SECOND LAW OF THERMODYNAMICS AND HUMAN BODY

Carlos Eduardo Keutenedjian Mady, cekm@usp.br
Maurício Silva Ferreira, mausferreira@usp.br
Jurandir Itizo Yanagihara, jiy@usp.br
Polytechnic School of the University of São Paulo

Paulo Hilário Nascimento Saldiva, pepino@usp.br
Faculty of Medicine of University of São Paulo

Silvio de Oliveira Júnior, soj@usp.br
Polytechnic School of the University of São Paulo

Abstract. *In this work the Second Law of Thermodynamics was applied from the use of exergy analysis to account for exergy destruction (entropy production) and Second Law efficiency in human body under basal conditions. The thermal model of human body was divided in 15 cylinders with elliptical cross section (which generates a model with realistic dimensions) representing: head, neck, trunk, arms, forearms, hands, thighs, legs, and feet. For each cylinder a combination of some of the following tissues was considered: skin, fat, muscle, bone, brain, viscera, lung, and heart. The heat conduction equation with constant heat generation is solved for each cylinder. From this model it was possible to obtain heat and mass transfer to the environment through skin due to radiation, convection and evaporation, as well as mass fluxes due to respiration (difference of temperature and humidity of inspired and expired air). It was also possible to obtain the transitory response of body due to a variation on environment conditions (temperature dependence with time). The Second Law of Thermodynamics was applied through the use of exergy analysis. So, it was necessary to obtain the exergy fluxes due to heat and mass exchange on skin (radiation, convection and evaporation) and exergy transfer by respiration fluxes. Also, it was possible to calculate exergy variation (temperature dependence with time) of each compartment's tissue and blood whose sum leads to entropy variation of the body. Results indicate that, although entropy production decreases with aging, the second law efficiency also reduces, the energy contribution of heat and mass fluxes was considerable, but exergy contribution was poor. Simulations were carried out for different parts of the body. With the exception of the head and trunk all human parts have lower exergy contribution of metabolism than exergy destruction. Also, the exergy analysis was used as a tool to determine the constants of thermoregulatory system equation. The minimum exergy destruction and maximum second law efficiency led to the constant that resulted in similar behavior of experiments.*

Keywords*: Human Body; Exergy Destruction; Second Law efficiency; Aging*

1. INTRODUCTION

The exergy analysis is a combination of the First and Second Law of Thermodynamics. From the concept of destroyed exergy (or entropy production) it is possible to compute the irreversibilities associated with human body and these quantities are always greater or equal to zero.

One of the first authors that tried to describe life as a function of the physical quantity entropy was Schrödinger (1945). He claims that the body extracts negative entropy from the environment to compensate the entropy produced continually. He used the idea of statistical mechanics that relates entropy with the degree of order of the system to affirm that the organism absorbs continually order from the environment.

Prigogine and Wiame (1946) proposed a principle that a biological organism tends to progress to a state of minimum entropy production (minimum entropy production principle), their theory is based on the foundation that most of entropy production is related to metabolism. Because Second Law dictates the direction of increasing chronological time it is often referred to as "time's arrow".

Several authors performed experimental studies attempting to confirm the minimum entropy principle. Stoward (1962) studied the entropy production in bacterial culture. Zotin and Zotina (1967) examined different organism (from trout eggs to organism). Balmer (1982) studied the fish *Nothobranchius guentheri*, a species that lives in interment rivers of the East Africa and has the life cycle of 12 months. They all based the idea that most of entropy production is related to metabolism. Other authors, such as Aoki (1987, 1989, 1990, 1991), Rahman (2007), Silva and Annamalai (2008, 2009) analyzed the entropy generation over the lifespan and their results confirmed the minimum entropy principle. Batato et al. (1990) performed the exergy analysis and found that, although the energy losses to the environment are considerable, the exergy losses are very small and the Second Law efficiency is almost zero. Ferreira and Yanagihara (2009a) performed a similar analysis, but using a numerical model for the thermoregulatory system which leaded to similar results. Prek (2005, 2006) and Prek and Butala (2010) aiming to obtain the relation between exergy consumption and a combination of environment conditions with thermal comfort simulated a two node model of human body. Finally, Albuquerque Neto et al. (2010) propound models for the respiratory system and thermal system to perform the exergy analysis of the human body under physical activities.

The purpose of the present work is to apply the exergy analysis on the thermal model developed by Ferreira and Yanagihara (2009b). Most of the analysis in the literature involves the calculus of entropy production as function of lifespan, but not much has been talked about the Second Law efficiency as function of aging. The exergy analysis was applied as a function of environment parameters. Furthermore, the analysis was performed to investigate the experimental constants of the thermoregulatory system. The aim is to obtain a response for a set of specific anatomic parameters that is close to experimental results.

2. MODEL DESCRIPTION

The human thermal model developed by Ferreira and Yanagihara (2009b) is composed of the thermoregulatory and passive system. The first is related to physiological responses to changes in thermal environment or activity level: vasodilatation or constriction, shivering and sweating. The second includes heat conduction inside the body, heat transfer by convection because of the flowing blood and heat and mass transfer between the body and the environment.

As presented by Ferreira and Yanagihara (2009b), the global data of the anatomic model used are: height 1.76 m, weight 67 kg, surface 1.8 m^2 and volume of 0.0627 m^3. The human body was divided in 15 cylinders representing the head, neck, trunk, arms, forearms, hands, thighs, legs and feet which represent a model with realistic dimensions. Each cylinder has a combination of some of these tissues: skin, fat, muscle, bone, brain, viscera, lung and heart. With exception of the head and trunk, that have composition as function of the cross section, all cylinders have composition independent of the cross section.

The heat conduction equation with constant density and specific heat and internal heat generation (metabolism) is solved for each tissue. The numerical solution is achieved using a coordinate transformation which transforms an elliptical cylinder in Cartesian space in a parallelepiped in the new coordinate system. To calculate the heat transfer between tissues and blood it was necessary to divide vessels in two classes the small ones (that can be treated as part of continuum) and the big ones. The model is similar to the one 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 big vessels can be modeled as proposed by Wissler (1985), using two reservoirs, one of arterial blood and other of venous blood, with exception of the trunk that is modeled with only one reservoir. From this model it is possible to obtain heat and mass transfer to the environment through skin due to radiation, convection and evaporation, as well as mass fluxes due to respiration (difference of temperature and humidity of inspired and expired air). It is also possible to obtain the transitory response of body due to a variation on environment conditions (temperature dependence with time). A representation of the model is indicated on Fig.1.

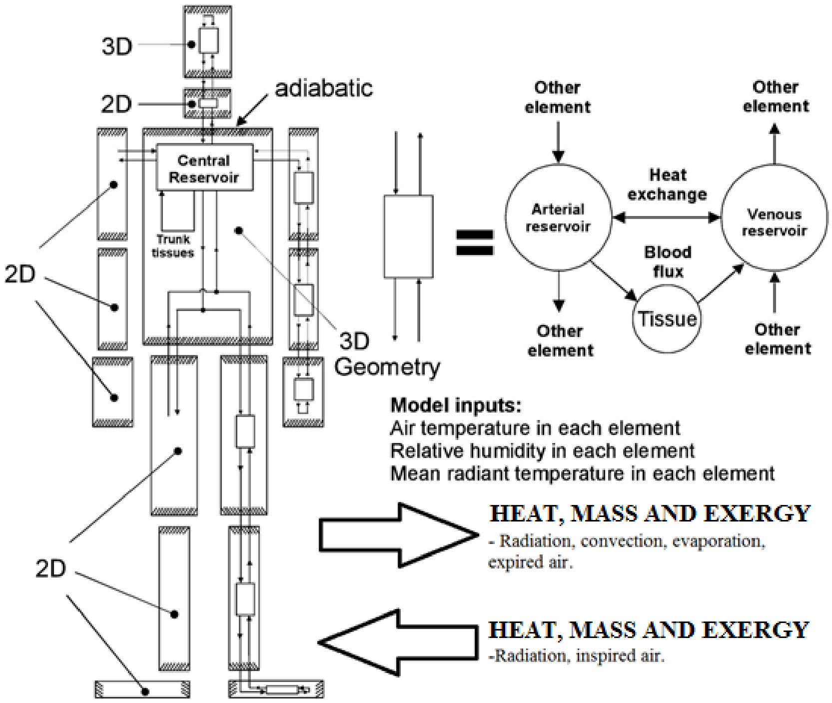

Figure 1. Overview of the passive system model, showing possible boundary conditions, geometry and circulatory system used in each segment. Adapted from Ferreira and Yanagihara (2009b)

To perform the simulations that correlate exergy destruction and age, an equation proposed by Harris and Benedict (1918) that correlates age, height and weight with metabolism was used for an adult man. For all other simulations the metabolism chosen was 79.1 W (middle aged person) originally used in Ferreira and Yanagihara (2009b). Table 1 indicates the results of metabolism as function of age. Ages lower than 18 years was not considered because the mode dimensions were fixes for an adult.

Table 1. Metabolism as function of age for men using Harris and Benedict (1918) equation

Age	M (W)	Age	M (W)
18	84.3	40	77.0
20	83.6	50	73.7
25	82.0	60	70.4
30	80.3	70	67.1

2.1. Thermoregulatory system

In Ferreira and Yanagihara (2009b) model, of thermoregulatory system comprises the mechanism of vasodilatation and constriction, shivering and sweating. Equation (1) is used for the vasomotor mechanism (variation of blood flow to the skin) and was proposed by Savage and Brengelmann (1996)

$$\Delta\omega_{sk} = k_1(T_{hy} - T_{hy,0}) + k_2(T_{sk} - T_{sk,0}) \tag{1}$$

where, $\Delta\omega_{sk}$ (m^3/(m^3.s)) is the skin blood perfusion rate variation ($814\text{x}10^{-6} \leq \Delta\omega_{sk} \leq 3345$ m^3/(m^3.s)), k_1 and k_2 are constants whose values are $1810\text{x}10^{-6}$ and $181\text{x}10^{-6}$ m^3/(m^3.s) respectively, T_{hy} and $T_{hy,0}$ (K) are the hypothalamus temperature and reference temperature (brain temperature in the model -), T_{sk} and $T_{sk,0}$ (K) are the skin temperature and reference temperature.

The equation proposed by Nadel et al. (1971) calculates the evaporation of sweat as indicated in Eq. (2).

$$E_{sw,i} = \left[k_3(T_{hy} - T_{hy,0}) + k_4(T_{sk} - T_{sk,0})\right]\exp\left(\frac{T_{sk,i} - T_{sk,0}}{10}\right) \tag{2}$$

where, $E_{sw,i}$ (W/m^2) is the evaporation of sweat in segment i, k_3 and k_4 are constants whose values are 197 and 23 W/(m^{2}K).

The Eq. (3) is similar to the one proposed by Gordon et al. (1976) and can be used to calculate the shivering.

$$M_{sh} = k_5(T_{hy} - T_{hy,0}) + k_6(T_{sk} - T_{sk,0}) + k_7\Delta Q \tag{3}$$

where, M_{sh} (W) is the change in the metabolism due to shivering ($0 \leq M_{sh} \leq 429$W), k_5, k_6 and k_7 are constants whose values are 250W/K, 40W/K and 0,06, and ΔQ (W) is the difference between heat lost through skin in any instant and in thermal neutrality.

2.2. Heat and mass transfer to the environment

Assuming symmetrical and uniform environments the heat transfer due to convection can be calculated as indicated in Eq. (4):

$$Q_c = Af_{cl}h_c(T_{cl} - T_a) \tag{4}$$

where, Q_c is the rate of heat transfer by convection in W, T_{cl} and T_a are the external surface temperature of the cloth and environment temperature in K, respectively, A is the body area in m^2, f_{cl} is the ratio between the surface area of the clothed segment and the nude one, and h_c is the convective heat transfer coefficient in W/(m^2 K) (Dear, et al., 1997).

The heat transfer due to radiation can be calculated as indicated by Eq. (5):

$$Q_r = Af_{cl}h_r(T_{cl} - \bar{T}_r) \tag{5}$$

where, Q_r is the rate of heat transfer by radiation in W, T_{cl} and $\overline{T}_r$ are the external surface of the cloth temperature and mean radiant temperature in K, respectively, and h_r is the linear radiant heat transfer coefficient (Dear, et al., 1997) in W/(m2 K).

If the person is naked, T_{cl} in Eq. (4) and (5) becomes the skin temperature (T_{sk}) and f_{cl} becomes equal to 1.

The combined effect of heat transfer due to radiation and convection can be calculated using Eq. (6).

$$Q_r + Q_c = \frac{T_{sk} - T_o}{R_{cl} + \dfrac{1}{f_{cl} h}} \tag{6}$$

where, T_o is the operative temperature (K), R_{cl} is the thermal resistance of the cloth (m^2K/W), and h is the combined heat transfer (convection + radiation) coefficient in the element in W/(m^2 K).

The enthalpy flow rate associated with evaporation at surface of each element can be calculated by Eq. (7).

$$E = A\omega \frac{P_{w,sk} - \phi_a P_{w,a}}{R_{e,cl} + \dfrac{1}{f_{cl} h_e}} \tag{7}$$

where, E is the enthalpy flow rate due to vapor mass fluxes trough skin in W, $P_{w,sk}$ is the water vapor pressure at the skin surface temperature, $P_{w,a}$ at the environment temperature (both in Pa), ω is the skin wettedness (varies from 0.06 when there is only water diffusion, to 1.0 when the skin is completely wetted by sweat), Ø (%) is the relative humidity of the air, $R_{e,cl}$ is the resistance to the evaporation imposed by clothes (m^2Pa/W), and h_e is the evaporative transfer coefficient of the element in W/(m^2Pa) (calculated from convective heat transfer coefficient using the analogy between heat and mass transfer).

The enthalpy flow rate to the environment due to respiration can be calculated by Eq. (8).

$$R_{res} = m_{res} c_{p,a} \left(T_{ex} - T_a\right) + m_{res}\left(\omega_{ex} h_w(T_{ex}) - \omega_a h_w(T_a)\right) \tag{8}$$

where, R_{res} is the enthalpy flow rates due to respiration in W, m_{res} is the pulmonary ventilation in kg/s, $c_{p,a}$ is the specific heat at constant pressure of the air in kJ/(kg.K), T_{ex} and T_a are the temperatures of the expired and inspired air, respectively, ω_{ex} and ω_a are the absolute humidity of expired and inspired air, respectively, and $h_{vap}(T_{ex})$ and $h_{vap}(T_a)$ are the vapor enthalpy at expired and air temperatures, respectively (kJ/kg).

As indicated by Fanger (1967), the pulmonary ventilation rate is directed related to the metabolic internal energy variation (M - metabolism) as indicated by Eq. (9).

$$m_{res} = 1{,}433.10^{-6} AM \tag{9}$$

The First Law of Thermodynamics (Eq. (10)) can be used to obtain the time dependent internal energy variation due to a transient environment conditions ($dU/dt|_{\Delta T}$) in W. Note that the total internal energy variation with time is $dU/dt=-M+ dU/dt|_{\Delta T}$.

$$\left.\frac{dU}{dt}\right|_{\Delta T} = M - W + Q_c + Q_r + E + R \tag{10}$$

2.3. Exergy analysis

The Exergy Analysis was applied on the control volume indicated in Figure 1. In order to develop the exergy balance it is necessary to have the environment/reference conditions such as temperature (T_a and T_0), pressure (P_a P_0) and relative humidity ($\emptyset_a$ and $\emptyset_0$). It is also necessary to know a time history of the temperature of the tissues and blood for all compartments nodes. The model was considered naked. Equation (11) indicates the exergy balance and Eq. (12) the application on human body. Note that dB/dt is the total variation rate of the exergy of the body and $dB/dt|_{\Delta T}$ is temperature dependent of the total variation of the body exergy, both in W.

$$\frac{dB}{dt} = \sum B_e - \sum B_s + \sum Q_i \left(1 - \frac{T_0}{T_i}\right) - W - B_{dest} \tag{11}$$

$$B_{dest} = B_c + B_r + B_E + B_{res} + \left(B_M - \left.\frac{dB}{dt}\right|_{\Delta T}\right) - W \tag{12}$$

where, B_{dest} is the rate of exergy destruction, B_M is the metabolic exergy rate, W is the work done by the body, B_{Qr}, B_{Qc}, B_E and B_R are exergy contribution of radiation, convection, evaporation and respiration respectively, all and $dB/dt|_{\Delta T}$ is the temporal variation of the exergy of the body. All magnitudes are in W.

Batato et al. (1990) achieved that the metabolic internal energy and the metabolic exergy are very close (difference below 3%). So, the approximation $B_M \approx M$ can be used. It is important to note that metabolic exergy constitutes a part of dB/dt.

Equation (13), indicate the exergy associated with heat exchange with the environment due to radiation. In Eq. (13), T_{sk} is the skin temperature (K).

$$B_r = Q_r \left(1 - \frac{T_0}{T_{sk}}\right) \tag{13}$$

The exergy contribution of convection can be calculated as indicated by Eq. (14).

$$B_c = Q_c \left(1 - \frac{T_0}{T_{sk}}\right) \tag{14}$$

The vapor diffusion through skin can be calculated by the Eq. (15). The First term of this equation is related to vaporization of the sweat on the skin, the second term is related to the difference in the concentration of saturated vapor near the skin and the concentration of the vapor in the environment.

$$B_E = -\left(m_w\left(h_{fg} - T_0 s_{fg}\right) + m_w R_w T_0 \ln\left(\frac{P_{w,sk}}{P_{w,0}}\right)\right) \tag{15}$$

where, m_w is the mass flow rate of water evaporated and diffused through skin, h_{fg} and s_{fg} are the enthalpy and entropy of vaporization respectively, R_w universal gas constant of water in kJ/(kgK), $P_{w,sk}$ and $P_{w,0}$ are the partial pressure of water vapor at skin temperature and at the environment respectively, both in Pa.

The exergy associated with the respiration can be calculated from Eq. (16), and due to the inspired and expired air fluxes. This equation was divided in two, one related to the dry air (Eq. (17)) and the other related to the water (Eq. (18)). Note that the second term in both equations becomes zero if the adopted reference is equivalent to the environment conditions. In Eq. (18) $c_{p,w}$ is the specific heat of the vapor in kJ/(kgK) and R_a universal gas constant of the air in kJ/(kgK).

$$B_R = -\left(\sum \dot{m}_s b_s - \sum \dot{m}_e b_e\right) = -\left(\Delta B_a - \Delta B_w\right) \tag{16}$$

$$\begin{aligned}\Delta B_a = {} & m_{res}\left[c_{p,air}\left(T_{ex} - T_0 - T_0 \ln\left(\frac{T_{ex}}{T_0}\right)\right) + R_a T_0 \ln\left(\frac{P_{a,ex}}{P_{a,0}}\right)\right] - \\ & m_{res}\left[c_{p,air}\left(T_a - T_0 - T_0 \ln\left(\frac{T_a}{T_0}\right)\right) + R_a T_0 \ln\left(\frac{P_{a,air}}{P_{a,0}}\right)\right]\end{aligned} \tag{17}$$

$$\Delta B_w = m_{res}\omega_{ex}\left[c_{p,w}\left(T_{ex} - T_0 - T_0 \ln\left(\frac{T_{ex}}{T_0}\right)\right) + R_w T_0 \ln\left(\frac{P_{w,ex}}{P_{w,0}}\right)\right] - m_{res}\omega_a\left[c_{p,w}\left(T_a - T_0 - T_0 \ln\left(\frac{T_a}{T_0}\right)\right) + R_w T_0 \ln\left(\frac{P_{w,a}}{P_{w,0}}\right)\right] \quad (18)$$

The time variation of the exergy can be calculated as indicated by Eq. (19), with the hypothesis of no volume variation of the model. The first term is the temporal variation of the internal energy and can be calculated from Eq. (7). The second is the temporal variation of the body entropy and can be calculated from each element (hand, arm, forearm, etc) as indicated on Eq. (20).

$$\left.\frac{dB}{dt}\right|_{\Delta T} = \left.\frac{dU}{dt}\right|_{\Delta T} - T_0 \left.\frac{dS}{dt}\right|_{\Delta T} \quad (19)$$

$$\left.\frac{dS}{dt}\right|_{\Delta T} = \sum_j \frac{dS_{element,j}}{dt} = \sum_j \left(\frac{dS_{bl}}{dt} + \frac{dS_{tissue}}{dt}\right) \quad (20)$$

where, dS_{bl}/dt is the temporal variation of entropy in the blood compartment (Eq. (21)) and dS_{tissue}/dt is the time variation of the entropy in the tissues (the blood in the small vessels are considered in the tissues), both in W/mK.

Equation (21) gives the entropy variation on the blood reservoirs, where the subscript *ar* indicates arterial 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 *j* in the instant *k* and *k+1* and c_{bl} is the specific heat of the blood.

$$\frac{dS_{bl}}{dt} = \frac{d}{dt}\left[m_{ar,j}c_{bl}\ln\left(\frac{T_{ar,k+1}}{T_{ar,k}}\right) + m_{ve,j}c_{bl}\ln\left(\frac{T_{ve,k+1}}{T_{ve,k}}\right)\right] \quad (21)$$

Equation (22) gives the entropy variation on the tissue *i* (skin, fat muscle, etc), $T_{tissue,k}$, $T_{tissue,k+1}$ are the temperatures of the tissue *i* in instants *k* and *k+1* respectively and c_{tissue} is the specific heat of the tissue.

$$\frac{dS_{tissue}}{dt} = \frac{d}{dt}\left[\sum_i m_{tissue_i} c_{tissue_i} \ln\left(\frac{T_{tissue_i,k+1}}{T_{tissue_i,k}}\right)\right] \quad (22)$$

Using Gibbs relations for each compartment, it is possible to obtain Eq. (23) that should result in similar values of Eq. (20), but with the only necessity to calculate the mean temperature (T_m) of the element (hand, arm, forearm, etc).

$$\left.\frac{dS}{dt}\right|_{\Delta T} = \frac{\left.dU/dt\right|_{\Delta T}}{T_m} \quad (23)$$

The Second Law Efficiency (η) can be calculated as indicated by Eq. (24)

$$\eta = \frac{B_M - B_{dest}}{B_M} \quad (24)$$

3. RESULTS AND DISCUSSION

To simulate conditions different than thermal neutrality in the model, it is necessary to know the thermal neutrality temperature (T_n) for each age (metabolism). According to ASHRAE (1993), the range of operative temperature from 29 to 31°C provides a thermal neutral condition. Figure 2 indicates the calculated T_n (for each metabolism) as a function of age, for relative humidity of 50% and air current of 0.15m/s. The nude model was considered in stand up position. This figure indicates that the lowest value of thermal neutrality is on the maximum metabolism (18 years) and it tends to increase over the life.

The principle of minimum entropy generation is valid for an adult (in this case the destroyed exergy - B_{dest}) as indicated by other authors. The Second Law efficiency (η) also tends to decrease over the lifespan (Fig. 3). Therefore, the maximum exergy destruction was obtained for 18 year old men. The environment conditions considered were: 32°C and ϕ=70%.

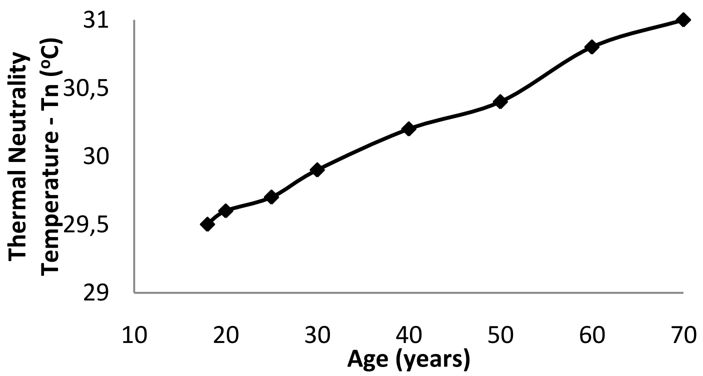

Figure 2. Thermal neutrality temperature as function of age

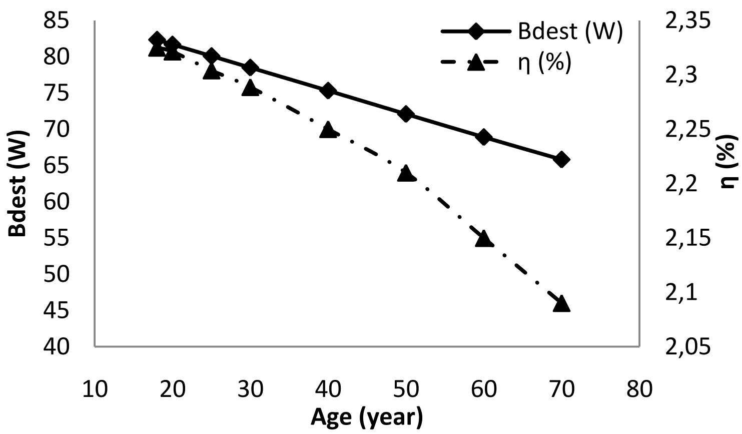

Figure 3. B_{dest} and η as function of lifespan. The environment condition adopted was:32°C and ϕ=70%

For an adult middle aged man (metabolism of 79.1W), the thermal neutrality temperature is 30°C as indicated by Ferreira and Yanagihara (2009b). Results presented in Tab. 2 confirns Batato et al. (1990) and Ferreira and Yanagihara (2009a) results that although the energetic contribution of radiation, convection, evaporation and respiration are large, the exergy contribution is almost negligible. Exergy data showed in Tab. 3 indicate that, for the neutrality condition, with the exception of trunk and head, all parts of human body destroy more exergy than produce, nevertheless, the sum indicates that the hole body produce more exergy than destroy (which is a expected result).

Table 2. Difference of the contribution of the energy and exergy fluxes (thermal neutrality)

	(W)		(W)
Q_r	29.0	B_{Qr}	0.35
Q_c	23.2	B_{Qc}	0.27
E	19.7	B_E	1.26
R	7.2	B_R	0.15

Table 3. Each member contribution on the exergy metabolism and exergy destruction (thermal neutrality)

	B_{dest} (W)	B_M (W)		B_{dest} (W)	B_M (W)
Hand	1.4	0.3	Thigh	7.6	2.9
Arm	2.3	0.5	Head	6.7	15.2
Forearm	3.3	0.9	Neck	2.7	0.5
Foot	2.4	0.5	Trunk	24.9	50.7
Leg	4.5	1.3	Total	77.2	79.1

The exergy analysis can be a powerful tool in adjusting the constants of Eq. (1) to (3), which are determined or from experimental results (whose values are hard to find and are specific to a person) or from methods to adjust these constants to the specific anatomic characteristics of the model. Figures 4 to 6 indicate the exergy destruction and Second Law efficiency as function of the thermoregulatory system. In Fig. (4), for a temperature of 30°C, the constants of vasomotor mechanism do not affect significantly the total of exergy destruction, but it is clear that the constant used in the model are close to the minimum of exergy destruction and close to maximum of exergy efficiency, which is indicated in (a) and (b) by an arrow.

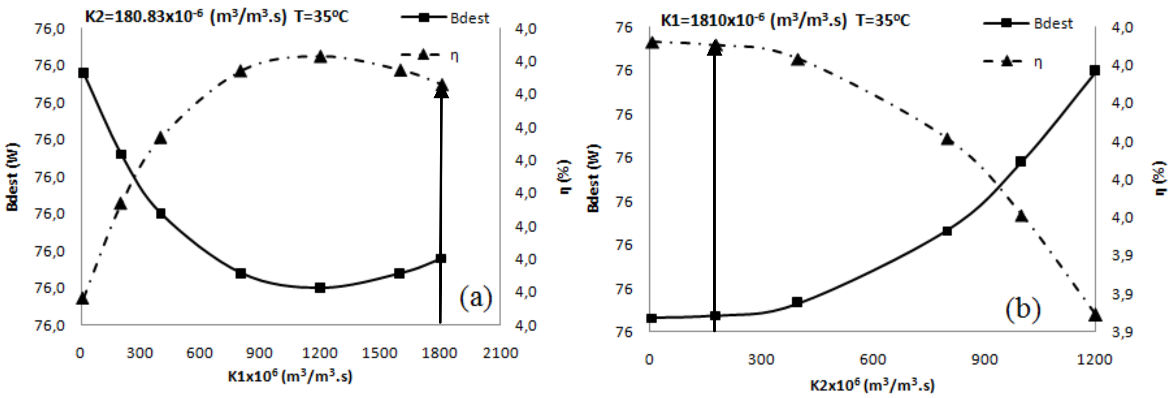

Figure 4. Exergy destruction and exergy efficiency as function of constants k_1 and k_2

In Fig. (5) the effects of the constants in total exergy destruction are poor, but the model constants values are at the minimum values of exergy destruction in Fig. (5-a) and close to the minimum in Fig. (5-b). Furthermore, the exergy efficiency is maximum for the model constants in Fig. (5-a), and close to the maximum in Fig. (5-b). So, the model constants (which gives results close to experimental results) leads to (or close to) the minimum exergy destruction and maximum second law efficiency.

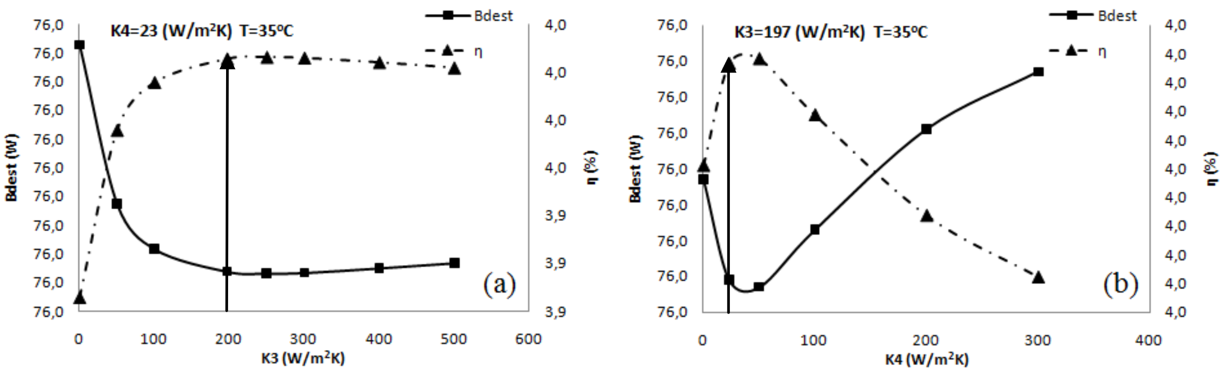

Figure 5. Exergy destruction and exergy efficiency as function of constants k_3 and k_4

Finally, the increase in the metabolism own to shivering has different effect on exergy analysis and the effect is more evident. The environment temperature chosen was 20°C (lower to thermal neutrality to exist the shivering). In Fig. 6 (a-c) the model constants are near the minimum of exergy destruction, but also the minimum of exergy efficiency, This is an expected result because an increasing in metabolism comes with an increasing of exergy destruction and on Second Law efficiency.

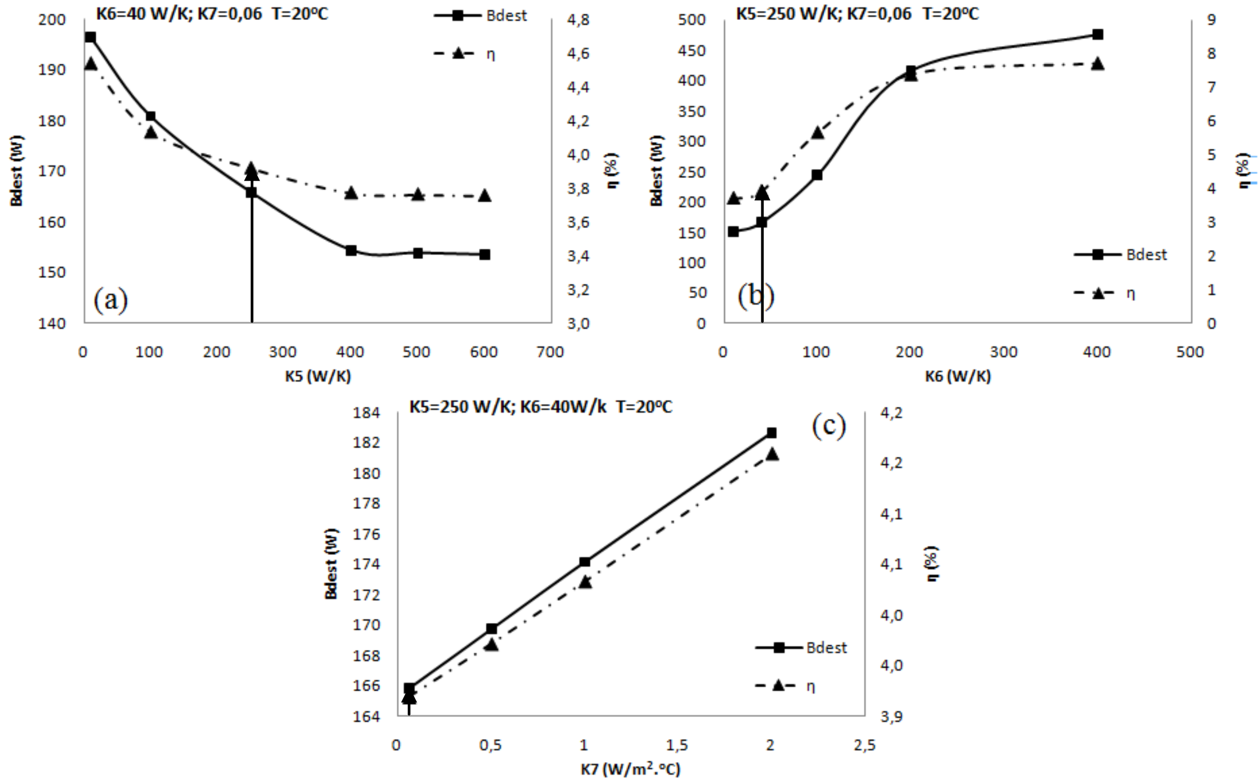

Figure 6. Exergy destruction and exergy efficiency as function of constants k_5, k_6 and k_7

4. CONCLUSIONS

In this work a thermal model was used to analyze the exergy behavior of the body. From the range analyzed it is possible to conclude that:

- The thermal neutrality temperature of a person is a function of age, and the minimum values occur when at the time of life that the person has the larger metabolism (18 years old). For an adult the temperature of neutrality tends to increase with life.
- The theory of minimum entropy production is confirmed for an adult, the Second Law efficiency also decreases during lifespan. Both quantities achieve the maximum value at the age of 18 years old.
- The energy contribution of heat and mass fluxes are relevant, although the exergy fluxes are almost negligible. Furthermore, with the exception of trunk and head, where the most of metabolic reaction occur, all the human parts destroy more exergy than their exergy metabolism.
- The exergy analysis can be used as a tool to determine the constants of the thermoregulatory system for specific anatomic condition. Destroyed exergy and Second Law efficiency indicate the results that leads to thermal response close to experiments in patients, even though the effect is not elevated the method indicates the point a possible parameter to choose. So, the model constants (which give results close to experimental results) lead to the minimum of exergy destruction.

5. ACKNOWLEDGEMENTS

The first author acknowledges FAPESP (São Paulo Research Foundation) for his grant 09/17578-0.

6. REFERENCES

Albuquerque Neto, C., Pellegrini, L.F., Ferreira, M.S., Oliveira Jr, S., Yanagihara, J.I., 2010, “Exergy Analysis of Human Respiration Under Physical Activity”, International Journal of Thermodynamics, Vol. 13, No. 3, pp. 105-109.

Aoki, I., 1987, “Entropy balance of white-tailed deer during a winter night”, Bulletin of Mathematical Biology, Vol. 49, No. 3, pp. 321-327

Aoki, I., 1989, “Entropy Flow and Entropy Production in the Human Body in Basal Conditions”, Journal of Theoretical Biology, Vol. 141, No. 1, pp. 11-21.

Aoki, I., 1990a, “Effects of Exercise and Chills on Entropy Production in Human Body”, Journal of Theoretical Biology, Vol. 145, No. 3, pp. 421-428.

Aoki, I., 1991, “Entropy Principle for Human Development, Growth and Aging”, Journal of Theoretical Biology, Vol. 150, No. 2, pp. 215-223.

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1993, Physiological principles and thermal comfort, in: Handbook of Fundamentals, Atlanta, chapter 8, pp.1–29, Atlanta.

Balmer, R.T., 1982, “Entropy and Aging in Biological Systems”, Chemical Engineering Communications, Vol. 17, No. 1, pp. 171-181.

Batato, M., Borel, L., Deriaz, O. and Jequier, E., 1990, “Analyse Exergétique Théorique et Expérimentale du Corps Humain”, Entropie, Vol. 26, No. 153/154, pp. 120-130.

Dear, J.D., Arens, E., Hui, Z. and Oguro, M., 1997, “Convective and Radiative Heat Transfer Coefficients for Individual Human Body Segments”, International Journal of Biometeorology, Vol. 40, No. 3, pp. 141–156.

Fanger, P.O., 1967, “Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation”, ASHRAE Transactions, Vol. 73, No. 2, p. III.4.1-20.

Ferreira, M.S. and Yanagihara, J.I., 2001, “Unsteady Heat Conduction in 3D Elliptical Cylinders”, International Communications in Heat and Mass Transfer, Vol. 28, No. 7, pp. 963–972.

Ferreira, M.S. and Yanagihara, J.I., 2009a, “Exergy Analysis of the Human Thermal System”, 2nd Brazilian Meeting of Biomechanical Engineering, Florianópolis, Brazil. (In Portuguese).

Ferreira, M.S. and Yanagihara, J.I., 2009b, “A Transient Three-Dimensional Heat Transfer Model of the Human Body”, International Communications in Heat and Mass Transfer, Vol. 36, No. 7, pp. 718–724.

Gordon, R.G., Roemer, R.B. and Horvath, S.M., 1976, “A Mathematical Model of the Human Temperature Regulatory System — Transient Cold Exposure Response”, IEEE Transactions on Biomedical Engineering, Vol. 23, No. 6, pp. 434–444.

Harris, J.A. and Benedict, F.G, 1918, “A Biometric Study of Human Basal Metabolism”, Proceedings of the National Academy of Sciences of the United States of America, Vol. 4, No. 12, pp. 370-373 .

Nadel, E.R., Bullard, R.W. and Stolwijk, J.A.J., 1971, “Importance of Skin Temperature in the Regulation of Sweating”, Journal of Applied Physiology, Vol. 31, No. 1, pp. 80–87.

Pennes, H.H., 1948, “Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm”, Journal of Applied Physiology, Vol. 1, No. 2, pp. 93–122.

Prek, M., 2005, “Thermodynamic Analysis of Human Heat and Mass Transfer and Their Impact on Thermal Comfort”, International Journal of Heat and Mass Transfer, Vol. 48, pp. 731-739.

Prek, M., 2006, “Thermodynamical Analysis of Human Thermal Comfort”, Energy, Vol. 31, No. 5, pp. 732-743.

Prek, M. and Butala, V., 2010, “Principles of Exergy Analysis of Human Heat and Mass Exchange with the Indoor Environment”, International Journal of Heat and Mass Transfer, Vol. 48, pp. 731-739.

Prigogine. I. and Wiame. J., 1946, “Biologic et Thermodynamique des Phenomenes Irreversibles”, Experimentia, Vol. 2, No. 11, pp. 451-453.

Rahman, M.A., 2007, “A Novel Method for Estimating Entropy Generation Rate in Human Body”, Thermal Science, Vol. 11, No. 1, pp. 75-92.

Savage, M.V. and Bregelmann, G.L., 1996, “Control of Skin Blood Flow in the Neutral Zone of Human Body Temperature Regulation”, Journal of Applied Physiology, Vol. 80, No. 4, pp. 1249–1257.

Schördinger, E., 1944, “What is life? The Physical Aspects of Living Cell”, Ed. Cambridge University Press, Cambridge, UK.

Silva, C. and Annamalai, K., 2008, “Entropy Generation and Human Aging: Lifespan Entropy and Effect of Physical Activity Level”, Entropy, Vol. 10, No. 2, pp. 100-123.

Silva, C. and Annamalai, K., 2009, “Entropy Generation and Human Aging: Lifespan Entropy and Effect of Diet Composition and Caloric Restriction Diets”, Journal of Thermodynamics, Vol. 2009, pp. 1-10.

Stoward. P.J., 1962, “Thermodynamics of Biological Growth”, Nature, Vol. 194, No. 4832, pp. 977-978.

Wissler, E.H, in: Shitzer, A. and Eberhart, R.C. (Eds.), 1985, “Mathematical Simulation of Human Thermal Behavior Using Hole Body Models” Heat Transfer in Medicine and Biology, Analysis and Applications, Vol. 1, Ed. Plenum Press, New York, U.S, pp. 325-373.

Zotin, A.I. and Zotina, R.S., 1967, “Thermodynamics Aspects of Developmental Biology”, Journal of Theoretical Biology, Vol. 17, No. 1, pp. 57-75.

7. RESPONSIBILITY NOTICE

The authors are the only responsibles for the printed material included in this paper.