

HUMAN BODY EXERGY ANALYSIS AS A FUNCTION OF BODY FAT AND MUSCLE PERCENTAGE. APPLICATIONS TO THERMAL COMFORT CONDITIONS

Matheus Martinez Garcia, m147395@dac.unicamp.br¹

Silvio de Oliveira Junior, soj@usp.br²

Carlos Eduardo Keutenedjian Mady, cekmady@fem.unicamp.br¹

¹University of Campinas, Faculty of Mechanical Engineering, Mandelleyev St., 200, 13083-970 Campinas – SP, Brazil

²Polytechnic School of University of São Paulo, Av. Luciano Gualberto 380, 05508-010, São Paulo, Brazil

Abstract: This paper's objective is to describe the relation between exergy analysis, human body constitution and thermal comfort indicators. The human body was assumed to be a cylinder with four layers: core, which contains all the organs, muscle, fat and skin. This model also takes into account the blood perfusion and some thermoregulation effects. The choice of a cylindrical model is due the facility to change the tissue proportions, since it is not necessary to know how this tissues spread in the human body. For every set of environmental temperature and humidity, the energy and exergy balances were solved, and the thermal comfort indicators calculated by using expressions from literature. Besides varying the environment conditions, the human body constitution changed during the simulations. The results obtained indicates that there is a linear relation between the thermal sensation scale and the exergy destruction for cold environments, and that the muscle is the tissue that most interfere in this sensations.

Keywords: Exergy analysis, Human thermal model, Thermal comfort conditions

1. NOMENCLATURE

Nomenclature

\dot{n}	Molar Flow Rate
\dot{B}_m	Exergy Metabolism
M	Energy Metabolism
σ	Stefan-Boltzmann constant
ε	Skin Emissivity
A	Area
B	Exergy
c_p	Specific heat
f	Human Body Shape Factor
H	Enthalpy
h_c	Convection Coefficient
h_e	Evaporative Coefficient
h_{lv}	Enthalpy of Vaporization of Water
I	Thermal Load
k	Thermal conductivity
L	Cylinder Height
m	Mass
PMV	Predicted Mean Vote
PPD	Predicted Percent Dissatisfied
Q	Heat
$q_{i \rightarrow j}$	Heat Flow Rate from i to j
QR	Respiratory Coefficient
R	Gas Constant
s_{lv}	Entropy of Vaporization of Water
T	Temperature
t	Time
V	Volume
v	Velocity
W	Work
w	Blood perfusion rate

Greek Symbols

ω	Air Humidity
ϕ	Relative Humidity
ρ	Density

Subscripts and Superscripts

0	Thermal Neutrality Condition
∞	Environment
b	Blood
bas	Basal
$carb$	Carbohydrate
$cons$	Consumed
$conv$	Convection
d	Destroyed
e	Evaporative
exp	Expired
$insp$	Inspired
lip	Lipid
M	Metabolic
mus	Muscle Layer
$prod$	Produced
$prot$	Protein
rad	Radiation
t	Tissue
v	Vapour

2. INTRODUCTION

The application of exergy analysis in the human body have already generated some interesting results. For example, in Batato *et al.* (1990), this analysis indicated that the heat exchanges with environment are essential in modeling, while the exergy transfer to the environment is negligible. Prek (2004), Prek (2006) and Prek and Butala (2010) obtained that the minimum exergy destruction is obtained only for a combination of environmental conditions, using a two layer body model. Mady *et al.* (2012) showed that the human body destroys less exergy in higher temperatures and lower humidities. Mady *et al.* (2014) proposes that the minimum exergy destruction corresponds to thermal comfort conditions for some environments, while in others it is necessary to combine the exergy destruction with the exergy transfer to environment to obtain the comfort conditions. Outside the thermal comfort area, Mady (2013) related the exergy analysis with physical exercises, evaluation of hypothermia techniques and modeling a cell with cancer.

This article is situated in the thermal comfort area, and its objective is to describe the relation observed between the human body exergy destruction and the literature known thermal comfort indicators, for some selected body constitutions. The idea was to study how environment, combined with specific tissue properties, as the high metabolism of muscle, or the insulating characteristic of fat, affects the exergy destruction and the way that the human body feels it by means of the Predicted Mean Vote and Predicted Percentage of Dissatisfied, available in ASHRAE (2005) and proposed by Fanger (1967).

3. MODEL DESCRIPTION

In this work, the human thermal model is based on Ferreira (1997) and Mady (2013). The human body is treated as cylinder with four layers, which are, from inner to outer: core, muscle, fat and skin. The thermal properties of the layers are calculated from data available in Ferreira (1997), with the experimental results found in Werner and Buse (1988), but using the Nadler *et al.* (1962) equation to obtain the standard man blood volume. These properties are in Tab. 1. It is important to discuss that each layer has its own metabolism, hence, there must be some difference in the thermal comfort conditions if there is a modification in the proportion of tissues (the most relevant are fat and muscle, as indicated in Tab. 1). The blood metabolism is null due to the use of Pennes (1948) perfusion model. It is assumed that its value was included in the tissue metabolisms.

To simulate the different tissue constitutions, it is considered that the core remains always the same. It means that the organs volume does not change with the geometry, resulting in a core radius of 6.078 cm. Besides that, the skin thickness is considered always the same, 0.28 cm. The cylinder height is maintained at 1.76 m. The percentage of fat and muscle will be varied aiming at obtaining relations between thermal comfort conditions and destroyed exergy.

Table 1: Layers and Blood Properties obtained in Ferreira (1997)

Layer	ρ (kg/m ³)	\dot{M}_{bas}''' (W/m ³)	k (W/m.K)	c_p (kJ/kg.K)	$w \cdot 10^6$ (m _b ³ /m _t ³ .s)
Core	1035	2629	0.5038	2.679	4157.5
Muscle	1006	684	0.5100	3.800	542.5
Fat	853	368	0.2100	2.300	76.7
Skin	1006	368	0.4700	3.680	361.7
Blood	1059	0	0.4700	3.850	-

3.1 Energy and Exergy Balances

Figure 1 indicates a model with a schematic representation of the human body, where it is indicated the heat transfer rate and mass flow rates associated with radiation (Q_{rad}), convection (Q_{conv}), vaporization (H_e), respiration ($H_{exp} - H_{\infty}$), food intake, food wastes, water intake and urine. 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.

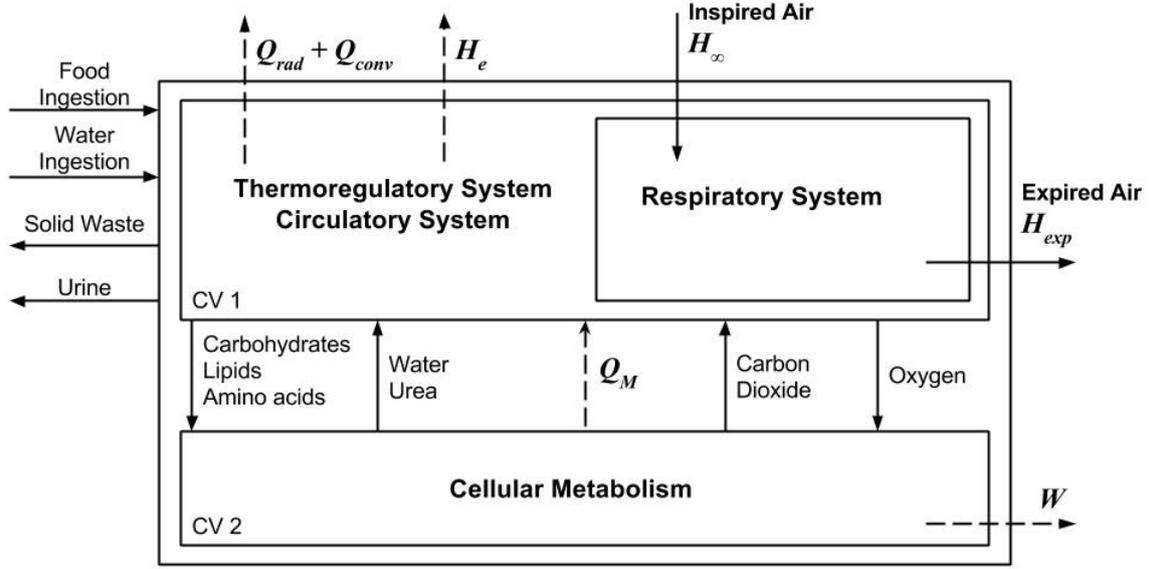


Figure 1: Human Body Schematic Heat and Enthalpy Exchanges

As shown in Mady (2013), the human body energy balance results in Eq.1, and the exergy balance results in Eq.2.

$$\frac{dU}{dt} = \dot{M} + \dot{H}_{\infty} - \dot{H}_{exp} - \dot{H}_e - \dot{Q}_{conv} - \dot{Q}_{rad} - \dot{W} \quad (1)$$

$$\dot{B}_{dest} = \dot{B}_m - \frac{dB}{dt} + \dot{B}_{\infty} - \dot{B}_{exp} - \dot{B}_e - \dot{B}_{conv} - \dot{B}_{rad} - \dot{W} \quad (2)$$

3.1.1 Cellular Respiration

One possible way to obtain the energy and the exergy metabolisms is by using the enthalpy variation and the exergy variation of the nutrients consumed during the cellular respiration. First, it is necessary to define these terms and Thermodynamic properties. The glucose was chosen as representative of the carbohydrates, an amino acid with average composition, calculated by Mady (2013), was chosen to represent the proteins and the palmitic acid was chosen to represent the lipids. From the enthalpy variation and exergy variation of the reactions of oxidation, as they occur in the body (physiological conditions, which are approximated to 298.15 K, 1 atm, $pH = 7$ and $pMg = 3$), it was obtained Tab.2.

Table 2: Enthalpy and Exergy variations in oxidation reactions, as they occur in the body

Nutrients	Δh (kJ/kg)	Δb (kJ/kg)
Glucose	-15594	-15956
Amino-acid	-17598	-17578
Palmitic Acid	-39020	-38281

The energy and exergy metabolisms are defined as the Eq.3 and Eq.4, respectively.

$$\dot{M} = -(\dot{m}_{carb}\Delta h_{carb} + \dot{m}_{prot}\Delta h_{prot} + \dot{m}_{lip}\Delta h_{lip}) \quad (3)$$

$$\dot{B}_m = -(\dot{m}_{carb}\Delta b_{carb} + \dot{m}_{prot}\Delta b_{prot} + \dot{m}_{lip}\Delta b_{lip}) \quad (4)$$

As seen in Tab.1, each layer has a basal metabolic rate. It implies that, by knowing the human body constitution, its possible to calculate the basal energy metabolism by using Eq.5.

$$\dot{M}_{bas} = V_{core}\dot{M}_{bas,core}''' + V_{mus}\dot{M}_{bas,mus}''' + V_{fat}\dot{M}_{bas,fat}''' + V_{skin}\dot{M}_{bas,skin}''' \quad (5)$$

Applying the hypothesis made by Diener (1997), that there is a daily excretion of 12 g of nitrogen in urea from proteins oxidation, and using the respiratory coefficient, defined as Eq.6, value of 0.83 (according to ASHRAE (2005) this value is representative for daily activities), it is possible to relate the energy metabolism calculation by Eq.3 and Eq.5, obtaining the nutrients consumption by the model. Eventually it becomes possible the application of Eq.4 to obtain the exergy variation of the reactions of oxidation (exergy metabolism). Moreover, it is possible to evaluate the respiration properly considering the effect of each component of the air and its modifications by the respiration.

$$QR = \frac{\dot{V}_{CO_2,prod}}{\dot{V}_{O_2,cons}} \approx \frac{\dot{n}_{CO_2,prod}}{\dot{n}_{O_2,cons}} \quad (6)$$

3.1.2 Energy transfer to environment

To obtain the convection heat transfer rate, it is used the convective coefficient calculated from the data obtained by Seppanen *et al.* (1972), extracted from ASHRAE (2005). This coefficient should be used for a person standing in an environment with circulating air, and follows in Eq.7. In this article the constant coefficient was chosen, since the human body is treated as being naked and in the standard anatomical position, in an environment without significant air circulation ($v_{air} < 0.15$ m/s). This conditions are very close to equation requirements.

$$h_c = \begin{cases} 14.8v_{air}^{0.69}, & 0.15 < v_{air} < 1.5 \\ 4, & 0 < v_{air} < 0.15 \end{cases} \quad (7)$$

The convection heat transfer rate is calculated by Eq.8.

$$\dot{Q}_{conv} = h_c A_{skin} (T_{skin} - T_{\infty}) \quad (8)$$

To calculate the radiation heat transfer rate, the skin is modeled with a constant emissivity, $\varepsilon = 0.9$, taken from Werner and Buse (1988). It is also necessary to consider a shape factor, since not all parts of the body exchanges heat to the environment by radiation. This factor, $f = 0.78$, to the standard anatomical position was obtained by Yang (1989). The mean radiant temperature is considered to be equal to the air temperature.

The radiation heat is calculated as Eq.9.

$$\dot{Q}_{rad} = f\varepsilon\sigma A_{skin} (T_{skin}^4 - T_{\infty}^4) \quad (9)$$

Gagge *et al.* (1971) demonstrated that the evaporation coefficient is related with the convective coefficient by the Eq.10.

$$\frac{h_e}{h_c} = 1.65 \cdot 10^{-2} \quad (10)$$

Without the presence of sweating, the skin has a water diffusion equivalent of 6% of its surface wet. The evaporative enthalpy flow rate then is given by Eq.11. Note that the sweat term has a maximum value, when all the skin surface is wet. The Eq.12 shows the range of this term.

$$\dot{H}_e = 0.06h_e A_{skin} (p_{v,skin} - p_{v,\infty}) + \dot{H}_{sweat} \quad (11)$$

$$0 \leq \dot{H}_{sweat} \leq 0.94h_e A_{skin} (p_{v,skin} - p_{v,\infty}) \quad (12)$$

To calculate the enthalpy variation due to respiration it is necessary first to obtain the air mass flow rate entering the lungs, which according to Fanger (1967), can be calculated by Eq.13.

$$\dot{m}_{air} = 1.433 \cdot 10^{-6} M \quad (13)$$

Furthermore defining the mass flow rate entering the lungs, it is necessary to obtain the temperature and humidity of the air leaving the human body. The Eq.14 and the Eq.15 are used for it, and were obtained by McCutchan and Taylor (1951).

$$T_{exp} = 32.6 + 0.066T_{\infty} + 32\omega_{\infty} \quad (14)$$

$$\omega_{exp} = 0.0277 + 6.5 \cdot 10^{-5} T_{\infty} + 0.2\omega_{\infty} \quad (15)$$

Considering the composition of dry air entering the lungs equal to atmospheric, and using the ideal gas model, it is possible to obtain the enthalpy flow rate of each element entering the human body. By using the oxidation reactions, it is obtained the molar flow rate variations due to cellular respiration, and, consecutively, the mass flow rates leaving the body. It is considered on dry air composition only N_2 , O_2 , Ar e CO_2 .

The enthalpy variation due to respiration is then given by Eq.16. Note that the total air mass leaving the lungs is higher than the air entering the lungs. It is important highlight that, for oxygen, carbon dioxide and water vapor, it is necessary to use the reference of $298K$ to calculate the enthalpies, since the enthalpy of formation of this elements were obtained at this temperature, and used to calculate the energy metabolism. In the case of water, the enthalpy at $298K$ used is the one corresponding to liquid.

$$\Delta \dot{H}_{resp} = \dot{H}_{exp} - \dot{H}_{\infty} = \sum_{i=1}^5 [\dot{m}_{i,exp}(h_{i,exp} - h_{i,298}) - \dot{m}_{i,insp}(h_{i,\infty} - h_{i,298})] \quad (16)$$

3.1.3 Exergy transfer to the environment

To calculate the exergy transfer to the environment, the reference state is considered the actual environment. The exergy transfer associated with convection and radiation can be evaluated by Eq.17 and Eq.18.

$$\dot{B}_{conv} = \left(1 - \frac{T_{\infty}}{T_{skin}}\right) \dot{Q}_{conv} \quad (17)$$

$$\dot{B}_{rad} = \left(1 - \frac{T_{\infty}}{T_{skin}}\right) \dot{Q}_{rad} \quad (18)$$

The evaporative exergy flow rate to environment is given by Eq.19.

$$\dot{B}_e = \dot{m}_e \left[h_{lv} - T_{\infty} s_{lv} + T_{\infty} R_v \ln \left(\frac{p_{v,skin}}{p_{v,\infty}} \right) \right] \quad (19)$$

The exergy variation of the air due to respiration can be found by using the Eq.20. Note that, by using the environment conditions as reference, $B_{\infty} = 0$.

$$\dot{B}_{exp} = \sum_{i=1}^5 \dot{m}_i \left[c_{p,i} \left(T_i - T_{\infty} - T_{\infty} \ln \left(\frac{T_i}{T_{\infty}} \right) \right) + T_{\infty} R_i \ln \left(\frac{p_{exp,i}}{p_{\infty,i}} \right) \right] \quad (20)$$

3.2 Control System

To develop a control system to human body, first it is necessary to define a reference. The reference adopted is called thermal neutrality conditions, and it is obtained by submitting the model to an environment with $T_{\infty} = 30^{\circ}C$ and $\phi = 50\%$. To obtain the constants of the control systems Mady (2013) demonstrated that they are related with minimum values of destroyed exergy and maximum exergy efficiency. As demonstrated by Ferreira (1997) these constant returns the thermal behavior of the human thermal model similar to real subjects.

To sweat control mechanism, Eq.21, taken from Nadel *et al.* (1971), was chosen. The constants, $K_1 = 197W/m^2K$ and $K_2 = 23W/m^2K$, were taken from Mady (2013).

$$\dot{H}_{sweat} = A_{skin} [K_1(\bar{T}_{core} - \bar{T}_{core}^0) + K_2(\bar{T}_{skinsurf} - \bar{T}_{skinsurf}^0)] \quad (21)$$

To model the vasoconstriction and vasodilation it is used the Eq.22, taken from Savage and Brengelmann (1996). This equation calculates the perfusion rate variation in skin layer, based on the core and skin surface temperatures. The constants, $K_3 = 1810.10^{-6}s^{-1}$ and $K_4 = 181.10^{-6}s^{-1}$ were, once again, taken from Mady (2013).

$$\Delta w = K_3(\bar{T}_{core} - \bar{T}_{core}^0) + K_4(\bar{T}_{skinsurf} - \bar{T}_{skinsurf}^0) \quad (22)$$

The model of shivering used was taken from Gordon *et al.* (1976), and the Eq.23 is used to calculate the muscle layer metabolism variation due the shivering. The constants, $K_5 = 250W/K$, $K_6 = 40W/K$ and $K_7 = 0.06$, were taken from Mady (2013). The ΔQ term represents the difference between the heat lost by the skin surface for the actual condition and for the thermal neutrality condition.

$$\Delta M = K_5(\bar{T}_{core} - \bar{T}_{core}^0) + K_6(\bar{T}_{skinsurf} - \bar{T}_{skinsurf}^0) + K_7 \Delta Q \quad (23)$$

3.3 Solution method

To simulate the human thermal model, an algorithm was implemented in C++ , where the energy and exergy balances were solved for 3 different kinds of simulation. In the first one, it had been chosen a constant fat mass of 15 kg, and the total body mass was picked as 70, 80 and 90 kg. In the second, it had been chosen a constant body mass of 80 kg, and the fat mass was considered as 8, 12 and 16 kg. In the last simulations, the muscle mass had been chosen as 30 kg, and the body mass, once again, varied between 70 and 90 kg. For each case of simulation, the temperature was varied between 25 and 35 °C, and, for each temperature, the relative humidity was varied between 10 % and 100 %.

To use the majority of equations cited in this paper it is necessary to obtain the model temperature profile. This project considers that each layer has a constant temperature. This approximation was validated by Mady (2013).

According to Pennes (1948) model of perfusion, the heat exchange between blood and tissue is given by Eq.24. Hence the small vessels are treated as a part of a continuum.

$$q_{b \rightarrow t} = \rho_b w_t V_t c_{p,b} (T_b - T_t) \quad (24)$$

Solving the blood energy balance, considering that there is one central reservoir to represent the big vessels which receives venous blood fro the entire body and returns to the rest of the arterial blood. Hence, Eq.25 is obtained.

$$V_b \frac{dT_b}{dt} = \sum_{i=1}^4 V_i w_i (T_i - T_b) \quad (25)$$

Equation 25 requires the knowledge of the human body blood volume. To predict this volume, Eq.26, obtained by Nadler *et al.* (1962), is used.

$$V_b = (0.3669L^3 + 0.03219m + 0.6041)10^{-3} \quad (26)$$

The energy balance in core results in Eq.27. Note that the enthalpy variation due to respiration is considered equally distributed in all core volume.

$$\rho_{core} V_{core} c_{p,core} \frac{dT_{core}}{dt} = -q_{core \rightarrow mus} + q_{b \rightarrow core} + \dot{M}_{core}''' V_{core} - \Delta \dot{H}_{resp} \quad (27)$$

Solving the same balance to muscle layer, Eq.28 is obtained.

$$\rho_{mus} V_{mus} c_{p,mus} \frac{dT_{mus}}{dt} = q_{core \rightarrow mus} - q_{mus \rightarrow fat} + q_{b \rightarrow mus} + \dot{M}_{mus}''' V_{mus} \quad (28)$$

The energy balance solved for the fat layer is similar to this balance for muscle layer. It follows in Eq.29.

$$\rho_{fat} V_{fat} c_{p,fat} \frac{dT_{fat}}{dt} = q_{mus \rightarrow fat} - q_{fat \rightarrow skin} + q_{b \rightarrow fat} + \dot{M}_{fat}''' V_{fat} \quad (29)$$

The energy balance for skin is represented in Eq.30.

$$\rho_{skin} V_{skin} c_{p,skin} \frac{dT_{skin}}{dt} = q_{fat \rightarrow skin} + q_{b \rightarrow skin} + \dot{M}_{skin}''' V_{skin} - \dot{Q}_{conv} - \dot{Q}_{rad} - \dot{H}_e \quad (30)$$

3.4 Thermal Comfort Indicators

To predict the thermal comfort conditions it is used the Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) indices, developed by Fanger (1970), obtained from ASHRAE (2005). This indices are calculated by Eq.31 and Eq.32, respectively. The thermal load, I , in Eq.31, represents the difference between the heat production (metabolism) and the heat lost to environment, considering the body in the thermal neutrality conditions.

$$PMV = [0.303e^{-0.036M} + 0.028]I \quad (31)$$

$$PPD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (32)$$

The PMV uses the ASHRAE thermal sensation scale to measure the body sensation. Therefore, if $PMV = 3$, the thermal sensation is “hot”, if $PMV = 0$, the thermal sensation is “neutral”, and ,finally, if $PMV = -3$, the thermal sensation is “cold”. The intermediate values represent thermal conditions such as “slightly warm”, or “slightly cool”.

4. RESULTS

Figure 2 indicates the values of $PMV \times B_d$, and, for every case studied, this graph had the same slope. To illustrate this similarity, it was chosen the condition where $m = 80$ kg and $m_{fat} = 8$ kg (Fig.2). In Figure 2b, each line represents the trend for a given ϕ (relative humidity). Observing the Fig.2b, it is possible to discuss that the $PMV \times B_d$ almost does not change with ϕ , especially when $PMV < 0$. It indicates that, for cold environments, the graphic can be approximated by one single straight line. This is useful because, besides obtaining a simple way to find the relation between B_d and PMV , it avoids the visual pollution in simultaneous plots (such as Fig.2b). A linear regression of all points of the cold area were used to obtain the graphics that follow. When $PMV > 0$, a simple linear regression do not represent properly the relation of the exergy destruction and the predicted mean vote, since B_d does not change significantly with relative humidities in hot environments (only for high temperatures and low relative humidities, as obtained by Mady *et al.* (2014), which can also be observed in Fig.2b). To analyze this area another exergy index may be proposed. The exergy transfer to environment or the exergy efficiency are possible choices to find this relation, as indicated in Mady *et al.* (2014). In this article, the focus will be given to the cold side of ASHRAE's scale.

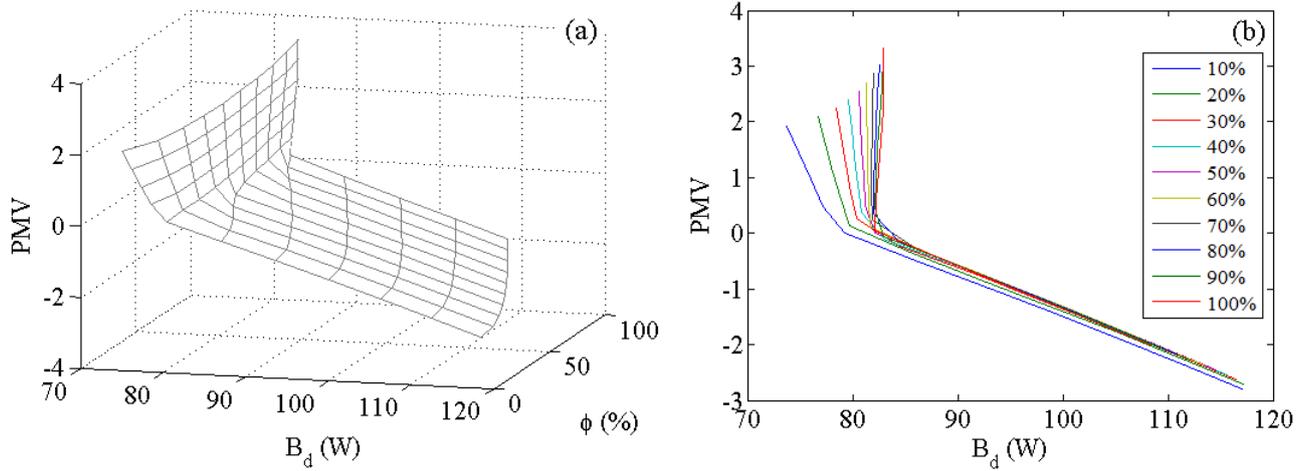


Figure 2: $PMV \times B_d$ for $m = 80$ kg and $m_{fat} = 8$ kg. (a): with an axis for relative humidity (ϕ), (b):with one curve for each ϕ simulated

Figure 3 represents the results obtained for a muscle mass equal to 30 kg. Analyzing Fig.3a, it is possible to conclude that for the same B_d , the PMV increases with the mass, but, when $PMV = 0$, the destroyed exergys are not the same. This implies that the variation of exergy destruction, $B_d - B_d^0$, is a better way to compare the results than the absolute values of B_d , since this variation indicates how far the body is from thermal neutrality conditions, showing the exergy destruction caused by the control system operation.

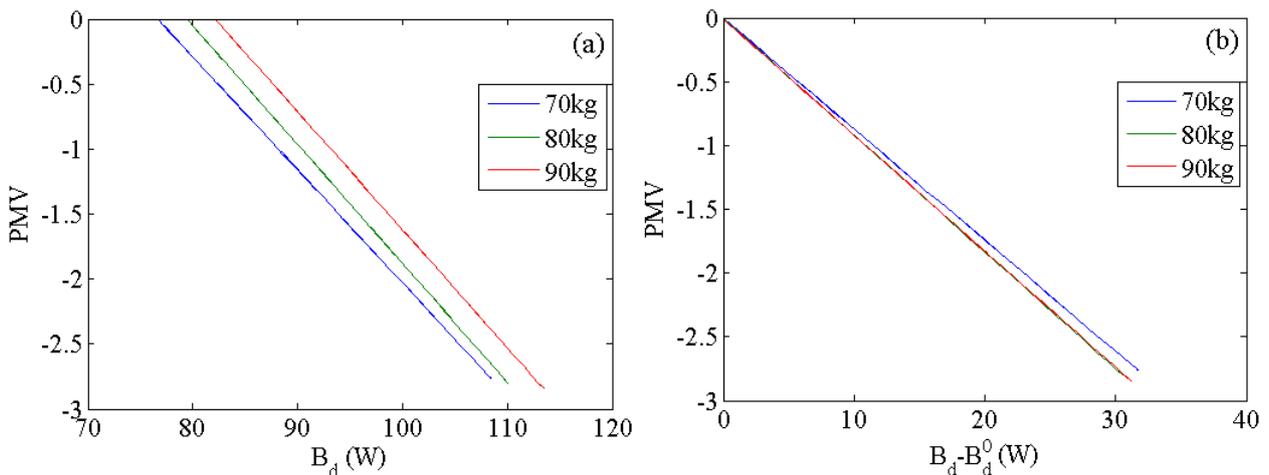


Figure 3: Results for $m_{muscle} = 30$ kg and m varying between 70 and 90 kg. (a): $PMV \times B_d$, (b): $PMV \times B_d - B_d^0$

Once $B_d - B_d^0$ was chosen to be related with PMV , analysing Fig.3b, a person with 70 kg would be closer to thermal comfort conditions than a person with 80 kg or 90 kg for the same variation of exergy destruction, which is an unexpected result, since it was thought that a person with more fat would be less susceptible to environment conditions. In fact, as the PMV uses an index based on integers, all the votes would be the same, in most of the cases. It is important to note that after a body mass between 70 kg and 80 kg, varying the mass maintaining the muscle fixed does not affect how the body

interacts with the environment.

Figure 4 represents the results obtained by keeping the fat mass at 15kg . By keeping the fat mass fixed, increasing the body mass is almost the same than increasing the muscle mass.

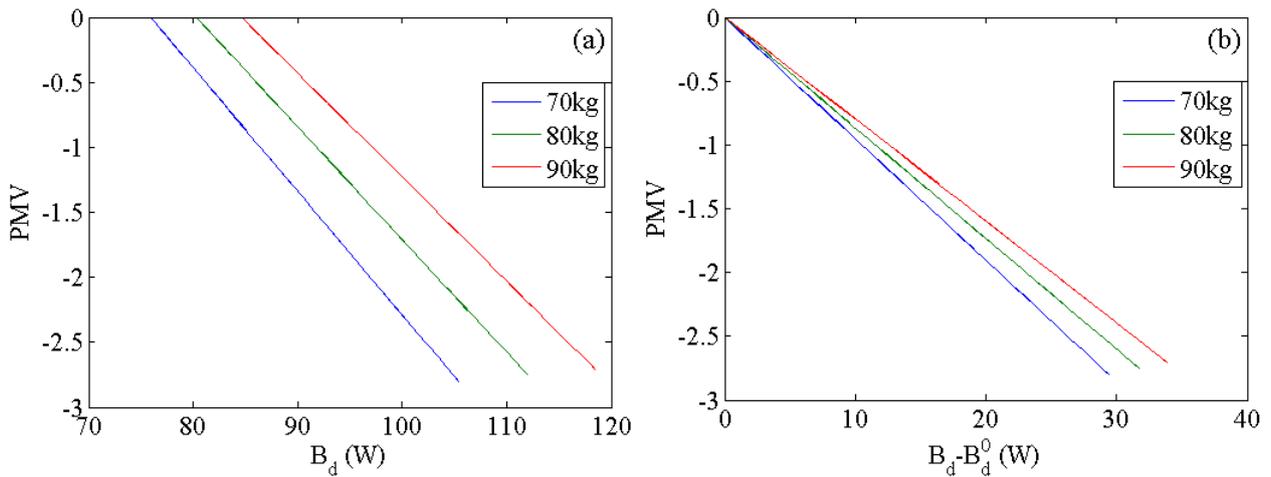


Figure 4: Results for $m_{fat} = 15\text{ kg}$ and m varying between 70 and 90 kg. (a): $PMV \times B_d$, (b): $PMV \times B_d - B_d^0$

In Fig.4b, it is notable that for the same variation of exergy destruction, the body with higher mass (and, consecutively, higher muscle mass), will be closer to thermal comfort for the same environmental conditions. Considering the same PMV, the exergy destruction variation is higher for higher masses. It means that a body with more muscle mass would have to be submitted to a place that activates more shivering to feel the same thermal sensation that a lean person, which are environments with lower temperatures.

Figure 5 indicates the results of $PMV \times B_d$ and $PMV \times B_d - B_d^0$ for a constant mass of 80kg , with different distributions of fat masses. By fixing the body mass, increasing fat amount implicates in reducing muscle mass. The results shown in Fig.5b follows the same principle from Fig.4b: for the same variation of exergy destruction, the body with lower fat mass will be closer to thermal comfort conditions than the ones with more fat, and, for the same PMV, the body with higher muscle mass (lower fat mass) has higher values of destroyed exergy.

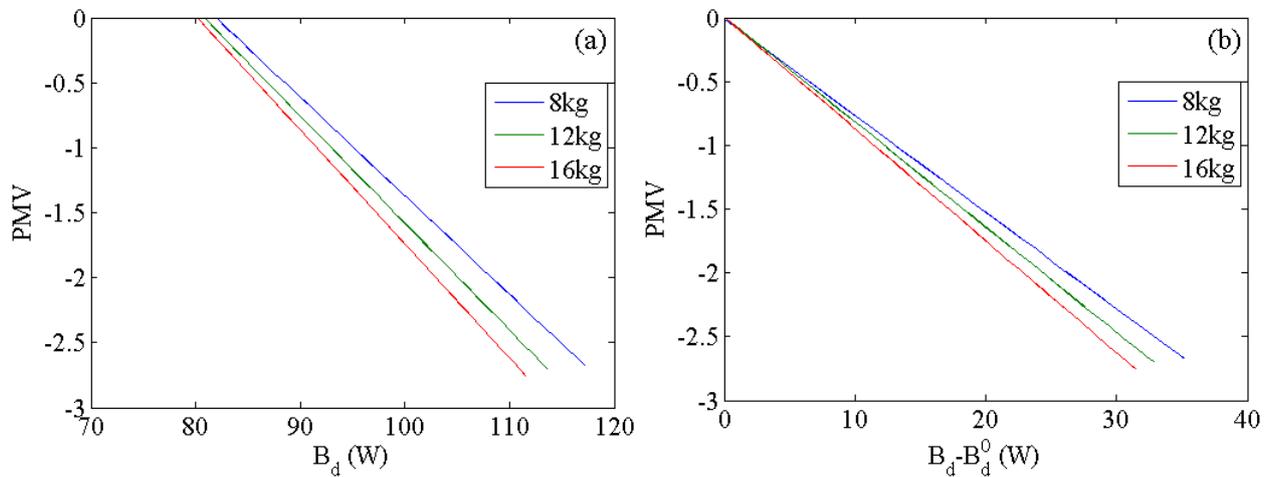


Figure 5: Results for $m = 80\text{ kg}$ and m_{fat} varying between 8 and 16 %. (a): $PMV \times B_d$, (b): $PMV \times B_d - B_d^0$

5. CONCLUSION

Literature analysis indicates that several authors performed the exergy analysis to the human body aiming at obtaining correlations of points of minimum B_d with thermal comfort conditions. A distinguished feature of this analysis is the modification of the person anatomy (fat mass and muscle) and the proposition of the exergy index $B_d - B_d^0$. From the range analyzed, it was possible to conclude that:

- It was confirmed the relation between exergy destruction and thermal comfort for cold environments. Working on this relation turns possible to use the exergy destruction as a thermal comfort indicator, when the body is subjected to temperatures lower than 30°C .
- For environments which may result in $PMV > 0$, there is no apparent relation between thermal comfort and exergy destruction. In this case, another thermodynamic property should be used as a thermal comfort indicator.

- Bodies with higher percentage of muscle are less susceptible to cold environments, since this tissue has a great influence in body metabolism.
- After some amount of fat, this tissue does not affect how a person feels the environment. In cold areas muscle has much more influence in the thermal sensation than fat.

6. ACKNOWLEDGEMENTS

The first and last authors acknowledge FAPESP (State of São Paulo Research Foundation) for the grant 2015/10034-5.

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