

Thermodynamic analysis of human heat and mass transfer and their impact on thermal comfort

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Abstract

In this paper a thermodynamic analysis of human heat and mass transfer based on the 2nd law of thermodynamics is presented. For modelling purposes the two-node human thermal model was used. This model was improved in order to establish the exergy consumption within the human body as a consequence of heat and mass transfer and/or conversion. It is shown that the human body's exergy consumption in relation to selected human parameters exhibit a minimal value at certain combinations of environmental parameters. The expected thermal sensation, determined by the PMV* value, shows that there is a correlation between exergy consumption and thermal sensation. Thus, our analysis represents an improvement in human thermal modelling and gives even more information about the environmental impact on expected human thermal sensation.

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1. Introduction

Human body acts as a heat engine and thermodynamically could be considered as an open system. The energy and mass for the human body's vital processes are taken from external sources (food, liquids) and then exchanged with the environment. These exchange mechanisms are of great importance, since they define the thermal sensation, i.e. thermal comfort. Therefore, the pathway of energy, mass, and the transformations associated with their generation leading to an exchange with the environment should be considered. Thermal models of the human body and its interaction with the surrounding thermal environment have been available for

more than 30 years. These models range from simple one-dimensional, steady-state simulations to complex, transient finite element models [1–5]. The main similarity of most models is the application of energy balance to a simulated human body (based on the 1st law of thermodynamics) and the use of energy exchange mechanisms. The models differ mainly in the physiological response models and in the criteria used to predict thermal sensation [6,7].

In this paper a different approach is presented, namely an analysis based on the 2nd law of thermodynamics. Every energy transfer and conversion is accompanied by an exergy transfer and conversion. Energy is conservative in its transfer and conversion process (1st law of thermodynamics: nothing disappears), while exergy is known to be non-conservative due to the irreversibility of its transfer process (2nd law of thermodynamics: everything disperses). As a result, exergy

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Nomenclature

A	area (m ²)
c	specific heat (J/kg K)
ex	exergy (J/kg)
E	exergy load (J)
f	correction factor for clothing surface area (–)
h	enthalpy (J/kg)
h_e	latent heat of evaporation (J/kg)
K	thermal conductivity (W/m K)
m	mass (kg)
\dot{m}	mass flow rate (kg/s)
M	metabolism (W/m ²)
p	pressure (Pa)
Q	heat load (J/kg)
R	gas constant (J/kg K)
R_{cl}	clothing thermal resistance (m ² K/W)
s	entropy (J/kg K)
S	heat storage (J/kg)
t	time (s)
T	temperature (°C, K)
W	specific work (J/kg)
x	humidity ratio (–)

Greek symbols

α	relative mass of the skin
φ	percent relative humidity

Subscripts

a	air
b	body
bl	blood
c	convective
ch	chemical
cl	clothing
cr	body core
diff	diffusive
Du	DuBois
e	evaporative
in	input
out	output
r	radiative
res	respirative
rsw	requested sweating
s	saturated state
sk	skin
th	thermal
w	water, water vapour
0	reference state

transfer has rules of its own which are different from those of energy transfer. Exergy is only conserved, or in balance, for a reversible process, but is partly consumed in an irreversible process. For a real process the exergy input always exceeds the exergy output; this unbalance is due to irreversibilities and represents exergy destruction or exergy consumption. There are corresponding entropy flows associated with heat and mass flows; combining the energy and entropy balance brings about exergy balance [8–10]. One of the objectives of the presented research is to calculate entropy generation or exergy destruction (based on the Gouy–Stodola theorem). The calculation of exergy destruction is usually based on second law analysis, either from the rate of exergy destruction within the relevant control volume, or from the unbalanced rate of exergy input within the control volume [11].

In the case of the human body, exergy is consumed as a consequence of heat and mass transfer and/or conversion. These processes are dependent on the human thermoregulatory system and on the state of the environment. Therefore, the human body generates specific mechanisms of irreversibilities. The purpose of the presented study is to introduce an approach to calculate the rate of exergy destruction within the human body

and to identify the magnitude and mechanisms of those irreversibilities.

An example is considered to verify the presented model and it is shown that there is a correlation between the exergy consumption within the human body and the expected level of thermal comfort. Furthermore, the existing methods for comfort assessment could be improved and expanded with the inclusion of exergy analysis.

2. Human thermal model

For analytical purposes, the chosen human thermal model must fulfil some basic conditions. For optimal thermal comfort three basic conditions must be fulfilled: heat balance must exist, and skin temperature and sweat rate must be within the comfort range. The human body produces heat, exchanges heat with the environment, and loses heat by diffusion and evaporation of body liquids. During normal rest and exercise these processes result in an average vital organ temperature of around 37°C. The body's temperature control system tries to maintain these temperatures even when thermal disturbances occur. The human thermoregulatory system is quite effective and creates heat balance within wide lim-

its of the environmental variables (air temperature, mean radiant temperature, air humidity, and relative air velocity). For a given activity level (metabolism), skin temperature and sweat rate are seen to be the major physiological variables influencing heat balance.

The model used as a starting point is comprised of a physiological part based on the Gagge two-node model [2] and a physical model describing the heat and mass transfer properties of clothing. The physiological model contains a number of control functions for physiological processes, as well as the heat transfer properties of the human body. Core, skin, and mean body temperatures are used as inputs for several set-point-defined feedback loops controlling effector responses [12,13]. The effector responses together with metabolic heat production result in a certain heat loss or gain, which then affects the body resulting in a new body temperature (i.e. feedback). The relation between effectors and the resulting body temperature is affected by environmental parameters (heat and mass transfer properties) and heat production level (activity).

Thermal regulation by the human body is mainly achieved by regulating blood flow [14]. The body regulates blood distribution by vasoconstriction and vasodilatation in order to control skin temperature and to increase or decrease heat loss to the environment. During work, blood carries the extra heat produced to the body surface where higher skin temperature increases heat loss through convection and radiation. During cold stress, vasoconstriction shunts blood flow from arteries to veins at deeper layers. Veins and arteries are paired and veins carry heat from the arteries back to the core. This counter-current heat exchange is a major process in decreasing heat loss and maintaining core temperature in a cold environment. In a hot environment, convective and radiative heat transfer from the body decreases due to the small difference between skin and ambient temperature. In this case, heat release from the body is governed by water diffusion and evaporation (latent heat). This mechanism enables the human body to release heat even in a hot environment where the ambient temperature is above skin temperature and the human body is gaining heat from the environment. Therefore, a thermal model for the body is only as accurate as the information provided about the heat and moisture exchange with the environment.

2.1. Heat balance equations

The effects of ambient conditions on the human thermoregulatory system and on heat flow within the human body can be investigated using the two-compartment (or two node) model [2]. This model represents the body as two concentric cylinders, where the inner cylinder repre-

sents the body core and the outer cylinder represents the skin layer. The core is the compartment with a regulated and defined temperature, while the skin is a buffer between the core and environment whose temperature is defined by heat and mass exchanges with the core and with the environment. The core and skin compartments exchange energy passively through direct contact and through the thermoregulatory controlled peripheral blood flow. Metabolic heat production at the core is released to the environment by two paths. The predominant pathway is the transfer of heat to the skin by blood flow and heat conduction, followed by release from the skin to the environment by convection, radiation, and evaporation. The minor pathway is the direct release of heat (and mass) to the environment through respiration. Therefore, two heat balance equations for the body core and the skin layer can be built up. The transient energy balance states that the rate of heat storage equals the net rate of heat gain minus heat loss. This thermal model is described by two coupled heat balance equations for the two compartments:

$$S_{cr} = M - W - (Q_{c,res} - Q_{e,res}) - Q_{cr \rightarrow sk} \quad (1)$$

$$S_{sk} = Q_{cr \rightarrow sk} - (Q_c + Q_r + Q_e) \quad (2)$$

The rate of heat storage in the body equals the rate of increase in internal energy. The rate of storage can be written separately for each compartment in terms of the thermal capacity and the rate of change of temperature as:

$$S_{cr} = (1 - \alpha) \cdot m \cdot c_b \cdot \frac{1}{A_{Du}} \cdot \left(\frac{dT_{cr}}{dt} \right) \quad (3)$$

$$S_{sk} = \alpha \cdot m \cdot c_b \cdot \frac{1}{A_{Du}} \cdot \left(\frac{dT_{sk}}{dt} \right) \quad (4)$$

when the body is able to maintain thermal equilibrium with the environment with minimal regulatory effort, a state of physiological thermal neutrality is reached and the average core and skin temperatures are: $T_{sk,neutral} = 33.7^\circ\text{C}$ and $T_{cr,neutral} = 36.8^\circ\text{C}$. In the case of temperature deviations from these respective neutral set points, we can assume that thermoregulatory control process (vasomotor, sweating, shivering) will be triggered. The core and skin temperature deviations act via blood flow. Since the heat is transferred from the core to the skin passively (conduction by direct contact between compartments) and through the skin blood flow, the combined heat flow is then:

$$Q_{cr \rightarrow sk} = (K + \dot{m}_{bl} \cdot c_{bl}) \cdot (T_{cr} - T_{sk}) \quad (5)$$

where K is massless thermal conductivity (heat conduction from the core to the skin). The effect of blood flow changes the relative masses of the skin and core compartments and can be determined as:

$$\alpha = 0.0418 + \frac{0.745}{3600 \cdot \dot{m}_{bl} - 0.585} \quad (6)$$

where α is the relative mass of the skin compartment with respect to the whole body mass. The resulting body temperature can be predicted as the weighted average of the skin and core temperatures:

$$T_b = \alpha \cdot T_{sk} + (1 - \alpha) \cdot T_{cr} \quad (7)$$

At the body surface, heat is exchanged by convection with ambient air, by radiation with surrounding surfaces, and by evaporation of moisture from the skin. The amount of dry heat loss depends on the temperature difference and on the corresponding heat transfer coefficients. For calculation purposes, the boundary conditions of the human body surface were calculated according to the equations, given in [2].

2.2. Mass balance equations

The activity of the sweat glands is set off by heat signals from the core and the skin. The evaporative heat loss from the skin is a combination of sweat secreted due to thermoregulatory control mechanisms and the natural diffusion of water through the skin. The latent energy transport, driven by the evaporative potential between the skin and the air, is effected by the amount of regulatory sweat production, moisture diffusion through the skin, and the vapour resistance of clothing (garments) [15–17]. Evaporative heat loss by regulatory sweating is directly proportional to the regulatory sweat output:

$$Q_{rsw} = \dot{m}_{rsw} \cdot h_e \quad (8)$$

The portion of a body that must be wetted for regulatory sweat to evaporate is:

$$w_{rsw} = \frac{Q_{rsw}}{Q_{e,max}} \quad (9)$$

Evaporative heat loss from skin depends on the driving mechanism, in this case the difference between the water vapour pressure at the skin surface and in the ambient air [18]. The maximum is reached when the whole skin surface is wetted ($w = 1$). Taking the evaporative heat transfer coefficient of clothing into account, the maximal heat transfer due to evaporation is:

$$Q_{e,max} = \frac{(p_{sk,s} - p_a)}{R_{cl} + 1/(f_{cl} \cdot h_e)} \quad (10)$$

where f_{cl} is the correction factor for the increase in available surface area for heat exchange caused by clothing. With no regulatory sweating, skin wetness due to diffusion is approximately 0.06 for normal indoor conditions. With regulatory sweating, only a portion of skin is not covered with sweat ($1 - w_{rsw}$) and the diffusive evaporative heat loss is:

$$Q_{diff} = 0.06 \cdot (1 - w_{rsw}) \cdot Q_{e,max} \quad (11)$$

Evaporative heat loss from the skin is a combination of evaporation of sweat output due to thermoregulatory control mechanism and natural diffusion of water through the skin:

$$Q_e = Q_{rsw} + Q_{diff} \quad (12)$$

Regarding exergy analysis, mass transfer through the skin can be determined using a modified Eq. (8) where the total evaporative heat transfer is considered.

During respiration, the body loses both sensible and latent heat by convection and evaporation of heat from the respiratory tract to the inhaled air. According to [4] the sensible and latent heat losses due to respiration are:

$$Q_{c,res} + Q_{e,res} = 0.0014 \cdot M \cdot (34 - T_a) + 0.0173 \cdot M \cdot (5.87 - p_a) \quad (13)$$

This model uses the above finite differential equations to estimate the physiological parameters for a given thermal environment, metabolic rate, and clothing insulation level. The integration loop (Eqs. (3) and (4)) predicts the responses induced by sweating or shivering and by skin blood flow necessary to maintain a set body temperature at heat and mass loads caused by the environment.

3. Exergy balance equations

In order to combine the human body's heat and mass transfer processes with room conditions, the system can be divided into two main parts. One is the indoor environment, the other is the human body. The human body works to convert energy (metabolism) into the necessary forms taking into account other factors (clothing, activity) and thereby provides the desired thermal comfort level. This process can be further classified as a conversion system and a calculation of exergy load can be performed. Exergy measures the ability of energy to do work and can be generally represented as:

$$E = (h - T_0 \cdot s) - (h_0 - T_0 \cdot s) \quad (14)$$

Since exergy is a measure of the maximum capacity of a system to perform useful work, it depends on the state of the energy source's environment. The greater the difference between the energy source and its surroundings, the greater the capacity to extract work from the system. Therefore, exergy is evaluated with respect to a reference environment (Index 0). It acts as an infinite system and is a sink or source for heat and mass. Considering the human body under indoor conditions, the reference temperature is set at the so-called operative temperature. This is the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as

in the actual environment. In the case where the relative velocity or the difference between the mean radiant and air temperature is small, the operative temperature can be calculated as the mean value of the air and the mean radiant temperature.

The processes related to human thermal comfort are heat and mass processes with one heat flow entering the skin compartment (“heating device”) and two heat flows leaving it. One of the heat flows leaves the human body due to heat transmission, thus warming the exhaled air, water diffusion, and sweat evaporation. The other part of the energy flow leaves the skin compartment via the blood flow returning to the body core (“heat source”). Therefore, the input to such a system can be regarded as the difference between the heat input into the human body (metabolism) and the heat in the return blood flow. Splitting one heat flow into two will lead to irreversibilities and exergy losses. The exergy is thus transferred into the environment and controlled by the environmental conditions, thus influencing heat and mass exchange. The general form of the exergy balance equation, regardless of the system, is as follows:

$$\begin{aligned} \text{Input exergy} - \text{Exergy consumption} \\ = \text{Stored exergy} + \text{Output exergy} \end{aligned}$$

To calculate the exergy consumption for given environmental conditions, we must first assume that the given time period is a series of finite time increments dt , small enough that the temperature and energy values appearing in Eqs. (1)–(4) can be assumed to be constant during each time increment dt . Calculations are repeated until a steady state is reached, this means that the heat storage (Eqs. (3) and (4)) is negligible. In this case, the exergy balance for the human body is:

$$\begin{aligned} E_{in} + \dot{m}_{a,in} \cdot e_{a,in} + \dot{m}_{w,in} \cdot e_{w,in} - E_{consumption} \\ = E_{out} + \dot{m}_{a,out} \cdot e_{a,out} + \dot{m}_{w,out} \cdot e_{w,out} \end{aligned} \quad (15)$$

The thermal exergy load for the sensible heat load at a constant temperature T can be calculated using the following equation:

$$E_{th} = \left(1 - \frac{T_0}{T}\right) \cdot Q \quad (16)$$

The chemical exergy load for the human body can be simply calculated as the difference between the exergy of the room air (inhaled air) and the exergy of the water input into the human body (exhaled air), which is assumed to be saturated. The reference state for the room air is selected to have an unsaturated humidity ratio φ_0 . Therefore, the room air will still possess available energy and will allow the water to diffuse into the unsaturated air until a saturated state is reached [19]. The saturated state is determined by the air temperature and the barometric pressure. Thus, the maximum useful work is:

$$W_{ch} = ex_0 + (\varphi_{0s} - \varphi_0) \cdot ex_w - ex_{0s} \quad (17)$$

where the exergy for water is determined to be

$$ex_w = -R_w \cdot T_0 \cdot \ln\left(\frac{p_{w0}}{p_{w0s}}\right) \quad (18)$$

In the case of the human body, the exergy is generated by metabolic chemical reactions within the human body. One part of the input exergy is a portion of the sensible heat, while the other part is the latent or wet exergy. Thus the exergy entering the human body E_{in} can be described as:

$$E_{in} = \left(1 - \frac{T_0}{T_{cr}}\right) \cdot M \quad (19a)$$

$$\dot{m}_{w,in} \cdot e_{w,in} = \dot{m}_e \cdot (-R_w \cdot T_0 \cdot \ln(\varphi)) \quad (19b)$$

$$\begin{aligned} e_{a,in} = (c_{p,a} + x_a \cdot c_{p,w}) \cdot \left[T_a - T_0 - T_0 \cdot \ln\left(\frac{T_a}{T_0}\right) \right] \\ + \left\{ R_a \cdot T_0 \cdot \left[\left(1 + 1.608 \cdot x_a\right) \cdot \ln\left(\frac{1 + 1.608 \cdot x_{0,s}}{1 + 1.608 \cdot x_a}\right) \right. \right. \\ \left. \left. + 1.608 \cdot x_a \cdot \ln\left(\frac{x_a}{x_{0,s}}\right) \right] \right\} \end{aligned} \quad (19c)$$

where diffusion, sweating, and humidification of exhaled air cause the evaporative mass transfer. Eq. (19c) refers to indoor air conditions and the system is assumed to be isobaric.

The exergy output of the human body can be similarly calculated. The exergy output consists of dry and evaporative heat transfer (thermal exergy load) and of chemical exergy load caused by water dispersion into the air (skin diffusion, air humidification by breathing, sweating). In this calculation, the humidifying load is introduced into the room air at a constant humidity ratio and a constant air temperature.

Although the first law of thermodynamics states that energy is conserved during heat conduction, the second law tells us that entropy is generated. Blood flows into the skin compartment at temperature T_{cr} and flows out at T_{sk} ($T_{sk} < T_{cr}$). The outer part of the body emits long-wave radiation and receives long-wave radiation emitted by the surrounding wall surfaces (T_{ms}). Convective and radiative heat transfer between the human body and environment (room) is included and the respective energy balance is:

$$\begin{aligned} c_{bl} \cdot \dot{m}_{bl} \cdot (T_{cr} - T_0) + A_{Du} \cdot \varepsilon \cdot \sigma \cdot T_0^4 \\ = c_{bl} \cdot \dot{m}_{bl} \cdot (T_{sk} - T_0) + h_c \cdot A_{Du} \cdot (T_{sk} - T_0) \\ + A_{Du} \cdot \varepsilon \cdot \sigma \cdot T_{sk}^4 \end{aligned} \quad (20)$$

In Eq. (20) the input terms are on the left side: the first term accounts for the thermal energy of the blood flow entering the skin compartment and the second term accounts for the radiation emitted by the surrounding surfaces. The right side of the equation represents the

output term: the thermal energy of the blood leaving the skin compartment, the convective heat transfer between the skin surface and the room air, and the radiation emitted at the skin surface. The corresponding exergy balance equation is as follows:

$$\begin{aligned}
 & c_{bl} \cdot \dot{m}_{bl} \cdot \left(T_{cr} - T_0 - T_0 \cdot \ln \frac{T_{cr}}{T_0} \right) + A_{Du} \cdot \varepsilon \cdot \sigma \\
 & \cdot \left[T_{cr}^4 - T_0^4 - \frac{4}{3} \cdot (T_{cr}^4 - T_0^4) \right] + E_{consumption} \\
 & = c_{bl} \cdot \dot{m}_{bl} \cdot \left(T_{sk} - T_0 - T_0 \cdot \ln \frac{T_{sk}}{T_0} \right) + A_{Du} \cdot h_c \\
 & \cdot (T_{sk} - T_a) \cdot \frac{(T_{sk} - T_0)}{T_{sk}} + A_{Du} \cdot \varepsilon \cdot \sigma \\
 & \cdot \left[T_{sk}^4 - T_0^4 - \frac{4}{3} \cdot (T_{sk}^4 - T_0^4) \right] \quad (21)
 \end{aligned}$$

Eq. (21) implies that exergy input minus exergy consumption equals the exergy output. Considering the first law of thermodynamics for this state, the rate of heat generation equals the rate of heat loss. Applying the exergy analysis, we are thus able to determine the exergy consumption within the human body.

4. Case study

From the above analysis, it can be seen that an exergy analysis of the human thermal model could be used for determining the connection between exergy consumption within the human body and environmental conditions. The human body is considered to be an open thermodynamic system in a steady-state condition. There are corresponding entropy flows associated with the energy flows; entropy production is a kind of measure of the degree of activity within the body (physical, chemical). Since a steady-state condition is being assumed, there is no entropy storage.

In our case study, the influence of room temperature on exergy consumption by the human body is calculated. Since the heat transfer between the human body and the environment depends on air temperature and the mean radiant temperature, both parameters were chosen to be between 10 and 30 °C. Other environment conditions were kept constant: air velocity 0.1 m/s and relative air humidity 50%. The following parameters were chosen for the human body: body mass 80 kg, activity 1 met (energy production 58 W/m² K), and clothing 1 clo (clothing thermal resistance $R_{cl} = 0.155 \text{ m}^2 \text{ K/W}$), while the set values for physiological thermal neutrality were: core set temperature 36.8 °C and skin set temperature 33.7 °C. To satisfy the steady-state condition, which is defined as a state without heat storage defined in Eqs. (4) and (5), the simulated time interval was 120 min with a time step of 60 s. Fig. 1 shows the exergy

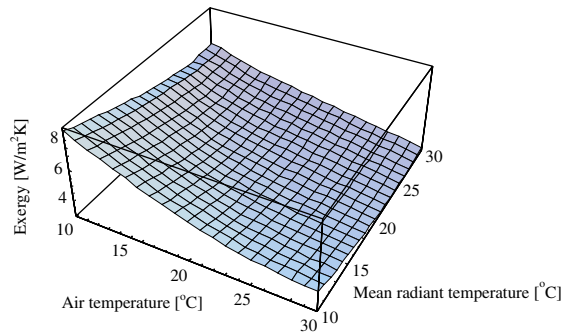


Fig. 1. Exergy input for human body in dependence on air and mean radiant temperature.

input for the human body in relation to the selected environmental parameters.

Exergy input consists of dry heat input, which is equal to metabolic rate plus the exergy of inhaled air, and of “wet” exergy input, which mass is equal to water output (mass balance). For the calculation of exergy output, the human thermoregulatory system had to be taken into account. Consequently, the relevant parameters determining the exergy output were adjusted via the thermoregulatory system in order to achieve the best possible thermal comfort level. Fig. 2 shows the exergy output. Exergy output is composed of dry exergy (determined by convective and radiative heat transfer from the skin, heat flow as the diffusion and evaporation of water from the skin surface, breathing) and wet exergy (diffusion and evaporation of water from the skin surface, air humidification while breathing).

The exergy consumption within the human body shown in Fig. 3 is most interesting. By increasing room temperature (operative temperature) from low to neutral temperatures, the exergy consumption rate decreases and at certain temperature reaches a minimum. From the analysis it is evident that the minimum is reached

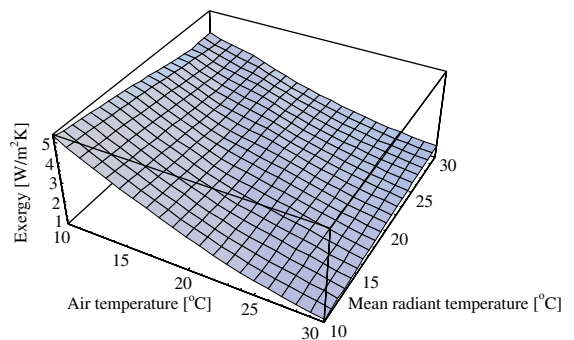


Fig. 2. Exergy output for human body in dependence on air and mean radiant temperature.

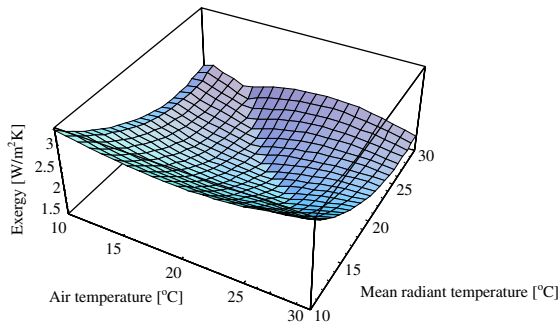


Fig. 3. Exergy consumption within the human body as a function of air and mean radiant temperature.

at only one combination of air and mean radiant temperature. At low room temperatures the energy generated by shivering (exergy) in order to maintain body temperature at an (almost) desirable level, caused higher exergy input and output. At lower skin temperatures, exergy consumption becomes higher as a consequence of the temperature difference between the core and the skin. Similarly, when the environment becomes rather hot, the exergy consumption rate increases despite a smaller temperature difference between the body and environment. In this case sweating takes place, triggered by the temperature difference between the neutral and actual skin/core temperature. Evaporative cooling of body increases exergy consumption; such a process will allow water to diffuse into the unsaturated air. According to Eq. (15), the driving mechanism is the water vapour pressure and the saturated vapour pressure of the environmental air. It is interesting that the minimal exergy consumption (for given human factors) occurs at a combination of air temperature $T_a = 19.2^\circ\text{C}$ and mean radiant temperature $T_{\text{mrt}} = 23.9^\circ\text{C}$. The occurrence of a minimal value indicates that there may exist a connection between exergy consumption and the expected level of thermal comfort.

4.1. Exergy consumption and expected level of thermal comfort

To verify the presented model, a comparison between exergy consumption and the expected level of thermal comfort was made. The thermophysiological definition of comfort is based on firing of the thermal receptors in the skin and in the hypothalamus. Comfort in this sense is defined as the minimum rate of nerve signalling from the receptors. According to its energetic definition, the state of thermal comfort is reached when the heat flows to and from the human body are balanced and the skin temperature and sweat rate are within a comfort range. For this purpose, we use predicted mean vote (PMV) model. The PMV is an index that predicts the

mean value of the votes of a large group of persons on the 7-point thermal sensation scale, ranging from -3 (cold) to $+3$ (hot). This model is derived from the physics of heat transfer combined with an empirical fit to sensation. It establishes a thermal strain based on a steady-state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain. The PMV equation postulates a link between the deviation from the minimum load on heat balance effector mechanisms, e.g. sweating, vasoconstriction, vasodilation, and the thermal comfort vote. The PMV model predicts the thermal sensation as a function of activity, clothing, and four thermal environmental parameters: air and mean radiant temperature, air velocity, and air humidity. The advantage of the PMV model is that it is a flexible tool that includes all the major variables influencing thermal sensation. The original PMV model was based on Fanger's one-compartment human thermal model; the major limitation of this model is the explicit constraint of skin temperature and evaporative heat loss to values for comfort and neutral sensation only at a given metabolism (activity level). Since in this analysis the two-node model is used and special attention is given to heat and mass transfer, we used a new PMV index (PMV*) [20]. PMV* index is proposed for any dry or humid environment by simply replacing the operative temperature in Fanger's comfort equation with rational effective temperature (ET*). This represents an improvement as it includes the physiological heat strain caused by the relative humidity and vapour permeability properties of clothing. The two-node model determines the heat flow between the core, the skin, and the environment on a per minute basis, starting from an initial condition. The model iterates until energy flow equilibrium has been reached; the final mean skin temperature and skin wettedness are then used to calculate the effective temperature.

For the PMV* model, the same personal and environmental parameters were used as for exergy analysis. The resulting PMV* values are shown in Fig. 5. For the sake of better visual interpretation, the PMV* values are plotted as absolute values. Negative values ranges from thermal neutral state (PMV* = 0) towards the lower left-hand corner; the thermal sensation is cold when the air and mean radiant temperature are lowered. A comparison between the exergy analysis (see Fig. 4) and PMV* value indicates that the minimal exergy consumption coincides with a neutral thermal sensation. Furthermore, we see from the exergy analysis that the combinations of air and mean radiant temperatures that assure neutral or pleasant thermal sensation are limited. Therefore, we can conclude that exergy analysis gives even more information about the environmental impact on expected human thermal sensation than other energy-based types of analysis.

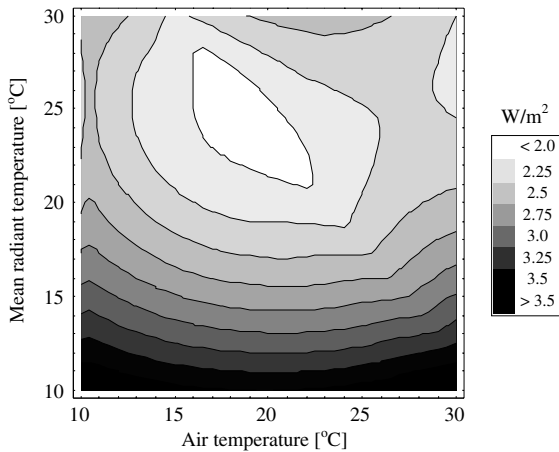


Fig. 4. Dependence of exergy consumption on air and mean radiant temperature. For the given environmental and physiological parameters, the minimum value is at $T_a = 19^\circ\text{C}$ and $T_{\text{mrt}} = 24^\circ\text{C}$.

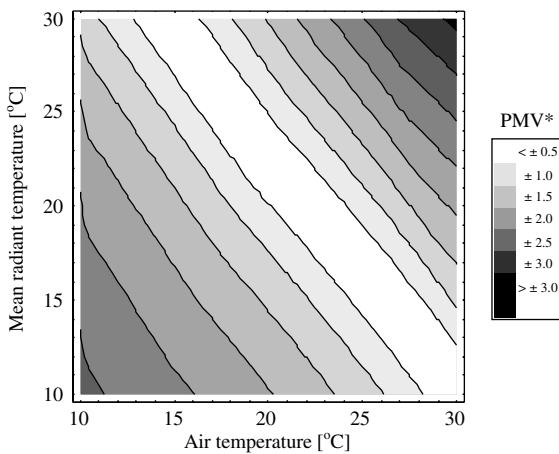


Fig. 5. Dependence of PMV* value on air and mean radiant temperature for the given environmental and physiological parameters.

5. Conclusions

Traditional methods of human thermal analysis are based on the first law of thermodynamics. These methods use an energy balance of the human body to determine heat transfer between the body and its environment. In this paper a different approach is presented, namely an analysis based on the second law of thermodynamics. There are corresponding entropy flows associated with the heat and mass flows; combining the energy and entropy balance brings about exergy balance.

The aim of this analysis is to identify an exergetical model that allow predictions of human responses to the thermal environment based on exergetical analysis. The two-node model was used, since it incorporates the 2nd law of thermodynamics and is relatively simple to compute. This model was further expanded taking into account the exergy consumption within the human body as a consequence of heat and mass transfer and/or conversion. Reference conditions were determined considering typical indoor conditions.

An example is given in order to verify the presented model. From the exergy analysis it was established that there is a minimum exergy consumption, dependent on physiological and environmental parameters. For given physiological conditions only one combination of environmental parameters ensures minimal exergy consumption. This result shows that the analysis based on 2nd law of thermodynamics provide more useful information regarding human physiological behaviour and responses than other analyses. Therefore such an analysis could be used to determine the connection between human thermal comfort and environmental parameters. It is also possible to investigate the effects of ambient conditions on thermal comfort based on the same thermodynamic law.

We show that the existing methods of human thermal comfort assessment could be further expanded by taking into account exergy analysis. Under steady-state conditions, the results indicate that there is a connection between exergy consumption and expected levels of thermal comfort. Such an extension better determines the connection between environmental conditions and predicted thermal sensation.

Exergy analysis clearly shows how human exergy consumption is coupled to environmental conditions. Furthermore, the results show that there is a correlation between exergy consumption by the human body and the expected level of thermal comfort, expressed as the PMV* value.

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