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

E. Walther[a], Q. Goestchel[b,*]

[a] AREP, 16 Avenue d'Ivry, 75013 Paris, France
[b] LMT-Cachan / ENS Paris-Saclay, 61 Avenue du Président Wilson 94230 Cachan, France

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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]).

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

* Corresponding author.
E-mail addresses: edouard.walther@arep.fr (E. Walther), quentin.goestchel@ens-cachan.fr (Q. Goestchel).

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

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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)):

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

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

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}]:

$$q_m^{resp} = M \times 1.44 \times 10^{-6}\,[\text{kg.m}^{-2}.\ \text{s}^{-1}] \quad (3)$$

The temperature of the air expired T_{exp} is correlated to the ambient air temperature T_a:

$$T_{exp} = 0.47 \times T_a + 21.0\,[°\text{C}] \quad (4)$$

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:

$$C_{resp} = c_a q_m^{resp} \times (T_a - T_{exp})\,[\text{W.m}^{-2}] \quad (5)$$

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 $p_{v\,exp}$ is calculated after the correlation for saturated vapour pressure:

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

The latent heat transfer E_{resp} is then calculated with the difference of vapour pressures as:

$$E_{resp} = 0.623 \times \frac{p_v - p_{v\,exp}}{p} L_v q_m^{resp}\,[\text{W.m}^{-2}] \quad (7)$$

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: $Q_{resp} = C_{resp} + E_{resp}$. 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).

$$A = 0.203 m^{0.425} \times H^{0.725}\,[\text{m}^2] \quad (8)$$

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:

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

The bare area A_{bare} is a fraction of the clothed surface:

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

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 $A \times (1 - f_{acl})$ to the clothing surface Af_{cl} :

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

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]):

$$f_{cl} = 1 + 0.31 \times i_{cl} \quad (12)$$

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

$$2\pi r_a H y = A f_{acl} \quad (13)$$

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

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

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

$$y = 0.1 \quad \text{for} \quad i_{cl} \le 0.3 \quad (16)$$

The exterior radius of the clothing cylinder of radius r_b and height $H \times y$ is calculated as follows:

$$2\pi r_b H y \quad = \quad A \times (f_{cl} - 1 + f_{acl}) \quad (17)$$

$$= A \times (0.31 \times i_{clo} + f_{acl}) \quad (18)$$

The bare area is the surface of the internal cylinder of radius r_a and height H that is not covered with clothing:

$$A_{bare} = 2\pi r_a \times H(1 - y) \quad (19)$$

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

$$h_{cl} = \frac{2\pi H y \lambda_{cl}}{A_{cl} \ln(r_b/r_a)}\,[\text{W.m}^{-2}.\ \text{K}^{-1}] \quad (20)$$