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Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles —

Part 4:
Determination of the equivalent temperature by means of a numerical manikin

Ergonomie des ambiances thermiques — Évaluation des ambiances thermiques dans les véhicules —

Partie 4: Détermination de la température équivalente à l'aide d'un mannequin numérique

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

A list of all parts in the ISO 14505 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The interaction of convective, radiant and conductive heat exchange in a vehicle compartment or similar confined space is highly complex. External thermal loads in combination with the air conditioning system in a vehicle compartment create non-uniform thermal environments, which are often the main cause of complaints of thermal discomfort. In vehicles with poor or non-existent air conditioning systems, non-uniform thermal environments can also be created by the interaction between the ambient climatic conditions and vehicle structures. While a subjective evaluation reflects the total sensations of a human body, these often incur great costs while the study phase is being conducted. Physical measurements provide detailed and accurate local information; however, these results must be integrated in some way to predict the thermal effects on humans. Furthermore, since specific climatic factors sometimes play a dominant role in the overall heat exchange of a human body, an evaluation method that accounts for the relative importance of these factors is required.

This document is part of the ISO 14505 series. To meet the above-stated requirements, this document provides calculation methods that utilize numerical simulations to assess the total thermal environment of vehicles. The equivalent temperature, obtained from measurements taken using a thermal manikin, is defined in ISO 14505-2. This document extends the definition of the ISO 14505 series to include numerical evaluation when this document is used in conjunction with the equivalent temperature defined in ISO 14505-2.

As described in ISO 14505-2, an equivalent temperature can be utilized in the assessment of vehicle cabins and other various enclosed spaces with non-uniform environments. As is the case for ISO 14505-2, this document can also be applied to vehicle cabins and other enclosed spaces.

This document supposes that the ISO 14505 series will be applied to various situations, such as:

— in the case of experimental facilities that are not prepared;

— in the case of prototypes that are incomplete;

— in the case of conditions that are difficult to simulate in controlled experimental settings;

— in the case that occupants are extrapolated to unknown or virtual environments.

Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles —

Part 4: Determination of the equivalent temperature by means of a numerical manikin

1 Scope

This document provides guidelines for extending the definition of equivalent temperature to predictive purposes and specifies a standard prediction method for the assessment of thermal comfort in vehicles using numerical calculations. Specifically, this document sets forth a simulated numerical manikin as a viable alternative to the thermal manikin for the purpose of calculating the equivalent temperature.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ISO 14505-2, *Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles — Part 2: Determination of equivalent temperature*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13731 and ISO 14505-2 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
numerical manikin
virtual thermal manikin recreating a thermal manikin, or a digital model of a thermal manikin used to calculate performance

3.2
physical manikin
real thermal manikin to measure real environment

3.3
computational fluid dynamics
CFD
simulation of a series of calculations based on specific boundary conditions and specific parameters associated with fluid and thermal fields using discrete equations based on the Navier-Stokes/Lattice-Boltzmann equations as well as heat transfer equations that consider convection, radiation and conduction, and generally account for the effects of turbulent flow

4 Symbols

A complete list of symbols used in this document is presented in Table 1.

Table 1 — Symbols and units

Symbol	Term	Unit
α	Solar absorptivity on clothing (skin on unclothed area) surface	–
A	Skin surface area	m^2
C	Convective heat loss from clothing (skin on unclothed area) surface	$W/m^2°C$
f_{cl}	Area factor (ratio of clothed to nude area)	–
h_c	Convective heat transfer coefficient	$W/m^2°C$
h_{cal}	Total heat transfer coefficient in a standard environment	$W/m^2°C$
h_{cs}	Convective heat transfer coefficient in a standard environment	$W/m^2°C$
h_r	Radiant heat transfer coefficient	$W/m^2°C$
h_{rs}	Radiant heat transfer coefficient in a standard environment	$W/m^2°C$
I_{cl}	Thermal insulation of clothing	$m^2°C/W$
Q	Total heat loss from skin surface	W/m^2
Q_{set}	Set value of Q at constant heat flux mode	W/m^2
R	Radiant heat loss from clothing (skin on unclothed area) surface, including effect of solar radiation	W/m^2
R_{cr}	Thermal insulation between core and skin assumed by comfort equation	$m^2°C/W$
R_t	Total thermal resistance between the manikin skin surface and the environment	$m^2°C/W$
S	Mean solar radiation reached on clothing (skin on unclothed area) surface	W/m^2
t_a	Air temperature	°C
t_{aset}	Air temperature at h_{cal} calculation	°C
t_{cl}	Clothing (skin on unclothed area) surface temperature	°C
t_{cr}	Core temperature assumed by the comfort equation	°C
t_{eq}	Equivalent temperature	°C
t_o	Operative temperature including the effects of solar radiation	°C
t_r	Mean radiant temperature	°C
t_{sk}	Skin surface temperature	°C
t_{skset}	Set value of t_{sk} at constant temperature mode	°C
v_a	Air velocity	m/s
n	Suffix: segment number of each body part	–
whole	Suffix: whole body	–
Symbols used in Annex E		
A_b	Body surface area of the manikin	m^2
$A_{e,i}$	Elemental surface area of the element i	m^2
A_n	Segmental surface area of the segment n	m^2
$B_{i,j}$	Absorption factor of radiation from surface elements i to j	–
$F_{i,j}$	View factor of radiation from surface elements i to j	–
$h_{cal,n}$	Total heat transfer coefficient of segment n for calibration	W/m^2K
$h_{cal,whole}$	Total heat transfer coefficient of the entire manikin for calibration	W/m^2K
i,j	Variable body surface element number	–

Table 1 *(continued)*

Symbol	Term	Unit
k	Variable spatial volume element number for calculation of t_a Variable body surface element number in the recurrence equation of $B_{i,j}$	–
m_b	Number of body surface elements	–
$m_{e,n}$	End body surface element number of segment n	–
$m_{s,n}$	Start body surface element number of segment n	–
m_v	Number of spatial volume elements	–
m_w	Number of wall surface elements	–
n	Variable local segment number of the manikin	–
n_{seg}	Number of manikin segments	–
$Q_{e,i}$	Heat flux of element i	W/m^2
Q_n	Averaged heat flux over segment n	W/m^2
Q_{whole}	Averaged heat flux over the entire manikin	W/m^2
R_{cr}	Thermal insulation between core and skin assumed by comfort equation	m^{2}K/W
$R_{cr,e,i}$	Thermal insulation of element i for the comfort equation mode calculation	m^{2}K/W
T_a	Averaged air temperature in the standard chamber (in Kelvins)	K
t_a	Averaged air temperature in the standard chamber (in Celsius)	°C
$t_{a,e,k}$	Air temperature of the spatial volume element k	°C
$t_{a,in}$	Air temperature entering the standard chamber	°C
t_{cr}	Core temperature assumed by the comfort equation	°C
$t_{cr,e,i}$	Core temperature of element i for the comfort equation mode calculation	°C
t_o	Operative temperature in the standard chamber	°C
T_r	Mean radiant temperature of the wall of the standard chamber (in Kelvins)	K
t_r	Mean radiant temperature of the wall of the standard chamber (in Celsius)	°C
t_{sk}	Skin surface temperature of the manikin	°C
$t_{sk,n}$	Averaged skin surface temperature of segment n	°C
$t'_{sk,n}$	Estimated average skin surface temperature of the segment n from the comfort equation	°C
$t_{sk,whole}$	Averaged skin surface temperature of the entire manikin	°C
T_w	Wall surface temperature of the standard chamber (in Kelvins)	K
t_w	Wall surface temperature of the standard chamber (in Celsius)	°C
u_a	Air flow velocity in the standard chamber	m/s
$\dot{V}_{a,in}$	Volumetric air flow rate entering the standard chamber	m^3/s
$V_{e,k}$	Volume of the spatial volume element k	m^3
V_0	Volume of the spatial region in the standard chamber	m^3
ΔQ_n	Correction amount for generated heat of segment n	W/m^2
Δt_{ce}	Threshold of difference between $t'_{sk,n}$ and $t_{sk,n}$ for iterative convergence	°C
Δt_o	Threshold of difference between t_a and t_r for iterative convergence	°C
ε_j	Emissivity of the surface element j	–
ε_{sk}	Emissivity of the manikin	–
ε_w	Emissivity of the wall of the standard chamber	–

Table 1 *(continued)*

Symbol	Term	Unit
ξ_m	Conversion factor between the actual wall surface temperature and mean radiant temperatures	–

5 Assessment of thermal environments in vehicles

The method of assessment by equivalent temperature is defined in ISO 14505-2. The assessment procedures in ISO 14505-2 are applicable to numerical evaluations, for which "numerical manikin" is defined in this document. Figure 1 shows the role of this document and its relations with the other parts of the ISO 14505 series as well as different International Standards.

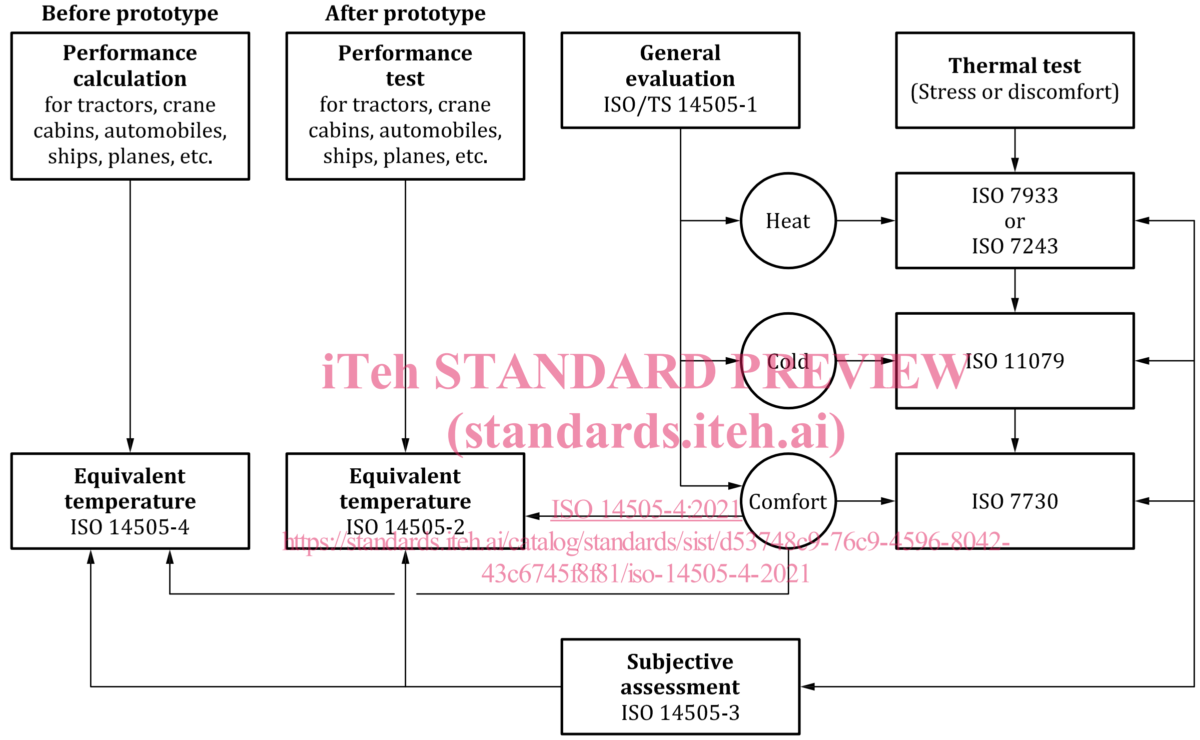


Figure 1 — Role of numerical evaluation among different International Standards

6 Principles of assessment utilizing a numerical manikin

This document presents two methods for calculating the equivalent temperature. One is a calculation method coupled with a numerical manikin, as described in Clause 7. The other is a calculation method using thermal factors, as described in Clause 8. Either method can be used to evaluate the thermal environment in vehicles.

The former calculation method coupled with a numerical manikin is intended for use with a simulation tool, such as computational fluid dynamics (CFD). A numerical manikin imitates a physical manikin to calculate the equivalent temperature. The method of calculation using thermal factors estimates the equivalent temperature by assuming the existence of the imaginary numerical manikin. In this method, the equivalent temperature is calculated using the thermal factors, air temperature, radiant temperature, air velocity and solar radiation. Figure 2 shows a schematic of the two methods.

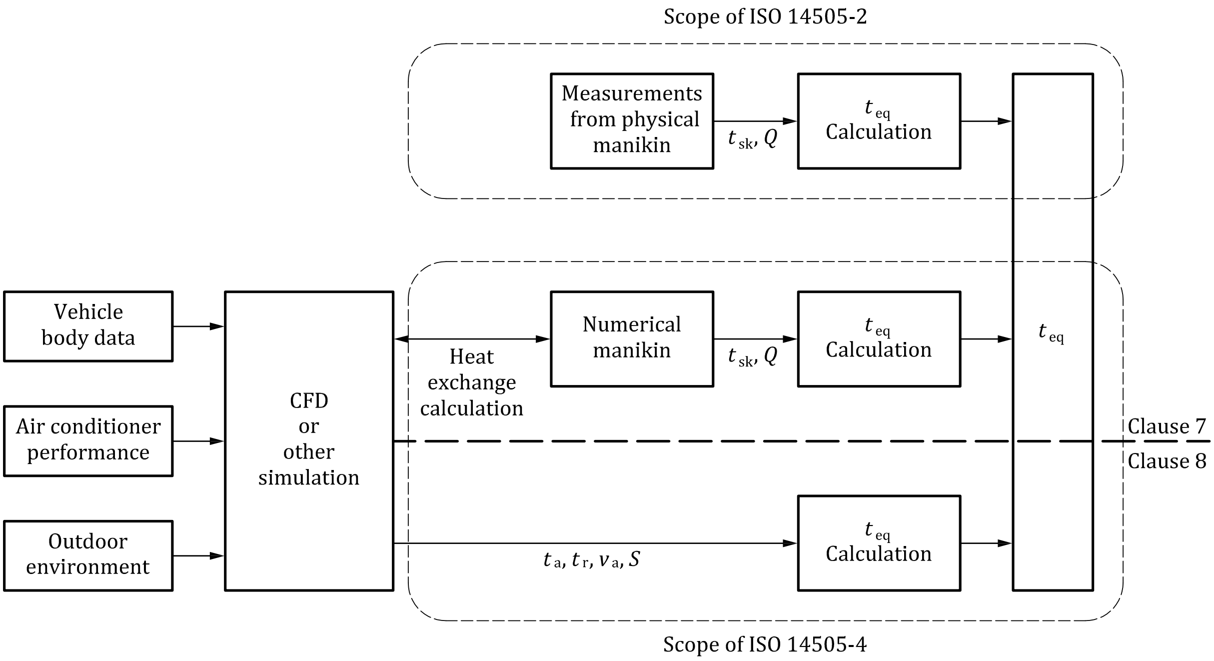


Figure 2 — Two methods for calculating equivalent temperature

7 Calculation method coupled with numerical manikin

7.1 General

This clause describes the framework of the calculation. To evaluate the indoor environment of a vehicle numerically, the following issues should be considered and taken account (see Figure 3):

a) heat flow through the shell structure of the vehicle;

b) flow and thermal field in the cabin;

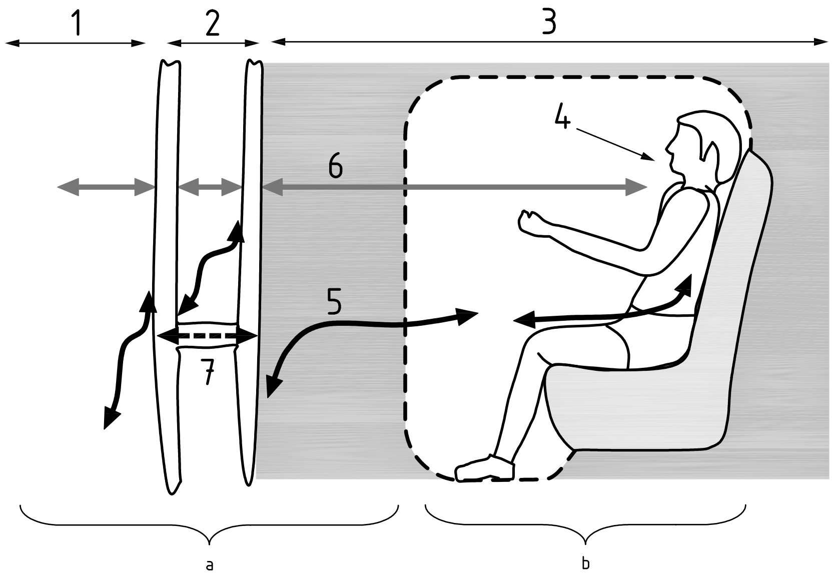
c) radiant field (including solar radiation) in the cabin;

d) conductive heat exchange;

e) heat balance of the thermal manikin model (numerical manikin).

This document is intended to be applied to the region around the manikin, relating to items b) and e). The heat flow through the structure of the vehicle body is defined as suitable. This document defines indispensable ideas concerning the above items, which will enable successful and useful calculations in these situations. However, this document does not define any specific methods for utilization because all methods present both advantages and disadvantages for particular problems.

Once the environmental state concerning thermal comfort in the cabin is calculated, evaluation becomes possible. Items a) to d) give the principal local parameters of air velocity, temperature and radiation, though some simultaneous calculation coupling with the heat balance calculation is required. This calculation will produce a heat transfer value close to that measured using the physical manikin. Therefore, the evaluation method described in ISO 14505-2 is applicable.



Key

1 outside of vehicle

2 shell structure

3 interior of vehicle

4 thermal manikin

5 convection

6 radiation

7 conduction

a Other standards (TC22 related).

b This document.

NOTE Evaluation of the area in contact with the seat is outside the scope of this document.

Figure 3 — Framework of heat transfer system

7.2 Flow and thermal field around manikin

7.2.1 Convective heat

The flow and thermal field in the cabin are estimated via calculations. One practical option for this is CFD. The informative concrete contents of this method are represented in Annex A. The outputs are the air velocity vector and air temperature in a cabin. The heat flux on the wall and surface are also obtained through this calculation.

The primary problem in CFD calculations is the treatment of boundary conditions. This can be overcome in practice by selecting any of the following:

a) Calculate the heat transfer on the surface of the manikin using CFD directly.

b) As a preliminary, calculate the heat transfer coefficient on the surface of the manikin using CFD. Then calculate the flow and thermal field coupling using the heat balance calculation of the manikin.

c) Utilize the heat transfer coefficient obtained by measurement. Then calculate the flow and thermal field coupling with the heat balance calculation of the manikin, as described in b).

d) Estimate the heat transfer coefficient using a predictive formula based on the air velocity or temperature. Then calculate the flow and thermal field coupling using the heat balance calculation for the manikin, as described in b).

7.2.2 Radiant heat

The radiant field is calculated based on the geometric condition in a cabin separated from the flow field calculation. Regarding long-wave radiation, as a preliminary, the view factor relating to all potential combinations between different surface elements of the wall and the manikin or human body should be calculated. Once those factors have been obtained, the radiant heat exchange is calculated when the temperature of a pair of surface elements is given. As stated previously, the radiant heat is involved in the boundary conditions of the heat transfer equation, so that the temperature is calculated iteratively until convergence. For convenience, those factors are converted to the mean radiant heat transfer coefficient.

Short-wave radiation (solar radiation) can be treated as energy flux striking the surface. Here, the transmission loss through the window glass should be taken into consideration. Solar radiation can be regarded as divided into the following components:

a) direct solar radiation;

b) sky solar radiation;

c) reflection on the ground.

The solar radiant heat is also involved in the boundary conditions of the heat transfer equation. In the case of a climate wind tunnel test performed without use of a solar lamp, it is supposed that the effects of solar radiation are neglected. Concrete informative treatments are represented in Annex C.

7.2.3 Conductive heat

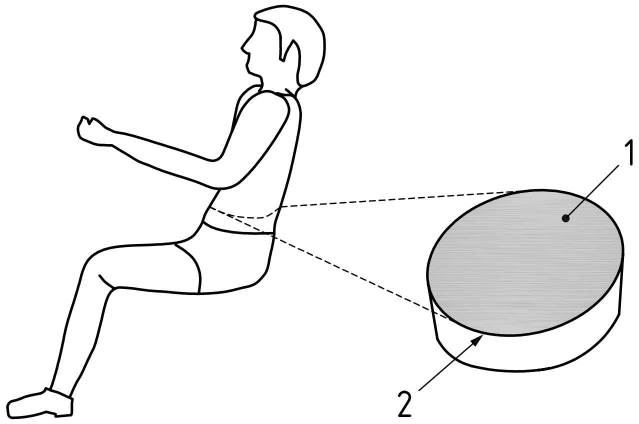
Evaluation of the contacted segment is outside the scope of this document. The conductive heat transfer between the manikin and seat is disregarded in the calculations.

7.3 Calculation of heat exchange on manikin

7.3.1 Structure and control of numerical manikin

Figure 4 shows the theoretical structure of the numerical manikin with regard to a human-shaped one. The centre of each segment is assumed to consist of an adiabatic core. A heat generator is equipped on the surface of the manikin.

The shape of the manikin is defined by calculation grids for CFD, as shown in Figure 5 a). The partition is performed to imitate an actual manikin, as in Figure 5 b). Boundary conditions are given for each segment.

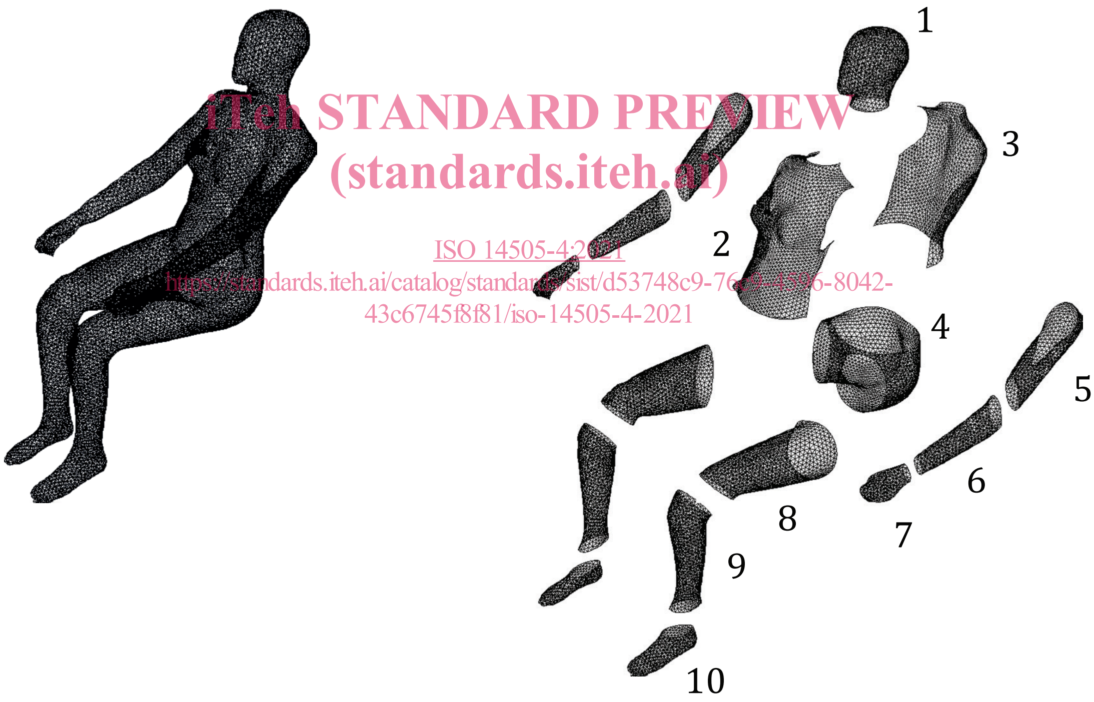


Key

1 adiabatic core

2 heat generator on surface

Figure 4 — Theoretical structure of numerical manikin



a) Full-body model of manikin **b) Partition of surface grids (16-segment case shown)**

Key

1 head

2 chest

3 back

4 pelvis

5 upper arm

6 forearm

7 hand

8 thigh

9 leg

10 foot

Figure 5 — Surface grids for numerical calculation

The control model is intended to imitate a physical manikin and includes the following three operating modes:

a) Controlled surface temperature (constant temperature mode): generally, the surface temperature of all segments is maintained at 34 °C (see ISO 14505-2).

b) Controlled heat generation (constant heat flux mode): this method uses a metabolic rate to represent the heat flux for all segments. An example of the metabolic rate during vehicle driving is shown in ISO/TS 14505-1 and ISO 8996. Note that this method is less commonly used than the other two.

c) Described by comfort equation (comfort equation mode): generally, the parameter values for all segments in this mode are t_{cr} = 36,4 °C and R_{cr} = 0,054 m^2°C/W[3].

7.3.2 Calculation of heat exchange

The primary problem for the heat transfer calculation is determining the appropriate treatment of the boundary condition on the surface of the manikin. Once this has been designated, the following treatments can be used:

a) Flow field, radiant field and heat transfer on the surface of the manikin are solved simultaneously. The temperature distribution is calculated directly by solving for entrainment of heat in the boundary layer; however, the convective heat transfer coefficient is not explicitly calculated. In this case, the grid size near the surface should be small enough to resolve the heat transfer (the boundary layer). Otherwise, a well-tuned wall function developed to calculate the heat transfer near the solid boundary should be adopted.

b) The convective and mean radiant heat transfer coefficients are treated as known values. In this case, the grid structure near the surface can be determined only to calculate the flow field, resulting in coarser grids compared to the prior treatment (a).

Regardless of the calculation method used, flow field calculations should account for buoyancy effects when the air velocity is small (i.e. less than 0,1 m/s). As such, the air motion should be calculated via coupling with the heat transfer equation.

7.4 Calculation of h_{cal}

Three methods of calculating and defining the value of h_{cal} are considered:

a) Apply the CFD calculation to standard conditions to obtain the “calibrated” characteristics of h_{cal}. Informative concrete treatments for this are presented in Annex E.

b) Adopt measured data gleaned using a physical manikin corresponding to the “numerical manikin”. Practical measurement methods for this item are detailed in ISO 14505-2.

c) Estimate it using Formula (10) in 8.3.

7.5 Calculation outputs

The input and output data to or from the numerical manikin is shown in Table 2. The informative concrete treatments used to calculate the equivalent temperature are presented in Annex B.

Table 2 — Input and output to or from the numerical manikin

Control principle	Inputs	Outputs
Constant temperature mode ($T_{sk,n} = T_{skset}$)	T_{skset}, $I_{cl,n}$	Q_n
Constant heat flux mode ($Q_n = Q_{set}$)	Q_{set}, $I_{cl,n}$	$T_{sk,n}$
Comfort control mode ($Q_n = (T_{cr} - T_{sk,n})/R_{cr}$)	T_{cr}, R_{cr}, $I_{cl,n}$	$T_{sk,n}$, Q_n