José A. Rabi
jrabi@usp.br
University of São Paulo
Faculty of Animal Science and Food Engineering
13635-900 Pirassununga, SP, Brazil

Robson L. Silva
robsonsilva@ufgd.edu.br
Federal University of Dourados
Faculty of Engineering / Energy Engineering
79804-970 Dourados, MS, Brazil

Celso E. L. Oliveira
celsooli@usp.br
University of São Paulo
Faculty of Animal Science and Food Engineering
13635-900 Pirassununga, SP, Brazil

Human Thermal Comfort: an Irreversibility-Based Approach Emulating Empirical Clothed-Body Correlations and the Conceptual Energy Balance Equation

Exergetic analysis can provide useful information as it enables the identification of irreversible phenomena bringing about entropy generation and, therefore, exergy losses (also referred to as irreversibilities). As far as human thermal comfort is concerned, irreversibilities can be evaluated based on parameters related to both the occupant and his surroundings. As an attempt to suggest more insights for the exergetic analysis of thermal comfort, this paper calculates irreversibility rates for a sitting person wearing fairly light clothes and subjected to combinations of ambient air and mean radiant temperatures. The thermodynamic model framework relies on the so-called conceptual energy balance equation together with empirical correlations for invoked thermoregulatory heat transfer rates adapted for a clothed body. Results suggested that a minimum irreversibility rate may exist for particular combinations of the aforesaid surrounding temperatures. By separately considering the contribution of each thermoregulatory mechanism, the total irreversibility rate rendered itself more responsive to either convective or radiative clothing-influenced heat transfers, with exergy losses becoming lower if the body is able to transfer more heat (to the ambient) via convection.

Keywords: *thermodynamics, exergetic analysis, thermal comfort, thermoregulation*

Introduction

Thermal comfort analyses may contribute to design bioclimatic and energy-efficient buildings as well as to outline safety (or health) precautions or standards for workers at food processing areas or refrigeration chambers. Several parameters have been defined to assess human thermal sensation, acceptability or comfort (Givoni, 1981; Parsons, 1993) and they are referred to as (*i*) direct, if based on data read from instruments used to imitate body responses, (*ii*) empirical, when obtained via numerical regression of human physiological responses as occupants become exposed to distinct ambient conditions, or (*iii*) rational, when based on theoretical reasoning.

Rational parameters have been usually defined in terms of an energy balance applied to the human body, accounting for concurrent effects from the well-known six basic factors, namely: air temperature, radiant temperature, air humidity, air speed, activity-related metabolism, and clothing (Fanger, 1970; Parsons, 1993). In other words, rational parameters have evoked the first law of thermodynamics to deal with thermoregulatory responses related to energy interactions between the human body and ambient parameters (the first four basic factors in the aforesaid list) combined with behavioural parameters (the last two factors in the list). Yet, the first law cannot identify imperfections in real processes while it makes no distinction between heat and work interactions.

Depending on the amount of energy that can be transformed into useful work, the second law introduces a qualitative feature to energy interactions. Taking into account the second law, the so-called objective thermal comfort index (OTCI) has been put forward as "the percentage deviation in the value of entropy generation from the comfort or equilibrium condition" (Boregowda, Tiwari and Chaturvedi, 2001):

$$\text{OTCI (\%)} = H[1-(S_{\text{gen,act}}/S_{\text{gen,com}})]\times 100 \qquad (1)$$

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where actual and comfort entropy generations ($S_{\text{gen,act}}$ and $S_{\text{gen,com}}$) are calculated based on occupants' responses and on ambient variables. Referred to as human coefficient, the dimensionless parameter H accounts for variations due to factors like age, sex and race. Bearing in mind ASHRAE (or ISO 7730) definition for thermal comfort, namely, "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2001), one may regard the coefficient H as an attempt to link physiological to psychological responses, which may vary from person to person. Such an idea of introducing particular corrections was similarly conceived by Humphreys and Hancock (2007) via an 'adjusted thermal sensation' concept to indicate how much occupant's actual thermal sensations exceed the desired ones on ASHRAE scale for thermal comfort.

First and second laws of thermodynamics can be suitably combined to improve process efficiency. Resulting from such combination, exergy is a property that can be interpreted as the useful energy available for a system (Kotas, 1985; Bejan, 1988; Szargut, Morris and Steward, 1988). Taking into account parameters related to the system as well as to its surroundings, exergetic analysis may identify dissipative or irreversible phenomena and compare a given process to the most efficient way by which it could be carried out, namely, an ideal reversible process.

Links between thermoregulation and exergy have already been attempted. Considering a two-compartment (core and skin) model for the human body, Prek (2004, 2005, 2006) and co-worker (Prek and Butala, 2010) discussed exergy consumption rates with respect to related values for standard predicted mean vote (PMV), based on one-compartment model (Fanger, 1970), and for its modified value (PMV*), proposed for any dry or humid environment (Gagge, Stolwijk and Nishi, 1971).

By the same token, one might attempt to correlate occupant's thermal discomfort and exergy losses, equally referred to as irreversibilities. Based on a steady-state model framework and preliminary concepts as discussed in a previous work (Rabi, Fresia and Benzal, 2006), the present work puts forward more insights to the exergetic analysis of human thermal comfort by relying on the so-called conceptual energy balance equation together with existing empirical correlations for the invoked thermoregulatory heat transfer rates expressed in terms of a clothed body. Bearing in mind a prospective rational assessment of thermal comfort, irreversibilities are calculated and discussed for a sitting person wearing relatively light clothes and subjected to some combinations of ambient air and mean radiant temperatures.

Another approach to human thermal comfort is given by Batato et al. (1990), where three different temperature levels are modelled and submitted to an exergetic analysis. The human body was considered at rest, which corresponds to the same condition considered herein, i.e., a sitting person wearing light clothes.

Data from Simone et al. (2011) point out a second-order polynomial relationship between human-body exergy consumption rates, i.e., irreversibility rates, with a slightly cool sensation, reaching minimum values when thermal sensation is close to neutrality. The study considered sedentary people, male and female, subjected to convective and radiant heat transfers.

In a recent work (Mady et al., 2012), the thermal behaviour of human body was simulated by dividing it into 15 compartments. Exergy balances were accomplished considering radiation, convection, evaporation and respiration and results indicated that human body becomes more efficient and destroys less exergy for lower relative humidity and higher temperatures. Mady et al. (2012) elaborated a human thermal model for each part of the human body and considered thermoregulation and passive systems for a healthy person under basal conditions. Their results indicate that minimum entropy production is achieved for an adult person and that exergy efficiency decreases during lifespan.

Nomenclature

A = *area, m²*
E = *energy content, J*
f = *clothing surface area factor, dimensionless*
H = *human coefficient, dimensionless*
h = *heat transfer coefficient (for convection or thermal radiation), W/(m²·K)*
I = *irreversibility (= exergy loss), J*
$\dot{I}$ = *irreversibility rate, J/s = W*
$\dot{I}''$ = *irreversibility rate per unit of area, J/(s·m) = W/m²*
i = *insulation (= thermal resistance), m²·K/W (or Clo = 0.155 m²·K/W)*
$\dot{m}$ = *mass flow rate, kg/s*
$\dot{m}''$ = *mass flow rate per unit of area (= mass flux), kg/(s·m²)*
P = *partial pressure (water vapour in air at saturation condition), kPa*
$\dot{Q}$ = *heat transfer rate, J/s = W*
$\dot{q}''$ = *heat transfer rate per unit of area (= heat flux), J/(s·m²) = W/m²*
$\dot{S}$ = *entropy (generation) rate, J/(s·K) = W/K*
s = *specific entropy, J/(K·kg)*
T = *temperature, K (or °C)*
t = *time, s*
v = *velocity (air speed), m/s*
$\dot{W}$ = *mechanical (muscular) work rate, J/s = W*
$\dot{w}''$ = *mechanical (muscular) work rate per unit of area, J/(s·m²) = W/m²*

Greek Symbols

ϕ = *air relative humidity, dimensionless*

Subscripts

act = *actual value (level) for entropy generation*
air = *surrounding (ambient) air*
body = *human body (or body core)*
cl = *clothing-influenced (clothing-related) value*
com = *comfort value (level) for entropy generation*
cond = *conductive heat transfer*
conv = *convective heat transfer*
evap = *evaporative heat loss*
gen = *generation (due to imbalance)*
in = *inlet (or input) of open system*
isol = *isolated system*
met = *metabolic value*
moist = *moisture (in air exhaled from lungs)*
musc = *muscular value*
out = *outlet (or output) of open system*
rad = *radiative heat transfer*
resp = *respiration value*
sat = *saturation value (water vapour)*
skin = *skin value*
sw = *sweat (evaporation from the skin)*
vap = *water vapour (diffusion through the skin)*
0 = *surrounding (ambient) reference value*

Acronyms

EMR = *exit matter reservoir*
MER = *mechanical energy reservoir*
TER = *thermal energy reservoir*

Theory

Preliminary concepts and ideas

Homeothermy is markedly characterized by energy interactions between body and ambient (Ivanov, 2006). Human body temperature should remain within a narrow range: between 36.7°C and 37.0°C, as measured in the mouth, while rectal temperature is about 0.6°C higher (Guyton, 1995). In line with the heat-dependent thermoregulation rationale (Webb, 1995) and pointing to the limited efficiency of thermoregulatory mechanisms, Ivanov (2006) discussed the responsiveness of the human thermoregulatory system with respect to body's energy content and mean temperature. Assuming that thermoregulation attempts to follow an energy-efficient path, one may, in principle, argue whether the body is equally sensitive to energy quality and enquire about its "preference" for a given energy interaction rather than another in order to achieve homeothermy.

An exergetic analysis of thermal comfort may indicate qualitative differences among distinct thermoregulatory heat transfers and one may start such analysis by discussing the following:

- *System definition*: Rigorously, the body is a control volume (open system) as it transfers water to the ambient as sweat and/or vapour through the skin (evapotranspiration) and as moisture in exhaled air (respiration). Food and water intakes play an opposite role. Yet, depending on the situation (e.g., short time exposure), the amount of mass transferred can be as small as to be practically disregarded so that the body can be treated as a control mass (closed system).
- *Process dynamics and irreversibility*: One may argue to what extent thermoregulation entails quasi-equilibrium or non-equilibrium processes, besides discussing whether or not they are steady-state processes. Comprising dissipative phenomena (direct dissipation of work into internal energy) or spontaneous non-equilibrium processes (natural tendency of systems to achieve equilibrium with their surroundings), irreversibilities always occur in real processes. Depending on the activity, muscular (mechanical) work varies from about zero up to 25% of the total metabolic energy release (Parsons, 1993), with the resulting excess being transferred to the ambient as heat, over a finite temperature difference.

- *Surroundings*: With respect to the body, the ambient may behave as a thermal energy reservoir (TER) for heat transfers and as an exit matter reservoir (EMR) for water transfers. Regarding muscular work (if any), the concept of mechanical energy reservoir (MER) can be considered. Irrespective of its interactions with the occupant, changes in the thermodynamic state of the ambient are only due to variations in the external conditions.

Human thermoregulation: conceptual heat balance equation and empirical correlations

The first law of thermodynamics expresses an energy balance of a system over its work and/or heat interactions with the surroundings regardless of how much heat can be converted into useful energy (work is useful energy by definition). Based on a one-compartment (one-node) approach for the human body, one may write the following energy balance (Bligh, 1985):

$$\frac{\mathrm{d}E_{\text{body}}}{\mathrm{d}t} = \left(\dot{Q}_{\text{met}} - \dot{W}_{\text{musc}}\right) + \left(\dot{Q}_{\text{evap}} + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}}\right) \tag{2}$$

In line with the so-called heat-engine sign convention, in the previous balance equation any $\dot{Q} > 0$ indicates a heat gain by the body while any $\dot{Q} < 0$ refers to a heat loss. One should be aware that a different sign convention is proposed for Eq. (2) in (ASHRAE, 2001).

In Eq. (2), energy accumulation is lumped into a sole system (one-node) so that $\mathrm{d}E_{\text{body}}/\mathrm{d}t > 0$ leads to a body temperature rise while $\mathrm{d}E_{\text{body}}/\mathrm{d}t < 0$ results in a temperature drop. Referred to as net heat release rate, the difference $(\dot{Q}_{\text{met}} - \dot{W}_{\text{musc}})$ gives the available energy from the total metabolic release ($\dot{Q}_{\text{met}} > 0$), after muscular power ($\dot{W}_{\text{musc}} > 0$) has been discounted. As $\dot{W}_{\text{musc}} \le 0.25\dot{Q}_{\text{met}}$ (Parsons, 1993), such difference is always positive. The summation ($\dot{Q}_{\text{evap}} + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}}$) comprises evaporative, conductive, convective, and radiative heat transfer rates, respectively. According to the heat-engine sign convention applied to Eq. (2), negative values for those rates denote heat transfers from the body to the ambient.

One may normalize Eq. (2) over different body sizes via its division by the body surface area, A_{body}. If steady-state (homeothermy) is assumed, one may then impose $\mathrm{d}(E_{\text{body}}/A_{\text{body}})/\mathrm{d}t = 0$ in order to obtain the so-called conceptual heat balance equation (Parsons, 1993) per unit of body area:

$$\left(\dot{q}''_{\text{met}} - \dot{w}''_{\text{musc}}\right) + \left(\dot{q}''_{\text{evap}} + \dot{q}''_{\text{cond}} + \dot{q}''_{\text{conv}} + \dot{q}''_{\text{rad}}\right) = 0 \tag{3}$$

where $\dot{w}''_{\text{musc}} = \dot{W}_{\text{musc}} / A_{\text{body}}$ and all $\dot{q}'' = \dot{Q} / A_{\text{body}}$ terms have dimensions of energy $\times$ time^{-1} $\times$ area^{-1}. Though muscular power $\dot{w}''_{\text{musc}}$ could, in principle, comprise involuntary motions (e.g., peristalsis or heart beating) as well as voluntary motions (e.g., writing or walking), the former have already been taken into account in experiments measuring the metabolic heat release $\dot{q}''_{\text{met}}$ (Nishi, 1981).

In the second pair of brackets of Eq. (3), conductive heat transfer $\dot{q}''_{\text{cond}}$ is usually neglected (Parsons, 1993) while evaporative, convective, and radiative terms are collected into heat transfers through two separate pathways: (*i*) skin ($\dot{q}''_{\text{skin}}$) and (*ii*) lungs due to respiration ($\dot{q}''_{\text{resp}}$). Accordingly, one may rewrite Eq. (3) as the following steady-state balance equation for the occupant's body:

$$\begin{aligned}&\left(\dot{q}''_{\text{met}} - \dot{w}''_{\text{musc}}\right) + \left(\dot{q}''_{\text{evap,skin}} + \dot{q}''_{\text{conv,skin}} + \dot{q}''_{\text{rad,skin}}\right) + \\ &+ \left(\dot{q}''_{\text{evap,resp}} + \dot{q}''_{\text{conv,resp}}\right) = 0\end{aligned} \tag{4}$$

Respiration heat transfer via thermal radiation is null ($\dot{q}''_{\text{rad,resp}} = 0$) as humid air is assumed transparent.

Fanger (1970) proposed to modify Eq. (4) to some extent, based on the subsequent premises:

- Heat balance prevails so that body temperature is steady (homeothermy); and
- Sweat rate and mean skin temperature are within comfort limits.

ASHRAE (or ISO 7730) has equally followed such thermal comfort approach (ASHRAE, 2001). Further modifications in Eq. (4) are such that (*i*) skin-related heat transfers $\dot{q}''_{\text{evap,skin}}$ are split up into $\dot{q}''_{\text{vap,skin}}$, due to water vapour diffusion, and $\dot{q}''_{\text{sw,skin}}$, due to sweat evaporation, while (*ii*) $\dot{q}''_{\text{conv,skin}}$ and $\dot{q}''_{\text{rad,skin}}$ become $\dot{q}''_{\text{conv,cl}}$ and $\dot{q}''_{\text{rad,cl}}$, respectively, i.e., convective and radiative heat transfers account for the clothing influence. In view of that, the conceptual energy balance equation becomes:

$$\begin{aligned}&\left(\dot{q}''_{\text{met}} - \dot{w}''_{\text{musc}}\right) + \left(\dot{q}''_{\text{vap,skin}} + \dot{q}''_{\text{sw,skin}} + \dot{q}''_{\text{conv,cl}} + \dot{q}''_{\text{rad,cl}}\right) + \\ &+ \left(\dot{q}''_{\text{evap,resp}} + \dot{q}''_{\text{conv,resp}}\right) = 0\end{aligned} \tag{5}$$

Following ASHRAE sign convention, Parsons (1993) presented empirical correlations for the heat transfers considered in Eq. (5). Yet, as this work follows the heat-engine sign convention, a minus sign must be properly introduced so that a negative value for $\dot{q}''$ refers to a heat transfer from the occupant to the ambient. The aforementioned empirical correlations then become:

$$-\dot{q}''_{\text{vap,skin}} = 3.05[5.733 - 0.00699(\dot{q}''_{\text{met}} - \dot{w}''_{\text{musc}}) - P_{\text{sat,air}}] \tag{6a}$$

$$-\dot{q}''_{\text{sw,skin}} = 0.42[(\dot{q}''_{\text{met}} - \dot{w}''_{\text{musc}}) - 58.15] \tag{6b}$$

$$-\dot{q}''_{\text{conv,cl}} = f_{\text{cl}}\, h_{\text{conv}}\, (T_{\text{cl}} - T_{\text{air}}) \tag{6c}$$

$$-\dot{q}''_{\text{rad,cl}} = 3.96\times10^{-8}\, f_{\text{cl}}\, [(T_{\text{cl}} + 273.15)^4 - (T_{\text{rad}} + 273.15)^4] \tag{6d}$$

$$-\dot{q}''_{\text{evap,resp}} = 0.00173\dot{q}''_{\text{met}}(5.867 - P_{\text{sat,air}}) \tag{6e}$$

$$-\dot{q}''_{\text{conv,resp}} = 0.0014\dot{q}''_{\text{met}}(34 - T_{\text{air}}) \tag{6f}$$

Similar expressions for the respiration-related heat fluxes are also found in Prek (2006).

In the equations (6), all heat fluxes $\dot{q}''$ are in W/m^2 provided that all temperatures (namely, air temperature T_{air}, mean radiant temperature T_{rad} and clothed-body surface temperature T_{cl}) are in °C while water vapour pressure $P_{\text{sat,air}}$ in ambient air (at the saturation condition) is in kPa. Referred to as clothing area factor, f_{cl} is a dimensionless parameter that depends on the clothing insulation i_{cl} and it can be assessed as (Parsons, 1993):

$$f_{\text{cl}} = 1 + 0.31 i_{\text{cl}} \quad (i_{\text{cl}} \text{ in Clo units, 1 Clo} = 0.155\ \text{m}^2\cdot\text{K}\cdot\text{W}^{-1}) \tag{7}$$

A different correlation for f_{cl} is found in Olesen (1982). The convective heat transfer coefficient h_{conv} can be assessed from T_{cl} and T_{air} together with the air speed v_{air} as (Olesen, 1982):

$$h_{\text{conv}} = \max\left(2.38(T_{\text{cl}} - T_{\text{air}})^{0.25}, 12.1 v_{\text{air}}{}^{0.5}\right) \ (\text{in W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}) \tag{8}$$

A simpler correlation based solely on v_{air} is presented in Parsons (1993) for a seated person.

In order to obtain the clothed-body surface temperature T_{cl} an iterative calculation procedure is here followed. Firstly, the sum $\dot{q}''_{conv,cl} + \dot{q}''_{rad,cl}$ is assessed by inserting in Eq. (5) all heat fluxes $\dot{q}''$ that are independent from T_{cl} in Eqs. (6). From a trial value assigned to T_{cl}, the radiative heat flux $\dot{q}''_{rad,cl}$ is assessed from Eq. (6*d*), which thus allows one to obtain $\dot{q}''_{conv,cl}$. With the help of Eqs. (6*c*) and (8), a new T_{cl} value is determined and the procedure is repeated until convergence is achieved. In the light of Eq. (5), such converged value for T_{cl} is exactly the one that satisfies the heat balance equation, thus rendering steady-state (i.e., homeothermy) a reasonable assumption. Conversely, a temperature T_{cl} different from such value leads to an energy imbalance, $d(E_{body}/A_{body})/dt \neq 0$, so that the body should undergo either a temperature rise or drop.

Human thermoregulation: irreversibility (exergy loss) analysis

Like entropy, exergy is exempt from a conservation law in the sense that an exergy-loss term must be introduced to close exergy balances. Also referred to as irreversibility, such term refers to the degraded useful energy when real processes are carried out. By taking into account the conceptual energy balance equation, Eq. (5), and auxiliary empirical correlations, Eqs. (6) to (8), irreversibilities can be assessed under two distinct approaches with respect to occupant's interactions via skin and lungs (respiration) with the ambient. Under the first approach, the occupant behaves as a control volume (open system) so that moisture and/or vapour losses are treated as mass flows, indicated as double-line arrows in Fig. 1(a). Under the second approach, the occupant behaves as a control mass (closed system) and the effects resulting from those mass transfers are modelled as heat transfers, Eqs. (6*a*), (6*b*) and (6*e*), indicated as single-line arrows in Fig. 1(b).

Regardless of the approach followed, it is herein assumed that:

- Ambient and occupant form an isolated system and the latter is undergoing a steady-state process;
- Heat-engine sign convention is adopted;
- No EMR is attributed for water / food intakes as occupant is presumably not eating or drinking;
- Muscular power per unit of body surface area $\dot{w}''_{musc}$ (if any) only comprises voluntary motions (as previously discussed) and it is always from occupant to ambient, the latter behaving as a MER (the direction of such energy interaction remains fixed as indicated by the arrowheads in Fig. 1);
- Direction of metabolic heat release remains fixed ($\dot{q}''_{met} > 0$), as indicated by arrowheads in Fig. 1, so that the occupant always receives energy from a TER presumably at temperature T_{body};
- Directions of evaporative mass transfers (first approach) or related heat fluxes (second approach) remain fixed from occupant to ambient, as indicated by the arrowheads in Fig. 1 (under the first approach the ambient behaves as an EMR while it becomes a TER under the second);
- In contrast, convective heat transfer via respiration $\dot{q}''_{conv,resp}$ as well as clothing-related heat fluxes $\dot{q}''_{conv,cl}$ and $\dot{q}''_{rad,cl}$ can be either from occupant to ambient or in the opposite direction; specifically, a common TER is assigned to the convective transfers $\dot{q}''_{conv,resp}$ and $\dot{q}''_{conv,cl}$ (namely, the ambient air at T_{air}) while a distinct TER (at T_{rad}) is appointed to the radiative transfer $\dot{q}''_{rad,cl}$.

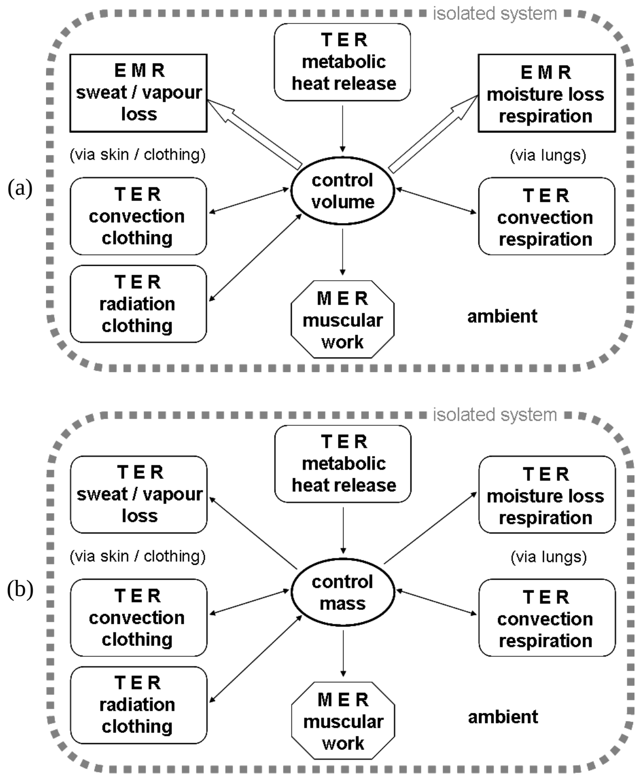


Figure 1. Sketch of the two possible model frameworks for irreversibility calculations: (a) occupant as a control volume (open system) or (b) occupant as a control mass (closed system).

Normalized to the body surface area A_{body}, one may assess the irreversibility rate (= exergy loss per unit of time) per unit of area under the first approach as (Kotas, 1985):

$$\dot{I}'' = T_0 \left[\sum_{EMR} \dot{m}''_{out} s_{out} - \sum_{EMR} \dot{m}''_{in} s_{in} - \sum_{TER} \frac{\dot{q}''}{T} \right] \tag{9}$$

where T_0 is ambient temperature, $\dot{m}''$ and s are respectively the mass flux and the specific entropy of every matter stream crossing the system boundary, and each $\dot{q}''$ is a heat flux interaction with a given TER at temperature T. One may follow a procedure similar to Prek (2004, 2005, 2006) so as to estimate outlet mass fluxes $\dot{m}''_{vap,skin}$, $\dot{m}''_{sw,skin}$ and $\dot{m}''_{evap,resp}$ by using the corresponding heat fluxes $\dot{q}''_{vap,skin}$, $\dot{q}''_{sw,skin}$ and $\dot{q}''_{evap,resp}$, given by Eqs. (6*a*), (6*b*) and (6*e*), together with the specific enthalpies for liquid and vapour phases (obtained via steam tables) at the thermodynamic conditions of skin and lungs. Specific entropies $s_{sw,skin}$, $s_{vap,skin}$ and $s_{evap,resp}$ at the outlet can be similarly obtained and it is assumed that $\sum_{EMR} \dot{m}''_{in} s_{in} = 0$ since water or food intakes are both disregarded.

Yet, the present work follows the second approach, which suppresses all aforesaid exit mass fluxes by assuming that the occupant behaves as a control mass instantaneously or for a short period of time. Each omitted mass flux is replaced (in compensation) by a heat transfer with a TER assigned at temperature T_{air}, as the suppressed EMR referred to ambient air. Accordingly, Eq. (9), under the second approach, renders itself to:

$$\dot{I}'' = T_0 \left(-\frac{\dot{q}''_{\text{vap,skin}}}{T_{\text{air}}} - \frac{\dot{q}''_{\text{sw,skin}}}{T_{\text{air}}} - \frac{\dot{q}''_{\text{evap,resp}}}{T_{\text{air}}} - \frac{\dot{q}''_{\text{conv,resp}}}{T_{\text{air}}} - \frac{\dot{q}''_{\text{conv,cl}}}{T_{\text{air}}} - \frac{\dot{q}''_{\text{rad,cl}}}{T_{\text{rad}}} - \frac{\dot{q}''_{\text{met}}}{T_{\text{body}}} \right) \tag{10}$$

Results and Discussion

A sitting person (occupant) wearing rather light clothes was preliminary considered and Table 1 presents the values assigned to some necessary thermal comfort parameters. By inserting those values in Eqs. (6*b*) and (7), one obtains some initial results (also presented in Table 1), which are independent from temperatures T_{air} and T_{rad}.

Table 1. Thermal comfort parameters and initial results independent of temperatures T_{air} and T_{rad}.

Thermal comfort parameter or initial result	Value assigned / calculated
Metabolic heat release flux per unit of body area	$\dot{q}''_{\text{met}} = 100$ W/m^2
Muscular power per unit of body area	$\dot{w}''_{\text{musc}} = 0$
Clothing insulation	$i_{cl} = 0.6$ Clo $= 0.093$ m^2·K/W
Ambient air velocity	$v_{air} = 0.25$ m/s
Ambient air relative humidity	$\phi = 1$ (100%)
Body (core) temperature	$T_{body} = 37.0^{o}$C
Heat flux due to sweating (from occupant to ambient)	$\dot{q}''_{\text{sw,skin}} = -17.577$ W/m^2
Dimensionless clothing area factor	$f_{cl} = 1.186$

According to model equations presented in section 2, subsequent results depend on either T_{air} or T_{rad} (or both) and care should be exercised to fulfil the applicability of the aforementioned correlations. One constraint refers to the fact that $\dot{q}''_{\text{vap,skin}}$ and $\dot{q}''_{\text{evap,resp}}$ cannot be positive (occupant may transfer heat to ambient by evapotranspiration but the opposite does not occur). In order to calculate those heat fluxes, values for the saturation pressure $P_{sat,air}$ were obtained from steam tables as a function of T_{air} assuming relative humidity as $\phi = 1$ (Table 1) and either $\dot{q}''_{\text{vap,skin}}$ or $\dot{q}''_{\text{evap,resp}}$ was deliberately set to zero whenever $P_{sat,air}$ led them to a prohibitive value (as discussed above).

As temperatures T_{air} and T_{rad} dictate the heat fluxes yielding the sum $\dot{q}''_{\text{conv,cl}} + \dot{q}''_{\text{rad,cl}}$ from Eq. (5), another important constraint refers to the clothed-body surface temperature T_{cl} obtained from the iterative procedure previously described. As discussed in section 2, the converged value for T_{cl} is the only one satisfying the homeothermy (i.e., steady-state) assumption of Eq. (5). Still, as far as heat transfers to the ambient (= body heat loss) are concerned, one should equally bear in mind that any clothing-influenced heat transfer ultimately starts at the body level so that $T_{body} > T_{cl}$ should be an additional requisite to allow either $\dot{q}''_{\text{conv,cl}} < 0$ or $\dot{q}''_{\text{rad,cl}} < 0$.

One could be tempted to wonder about a probable scenario where $T_{cl} > T_{body}$ with the body (or only part of it) behaving as a heat pump. Accordingly, one should then infer about the temperature differences as well as the source for and the nature of the necessary work input. Furthermore, one may also abandon the steady-state assumption for thermal comfort (Fanger, 1970) and put forward a transient model. By acknowledging that thermal sensations (e.g., thermal pleasure) are transient in nature and cannot be experienced under steady-state conditions, Parsons (1993) regarded thermal comfort simply as "a lack of discomfort". One could also propose a two-node (e.g., body-clothing) model framework, but any of those previous issues are beyond the scope of this work.

By interpreting T_{cl} as the clothing temperature, one may suggest that any heat loss $\dot{q}''_{\text{conv,cl}} < 0$ or $\dot{q}''_{\text{rad,cl}} < 0$ first occurs from body to clothing over a temperature difference $T_{body} - T_{cl} > 0$ and then transferred from clothing to ambient over a difference $T_{cl} - T_{air} > 0$ or $T_{cl} - T_{rad} > 0$, depending on the heat transfer mechanism. In order to prevent violations of the second law of thermodynamics (i.e., heat being spontaneously transferred from a colder system to a hotter one), care was exercised to only consider allowable combinations of T_{air} and T_{rad}. For some mean radiant temperature values (namely, T_{rad} = 16^{o}C, 18^{o}C, 20^{o}C, 22^{o}C, 24^{o}C and 26^{o}C) and using a proper variation range for the air temperature (namely, 17°C ≤ T_{air} ≤ 33°C), Fig. 2 shows the converged values for the clothed-body surface temperature T_{cl}, which seems to vary almost linearly with temperature T_{air}.

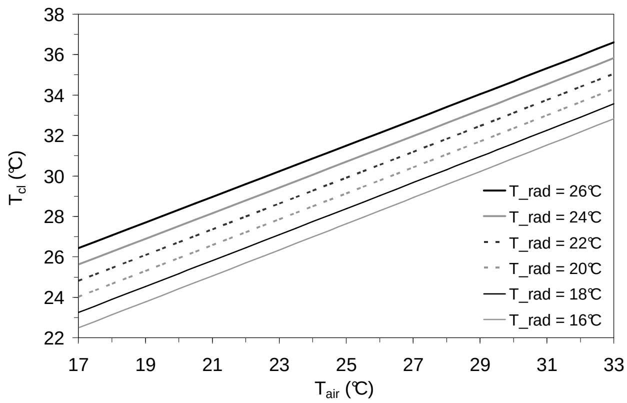


Figure 2. Clothed-body surface temperature T_{cl} (converged value) as a function of surrounding air temperature T_{air} for some values of mean radiant temperature T_{rad}.

In line with the second approach (i.e., occupant as a control mass), irreversibility rates per unit of area $\dot{I}''$ were assessed assuming $T_0 = T_{air}$ in Eq. (10). Using the values for T_{rad} and the variation range for T_{air} as considered in Fig. 2, Fig. 3 shows the values resulting for the irreversibility rate per unit of area $\dot{I}''$. Except for relatively low air temperatures (T_{air} ~ 17°C) where values for $\dot{I}''$ are comparable to some extent (and among the highest ones), irreversibility rate levels increase inasmuch as T_{rad} decreases, i.e., as T_{rad} departs from T_{body}. Bearing in mind the irreversibility rates obtained for relatively low T_{rad} values, there seems to be a critical T_{air} value that minimizes $\dot{I}''$. As T_{rad} increases, such critical T_{air} also increases and approaches T_{body}, as indicated in Table 2. Such rationale also seems to hold for relatively high T_{rad} (namely, T_{rad} = 24°C or 26°C), but minimum $\dot{I}''$ values could not be observed due to the temperature constraints previously discussed in this work and pointed out in Fig. 2.

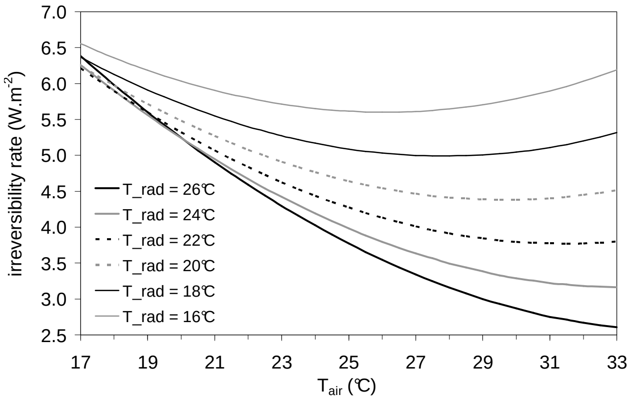


Figure 3. Irreversibility rates per unit of (body surface) area $\dot{I}''$ as a function of surrounding air temperature T_{air} for some values of mean radiant temperature T_{rad}.

Table 2. Minimum irreversibility rates $\dot{I}''$ and corresponding minimizing air temperatures T_{air} for some mean radiant temperatures T_{rad}.

Radiant temperature T_{rad} (°C)	Irreversibility rate $\dot{I}''$ (W/m²)	Air temperature T_{air} (°C)
16.0	5.601	26.0
18.0	4.994	28.0
20.0	4.383	29.5
22.0	3.773	31.5

Irreversibilities reduce thermodynamic efficiency and they can be either intrinsic or avoidable (Kotas, 1985). The latter could be associated to behaviour-influenced irreversibilities (clothing and activity), while the former could be linked to irreversibilities related to basal metabolism or, instead, to some thermal comfort zone. In order to fulfil homeothermy necessities, one could claim that exergy deficits should be somehow compensated (e.g., via a shortfall or collapse of a thermoregulatory mechanism in detriment of another). Bearing in mind the prospective definition of an irreversibility-based thermal comfort index, those irreversibility dissimilarities in nature could be accounted for.

In order to compare each contribution to the total irreversibility rate per unit of area, one may consider $\dot{I}''$ in Eq. (10) as the sum of the following irreversibility terms (or components):

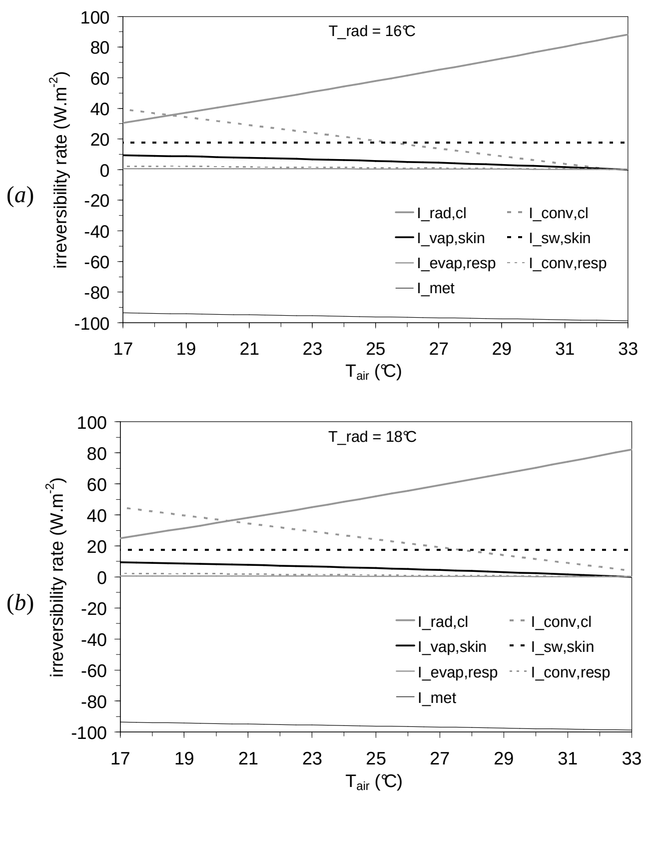
$$\dot{I}'' = \dot{I}''_{\text{vap,skin}} + \dot{I}''_{\text{sw,skin}} + \dot{I}''_{\text{evap,resp}} + \dot{I}''_{\text{conv,resp}} + \dot{I}''_{\text{conv,cl}} + \dot{I}''_{\text{rad,cl}} + \dot{I}''_{\text{met}} \tag{11}$$

where:

$$\begin{aligned} &\dot{I}''_{\text{vap,skin}} = -\frac{T_0}{T_{\text{air}}}\dot{q}''_{\text{vap,skin}} , \quad \dot{I}''_{\text{sw,skin}} = -\frac{T_0}{T_{\text{air}}}\dot{q}''_{\text{sw,skin}} , \\ &\dot{I}''_{\text{evap,resp}} = -\frac{T_0}{T_{\text{air}}}\dot{q}''_{\text{evap,resp}} , \quad \dot{I}''_{\text{conv,resp}} = -\frac{T_0}{T_{\text{air}}}\dot{q}''_{\text{conv,resp}} , \\ &\dot{I}''_{\text{conv,cl}} = -\frac{T_0}{T_{\text{air}}}\dot{q}''_{\text{conv,cl}} , \quad \dot{I}''_{\text{rad,cl}} = -\frac{T_0}{T_{\text{rad}}}\dot{q}''_{\text{rad,cl}} , \\ &\dot{I}''_{\text{met}} = -\frac{T_0}{T_{\text{body}}}\dot{q}''_{\text{met}} \end{aligned} \tag{12}$$

It is worth noting that Prek´s approach (Prek, 2004, 2005, 2006; Prek and Butala, 2010), i.e., $\dot{I}''_{\text{vap,skin}}$, $\dot{I}''_{\text{sw,skin}}$ and $\dot{I}''_{\text{evap,resp}}$ evaluated via heat transfer rates, Eqs. (10), (11) and (12), may lead to inaccuracy with respect to the entropy balance. On the other hand, one may observe that variations of irreversibility rates $\dot{I}''_{\text{vap,skin}}$, $\dot{I}''_{\text{sw,skin}}$, $\dot{I}''_{\text{evap,resp}}$, $\dot{I}''_{\text{conv,resp}}$ and $\dot{I}''_{\text{met}}$ (as a function of T_{air}) are sensibly minor when compared to those for $\dot{I}''_{\text{conv,cl}}$ and $\dot{I}''_{\text{rad,cl}}$. Respiration and sweat irreversibility rates were also found to be negligible in a different calculation approach, as pointed by Batato et al. (1990) under the same conditions considered herein, i.e., human body at rest (sitting person wearing light clothes). Batato et al. (1990) suggested another approach to human thermal comfort where three different temperature levels are modelled and submitted to exergetic analysis. Respiration exergy rates also presented minor values in the studies performed by Mady et al. (2012).

Over the same values and range for T_{rad} and T_{air}, plots in Fig. 4 present the behaviour of each contribution to the total irreversibility rate $\dot{I}''$. One may also verify that, as T_{rad} increases, so does the air temperature T_{air} at which related contributions become equal (i.e., $\dot{I}''_{\text{conv,cl}} = \dot{I}''_{\text{rad,cl}}$). It is worth remembering that the corresponding heat transfers occur at TERs at distinct temperatures (namely, T_{air} and T_{rad}) while relying on a common auxiliary temperature T_{cl} determined from an iterative procedure satisfying a steady-state energy balance (i.e., the conceptual heat balance equation). Furthermore, by analysing $\dot{I}''_{\text{rad,cl}}$ as a function solely of T_{rad} (over the range 17°C ≤ T_{air} ≤ 33°C), it is worth noting that $\dot{I}''_{\text{rad,cl}}$ reduces as T_{rad} increases and approaches to T_{body}, which may suggest a link between thermal comfort and exergy loss reduction as far as such heat transfer mechanism is concerned.



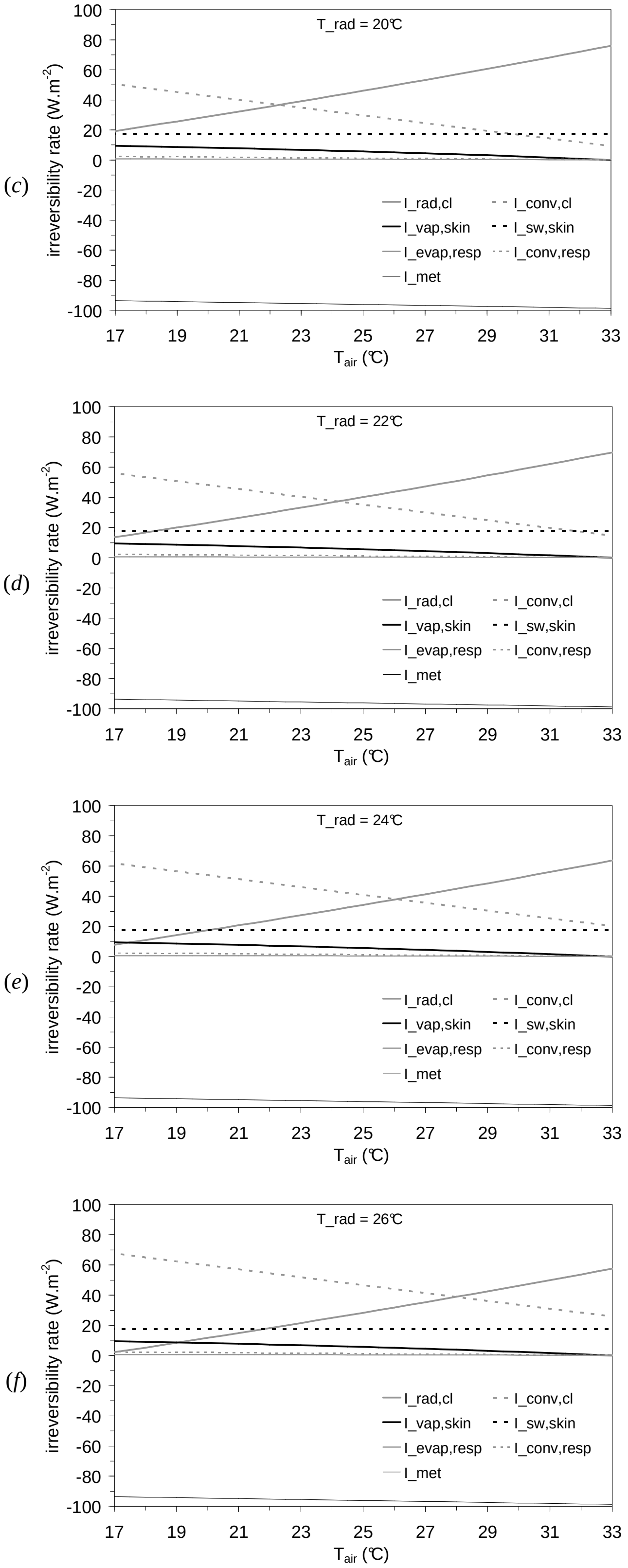


Figure 4. Components of the irreversibility rate per unit of area as a function of T_{air} for: (a) T_{rad} = 16℃, (b) T_{rad} = 18℃, (c) T_{rad} = 20℃, (d) T_{rad} = 22℃, (e) T_{rad} = 24℃ and (f) T_{rad} = 26℃.

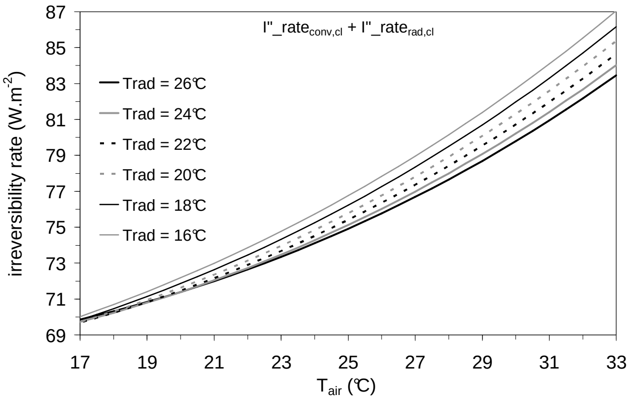


Figure 5. Variation of $\dot{I}''_{\mathrm{conv,cl}} + \dot{I}''_{\mathrm{rad,cl}}$ (clothing-influenced irreversibility rates per unit of area) as a function of air temperature T_{air} for some values of mean radiant temperature T_{rad}.

Although temperature T_{air} influences $\dot{q}''_{\mathrm{conv,cl}}$ while temperature T_{rad} dictates $\dot{q}''_{\mathrm{rad,cl}}$, it is worth recalling that those clothing-influenced heat transfer rates are linked to each other via the clothed-body surface temperature T_{cl}. As already described, the evaluation of the latter depends on the sum $\dot{q}''_{\mathrm{conv,cl}} + \dot{q}''_{\mathrm{rad,cl}}$ as given by Eq. (5), so that the decrease of one heat transfer mechanism is somehow compensated by the augmentation of the other. In view of that, Fig. 5 shows the behaviour of the sum $\dot{I}''_{\mathrm{conv,cl}} + \dot{I}''_{\mathrm{rad,cl}}$ over the same values and range for T_{rad} and T_{air}.

Similarly to the behaviour of $\dot{I}''_{\mathrm{rad,cl}}$ rates, one can observe that the sum $\dot{I}''_{\mathrm{conv,cl}} + \dot{I}''_{\mathrm{rad,cl}}$ reduces as T_{rad} approaches T_{body}. One also verifies that $\dot{I}''_{\mathrm{conv,cl}} + \dot{I}''_{\mathrm{rad,cl}}$ diminishes inasmuch as T_{air} decreases and, hence, inasmuch as $\dot{q}''_{\mathrm{conv,cl}}$ increases and compensates $\dot{q}''_{\mathrm{rad,cl}}$ more and more. In other words, exergy (useful energy) losses are minor whenever the body is able to transfer more heat via convection.

For thermoregulation purposes, those previous results may point to a prospective body's "preference" for losing heat via convection rather than by thermal radiation. Indeed, bearing in mind Eqs. (6c) and (6d), by increasing T_{rad} one increases $\dot{I}''_{\mathrm{rad,cl}}$ while decreasing $\dot{I}''_{\mathrm{conv,cl}}$. In view of Eq. (6f), $\dot{I}''_{\mathrm{conv,resp}}$ also decreases, though to minor extent if compared to other irreversibility rates, as pointed out previously.

As far as thermoregulation is concerned, there has been some dispute about what variables are in effect the regulated ones from the control theory viewpoint (Blight, 1985) and the "nominees" have comprised distinct temperatures (e.g., core, skin, or brain), body energy content, or heat outflow rate. While widely accepted indices have been proposed for uniform thermal ambient, it is claimed that thermally non-uniform surroundings still lacks a universal index (Zhang and Zhao, 2008). By taking into account thermodynamic factors related to both ambient and the occupant, exergy loss may become another promising "contender" in the previous list of thermoregulated variables. Indeed, exergy is known to increase as the thermodynamic state of a system departs from that of its surroundings so that exergy has the ability to evenly assess both extremes of thermal comfort or sensation scale, spanning from the uncomfortably cold up to the uncomfortably hot.

Results in the literature have indicated that humans perceive hot or cold discomfort more intensively as thermal conditions depart more and more from a given comfort range (Parsons, 1993; ASHRAE, 2001). Recalling that exergy increases as the thermodynamic state of any system departs from that of its surroundings and expecting a similar trend for irreversibilities (exergy losses), one could wonder whether thermoregulation has exergy-saving or entropy-efficient criteria. If so, one may think of irreversibility-based indices as prospective quantitative parameters to assess thermal comfort, based on a rational approach combining both first and second laws of thermodynamics.

Last but not least, it is worth remembering that steady-state was assumed for preliminary calculations herein performed, the analysis of transient equations is beyond the scope of this work. Yet, it is known that beyond a critical head temperature (set-point) a sharp shift occurs from heat loss through insensible evaporation to heat loss via sweating (Guyton, 1995). With respect to the metabolic heat release, there is also a similar set-point shift from basal to shivering-induced and it is interesting to observe that both set-points depend on skin temperature. Reminding that humans are able to either acclimatize or acclimate, i.e., to naturally or artificially acquire physiological response changes after long exposure to either hot or cold environments, it is worth investigating potential connections between the coefficient H introduced by OTCI definition (Boregowda, Tiwari and Chaturvedi, 2001) and the basic factors for thermal comfort. One should recall that OTCI depends on entropy generation rates while calculations herein presented depend on irreversibility rates ($\dot{I}$) or irreversibility rates per unit of area ($\dot{I}''$). However, by properly identifying a reference temperature T_0 in the surroundings, one can relate these irreversibility rates by means of Gouy-Stodola relation (Kotas, 1985; Bejan, 1988; Szargut, Morris and Steward, 1988).

Concluding Remarks

As suggested elsewhere (e.g., definition of PMV - predicted mean vote and PPD - predicted percentage dissatisfied), energy balance (i.e., first-law analysis) for occupant's body is a necessary condition for thermal comfort but it may not be a sufficient one. Recognizing that both ambient and personal (human) conditions affect thermal sensations, one may attempt to assess either hotness or coldness experiences by taking into account the second-law of thermodynamics as well. By lumping information related to both ambient and occupant, an analysis combining first and second laws may enable one to identify process thermodynamic inefficiencies as exergy losses (irreversibilities) thus helping one to quantify thermal efficiency either at optimal conditions (minimum exergy loss) or at non-optimal conditions, with thermoregulatory mechanisms rendering thermal discomfort.

An underlying question refers to the human body susceptibility to irreversibilities resulting from its own thermoregulatory mechanisms and this paper suggested more insights to exergetic analysis of thermal comfort, bearing in mind a prospective definition of an irreversibility-based index. Accordingly, preliminary calculations were performed following a model framework that evoked empirical heat-transfer correlations for a human clothed body and the so-called conceptual heat balance equation, which is based on a steady-state energy balance for the human body.

For a sitting person under distinct combinations of ambient air and mean radiant temperatures, results showed that a minimum irreversibility rate may exist for particular combinations of ambient air and mean radiant temperatures. In addition, by comparing irreversibility contributions from each energy interaction, results suggested a stronger influence of both clothing-influenced heat transfers' mechanisms, i.e., convective and radiative heat transfers, on total irreversibility rate. Among those two mechanisms, exergy losses become lower whenever the body is able to transfer more heat via convection other than by thermal radiation, which could be linked to a prospective "preference" for losing heat via convection for thermoregulation purposes.

Despite results may eventually encourage the definition of an irreversibility-based thermal comfort index, it should be stressed that irreversibilities were here calculated relying on a steady-state assumption, which can be quite restrictive. Including other scenarios, potential links to thermal comfort claim for future analysis or improvement as, for example, eventual links between intrinsic irreversibilities and basal metabolic and/or comfort zone levels as well as between avoidable irreversibilities and the departure of such minimum physiological condition.

Bearing in mind second-law efficiency of thermoregulatory mechanisms for a resting person, this paper attempted to put forward a model framework to identify minimum irreversibility rates for a wide range of air temperature. As it is well known, minimum irreversibility rates imply minimum entropy generation and, thus, maximum second-law efficiency. Finally, as the literature reviewed in this work suggests, comfort thermal sensation is clearly attached to minimum human-body exergy consumption-rates, which is also expected to render neutral thermal sensation vote (TSV) or neutral predicted mean vote (PMV).

Future developments may improve or extend the proposed model framework as, for example, (*i*) broader range of $T_{\rm rad}$ values, (*ii*) distinct body conditions (e.g., performing physical activity) and (*iii*) different boundary conditions (e.g., surroundings or climatic regions). It is believed that a comprehensive exergy balance of the human body may lead to a better understanding of human thermal comfort and its relation to irreversibility rates.

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