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ORIGINAL ARTICLE

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The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment

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Abstract With considerably increased coverage of weather information in the news media in recent years in many countries, there is also more demand for data that are applicable and useful for everyday life. Both the perception of the thermal component of weather as well as the appropriate clothing for thermal comfort result from the integral effects of all meteorological parameters relevant for heat exchange between the body and its environment. Regulatory physiological processes can affect the relative importance of meteorological parameters, e.g. wind velocity becomes more important when the body is sweating. In order to take into account all these factors, it is necessary to use a heat-balance model of the human body. The physiological equivalent temperature (PET) is based on the Munich Energy-balance Model for Individuals (MEMI), which models the thermal conditions of the human body in a physiologically relevant way. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. This way PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors. On hot summer days, for example, with direct solar irradiation the PET value may be more than 20 K higher than the air temperature, on a windy day in winter up to 15 K lower.

Key words Thermal comfort · Energy balance model · Comfort index

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Introduction

In recent years there has been a tendancy for weather reports from the media to give more useful information. This includes, for example, forecasts of pollen counts, indices of UV radiation intensity or information on expected probability of weather-related symptoms like headaches or cardiocirculatory problems. Perhaps most useful for the audience of such weather forecasts would be some advice about kind of clothing to choose before going out, particularly the clothing most likely to provide thermal comfort. Besides this increasing demand for biometeorological information in daily weather reports, urban and regional planners intending to create comfortable microclimates are also asking for easily understandable methods for the assessment of the thermal component of climate.

As early as 1938, Büttner recognized that, for the assessment of the thermal influence of the environment on the human body, the integrated effects of all thermal parameters have to be taken into account. He postulated: "If one wants to assess the influence of climate on the human organism in the widest sense, it is necessary to evaluate the effects not only of a single parameter but of all thermal components. This leads us to the necessity of modelling the human heat balance" (Büttner 1938). In this sense, empirical thermal indices, like the discomfort index (Thom 1959), apparent temperature (Steadman 1979), wind-chill index (Steadman 1971) or similar ones considering only some of the relevant meteorological parameters and not accounting for thermal physiology, have to be regarded as not being "state of the art" – yet they are used very often. They might be helpful in very specific situations as they can be calculated easily but they have many limitations.

On the basis of Büttner's conclusions, since the 1960s heat-balance models of the human body have gained more and more acceptance in the assessment of thermal comfort. The basis for all of these models is the heat-balance equation for the human body (1):

$$M+W+R+C+E_D+E_{Re}+E_{Sw}+S=0 \tag{1}$$

In Eq. 1 M is the metabolic rate (internal energy production by oxidation of food), W the physical work output, R the net radiation of the body, C the convective heat flow, E_D the latent heat flow to evaporate water into water vapour diffusing through the skin (imperceptible perspiration), E_{Re} the sum of heat flows for heating and humidifying the inspired air, E_{Sw} the heat flow due to evaporation of sweat, and S the storage heat flow for heating or cooling the body mass. The individual terms in this equation have positive signs if they result in an energy gain for the body and negative signs in the case of an energy loss (M is always positive; W, E_D and E_{sw} are always negative). The unit for all heat flows is the watt. The individual heat flows of Eq. 1 are affected directly by the following meteorological parameters:

Air temperature: C, E_{Re}
Air humidity: E_D, E_{Re}, E_{Sw}
Air velocity: C, E_{Sw}
Mean radiant temperature: R

The human body does not have any selective sensors for the perception of individual climatic parameters, but can only register (by thermoreceptors) and make a thermoregulatory response to the temperature (and any changes) of the skin and blood flow passing the hypothalamus. These temperatures, however, are influenced by the integrated effect of all climatic parameters, which are in some kind of interrelation, i.e. affect each other. In weather situations with little wind, for instance, the mean radiant temperature has roughly the same importance for the heat balance of the human body as the air temperature. On days with higher air velocities, air temperature is far more important than the mean radiant temperature because it now dominates the increased convective heat exchange. These complex interactions are only quantifiable in a realistic way with the help of heat-balance models.

One of the first and still very popular heat-balance models is the comfort equation defined by Fanger (1972). It was developed for the calculation of the indices "predicted mean vote" (PMV) and "predicted percentage dissatisfied" (PPD), which were thought mainly to help air-conditioning engineers to create a thermally comfortable indoor climate. After the much more complex outdoor radiation conditions had been taken into account and assigned appropriate parameters by Jendritzky et al. (1979, 1990), this approach has increasingly been applied to outdoor conditions and is now also known as the Klima Michel model. Since this model was only designed for calculating an integral index for the thermal component of climate and not to give a realistic description of the thermal conditions of the human body, it could get by without considering fundamental thermophysiological regulatory processes. For example, in Fanger's approach the mean skin temperature and sweat rate are quantified as "comfort values", being only dependent on activity and not on climatic conditions at all.

More universally applicable than these models, primarily designed for the calculation of a thermal index such as PMV, are those that enable the researcher to predict "real values" of thermal quantities of the body, i.e. skin temperature, core temperature, sweat rate or skin wetness. For this purpose it is necessary to take into account all basic thermoregulatory processes, like the constriction or dilation of peripheral blood vessels and the physiological sweat rate (Höppe 1993). Such a thermophysiological heat-balance model is the Munich energy-balance model for individuals" (MEMI) (Höppe 1984, 1994), which is the basis for the calculation of the physiological equivalent temperature, PET.

The model MEMI

The heat-balance model MEMI is based on the energy-balance equation of the human body Eq. 1 and some of the parameters of the Gagge two-node model (Gagge et al. 1971). In Eq. 1 some terms are dependent on the mean clothing surface temperature, the mean skin temperature or the sweat rate, all of which are affected by the ambient conditions – the physiological sweat rate (the basis for the calculation of E_{sw}) is also a function of the core temperature, which depends on both ambient conditions and activity. Therefore, in order to solve Eq. 1 the three unknown quantities first have to be evaluated, i.e. the mean surface temperature of the clothing (T_{cl}), the mean skin temperature (T_{sk}) and the core temperature (T_c). For the quantification of these unknowns two more equations in addition to Eq. 1 are necessary. These are the equations describing the heat flows from body core to skin surface, F_{CS} Eq. 2 and from skin surface through the clothing layer to the clothing surface, F_{SC} Eq. 3. They are made up as follows:

$$F_{CS}=v_b\times\rho_b\times c_b\times(T_c-T_{sk}) \tag{2}$$

In Eq. 2 v_b stands for the blood flow from body core to skin (in $ls^{-1}\ m^{-2}$, depending on the level of skin and core temperature), ρ_b for blood density (kg/l) and c_b for the specific heat ($W\ sK^{-1}\ kg^{-1}$).

$$F_{SC}=(1/I_{cl})\times(T_{sk}-T_{cl}) \tag{3}$$

In Eq. 3 I_{cl} is the heat resistance of the clothing (in $K\ m^2\ W^{-1}$)

By means of this system of Eqs. 1–3 and some thermophysiological considerations (details in Höppe 1984) it is possible to calculate, for any given combination of climatic parameters, activity and type of clothing, the resulting thermal state of the body, characterized by the heat flows, body temperatures and sweat rate. MEMI therefore presents a basis for the thermophysiologically relevant evaluation of the thermal component of climate. The most important differences from the Gagge two-node model are the way of calculating the physiological sweat rate (as a function of T_{sk} and T_c) and the separate calculation of heat flows from parts of the body surface that are covered or uncovered by clothing. In Fig. 1 the results of a calculation with MEMI for warm weather conditions with direct solar irradiation are shown as an example.

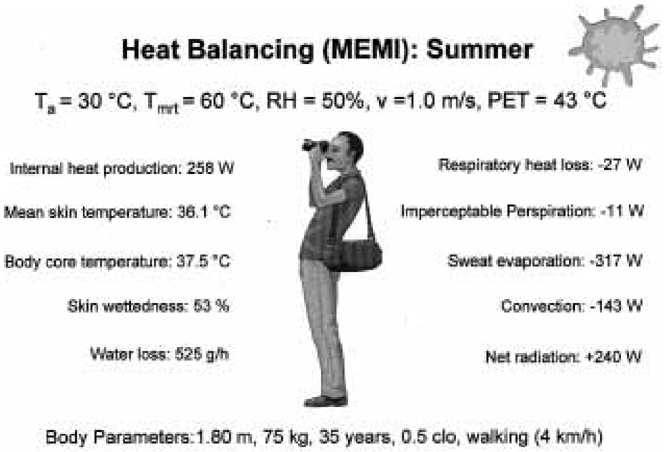

Fig. 1 Sample heat-balance calculation with the Munich energy-balance model for individuals (MEMI) for warm and sunny condition

For people not conversant with the fields of thermophysiology or biometeorology, the expected body temperatures or heat flows may not be very meaningful. This fact is certainly one of the reasons why Gagge et al. (1971) have developed an index, the new effective temperature (ET*), based on their two-node model. With ET* the thermal effects of complex meteorological ambient conditions can be compared to the conditions in a standardized room with a mean radiant temperature not differing from the air temperature and a constant relative air humidity of 50%.

The physiological equivalent temperature, PET

Similar in definition to ET* (Gagge et al. 1971), but based on the MEMI, the PET was introduced by Höppe and Mayer (Höppe and Mayer 1987; Mayer and Höppe 1987). PET is defined as the physiological equivalent temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed.

The following assumptions are made for the indoor reference climate:

Mean radiant temperature equals air temperature ($T_{mrt}=T_a$)
Air velocity is set to 0.1 m/s
Water vapour pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at T_a=20°C)

The procedure for calculating PET consists of the following steps:

Calculation of the thermal conditions of the body with MEMI for a given combination of meteorological parameters

Table 1 Examples of physiological equivalent temperature (*PET*) values for different climate scenarios. T_a air temperature, T_{mrt} mean radiant tempertaure, v air velocity, *VP* water vapour pressure

Scenario	T_a (°C)	T_{mrt} (°C)	v (m/s)	VP (hPa)	PET (°C)
Typical room	21	21	0.1	12	**21**
Winter, sunny	–5	40	0.5	2	**10**
Winter, shade	–5	–5	5.0	2	**–13**
Summer, sunny	30	60	1.0	21	**43**
Summer, shade	30	30	1.0	21	**29**

Insertion of the calculated values for mean skin temperature and core temperature into the model MEMI and solving the equation system (Eqs. 1 and 3) for air temperature T_a (with v=0.1 m/s, VP=12 hPa and $T_{mrt}=T_a$)
The resulting air temperature is equivalent to PET

Examples of PET applications

In the concrete case of the warm and sunny outdoor conditions described in Fig. 1 the PET value would be 43°C. This means that an occupant of a room with an air temperature of 43°C reaches the same thermal state as in the warm and sunny outdoor conditions. If he were to move out of the direct solar irradiation into the shade this would result in a reduction of PET by 14 K to 29°C (see also Table 1). The same outdoor air temperatures thus result in a very different thermal strain, which can be quantified very clearly by the PET values. Large differences between air temperature and PET also arise in winter-time on days with high wind velocities (see Table 1).

The assumption of constant values for clothing and activity in the calculation of PET was made deliberately to define an index independent of individual bevaviour. On the other hand, this does not essentially restrict its applicability, as the variation of clothing and activity – if varied equally outdoors and in the reference indoor climate – does not lead to significantly different PET values. So with thicker clothing for example, (higher heat resistance), for the climate to be assessed, higher skin and core temperatures are calculated than for the reference clothing of 0.9 clo. This higher body temperature level, however, does not lead to higher PET values, as this thicker clothing has a similar influence in the reference indoor climate also. In other words at a constant PET of say 20°C, a person clad with 0.9 clo (work metabolism 80 W) will reach a mean skin temperature of 33.7°C, a person carrying out the same activity and wearing a coat (2.0 clo), however, will have a skin temperature of 34.7°C.

There are already some everyday applications for PET, as shown in Fig. 2. This figure shows weather information charts as posted on the Internet (www.mmc.de) by a private weather company (More and More Communications, Ismaning, Germany) for 11 No-

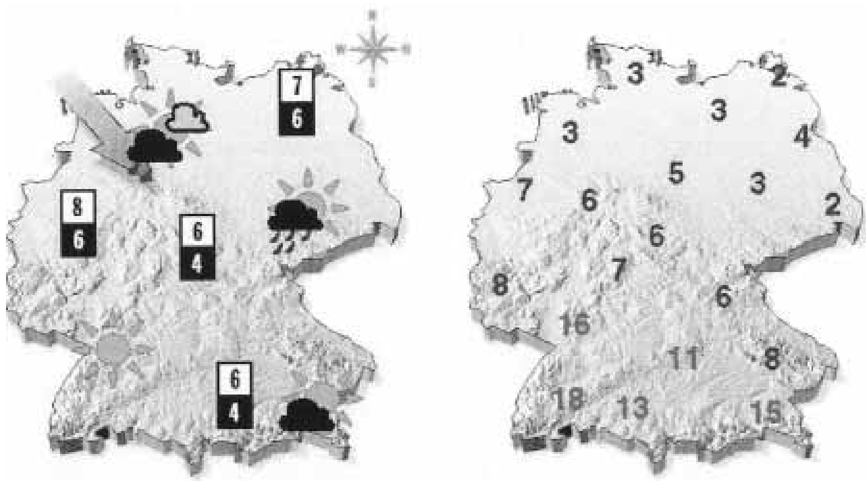

Fig. 2 Weather charts for Germany, 11 November 1998 (source: More and More Communication, Ismaning, Germany, www.mmc.de). *Left* chart showing conventional weather information: minimum and maximum air temperatures, wind, cloud cover. *Right* chart showing the distribution of physiological equivalent temperature (PET) values for midday

vember 1998 for Germany. The left-hand chart displays forecast minimum and maximum air temperatures, wind and cloud cover. The right chart shows the distribution of expected midday PET values. In the original coloured version blue numbers are used for values lower than the air temperature and red ones for those higher. While maximum air temperatures within Germany were forecast to be between 6°C and 8°C, the PET range is far wider, from 2°C to 18°C. The low PET values in Northern Germany are caused by relatively high wind velocities and little sunshine, the high PET values in Southern Germany are due to low wind velocities and high solar radiation.

Discussion

A different way of calculating an equivalent or perceived temperature is the *Gefühlte Temperatur* (Jendritzky et al. 1998); in which different types of reference clothing and a real outdoor climate are assumed. Therefore such temperatures have a behavioural component (the subject can adjust his/her heat loss by different clothing) and are no longer simply climatic indices (only dependent on meteorological parameters). PET, however, is a real climatic index describing the thermal environment in a thermophysiologically weighted way.

The use of PET as a single index enables a layperson to assess the thermal component of climate on the basis of personal experience. It is much easier to imagine what it means thermally if the air temperature in a room reaches 30°C than if people just learn from the weather report that, with clear skies and low wind, an air temperature of 20°C is expected. In general people then can use their own experience to tell them what type of clothing would be suitable for a certain activity; in other words, by providing the PET values, they get the information from the weather people they need to adapt their behaviour.

Its definition (independent of activity and clothing) makes PET a genuine climate index, which, in contrast to most other biometeorological indices (e.g. wind chill, apparent temperature or heat stress index), considers the influences of all thermally relevant climate parameters (air temperature, radiant temperature, air velocity, air humidity) in a thermophysiologically relevant way, evaluating their real effect on the regulatory processes and on the thermal state of the body. This means, however, that PET cannot be an absolute measure of thermal comfort or thermal strain, because, for example, somebody would feel very cold at PET=20°C if clad only in swimming trunks while he would sweat when wearing a coat. If he were working hard, he would assess this PET value as "too warm" while such thermal conditions at rest might be regarded as "too cool". PET therefore only can be regarded as a basis for an assessment of the thermal environment that has to be adjusted to the subjective characteristics in terms of clothing and activity. For this purpose, however, PET is much more advantageous and universal than the traditional thermal indices. Because of its thermophysiological background PET is certainly more appropriate than other biometeorological indices like the wind-chill temperature (Siple and Passel 1945), the apparent temperature (Steadman 1979) or the effective temperature (Yaglou 1927). It can be used for the assessment of both hot and cold conditions and therefore all year round. People can therefore become familiar with such an index more easily than if different methods are used, as occurs in Canada where wind-chill temperatures are used in winter-time and the HUMIDEX index in summer-time.

An often-stated argument against thermal indices derived from heat-balance models like PET is that it is sometimes impossible to obtain a complete input data set consisting of air temperature, air humidity, air velocity and mean radiant temperature, the last two being the main problem. But there are many ways to estimate air velocity from routine measurements (reduction of values measured 10 m above ground to the relevant level occupied by humans) or to estimate the mean radiant temperature by cloud cover, time of the year and type of surface cover. In any case, even a rough estimation of these two parameters (especially if done by an experienced meteorologist) will provide better evaluations of the thermal bioclimate than simple indices not considering these parameters at all.

PET has been applied already, e.g. for the prediction of changes in the thermal component of urban or regional climates after projected changes in construction or land use, and is one of the recommended indices in new German guidelines for urban and regional planners (VDI 1998). PET also can be used as additional information in every-day weather news, as done by some weather agencies already (see Fig. 2). This is helpful, especially on days when expected PET values differ significantly from the air temperature, as occurs in winter at high wind velocities or on calm and clear summer days. For more examples of potential applications of PET, see the following paper by Matzarakis et al. (1999) in this journal. As PET allows both cold and heat to be assessed with the same index all year round, there is a good chance that people will get used to it, as they are already accustomed to other weather data like probability of precipitation. There are certainly thermal indices other than PET that also fulfil the same requirements that all relevant meteorological parameters are considered in a thermophysiologically relevant way. It would be very helpful if the international community of biometeorologists could start to discuss these indices and perhaps develop guidelines recommending one of them for international use, as has been the case with the now internationally acknowledged UV index.

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