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Human body exergy analysis and the assessment of thermal comfort conditions

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ABSTRACT

Exergy analysis is applied to assess the quality of the energy conversion processes that take place in the human body, aiming at developing indicators of thermal comfort based on the concepts of destroyed exergy rate, exergy transfer rate to the environment and exergy efficiency. In literature only destroyed exergy has been used to evaluate thermal sensation. To perform the exergy balance it is necessary to calculate the exergy variation of the body over time which is a composition of metabolic exergy and the exergy variation due to transient environmental conditions. The exergy transfer to the environment is calculated as the sum of the terms associated with radiation, convection, evaporation and respiration. The thermal behavior of the human body is simulated by a model composed of 15 cylinders, naked and dressed for winter seasons, as a function of the air temperature, mean radiant temperature and relative humidity. The energy equation is solved to obtain transitory response of the body due to a variation in environmental conditions and the energy transfer to the environment. For relative humidities between 40% and 60%, results indicate that the destroyed exergy is minimal for thermal comfort conditions. Nevertheless, for low relative humidities and high temperatures the destroyed exergy is also minimal, indicating the necessity of another physical quantity to evaluate thermal comfort conditions. At this point the exergy transfer to environment is high, showing that the body may not be at thermal comfort condition. This article proposes is to use two terms of the exergy analysis to evaluate the thermal comfort condition: destroyed exergy and exergy transfer to environment.

1. Introduction

The comprehensive study of human body behavior requires the use of the Second Law of Thermodynamics in order to assess the quality of the energy conversion process that takes place in its several organs and systems. Exergy analysis was first applied to the human body by Batato et al. [1]. In the past decade, this kind of analysis has been extensively applied to the human body to correlate the destroyed exergy with thermal comfort and thermal sensation conditions [2–14].

The first attempts to use the Second Law of Thermodynamics in biological systems sought to prove Prigogine and Wiame principle [15] which states that all living organisms tend to a minimum entropy production [16–22]. Albuquerque-Neto et al. [23], Henriques et al. [24] and Mady et al. [25] applied the exergy analysis to the human body during physical activities. Moreover, this analysis was also applied in cancerous [26] and neurons [27] cells.

Isawa et al. [2], Prek [3,4], Shukuya [5,6] were the first authors who tried to correlate the point of minimum destroyed exergy with thermal comfort conditions. These ideas were extensively analyzed in [7–14], where [10] correlated thermal sensation data from literature with the minimum destroyed exergy which was close to neutrality tending to a slightly cool sensation. Dovjak et al. [11] used the destroyed exergy to obtain optimal conditions for healthcare and treatment of burn patient. Wu et al. [13] compared the destroyed exergy with mean performance and thermal sensation conditions. Although the slope of the curves of these quantities was different, there was a point at which the curves intersect (optimum point).

Mady et al. [22] calculated, for a naked subject, the destroyed exergy and exergy efficiency as a function of the operative temperature and relative humidity, where it was found that the body destroys less exergy and is more efficient in higher temperatures and lower relative humidities. Therefore, according to these

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Nomenclature

A	area, m^2
B	exergy rate and flow rate, W
$\mathbf{B}$	body exergy, J
b	exergy rate/flow rate per subject mass, J/kg
$\mathbf{b}$	body specific exergy, J/kg
c_p	specific heat at constant pressure (J/(kg K))
f_{cl}	ratio between the surface area of the clothed and the nude segment (–)
h	specific enthalpy (J/kg)
$\bar{h}$	heat transfer coefficient (W/(m^2 K))
H	enthalpy flow rate, W
h_{lv}	enthalpy of vaporization, J/(kg)
M	metabolism, W
m	body mass, kg and mass flow rate, kg/s
P	pressure, Pa
Q	heat transfer rate, W
R	gas constant, J/(kg K)
R_{cl}	thermal resistance of clothes (m^2 K/(W))
S	entropy rate, W/K
s_{lv}	entropy of vaporization, J/(kg K)
T	temperature, °C or K
t	time, s
U	internal energy, J
W	performed power, J/s

Greek symbols

η	efficiency, %
ϕ	relative humidity, %

Subscripts and superscripts

0	thermodynamic reference
a	environment air
b	exergy and body
c	convective
$carb$	carbohydrates
d	destroyed
e	evaporative
en	energy
env	environment
ex	expired
hy	hypothalamus
in	inflow
lip	lipids
M	metabolic
o	operative
out	outflow
r	radiative
mr	mean radiant
res	respiration
sk	skin
ΔT	due to body temperature variation
w	water vapor

results, only the exergy destruction may not be sufficient to determine thermal comfort conditions from the exergy analysis.

Since the exergy transfer to the environment is one of the physical quantities that take into account the quality of the energy conversion in a given process, in this article it will be proposed that to estimate thermal comfort conditions using exergy analysis the destroyed exergy rate and exergy transfer to environment rate are needed. To this aim, exergy analysis is applied according to the method previously indicated by Mady et al. [22,25] and Mady and Oliveira Jr. [28], based on the thermal model developed by Ferreira and Yanagihara [29]. Comparisons of the energy and exergy behavior of the body as a function of relative humidity, air temperature and mean radiant temperature for a nude and clothed model were made.

2. Methods

Fig. 1 indicates a model with a schematic representation of the human body, where it is indicated the heat transfer rate and enthalpy flow rates associated with radiation (Q_r), convection (Q_c), vaporization (H_e), respiration ($H_{ex} - H_a$), food intake, food wastes, water intake and urine. The model was previously demonstrated in Mady and Oliveira Jr. [25]. The term Q_M is the heat released to the body caused by the cellular metabolism. In this figure the human body is divided in two control volumes, CV1 and CV2. The first one represents the thermal and respiratory systems and the second the cellular metabolism. The energy balance is solved as indicated by Mady et al. [22].

The Energy and Exergy Analysis were applied to the control volume shown in Fig. 1, with given environment and reference conditions such as temperature ($T_0 = T_o$), pressure ($P_0 = P_a$) and relative humidity ($\Phi_0 = \Phi_a$). Thus, Eq. (1) indicates a general equation of the exergy balance.

$$\frac{dB}{dt} = \sum B_{in} - \sum B_{out} + \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W - B_d \qquad (1)$$

The energy metabolism (M) and exergy metabolism (B_M) for the whole body are part of the total internal energy (dU/dt) and exergy ($d\mathbf{B}/dt$) variation of the body over time as indicated in Eqs. (2) and (3), where, U is the internal energy of the body, $\mathbf{B}$ is the exergy of the body, $dU/dt|_{\Delta T}$ and $d\mathbf{B}/dt|_{\Delta T}$ are the internal energy and the exergy variation of the body due to a variation in environmental conditions, respectively. This last term is related to the variation of the energy and entropy of the body over time, as in Eq. (2) and (3). Moreover, there is an assumption that the variation of the volume of the body is neglected.

$$\frac{dU}{dt} = -M + \left.\frac{dU}{dt}\right|_{\Delta T} \qquad (2)$$

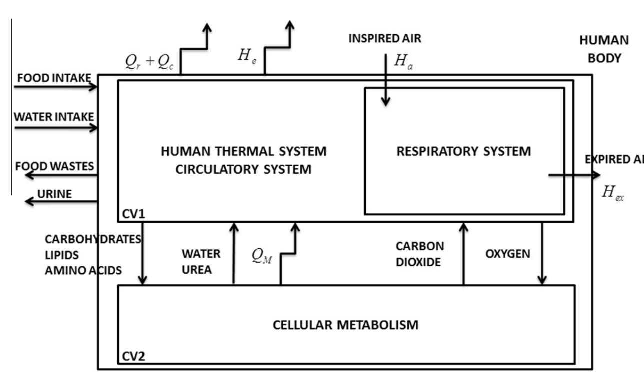

Fig. 1. Schematic representation of the human body, with the intake of food, water and inspired air; and output of food, urine, expired air, vaporization trough skin and heat release due to radiation and convection. Based on Mady and Oliveira Jr. [25].