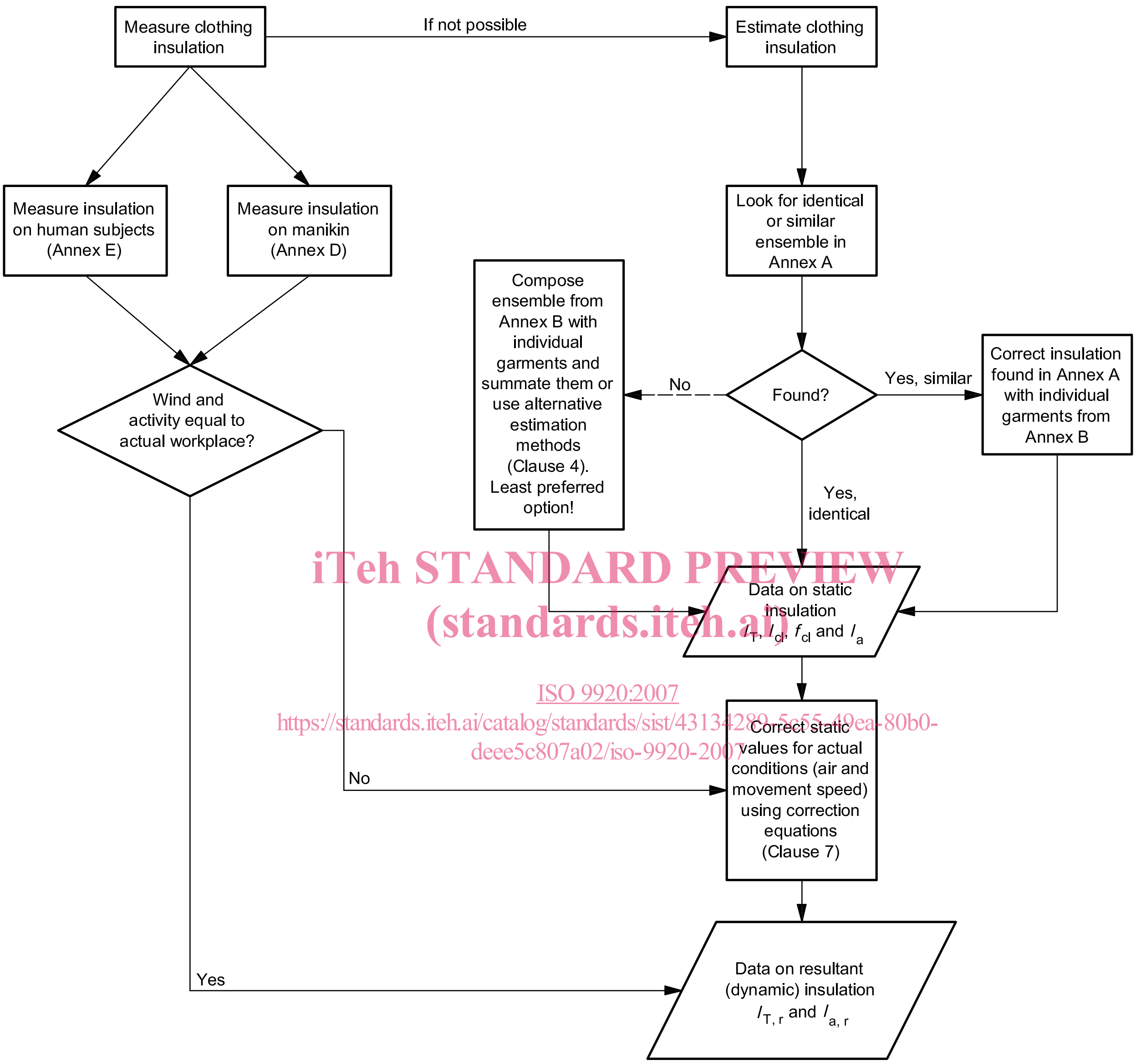


Figure 2 — Determining clothing insulation

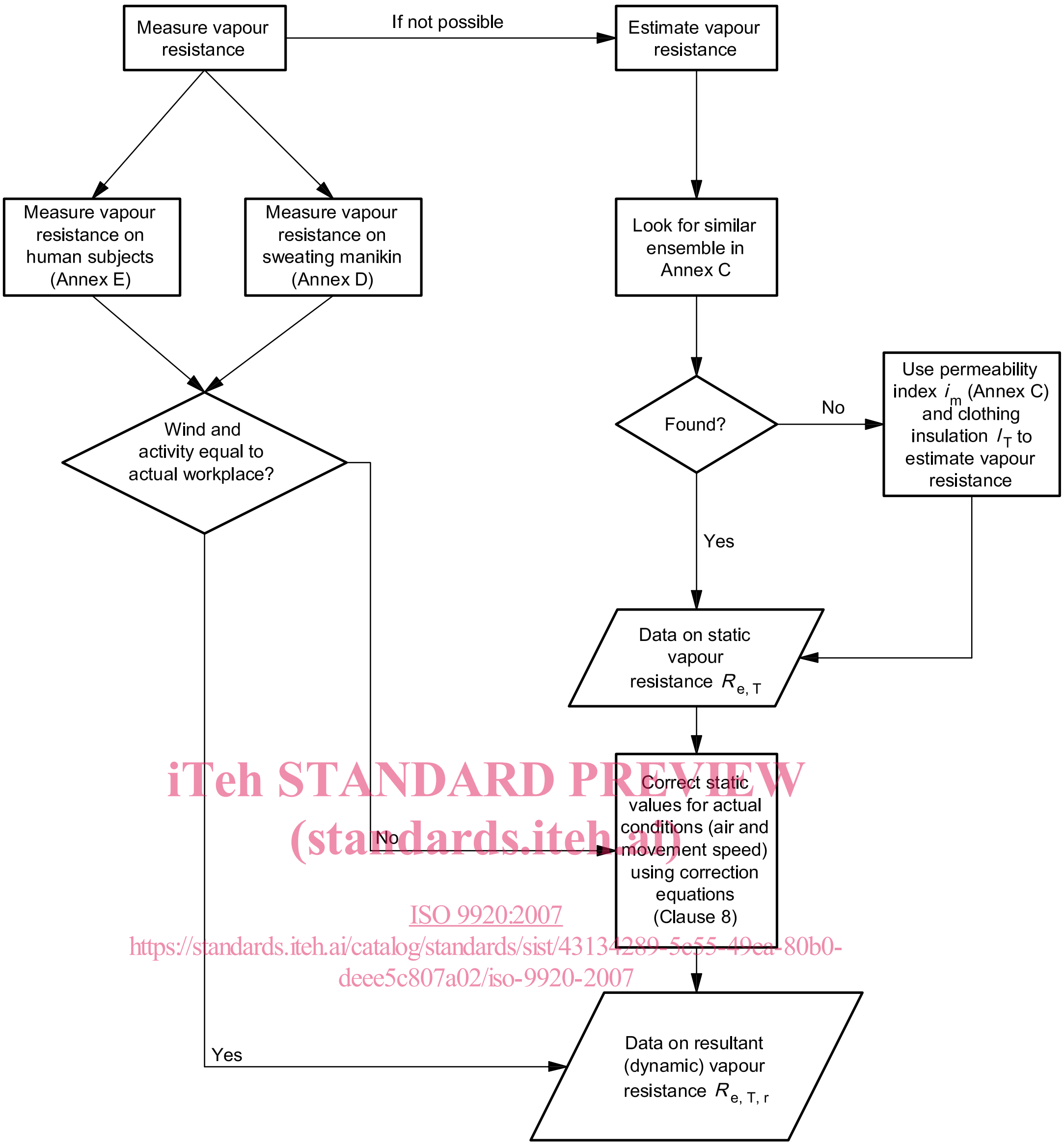


Figure 3 — Determining clothing vapour resistance

4 Estimation of thermal insulation of clothing ensemble based on tables and with values measured on a standing thermal manikin

4.1 General

Tables in this International Standard provide data on the insulation of complete clothing ensembles, as well as insulation values for individual garments that can be added to create complete ensembles. It is advisable to use the tables of complete ensembles to match the actual ensemble, as this will provide a more accurate value for clothing insulation than the summation of individual garments. Interpolation between the thermal insulation of two ensembles may be used and, when an ensemble is found similar to the actual ensemble, small corrections may also be made by adding or subtracting individual garment insulations to achieve the best estimate of the insulation of the actual ensemble. Finally, corrections for movement and air velocity shall be applied.

4.2 Insulation values of complete ensembles

In Annex A, I_T and I_{cl} values are listed for a selection of clothing ensembles. All of the values were measured on a static, standing, thermal manikin in low air movement ($< 0{,}2\ m \cdot s^{-1}$). In Table A.1, a short description of the clothing ensembles is given. Tables A.2 to A.10 present more extended lists that can be used for finding a clothing ensemble that is comparable with the actual clothing ensemble; f_{cl} values are also given. The total clothing mass, where this is given, is based on garments that fit a standard person (European male size 52) and does not include shoes. A number following the listing in the tables of individual garments making up most of the ensembles refers to Annex B, where a more detailed description of the individual garment is presented, including figures.

Annex A can also be used to select clothing for a workplace when the required insulation is known.

4.3 Ensemble thermal insulation values based on individual garments

Instead of using the ensembles in Annex A, the insulation for an ensemble, I_{cl}, expressed in clo, may also be estimated, based on a summation of the insulation of individual garments using the following empirical equation [31], [36]:

$$I_{cl} = 0{,}161 + 0{,}835 \sum I_{clu} \qquad (11)$$

expressed in clo.

Or, with slightly reduced accuracy [32], [37]:

$$I_{cl} = \sum I_{clu} \qquad (12)$$

expressed in square metres Kelvin per watt, or clo, and where I_{clu} is the effective thermal insulation of the individual garments making up the ensemble, in values of either square metres Kelvin per watt or clo.

Such values are listed in Annex B.

The design of the various garments in Annex B is indicated by a type number, referring to drawings showing a person dressed in various garment designs (Figures B.1 to B.14).

In some cases, the fabrics used are also listed. The type of material, however, has a limited influence on the thermal insulation. Instead, the insulation is mainly influenced by the thickness (indicated in Annex B) and the body surface area covered (indicated on the drawings).

It should be noted that the summations presented in Equations (11) and (12) are based on data with rather uniform insulation distributions over the body. Such summations should not be used for extreme situations (e.g. three layers on lower body and only a thin layer on upper body). The accuracy of the summation was acceptable when actually measured data for the respective garments were used. When the separate garments' insulations were obtained from the tables, the accuracy of the summation was limited. Hence, it is preferable to work with values of full ensembles (see Annex A).

The application range for which these relationships [Equations (11) and (12)] were tested is between 0,2 clo and 1,6 clo.

4.4 Complete ensemble insulation corrected for small differences in composition

The accuracy of the summation of individual garments (4.3) is much less than that of matching the actual ensemble with an ensemble taken from Annex A (4.2). Hence, when an exact match of the actual ensemble with those of the tables of Annex A is not possible, but similar ensembles can be found, it is best to take the similar ensemble insulation value and correct this for the difference in ensemble composition. For example, if the actual ensemble has a different type of sweater, the ensemble insulation may be corrected for the difference in insulation between the actual sweater and that of the sweater in the ensemble description of

Annex A. For this purpose, the effective insulations of both clothing items are compared and the difference used for adjustment of the ensemble value:

$$I_{\mathrm{cl,a}} = I_{\mathrm{cl,A}} + 0{,}835 \times \Delta I_{\mathrm{cl}u} \quad (13)$$

with the result expressed in clo or in $m^2 \cdot K \cdot W^{-1}$, and where $I_{\mathrm{cl,a}}$ is the basic insulation of the actual ensemble, $I_{\mathrm{cl,A}}$ is the basic insulation of the ensemble according to Annex A, and $\Delta I_{\mathrm{cl}u}$ is the correction for the difference in individual garments (negative for subtracting a garment or when replacing with a less insulative garment).

This can be the difference between two garments of the same type (replacing one sweater by another), or the effective insulation of an extra garment, or a negative value in the case where the actual ensemble contains one garment less. The $I_{\mathrm{cl}u}$ values are taken from Annex B.

Corrections should be kept to a minimum, and interpolation between two relevant ensembles is preferred. In adding and removing garments, it should be considered how the insulation is distributed. Adding a thin layer to an already covered part of a cold weather ensemble will have minimal impact, compared with the large impact of adding a thin layer to a nude part in such an ensemble.

4.5 Calculation of thermal insulation for clothing ensembles

As an alternative to the selection of an ensemble from the tables, it is also possible to determine the clothing insulation of an ensemble using the following empirically determined relationship [32], [37]:

$$I_{\mathrm{cl}} = 0{,}919 + 0{,}255 \times m - 0{,}008\,74 \times A_{\mathrm{COV,0}} - 0{,}005\,10 \times A_{\mathrm{COV,1}} \quad (14)$$

where

- I_{cl} is the intrinsic clothing insulation, in clo;
- m is the clothing mass (without shoes), in kilograms;
- $A_{\mathrm{COV,0}}$ is the body surface area not covered by clothing, as a percentage of total body surface area;
- $A_{\mathrm{COV,1}}$ is the body surface area covered by a single clothing layer, as a percentage of total body surface area.

In effect, Equation (14) assumes a certain multi-layer insulation for a given clothing mass and then subtracts insulation for areas only covered with a single layer and for areas without clothing. The application range for which this relation was tested is between 0,2 clo and 1,8 clo.

Guidance on how to calculate A_{COV} is given in Annex H.

4.6 Calculation of thermal insulation for individual garments

The effective thermal insulation of an individual garment, $I_{\mathrm{cl}u}$ ($m^2 \cdot K \cdot W^{-1}$), may also be estimated by

$$I_{\mathrm{cl}u} = 0{,}00095 \times A_{\mathrm{COV}} \quad (15)$$

or, if expressed in clo, using

$$I_{\mathrm{cl}u} = 0{,}0061 \times A_{\mathrm{COV}} \quad (16)$$

where A_{COV} is the body surface area covered by clothing (percentage of total skin area).

The values for body surface area covered by clothing are shown for garments in the figures of Annex B. Garment mass on its own is not a good predictor of garment insulation [32].