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Exergy Analysis of Human Respiration under Physical Activity*

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Abstract

This paper presents an exergy analysis of the human body under physical activity. A model of the respiratory system and a model of the thermal system were used for this purpose. These models consider heat and mass transfers in lungs, tissues and blood. Each component of these models is represented by a uniform compartment governed by equations for diffusion, convection, O_2 consumption, CO_2/heat generation and heat and mass transfer with the environment. The models allow the calculation of the exergy destruction in the lung and tissues, and the contribution of each entropy generation mechanism in the total generation. Furthermore, a discussion is proposed regarding the efficiency of the human body under physical exercise.

Keywords: *Thermoregulation, respiration physiology, bio-tr'ansport, exergy analysis.*

1. Introduction

When the human body is under physical activity, several mechanisms change their behavior in order to perform muscular work. The main source of energy is the metabolic oxidation of carbohydrates, which generates heat and carbon dioxide. Two physiological systems have a direct engagement in those processes. One is the respiratory system and the other is the thermoregulatory system. The former accounts for oxygen availability and carbon dioxide elimination, and the latter for the balance between internal heat generation and heat loss to the environment. Both systems have regulation mechanisms to support their tasks.

The application of exergy analysis in the human body has been carried out by various researchers. The pioneer work was carried out by Batato et al. (1990), which analyzed a human thermal system at rest. They were concerned about the relation between the exergy contribution of the metabolism and the environment heat losses. Another example is the work by Prek (2005 &2006), which is also similar to the previous one since it evaluates the thermal system, but aiming at the relations between exergy consumption and indoor thermal comfort. The author developed a model that comprised a physiological part based on the two-node model and a physical model describing the heat and mass transfer properties of clothing to simulate the thermoregulatory system. In both works, Batato et al (1990) and Prek (2005&2006), the control volume enclosed the whole body, in order to evaluate the heat and mass transfer between the body and the environment. Ferreira and Yanagihara (2009a) also developed an exergy analysis of the human body, considering a more rigorous model for the thermoregulatory system. It is worth mentioning that none of these works dealt with the way in which energy conversion processes take place inside the human body.

Recently, Lems (2009) presented an exergy analysis for different energy conversion processes of living systems, including cells metabolism and photosynthesis. The work presents a very detailed methodology to calculate the exergy of the different streams involved in the biochemical processes. The results obtained account for efficiencies up to 60% considering the conversion of carbon fuels into ATP (Adenosine-triphosphate) in living cells. However, the way in which this ATP is used was not considered.

The present paper aims at evaluating the exergy performance of the human respiratory system under physical activity. In this sense, the analysis involves the rate at which oxygen is supplied to the lungs and transported by the blood to the tissues, and the rate of CO_2.elimination. The exergy analysis presented here is based on results generated by models of the human respiratory and thermal systems previously developed in the Laboratory of Energy and Thermal Engineering of the University of São Paulo. Those are respectively the model by Albuquerque-Neto et al. (2008), and a simplification of the model by Ferreira and Yanagihara (2009b).

2. Thermal System Model Description

The mathematical model of the human thermal system used here is based on the complete model of Ferreira and Yanagihara (2009b), with some simplifications. The human body is divided into seven segments: head, trunk, abdomen, arms and legs. The tissues with common characteristics of each segment are represented as compartments. Those are skin, fat, muscle, bone (except for the abdomen), brain (only in the head), lung (only in the trunk), and viscera (only in the abdomen). The segments are connected by blood flow. The blood volume is divided into large and small vessels. The small vessels are considered a continuum. The large vessels are represented as an arterial and a venous compartment inside each segment. The blood gets inside a segment and follows to the arterial compartment. Then, a fraction of the blood follows to the next segment. The other fraction follows to the tissue

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compartment. Leaving the tissues, the blood follows to the venous compartment, which also receives blood from the next segment. In the trunk; the blood that flows through the lung comes from the venous to the arterial compartment. Figure 1 shows a general description of the human geometry. It contains the disposition of the segments, and the blood flow inside them.

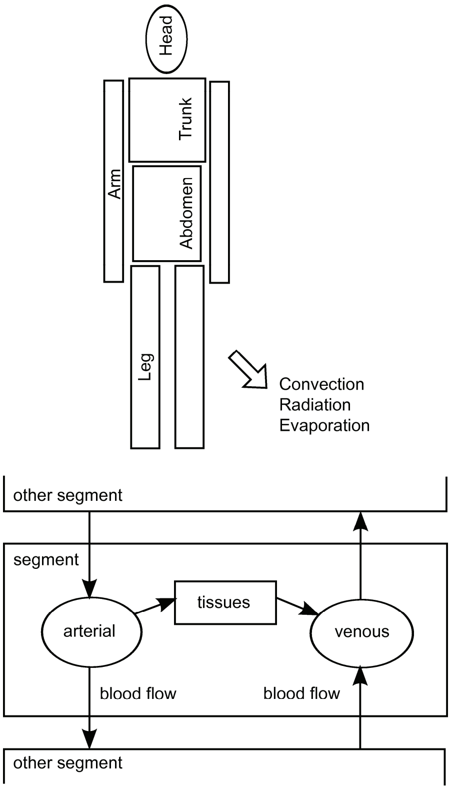

Figure 1. Thermal system representation.

Radial heat conduction is considered in each segment. Heat transfer between blood and tissue, and metabolic heat generation are also included in the model. Heat exchange by convection, radiation and evaporation are considered at the skin surface. The body temperature regulation includes variations in the skin blood flow and sweat. When the body is under physical activity, the muscle internal energy variation and blood flow rise. The model allows the determination of the temperature inside all blood and tissues compartments. The environment conditions (operating temperature, humidity and altitude) and the physical activity are set as model inputs. They may vary with time.

3. Respiratory System Description

The mathematical model of the human respiratory system used herein was developed by Albuquerque-Neto et al. (2008). In this model, the human body is also represented by compartments. The model does not take into account the same tissue distribution of the thermal model. It is focused on the lung representation. The model considers the exchange of oxygen O_2 and carbon dioxide CO_2 in the human body. The places where those gases are present are divided into compartments. A description of the model is given in Figure 2.

The air inside the lung alveolus is represented by the alveolar compartment. The flow through this compartment is the alveolar ventilation. It is the result of the inspiration and expiration mechanisms. The pulmonary capillaries are represented by a series of blood compartments. Venous blood enters the first compartment and flows through them exchanging gases with the alveolar compartment by diffusion.

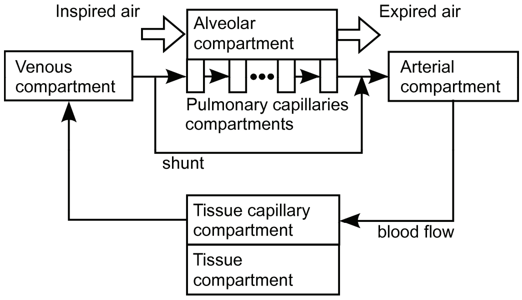

Figure 2. Respiratory system representation.

The blood inside the large vessels is represented by two compartments, arterial and venous. The arterial compartment receives blood from the lung, and also a smaller fraction of venous shunted blood. Then, the blood follows to the small vessels, which are connected to the tissues by diffusion. In the tissues, oxygen is consumed and carbon dioxide is generated by the metabolism. Leaving the small vessels, the blood follows to the venous compartment and returns to the lung.

The O_2 and CO_2 are transported by the blood and tissues dissolved and chemically reacted. Around 98% of the total O_2 is transported chemically associated to erythrocytes, while 2% is diluted in the plasma. As for the CO_2, 70% is transported as bicarbonate ion, 23% associated to erythrocytes and 7% diluted in the plasma. Several equations are used to relate the gases concentration with their corresponding partial pressures.

The ventilation, the cardiac output and the lung diffusion coefficient depend on the physical activity. They are related to the oxygen consumption rate.

With this model, it is possible to calculate the volumetric concentration and the partial pressure of the oxygen and carbon dioxide in all the compartments. The fraction of the gases in the ambient air, the altitude and the level of physical activity are set as model inputs.

4. Exergy Analysis

Two control volumes were defined for the exergy analysis as seen in Figure 3. The first control volume (CV_1) includes the lung, the arterial compartment and the venous compartment. Across the control volume boundary, there are flow of blood, which comes from the tissue outlet and goes into the tissue entrance, and air flow, a consequence of inspiration and expiration.

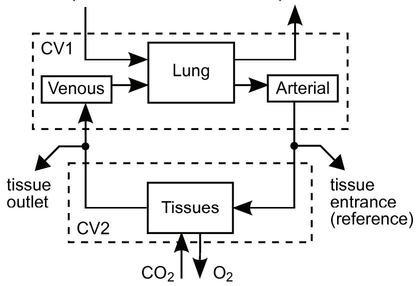

Figure 3. Control volume definition.

The second control volume (CV_2) includes the blood in the small vessels and in the tissues. Blood flows across the control volume boundary. It comes from the arterial compartment and goes to the venous compartment. The tissue metabolism is represented by oxygen and carbon dioxide flow across the boundary. The purpose of this simplification is to disregard the complexity of the metabolic chemical reactions. Hence, the energy conversion due to the oxidation of carbon fuels inside the cells is characterized by exergy difference between the inlet oxygen and outlet carbon dioxide streams in the tissues.

In order to develop an exergy balance, it is required that data for temperature, pressure and composition of each stream are available, as well as mass flowrates. The respiratory system model allows the determination of the oxygen and carbon dioxide partial pressure and the volumetric concentration in all the places across the boundaries: inspiration and expiration air, tissue entrance and tissue outlet blood, and tissues. The thermal system model permits the determination of the temperature in all those points. Furthermore, to calculate the exergy of each stream, a reference state must be set. In this paper, the thermodynamic state of the blood, O_2 and CO_2 at the tissue entrance is defined as the reference state (Figure 3).

For the exergy analysis, some simplifications were adopted. The blood is considered to be an ideal mixture of liquid and two ideal gases (CO_2 and O_2). Thus, the exergy associated to different ways in which O_2 and CO_2 are chemically combined in the blood are not taken into consideration. These simplifications allow calculating the exergy of O_2 and CO_2 using specific heats and respective gas constants (R_{O2} and R_{CO2}). As for the liquid part, the influence of pressure on the exergy value is considered negligible. As the reference state is set at the entrance of the tissues, the exergy of the blood at this point is equal to zero, and the exergy of the blood at the lungs entrance is calculated considering the following equations:

$$\dot{B}_{liq} = \dot{m}_{liq} c_{p,liq} \left(T_t - T_0 - T_0 \ln \frac{T_t}{T_0} \right) \tag{1}$$

$$\dot{B}_{O_2,bl} = \dot{m}_{O_2,bl} \left[c_{p,O_2} \left(T_t - T_0 - T_0 \ln \frac{T_t}{T_0} \right) + T_0 R_{O_2} \ln \frac{P_{O_2,t}}{P_{O_2,0}} \right] \tag{2}$$

$$\dot{B}_{CO_2,bl} = \dot{m}_{CO_2,bl} \left[c_{p,CO_2} \left(T_t - T_0 - T_0 \ln \frac{T_t}{T_0} \right) + T_0 R_{CO_2} \ln \frac{P_{CO_2,t}}{P_{CO_2,0}} \right] \tag{3}$$

$$\dot{B}_{bl} = \dot{B}_{liq} + \dot{B}_{O_2,bl} + \dot{B}_{CO_2,bl} \tag{4}$$

Across the boundaries of the lung control volume (CV_1), besides the blood flow, there are inspiration and expiration. The exergy of the inspiration has just the O_2 component, and the expiration has the O_2 and CO_2 components. The exergy of the N_2 and water are not taken into consideration, since these components are not transferred to the blood stream, leaving with the expired air, with almost the same composition of the inlet. The following equations are used to calculate the exergy of the inspiration and expiration components:

$$\dot{B}_{O_2,in} = \dot{m}_{O_2,in} \left[c_{p,O_2} \left(T_a - T_0 - T_0 \ln \frac{T_a}{T_0} \right) + T_0 R_{O_2} \ln \frac{P_{O_2,a}}{P_{O_2,0}} \right] \tag{5}$$

$$\dot{B}_{O_2,ex} = \dot{m}_{O_2,ex} \left[c_{p,O_2} \left(T_{ex} - T_0 - T_0 \ln \frac{T_{ex}}{T_0} \right) + T_0 R_{O_2} \ln \frac{P_{O_2,ex}}{P_{O_2,0}} \right] \tag{6}$$

$$\dot{B}_{CO_2,ex} = \dot{m}_{CO_2,ex} \left[c_{p,CO_2} \left(T_{ex} - T_0 - T_0 \ln \frac{T_{ex}}{T_0} \right) + T_0 R_{CO_2} \ln \frac{P_{CO_2,ex}}{P_{CO_2,0}} \right] \tag{7}$$

The exergy destroyed in the lung control volume (CV_1) is equal to:

$$\dot{B}_{dest,1} = \dot{B}_{O_2,in} + \dot{B}_{bl} - \dot{B}_{O_2,ex} - \dot{B}_{CO_2,ex} \tag{8}$$

Across the boundaries of the tissue control volume (CV_2), there are the O_2 and CO_2 flows due to the metabolism. The exergy of these flows are calculated by the following expressions:

$$\dot{B}_{O_2,met} = \dot{m}_{O_2,met} \left[c_{p,O_2} \left(T_t - T_0 - T_0 \ln \frac{T_t}{T_0} \right) + T_0 R_{O_2} \ln \frac{P_{O_2,t}}{P_{O_2,0}} \right] \tag{9}$$

$$\dot{B}_{CO_2,met} = \dot{m}_{CO_2,met} \left[c_{p,CO_2} \left(T_t - T_0 - T_0 \ln \frac{T_t}{T_0} \right) + T_0 R_{CO_2} \ln \frac{P_{CO_2,t}}{P_{CO_2,0}} \right] \tag{10}$$

The exergy destroyed in the tissue control volume (CV_2) is equal to:

$$\dot{B}_{dest,2} = \dot{B}_{CO_2,met} - \dot{B}_{O_2,met} - \dot{B}_{bl} \tag{11}$$

The exergy destruction rate in the whole respiratory system is the sum of the exergy destroyed in each control volume.

5. Results

An experiment conducted by Nagle et al. (1990), and graphically published by Webb (1995), was chosen for simulation. The subject was a 34-year old man, 1.75 m tall, and a mass equal to 74 kg. In the beginning of the experiment, the subject was kept still for the measurement of its initial condition. After that, he started to walk on a treadmill simulating a -5% grade downhill. Then he rested for 15 minutes and started to walk again, but this time simulating a 5% grade uphill. Its metabolism and the environment heat loss were measured. The exposition to heavier exercise levels is not considered in the present work because the model results do not fit the experimental data. For simulation, an operative temperature equal to 28°C and relative humidity equal to 40% at sea level were considered.

Figure 4 and Figure 5 show the conditions of the blood in the tissue entrance and outlet. Figure 4 also shows the oxygen consumption of the human body during the simulation. It starts to rise when the exercise begins (0.3 h).

These figures contain the blood data used for the exergy analysis. Besides them, the conditions of the inspired and expired air and the flow are also used for the analysis. The state of the inspired air is constant, and the state of the expired air has small variation during simulation. The ventilation and the blood flow follow the variation of O_2 consumption.

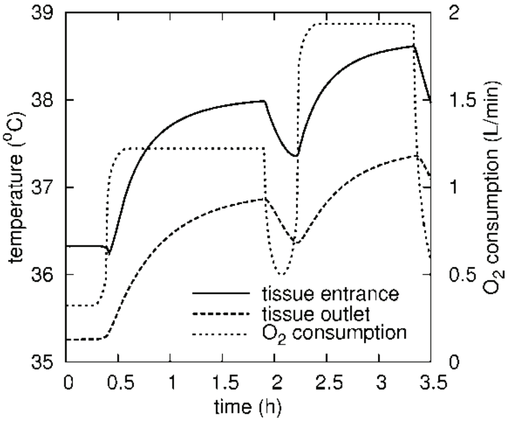

Figure 4. Blood temperature in the tissue entrance and outlet and O_2 consumption during simulation.

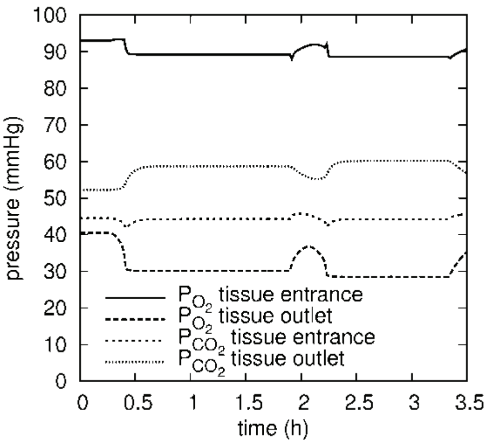

Figure 5. O_2 and CO_2 blood partial pressure in the tissue entrance and outlet during simulation

The exergy destruction rate was calculated for the lung and tissues during simulation. The result is shown in Figure 6. The sum of both contributions is also shown. It represents the exergy destruction of the whole body. The increase of the overall exergy destruction is proportional to the internal energy variation due to the metabolism, which is equal to 110 W in the beginning of the simulation, 417 W in the first level of physical activity, and 661 W in the second level of physical activity. Using the assumption proposed by Prek (2005), in which the metabolism is viewed as a heat source, and its exergy is associated to the difference between the body and the ambient temperature, then it is possible to correlate the exergy destruction rate to that related to the metabolism. For the first level of exercise, the mean body temperature is around 37°C, leading to a Carnot factor of 0.031, and a metabolism exergy of 12 W, while the exergy destruction is slightly higher than 8 W. As for the second level, the exergy associated with the metabolism is 20 W, and the exergy destruction is around 12 W. These figures indicate that more than 60% of the exergy associated with the metabolism is destroyed in the respiratory system. Furthermore, there is an increase of the exergy destruction in the respiratory system as the level of physical activity increases, which could be associated to the higher destruction of exergy in the thermoregulatory system in order to regulate the body temperature.

The relation between the destroyed exergy rate and the O_2 consumption is shown in Figure 7. Despite the increase of the exergy destruction in the tissues under physical activity (Figure 6), the relation between exergy destruction and O_2 consumption (Figure 7) shows an increase in the efficiency of the tissue O_2 consumption.

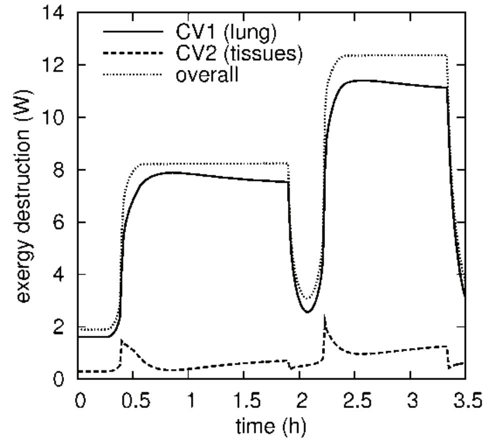

Figure 6. Rate of exergy destruction in the lung, tissues and whole body during simulation.

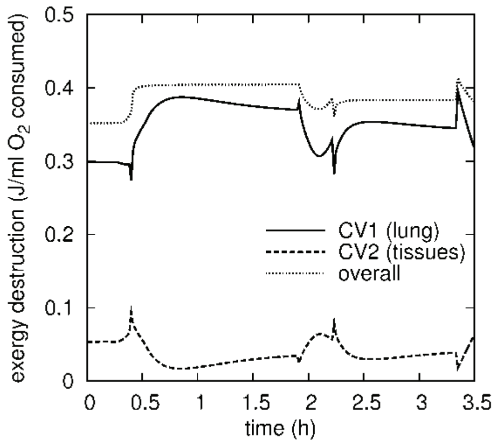

Figure 7. Relation between exergy destruction and O_2 consumption in the lung, tissues and whole body during simulation.

In the beginning of the exercise (Figure 7), the exergy destruction in the tissues decreases while the exergy destruction in the lung rises. That is, the tissues become more effective under exercise, and the lung is less effective. An explanation for this fact is that the O_2 is more available to the tissues from the blood, than from the environment to the blood. The difference between the blood O_2 partial pressure and the tissue O_2 partial pressure is small. The human blood has physical-chemical characteristics that make the oxygen be delivered to the tissues with this small difference in pressure. On the other hand, the difference of the O_2 partial pressure between the environment and the blood is larger. The air takes a longer path from the mouth to the alveolus, where the gas diffusion with the blood takes place. Furthermore, the alveolar space has a large volume (approximately 2000 ml at the end of an expiration). At each respiratory cycle, just 15% of the air is renewed. This delay prevents the alveolar air concentration from having abrupt alterations. The CO_2 also has similar characteristics: small difference between blood and tissue CO_2 partial pressure; and a large difference between blood and environment CO_2 partial pressure. The exergy destruction of the whole body has a small variation during exercise, a consequence of the opposed variations of the lung and tissues.

6. Conclusion

The exergy destruction of the human body under physical activity was determined. The variables used in the exergy analysis were generated by two physiological models, one for the thermal system and the other for the respiratory system. The rate of exergy destruction was obtained for the lung and the tissues. The results show that the tissues are more effective under physical activity, while the lung is less effective. Also, when compared to the exergy associated to the metabolism, calculated based on Prek (2005), more than 60% of it is destroyed in the respiratory system. This is a first attempt to analyze the human body exergy considering the respiratory and thermal systems under physical activity.

Some simplifications were considered. One is the use of two distinct non-integrated physiological models. Other simplifications are in the exergy analysis: the metabolic chemical reactions are not considered; the rise of the expired air temperature is not related with the metabolism. Prek (2005) considered the metabolism as a heat source, and the exergy associated with it was given by the Carnot factor, calculated with the body temperature and the ambient temperature. This approach was considered in this paper as a first attempt to compare the exergy destruction with the metabolism exergy. However, the authors do not view the metabolism as a simple heat flux, but as a chemical reaction (oxidation of carbohydrates), as discussed in Lems (2009). Hence, a new proposal should be sought in future works.

The exergy analysis of the human body will be improved as the physiological models become more accurate. The analysis could be further improved by associating the conversion of O_2 into CO_2 inside the cells, considering the approach described in Lems (2009)

Nomenclature

ATP	adenosine triphosphate	
$\dot{B}$	exergy rate	[W]
c_p	specific heat capacity	[J/kg.K]
$\dot{m}$	mass flow rate	[kg/s]
P	partial pressure	[Pa]
R	gas constant	[J/kg.K]
T	temperature	[K]

Subscripts

0	reference
1	lung control volume
2	tissue control volume
a	ambient air
bl	blood
CO_2	carbon dioxide
dest	destruction
ex	expired air
in	inspired air
liq	liquid part of the blood
O_2	oxygen
met	metabolism
t	tissues

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