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The P.E.T. comfort index: Questioning the model

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ABSTRACT

This work is a first thorough presentation of the widely used PET (*Physiological Equivalent Temperature*) comfort index. It underlines the simplifications made in solving the equation system for the PET and proposes a correction of the errors in the widespread version of the PET calculation routine. A comparison of the corrected model with a stringent solving of the equation system is made: as a result, the PET calculated after the original method introduces a bias of − 0.5 to + 2.3 [K] in the studied conditions (operative temperature, high mean radiant temperature and windy environments).

The original vapour diffusion model is also examined and shows no dependency to the clothing level. The comparison with a state-of-the-art vapour transfer model exhibits a significant − 7 to + 2.6 [K] discrepancy with the corrected PET model in the aforementioned studied conditions. Links to the two versions of the code are provided in the appendix.

1. Introduction

The PET comfort index is based on the original work by Refs. [1,2] and used as a reference in the German norm VDI [3], which provides a base for the source code of the GrassHopper/LadyBug tool [4]. Over the past decade it has been used in numerous case studies [5–9].

This comfort index is based on a "two-node model" of the human thermoregulation system after [10,11], from which the *Standard Effective Temperature* (SET*) was derived. Such models yield the key parameters in the estimation of comfort: core temperature, skin temperature and skin wettedness resulting from the exposition to the environment considered.

The principle of these is to retrieve the temperature of a reference environment that would provoke the same physiological response as the studied environment. For both the PET and SET*, the reference environment is very similar to an office: low air velocities (respectively 0.13 [m.s^{-1}] and 0.1 [m.s^{-1}]), 50% relative humidity (or 1200 [Pa] for PET). The metabolic level for PET is composed of 80 [W] activity plus the basal metabolism which depends on the age, gender and morphology of the subject.

The main difference between the SET* and PET* comfort indexes are following:

- The SET* is the air temperature in the reference environment yielding the same skin temperature and skin wettedness as the actual environment, whereas the PET is the air temperature in the reference environment yielding the same skin and core temperatures as the actual environment.
- The PET clothing level is set at 0.9 [clo] for the standard environment, whereas the SET* clothing level is calculated to match the activity level.
- The SET* is calculated after a transient calculation where the two-node model of metabolism is exposed to the conditions for which comfort has to be evaluated. The PET may be calculated in both steady and unsteady conditions of the metabolism (it the latter case it is used with the IMEM "*Instationary Munich Energy balance Model*" [2,12]). In this work, we examinate the steady-state calculation.

In comparison with the well-known PMV index [13] that uses a thermal sensation scale, the results of the PET and SET* are easier to understand as they represent a temperature. The PET is also adapted to evaluating outdoor environment where thermal discomfort can be high, whereas the PMV was constructed for the indoor space. Moreover, results provided by the PMV are to be taken with care when out of the temperature range for which it has been established (*id est* 10 to 40[°C] of radiant temperature [13]).

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To the best of the authors' knowledge, the original development of the PET [14] can only be found as hard copy. Details of the model can otherwise only be read partially in Refs. [1–3] or decrypted from the code in the appendix of [3,9].[1] Therefore it is justified to expose the model thoroughly first, showing the assumptions made when solving for the PET. Discrepancies that result from the simplifying assumptions and shortcomings of the model are exposed in the second part of the article.

The purpose and objectives of this paper are hence the following:

- Provide an exhaustive description of the model and its original resolution (respectively in sections 2 and 3)
- Underline the errors of the widespread PET routine used in Refs. [3,4,9] (in section 3.3) and provide a corrected version (in the Appendix B.2)
- Compare the simplified resolution used in the original model with a stringent resolution of the equation system for the PET (in section 4.2)
- Compare the effect of the original vapour diffusion model with a state-of-the-art one (in section 4.3) and provide the corresponding routine (in the Appendix B.3)

2. Description of the two-node model

A common approach for the evaluation of comfort in semi-outdoor spaces is to use a model of the human metabolism represented as two concentric-cylinders for core and skin compartments, as described in the work of [10,11]. An updated version can also be found in Ref. [15]. All equations in this section originate from the code in the appendix of [3], unless specified otherwise.

2.1. Heat transfer with the environment

The metabolic internal energy is calculated after the basal metabolism and the activity of the subject. The basal metabolism M depends on the mass m, height H and age for male (Equation (1)) and female individuals (Equation (2)):

$$M_m = 3.45 \times m^{0.75} \left(1 + 0.004\,(30.0 - \text{age}) + 0.01\left(H\frac{100}{m^{1/3}} - 43.4\right)\right)\ [\text{W}] \tag{1}$$

$$M_f = 3.19 \times m^{0.75} \left(1 + 0.004\,(30.0 - \text{age}) + 0.018\left(H\frac{100}{m^{1/3}} - 42.1\right)\right)\ [\text{W}] \tag{2}$$

The heat exchange occurring when the air is heated or cooled by the lungs at core temperature as well as the mass exchange with the ambient air are also taken into account. The breathing flow rate q_m^resp is dependent on the activity level M [W.m^{-2}]:

$$q_\text{m}^\text{resp} = M \times 1.44 \times 10^{-6}\ \left[\text{kg.m}^{-2}.\text{s}^{-1}\right] \tag{3}$$

The temperature of the air expired T_exp is correlated to the ambient air temperature T_a:

$$T_\text{exp} = 0.47 \times T_a + 21.0\ [°\text{C}] \tag{4}$$

The sensible heat loss C_resp is then calculated with the temperature difference between inspired and expired air and the air specific heat capacity c_a:

$$C_\text{resp} = c_\text{a} q_\text{m}^\text{resp} \times \left(T_a - T_\text{exp}\right)\ \left[\text{W.m}^{-2}\right] \tag{5}$$

As for latent heat transfer, it is assumed that the air is saturated with humidity when exiting the lungs at temperature T_exp (Equation (4)) (air close to saturation or saturated was measured by Ref. [16]). The vapour pressure of air expired $p_\text{v exp}$ is calculated after the correlation for saturated vapour pressure:

$$p_\text{v exp} = 611 \times 10^{7.45 \times \frac{T_\text{exp}}{235 + T_\text{exp}}}\ [\text{Pa}] \tag{6}$$

The latent heat transfer E_resp is then calculated with the difference of vapour pressures as:

$$E_\text{resp} = 0.623 \times \frac{p_\text{v} - p_\text{v exp}}{p} L_\text{v} q_\text{m}^\text{resp}\ \left[\text{W.m}^{-2}\right] \tag{7}$$

where p is the atmospheric pressure and L_v the latent heat of vaporization.

Actually the heat exchange by breathing Q_resp is the sum of the sensible and latent heat fluxes: $Q_\text{resp} = C_\text{resp} + E_\text{resp}$. Equations (5) and (7) are simplified versions of the actual breathing heat transfer, however with a correct level of approximation (a detailed analysis is given in Appendix A).

The body surface is calculated after the Dubois surface A in square meters, depending on the body mass m and height H, described in Equation (8).

$$A = 0.203 m^{0.425} \times H^{0.725}\ \left[\text{m}^2\right] \tag{8}$$

The surfaces of exchange with the ambient conditions are split into bare and clothed areas. The fraction of the body covered by clothes is given by following correlation, depending on the clothing level i_cl in clo:

$$f_\text{acl} = \frac{173.51 \times i_\text{cl} - 2.36 - 100.76 \times i_\text{cl}^2 + 19.28 \times i_\text{cl}^3}{100} \tag{9}$$

The bare area A_bare is a fraction of the clothed surface:

$$A_\text{bare} = A \times \left(1 - f_\text{acl}\right)\ \left[\text{m}^2\right] \tag{10}$$

At the surface of the body, convection and radiation losses are proportional to the clothing surface A_cl, which is calculated by subtracting the surface of the bare cylinder $A \times (1 - f_\text{acl})$ to the clothing surface Af_cl :

$$A_\text{cl} = A \times f_\text{cl} - A \times \left(1 - f_\text{acl}\right)\ \left[\text{m}^2\right] \tag{11}$$

In Equation (11) the term f_cl is the Burton coefficient that describes the linear increase of heat exchange area with clothing level i_cl (the increase can also be a piecewise linear function [17,18]):

$$f_\text{cl} = 1 + 0.31 \times i_\text{cl} \tag{12}$$

The heat flux through the clothing is calculated after Fourier's law through a cylinder. The internal and external radius of the cylinder are required. Let r_a be the inside radius of clothing. For an individual height of H and a clothed fraction of body y, the clothed area is the one of a cylinder of height $H \times y$ and is equal to the total surface of the body mul-

[1] The Python source code for PET calculation can also be downloaded on Github.

tiplied by the fraction covered by clothing $A \times f_{\mathrm{acl}}$:

$$2\pi r_{\mathrm{a}} H y = A f_{\mathrm{acl}} \tag{13}$$

In the original PET model, the clothed fraction of body varies in dependency with the level of clothing i_{clo} after following relationships:

$$y = \frac{H - 0.2}{H} \quad \text{for} \quad 0.6 \le i_{\mathrm{cl}} \le 2 \tag{14}$$

$$y = 0.5 \quad \text{for} \quad 0.3 \le i_{\mathrm{cl}} \le 0.6 \tag{15}$$

$$y = 0.1 \quad \text{for} \quad i_{\mathrm{cl}} \le 0.3 \tag{16}$$

The exterior radius of the clothing cylinder of radius r_{b} and height $H \times y$ is calculated as follows:

$$2\pi r_{\mathrm{b}} H y \quad = \quad A \times \left(f_{\mathrm{cl}} - 1 + f_{\mathrm{acl}} \right) \tag{17}$$

$$= A \times \left(0.31 \times i_{\mathrm{clo}} + f_{\mathrm{acl}} \right) \tag{18}$$

The bare area is the surface of the internal cylinder of radius r_{a} and height H that is not covered with clothing:

$$A_{\mathrm{bare}} = 2\pi r_{\mathrm{a}} \times H\,(1 - y) \tag{19}$$

The clothing heat transfer conductance is calculated after Fourier's law through a cylinder:

$$h_{\mathrm{cl}} = \frac{2\pi H y \lambda_{\mathrm{cl}}}{A_{\mathrm{cl}} \ln \left(r_{\mathrm{b}} / r_{\mathrm{a}} \right)} \left[\mathrm{W.m^{-2}.K^{-1}} \right] \tag{20}$$

The equivalent conductivity of clothing, λ_{cl} is calculated using the clothing thickness $r_{\mathrm{b}} - r_{\mathrm{a}}$:

$$\lambda_{\mathrm{cl}} = \frac{r_{\mathrm{b}} - r_{\mathrm{a}}}{i_{\mathrm{cl}} \times 0.155} \left[\mathrm{W.m^{-1}.K^{-1}} \right] \tag{21}$$

At the clothing and skin surface, the convection heat transfer coefficient h_{c} is calculated after correlation:

$$h_{\mathrm{c}} = 2.67 + 6.5 \times v^{0.67} \; \left[\mathrm{W.m^{-2}.K^{-1}} \right] \tag{22}$$

Convection losses are calculated for both bare (C_{bare}) and dressed areas of the body (C_{clo}), depending on air, skin and clothes temperatures, such that:

$$C_{\mathrm{bare}} = h_{\mathrm{c}} \times \left(T_a - T_{\mathrm{sk}} \right) \times \frac{A \times \left(1 - f_{\mathrm{acl}} \right)}{A} \; \left[\mathrm{W.m^{-2}} \right] \tag{23}$$

$$C_{\mathrm{clo}} = h_{\mathrm{c}} \times \left(T_a - T_{\mathrm{cl}} \right) \times \frac{A_{\mathrm{cl}}}{A} \; \left[\mathrm{W.m^{-2}} \right] \tag{24}$$

Before calculating radiation losses, the fraction of the body effectively subject to radiation is defined as f_{eff}. It is a reduction factor that depends on the position of the individual. The effective radiative area is then $A \times f_{\mathrm{eff}}$. The radiation losses R_{bare} of the bare fraction of the body, temperatures being expressed in Kelvin, is as follows:

$$R_{\mathrm{bare}} = \frac{A f_{\mathrm{eff}} \left(1 - f_{\mathrm{acl}} \right)}{A} \varepsilon_{\mathrm{sk}} \sigma \times \left(T_{\mathrm{mrt}}^4 - T_{\mathrm{sk}}^4 \right) \; \left[\mathrm{W.m^{-2}} \right] \tag{25}$$

In equation (25) $\varepsilon_{\mathrm{sk}}$ is the emissivity of skin and σ is the Stefan-Boltzmann constant.

Radiation losses of the clothed fraction of the body R_{clo} with a clothing emissivity $\varepsilon_{\mathrm{cl}}$ are such that:

$$R_{\mathrm{clo}} = \frac{A_{\mathrm{cl}}}{A} f_{\mathrm{eff}} \varepsilon_{\mathrm{cl}} \sigma \times \left(T_{\mathrm{mrt}}^4 - T_{\mathrm{cl}}^4 \right) \; \left[\mathrm{W.m^{-2}} \right] \tag{26}$$

The heat transfer from the core to the skin layer occurs in parallel *via* conduction through the skin with a heat transfer coefficient U_{sk} along with blood flow q_{b} which creates an additional flux (these terms are explained in Section 2.2).

A representation of heat transfer through the body shell is drawn with the equivalent electrical scheme on Fig. 1. On the left-hand side of the figure, one can observe the parallel heat transfer resistances between core (T_{c}) and skin (T_{sk}) related to tissue conductance and blood flow. On the right-hand side of Fig. 1, the heat transfer resistance between the skin temperature and the environment at air temperature T_{a} and radiant temperature T_{mrt} is drawn: the lower two resistances represent the convective and radiative heat transfer resistance between skin and environment; the upper part includes the clothing layer resistance R_{cl} in between skin and environment.

2.2. Thermal control of the body

The physiological control model of the PET is based on the Pierce two-node model [10]. It can be seen as a thermally regulated system evolving in response to the temperature difference with the skin, core and body set temperatures. Vasomotricity and sweating are the two main phenomena used for temperature control. The shivering effects presented for instance in Refs. [1,11] are not used in the original version of the routine [3].

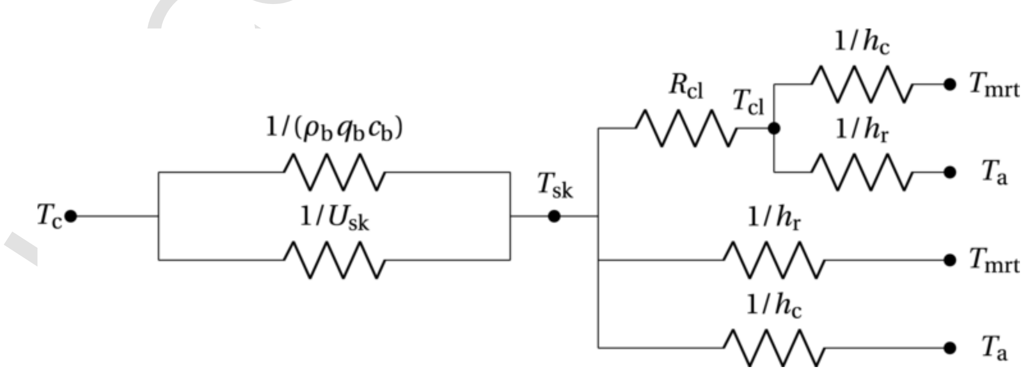

Fig. 1. Equivalent electrical scheme for the steady-state heat transfer from core to skin.

The blood flow rate q_{b} is ruled by the difference of both skin and core temperatures with their set values $T_{\mathrm{sk}}^{\mathrm{set}}, T_{\mathrm{c}}^{\mathrm{set}}$ as per Equation (27):

$$q_{\mathrm{b}} = \frac{q_{\mathrm{b}}^{\mathrm{set}} + C_d\left(T_{\mathrm{c}} - T_{\mathrm{c}}^{\mathrm{set}}\right)}{1 + C_s\left(T_{\mathrm{sk}}^{\mathrm{set}} - T_{\mathrm{sk}}\right)}\Bigg)\left[\mathrm{L.m^{-2}.h^{-1}}\right] \tag{27}$$

The coefficients C_d and C_s relate to the dilation and constriction phenomena. The control mechanism is such that the temperature differences are set to zero in Equation (27) when they are negative. The upper limit of blood flow is set at 90 [L.m^{-2}.h^{-1}] where as the set value $q_{\mathrm{b}}^{\mathrm{set}}$ is 6.3 [L.m^{-2}.h^{-1}].

The body temperature T_{b} is the weighted average of skin and core temperature:

$$T_{\mathrm{b}} = 0.1 \times T_{\mathrm{sk}} + 0.9 \times T_{\mathrm{c}} \ \ [^{\circ}\mathrm{C}] \tag{28}$$

In the VDI norm, the mass fraction of body composed of skin or core is constant and does not depend on blood flow, hence it does not affect the calculation of T_{b}, unlike in the transient two-node model in Refs. [10,11,19]. Equation (28) has a major influence insofar as it provides the temperature at which the sweating latent heat flux begins.

Sweating is controlled by the body temperature, triggering the production of sweat depending on the discrepancy with the body set temperature and the sweating coefficient $C_{\mathrm{sw}} = 304.94 \times 10^{-3}$ [kg.m^{-2}.h^{-1}.K^{-1}] as per:

$$q_{\mathrm{m}}^{\mathrm{sw}} = C_{\mathrm{sw}} \times \left(T_{\mathrm{b}} - T_{\mathrm{b}}^{\mathrm{set}}\right) \ \left[\mathrm{kg.m^{-2}.h^{-1}}\right] \tag{29}$$

In the original model [1,3], an additional coefficient of 0.7 applies to Equation (29) for female individuals.

The evaporation E_{sw} at skin surface depends on the production of sweat and on the latent heat L_{v}:

$$E_{\mathrm{sw}} = L_{\mathrm{v}} \frac{q_{\mathrm{m}}^{\mathrm{sw}}}{3600} \ \ \left[\mathrm{W.m^{-2}}\right] \tag{30}$$

The maximum heat flux E_{max} that could evaporate from the skin at saturated vapour pressure $p_{\mathrm{vs}}(T_{\mathrm{sk}})$ to the given environment at a vapour pressure p_{a} is depending on the vapour transfer efficiency F_{pcl} and the latent heat transfer coefficient he:

$$E_{\mathrm{max}} = L_v F_{\mathrm{pcl}} f_{\mathrm{cl}} h_e \left(p_{\mathrm{vs}}\left(T_{\mathrm{sk}}\right) - p_{\mathrm{a}}\right) \ \left[\mathrm{W.m^{-2}}\right] \tag{31}$$

In the literature, the vapour transfer efficiency factor F_{pcl} of Equation (31) is often expressed as follows [19] (see also the detailed explanation of [20]):

$$F_{\mathrm{pcl}} = \frac{1}{1 + \frac{f_{\mathrm{cl}} h_e}{h_{\mathrm{e\ cl}}}} \tag{32}$$

The latent heat transfer coefficient h_{e} in [W.m^{-2}.Pa^{-1}] is given after the Lewis relation LR such that:

$$h_{\mathrm{e}} = LR \times h_{\mathrm{c}} \tag{33}$$

The Lewis relationship LR is calculated after the analogy between heat and mass transfer [21].

$$LR = \frac{L_v}{\rho C_p K} \frac{M_{\mathrm{w}}}{RTLe^{\frac{2}{3}}} = \frac{L_v}{\rho C_p K} \frac{D^{\frac{2}{3}}}{\alpha^{\frac{2}{3}}} \times \frac{M_{\mathrm{w}}}{RT} \ \ \left[\mathrm{K.Pa^{-1}}\right] \tag{34}$$

In general the Lewis ratio stands by $LR \sim 0.0165$ [K.Pa^{-1}]. The K factor in Equation (34) accounts for molecular counter diffusion of dry air against the flow of water vapour and is generally comprised around 4% of the vapour flow [21]. The calculation for ambient conditions of 20C/50% relative humidity and a saturated skin at 34C yields $K = 1.049$ (detailed explanations of the calculation can be found in Chapter 6 of [22]).

In the code provided along the VDI norm, the relationship for the evaporative heat transfer coefficient is given after Equation (35) for which no reference could be found:

$$h_{\mathrm{e}} = 0.633 \times \frac{h_{\mathrm{c}}}{p_{\mathrm{atm}} c_{\mathrm{a}}} \ \ \left[\mathrm{W.Pa^{-1}}\right] \tag{35}$$

This expression yields an order of magnitude of the Lewis ratio, however it is generally $\sim$10% below the values given by Equation (34).

The total latent flux E_{tot} at skin surface is then the sum of the sweating and diffusion phenomena:

$$E_{\mathrm{tot}} = E_{\mathrm{diff}} + E_{\mathrm{sw}} \tag{36}$$

In order to calculate the diffusion losses E_{diff}, the skin wettedness w is introduced. It represents the ratio of the latent flux dissipated by sweat at the surface of skin E_{tot} against the maximum latent flux E_{max}.

$$w = \frac{E_{\mathrm{tot}}}{E_{\mathrm{max}}} \tag{37}$$

If the skin wettedness w is greater than one it is set to unity and the latent flux is at the surface of skin is such that $E_{\mathrm{sw}} = E_{\mathrm{max}}$. Otherwise diffusion occurs through the so called "non-wetted" part of skin $(1 - w)$ and following relation applies in the VDI norm:

$$E_{\mathrm{diff}} = \frac{L_{\mathrm{v}} \times (1 - w)\left(p_{\mathrm{vs}}\left(T_{\mathrm{sk}}\right) - p_{\mathrm{v}}\right)}{R_{\mathrm{d}}} \ \ \left[\mathrm{W.m^{-2}}\right] \tag{38}$$

The resistance to vapour diffusion R_{d} of Equation (38) is simply defined (without supporting justification) as a constant $R_{\mathrm{d}} = 0.79 \times 10^{7}$ [Pa.s.kg^{-1}], for which no reference could be found. We speculate that this might be a skin tissue vapour diffusion coefficient, however this formulation is surprising as it would take the vapour pressure at skin temperature instead of tissue temperature and neglects the effect of clothing on vapour diffusion.

A generic formulation for the vapour diffusion heat loss from the non-wetted surface of skin would be following [20]:

$$E_{\mathrm{diff}} = \frac{(1 - w)\left(p_{\mathrm{vs}}\left(T_{\mathrm{sk}}\right) - p_{\mathrm{v}}\right)}{R_{\mathrm{e}}} \ \ \left[\mathrm{W.m^{-2}}\right] \tag{39}$$

Equation (39) requires the computation of the evaporative resistance of the air and clothing layers R_{e} for example by the method thoroughly described in Ref. [20]. The evaporative resistance is computed after the heat transfer resistance of air R_{air} and clothing R_{cl} such that:

$$R_{\mathrm{e}} = \frac{R_{\mathrm{air}} + R_{\mathrm{cl}}}{LR \times i_m} \tag{40}$$

where R_{air} is the combined convective and linearized radiative heat transfer resistance and i_m is the Woodcock permeability index, generally taken at 0.38 [23].

3. Original solving of the model

In this section, the method for solving the PET equation described in the VDI norm is presented.

3.1. Governing equations

Höppe's representation of the human metabolism is also based on the Pierce two-node model as per [10,11]. Writing the heat flux equality through clothes that equals convection and radiation losses at the clothing surface, as per Fig. 1, one obtains:

$$\frac{\left(T_{\mathrm{sk}}-T_{\mathrm{cl}}\right)}{R_{\mathrm{cl}}} = h_{\mathrm{c}}\frac{A_{\mathrm{cl}}}{A}\left(T_{\mathrm{cl}}-T_{\mathrm{a}}\right) + \sigma\varepsilon_{\mathrm{cl}} f_{\mathrm{eff}}\frac{A_{\mathrm{cl}}}{A}\left(T_{\mathrm{cl}}^4-T_{\mathrm{mrt}}^4\right) \quad (41)$$

The second equation of the model is a balance on the core node. The algebraic sum of metabolic rate and respiratory losses equals the heat flux exchanged from core to skin by conduction and blood flowrate through the skin layer:

$$M+Q_{\mathrm{resp}} = \left(T_{\mathrm{c}}-T_{\mathrm{sk}}\right) \times\left(U+\rho_{\mathrm{b}}c_{\mathrm{b}}\times\frac{q_{\mathrm{b}}^{\mathrm{set}}+C_d\left(T_{\mathrm{c}}-T_{\mathrm{c}}^{\mathrm{set}}\right)}{1+C_s\left(T_{\mathrm{sk}}^{\mathrm{set}}-T_{\mathrm{sk}}\right)}\right) \quad (42)$$

In Equation (42), the right-hand side represents the heat transfer from the inside of the body towards the surface of the skin via the flesh equivalent conduction U and blood flow q_{b}. The left-hand side stands for the metabolic heat production rate M as well as the sensible and latent losses by breathing.

The third equation of the model is a global steady-state balance on the body, summing metabolic activity, convection, radiation, sweating, diffusion losses and respiratory losses:

$$M+C+R+E_{\mathrm{sw}}+E_{\mathrm{diff}}+Q_{\mathrm{resp}}=0 \quad (43)$$

where C and R stand for the convection and radiation on both the clothed and bare fractions of the body. Equation (43) intrinsically contains the metabolic reactions of temperature regulation of the body in the considered.

When T_{c} and T_{sk} resulting from the studied environment are known the air and clothing temperatures are iteratively adjusted such that Equation (43) equals zero, the body being in the reference environment described in Section 1. The air temperature obtained is the PET.

Using the hypothesis that the three unknown temperatures T_{c},T_{sk},T_{cl} are independent, solving for the each of them separately is possible. In order to reduce the numerical complexity of the problem, the original version of the code developed by Höppe, and provided along with [3], neglects the dependency between core and skin temperature with their environment. The influence of the environment on the body temperatures appears only through the calculation of T_{sk}.

3.2. Second-order polynomials for thermoregulation cases

Making the assumption that equations are independent reduces the problem to solving the second order polynomial (42) with T_{c} being the unknown. The skin temperature is supposed constant during the iteration and the procedure repeats over the whole system until convergence is reached. The different polynomials that correspond to the thermoregulation possibilities depending on vasomotricity are presented in this paragraph.

- Set value of the blood flow rate: In this situation, the balance equation simplifies to the following:

$$\left(T_{\mathrm{c}}-T_{\mathrm{sk}}\right)\times\left(U_{\mathrm{sk}}+\rho_{\mathrm{b}}c_{\mathrm{b}}\times q_{\mathrm{b}}^{\mathrm{set}}\right) = M+Q_{\mathrm{resp}} \quad (44)$$

- Maximum blood flow rate: following equation represents the maximum blood flow rate configuration in Höppe's original code:

$$\left(T_{\mathrm{c}}-T_{\mathrm{sk}}\right)\times\left(U_{\mathrm{sk}}+\rho_{\mathrm{b}}c_{\mathrm{b}}\times q_{\mathrm{b}}^{\mathrm{max}}\right) = M+Q_{\mathrm{resp}} \quad (45)$$

- Set value of blood flow and cold signal from the skin. In this case, the general equation reads:

$$\left(T_{\mathrm{c}}-T_{\mathrm{sk}}\right)\times\left(U_{\mathrm{sk}}+\rho_{\mathrm{b}}c_{\mathrm{b}}\times\frac{q_{\mathrm{b}}^{\mathrm{set}}}{1+C_s\left(T_{\mathrm{sk}}^{\mathrm{set}}-T_{\mathrm{sk}}\right)}\right) = M+Q_{\mathrm{resp}} \quad (46)$$

The striction constant is taken as $C_s = 0.5$ [K^{-1}].

- In the case of pure vasodilatation, Equation (42) reduces to a second order polynomial such that:

$$aT_{\mathrm{c}}^2+bT_{\mathrm{c}}+c=0 \quad (47)$$

In Equation (47), the coefficients a,b,c are as:

$$a=C_d\rho_{\mathrm{b}}c_{\mathrm{b}} \quad (48)$$

$$b=U_{\mathrm{sk}}-T_c^{\mathrm{set}}\times C_d\rho_{\mathrm{b}}c_{\mathrm{b}}-C_d\rho_{\mathrm{b}}c_{\mathrm{b}}T_{\mathrm{sk}} \quad (49)$$

$$c=-\left(M+Q_{\mathrm{resp}}\right)+T_c^{\mathrm{set}}\times C_d\rho_{\mathrm{b}}c_{\mathrm{b}}T_{\mathrm{sk}}-U_{\mathrm{sk}}\times T_{\mathrm{sk}} \quad (50)$$

- When vasodilation and constriction occur, a similar second order polynomial can be derived and the coefficients a,b,c of Equation (47) take following values:

$$a=C_d\rho_{\mathrm{b}}c_{\mathrm{b}} \quad (51)$$

$$b=U_{\mathrm{sk}}\times C_s\left(T_{\mathrm{sk}}^{\mathrm{set}}-T_{\mathrm{sk}}\right)-T_c^{\mathrm{set}}\times C_d\rho_{\mathrm{b}}c_{\mathrm{b}}-C_d\rho_{\mathrm{b}}c_{\mathrm{b}}T_{\mathrm{sk}} \quad (52)$$

$$c=-\left(M+Q_{\mathrm{resp}}\right)\times C_s\left(T_{\mathrm{sk}}^{\mathrm{set}}-T_{\mathrm{sk}}\right)-T_{\mathrm{sk}}U_{\mathrm{sk}} \times C_s\left(T_{\mathrm{sk}}^{\mathrm{set}}-T_{\mathrm{sk}}\right)+T_c^{\mathrm{set}}\times C_dT_{\mathrm{sk}}\rho_{\mathrm{b}}c_{\mathrm{b}} \quad (53)$$

The results of this modelling choice will be presented in Section 3.3 and compared with the stringent solving of the equation system.

3.3. Errors in the existing procedures for the PET calculation

In the original formulation of the code, several typos can be corrected (see respectively appendix B1 and B2). The code provided at the end of [3,9] or used in the PET routine of [4] contains moreover three major errors:

- the metabolic activity level is kept as the one of the real environment whereas it should be defined as 80 [W], the term M of Equation (43) is hence incorrect,
- the breathing sensible and latent losses are defined after the activity level are subsequently incorrect as it depends on the activity level as per Equation (3),
- the vapour transfer E_{max} is calculated for the clothing level of the real environment whereas it should be calculated with 1200 [Pa] and a clothing level of 0.9 [clo]. The calculation of w and E_{diff} are subsequently affected.

The procedure was subsequently amended to include a correction of the errors mentioned above (it can be found in the appendix B.2). The results obtained were compared to the reference values published in Ref. [2] for 80 [W] activity and a clothing level of 1 [clo]. They are presented in Table 1 and present a difference lying between − 3.8% and + 10.1%, respectively for summer, shady conditions and winter, windy conditions.

The original PET resolution was then compared to the corrected version for various ambient conditions and both methods tend to produce similar results. However, ambient conditions referring to a high mean radiant temperature present a more significant difference: on Fig. 2, the PET is plotted on the psychrometric chart for a mean radiant temperature taken 30 [K] above the air temperature whereas the wind velocity remains at a 0.2 [m.s^{-1}] (for instance in the case of a ~800 [W.m^{-2}] incident solar radiation and still air). The iso-value lines of the original PET are slightly overestimating compared to the corrected version. This relates to the fact that, unlike in the amended procedure, the skin wettedness is not calculated again in the original version, which affects the latent heat flux *via* evaporation at skin surface. A similar trend can be observed in operative temperature conditions as well as windy conditions, with lower differences between the VDI method and its correction.

Another simplification was made for the solving of the equations: the three temperatures T_c,T_{sk},T_{cl}, are supposed to be independent, which means the coupling between skin and core temperatures is not considered in the model. Next section deals with this aspect of the subject.

4. Comparisons with an improved model

In this Section, the method for calculating the PET from the coupled system of equations is first presented. The results obtained with the original method, presented in Section 3 (including the correction of errors mentioned in Section 3.3) are then compared to the PET obtained with the coupled system of equations. As the original vapour diffusion model appears to be insensitive to the level clothing, an improvement of the equation for diffusion is proposed. The results are compared with those of the corrected original model.

4.1. Resolution of the non-linear model

In steady-state, heat flows from the core to the ambient atmosphere through the skin layer and the bare skin according to the equivalent electric scheme presented on Fig. 1. The skin, core and clothing temperatures are dependent on each other, resulting in a system of three equations.

The core node equation is the algebraic sum of metabolic rate, respiratory losses and core to skin heat transfer:

$$M + Q_{\mathrm{resp}} - \left(\rho_{\mathrm{b}} q_{\mathrm{b}} c_{\mathrm{b}} + U_{\mathrm{sk}}\right) \times \left(T_c - T_{\mathrm{sk}}\right) = 0 \tag{54}$$

The heat balance on the skin node shows the equality between the heat flux from core to skin and the heat transferred from skin to the environment, either directly for bare skin or through the clothing:

$$\begin{aligned} &R_{\mathrm{bare}} + C_{\mathrm{bare}} + E_{\mathrm{tot}} + \left(\rho_{\mathrm{b}} q_{\mathrm{b}} c_{\mathrm{b}} + U_{\mathrm{sk}}\right) \\ &\quad \times \left(T_c - T_{\mathrm{sk}}\right) - h_{\mathrm{cl}} \times \left(T_{\mathrm{sk}} - T_{\mathrm{cl}}\right) = 0 \end{aligned} \tag{55}$$

The balance on the clothing node yields the equality of flux between the clothed fraction of skin and the environment:

$$C_{\mathrm{clo}} + R_{\mathrm{clo}} + h_{\mathrm{cl}} \times \left(T_{\mathrm{sk}} - T_{\mathrm{cl}}\right) = 0 \tag{56}$$

The system of equations (54)–(56) is non-linear as the coefficients q_{b} and E_{sw}, representing the human thermal regulation in Equation (54), depend on the values of T_{sk} and T_{c} as described previously. This crossed non linear system is solved with a hybrid Powell scheme from the standard Python function *fsolve* (the routine used is provided in appendix B.3).[2]

After the values for T_{cl}, T_{sk} and T_{c} are known, the PET is calculated by dichotomy, solving for the steady state Equation (43) with the reference ambient conditions defined in Section 1. The dichotomy method proves to be efficient in this case as it only requires a search interval instead of an initial value. The PET calculation can be illustrated in following frame:

$$\text{Steps}\begin{cases} \text{Calculation of } T_{\mathrm{c}}, T_{\mathrm{sk}}, \text{ and} T_{\mathrm{cl}} \text{with a Powell} \\ \text{Solving for the operative temperature such that E} \\ \text{in the reference} \end{cases}$$

4.2. Influence of the resolution method

Three situations are examined in order to evaluate the influence of the numerical simplification on the resulting comfort. The calculated PET values are plotted on the psychrometric chart for an activity level of 80 [W] and 1 [clo] insulation of clothing. The skin diffusion losses E_{diff} were kept as per their original definition in Equation (38) and no amendments were made, except for the typos mentioned in appendix A2.

- **Operative temperature environment:** The original model was compared with the stringent resolution for "operative temperature" conditions, *id est* with no difference between the air temperature and the mean radiant temperature. The air velocity was chosen as v = 0.2 [m.s^{-1}]. Fig. 3 shows the difference between the two resolution methods in an operative temperature environment. Discrepancies can be observed of about − 0.5 to + 0.75 degree between the original model and the present work.
- **High mean radiant temperature environment:** the mean radiant temperature is taken 30 [K] higher than the air temperature and the wind velocity remains at a low value of 0.2 [m.s^{-1}]. These conditions could correspond to a ~800 [W.m^{-2}] solar radiation and still air. The iso-PET values drawn on Fig. 4 show that the PET computation after the VDI norm overestimates the PET value after the present work by

[2] Using a standard Newton-Raphson procedure proved to be inefficient: given the thermal regulation of metabolism and the dependency of skin and cloth temperature to the power of four, the algorithm is likely to diverge if an improper initial value of T_{cl} is chosen.

Table 1
PET values obtained with the corrected procedure compared to [2] for 80 [W] activity and 0.9 [clo].

T_{air} [C]	T_{mrt} [C]	V_{air} [m.s^{-1}]	p_v [hPa]	PET after [2]	Corrected PET	Difference [%]
21	21	0.1	12	21	21	0
−5	40	0.5	2	10	10.09	−0.9
−5	−5	5	2	−13	−11.69	10
30	60	1	21	43	42.70	0.2
30	30	1	21	29	28.95	−3.8

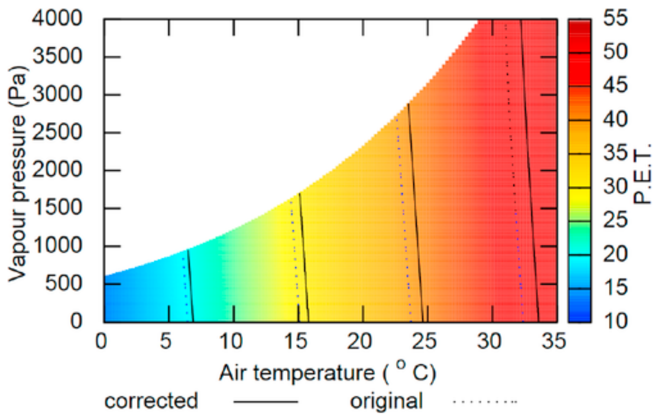

Fig. 2. High mean radiant temperature conditions - Original versus corrected PET. Iso-PET values: 20, 30, 40 and 50 °C.

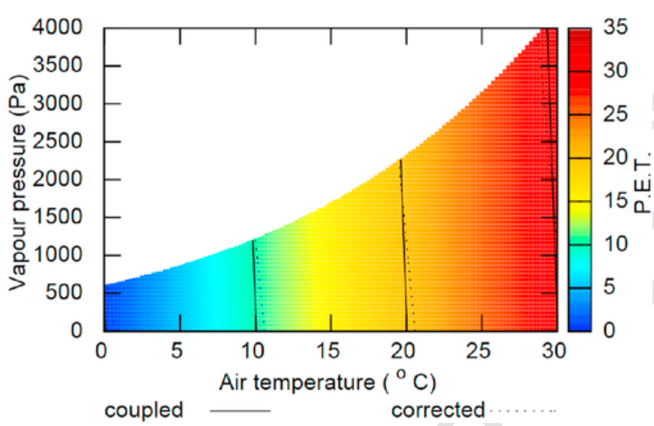

Fig. 3. Operative temperature conditions - PET after the corrected VDI versus present work. Iso-PET values: 0, 10, 20 and 30 °C.

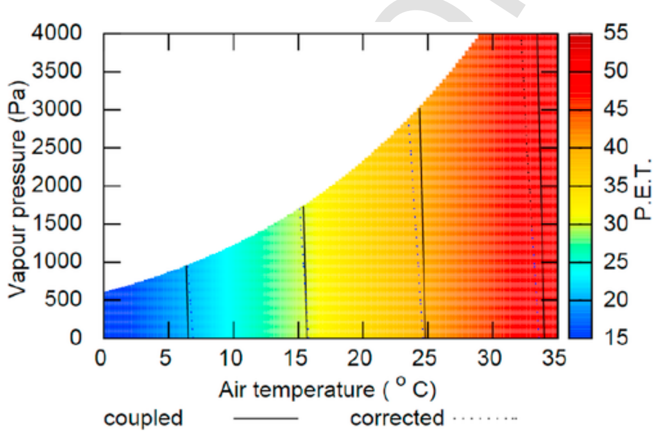

Fig. 4. High mean radiant temperature - PET after the corrected VDI versus present work. Iso-PET values: 20, 30, 40, 50 °C.

− 0.4 to ∼2 [K] at the maximum in environments with high mean radiant temperatures. The difference increases with elevated temperatures as well as elevated vapour pressures (*id est* high relative humidities).

- **Windy environment:** A comparison was also made between the classical PET and the stringent, coupled solution in an environment with an air velocity of 1.5 [m.s^{-1}] where air and mean radiant temperatures are equal. The results are presented on Fig. 5. In this situation, a similar tendency can be found between both methods and the PET deviates by about + 1 [K] at the maximum. In environments with high wind speed, the same trend can be observed: the classical calculation gives a slight overestimation of the PET calculated after the coupled system, as illustrated on Fig. 5. The difference ranges from − 0.4 [K] to 2.3 [K].

The method for resolution used in the original PET hence induces a bias evaluated between − 0.5 and + 2.3 [K] in the conditions studied. Surprisingly, the PET does not exhibit an important sensitivity to humidity: the iso-PET lines are almost vertical for both calculation methods. In the literature, the comfort indexes based on the same two-node model such as the ET* or SET* show a much stronger dependence to humidity (see the graphs in Refs. [11,20,24,25]). The weak influence of clothing and humidity on PET was also underlined by Ref. [26].

This behaviour can be explained by the equation chosen for the modelling of diffusion at skin surface and will be dealt with in the next Section.

4.3. Diffusion heat transfer E_{diff}

In this section, the diffusion heat flux E_{diff} was amended after Equation (39), corresponding to the state of the art [20], instead of using Equation (38) for which no justification could be found. Equation (39) also has the advantage of accounting for the clothing resistance to vapour transfer, which Equation (38) does not allow.

The results obtained for the two diffusion heat transfer models are shown for 0.5 [clo] and 1 [clo] clothing level on Fig. 6. The coupled resolution presented in Section 4.1 was used for the computation of the PET

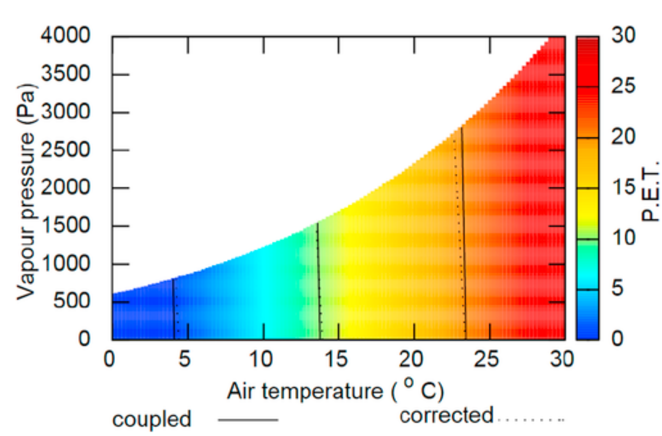

Fig. 5. Windy environment – PET after the corrected VDI versus present work. Iso-PET values: 0, 10, 20 °C.

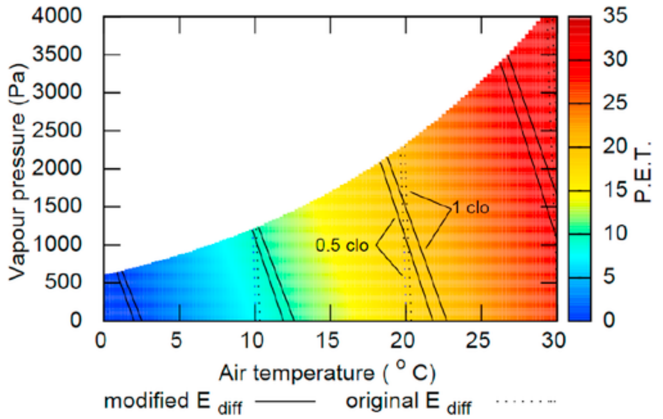

Fig. 6. Comparison of the original skin diffusion model versusE_{diff} after Equation (39) with and activity level of 80 [W].

to reduce the discrepancy induced by the numerical procedure. It can be seen on Fig. 6 that the iso-PET depend more strongly on humidity compared to the original formulation. The difference between 0.5 and 1 [clo] is also slightly narrower for the original E_{diff} model, whereas it is more significant for the diffusion model of Equation (39).

The influence of the choice of the diffusion model was compared for the three environments studied in Section 4.2. The same activity and clothing levels were used. The version of the PET routine provided in Appendix B.2 was used, including the corrections of errors mentioned in Section 3.3.

Operative temperature: In such environments, the influence of the diffusion model shows several degrees difference at high and low relative humidities (see Fig. 7). The difference between both methods ranges from − 4.8 to 2 [K].

High mean radiant temperature environment: The comparison of the methods for high mean radiant temperature environments presented on Fig. 8 range from − 7 to + 2.6 [K].

Windy environment: The comparison of the methods for windy environments presented on Fig. 9 range from − 3.6 to 2.2 [K].

In the studied conditions, the difference between the correct VDI and the coupled resolution with implementation of the diffusion heat transfer after Equation (39) ranges − 7 to + 2.6 [K]. The PET comfort zone being 5 [K] broad (from 18 to 23 °C PET is considered to be the range without thermal stress), this variation represents a significant discrepancy.

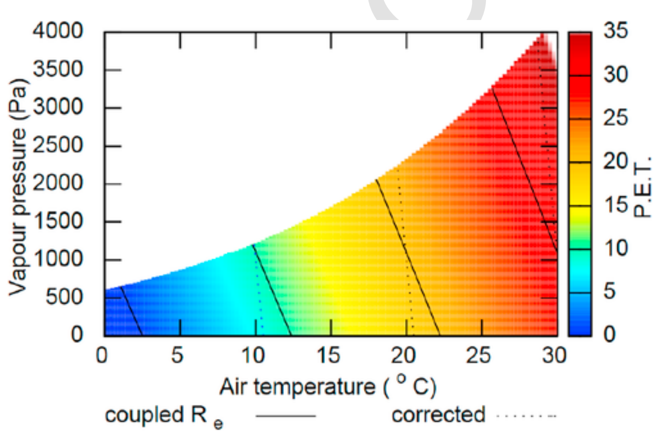

Fig. 7. Operative temperature environment – Original skin diffusion model versusE_{diff} after Equation (39). Iso-PET values: 0, 10, 20 and 30 °C.

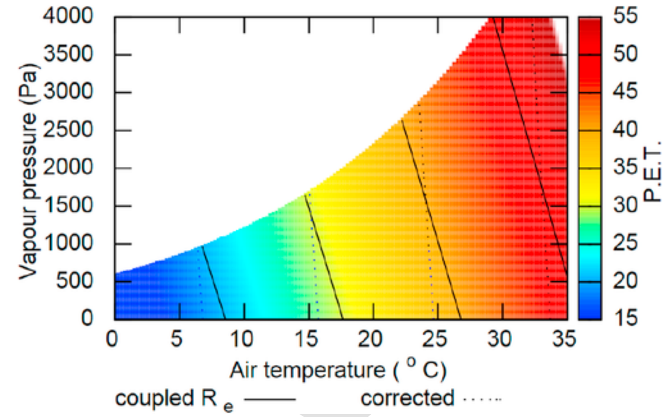

Fig. 8. High mean radiant temperature environment – Original skin diffusion model versusE_{diff} after Equation (39). Iso-PET values: 20, 30, 40 and 50 °C.

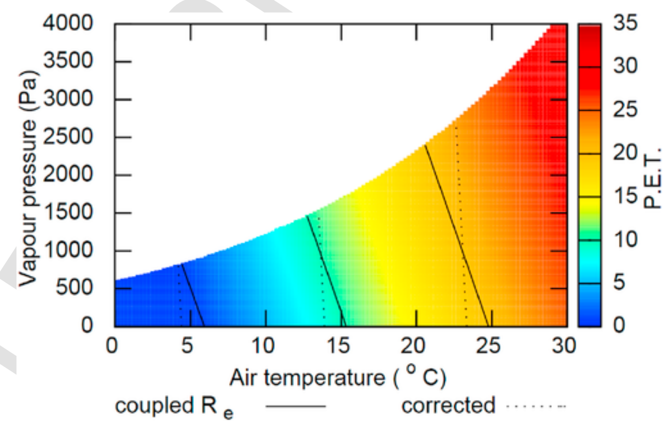

Fig. 9. Windy environment –Original skin diffusion model versusE_{diff} after Equation (39). Iso-PET values: 0, 10, 20 °C.

5. Conclusion & perspectives

This work presents a full description of the PET model, which can be partially found in different articles of the literature. The analysis of the model with reference publications proved that the code provided by the German VDI standard contains several errors.

The main findings of this work are the following:

- The procedures in Refs. [3,4,9] should not be used as they contain errors and incoherences. The authors of this paper present a revised version of the code (provided in Appendix B.2).
- Given the few available numerical tools at the time the PET outdoor comfort indicator was constructed, the simplified formulation of the problem is elegant. It allows for the resolution of the non-linear equation system yielding the physiological equivalent temperature, using second-order polynomials. However, for outdoor environments, the assumption that skin and core temperature are independent, as suggested at the end of [1], proved to be inaccurate given the numerical results obtained in this work. The influence on the calculated PET ranges from − 0.5 to + 2.4 [K] and is detailed in Section 4.2.
- The procedure used for resolution has a limited effect on accuracy, however using up to date tools for the resolution of non linear systems of equations proved to be faster by a factor of two versus the classical one, with a more readable and compact code. The coupled solving procedure for PET is provided in the appendix B.3 of the present work.
- The sensitivity to humidity of the original model is very low and can be explained by a surprising choice for the equation of vapour diffu-

sion that does not depend on the clothing level in the original PET model. The diffusion model should hence be modified for instance after the state of the art [20] (an implementation is provided in the code of Appendix B.3). The difference between both vapour diffusion models produces a significant variation in the PET, ranging from -7 [K] to $+2.6$ [K], as shown in Section 4.3.

It was shown that the heat and mass transfer dependency with ambient air velocity can cause an important shift of the comfort zone [18,23,27]. The heat and vapour transfer modelling in comfort indices should hence be improved after [18,23] to include wind effect on clothes properties. The PET vapour transfer model should also be modified, for instance after the state of the art [20].

The variety of constants found in the literature, *e.g.* regarding body set point temperatures [10,15] or dilatation/constriction coefficients for blood flow, leads us to think that variability should be taken into account when modelling the human metabolism, especially for comfort purposes [28–30] The impact of physiological variability on the dispersion of two-node-models-based comfort indexes is currently explored and will be presented in another work.

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Nomenclature

λ_{cl}	equivalent conductivity of cloth [W.m^{-1}.K^{-1}]
ρ_b	blood density = 1060 [kg.m^{-1}]
σ	Boltzmann's constant = 5.67×10^{-8}[W.m^{-2}.K.$^{-4}$]
ε_{cl}	emissivity of clothes = 0.95 [-]
ε_{sk}	emissivity of skin = 0.99 [-]
A	body surface after Dubois $A = 0.203m^{0.425}\times H^{0.725}$[m^2]
A_{bare}	bare surface of the body [m^2]
A_{cl}	clothed surface of the body [m^2]
c_a	specific heat capacity of air = 1010 [J.kg^{-1}.K^{-1}]
C_{bare}	Convection losses for bare area [W.m^{-2}]
c_b	specific heat capacity of blood = 4180 [J.kg^{-1}.K^{-1}]
C_{clo}	Convection losses for dressed area [W.m^{-2}]
C_d	dilatation coefficient = 75 [L.m^{-2}.h^{-1}.K^{-1}]
C_{resp}	sensible heat loss by the air expired [W.m^{-2}]
C_{sW}	sweating coefficient = 304.94 [g.m^{-2}.h^{-1}.K^{-1}]
C_s	striction coefficient = 0.5 [K^{-1}]
c_v	specific heat capacity for of water vapour = 1830 [J.kg^{-1}.K^{-1}]
E_{diff}	heat loss by diffusion [W.m^{-2}]
E_{resp}	Latent heat transfer by breathing [W.m^{-2}]
E_{sk}	total latent skin heat loss [W.m^{-2}]
E_{sw}	heat loss by sweating [W.m^{-2}]
f_{acl}	fraction of the body covered by clothing [-]
f_{cl}	Burton factor for the increase of exchange surface with clothing insulation = 0.31 [clo^{-1}]
f_{eff}	factor for the effective surface subject to radiation (ex: 0.725 when standing)
H	height of the individual [m]
h_{cl}	clothing conductance [W.m^{-2}.K^{-1}]
h_c	convective heat transfer coefficient [W.m^{-2}.K^{-1}]
$h_{e\ cl}$	latent heat transfer coefficient for clothing [W.m^{-2}.Pa^{-1}]
h_e	latent heat transfer coefficient for air [W.m^{-2}.Pa^{-1}]
h_r	radiative heat transfer coefficient [W.m^{-2}.K^{-1}]
i_{cl}	clothing insulation level [clo]
i_m	Woodcock's permeability index taken as 0.3
L_v	latent heat of water = 2400 [J.g^{-1}]
Le	Lewis number [-]
LR	Lewis ratio ~0.0165 [K.Pa^{-1}] for usual ambient conditions
M	metabolic heat rate [W.m^{-2}]
m	mass of the individual [kg]
M_f	female metabolism [W]
M_m	male metabolism [W]
p_a	vapour pressure of ambient air [Pa]
$p_{v\ exp}$	vapour pressure of expired air [Pa]
p_v	vapour pressure of air [Pa]
q_b	blood mass flow rate from core to skin [L.m^{-2}.h^{-1}]
q_b^{set}	set blood flow rate from core to skin = 6.3 [L.m^{-2}.h^{-1}]
q_m^{resp}	flow rate of inspired air [kg.m^{-2}.h^{-1}]
q_m^{sw}	sweating rate [kg.m^{-2}.h^{-1}]
Q_{resp}	Sum of the heat exchanges by breathing [W.m^{-2}]
R_{air}	convective and radiative heat transfer resistance to the environment [m^{2}K.W^{-1}]
r_a	internal radius of clothing [m]
R_{bare}	Radiation losses for bare area [W.m^{-2}]
r_b	external radius of clothing [m]
R_{clo}	Radiation losses for dressed area [W.m^{-2}]
R_{cl}	clothing heat transfer resistance [K.W^{-1}]
T_a	temperature of ambient air [°C]
T_b	body temperature [°C]
T_b^{set}	body set temperature = 36.34 [°C]
T_{cl}	clothing temperature [°C]
T_c	core temperature [°C]
T_c^{set}	core set temperature = 36.6 [°C]
T_{exp}	temperature of expired air [°C]
T_{mrt}	mean radiant temperature
T_{sk}	skin temperature [°C]
T_{sk}^{set}	skin set temperature = 34 [°C]
U_{sk}	skin heat transfer coefficient = 5.28 [W.m^{-2}.K^{-1}]
V	air velocity [m.s^{-1}]
w	skin wettedness [-]
y	clothed fraction of the body [-]

Appendix A. Respiration losses

Equation (7) assumes that $(p_{atm} - p_v) \simeq (p_{atm} - p_{v\ exp}) \simeq p_{atm}$. This allows for a simplified version of the vapour transfer between expired air at moisture content w_{exp} [kg_{water}/kg_{air}] and outside air with moisture content w_a given in Equation (58):

$$E_{\text{resp}} = \left(w_{\text{a}} - w_{\text{exp}}\right) L_{\text{v}} q_{\text{m}}^{\text{resp}} \ \left[\text{W.m}^{-2}\right] \tag{57}$$

$$= 0.622 \times \left(\frac{p_{\text{v}}}{p_{\text{atm}} - p_{\text{v}}} - \frac{p_{\text{v exp}}}{p_{\text{atm}} - p_{\text{v exp}}} \right) \times L_{\text{v}} q_{\text{m}}^{\text{resp}} \ \left[\text{W.m}^{-2}\right] \tag{58}$$

The sensible heat required for the temperature variation of water vapour is also neglected in Equation (5). A stringent expression would be as per Equation (59):

$$C_{\text{resp}} = q_{\text{m}}^{\text{resp}} \times \left(c_{\text{a}} + w_{\text{a}} c_{\text{v}}\right) \times \left(T_{\text{a}} - T_{\text{exp}}\right) \tag{59}$$

The influence of the assumption is however limited: depending on the environment conditions, the bias induced by Equation (7) is of $\sim$ 7% compared to Equation (58) depending on the air temperature and vapour pressure, as presented on Fig. 10. The impact on the PET calculation could be non negligible in specific conditions. Indeed, total breathing losses account for $\sim$25 to 30% of the resting metabolism in the measurements by Ref. [16].

Appendix B. Analysis of the VDI original code

The user may find it difficult to understand the code provided with the VDI norm [3]. It is indeed poorly commented and profusion of numerical constants are used. This section might prove to be useful for whom has the soul of a Champollion and would wish to decode the VDI original code (to be found for instance in the appendix of [9]), as it provides the origin of some numerical constants.

B1. Explanation of the numerical constants and errors

The correspondence between numerical constants and literal expressions hard coded in Höppe's Fortran code are provided hereafter.

$$0.0208 = \frac{13}{635} = \frac{75}{3600} = \frac{C_d}{3600} \ \left[\text{L.m}^{-2}.\text{s}^{-1}.\text{K}^{-1}\right] \tag{60}$$

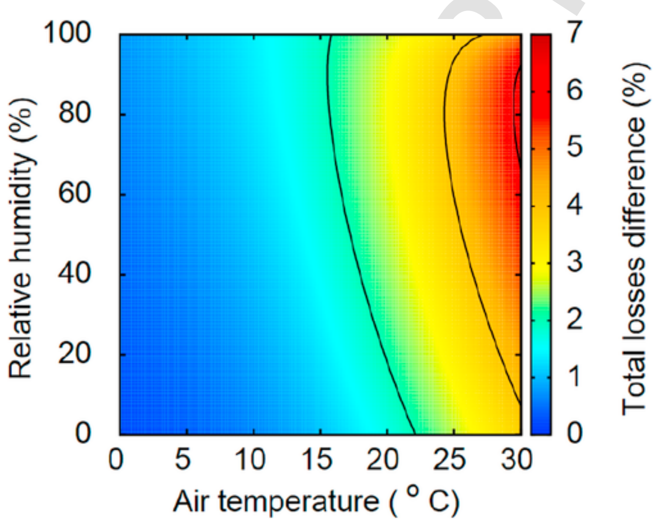

Fig. 10. Difference between the simplified the exact expression of Q_{resp} depending on relative humidity and air temperature.

$$0.7625 = \frac{36.6 \times 75}{3600} = \frac{T_c^{\text{set}} \times C_d}{3600} \ \left[\text{L.m}^{-2}.\text{s}^{-1}\right] \tag{61}$$

$$\frac{1}{40} = \frac{90}{3600} = \frac{q_b^{\text{max}}}{3600} \ \left[\text{L.m}^{-2}.\text{s}^{-1}\right] \tag{62}$$

Several typographical mistakes can also be noted:

- The skin set temperature is taken as $T_{\text{sk}}^{\text{set}} = 36$ [C] whereas it should be 34 [C] for the sake of coherence throughout the program (lines 245 and 256 of the Fortran code).
- The body set temperature is taken as $T_{\text{b}}^{\text{set}} = 36.6$ [C] whereas it should be 36.4 [C] for the sake of coherence (line 271 of the Fortran code).
- The constant "0.7625" explained in Equation (61) is mistyped as "0.76075" throughout the VDI code.

B2. Corrected version of VDI code

The amendment proposed can be found thereafter in Python language https://github.com/eddes/AREP/blob/master/VDI_PET_corrected.py.

B3. Coupled resolution of the code

The amendment exposed in Section 4.1 can be found thereafter in Python language. The version proposed is more compact and exhibits a faster computation time: https://github.com/eddes/AREP/blob/master/PET_fsolve_code.py.

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