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THERMAL COMFORT AND SECOND-LAW ANALYSIS OF THERMOREGULATION MECHANISMS: PRELIMINARY CONSIDERATIONS AND PROSPECTIVE EXTENSIONS

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Abstract. *Mathematical modeling has played important role regarding the definition of parameters to assess and quantify biological or physiological phenomena. Of particular interest, second-law analysis can provide useful information about thermal and chemical processes as it identifies irreversible phenomena bringing about entropy generation and, hence, exergy losses. Accordingly, the so-called objective thermal comfort index (OTCI) has been recently defined in terms of entropy generation related to human thermoregulation in response to changes in ambient conditions. Alternatively, the present paper discusses a prospective definition of a thermal comfort or heat (cold) stress index based on the exergetic analysis of human thermoregulatory mechanisms. Inasmuch as irreversibilities reduce process effectiveness, additional metabolic exergy loss (beyond a "comfort" level) could in principle lead a living organism to experience discomfort of some kind. Bearing in mind that exergy is evaluated based on thermodynamic state parameters related to the ocupant (system) as well as to the corresponding ambient (surroundings), this paper suggests preliminary connections between thermal comfort and exergy losses in line with the so-called heat balance equation for the human body. Potential extensions of such exergetic analysis are also discussed upon.*

Keywords. *mathematical modeling, thermal comfort, thermoregulation, second-law analysis, exergy*

1. Introduction

Several parameters have been defined so as to assess human thermal comfort as well as heat or cold stress. Among those one may list: resultant temperature, equivalent temperature, effective temperature (new and standard), predicted mean vote and predicted percentage dissatisfied, heat stress index, index of thermal stress, required sweat rate, predicted four-hour sweat rate, heart rate prediction, wet bulb and wet globe temperature index, wind-chill index, equivalent still air temperature, shade temperature (equivalent or still) and required clothing insulation index (Parsons, 1993). They are referred to as direct parameters if based on data read from instruments used to mimic human body responses, empirical parameters if obtained by means of numerical regression of human physiological responses as subjects undergo distinct ambient conditions or rational parameters when based on theoretical reasoning.

The aforesaid parameters are helpful to bioclimatic and energy-efficient building design – a notable effort towards energy saving. For that reason, occupants' thermal comfort analysis should be based on indices depicting physiological responses to ambient as reliably as possible. Likewise, there are issues concerning Food Engineering workplaces (e.g. refrigeration chambers, food processing areas or food storage rooms) for which thermodynamic modeling may help defining specific working and/or production practices, precautions or standards for occupants (workers).

Mathematical modeling has been playing a role of rising importance to many fields. In particular, its association to life sciences is mutually interesting with regards to understanding and analyzing biological systems. On one hand, new and wide research horizons become available to Physics and Engineering. Natural phenomena have indeed served as inspiration to technological advances and innovation (Mammana, 1981), which should not be surprising if one considers that existing biological systems have already undergone natural (and rigorous) selection. On the other hand, Medicine and Biology have progressively benefited from the utilization of calculus apparatus and information technology. Such (should one say symbiotic?) cooperation enables not only the design of multipurpose equipment but also the inference of assessment methodologies for biological or physiological phenomena.

As far as thermal comfort and/or heat (cold) stress are concerned, rational parameters can be defined based on an energy balance applied to the human body, accounting for concurrent effects from the ambient such as air temperature and humidity, radiant temperature and air speed, in conjunction with behavioral (human) factors like activity-related metabolism and clothing. In other words, rational parameters evoke the first law of thermodynamics. Yet, in terms of energy consumption (or conversely, energy saving), second-law analysis can improve process efficiency by identifying irreversible phenomena bringing about exergy losses. Taking into account both ambient conditions and the process itself, exergy is a physical property that can be properly introduced in the analysis in order to enhance our grasp on process thermodynamic efficiency (Szargut *et al.*, 1988).

Boregowda *et al.* (2001) used second-law analysis to quantify thermal comfort. As a result, the so-called objective thermal comfort index (OTCI) was put forward as a function of entropy generation, combining both human thermal responses and environmental variables. More recently, Prek (2004) evoked the exergy concept in order to predict those human physiological responses in steady-state, based on the so-called two-compartment (or two-node) model for the human body as well as having in mind the need for such sort of thermodynamic analysis in line with current exergetic research in the building sector (e.g. low-exergy HVAC systems).

Accordingly, the present paper outlines some preliminary exergetic concepts based on the energy balance equation applied to the human body, as an attempt to set groundwork to define a thermal comfort (or heat / cold stress) parameter based on human thermoregulatory mechanisms. Ultimately, the paper prospects potential correlations between exergy losses due to distinct heat and/or mass transfers in response to changes in ambient thermodynamic conditions.

2. Human thermoregulation and thermodyncamic analysis: basic concepts

In order to sustain its own life, organisms continuously burn some sort of “fuel” (i.e., food) so as to liberate energy to meet its metabolic requirements. The designation bradymetabolism applies to those life forms whose metabolic heat release rate is insufficient to maintain an appreciable thermal gradient between its core and the surroundings (Bligh, 1985). On the contrary, tachymetabolism refers to those organisms presenting fast fuel consumption and heat release rates. On body temperature basis, species can be classified as poikilotherms or homeotherms whether such temperature fluctuates or is kept somewhat constant over a range of environmental conditions, respectively. Moreover, endothermic species are able to derive most of their energy needs from internal metabolism whereas ectothermic species are able to control heat uptake from the environment.

Human normal temperature ranges from 36°C to 37.5°C so that average figures should be generally found between 36.7°C and 37°C as measured in the mouth (oral temperature) while rectal temperature is about 0.6°C higher (Guyton, 1995). It is important to mention that positive or negative deviations of more than a few degrees from those mean values bring about serious health disorders or even life threats. The fact that humans (and all other mammals) are homeotherms implies that energy interactions take place between body and environment.

The first law of thermodynamics should be evoked for the analysis of such energy transfers. Yet, this law makes no quantitative distinction between energy interactions so that work and heat, for example, are treated as equivalent forms of energy in transit. Assuming that body processes follow a spontaneous path, one could in principle go beyond and question whether the body is sensitive to energy quality. In order words, one could ask about the body “preference” to exchange a given quantity of an energy form rather than transferring the same amount of another form so as to fulfill its homeostasis. In this sense, second-law analysis could play an important role to set energy quality differences among distinct thermoregulatory mechanisms.

Initially, assumptions should be made about some basic issues concerning the thermodynamic analysis of human thermoregulation. Among those, it is possible to point to the following:

- *System definition*: Depending on the level of comprehensiveness, the body can be treated either as a closed system (control mass) or as an open system (control volume). If heat losses from evapotranspiration or from respiration are accounted for, water is transferred to ambient as sweat / water vapor from the skin or as exhaled air moisture from lungs. Conversely, water and food intakes play the counterpart role. In both cases, the body rigorously behaves as an open system (control region). Yet, the amount of transferred matter (e.g. lost water) might be small enough so that the body can be seen as a closed system (at least for short time periods).
- *Process classification*: From thermal comfort (or discomfort) dynamics standpoint, one could argue to what extent thermoregulation entails quasi-equilibrium or non-equilibrium processes and whether such mechanisms complete a cycle or constitute some sort of steady-state “operation”. As cited by Parsons (1993), ASHRAE / ISO 7730 define thermal comfort as ‘that condition of mind which expresses satisfaction with the thermal environment’. In steady-state, Parsons (1993) simply regards it as a lack of discomfort but also acknowledges that thermal sensations (e.g. thermal pleasure) are transient in nature and thus cannot be experienced in steady-state conditions.
- *Irreversibility nature*: Fully reversible process is a well-known idealization and two basic groups of irreversibilities are found in real processes, namely, spontaneous non-equilibrium processes and dissipative phenomena. The latter refer to direct dissipation of work into internal energy whereas the former reflect the natural tendency of systems to achieve equilibrium state with its surroundings (e.g. temperature equalization). As far as human body is concerned, metabolic energy production is deeply related to occupant’s activity. Energy for mechanical (muscular) work varies from approximately zero up to 25% of total metabolic rate (Parsons, 1993) and the excess is released as heat to the ambient, mostly over a finite temperature difference with respect to body (fairly constant) temperature.

- *Ambient characterization*: According to its usual definition, everything outside the system boundary comprises the surroundings. In the present analysis, the later could correspond to the indoor ambient whereas the former refers to the occupant. Clearly, the occupant (system) is not isolated as there are at least heat interactions with the ambient (surroundings). In the light of such energy transfers, the ambient could be thought as a thermal energy reservoir (TER). Similar rationale could be applied with respect to mass (sweat, water vapor, moisture) transfers so that the ambient could also be modeled as an inlet matter reservoir (IMR). Mechanical energy reservoir (MER) concepts are evoked for muscular work, if any. It is worth noting that, despite the ambient thermodynamic state may undergo variations, they are not caused by interactions with the occupant but they are responses to prevailing meteorological (external) conditions. Therefore, for a given short time period, stable equilibrium can be assumed to the ambient.

2.1. Thermoregulation and first-law analysis: energy balance

The first law of thermodynamics deals with energy interactions concerning the energy content variation of a system (open or closed). Expressed by means of an energy balance, such conservation principle has basically a quantitative nature as it accounts for all energy forms and interactions equivalently, regardless of its potential to be converted into useful work. Accordingly, by involving heat transfers between human body and its neighboring environment, one may assess the corresponding body energy balance in line with (Bligh, 1985), namely:

$$\frac{\mathrm{d}E_{\mathrm{body}}}{\mathrm{d}t} = \left(\dot{Q}_{\mathrm{met}} - \dot{W}_{\mathrm{musc}}\right) - \left(\dot{Q}_{\mathrm{evap}} + \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{rad}}\right) \tag{1}$$

Each term in the above equation has dimension of energy × time^{-1} and, along with its sign convention, such equation is also in line with that presented by ASHRAE (2001), where $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t$ is identified to the so-called (total) heat storage. It is implicitly assumed that $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t$ lumps the heat storage rates in both core and skin (shell) compartments.

Alternatively, Prek (2004) split up those compartments, thus ascribing a heat balance equation for each one. Even so, such equations were coupled to one another by a common heat transfer rate comprising both heat conduction (passive exchange due to direct contact) and heat transfer through blood flow. Thermoregulation tries to keep core temperature as steady as possible (around $T_{\mathrm{core}} \cong 37^{\circ}\mathrm{C}$) while skin temperature varies. The later is often assessed as an average skin temperature T_{skin} so that mean body temperature T_{body} can be evaluated as the following weighted sum:

$$T_{\mathrm{body}} = \alpha T_{\mathrm{skin}} + (1-\alpha) T_{\mathrm{core}} \tag{2}$$

The weighting factor α varies from 0.1 to 0.3 for vasodilated and vasoconstricted skin, respectively (Parsons, 1993).

The difference $(\dot{Q}_{\mathrm{met}} - \dot{W}_{\mathrm{musc}})$ in the first pair of brackets in Eq. (1) is referred to as net heat production (i.e., heat release) rate and it is always positive because $\dot{Q}_{\mathrm{met}} > \dot{W}_{\mathrm{musc}}$. It corresponds to the remaining energy released from total metabolic heat production rate $\dot{Q}_{\mathrm{met}}$ (which might include shivering) as external mechanical (muscular) power $\dot{W}_{\mathrm{musc}}$ is discounted. The second pair of brackets comprises the sum of four heat transfer rates $\left(\dot{Q}_{\mathrm{evap}} + \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{rad}}\right)$, respectively due to sweat or moisture evaporation, convection, conduction and thermal radiation. According to the sign convention introduced in Eq. (1), positive values for $\dot{Q}_{\mathrm{evap}}$, $\dot{Q}_{\mathrm{conv}}$, $\dot{Q}_{\mathrm{cond}}$ and $\dot{Q}_{\mathrm{rad}}$ correspond to heat losses to the environment through the skin surface and respiratory tract (ASHRAE, 2001).

When the abovementioned energy interaction rates are combined as indicated by Eq. (1), $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t$ assesses the energy content variation within the occupant's body. In view of that, a temperature rise is related to $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t > 0$ while a temperature drop refers to $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t < 0$. If steady-state is then assumed, $\mathrm{d}E_{\mathrm{body}}/\mathrm{d}t = 0$ should be introduced in Eq. (1), leading to the so-called conceptual heat balance equation (Parsons, 1993):

$$0 = \left(\dot{Q}_{\mathrm{met}} - \dot{W}_{\mathrm{musc}}\right) - \left(\dot{Q}_{\mathrm{evap}} + \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{rad}}\right) \;\Rightarrow\; \dot{Q}_{\mathrm{met}} - \dot{W}_{\mathrm{musc}} = \dot{Q}_{\mathrm{evap}} + \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{rad}} \tag{3}$$

It is useful to normalize the previous energy balance over different body sizes by considering heat transfer rates on a per unit-area basis, specifically, per unit of body surface area $\dot{q} = \dot{Q}/A_{\mathrm{body}}$ (= energy flux = energy × time^{-1} × area^{-1}), so that the conceptual heat balance equation under steady-state conditions can be expressed as:

$$\dot{q}_{\mathrm{met}} - \dot{w}_{\mathrm{musc}} = \dot{q}_{\mathrm{evap}} + \dot{q}_{\mathrm{conv}} + \dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{rad}} \tag{4}$$

One may also conceive a net heat transfer taking place from inner cells to body surface (system boundary) so that heat is eventually transferred to the ambient from the skin and lungs (through respiration). Considering heat transfer mechanisms on the right-hand side of Eq. (3), it is thus convenient to identify and group those taking place through the skin $\dot{q}_{\text{skin}}$ and those related to respiration $\dot{q}_{\text{resp}}$. Consequently, Eq. (3) can be conveniently cast into:

$$\dot{q}_{\text{met}} - \dot{w}_{\text{musc}} = \dot{q}_{\text{skin}} + \dot{q}_{\text{resp}} \tag{5}$$

As implicitly assumed in the above equation, conductive heat transfer $\dot{q}_{\text{cond}}$ is usually neglected for typical situations (Parsons, 1993). Although $\dot{w}_{\text{musc}}$ may comprise voluntary (e.g. walking and typewriting) and involuntary motions (e.g. heart beating and peristalsis), the later are likely to be already accounted for depending on the way the metabolic heat release $\dot{q}_{\text{met}}$ is experimentally measured as based on the rate of respiratory O_2 consumption and CO_2 production. As presented in ASHRAE (2001), an empirical equation for $\dot{q}_{\text{met}}$ has been suggested by Nishi (1981).

2.2. Thermoregulation and second-law analysis: entropy generation

Due to its quantitative nature, the first law of thermodynamics is not able to point to imperfections of thermal and chemical processes. Conversely, opting for the capacity for doing work as a measure of energy quality, the second law imposes restrictions to energy conversions. In other words, it introduces a qualitative character to distinct energy forms and interactions depending on its equivalent potential to be converted into useful work. This law grants thorough and spontaneous transformation of a “noble” (organized) energy form (e.g. potential energy) into a “poor” (chaotic) form (e.g. internal energy) but the opposite conversion cannot be fully accomplished.

The second law can be expressed in terms of entropy variation ΔS. When applied to an isolated system, which in the present analysis comprises the human body and its surrounding ambient, it states that:

$$\Delta S_{\text{isol}} = \Delta S_{\text{body}} + \Delta S_{\text{surr}} \geq 0 \tag{6}$$

where the equality sign (i.e., entropy conservation) refers to idealized reversible process. Real processes are intrinsically irreversible so that the second law predicts $\Delta S_{\text{isol}} > 0$. Such entropy increase within an isolated system can be directly identified to an entropy generation term S_{gen} (Kotas, 1995). The more irreversible a process is, the greater the value resulting for the entropy generation, which can also be expressed as a rate term $\dot{S}_{\text{gen}}$ (= entropy × time^{-1}).

Combining human thermal physiological responses and thermal environmental variables into an entropy generation term, Boregowda *et al.* (2001) introduced the so-called objective thermal comfort index (OTCI). According to their formulation, OTCI is evaluated as ‘the percentage deviation in the value of entropy generation from the comfort or equilibrium condition’, which it is assumed to provide ‘a measure of the level of satisfaction expressed by the mind with thermal environment’. The OTCI is mathematically defined as:

$$\text{OTCI}(\%) = H\left[1 - \frac{(S_{\text{gen}})_{\text{act}}}{(S_{\text{gen}})_{\text{com}}}\right] \times 100 \tag{7}$$

where subscripts ‘act’ and ‘com’ refer to actual and comfort values of the entropy generation term, respectively. The later is presumed to be a function of both environmental variables and human thermal responses, namely:

$$S_{\text{gen}} = S_{\text{gen}}\left(T_{\text{skin}}, T_{\text{core}}, Q_{\text{evap,skin}}, Q_{\text{conv,skin}}, Q_{\text{rad,skin}}, Q_{\text{evap,resp}}, Q_{\text{conv,resp}}, Q_{\text{met}}, I_{\text{cl}}, T_{\text{air}}, \phi\right) \tag{8}$$

Apart from previously defined quantities, I_{cl} is the thermal insulation (resistance) of the clothing worn by the occupant whereas T_{air} and ϕ are air temperature and relative humidity, respectively.

At this point, it is worth commenting the dimensionless coefficient H introduced by the OTCI definition. Referred to as human coefficient, H accounts for the variation in individual responses to thermal environment and it depends on age, sex, race and other related factors. In view of that, one could point out that H is an attempt to bridge physiological and psychological responses, in line with ASHRAE / ISO 7730 standard definition for thermal comfort. For pilot OTCI calculations, Boregowda *et al.* (2001) assumed $H = 1$ under the assumption of a ‘standard human’.

2.3. Thermoregulation and second-law analysis: exergy loss

The first and second laws of thermodynamics can be suitably combined to assess the maximum work available from a given energy form (interaction) or to assess the required work to restore the system back to its initial condition after carrying out an irreversible process (Kotas, 1995). Either way, exergy is a thermodynamic property introduced to allow process inspection with regard to the most efficient (hypothetically reversible) way by which it could be achieved.

Exergetic analysis may help identifying thermal processes inefficiencies by evaluating thermodynamic imperfections. It is worth noting that exergy is a function of state parameters related to the system under investigation (= occupant) as well as to the surroundings (= ambient).

By reasoning that exergy of a given system increases as it presents any parameter (e.g. temperature, pressure and chemical potential) that differs from its counterpart in the environment, one might suppose that thermal discomfort (or stress) could originate from an exergy loss excess as occupant's body departs from some comfort set point. Exergetic analysis may then lead to the concept of a thermal comfort (or stress) index for humans (or perhaps animals, from the Animal Science perspective) as thermoregulatory mechanisms attempt to bring the body back to a "comfortable" (i.e., minimum) exergy loss rate or level with reference to the ambient.

In order to propose such "comfortable" exergy loss rate (level), one should ascertain a set of environmental factors (air temperature and humidity, radiant temperature and air speed) as well as behavioral factors (activity and clothing) that in conjunction best meet occupant's satisfaction feeling. As total exergy loss equals the sum of exergy losses from single components (Szargut *et al.*, 1988), losses due to physical and chemical processes related to each physiological thermoregulatory mechanism should be accounted for in principle.

Occupant's total exergy can be divided into four components: kinetic, potential, physical and chemical. While the first two are related the high-grade energy (i.e. organized, fully convertible to work), the last two concern to low-grade energy (i.e., disorganized, partially convertible) and depend on both temperature and pressure of the prevailing ambient (Kotas, 1995). Hence, it seems plausible that these last two exergy components (physical and chemical) should suffice for a preliminary whole-body comfort exergetic analysis.

Just like entropy, exergy is exempt from a conservation law and an exergy loss term is thus introduced in order to close the exergy balance for the system under investigation. Exergy loss is consistent with the degraded useful energy due to process irreversibilities and it is worth recalling that Gouy-Stodola law (Szargut *et al.*, 1988; Kotas, 1995) relates exergy loss $\Delta\Xi$ (= irreversibility I) to entropy generation of an isolated system ΔS_{isol} according to:

$$\Delta\Xi = I = T_0 \ \Delta S_{\text{isol}} \tag{9}$$

where T_0 is the temperature of the surroundings.

Two sorts of irreversibility can arise in real processes, namely, intrinsic and avoidable. The former has to do with minimum irreversibilities imposed by constraints (e.g. uncontrolled chemical reactions and heat capacities mismatch) whereas the later is simply evaluated from the difference between actual (total) and intrinsic irreversibilities (Kotas, 1995). Thus, intrinsic irreversibility and its corresponding exergy loss could then be identified to basal metabolism or, rather, to some comfort zone, which would help defining the proposed comfort exergy loss rate (level).

Bearing in mind that humans do have the ability to acclimatize or acclimate (i.e. to naturally or artificially acquire physiological response changes after prolonged exposure to heat), an issue that remains and deserves to be studied is a prospective connection between the ambient temperature and the dimensionless human coefficient H introduced in the OTCI definition (Boregowda *et al.*, 2001), as previously discussed. For instance, it is well known that beyond a critical head temperature (set-point) a sharp shift occurs from heat loss through insensible evaporation to heat loss through sweating (Guyton, 1995). There is also a similar set point shift from the basal heat release to the shivering-induced heat release. It is interesting to observe that both set points are skin-temperature dependent.

3. Thermal comfort as a steady-state condition: preliminary model

As already cited, in steady-state Parsons (1993) simply regards thermal comfort as a lack of discomfort. In view of that and as a preliminary approach, the present work assumes that the occupant is an open system undergoing a steady flow process (e.g. a short-time exposure to a given ambient).

Human responses to thermal environments have been traditionally attributed to body interactions with four ambient parameters – air temperature and humidity, radiant temperature and air speed – combined to two personal parameters – human metabolism and clothing. These factors are then claimed to provide the six basic parameters defining human thermal environments (Fanger, 1970; Parsons, 1993) and, from the thermodynamic viewpoint, they refer to measurable physical quantities employed in the corresponding energy interactions calculations.

As suggested by Eq. (5), for practical purposes thermal interactions are grouped into heat losses due to respiration, heat losses occurring at the skin, metabolic heat production and mechanical (muscular) work. As a result, the right-hand side of Eq. (5) is rewritten as.

$$\dot{q}_{\text{met}} - \dot{w}_{\text{musc}} = \left(\dot{q}_{\text{evap,skin}} + \dot{q}_{\text{conv,skin}} + \dot{q}_{\text{rad,skin}}\right) + \left(\dot{q}_{\text{evap,resp}} + \dot{q}_{\text{conv,resp}}\right) \tag{10}$$

As implicitly assumed, conductive heat transfer is neglected for typical situations (Parsons, 1993) while radiative heat transfer has virtually no contribution to the respiration term since air is presumably transparent to thermal radiation.

It is worth recalling that evaporative heat losses $\dot{q}_{\text{evap,resp}}$ and $\dot{q}_{\text{evap,skin}}$ are inherently based on mass transfers to the ambient, which then behaves like an EMR. One could argue that an IMR should be attributed to water intake (as well as food). Nonetheless, it seems reasonable to assume that it is precisely an excessive water loss as sweat, water vapor or moisture that helps to build up and/or enhance (thermal) discomfort.

As far as heat transfers are concerned, a TER is referred to each convective term $\dot{q}_{\text{conv,resp}}$ and $\dot{q}_{\text{conv,skin}}$. The later may "lump" the TER for thermal radiation $\dot{q}_{\text{rad,skin}}$ as corresponding heat losses from the skin are sometimes modeled into a single term. By the same token, an additional TER is assigned to the metabolic heat source term $\dot{q}_{\text{met}}$ whereas a MER is ascribed to the muscular power term $\dot{w}_{\text{musc}}$.

The proposed model framework is sketched in Fig. (1). As $\dot{q}_{\text{met}}$ is strictly positive, the direction of the associated heat flow is indicated by the arrow in Fig. (1). On the other hand, heat flow direction can be opposite with respect to the other two TER's depending on the temperature difference between ambient and occupant's (control mass) skin and core temperature. Furthermore, it is here assumed that the ambient and the occupant form an isolated system.

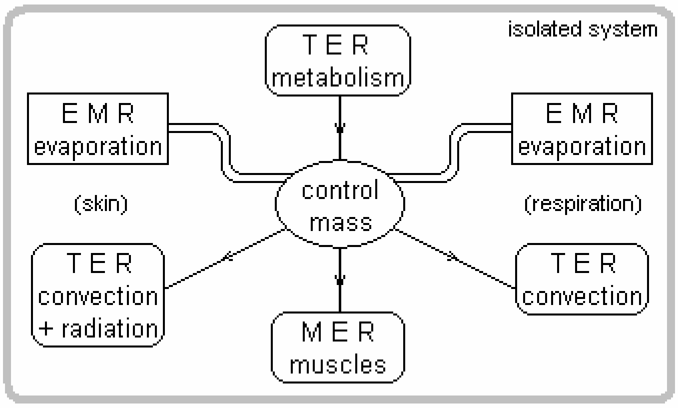

Figure 1. Thermodynamic model framework based on the heat balance equation for thermal comfort.

A classical approach for Eq. (10) has been proposed by Fanger (1970), also adopted by ASHRAE / ISO 7730, based on the following conditions: (*i*) the body is heat balance (i.e., body temperature is steady so that $dE_{\text{body}}/dt = 0$), (*ii*) sweat rate and (*iii*) mean skin temperature are within comfort limits. Employing the six fundamental parameters, the proposed equation for thermal comfort assessment is somewhat changed to:

$$\dot{q}_{\text{met}} - \dot{w}_{\text{musc}} = \dot{q}_{\text{vap,skin}} + \dot{q}_{\text{sw,skin}} + \dot{q}_{\text{conv,cl}} + \dot{q}_{\text{rad,cl}} + \dot{q}_{\text{evap,resp}} + \dot{q}_{\text{conv,resp}} \tag{11}$$

It is observed that heat transfers by convection or thermal radiation now include clothing interference while $\dot{q}_{\text{evap,resp}}$ was split into $\dot{q}_{\text{vap,skin}}$ = heat loss by water vapor diffusion through skin and $\dot{q}_{\text{sw,skin}}$ = heat loss by sweat evaporation from skin surface. Provided that units for all terms in Eq. (11) are $\text{W}\cdot\text{m}^{-2}$, empirical correlations suggest that:

$$\begin{aligned}
\dot{q}_{\text{vap,skin}} &= 3.05[5.733 - 0.00699(\dot{q}_{\text{met}} - \dot{w}_{\text{musc}}) - P_{\text{sat,air}}] \\
\dot{q}_{\text{sw,skin}} &= 0.42[(\dot{q}_{\text{met}} - \dot{w}_{\text{musc}}) - 58.15] \\
\dot{q}_{\text{conv,cl}} &= f_{\text{cl}}\, h_{\text{conv}}\,(T_{\text{cl}} - T_{\text{air}}) \\
\dot{q}_{\text{rad,cl}} &= 3.96\times10^{-8} f_{\text{cl}}\,[(T_{\text{cl}} + 273)^4 - (T_{\text{rad}} + 273)^4] \\
\dot{q}_{\text{evap,resp}} &= 0.00173\,\dot{q}_{\text{met}}\,(5.867 - P_{\text{sat,air}}) \\
\dot{q}_{\text{conv,resp}} &= 0.0014\,\dot{q}_{\text{met}}\,(34 - T_{\text{air}})
\end{aligned} \tag{12}$$

In all previous equations, the sign convention follows the one adopted in Eqs. (1), in line with ASHRAE (2001), so that positive values correspond to heat losses from body to the environment. In those equations, $P_{\text{sat,air}}$ is water vapor partial pressure (kPa) at prevailing ambient air conditions while T_{air}, T_{rad} and T_{cl} are air, radiant and the so-called clothed-body surface temperatures ($^{\text{o}}$C), respectively. The later depends, for example, on clothing insulation I_{cl} (in Clo units, 1 Clo = 0.155 $\text{m}^2\ \text{K}\cdot\text{W}^{-1}$) and it can be given by a quite lengthy expression:

$$T_{\text{cl}} = 35.7 - 0.0275(\dot{q}_{\text{met}} - \dot{w}_{\text{musc}}) - 0.155\, I_{\text{cl}}\,\{3.96\times10^{-8} f_{\text{cl}}[(T_{\text{cl}} + 273)^4 - (T_{\text{rad}} + 273)^4] + f_{\text{cl}} h_{\text{conv}}(T_{\text{cl}} - T_{\text{air}})\} \tag{13}$$

Convective heat transfer coefficient h_{conv} ($\text{W}\cdot\text{m}^{-2}\ \text{K}^{-1}$) is given by:

$$h_{\text{conv}} = \max[2.38\,(T_{\text{cl}} - T_{\text{air}})^{0.25}\,, 12.1\sqrt{v}] \tag{14}$$

where v is air speed (m·s^{-1}). For a seated person, there are the following correlations, adapted from (Parsons, 1993):

$$h_{\text{conv}} = \begin{cases} 8.3 v^{0.6} & , \quad 0.2 < v < 4.0 \\ 3.1 & , \quad 0 < v < 0.2 \end{cases} \tag{15}$$

Finally, the so-called clothing dimensionless area factor f_{cl} is given by:

$$f_{\text{cl}} = \begin{cases} 1.00 + 0.2\, I_{\text{cl}} & , \quad I_{\text{cl}} < 0.5 \text{ clo} \\ 1.05 + 0.1\, I_{\text{cl}} & , \quad I_{\text{cl}} > 0.5 \text{ clo} \end{cases} \tag{16}$$

while Parsons (1993) presents the following correlation

$$f_{\text{cl}} = 1 + 0.31\, I_{\text{cl}} \;\; (I_{\text{cl}} \text{ in Clo units}) \quad \text{or} \quad f_{\text{cl}} = 1 + \frac{0.31}{0.155} I_{\text{cl}} \;\; (I_{\text{cl}} \text{ in m}^2\text{ K}\cdot\text{W}^{-1}) \tag{17}$$

Based on the prior heat balance equation, Eq. (11), its auxiliary empirical correlations, Eq. (12), and the proposed model framework, Fig. (1), irreversibilities (total exergy losses) related to human thermoregulation mechanisms can be assessed. Thus, applying Gouy-Stodola relation, Eq. (9), for an open system (occupant) undergoing a steady flow process, irreversibility rate can be generally assessed as (Kotas, 1985):

$$\dot{I} = T_0 \left[\sum_{\text{EMR}} \dot{m}_{\text{out}}\, s_{\text{out}} - \sum_{\text{IMR}} \dot{m}_{\text{in}}\, s_{\text{in}} - \sum_{\text{TER}} \frac{\dot{Q}}{T} \right] \tag{18}$$

where T_0 is the environment temperature (K), $\dot{m}$ and s stand respectively for mass flow (kg·s^{-1}) and specific entropy (J·K^{-1} kg^{-1}) of the related matter stream and $\dot{Q}$ is the thermal energy transferred through heat interaction with a given TER at temperature T. It is worth remembering that the above equation should be normalized to the total body surface area and also that no IMR is considered in the present analysis.

As previously mentioned, convective and radiative heat transfer from skin can be "lumped" into a single term. In order to do so, the later is linearized as follows:

$$\dot{q}_{\text{rad,cl}} = f_{\text{cl}}\, h_{\text{rad}}\, (T_{\text{cl}} - T_{\text{rad}}) \tag{19}$$

so that:

$$\dot{q}_{\text{conv,cl}} + \dot{q}_{\text{rad,cl}} = \dot{q}_{\text{c+r,cl}} = f_{\text{cl}}\, h_{\text{c+r}}\, (T_{\text{cl}} - T_{\text{ref}}) \quad , \quad h_{\text{c+r}} = h_{\text{conv}} + h_{\text{rad}} \quad \text{and} \quad T_{\text{ref}} = \frac{h_{\text{conv}} T_{\text{air}} + h_{\text{rad}} T_{\text{rad}}}{h_{\text{conv}} + h_{\text{rad}}} \tag{20}$$

For 'most typical indoor conditions', ASHRAE (2001) recommended value for the radiative heat transfer coefficient is $h_{\text{rad}} = 4.7$ W·m^{-2} K^{-1}.

In addition, two approaches could be followed for the irreversibility due to heat loss by mass transfer. One is to strictly use an EMR for all water losses through skin and lungs. In this case, one should be able to infer mass flows from Eqs. (11) and (12), using values from steam tables, i.e., vaporization enthalpy h_{fg} at the related skin and lung condition to be used with $\dot{q}_{\text{vap,skin}}$ and $\dot{q}_{\text{evap,resp}}$, respectively, and vapor enthalpy h_{f} for the skin-diffusion term $\dot{q}_{\text{sw,skin}}$. On the other hand, for the benefit of simplicity, one could ascribe a TER (at a suitable temperature T) for each aforementioned heat loss in order to be included into the last summation on the right-hand side of Eq (18). If the first approach is adopted along with the proposed linearization for the thermal radiation term, surface-normalized Eq (18) then results to:

$$\dot{I} = T_0 \left[\left(\dot{m}_{\text{vapor,skin}}\, s_{\text{g,skin}} + \dot{m}_{\text{sweat,skin}}\, s_{\text{f,skin}} + \dot{m}_{\text{moist,resp}}\, s_{\text{f,resp}} \right) - \left(\frac{\dot{q}_{\text{met}}}{T_{\text{core}}} - \frac{\dot{q}_{\text{c+r,cl}}}{T_{\text{rad}}} - \frac{\dot{q}_{\text{conv,resp}}}{T_{\text{air}}} \right) \right] \tag{21}$$

where the mass flows for water vapor, sweat (both from skin) and moisture (from lungs) are estimated as:

$$\dot{m}_{\text{vapor,skin}} = \frac{\dot{q}_{\text{vap,skin}}}{h_{\text{g,skin}}} \quad , \quad \dot{m}_{\text{sweat,skin}} = \frac{\dot{q}_{\text{sw,skin}}}{h_{\text{fg,skin}}} \quad , \quad \dot{m}_{\text{moist,resp}} = \frac{\dot{q}_{\text{evap,resp}}}{h_{\text{fg,resp}}} \tag{22}$$

4. Thermal sensation during transient process: prospective mathematical model

Because they are transient in nature, Parsons (1993) claims that thermal sensations cannot be experienced in steady-state conditions. For that reason, this paper also puts forward a mathematical model for the dynamic behavior (i.e. transient process) of the entropy generation (like the function S_{gen} used in OCTI calculations) and exergy loss referring to an occupant in a given ambient.

The model proposed in this work is an autonomous dynamic system which is non-linear with respect to variables $S = \Delta S$ (entropy generation) and $I = \Delta\Xi$ (total irreversibility = total exergy loss). Auxiliary parameters are also introduced (aiming at dimensional consistency) so that the following rate equations are put forward:

$$\begin{cases} \dfrac{dI}{dt} = f(I, S, \tau_1, \alpha_1, \beta_1) \\ \dfrac{dS}{dt} = g(I, S, \tau_2, \alpha_2, \beta_2) \end{cases} \Rightarrow \begin{cases} \tau_1 \dfrac{dI}{dt} = I(1-\alpha_1 I) + \beta_1 IS \\ \tau_2 \dfrac{dS}{dt} = S(1-\alpha_2 S) - \beta_2 SI \end{cases} \tag{23}$$

where the time parameters τ_i are here taken as $\tau_1 = \tau_2 = 1$ (in time units), for the sake of simplicity. For consistency purposes, proportionality parameters dimensions are $[\alpha_1]$ = (exergy flux)$^{-1}$ = (energy flux)$^{-1}$ and $[\alpha_2]$ = (entropy flux)$^{-1}$ = clothing insulation, respectively, while for the other parameters $[\beta_1]$ = (entropy flux)$^{-1}$ = clothing insulation and $[\beta_2]$ = (exergy flux)$^{-1}$ = (energy flux)$^{-1}$, respectively.

With respect to the equation system, Eqs. (23), d*I*/d*t* represents the irreversibility (= exergy loss) variation rate. The first term on the right-hand side of this equation stands for a logistic behavior, suggesting a limited increase for *I*. The second cross-term contributes for irreversibility enhancement due to the presence of both *I* and *S*. Similarly, in the d*S*/d*t* equation for the variation rate of the entropy generation, the first term on the right-hand side also represents a limited augment for *S*, while the second cross-term contributes to the entropy generation increase due to both *I* and *S*.

From a qualitative study, four critical or equilibrium points are found, all belonging to the first quadrant: $(0,0)$, $(I_c,0)$, $(0,S_c)$ and (I_c,S_c). The origin, the second and third points are unstable because the related eigenvalues of the Jacobian are real and of opposite sign. They are referred to as nodal source points and they behave like repulsion points for nearby trajectories. The last critical point $(I_c, S_c) = (f_1(\alpha_1,\beta_1,\alpha_2,\beta_2), f_2(\alpha_1,\beta_1,\alpha_2,\beta_2))$ is asymptotically stable and it is referred to as a nodal sink point (Jacobian eigenvalues are real and negative). If this later equilibrium point is identified to the comfort condition, then S_c and I_c correspond to thermal comfort levels (rates) of entropy generation and irreversibility, respectively. It should be noted that such values depend on α_i and β_i parameters to be introduced.

The behavior of solution trajectories $(I(t), S(t))$ for transient processes (i.e., thermal sensations) is sketched in the phase plane in Fig. (2) (obtained through MATLAB 6.0). In other words, trajectories shown in Fig. (2) represent the evolution of both entropy generation and irreversibility during the process. One observes that trajectories approach the equilibrium point (I_c,S_c), with the tendency to move away from saddle points.

Critical points were calculated by attributing usual values to parameters characterizing a occupant-ambient system (i.e., human and environmental parameters). The model thus attempts to represent the dynamics of thermal sensation experienced by such isolated system. Adopted numerical values include $\alpha_1 = 1/0.8$ Met^{-1} and $\beta_2 = 0.8$ Met (based on data for a person lying down and 1 Met = 58.15 W·m^{-2}) as well as $\beta_1 = 0.30$ Clo and $\alpha_2 = 1/0.30$ Clo^{-1} (based on data for typical tropical clothing outfit and 1 Clo = 0.155 m^2 K·W^{-1}).

In order to analyze the behavior of obtained trajectories, the phase plane is divided into four regions so that an initial condition (I_0,S_0) is assigned to each of them as presented in Tab. (1). It is then assumed that the occupant-ambient system is already defined so that point (I_0,S_0) represents occupant's initial state with respect to the variables *I* and *S* as well as to model parameters. Starting from the initial condition (I_0,S_0), Fig. (2) shows that trajectories asymptotically approach the comfort state given by equilibrium point (I_c,S_c), with distinct velocities. In what follows, the process behavior of both *I* and *S* variables is analyzed for different regions.

Table 1. Initial condition assignment to distinct sub-regions within the $I \times S$ phase plane.

Region I	Region II	Region III	Region IV
$S_0 > S_c$; $I_0 < I_c$	$S_0 > S_c$; $I_0 > I_c$	$S_0 < S_c$; $I_0 > I_c$	$S_0 < S_c$; $I_0 < I_c$

For example, if (I_0, S_0) belongs to region I, one observes that S decreases very fast (while I keeps a small value) down to a minimum value near to the repulsion point $(0, S_c)$. From this state on, both I and S asymptotically increase up to the point (I_c, S_c). Similarly, if the initial condition (I_0, S_0) belongs to region III, one verifies that I reduces down to a minimum value close to the repulsion point $(I_c, 0)$. Thereafter, both I and S asymptotically augment up to the comfort state point (I_c, S_c).

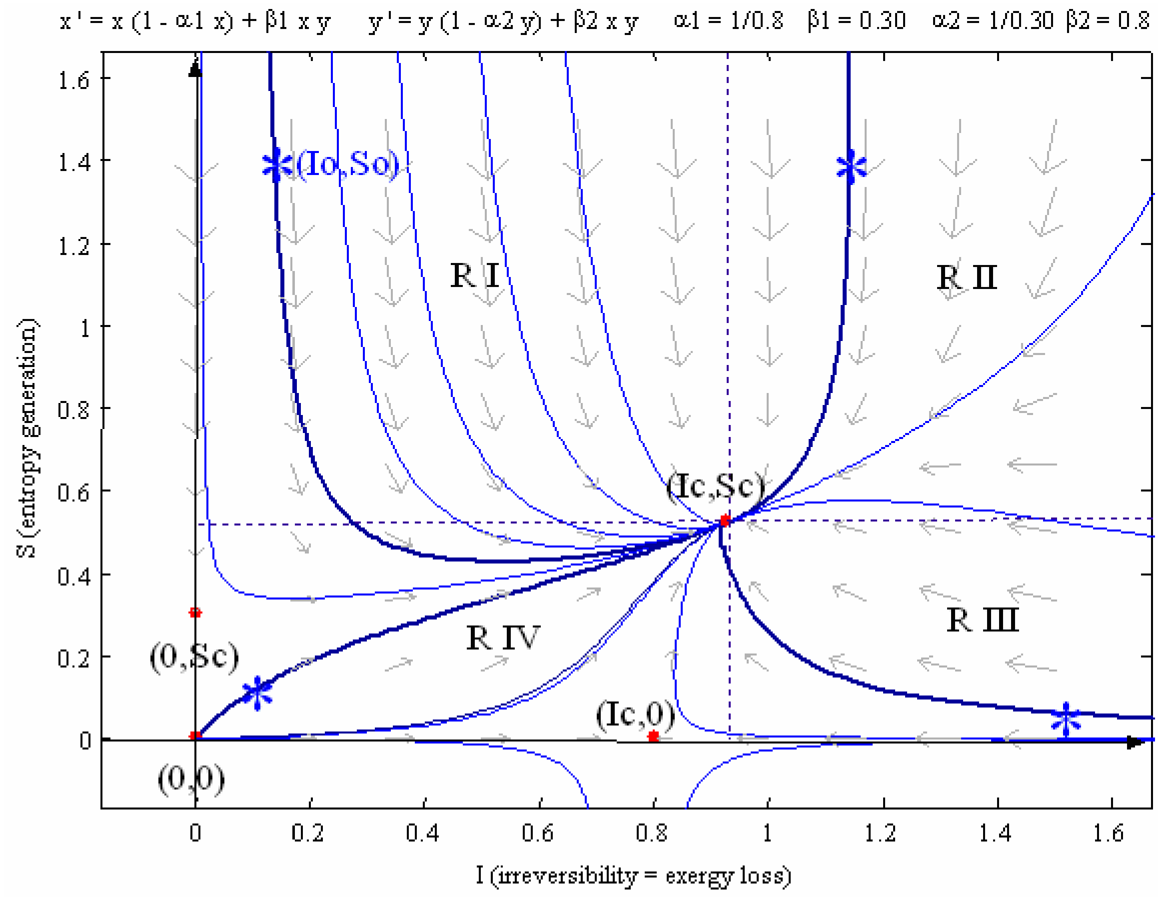

Figure 2. Trajectories in the phase plane obtained from the proposed model.

In region IV, it is worth discussing the distinct observed behavior. In this case, if the initial condition is close to the origin, then I and S have very small values. Trajectories show quite a uniform and asymptotic behaviour up to comfort point (I_c, S_c). It should be noted that in the proposed model both S and I never reach null values due to the repulsive nature related to the origin.

Mechanisms employing the model here proposed correspond to limited and symbiotic growth or decay. Behavior of entailed variables is of cooperative kind, i.e., the variation of one or another is such that both coexist along the time. Those variables undergo (process) variations so as to simultaneously reach a desired equilibrium state.

5. Closing remarks (towards future developments and model validation)

In order to survive, humans consume food, which is then converted into heat. As food seems to retain a higher level of organization (i.e., order) when compared to heat itself, one could claim that the human body has a low *mechanical* efficiency if heat should be considered a by-product from living cells. Such rationale can be misleading inasmuch as metabolically released heat is in fact crucial for life.

One could also postulate that natural selection applies to entropy-efficient or, alternatively, exergy-saving species. Irreversible phenomena do cause exergy losses, which in turn reduce process efficiency. As a consequence, there could be a shortfall of useful physiological effects or, rather, an increase of energy consumption (from whatever source such energy is derived) in order to have those biological effects suitably accomplished.

Energy balance for occupant's body is a necessary but not sufficient condition for thermal comfort as suggested, for example, by Fanger's predicted mean vote (PMV) definition. In addition, thermal feelings of hotness or coldness is a sensory experience (i.e. a psychological phenomenon), which is difficult to be defined on physical or physiological basis. Yet, it is recognized that environmental as well as personal conditions affect thermal sensation.

In thermoregulation, there has been some dispute about what is indeed the regulated variable and the list include all sort of temperatures (core, body, skin, brain), body energy content or heat outflow rate. As exergy function takes into account both ambient and occupant thermodynamic state parameters, it could be another promising "contender" in the above roll. At least, it has the ability to quite equally assess both extremes of thermal sensation and thermal comfort, namely, from uncomfortably cold up to uncomfortably hot.

The present work has presented and discussed concepts and directions which are believed to provide groundwork for the definition of a prospective exergy or irreversibility-based thermal comfort (or stress) index. The underlying question is whether or not the human body is sensible to irreversibilities (= exergy losses) as far as thermoregulatory mechanisms are concerned.

It is here presumed that steady-state thermal comfort could be probably identified to a minimum (= comfortable) irreversibility rate with respect to the prevailing ambient and occupant behavior. Means to validate (or not) all previous assumptions could include the comparison of results yielded from such exergetic analysis to those obtained based on well-established thermal comfort indexes as the PMV itself, which is in fact presently under way.

Concerning the transient model, depicted in Fig. (2), each solution trajectory can be attributed to thermodynamic state of the system, which evolves from an extreme (initial state) to another (steady-state), going through thermal comfort state. The later could eventually coincide with the final steady-state, as it occurs to most of trajectories in region II. On the other hand, trajectories in region I (for low I values) are observed to achieve a minimum point before reaching steady-state. In other instances, like trajectories in regions III and IV, thermal comfort state may correspond to the respective minimum point, which does not necessarily match with the steady-state for some trajectories.

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