0014-4754/93/090741-06$1.50 + 0.20

Heat balance modelling

P. R. Höppe

Institute and Outpatient Clinic for Occupational Medicine, University of Munich, Ziemssenstr. 1, D-80336 München (Germany)*

Abstract. The only way to describe the effects of the thermal environment on the human body completely is to do it by means of an energy balance equation. In such an equation all relevant meteorological parameters, behavioral characteristics (activity and clothing) and body measurements can be considered. Using Fanger's comfort equation and the models MEMI and IMEM as examples, the problems of energy balancing and ways of solving them are described. The value of energy balance models is documented by examples from the field of application.
Key words. Heat balance; thermal comfort; thermophysiology.

Introduction

For many decades it has been one of the major objectives in human biometeorology to assess the effects of the thermal environment on thermal comfort or in general on the thermal state of the body. At the beginning of this period empirical indices were used as indicators for the thermal environment. One of the first, and still quite popular, indexes of this kind is the effective temperature ET of Yaglou[27]. In the first definition ET was only dependent on air temperature and humidity. Later the effects of radiation were also considered. The nomograms from which ET can be derived are based on tests in climatic chambers, in which the subjects were moved from a chamber with varying combinations of air temperature and humidity into a standardized chamber where the relative humidity was always kept at 100% and the air velocity at 0.1 m/s. The air temperature in this reference chamber was changed until the thermal sensation of the subjects was equal to the sensation in the first chamber. The air temperature at which this equal sensation occurred was defined as the effective temperature ET. The example of the thermal index ET reveals clearly the general problems of 'simple' indices for the thermal environment. The following statements are therefore valid for all of these indices.

Empirical indices do not consider

- all the relevant meteorological parameters
- activity
- clothing
- personal parameters like height, weight, age and sex.

Nor do empirical indices quantify thermophysiologically relevant parameters of the human body; equal values of an empirical index thus do not necessarily indicate equal thermal states of the human body.

A way to overcome these shortcomings and to achieve a generally applicable assessment of the thermal environment is the calculation of the heat balance of the human body. One of the first people who published a model on the calculation of the heat balance of the human body was Büttner in 1932[5]. At this time the basic physical foundation for the quantification of the heat fluxes from and to the body was already laid. The first heat balance models, however, still lacked comprehensive thermophysiological knowledge. The main reason why many years passed until the use of heat balance modelling became widespread in human biometeorology was the lack of computers. At the end of the sixties, when computers became available in research, the era of heat balance modelling in human biometeorology was initiated by Fanger's 'Thermal Comfort'[8]. This was followed by a great number of publications by other authors with heat balance models of the human body[4,7,9,18,20]. Today the calculating capacity is no longer a limiting factor, which makes it possible to consider even very complex thermophysiological feedback processes. Therefore the complexity of the models compared to the empirical indices is no valid argument for excluding them for practical applications, for example in comfort assessments for indoor climates or urban planning, when the necessary input parameters are available.

Thermophysiological principles in heat balance modelling

Modelling the human heat balance is not a mere physical problem and therefore cannot be done by just considering the physical heat transfer processes. As thermophysiological mechanisms interfere actively, and can thus alter the heat exchange conditions, they have to be considered in a heat balance model of the human body[25]. The most important thermophysiological processes are the constriction or dilation of the peripheral blood vessels, sweating, and the production of heat by shivering. More details on thermophysiological regulating mechanisms are given in reference 28.

Peripheral vasomotoric processes

According to the thermal state of the body the peripheral blood vessels are dilated or constricted. The sensors for this regulatory mechanism are the thermoreceptors in the hypothalamus and the cold and warmth receptors in the skin. By this kind of thermoregulation the amount of heat loss can be influenced. When the blood vessels are dilated, more blood from the body core is transported to the body shell and this increases the temperature of the skin. Higher skin temperatures result in a greater energy loss from the body as the temperature gradient between the body surface and the ambient air is increased. In cases where the ambient temperature is higher than the temperature of the body surface the heat gain of the body is reduced by vasodilation. Vasoconstriction leads to the opposite effect, saving energy for the body. In order to consider the vasomotoric regulation in heat balance models they have to be parameterized. A parameterization is given in reference 10 by the equation 1 for the circulatory blood flow v_b (in l/(hm^2)) from the core to the shell of the body.

$$v_b = (6.3 + 75 \times (T_c - 36.6))/(1 + 0.5 \times (34.0 - T_{sk})) \qquad (1)$$

In (1) T_c is the core temperature and T_{sk} the mean skin temperature. As the equation for v_b shows, the blood flow to the periphery of the body is governed by both the core and the skin temperature. High core temperatures promote v_b while low skin temperatures inhibit it. By vasoconstriction or dilation, not only the peripheral blood flow but also the portions of the body belonging to the body shell and the body core are affected. This is demonstrated very clearly in figure 1 where the extensions of the different body layers are shown for a hot and a cold environment.

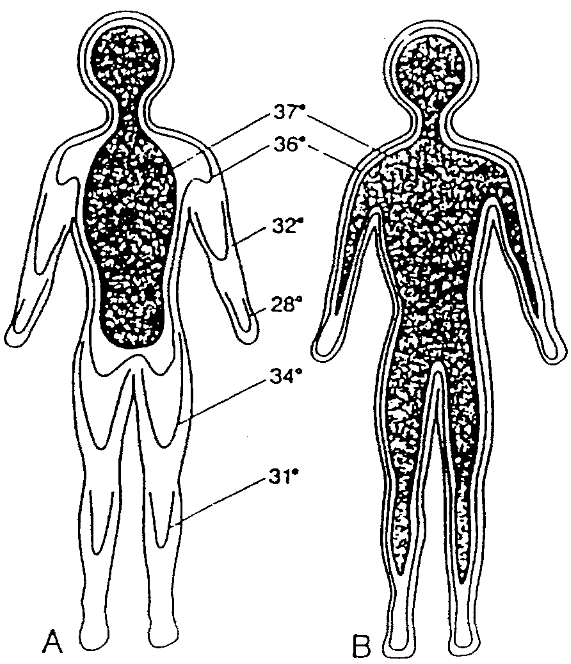

Figure 1. Temperature fields of body core and shell in cold (A) and hot (B) environments (after Aschoff et al.[1]).

The mass distribution of body core and shell can be calculated after equation 2[2] where alpha is a dimensionless factor describing the mass proportion of the body shell to that of the whole body

$$\text{alpha} = 0.044 + 0.35/(v_b - 0.1386) \qquad (2)$$

Sweating

Sweating is the most effective thermoregulatory process when the body is in a condition of heat strain caused by hot ambient conditions or a high metabolic rate, produced, for example, by hard work. The major releasing parameter for the onset of sweating is the transgression of a certain threshold of the core temperature (blood temperature at the hypothalamus). But also high skin temperatures can evoke the onset of sweating. Therefore in many models the onset of sweating is parameterized as a function of the mean body temperature, being calculated as a weighted mean value of body core and skin temperature. A very plausible equation for the sweat rate is given in equation 3[13].

$$SW = 8.47 \times 10^{-5} \times ((0.1 \times T_{sk} + 0.9 \times T_c) - 36.6) \quad (\text{in kg/(s m}^2)) \qquad (3)$$

The fact that the sweat rate of women, owing to a lower density of sweat glands and different hormone patterns, is significantly smaller compared to that of men, can be considered by including the factor 0.7 in equation 3[26] when model calculations are done for a female subject.

Heat production by shivering

In very cold ambient conditions the core temperature decreases in spite of vasoconstriction. When the core temperature reaches a certain threshold, shivering starts. By shivering the metabolic rate can be increased two to threefold[28]. A parameterization of this additional heat production is given in equation (4)[2] where the deviation terms are set to zero if they become negative.

$$M_{shiv} = 19.4 \times (34.0 - T_{sk}) \times (37.0 - T_c) \quad (\text{in W/m}^2) \qquad (4)$$

Heat fluxes from and to the human body

The basis of a heat balance model is the calculation of the different heat fluxes from and to the human body depending on the different ambient parameters. The derivation of the equations for the calculation of the single heat fluxes is described in detail in reference 16.

Metabolic heat production

By the oxidation of the constituents of food (carbohydrates, fat or proteins) energy is transformed into heat in the body. The amount of metabolic energy is primar-

Table 1. Metabolic rates (in W) at different activities[24]

Activity	Metabolic rate M in W
Sleeping	87
Sitting	112
Standing	130
Walking (4 km/h)	260
Tennis	500
Jogging	600
Rowing (Competition)	1800

ily dependent on the activity. The basal metabolism at rest, however, is also a function of body height and weight, age and sex[19]. Some examples for metabolic rates are given in table 1 for a young man (1.80 m, 75 kg, 30 years)[24].

According to the kind of activity, part of the metabolic rate is transferred into physical work. This portion, defined as the mechanical efficiency (η), lies between 0% and 20%. That means that even during very strenuous activities, like mountain climbing, more than 80% of the energy produced by metabolism is transformed into internal heat. In a heat balance model of the body only the internal heat H has to be considered, as the physical work is transformed into heat outside the body. This leads to the equation for internal heat H:

$$H = M \times (1 - \eta) \qquad (5)$$

Convective heat flux

The convective heat flux represents the interchange of heat between the surface of the body (either skin or clothing) and the ambient air. It can be quantified by:

$$C = A_{Du} \times f_{cl} \times h_c \times (T_a - T_s) \qquad (6)$$

In (6) A_{Du} is the surface area of the unclothed body, f_{cl} is the surface enlargement factor for the clothed body, h_c is the heat transfer coefficient depending on the air velocity, T_a is the temperature of the ambient air and T_s is the surface temperature of the body (skin or/and clothing surface temperature).

Radiative heat flux

The radiative heat flux describes the amount of heat exchanged by radiation between the body and the environment. The corresponding equation is:

$$R = A_{DU} \times f_{cl} \times f_{eff} \times \varepsilon_p \times \sigma \times (T_{mrt}{}^4 - T_s^4) \qquad (7)$$

In (7) f_{eff} is the factor giving the relation between the body surface and the effective surface for radiative exchanges ($f_{eff} = 0.7$ for standing persons), ε_p is the emission coefficient for the human surface, σ is the Stefan-Boltzmann constant and T_{mrt} is the mean radiation temperature of the environment.

Water vapor diffusion

By the so called 'perspiratio insensibilis' water vapor is diffusing from the subcutaneous tissues through the skin into the ambient air. This water loss also means a heat loss E_D, because the heat necessary to evaporate the water is taken from the tissue. It can be quantified by:

$$E_D = m \times r \times (VP_a - SVP_{sk}) \qquad (8)$$

In (8) m is the permeance coefficient of the skin for water vapor, r the vaporization heat of water, VP_a is the ambient water vapor pressure and SVP_{sk} is the saturation vapor pressure at skin temperature.

Respiratory heat fluxes

In general, heat is transferred from the surface of the respiratory tract (mucous membranes) into the respired air, which is expired at higher temperatures and with a higher moisture content than the inspired air.

Heating of respired air

The inspired air is always heated to the core temperature of the body by the time it reaches the lower airways. During expiration some heat is regained by cooling it in the upper airways. The temperature of the expired air T_{ex} depends on the temperature of the inspired air[14]. The effective heat loss of the upper respiratory tract E_{Res} is quantified by:

$$E_{Res} = RTM \times c_p \times (T_a - T_{ex}) \qquad (9)$$

where RTM is the mass of air respired per second and c_p is the specific heat of air.

Humidification of respired air

As the respired air reaches the lungs it is saturated with water vapor. The humidification necessary to reach that state which is combined with a corresponding heat loss occurs at the mucous membranes of the upper airways. Part of the water and heat is regained when the expired air is cooling during expiration, but when the respired air leaves the body it generally contains more water vapor than on inspiration. The corresponding heat loss E_{Rel} can be quantified by:

$$E_{Rel} = RTM \times r \times (VP_a - SVP_{Tex})/p \qquad (10)$$

where SVP_{Tex} means the saturation vapor pressure at expiration temperature and p the air pressure.

Sweat evaporation

In the calculation of the heat loss by evaporation of sweat E_{Sw} two cases have to be distinguished. The first case is where the body produces less sweat than can evaporate from the body surface. This means that all sweat produced will evaporate. The body loses the corresponding evaporation heat (eq. 11).

$$E_{Sw} = SW \times r \quad (11)$$

where SW is the sweat rate in kg/s.

In the second case, the potential evaporation from the body is lower than the amount of sweat produced. This means that part of the sweat drips off and does not contribute to the heat loss of the body. Here, the potential evaporation, which is governed by the ambient exchange conditions, is the measure for the heat loss E_{sw}. The corresponding equation is:

$$E_{Sw} = (A_{Du} \times r \times h_c \times 0{,}622/p) \times (VPa - SVP_{Tsk}) \quad (12)$$

Sensible heat flux from food

If the temperature of food or drink is different from the core temperature this means a heat loss or gain (F) of the body. F can be quantified by:

$$F = m_F \times c_F \times (T_F - T_c)/t \quad (13)$$

In (13) m_F is the mass of food taken, c_F is the specific heat of the food, T_F is the food temperature and t is the time for the heat transfer. In general the heat flux F can be neglected as it only occurs for a short time during eating or drinking. But in some situations it can reach the same scale as the other heat fluxes. For instance, 100 g of ice cream within 10 min results in a rate of heat loss of 83 W, and consuming 0,25 l of hot soup within 5 minutes yields a rate of heat gain of 80 W[16].

Heat balance equation

The sum of the heat gains and losses described above is expressed by the heat balance equation:

$$H + C + R + E_D + E_{Res} + E_{Rel} + E_{Sw} + F = S \quad (14)$$

In the heat balance equation S is the storage flow of sensible heat in the body tissue, which means body heating when positive and cooling when negative. When S is equal to 0 the amount of heat that is produced in the body and gained from the environment is the same as that lost to the environment, and the body temperatures are in a steady state.

Heat balance models

On the basis of the heat balance equation a multitude of energy balance models have been derived. Some of them have the aim of calculating a comfort index[6,8,18] which, in contrast to the old empirical indices, has a physical and also thermophysiological background and considers all relevant meteorological parameters. This way of heat balance modelling is described in the following by Fanger's comfort equation[8].

Under the assumption that meteorological parameters, clothing characteristics and activity are given in equation 14 there are still four unknown quantities: skin temperature, T_{sk}; clothing surface temperature, T_{cl}; sweat rate, SW; and heat storage, S. Fanger replaces T_{sk} and SW by expected values for comfort conditions, which he gained from climatic chamber studies with hundreds of subjects. The comfort values turned out to be only dependent on the activity. In order to be able to solve the heat balance equation with the remaining two unknown quantities, one more equation is needed. This is the equation to describe the heat flow from the skin surface through the clothing layer to the surface of the clothing F_{sc}:

$$F_{sc} = 1/I_{cl} \times (T_{sk} - T_{cl}) \quad (15)$$

where I_{cl} is the heat transfer resistance of the clothing. Under the assumption that the clothing layer has no heat capacity, F_{sc} has to be equal to the sum of the radiative and convective heat fluxes (R + C).

Using both equations 14 and 15, S can be calculated. It has to be pointed out that S here is not a real value for heat storage in a simulated environment, as the input values of T_{sk} and SW are not real but comfort values. But the value of S provides good information on the deviation from the comfort zone where S should be zero. By an empirical regression analysis Fanger calculates the PMV-value (predicted mean vote) from the fictive heat storage S. Fanger's comfort equation therefore is a 'state of the art' model to calculate a comfort index but cannot be used to quantify real values of heat fluxes or body temperatures for given environmental conditions. If this is desired an energy balance model like MEMI (Munich Energy Balance Model for Individuals, eq. 16) has to be applied.

In these models the skin temperature is not given but calculated as a result of the model. The sweat rate is modelled as a function of the core and skin temperature (eq. 3). In these 'physiologically realistic' models T_{sk}, T_c, T_{cl} and S are unknown parameters at the beginning of the calculation. At steady state the number of unknown quantities is reduced to three as S is zero then. So still another equation in addition to (14) and (15) is needed. This is the equation for the heat flow from the body core to the skin F_{cs}:

$$F_{cs} = v_b \times \rho_b \times c_b \times (T_c - T_{sk}) \quad (16)$$

In (16) v_b is the blood flow from the core to the skin (dependent on the skin and core temperature (eq. 1), ρ_b is the density of blood and c_b its specific heat.

The system of the three equations 14, 15 and 16 allows the calculation of all relevant heat fluxes and thermophysiological relevant body parameters for any given climatic situation. Also, comfort indices like the effective temperature ET*[10] or the Physiological Equivalent Temperature PET[21] can be calculated from these kinds of models.

In case the climatic conditions, activity or clothing change significantly within the time scale of some minutes, it may be appropriate to use dynamic (instationary) models of the human heat balance. In these models, like the Gagge two-node-model[10] or IMEM (Institutionary Munich Energy balance Model)[17], the consideration of the heat storage allows the calculation of changes in the body temperatures. The calculation procedure of these dynamic models commences by entering starting values for the body temperatures. These starting values can be defined or calculated from steady state models. With the starting values the energy balance equation is solved and the value of S calculated. By numeric integration over time steps (e.g. 1 second) the heat storage and the resulting change in body temperatures is evaluated. The calculated values are then the starting values for the next step. Considering the varying proportions of body core and body shell and the heat flow from the core to the skin F_{cs} even the changes of skin temperature and core temperature can be calculated separately.

Applications of heat balance models

The applications of heat balance models in human biometeorology today are manifold[3,6,11,12,15,22,23]. They are used in urban climatology, for example for the assessment of the thermal effects of different urban structures, or by air-conditioning engineers in order to calculate the climate parameters for comfort. Another field of application is clothing physiology; for instance the required heat transfer resistance of a clothing ensemble for comfort can be calculated, or at a given heat transfer resistance the corresponding range of climatic conditions. In figure 2 the calculated heat fluxes and body temperatures for typical indoor conditions are shown.

A wide field for the use of dynamic heat balance models is in medicine where the controlled heating or cooling of the body is used therapeutically. The models provide information, for example, on the time until certain threshold values of the body temperatures is reached in dependence on the environmental conditions. But also for indoor or outdoor assessments it can be valuable to know whether a short stay in thermally adverse conditions will affect the state of the body core or not.

As all relevant parameters are considered, energy balance models of the human body are the 'state of the art' tool for the assessment of the thermal component of the climate.

* Director, Prof. Dr. G. Fruhmann.

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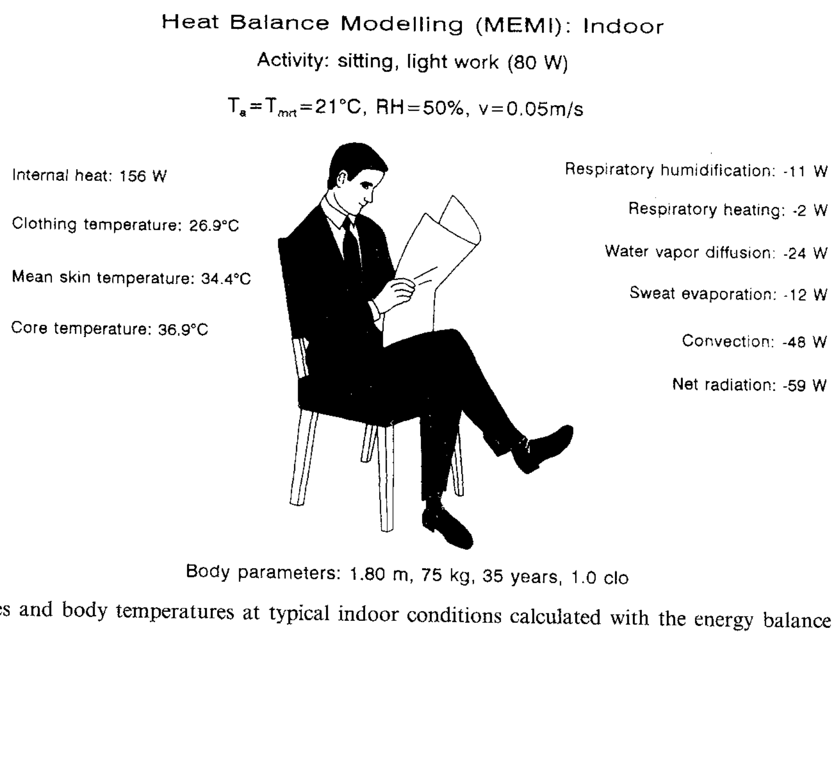

Figure 2. Energy fluxes and body temperatures at typical indoor conditions calculated with the energy balance model MEMI.

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