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A FIRST COMPARISON OF DIFFERENT EXERGY ANALYSIS APPLIED TO THE HUMAN BODY TO ASSESS THERMAL COMFORT CONDITIONS

Thatiana Jéssica da Silva Ribeiro

Carlos Eduardo Keutenedjian Mady

University of Campinas, Cidade Universitária Zeferino Vaz - Barão Geraldo, Campinas - SP, 13083-970

jessicathatiana@gmail.com, cekmady@fem.unicamp.br

Abstract. *In this work, three different methods used to perform the exergy analysis to the human body were evaluated in order to obtain thermal comfort indexes. The human thermal model used is composed by 15 cylinders with elliptical cross section, from which it was obtained the temperature distribution of the body over time. The analysis comprises the evaluation of parameters such as destroyed exergy rate, also denominated exergy consumption rate by previous authors, and exergy transfer rate to the environment. The results obtained indicates that some methods available in the literature might not be describing accurately the irreversibilities within the human body.*

Keywords: *exergy analysis, human body, thermal comfort.*

1. INTRODUCTION

Thermodynamics concepts have been extensively applied on the analysis of living organisms, such as the human body. The First Law of Thermodynamics of human body was first performed experimentally for male subjects without clothes by Hardy and DuBois (1938a) and Hardy and DuBois (1938b). It was also used to analyze the effect of exercise, chills, forced air currents and clothing on the human body by Hardy *et al.* (1938a) and Hardy *et al.* (1938b). Later, these analysis were extended to female subjects by Hardy and DuBois (1940), Hardy *et al.* (1941) and DuBois *et al.* (1952).

Following, the concept of entropy generation was included in thermodynamics analysis of the human body in order to promote a better understanding of its functioning. As discussed in the work of Schrödinger (1944), life is maintained in the human body due to an extraction of "negative entropy flow" from the environment, which compensates the increase in human body entropy throughout time. Entropy generation was formally included in the scope of the human body analysis in the work of Prigogine and Wiame (1946), which stated that all living things tend to a minimum entropy production. The Second Law of Thermodynamics was applied to the human body by Aoki (1989), Aoki (1990) and Aoki (1991), based on energetic data of Hardy *et al.* (1938b), DuBois (1939), Hardy and DuBois (1938a), Hardy and DuBois (1938b) and DuBois *et al.* (1952). The concept of entropy generation was first correlated with the exergy destruction concept by means of the Gouy-Stodola theorem in the work of Aoki (1990). Moreover, a pioneer exergy analysis of the human body was performed in the work of Batato *et al.* (1990).

Prek and Butala (2010) applied the exergy analysis to the human body using a two-node cylindrical model. It was concluded that, with fixed physiological parameters, a single combination of environmental conditions guarantee minimal destroyed exergy. According to the referred authors, there is a correlation between this set of parameters and human expected thermal comfort sensation. Tokunaga and Shukuya (2011) performed an exergy analysis to a human body under unsteady state conditions taking into consideration changes in the thermal environment. By performing an exergy analysis, all the processes occurring inside the human body and those that occurs at the indoor or outdoor environment are taken into account. This is useful because interventions at the indoor environment can be made in order to provide a thermal comfort condition. Eventually, Mady *et al.* (2014) stated that the use of the destroyed exergy by itself is not enough to determine the thermal comfort conditions. It was obtained by the referred authors that, for some specific environmental conditions, the destroyed exergy should be analyzed together with the exergy transfer to the environment.

The present study aims to apply the exergy analysis to the human thermal model proposed by Ferreira and Yanagihara (2009) based on the method proposed by Prek and Butala (2010), Tokunaga and Shukuya (2011) and Mady *et al.* (2014). This article present the first attempt to compare exergy approaches from the literature in the same human thermal model.

2. EXERGY ANALYSIS OF HUMAN BODY

2.1 Human thermal model

The complexity of the human thermal model representation varies from author to author. One of the first human thermal model was proposed by Fanger (1972). It represents the human body as a single cylinder surrounded by another concentric cylinder, which represents the clothing insulation. In his model, it was assumed that the body was at steady state conditions, near to the thermal equilibrium condition. As the skin and inner body was treated as just one cylinder, factors such as vasomotor mechanisms could not be taken into account by this model. According to Fanger (1972), the thermal comfort condition is only achieved when basics conditions are satisfied: the thermoregulatory system acts in order to control the heat transfers with the environment, even for a wide variation of environment conditions, and, both skin temperature and evaporative energy transfer to environment are within a determined range, even though the skin is not treated as a single compartment. In addition, his work also determined that, under neutrality conditions, i.e, when there is no influence of the thermoregulatory system, when some activity is performed the skin temperature tends to decrease, while the evaporative energy transfer tends to increase.

The human thermal model proposed by Gagge (1973) and Gagge *et al.* (1986) represents the human body as a set of two concentric cylinders. The inner cylinder represents the core of the body, while the outer cylinder represents the skin compartment. This model was latter denominated as the two-node model. Both authors, Prek and Butala (2010) and Tokunaga and Shukuya (2011) performed the exergy analysis using this model. However, each one proposed different input and output terms, as will be discussed in the following sections. Ferreira and Yanagihara (2009) proposed a more complex human thermal model at which the different body limbs were represented. This complex model was also used in order to obtain the exergy behavior of the human body as performed by Mady *et al.* (2014).

In the present study, the human thermal model proposed by Ferreira and Yanagihara (2009) was used. It has 15 cylinders with elliptical cross section representing the head, neck, trunk, arms, forearms, hands, thighs, legs and feet. Each cylinder has a specific combination of tissues, with its own thermophysical properties and uniform parameters.

2.2 Environment parameters

Exergy is a thermodynamic property which evaluates the maximum work potential of a system or a control volume when it is brought from a determined condition of P , T , μ to the equilibrium with the environment, characterized by P_0 , T_0 and μ_0 . Therefore, the description of the environment parameters is an important step in order to obtain the exergy behavior of the human body.

In this study, the human body was submitted to different scenarios, where the temperature varied from 20 to 35 °C with a relative air humidity of 10 %, 50 % and 90 %. Even though Prek and Butala (2010) method described the environmental reference as a saturated air, many authors (including the normative American Society of Heating and Engineers (2005)) highlights the chemical potential of the nearly saturated water vapor contained in the expired air to diffuse into the environment air. Thus, it was chosen to maintain the relative air humidity values of 10 %, 50 % and 90 % in order to evaluate all three methods at the same environmental basis.

2.3 Evaluating destroyed exergy

Generally, the expression to perform the exergy analysis to a control volume is defined as shown in Eq.1.

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

Where $\frac{d\mathbf{B}}{dt}$ is the variation of exergy (J) over time (s), B_{in} the input exergy rate (W), B_{out} the output exergy rate (W), Q_k the heat transfers rates which might occur at the boundary "k" (W), T_0 the environment temperature (K), T_k the temperature at which the heat transfer occurs (K), W the power (W) and B_d the destroyed exergy rate (W). With the knowledge of the other variables, the destroyed exergy rate (and therefore the irreversibilities) can be evaluated with Eq.1. For the control volume used in the model proposed by Mady *et al.* (2014), Eq.2 evaluates the destroyed exergy rate in the human body.

$$B_d = \left(B_M - \frac{d\mathbf{B}}{dt} \right) - B_{env} - W \quad (2)$$

At which the metabolism exergy rate, B_M (W), is the input term for the human body and is calculated based on the exergy associated with chemical reaction processes of the nutrients (carbohydrates, lipids and amino acids). The output term is the exergy transfer rate to the environment, B_{env} (W), composed by exergy transfer rate due to radiation, convection, vaporization trough the skin and respiration. For resting conditions and steady state, there are no performed work ($W = 0$) and no exergy variation over time ($\frac{d\mathbf{B}}{dt} = 0$).

Tokunaga and Shukuya (2011) model evaluates the destroyed exergy as shown in Eq.3.

$$B_d = \sum B_{in} - \sum B_{out} - \sum B_{stored} \quad (3)$$

According to the authors, the exergy input for the human body, $\sum B_{in} (W)$, is the summation of the exergy associated to the metabolism, exergy of the inhaled humid air, exergy of the liquid water generated in the core by the metabolism, exergy of the liquid water generated in the shell by the metabolism added to a certain amount of exergy associated with a dry air and exergy associated with the radiation absorbed by the skin. Shukuya *et al.* (2010) states that the exergy of the dry air must be taken into account because the water vapor from sweating on the skin surface, which is an exergy output from the human body, does not disperses into a space of vacuum. It disperses into an environmental space that already has some water vapor molecules. Therefore, once the exergy of the dry air is added to the output exergy, it also has to be added on the exergy input, and, they chose to include it in the term related to the liquid water generated in the core by the metabolism. The metabolism exergy rate is evaluated as an exergy related with a heat transfer process, which according to Mady *et al.* (2014) is about one order of magnitude lower than the metabolic exergy calculated based on the chemical reaction processes.

Shukuya *et al.* (2010) states that the terms related to water generation due to metabolism are required in the balance because hydrogen atoms that composes organic matter metabolized within the body would react with oxygen atoms from the inhaled air, generating water molecules. Further comments about the influence of this term in the exergy analysis will be discussed on following sections.

The exergy output, $\sum B_{out} (W)$, is composed by the exergy of exhaled air, the exergy of water vapour from sweating process added to an exergy of a dry air, the exergy due to radiation released from the body and the exergy due to convection.

The so called "exergy stored", $\sum B_{stored} (W)$, is treated as the variation of a thermal exergy in respect to time, i.e, exergy terms associated with heat transfer on both core and shell, which actually gives margin to some discussion. Its reasonable to argue that under unsteady state what will take place at the human body is a variation of the thermodynamic property exergy contained within the body in relation to the time, as it is observed on internal energy, volume and entropy, and not a thermal exergy carried out by a frontier effect, such as a heat transfer.

Prek and Butala (2010) method evaluates the destroyed exergy within the body as presented on Eq.4.

$$\Delta B_{tot} = \Delta B_{cr-sk,K} + \Delta B_{cr-sk,bl} + \Delta B_{conv} + \Delta B_{rad} + \Delta B_{vap} + \Delta B_{a,th} + \Delta B_{a,ch} + \Delta B_{res,th} + \Delta B_{res,ch} \quad (4)$$

An input-output relationship is not observed on the referred author's model. Instead, they chose to treat each heat and mass transfer processes individually and add them all up the end to account for the destroyed exergy within the human body related to heat and mass transfer phenomena. It is possible to conclude that the author takes into account the irreversibilities associated only with these transport phenomena.

The $\Delta B_{cr-sk,K} (W)$ and $\Delta B_{cr-sk,bl} (W)$ terms are exergy transfers observed at the inner part of the human body, between the core and skin. The former accounts for the destroyed exergy associated with a passive heat transfer which occurs due the finite temperature difference between the core and skin. The latter represents an exergy associated with heat transfer between blood flow and the core and the skin compartment.

The $\Delta B_{cr-sk,bl} (W)$ term was not included in the simulations of this study because it requires further analysis of whether this term should be accounted or not in the control volume of the whole human body. It was accounted by Prek and Butala (2010) because they decided to subdivide the human body model into two different control volumes: the first control volume had its border between the core and the skin compartment, while the second control volume border was at the interface between the skin compartment and the environment. However, if the boundary is placed at the skin, such as the others methods analyzed in this study, this term become an internal irreversibility, which appears to be the intention of the author to account for internal and external irrevesibilities associated with transport phenomena. Furthermore, models such as Pennes (1948) could be used in order to account for blood-tissue energy transfer.

The terms $\Delta B_{conv} (W)$, $\Delta B_{rad} (W)$, $\Delta B_{vap} (W)$, $\Delta B_{a,th} (W)$ and $\Delta B_{a,ch} (W)$ accounts for exergy transfers related to convection, radiation, sweat vaporization and mass transfers between the skin compartment and the environment while the terms $\Delta B_{res,th} (W)$ and $\Delta B_{res,ch} (W)$ account for exergy transfers due to the respiration between the core and the environment.

2.4 Simulation Procedure

Destroyed exergy rate was calculated using the three methods described previously applied to the human body thermal model described by Ferreira and Yanagihara (2009). As the aim of this study is only to promote a comparison between the models, some considerations has been made in order to simplify the process, such as:

- It is assumed that the thermal model, which operates in unsteady state, has reached a certain condition at which there are no variation of energy, exergy and internal temperature over time;
- There are no performed work, i.e, the human body is at resting conditions;
- The model is without clothes;

- Parameters such as convective heat transfer coefficients, which in reality varies according to environmental variables such as air velocity, as shown on American Society of Heating and Engineers (2005), were kept constant;
- The operative temperature and the mean radiant temperature were assumed to be equal to the air temperature;
- Tokunaga and Shukuya (2011) model was developed taking into account a different reference environment, denominated outdoor environment. In order to compare all three models using the same basis, the outdoor environment parameters were considered equal to the indoor environment at which the human body is located.

3. RESULTS AND DISCUSSIONS

Figure 1 indicates the destroyed exergy rate and the environmental exergy transfer obtained using the model proposed by Mady *et al.* (2014). Two trends are observed on Fig.1a: for temperatures below the thermal neutrality temperature, defined by American Society of Heating and Engineers (2005) as operative temperatures comprehended between 29 °C and 31 °C, the destroyed exergy rate is higher for environment with lower relative humidity, whereas, for temperatures above it, the destroyed exergy rate is higher for environment with higher relative humidities. Previous studies, except for Mady *et al.* (2014) and Henriques *et al.* (2017), usually describes the effect of changes in the environmental temperature on the destroyed exergy rate, not the effect of variations in relative humidity.

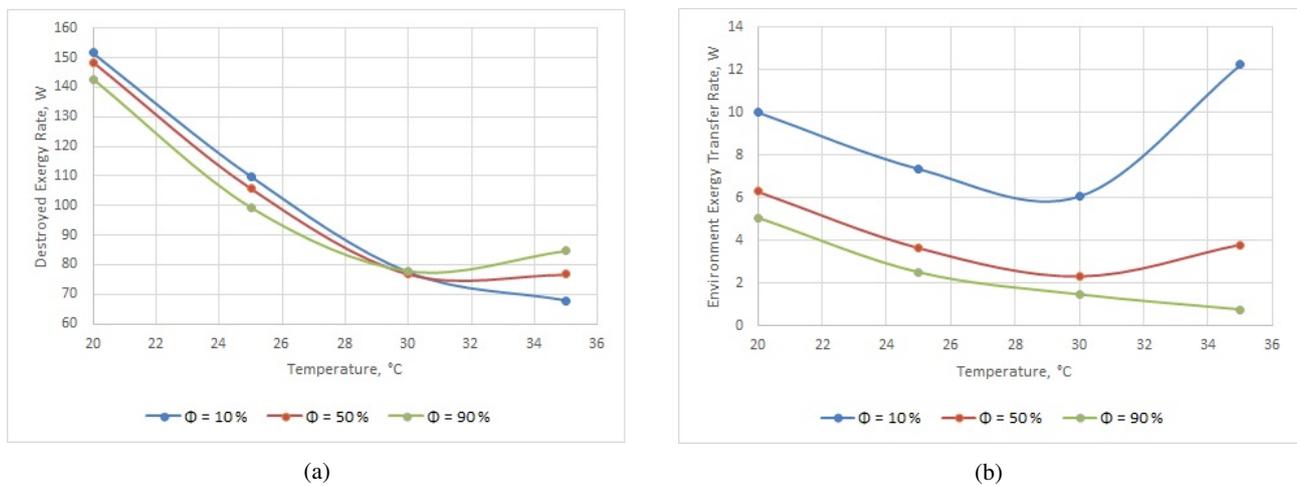


Figure 1: Results obtained using Mady *et al.* (2014) method. (a) Destroyed Exergy Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %. (b) Environment Exergy Transfer Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %.

From the observation of Fig.1a, for temperatures above 30 °C with high values of relative humidity, it is observed an increase of the destroyed exergy rate. As the environmental temperature is high, exergy transfers due to convection and radiation becomes negligible and the only form that the body has to dispose of the "metabolism exergy" is by sweat vaporization and respiration. However, since the relative humidity of the environment is also high, those mechanisms are also affected. Thus, there is a difficulty for the body to transfer exergy to the environment, causing an increase in the internal temperature as described in Mady *et al.* (2014), named hyperthermia. This increase of internal temperature triggers the Q_{10} effect, which quantifies the dependence between the rate of metabolic reactions and the variation in body tissue temperature (Mountcastle, 1980), generating an increase in the metabolism. The destroyed exergy rate is strictly related to the metabolism, therefore it also increases.

The shift of behavior on the destroyed exergy rate for temperatures higher and lower than 30 °C, shown at Fig.1a, is observed also for intermediate relative humidities values, however it is driven only by the increase in the metabolism, since the exergy transfer to the environment in this case slightly increases, as shown on Fig.1b.

As can be seen on Fig.1b, for any temperature analyzed, when the body is exposed to a dry environment, such as the case of 10 % of relative humidity, a considerable increase in the exergy transfer rate to the environment is observed, driven mostly by the increase of the exergy transfer to the environment due to sweat vaporization.

For temperatures above 30 °C with low values of relative humidity, the destroyed exergy rate decreases as a function of the temperature increment, as presented on Fig.1a. This occur because the metabolism does not varies significantly while the exergy transfer to the environment presents a rapid increase, as shown on Fig.1b, driven by the contribution of the sweat vaporization exergy transfer.

Figure 2 illustrates the destroyed exergy rate and the environment exergy transfer obtained by using Prek and Butala (2010) method.

Figure 2a is in accordance with results presented on Prek and Butala (2010) for some scenarios analyzed. According to the referred authors, there is a minimal point of destroyed exergy rate as a function of temperature at the point of

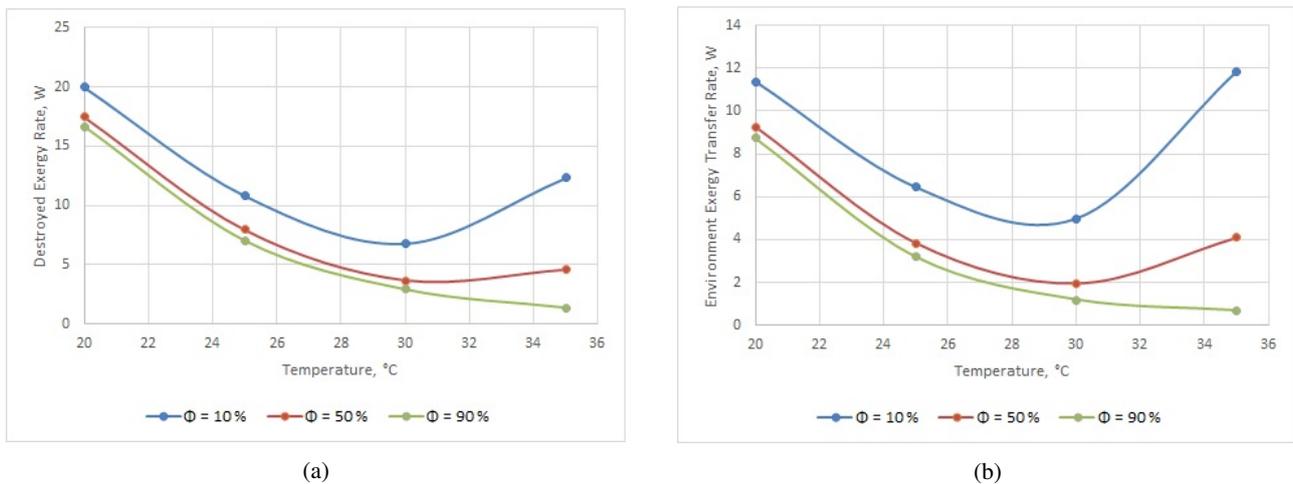


Figure 2: Results obtained using Prek and Butala (2010) method. (a) Destroyed Exergy Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %. (b) Environment Exergy Transfer Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %.

thermal comfort condition. However, this minimum does not occur for all values of relative humidity. There is no point of minimum observed on the 90 % relative humidity curve for the analyzed temperature range on Fig.2a.

An attempt to propose a term which depicts the exergy transfer to the environment is shown on Fig.2b. The elements of exergy destruction that occurs directly between the skin compartment and the environment are added, however the same behavior that was observed in the destroyed exergy rate is also observed in the exergy transfer to the environment, even though they represent different physiological phenomena. This can be explained because of the proposition of the exergy analysis by Prek and Butala (2010). As the equation related to the heat transfer between blood flow and the tissues of the core and skin compartment was not included in this study (term $\Delta B_{cr-sk,bl}$ on Eq.4), the only difference between the destroyed exergy rate (shown on Fig.2a) and the environment exergy transfer rate (shown on Fig.2b) is the exergy associated with the metabolism released as "heat" to the body, therefore, this physical quantity multiplied by the Carnot factor.

The behavior of the destroyed exergy rate curve evaluated by Prek and Butala (2010) method and by Mady *et al.* (2014) method are identical for temperatures lower than the thermal neutrality, even though the equation and the order of magnitude differs. For temperatures between 30 and 35 °C, it is observed on Fig.2a that, for lower relative humidities, instead of decreasing, as in Mady *et al.* (2014) method, the destroyed exergy rate increases. It is driven mostly by the rapid increase in the exergy destroyed due to the vaporization of sweat, which is the dominant phenomena on the calculation of the destroyed exergy rate. In this same range of temperature, the inverse trend is observed for environment with high values of relative humidity. The reduction of the destroyed exergy rate is caused by the reduction on the terms related to radiation and convection for higher environment temperatures, seen indirectly on Fig.2b. This reduction is also highlighted by Hardy and DuBois (1938a), Hardy *et al.* (1938b), Hardy and DuBois (1940) and DuBois *et al.* (1952) using the first law.

Figure 3 displays the destroyed exergy rate and the environment exergy transfer obtained by using Tokunaga and Shukuya (2011) method.

The behavior of the destroyed exergy rate as a function of temperature is different from the others methods analyzed in this study. The values of destroyed exergy rate obtained by Tokunaga and Shukuya (2011) model is at least one order of magnitude different from what have been observed by the other methods, specially for dry environments, as shown on the secondary axis of Fig.3a. This high values are caused mostly by the input exergy term related to the water generated in the core due to the metabolic reactions. One cannot affirm that the exergy of this water molecules can be entirely treated as an input term, since there are other water terms that should be analyzed when performing a water mass balance, such as ingestion of water and elimination of water within the urine. The water that is generated as a result of the metabolism is taken into account by Mady *et al.* (2014) and Batato *et al.* (1990) in the metabolic reactions, and, in none of the proposed scenarios it has given values of this order of magnitude. Shukuya *et al.* (2010) highlights the same correlation proposed by Prek and Butala (2010) between the minimum destroyed exergy rate and thermal comfort conditions, at least for winter conditions. However, a minimum point of exergy destruction was not observed in the proposed scenarios.

Figure 3b displays the environment exergy transfer rate, which accounts for exergy transfers due to radiation released from the body, convection between the body and the environment, sweat vaporization and exhaled air. The same trend observed in the previous methods were expected here, i.e., there was expected a shift of trend for temperatures higher than the thermal neutrality temperature. However, it is observed that for higher temperatures the exergy transfer to the

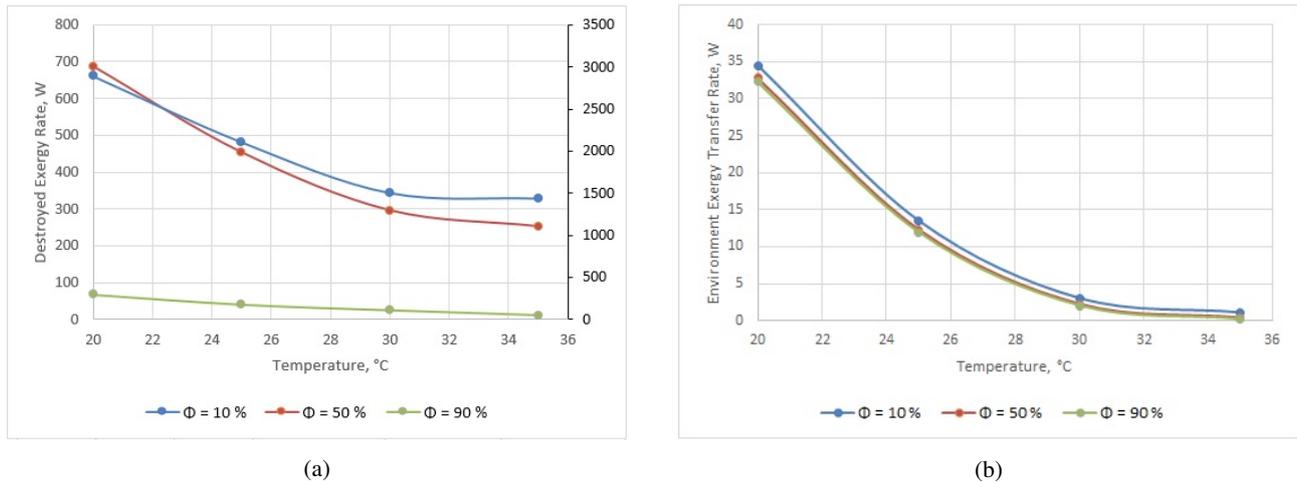


Figure 3: Results obtained using Tokunaga and Shukuya (2011) method. (a) Destroyed Exergy Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %. (b) Environment Exergy Transfer Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 %.

environment continues to decrease. This goes against all the literature basis existent in thermal comfort studies because when temperatures goes higher the energy transfer due to sweat vaporization, and consequently its related exergy, is expected to affect the environment exergy transfer rate increasing it. Nevertheless, it is observed that exergy values related to sweat vaporization not only decrease with increasing temperature but are of order of magnitude below the other outputs terms.

Considering that the input terms used by Tokunaga and Shukuya (2011) have been questioned in recent publications, such as Wu *et al.* (2013) and Guo and Michael Meggers (2016), it was decided to neglect both terms of exergy associated with generated water in the balance. The destroyed exergy rate taking this consideration into account is presented on Fig.4a. Moreover, it was observed that the values of exergy transfer rate to the environment displayed on Fig.3b was not in accordance with the values observed on the other two models. Thus, a small modification in the exergy transfer rate to the environment calculation is proposed and the obtained results shown on Fig. 4b.

Instead of computing the radiation released from the body to the surrounding environment as shown on Eq.5, it was calculated as used in Mady *et al.* (2014), shown on Eq.6, because it was the more influential term on the exergy transfer rate to the environment. Given that Tokunaga and Shukuya (2011) equation made a distinction between the walls temperature and in this study they were considered to be constant and equal to the air temperature, this might be a source of error in the present comparison.

$$B_{rad_{released}} = f_{eff} f_{cl} \epsilon_{cl} h_{rb} \frac{(T_{cl} - T_0)^2}{(T_{cl} + T_0)} \quad (5)$$

$$B_{rad} = Q_{rad} \left(1 - \frac{T_0}{T_{cl}} \right) \quad (6)$$

On Eq.5, according to Tokunaga and Shukuya (2011), the f_{eff} is the the ratio of the effective area of human body for radiant-heat exchange to the surface area of the human body with clothing, f_{cl} is the ratio of human body area with clothing to the naked human body area, ϵ_{cl} the emittance of clothing surface, h_{rb} the radiative heat-transfer coefficient of a black surface ($W/(m^2K)$), T_{cl} the clothing surface temperature (K) and T_0 the environment temperature (K). Since the body is naked in this study, it was assumed that f_{eff} , and f_{cl} are equal to the unity. According to Hardy (1934) and Hardy and DuBois (1938a), the human skin radiates like a black body irrespective of its visible color, thus, $\epsilon_{cl} = 1$. On Eq.6, Q_{rad} is the heat transfer rate due to radiation (W), T_0 the environment temperature (K) and T_{cl} the temperature on the clothing surface (K). As the human body is naked in this study, T_{cl} is equal to the skin temperature.

Even with the proposed modifications, the method does not gives reasonable results, since some negative values of destroyed exergy rate were obtained. Future analyzes should be performed in order to better analyze and understand these results. In order to obtain some satisfactory results, the absolute value of the destroyed exergy rate was calculated and then the result obtained is plotted on Fig.4a.

The destroyed exergy rate calculated considering the modifications previously described presents now a similar behavior of the destroyed exergy rate calculated by the other methods for temperatures bellow 30 °C. Even the values obtained are now similar to what is obtained with Prek and Butala (2010) method, shown on Fig.2a, sustaining the argument that the term developed by Tokunaga and Shukuya (2011) to account for water related to metabolism might not be describing

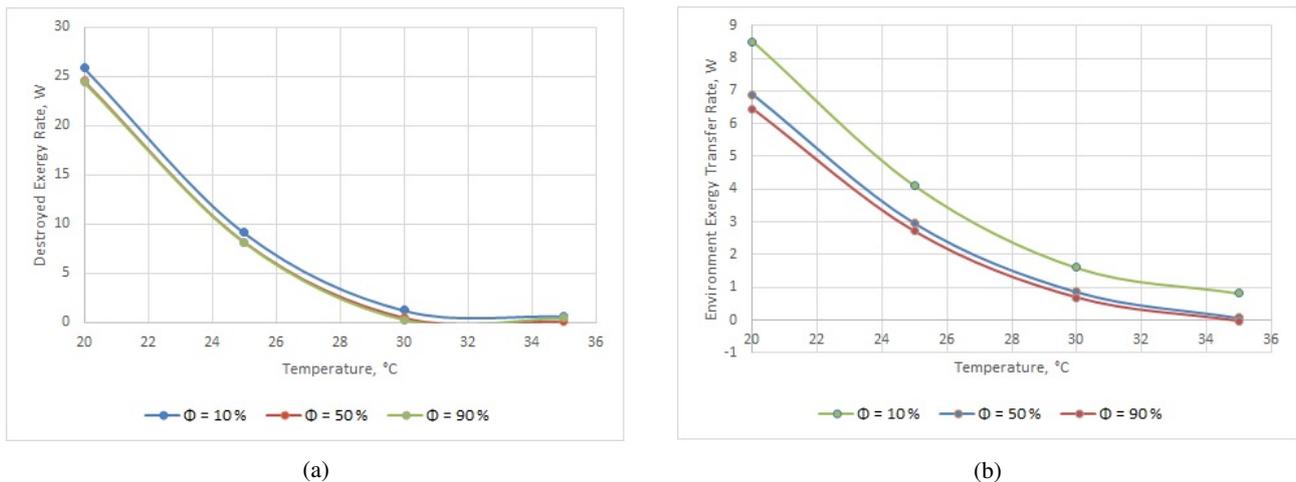


Figure 4: Results obtained using Tokunaga and Shukuya (2011) method. (a) Destroyed Exergy Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 % without the terms related to water generated within the body by metabolism. (b) Environment Exergy Transfer Rate versus Air Temperature for relative humidities of 10 %, 50 % and 90 % considering exergy due to radiation according to Mady *et al.* (2014) model.

the phenomenon accurately. Still, this model does not give satisfactory results for environment with high values of temperature. On Fig.2a, for temperatures higher than 30 °C, the destroyed exergy rate for higher temperatures was supposed to increase due to the increase in the sweat vaporization term, instead this term surprisingly decreased.

4. CONCLUDING REMARKS

A wide variety of exergy analysis of the human body have been proposed throughout time. In this study, three different methods used on the exergy analysis of the human body were evaluated in order to promote a comparison among them. Parameters obtained with the exergy analysis, such as the destroyed exergy rate, were shown for each of the methods analyzed. The results obtained indicates that some methods available in the literature might not be describing accurately the irreversibilities within the human body. Hence, some of the discussions highlighted by this study are:

- Similar behavior of the variation of destroyed exergy rate with temperature was found between Mady *et al.* (2014) and Prek and Butala (2010) method until the temperature of 30 °C. However, the magnitude of the destroyed exergy rate is quite different;
- The environment exergy transfer rate proposed to Prek and Butala (2010) method expressed that this model might actually be in accordance with Mady *et al.* (2014), even though this author disagree with the equations used to evaluate some phenomena, such as the exergy associated with convection and radiation;
- The correlation between minimum destroyed exergy and thermal comfort condition does not hold for all ranges of relative humidity. Thereby, the destroyed exergy is not sufficient to determine thermal comfort conditions;
- The method proposed by Tokunaga and Shukuya (2011) is not in accordance with the other two methods analyzed. The values obtained for destroyed exergy rate are at least one order of magnitude different from what was found using the other models, due mostly to the term that accounts for exergy associated with the water generated in the core due to metabolism;

5. ACKNOWLEDGEMENTS

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