EXERGY ANALYSIS OF HUMAN BODY UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

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Abstract. *Exergy analysis was applied to assess the energy conversion processes that take place in the human body aiming to obtain indicators of thermal confort conditions, from correlations of the destroyed exergy and exergy efficiency with environmental parameters. The human thermal model used to perform the exergy analysis is composed of 15 cylinders with elliptical cross section (which leads to realistic dimensions) representing: head, neck, trunk, arms, forearms, hands, thighs, legs, and feet. For each cylinder a combination of the following tissues was considered: skin, fat, muscle, bone, brain, viscera, lung, and heart. The exergy analysis was applied for each element, being possible to obtain exergy rates and flow rates associated with radiation, convection, vaporization and respiration. Besides, it was possible to determine a transitory response of the body over time. Results indicate that the body destroys less exergy and is more efficienct for higher operative temperatures. Moreover, a combination of low air temperature and high mean radiant temperature leads to a higher exergy efficiency and a lower destroyed exergy.*
Keywords*: Exergy analysis, exergy efficiency, human body behavior*

1. INTRODUCTION

Exergy analysis was applied to assess the energy conversion processes that take place in the human body during basal conditions, aiming at developing indicators of thermal comfort conditions based on the concepts of exergy destroyed rate and exergy efficiency.

Batato et al. (1990) was one of the first authors that applied the exergy analysis to the human body. The authors found that, although the energy losses to the environment are considerable, the exergy losses are negligible; similar results were obtained by Mady et al. (2012a). Mady and Oliveira Jr (2012) proposed a model to calculate the human body exergy metabolism which takes into account the consumption of nutrients (carbohydrates, lipids and proteins). Both authors obtained that in basal conditions the metabolism in energy and exergy basis have similar magnitudes.

Prek (2005, 2006), Prek and Butala (2010) aiming to obtain the relation between exergy consumption with thermal comfort conditions proposed a two node model of human body, where it was obtained that only a combination of environmental conditions ensures minimum destroyed exergy. Simone et al. (2011) performed the exergy analysis for the human body to obtain relations of destroyed exergy with thermal comfort and thermal sensation conditions for different sets of experimental conditions. Mady et al. (2012a) showed that the human body destroys less exergy and is more efficient in higher temperatures and lower relative humidities.

Albuquerque Neto et al. (2010) and Mady et al. (2012b) applied the exergy analysis to runners in treadmill during an exercise test.

The purpose of the present work is to apply the exergy analysis, previously indicated in Mady et al. (2012a) and Mady and Oliveira Jr (2012) on the thermal model developed by Ferreira and Yanagihara (2009). It was made a comparison of the energy and exergy rates and flow rates to environment as a function of relative humidity, air temperature and mean radiant temperature. Furthermore, the exergy analysis was performed obtain the exergy behavior (destroyed exergy and exergy efficiency) of a healthy human body.

2. MODEL DESCRIPTION

Figure 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 previous demonstrated in Mady and Oliveira Jr (2012). 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 system and respiratory system and the second the cellular metabolism. The energy balance is solved as indicated by Mady et al. (2012a).

According to Rahman (2007) in a period of one day the mass input (food, liquids and inspired gases) is equivalent to the mass output (food wastes, urine, expired gases and vaporization). In shorter periods of time this may not be verified. In this article, for the sake of the simplicity, the variation of body mass due to food and water intake, wastes and accumulation are neglected.

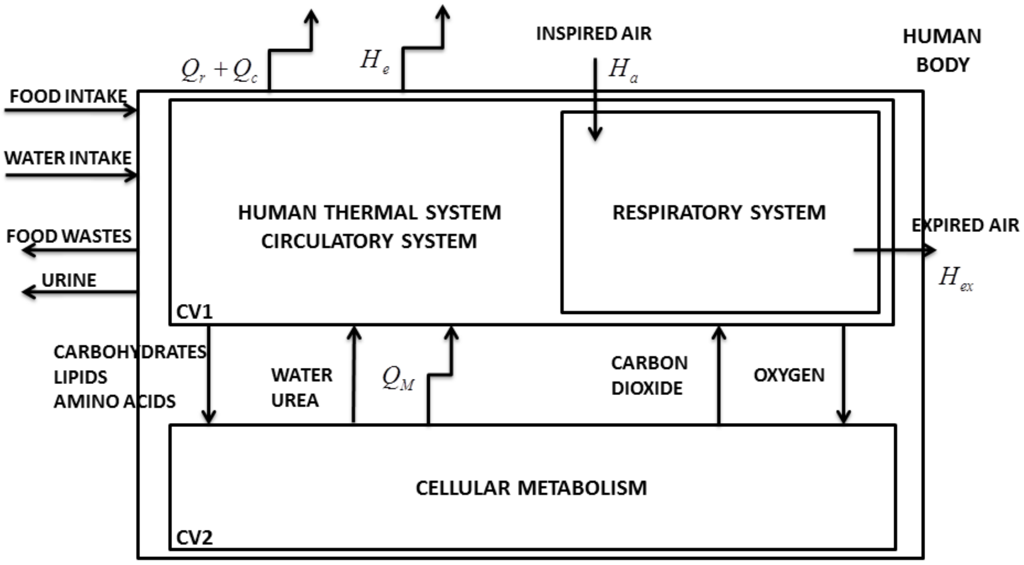

Figure 1. Schematic representation of the human body, with the intake of food, water and inspired air; and output of food, urine, expired air, vaporization trough skin and heat release due to radiation and convection

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

$$\frac{d\mathbf{B}}{dt} = \sum B_{in} - \sum B_{out} + \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W - B_{dest} \tag{1}$$

The energy (M) and exergy (B_M) metabolism 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; $dU/dt\big|_{\Delta T}$ and $d\mathbf{B}/dt\big|_{\Delta T}$ 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 internal energy and entropy variation of the body over time, as in Eq. (3). In Eqs. (2) and (3) there is an assumption that the variation of the volume of the body is neglected and the energy and exergy variation of the body over time due to transient conditions is considered only in CV1.

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

$$\frac{d\mathbf{B}}{dt} = -B_M + \left.\frac{d\mathbf{B}}{dt}\right|_{\Delta T} = -B_M + \left(\left.\frac{dU}{dt}\right|_{\Delta T} - T_0 \left.\frac{dS}{dt}\right|_{\Delta T}\right) \tag{3}$$

Equation (4) indicates the energy balance applied to CV1, where the energy intake is Q_M is the heat released to the body caused by the metabolism. The terms Q_c, Q_r are the heat transfer rate to the environment associated with convection and radiation, H_e and ΔH_{res} are the enthalpy flow rate related to vaporization and respiration.

$$\left.\frac{dU}{dt}\right|_{\Delta T} = Q_M - \left(Q_c + Q_r + H_e + \Delta H_{res}\right) \tag{4}$$

Equation (5) indicates the exergy balance applied to CV1. The exergy intake is B_{QM}, indicated by Eq. (6). Where, B_{QM} is the exergy transferred to the body caused by the exergy metabolism, T_0 is the environment/reference temperature and T_b the body temperature. The exergy rate and flow rates B_c, B_r, B_e and ΔB_{res} ($B_{ex} - B_a$) are the exergy rates and flow rates associated with convection, radiation, vaporization and respiration, previously determined in Mady et al. (2012).

$$B_{dest}^{CV1} = B_{Q_M} - \left(B_c + B_r + B_e + \Delta B_{res}\right) - \left.\frac{d\mathbf{B}}{dt}\right|_{\Delta T} \tag{5}$$

$$B_{Q_M} = Q_M \left(1 - \frac{T_0}{T_b} \right) \tag{6}$$

The cellular metabolism is a representation of the human cells energetic behavior. In this control volume (CV2) the reactions of oxidation of the energy substrates, also called metabolism, take place. Equations (7) and (8) indicates the energy and exergy balances for CV2, where H_{reac} is the enthalpy of the reactants (carbohydrates, lipids, amino acids and oxygen), H_{prod} is the enthalpy of the products (urea, liquid water and carbon dioxide), B_{reac} is the exergy content of the reactants and B_{prod} is the exergy content of the products.

$$Q_M = H_{reac} - H_{prod} \tag{7}$$

$$B_{dest}^{CV2} = B_{reac} - B_{prod} - Q_M \left(1 - \frac{T_0}{T_b} \right) \tag{8}$$

The metabolism is defined as indicated in Eq. (9). Note that, in steady state condition, Q_M=M.

$$M = H_{reac} - H_{prod} \tag{9}$$

The exergy metabolism is defined as Eq. (10).

$$B_M = B_{reac} - B_{prod} \tag{10}$$

When the control volume is the whole body, the energy and exergy balances can be written as in Eq. (11) and (12). For basal conditions $W=0$.

$$\left. \frac{dU}{dt} \right|_{\Delta T} = M - \left(Q_c + Q_r + H_e + \Delta H_{res} \right) \tag{11}$$

$$B_{dest}^{body} = \left(B_M - \left. \frac{d\mathbf{B}}{dt} \right|_{\Delta T} \right) - \left(B_c + B_r + B_e + \Delta B_{res} \right) \tag{12}$$

Note that Eq. (5) takes into account only the thermal part of metabolism. Equation (12) is similar to the analysis proposed by Batato et al. (1990). The difference between these two approaches is that all the exergy released to the body in CV2 is neglected if Eq. (4) is used as the metabolic exergy as indicated in Mady and Oliveira Jr (2012). Although, for the energy balance, Eq. (4) is equal to Eq. (11), because M=Q_M.
The exergy efficiency can be calculated by Eq. (25). If the body temperature is constant, than $\left. d\mathbf{B}/dt \right|_{\Delta T}$ becomes zero.

$$\eta_b = 1 - \frac{B_{dest}}{\left| d\mathbf{B}/dt \right|} = 1 - \frac{B_{dest}}{\left| - B_M + \left. \frac{d\mathbf{B}}{dt} \right|_{\Delta T} \right|} \tag{13}$$

2.1 Human thermal model

The human thermal model developed by Ferreira and Yanagihara (2009) is composed of the thermoregulatory and passive system. The former is related to physiological responses to changes in thermal environment or activity level: vasodilation or constriction, shivering and sweating. The latter includes heat conduction inside the body, heat transfer by convection because of blood flow and heat and mass transfer between the body and the environment.
As indicated in Ferreira and Yanagihara (2009), the global data of the anatomic model used are: height 1.76 m, weight 67kg, surface 1.8m^2 and volume 0.0627m^3. The human body was divided into 15 cylinders with elliptical cross section representing the head, neck, trunk, arms, forearms, hands, thighs, legs and feet. Each cylinder has a combination of some of these tissues: skin, fat, muscle, bone, brain, viscera, lung and heart. Basically, the segments from the upper and lower limbs have the same arrangement formed by concentric annular layers in the following order (from the center to surface): bone, muscle, fat and skin. Both, trunk and head have three cross sections with different layers distributions. In the middle cross section of the trunk, for instance, the following sequence is considered: heart, lung, bone, muscle, fat and skin. In the middle cross section of the head the following sequence is considered: brain, bone, muscle, fat and skin.

The energy equation is solved for each tissue with its own metabolism, blood perfusion rate and thermophysical properties. To calculate heat transfer between tissues and blood, it was necessary to divide vessels into two classes: the small ones (that can be treated as part of a continuum) and the large ones Ferreira and Yanagihara (2009). The small vessels are treated similarly to the model proposed by Pennes (1948) with the difference that the arterial blood temperature depends on the position inside the tissue and it is not equal to the body core temperature. The large vessels can be modeled as proposed by Wissler (1985), using two reservoirs, one of arterial blood and the other of venous blood, with the exception of the trunk that is modeled with only one reservoir. Considering heat and mass transfer through skin to the environment each cylinder is subjected to radiation, convection and vaporization. Respiration enthalpy rates were divided into 45% and 25% for the head and neck muscles and 30% for the lung. It is also possible to obtain the transitory response of the body due to a variation in environmental conditions (temperature dependence over time). A representation of the model is indicated in Fig. 2.

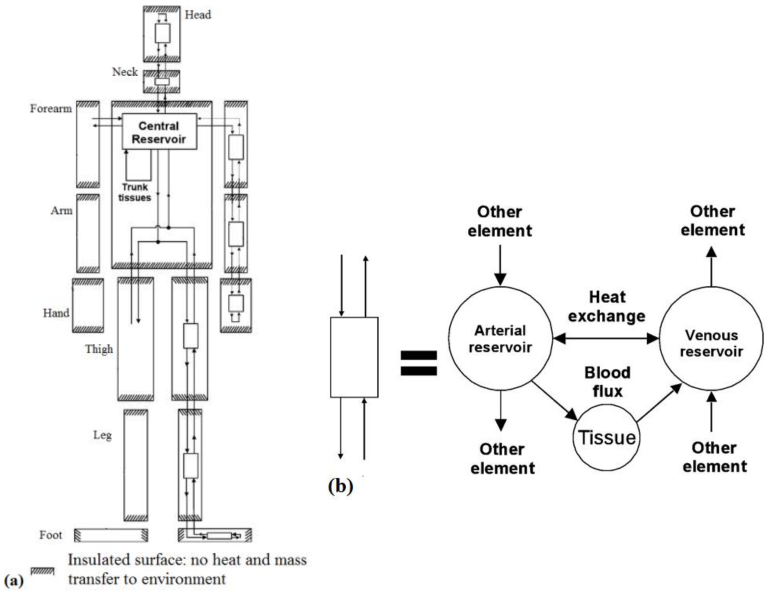

Figure 2. (a) Human thermal model with the circulatory system; (b) a representation of each segment with the circulatory system. Obtained in Mady et al. (2012a) and in Ferreira and Yanagihara (2009)

2.1.1 Energy an exergy analysis

As indicated by Mady and Oliveira Jr (2012) the energy and exergy metabolism can be calculated from the enthalpy and exergy variation of three reactions of oxidation: carbohydrates, lipids and amino acids (represented by glucose, palmitic acid and an amino acid with mean composition). Therefore, it is possible to obtain an equation of the metabolism in energy and exergy basis as a function of nutrients consumption, or carbon dioxide production and oxygen consumption as in Mady and Oliveira Jr (2012)

2.1.2 Energy and exergy transfer to the environment

The energy and exergy analysis proposed in the present work is based on a previous study by Mady et al (2012a). The heat transfer rate and mass flow rates to the environment were obtained from a procedure described in Ferreira and Yanagihara (2009).

Equation (14), indicates the exergy associated with heat exchange with the environment due to radiation. In Eq. (17), T_{sk} is the skin temperature and T_{rm} is the mean radiant temperature.

$$B_r = Q_r\left(1 - \frac{T_{rm}}{T_{sk}}\right) \tag{14}$$

The exergy contribution of convection can be calculated as indicated by Eq. (15). In this equation T_a is the air temperature.

$$B_c = Q_c\left(1 - \frac{T_a}{T_{sk}}\right) \tag{15}$$

The exergy flow rate due to vaporization through skin is determined by Eq. (16). The first term is related to the vaporization of the sweat on the skin and the second term is related to the difference in the concentration of saturated vapor near the skin and concentration of the vapor in the environment. In this equation, m_w is the mass rate of sweat evaporated, h_{lv} and s_{lv} are the enthalpy and entropy of vaporization of the water, respectively; $P_{w,sk}$ is the water vapor pressure at skin temperature and $P_{w,0}$ is the water vapor pressure at reference temperature.

$$B_e = m_w\left(h_{lv} - T_0 s_{lv}\right) + m_w R_w T_0 ln\left(\frac{P_{w,sk}}{P_{w,0}}\right) \tag{16}$$

The exergy variation of the body associated with respiration can be calculated according to Eq. (20). In this equation, m_{res} is the pulmonary ventilation, $y_{i,ex}$ is the mass fraction of the gas i (oxygen, carbon dioxide, nitrogen, water vapor) in the expired air, $c_{p,i}$ is the specific heat, T_{ex} is the expired air temperature, $P_{i,ex}$ is the expired partial pressure of the gas i and $P_{i,0}$ is the partial pressure of the gas i, in the environment.

$$\Delta B_{res} = m_{res}\sum_i\left[y_{i,ex}c_{p,i}\left(T_{ex} - T_0 - T_0 ln\left(\frac{T_{ex}}{T_0}\right)\right) + y_{i,ex}R_i T_0 ln\left(\frac{P_{i,ex}}{P_{i,0}}\right)\right] \tag{17}$$

2.1.3 Transient analysis

The temporal variation of exergy due to a variation in environment temperature over time ($d\mathbf{B}/dt\big|_{\Delta T}$) is indicated by Eq. (3). The first term is the temporal variation of the internal energy and can be calculated from Eq. (11). The second term is the temporal variation of the body entropy and can be calculated for each element (j= hand, arm, forearm, etc) according to Eq. (18).

$$\left.\frac{dS}{dt}\right|_{\Delta T} = \sum_j \frac{dS_{element,j}}{dt} = \sum_j\left(\frac{dS_{bl,j}}{dt} + \frac{dS_{ti,j}}{dt}\right) \tag{18}$$

For each cylinder j, the term $dS_{bl,j}/dt$ is the temporal variation of entropy in the blood compartment indicated in Eq. (22) and $dS_{ti,j}/dt$ is the temporal variation of the entropy in the tissues indicated in Eq. (23) (the blood in the small vessels is already considered in the tissues). In Eq. (22), the subscript *ar* indicates arterial blood reservoir and *ve* indicates venous blood reservoir. $T_{ar,k}$, $T_{ar,k+1}$, $T_{ve,k}$ and $T_{ve,k+1}$ are the temperatures of the reservoir of the component j at instant k and $k+1$ and c_{bl} is the specific heat of the blood. In Eq. (23), i represents the tissue (skin, fat, muscle, etc), $T_{ti,k}$, $T_{ti,k+1}$ are the temperatures of the tissue i at instants k and $k+1$,respectively, and c_{ti} is the specific heat of the tissue.

$$\frac{dS_{bl,j}}{dt} = \frac{d}{dt}\left[m_{ar,j}c_{bl} ln\left(\frac{T_{ar,k+1}}{T_{ar,k}}\right) + m_{ve,j}c_{bl} ln\left(\frac{T_{ve,k+1}}{T_{ve,k}}\right)\right] \tag{19}$$

$$\frac{dS_{ti,j}}{dt} = \frac{d}{dt}\left[\sum_i m_{ti_i} c_{ti_i} ln\left(\frac{T_{ti_i,k+1}}{T_{ti_i,k}}\right)\right] \tag{20}$$

3. RESULTS AND DISCUSSION

Figures 3 and 4 indicate the energy and exergy transfer rates to the environment associated with radiation, convection, respiration and vaporization as a function of relative humidity, operative temperature, air temperature and mean radiant temperature.

The data obtained in Figure 3 resulted from energy analysis. The magnitude of the heat and mass transfer rates and flow rates to the environment is the same of the metabolism (energy conservation). But, a comparison with Figure 4 indicates that the exergy analysis gives additional information. The exergy transfer rate to environment is order of magnitude lower than the energy transfer rate (similar to Mady et al. (2012a) and Batato et al. (1990)) and the trend is different. This result indicates the additional information brought from the exergy analysis: the quality of the energy conversion process that takes place in the human body.

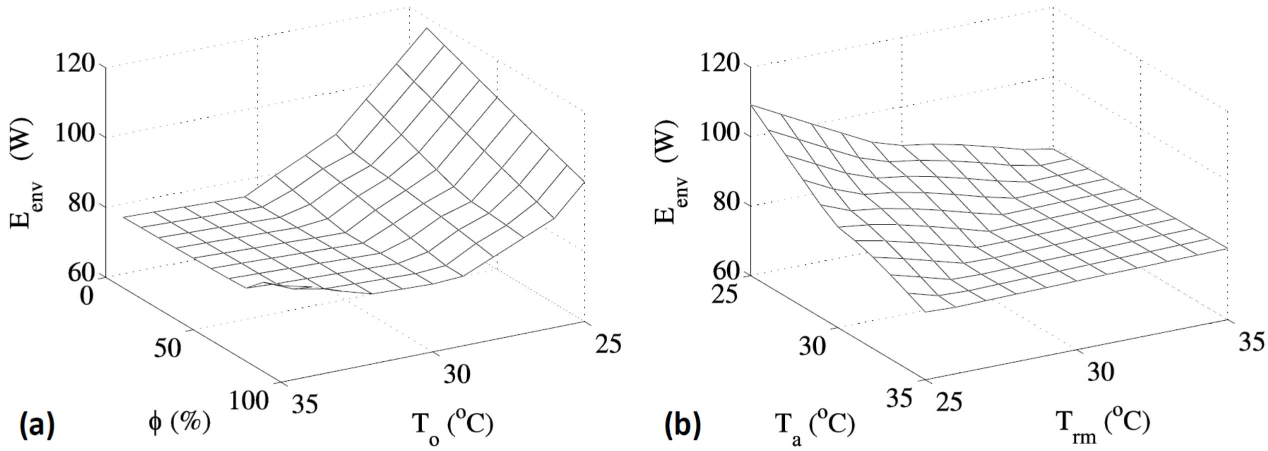

Figure 3. Energy transfer to the environment as a function of: (a) operative temperature and relative humidity, (b) air temperature and mean radiant temperature.

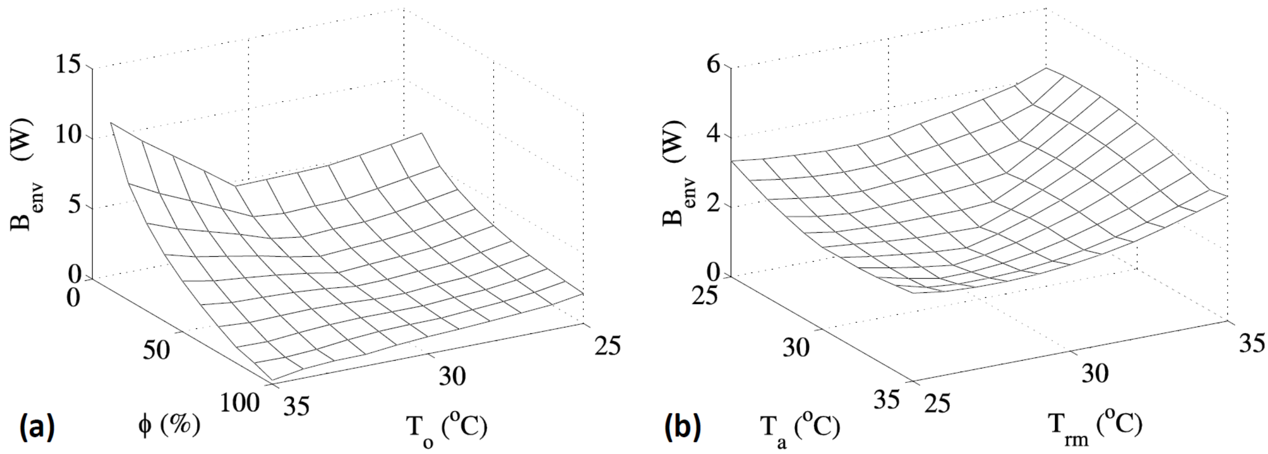

Figure 4. Exergy transfer to the environment as a function of: (a) operative temperature and relative humidity, (b) air temperature and mean radiant temperature.

Figure 5 (a) and (b) indicate B_{dest} and η_b as a function of mean radiant temperature and air temperature. Mady et al. (2012a) obtained a similar result of these quantities as a function of relative humidity and operative temperature. Their results indicate that the body destroys less exergy and is more efficient (from the exergy point of view) in higher temperatures and lower relative humidities. In Figure 5(a) the minimum destroyed exergy occur in higher mean radiant temperatures and lower air temperatures, moreover there is a diagonal (which features a line operative temperature close to 30^{o}C) from which there is a surface of minimum destroyed exergy. The exergy efficiency has a similar trend of the exergy transfer to environment, this last one dictates the exergy efficiency in basal conditions (Eq. (13) becomes $\eta=B_{env}/B_M$). The point of minimum exergy efficiency is for: T_a=32^{o}C and T_{rm}=28^{o}C (correspond to the point of minimum B_{env}) and the maximum exergy efficiency is in the same point of minimum exergy destruction (T_a=25^{o}C and T_{rm}=35^{o}C). Although it is not proven yet, Simone et al (2011) states that higher surface temperatures in combination with lower air temperatures lead to an improvement in thermal comfort conditions.

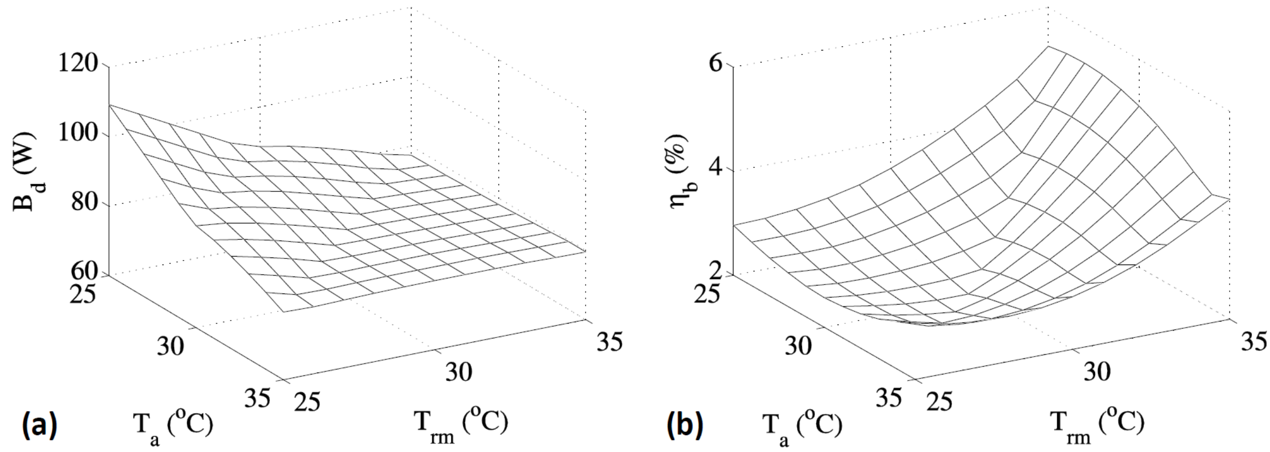

Figure 4. Destroyed exergy (a) and exergy efficiency (b), as a function of mean radiant temperate and air temperature.

4. CONCLUSIONS

The exergy analysis was applied to the human body aiming at establishing relations of the exergy destruction rate and exergy efficiency with environment conditions. Therefore a reference behavior for a healthy person under basal conditions was established. Based on the analyzed range of parameters one can conclude that exergy transfer to the environment has a different trend and order of magnitude than the energy transfer rate to envionment, indicating the quality of the energy transfer to the environment. Moreover, it was obtained that the human body is more efficient and destroys less exergy in lower air temperatures and higher mean radiant temperatures.

5. ACKNOWLEDGEMENTS

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