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Thermodynamical analysis of human thermal comfort

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Abstract

Traditional methods of human thermal comfort 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. By contrast, the second law of thermodynamics introduces the useful concept of exergy. It enables the determination of the exergy consumption within the human body dependent on human and environmental factors. Human body exergy consumption varies with the combination of environmental (room) conditions. This process is related to human thermal comfort in connection with temperature, heat, and mass transfer. In this paper a thermodynamic analysis of human heat and mass transfer based on the 2nd law of thermodynamics in presented. It is shown that the human body's exergy consumption in relation to selected human parameters exhibits a minimal value at certain combinations of environmental parameters. The expected thermal sensation also shows that there is a correlation between exergy consumption and thermal sensation. Thus, our analysis represents an improvement in human thermal modelling and gives more information about the environmental impact on expected human thermal sensation.

1. Introduction

The complex interaction of air temperature, mean radiant temperature, air velocity and humidity makes up the human thermal environment. To achieve a satisfactory thermal environment it is useful to be able to predict what the effect of a particular combination of thermal conditions will be on human occupants. Modern indoor design methods are based on the heat exchange conditions of the human body. The calculation of heat exchange can be executed with the help of the so-called heat balance equation, as

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Nomenclature

A	area, m^2
c	specific heat, J/kg K
E	exergy load, J
ex	exergy, J/kg
f	correction factor for clothing surface area, –
h	enthalpy, J/kg
h_e	latent heat of evaporisation, J/kg
K	thermal conductivity, W/m K
M	metabolism, W/m^2
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
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 or K
W	specific work, J/kg
x	humidity ratio, –

Greek letters

α	relative mass of the skin, –
ε	emissivity, –
ϕ	relative humidity ratio, –
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant

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

studies have proved that the subjective heat sensation is pleasant if the heat generated within the human body (metabolism) and the heat dissipated in the various ways are in balance.

Human thermal models range from simple one-dimensional, steady-state simulations by Fanger [1] and multi-node models as given by Wissler [2] to complex, transient finite element models by Fu [3] and Tanabe [4]. Some of these models include a thermoregulatory system with sweating and blood flow regulation, e.g. Stolwijk [5], Fiala [6], and the physics of clothing, e.g. Werner [7], Havenith [8]. Some of the newer models, Lotens [9] and Murakami [10], have focused on detailed analysis of transient heat and moisture transport through clothing, or on the influence of body posture, as shown by Kaynakli [11]. The main similarity of most models is the application of energy balance to a person and the use of energy exchange mechanisms, along with experimentally derived physiological responses, in order to predict thermal sensation. The models differ mainly in the physiological models (human passive heat transfer system and control system) and in the criteria used to predict thermal sensation.

For comfort assessment of the indoor environment, several standardized methods are available. Typically, six parameters are used, requiring as input four indoor climatic parameters and two parameters related to the occupants: metabolic heat production and clothing insulation. For optimal thermal comfort, three basic conditions must be satisfied. The first condition is the existence of heat balance, based on the first law of thermodynamics, which is a far from easy condition to satisfy. The human thermoregulatory system is quite effective and creates heat balance within wide limits of the environmental variables. For a given activity level (metabolism), skin temperature and sweat secretion are seen to be the only physiological variables influencing heat balance. Consequently, the sensation of thermal comfort has been related to the magnitude of these two variables. Experiments involving a group of persons at different activity levels have been performed to determine mean values of skin temperature and sweat secretion as the second and the third basic conditions for thermal comfort.

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 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 imbalance 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 as is shown by Bejan [12,13] and Dincer [14].

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.

An example is given in order 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 by the inclusion of exergy analysis.

2. Thermal comfort models

The steady-state model developed by Fanger [1] assumes that the body is in thermal equilibrium with negligible heat storage. There is no shivering and vasoregulation is not considered because the core and skin are modelled as one compartment. The rate of heat generation equals the rate of heat loss and the energy balance can be written as:

$$\dot{M} - \dot{W} = \dot{Q}_{\mathrm{c}} + \dot{Q}_{\mathrm{r}} + \dot{Q}_{\mathrm{e}} + \dot{Q}_{\mathrm{c,res}} + \dot{Q}_{\mathrm{e,res}} \quad (1)$$

This simplified model does not attempt to simulate transients or thermal regulation, and is focused primarily on the thermal physiology of the human body. However, a thermal model for the body is only as accurate as the information provided about its heat and moisture exchange with the environment. Consequently, if the indoor environment is controlled with a HVAC system, the heat and moisture exchange with the environment must be evaluated since the thermoregulatory control mechanisms of the body are influenced by environmental conditions.

The effects of the ambient conditions on the human thermoregulatory system and heat flow within the human body can be investigated using the two compartments (or two node) model developed by Gagge [15]. This model represents the body as two concentric cylinders, where the inner cylinder represents the body core and the outer cylinder represents the skin layer. The core and skin compartments exchange energy (heat) passively through direct contact and dynamically through the thermoregulatory controlled peripheral blood flow.

A transient energy balance states that the rate of heat storage equals the net rate of heat gain minus the heat loss. This thermal model is described by two coupled heat balance equations for the two compartments:

$$S_{\mathrm{cr}} = M - W - (Q_{\mathrm{c,res}} - Q_{\mathrm{e,res}}) - Q_{\mathrm{cr}\to\mathrm{sk}} \quad (2)$$

$$S_{\mathrm{sk}} = Q_{\mathrm{cr}\to\mathrm{sk}} - (Q_{\mathrm{c}} + Q_{\mathrm{r}} + Q_{\mathrm{e}}) \quad (3)$$

where S_{cr} is the rate of heat storage in the core compartment, S_{sk} is the rate of heat storage in the skin compartment and $S_{\mathrm{cr}\to\mathrm{sk}}$ is heat flow from the core to the skin compartment. 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:

$$S_{cr} = (1-\alpha)mc_b \frac{1}{A_{Du}}\left(\frac{dT_{cr}}{dt}\right) \tag{4}$$

$$S_{sk} = \alpha mc_b \frac{1}{A_{Du}}\left(\frac{dT_{sk}}{dt}\right) \tag{5}$$

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: $T_{sk,neutral} = 33.7$ °C and $T_{cr,neutral} = 36.8$ °C. In the case of temperature deviations from these respective neutral set points, we can assume that thermoregulatory control processes (vasomotorical, sweating, shivering) will be triggered. The core and skin temperature deviations act via blood flow. Since the heat is transferred from the core to skin passively (conduction by direct contact between compartments) and through the controllable skin blood flow, the combined heat flow is then:

$$\dot{Q}_{cr\rightarrow sk} = (k + \dot{m}_{bl}c_{bl})(T_{cr} - T_{sk}) \tag{6}$$

The effect of blood flow changes the relative masses of the skin and core compartments and can be determined according to Wang [16] as:

$$\alpha = 0.0418 + \frac{0.745}{3600\dot{m}_{bl} - 0.585} \tag{7}$$

The activity of the sweat glands is set off by warm signals from the core and the skin. While in the case of simultaneous cold signals from both the core and the skin, additional metabolic heat through shivering and muscle tension is generated. 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, taking into account clothing evaporative resistance, as is defined by Toftum [17]. Evaporative heat loss by regulatory sweating is directly proportional to the regulatory sweat output:

$$\dot{Q}_{rsw} = \dot{m}_{rsw}h_e \tag{8}$$

During respiration, the body loses both sensible and latent heat by convection and evaporation of heat from the respiratory tract to the inhaled air. The respirative sensible and latent heat losses are:

$$\dot{Q}_{c,res} + \dot{Q}_{e,res} = [0.0014M(34 - T_a) + 0.0173M(5.87 - p_a)] \tag{9}$$

3. Introducing the exergy concept into the human thermal comfort model

In order to combine thermal comfort with room conditions, the system can be divided into two main parts. One is conditioned space; the other is the human body. The human body works to convert energy (metabolism) into the necessary forms taking into account other personal factors (clothing, activity) and to provide the desired thermal comfort level. This process can be further classified as a conversion system and thus a calculation of exergy load can be performed. Exergy measures the ability of energy to do work and can be generally represented as:

$$E = (h - T_o s) - (h_o - T_o s) \tag{10}$$

The thermal exergy load for the sensible load can be calculated by the following equation:

$$E_{th} = \left(1 - \frac{T_o}{T}\right) Q \tag{11}$$

Eq. (11) determines the exergy content at a constant temperature T. The term in brackets is also known as the Carnot efficiency. For a limited heat content or if the temperature T varies during heat transfer (e.g. blood cooling during flow through skin compartment), the exergy load is determined as:

$$E_{th} = \left(1 - \frac{T_0}{T - T_0} \ln \frac{T_0}{T}\right) Q_c \tag{12}$$

This is true for convection heat transfer (therefore the index c is used in Eqs. (1) and (2)) but not for radiation heat transfer. Surface radiation is controlled by surface temperature according to the Stefan–Boltzmann Law, while the rate of convection heat transfer is controlled by the temperature gradient between the environment temperature T_0 and T. Therefore, energy transferred by radiation actually transfers a third more entropy with it than convection or conduction heat transfer, as shown by Bejan [12]. For a given radiation heat transfer Q_r the exergy load E_r is defined as:

$$E_r = \left(1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\frac{T_0^4}{T^4}\right) Q_r \tag{13}$$

The net radiation transfer to the surface of a system (at temperature T) is the sum of the incoming radiation by that surface minus the radiation emitted by that surface into the environment (at temperature T_0). From the above analysis, it is obvious that the reference environment cannot be defined by one single temperature.

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 exhaled air, which is assumed to be saturated. Thus, the maximum useful work is:

$$W_{ch} = E_o + (\varphi_{os} - \varphi_o) E_w - E_{os} \tag{14}$$

where the exergy for water is determined to be:

$$E_w = -R_w T_o \ln\left(\frac{p_{wo}}{p_{wos}}\right) \tag{15}$$

Finally, the chemical exergy load is:

$$E_{ch} = 1.608 R_w T_o \ln\left[\frac{(1 + 1.608\varphi_{os})\varphi}{(1 + 1.608\varphi)\varphi_{os}}\right] W_{ch} \tag{16}$$

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 warming the exhaled air, as well as to water diffusion and sweat evaporisation. 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 a 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, thereby influencing heat and mass exchange. The general form of the exergy balance equation, regardless of the system, is as follows:

$$\text{Input exergy} - \text{Exergy consumption} = \text{Stored exergy} + \text{Output exergy} \tag{17}$$

In the case of the human body, exergy is generated by metabolic chemical reactions within the human body. One part of the input exergy is a portion of the sensible heat (with the possibility for diffusion), while the other part is latent or wet exergy with the possibility of evaporative dispersion of water into the environment. The exergy entering the human body E_{in} can be described as:

$$E_{in} = \left(1 - \frac{T_{room}}{T_{cr}}\right)M + R_w T_a \ln(\varphi)\dot{m}_e \tag{18}$$

where diffusion, sweating, and humidification of exhaled air cause evaporative mass transfer.

Similarly the human body exergy output can be 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 humidifying by breathing, sweating).

4. Exergy consumption

To calculate exergy consumption at various parts of a human body (according to Gagge [15]), the body is divided into subsystems, namely into core and skin compartments. Each of the systems is a place, where the exergy is consumed as a consequence of energy transfer or energy conversion. Human body thermal regulation is mainly achieved by regulating blood flow as is shown by Huizenga [18]. It is by vasoconstriction and vasodilatation that the body regulates blood distribution in order to control skin temperature and 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. 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 heat transfer between the human body and room air is also considered and the respective energy balance is:

$$c_{bl}\dot{m}_{bl}(T_{cr} - T_0) + A_{Du}\varepsilon\sigma T_{sk}^4 = c_{bl}\dot{m}_{bl}(T_{sk} - T_0) + h_c A_{Du}(T_{sk} - T_0) + A_{Du}\varepsilon\sigma T_0^4 \tag{19}$$

The corresponding exergy balance equation is as follows:

$$c_{\mathrm{bl}}\dot{m}_{\mathrm{bl}}\left(T_{\mathrm{cr}}-T_0-T_0\ln\frac{T_{\mathrm{cr}}}{T_0}\right)+A_{\mathrm{Du}}\varepsilon\sigma\left[T_{\mathrm{cr}}^4-T_0^4-\frac{4}{3}(T_{\mathrm{cr}}^3-T_0^3)\right]-E_{\mathrm{consumption}}$$
$$=c_{\mathrm{bl}}\dot{m}_{\mathrm{bl}}\left(T_{\mathrm{sk}}-T_0-T_0\ln\frac{T_{\mathrm{sk}}}{T_0}\right)+A_{\mathrm{Du}}h_{\mathrm{c}}(T_{\mathrm{sk}}-T_{\mathrm{a}})\frac{(T_{\mathrm{sk}}-T_{\mathrm{o}})}{T_{\mathrm{sk}}}$$
$$+A_{\mathrm{Du}}\varepsilon\sigma\left[T_{\mathrm{sk}}^4-T_0^4-\frac{4}{3}(T_{\mathrm{sk}}^3-T_0^3)\right] \qquad (20)$$

Eq. (20) implies that exergy input minus exergy consumption equals exergy output. To calculate the exergy consumption for given environmental conditions, we 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. (4) and (5) can be assumed to be constant during each time increment dt. Calculations are repeated until a steady state is reached, which means that the heat storage is negligible. 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.

5. Case study

The human body is considered to be an open thermodynamic system in a steady-state condition. There are corresponding entropy flows and 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 mean radiant temperature, both parameters were chosen to be between 14 and 28 °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 1.1 met (energy production 63.8 W/m^2 K), and clothing 0.9 clo (clothing thermal resistance $R_{\mathrm{cl}}=0.14$ m^2 K/W and vapour permeability index $i_{\mathrm{m}}=0.38$), while the set values for physiological thermal neutrality were: core set temperature 36.8 °C and skin set temperature 33.7 °C.

Exergy input consists of dry heat input, which is equal to the metabolic rate plus the exergy of inhaled air, and of ‘wet’ exergy input, where mass is equal to the water output (conservation of mass). In order to calculate the exergy output, the human thermoregulatory system had to be taken into account. Consequently, the relevant parameters determining exergy output were adjusted via the thermoregulatory system in order to achieve the best possible thermal comfort level. 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 is shown in Figs. 1 and 2.

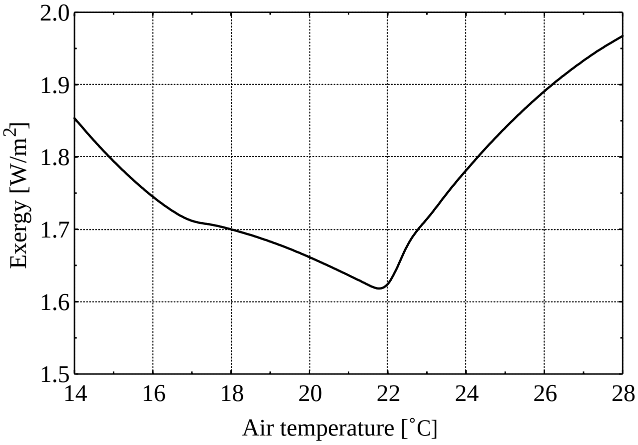

Fig. 1. Exergy consumption dependent on air temperature ($T_{mrt}=20$ °C).

By increasing room temperature (air and mean radiant temperature) from low to neutral temperatures, the exergy consumption rate decreases and reaches a minimum at a certain temperature. From the analysis it is evident that the minimum is reached 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 a (almost) desirable level, causes 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 the body increases exergy consumption and allows water to diffuse into the unsaturated air. It is interesting that the minimal exergy consumption (for given human factors) occurs at a certain combination of air and mean radiant temperature.

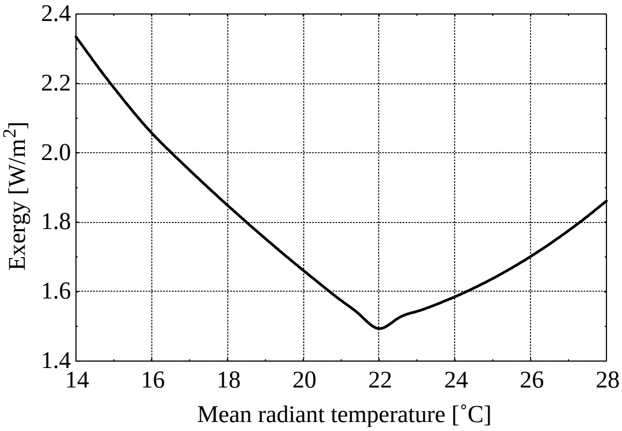

Fig. 2. Exergy consumption dependent on mean radiant temperature ($T_a=20$ °C).

The energetical analysis shows that there are many combinations of air and mean radiant temperature which satisfy thermal neutrality. Exergy analysis invokes an additional parameter, namely mass transfer, which limits the thermal neutrality range. The existence of minimum exergy consumption reduces the range of combinations of environmental parameters, which assures the expected level of the thermal comfort. The thermophysiological definition of comfort is based on firing of the thermal receptors in the skin and in the hypothalamus. 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 the modified PMV (predicted mean vote) model. Since, in this analysis, the two-node model is used and special attention is given to heat and mass transfer, we used a PMV* index as introduced by Gagge [19] and Ye [20]. The PMV* index is proposed for any dry or humid environment by simply replacing the operative temperature in Fanger's comfort equation with a 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. For the PMV* model, the same personal and environmental parameters were used as for exergy analysis (Figs. 1 and 2). The exergy consumption is shown in Fig. 3 and the resulting PMV* values are shown in Fig. 4.

The PMV* values are plotted as absolute values. Negative values range from a thermal neutral state (PMV* = 0) towards the lower left-hand corner; indicating that the thermal sensation is cold when the air and mean radiant temperature are lowered. A comparison between the exergy analysis 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. 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.

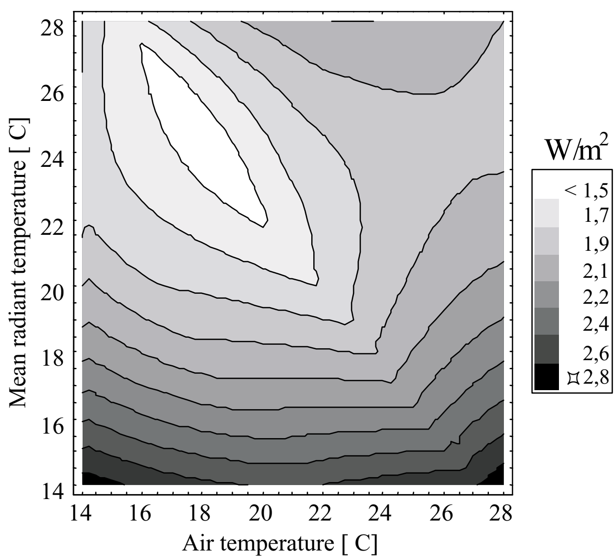

Fig. 3. Exergy consumption as a function of air and mean radiant temperature.

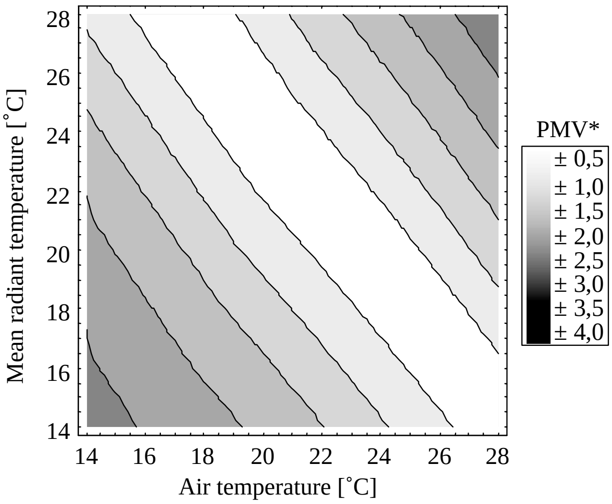

Fig. 4. PMV* values as a function of air and mean radiant temperature.

6. Conclusion

One way to open up the saving potentials for room air conditioning systems is to employ extremely low temperature heating and cooling systems. These low exergy systems (using low valued energy) can provide room air conditioning in a safe and economic way, while still preserving the desired level of thermal comfort. Introducing the term exergy into energy research in the building sector implies the need for an exergetical analysis of the human physiological response to environmental conditions. These processes are dependent on human thermoregulatory system and on the state of the environment. Therefore the model used is comprised of a physiological part based on the two-node model and a physical model describing the heat and mass transfer properties of clothing, since it enables the use of the second law of thermodynamics. We show that the existing methods of human thermal comfort assessment could be further expanded using exergy analysis. The presented model allows us to investigate the effects of ambient conditions on thermal comfort based on the same thermodynamic law.

The aim of this analysis is to identify the exergetical model that would provide predictions of human responses to the thermal environment based on exergetical analysis. Exergy analysis clearly shows how human exergy consumption is coupled to environmental conditions. Furthermore, under steady-state conditions, the results indicate that there is a correlation between the exergy consumption of the human body and the expected level of thermal comfort.

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 the 2nd law of thermodynamics provides more useful information regarding human physiological behaviour and responses than other analyses. Such an extension better determines the connection between environmental conditions and predicted thermal sensation.

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