A NOVEL METHOD FOR ESTIMATING THE ENTROPY GENERATION RATE IN A HUMAN BODY

by

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The main objective of this study is to show a method for calculating entropy generation (S_{gen}) in a human body under various environmental and physiological conditions. The S_{gen} in a human body is a measure of activeness of motions, reactions, and irreversibility of processes occurring in a body and is a kind of holistic and thermodynamic index, which characterizes a human body as a whole. Human body at healthier and normal condition generates the least amount of S_{gen}. Heat transfer over a human body, activity (at rest, S_{gen} = 0.21 J/sK or exercise, S_{gen} = 2.19 J/sK or at death, S_{gen} = 0 J/sK), ambient, body and mean radiant temperatures, emissivity and absorbity of human skin, internal heat elimination, body weight and height, and air speed effect much more on the S_{gen} in a human body compared to the effects of mass exchange into and out of the body, internal heat production, cross-sectional area of human body, clothing, altitude, and relative humidity of the surrounding air. Among these factors entropy production due to heat transfer over a human body plays a significant role in the total entropy generation rate.

Key words: *entropy generation, human body surface area, heat transfer, age, metabolism*

Introduction

The human body is an open thermodynamic system. The state of the system, in this case a human body, including its thermal state, results from the processes of interaction between the body and its thermal environment. These are, on the one hand, the metabolic heat production of the body and, on the other, heat and mass transfer processes at the boundary between the body surface and ambient air. Respiratory heat loss plays an insignificant part in the thermal balance of the body [1], whereas the transfer processes through the skin are the basic mechanism for maintaining a human body isothermia [2]. This study examins a human body as an open system in unsteady-state.

Previously Aoki [5-8] implemented a great amount of efforts to model entropy generation rate from a human body. Hardy *et al.* [3, 4] have intensively studied the human body as a whole using energy concepts, which are essentially formulated in the First law of thermodynamics (FLT). In this paper, energy concept has been employed to evaluate the entropy generation, S_{gen}, in human body using the key idea of the Second law of thermodynamics (SLT). Entropy and entropy related quantities such as free energy are the only physical quantities, which have directionality with time. Hence, it is natural to try to describe biological phenomena (growth and aging) as having directionality in term of the entropy concept [5]. Especially, the S_{gen} is a kind of global measure, which specifies how violent motions and reactions occurring in nature are [6]. Hence, the S_{gen} in the human body shows the extent of activeness of heat flows and motions or reactions of substances within the body as a whole [7]; thus the S_{gen} is a significant physiological quantity, which can characterize a human body from thermodynamic and holistic viewpoints [8]. Prigogine [9] proposed a principle that a biological organism tends to progress to a state of the minimum S_{gen}, that is, the S_{gen} in an organism decreases with time and approaches to a minimum and stationary level (the minimum S_{gen} principle). In this paper, it is highlighted that Prigogine minimum S_{gen} theory in not valid for human body.

The S_{gen} analysis conducted by Aoki [5] and several other researchers were based on some simplified assumptions. Aoki [5] assumed the rectal temperature (T_r) is equal to the body temperature (T_b). In addition, in the S_{gen} calculation he assumed the predicted T_r and S_{mtb} (entropy generation rate due to metabolism) value can be applied for all ages of men and women. In reality these two values vary significantly for different ages and in gender. In the previous literature, the researches did not take into account the effect of *MRT* to calculate the entropy flow associated with the infrared radiation. *MRT* is the average of the surface temperature of the surroundings with which the body can exchange heat by radiant transfer [10]. In addition, in the previous literature the researchers assumed the T_b is equal to the T_r to calculate the S_{gen}, which leads to different result from the actual one. In addition, in the previous work the researchers took into account the d (average diameter of the body) value as 0.30 m [2] and w (average width of the body) and h (average height of the body) parameter as a constant value for all ages of people irrespective of gender. Aoki [6] assumed the average surface area of human is constant. In reality, the average surface area varies of a human with varying ages and gender. In this paper these effects have taken into consideration.

Mathematical model

Methods of calculation of the S_{gen} in a human body already described by Aoki [8] and Hardy *et al*. [11]. Outline of the calculating method to find out the S_{gen} in a human body is reproduced in this paper with some modifications. As already mentioned, the previous analytical method was based upon some simplified assumptions; in this paper these obsessions have taken into consideration. The total S_{gen} can be calculated using the SLT for an open system as follows:

$$S_{gen} = \Delta S - S_{flow} \tag{1}$$

After rewriting the above equations, the total S_{gen} per human individual can be written as follows:

$$S_{\text{gen (human)}} \quad S_{\text{gen}} \frac{A_{\text{s}}}{A_{\text{r}}} \tag{2}$$

The total entropy flow into the body can be calculated as follows:

$$S_{\text{flow}} \quad S_{\text{flow (energy)}} \quad S_{\text{flow (mass)}} \tag{3}$$

The entropy flow into the body due to heat transfer can be expressed as follows:

$$S_{\text{flow (energy)}} = S_{\text{in}} - (S_{\text{out}} + S_{\text{cnv}} + S_{\text{evp}}) \tag{4}$$

The entropy inflow associated with infrared radiation emitted by the surrounding surface and absorbed by the human body is as follows:

$$S_{\text{in}} \quad \eta A_{\text{r}} \frac{4}{3} \sigma MRT^{3} \tag{5}$$

This equation is the improved version of Aoki's model [12] equation. The effective radiating surface area (A_{r}) for a human body is assumed to be 1.54 m^2 [12]. The entropy out flow associated with infrared radiation emitted by the body is as follows:

$$S_{\text{out}} \quad \varepsilon A_{\text{r}} \frac{4}{3} \sigma T_{\text{s}}^{3} \tag{6}$$

The entropy loss by convection and evaporation can be calculated as follows:

$$S_{\text{cnv}} \quad \frac{E_{\text{cnv}}}{T_{\text{s}}} \tag{7}$$

$$S_{\text{evp}} \quad \frac{E_{\text{evp}}}{T_{\text{r}}} \tag{8}$$

The rates of convection and evaporation at the interface between the human body and the surrounding air are expressed by the parameter of convective and evaporative heat transfer coefficients (h_{c} and h_{e}). This parameters can be evaluated by heat transfer equations [2], which also depend on the velocity of the airstreams around the body, that is still air (free convection) and moving air (forced convection), vapor pressure, the H, d, T_{b}, T_{s}, T_{r} values. E_{cnv} and E_{evp} can be evaluated using Kandjov's [2] equation as follows:

$$E_{\text{cnv}} = h_{\text{c}} \pi d^{2} \Delta T \tag{9}$$

$$E_{\text{evp}} = h_{\text{e}} \pi d^{2} \Delta P \tag{10}$$

here d^{2} is the effective body surface.

Case 1: Free convection of the air over the human body:

$$h_\mathrm{c} \quad 1.87\Delta T 0.25 \quad \frac{P}{P_0}^{0.5} \quad \mathrm{W/m^2{}^\circ C} \tag{11}$$

$$h_\mathrm{c} \quad 3.08\Delta T 0.25 \quad \frac{P_0}{P}^{0.5} \quad \mathrm{Wh/m^2Pa} \tag{12}$$

Case 2: Forced convection of the air over the human body for $V_\mathrm{a} < 2.0$ m/s

$$h_\mathrm{c} \quad 6.88\, V_\mathrm{a}^{0.618} \quad \frac{P}{P_0}^{0.618} \quad \mathrm{W/m^2{}^\circ C} \tag{13}$$

$$h_\mathrm{e} \quad 11.35\, V_\mathrm{a}^{0.618} \quad \frac{P_0}{P}^{0.382} \quad \mathrm{Wh/m^2Pa} \tag{14}$$

Case 3: Forced convection of the air over the human body for $V_\mathrm{a} > 2.0$ m/s

$$h_\mathrm{c} \quad 6.08\, V_\mathrm{a}^{0.805} \quad \frac{P}{P_0}^{0.805} \quad \mathrm{W/m^2{}^\circ C} \tag{15}$$

$$h_\mathrm{e} \quad 10.0\, V_\mathrm{a}^{0.805} \quad \frac{P_0}{P}^{0.195} \quad \mathrm{Wh/m^2Pa} \tag{16}$$

Here, $d = 0.3$ m, and $\Delta T = T_\mathrm{s} - MRT$ [°C], $\Delta P = P_0 - P$ [hPa]. The entropy flow into the body due to mass transfer can be expressed as follows:

$$S_\mathrm{flow\ (mass)} = S(O_2)M(O_2) - S(CO_2)M(CO_2) + $$
$$+ S(H_2O)M(H_2O_\mathrm{in}) - S(H_2O)M(H_2O_\mathrm{out}) \tag{17}$$

The values of $M(O_2)$, $M(CO_2)$, $M(H_2O_\mathrm{in})$, and $M(H_2O_\mathrm{out})$ were taken from Walker [26] and is depicted in fig. 1. The entropy content of O_2, CO_2, and H_2O were taken from a standard table and these values vary with temperature. The change of entropy content in a human body can be calculated as follows:

$$\Delta S \quad \frac{\Delta Q}{T_\mathrm{b}} \tag{18}$$

$$\Delta Q = Q_\mathrm{p} - Q_\mathrm{e} \tag{19}$$

The Q_p and Q_e values were taken as a whole from the experimental measurements obtained by Hardy *et al*. [13]. S_flow value takes into account convection and evaporation from a body based on the average body surface temperature and entropy flow into the body due to mass transfer. On the other hand the Q_p and Q_e values take into account

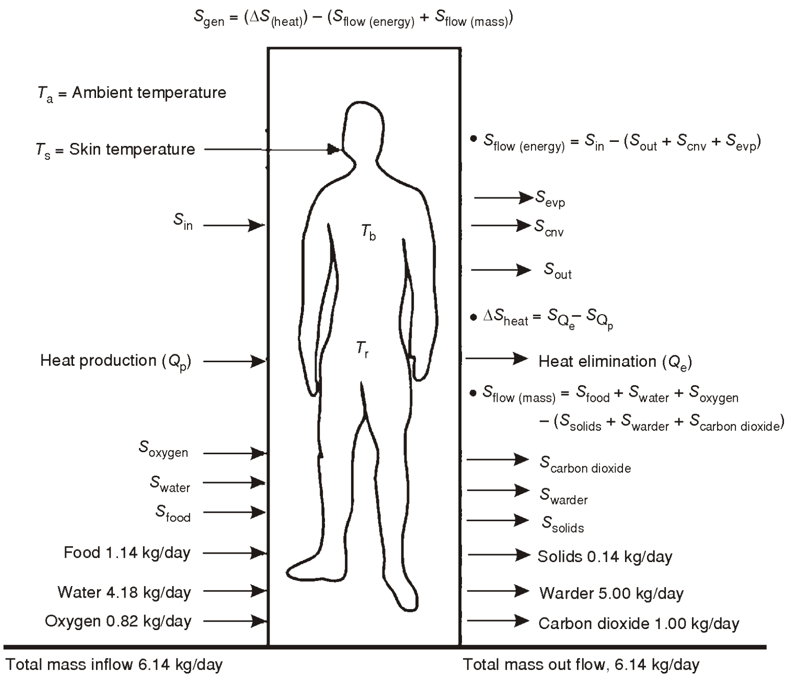

Figure 1. Typical human mass flow and corresponding S_{gen} (adapted from [27])

the internal heat generation and elimination, respectively, of a body. The ΔQ ($Q_p - Q_e$) measures the change of (internal) energy of a body. Hardy *et al.* [13] highlighted in the environment colder than 33 °C, the average skin temperature (T_s) fell almost linearly with the ambient temperature T_a. Above 33 °C the value of the T_s is almost constant and it is about 36 °C in value. In addition, they pointed out that sweating and the T_s are interdependent. Hardy [14] and Hardy *et al.* [4] emphasized the T_s is function of the T_b and T_r. The average T_s of the body may be calculated as follows:

$$T_s = 0.07T_1 + 0.14T_2 + 0.05T_3 + 0.07T_4 + 0.13T_5 + 0.19T_6 + 0.35T_7 \tag{20}$$

The various weighting factors were computed from the linear formula measurements of sixteen human bodies [11]. The rectal temperature can be calculated as follows [15]:

$$T_r \quad 36.75 \quad 0.004M_{net} \quad \frac{0.025}{Clo}(T_a \quad 36) \quad 0.8\,e^{0.0047(E_{req} \quad E_{max})} \tag{21}$$

$$E_{req} = M_{net} + E_{R+C} \tag{22}$$

$$E_{R\ C} \quad \frac{11.6}{Clo}(T_a \quad 36) \tag{23}$$

Burton [16] proposed eq. 24 to calculate the body temperature (T_b) in a human body due to the change in the T_r and the T_s. In the eq. 24, the weighting factor is important parameter to find out a true value of the T_b. In reality, no one formula can be used for the whole rage in the T_s and T_b in a human body. The eq. 24 gives the best result for the temperature range from 22 to 35 °C:

$$T_b = 0.65T_r + 0.35T_s \tag{24}$$

Heat exchange by radiation, convection, or evaporation is always related in some way to the surface area of the body. The most commonly used measure of the body surface area of humans is that proposed by DuBois *et al*. [17]:

$$A_s = 0.202w^{0.425}h^{0.725} \tag{25}$$

M_{net} value can be calculated using Harris-Benedict formula (18) as follows:

$$M_{net\,(women)} = 655 + 9.6w + 1.8h\ (\text{in cm}) - 4.7a \tag{26}$$

$$M_{net\,(men)} = 66 + 13.7\,w + 5h\ (\text{in cm}) - 6.8a \tag{27}$$

To determine the actual M_{net}, one must multiply the calculated M_{net} by the appropriate activity factor as follows: (a) for sedentary – little or no exercise: $1.2M_{net}$, (b) for lightly active – light exercise/sports, 1-3 days/week: $1.375M_{net}$, (c) for moderately active – moderate exercise/sports, 3-5 days/week: $1.55M_{net}$, (d) for very active – hard exercise/sports, 6-7 days/week: $1.725M_{net}$, and (e) for extra active – very hard daily exercise/sports and physical job: $1.9M_{net}$. The response of the T_r to changes in metabolic rate and environmental conditions has been studied in numerous experiments with unclothed subjects. There have been few studies with clothing and very few attempts to develop a formula, which will describe the biophysical processes that determine the T_r response with clothing [15]. The *Clo* and i_m/*Clo* values can be calculated from [15], using the following equations:

$$E_{max}\quad 25.5\frac{i_m}{Clo}(44\quad \phi_a P_a) \tag{28}$$

Results and discussions

In this study, it is found that for a 74.74 kg body weight, and 1.52 m height of female, with unit emissivity, unit absorbity, 1.72 m^2 body surface area, 1.54 m^2 radiating surface area, 101.3 kPa atmospheric pressure, 2 m/s air currents, 10.62 W/m^2°C forced convection coefficient, 17.47 W/m^2°C evaporative convection coefficient, and 0.46 *Clo* value, the total S_{gen} is 1.63 J/sK. For the similar condition, the total S_{flow} is –1.79 J/sK. The contribution of the S_{flow} due to mass and heat transfer over this human body is –1.74 J/sK and –0.05 J/sK, respectively. In addition, the change in entropy content (ΔS) for this human body is –0.17 J/sK. On the average of one day, the change of entropy content for this body will be near zero ($2\cdot10^{-6}$ J/dayK). Here author just demonstrated the values used in the calculation and illustrated one example describing the results. In the subsequent paragraph author explain extensively some important observations from this study.

As shown in fig. 2, the S_{gen} per individual consists of two phases over the human life span: an early increasing stage (age 0-20) and a later decreasing stage (age 20-60). This trend can be called the "two-stage principle". These trends also observed in the earlier cases by Aoki [5, 12, and 19]. In literature, another "Uni-stage principle" proposed by Prigogine [9] states that the S_{gen} in organisms always decreases monotonously with time and approaches a minimum in a stationary level. From fig. 2, it is evident that Prigogine's principle does not hold for human life span. It should be emphasized that the minimum S_{gen} principle is valid only very near to thermodynamic equilibrium and that is essentially can not be applied to living systems, which are far from thermodynamic equilibrium. Another important thermodynamic quantity, which is also related to irreversibility, is energy or availability, which is a measure of the departure of system from its reference environment [20]. Since entropy production is proportional to energy annihilation according to Gouy-Stodola theorem [21], the "two-stage" hypothesis stated above is also applied to energy annihilation. The energy annihilation will show rapid increase in the development stage and gradual decrease in the later stage. This is an energy principle for human life span. As shown in fig. 2, it is noticed that the S_{gen} effects significantly due to various activity. The largest S_{gen} occurs due to very hard work and the least amount of S_{gen} occurs due to rest condition. The human body constantly produces heat, but at a varying rate. Metabolism is the biological processes within the body that leads to the production of heat [10]. The human body generates more heat when exerting physically in comparison to when at rest.

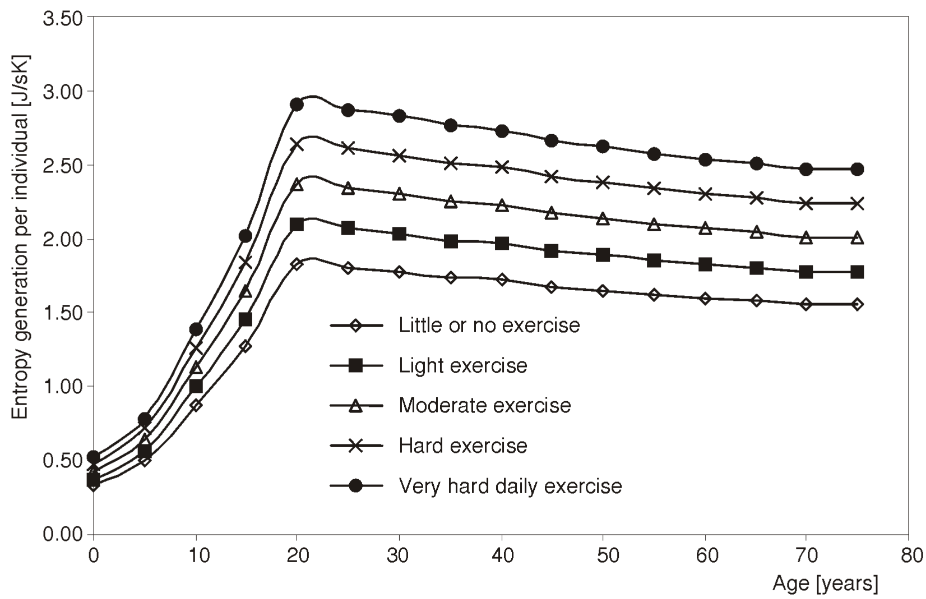

Figure 2. Entropy generation per individual with changing activity

Since human being is a warm-blooded creature, its body attempts to keep its internal temperature at constant level. Human life is only compatible with a narrow range of body temperatures (T_b) [22]. From an entropy generation viewpoint, it was noticed at the T_b of 44 °C value the human may pass away and before death the S_{gen} exceeds a certain optimum value. Similarly at T_b of 28 °C, the muscle failure occurs and the subsequent S_{gen} also exceeds the certain optimum value. Results show that, at T_b of 37 °C the S_{gen} reveals the least value. The optimum value of entropy generation is 1.22 J/sK at T_b of 37 °C value as the conditions described in this paper. For different conditions this optimum value will be differed considerably.

As shown in fig. 2, the S_{gen} at the age of 30 in violent exercise is 1.5-1.7 times as great as that in the rest conditions without exercise. The increase in the S_{gen} by violent exercise is 40% in this case. In addition, results indicate that the S_{gen} in involuntary violent contraction of the muscles and shivering of the body is 1.2-1.3 times as great as that in the normal conditions. Increase in the S_{gen} by chills is 20% in this case. Increase of the S_{gen} in exercise and malarial chills is accompanied by the increase of the heat production [24]. Aoki [6] and Hardy *et al*. [23] observed that before a chill the patient in malarial fever retains high level of the S_{gen} and after a chill the S_{gen} falls but does not reach the level before a chill within 2 hour. These characteristics (high level of the S_{gen} before and after a malarial chill) are contrasted to the case of chills in cold environments discussed in the later section. These are the characteristics of patient in malarial fever with the high S_{gen}.

Human body feels comfort at the ambient temperature (T_a) ranging from 22 to 35 °C [13]. As shown in fig. 3, the S_{gen} in sweating (above 35 °C) is 2.5-2.6 times as great as that in

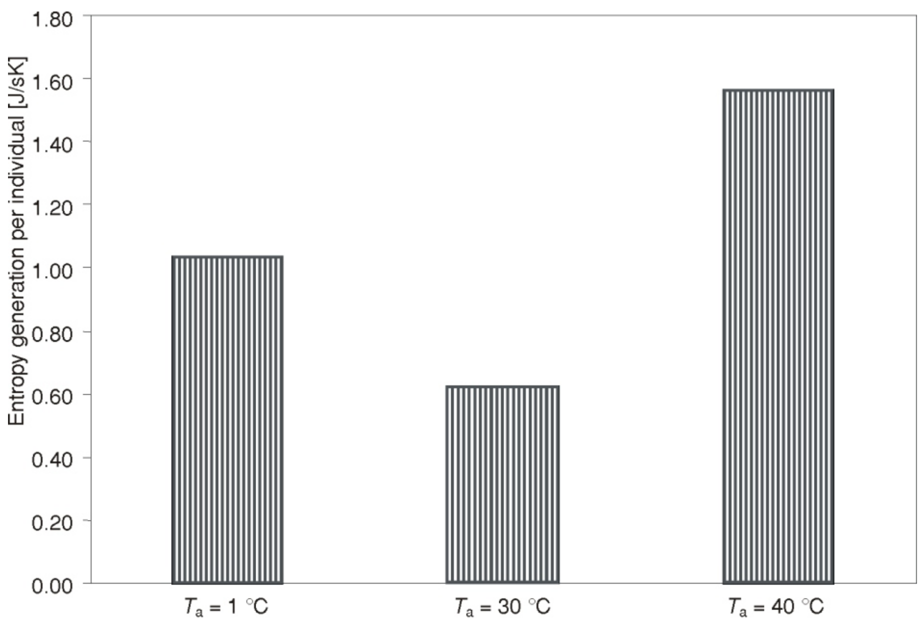

Figure 3. Concequences of the different T_a on entropy generation in human life

the normal conditions (30 °C). The increase in the S_{gen} by sweating is 60% in this case. When a human body in the T_a below 25 °C for an hour, the human being begins to feel shivering [6]. Shivering is a random, inefficient quivering of muscles. It produces heat at a rate five times greater than normal metabolic rate [6]. As shown in fig. 3, the S_{gen} in cold environment (1 °C) is 1.6-1.7 times as great as that in the normal conditions. Increase in the S_{gen} by shivering is 40% in this case. Hardy *et al.* [23] found in their experimental study that high metabolism rate is occurred in the high and low T_a and low metabolism is occurred at normal zone or TNZ zone.

As shown in fig. 4, the S_{gen} value increases as the skin temperature (T_s) of a human body increases. At the age of 25 years, increase in the S_{gen} is 19% due to 12% increase in the T_s. Similarly at the age of 60 years, increase in the S_{gen} is 19% due to 12% increase in the T_s and at the age of 5 years, increase in the S_{gen} is 23% due to 12% increase in the T_s. The T_s plays an important role in the S_{gen} as it maintains body temperature. In addition, entropy flow associated with the infrared radiation emitted by the A_r area of a human body and the entropy lost by convention largely depends on the T_s of a human body. The T_s is a function of the T_b, T_r, and sweating condition of a body.

As shown in fig. 5, the S_{gen} value increases as the rectal temperature (T_r) of a body increases. At the age of 25 years, increase in the S_{gen} is 20% due to 12% increase in the T_r. Similarly at the age of 60 years, increase in the S_{gen} is 17% due to 12% increase in the T_r and at the age of 5 years, increase in the S_{gen} is 13% due to 12% increase in the T_r. The T_r plays an important role in the S_{gen} as it maintains body temperature. In addition,

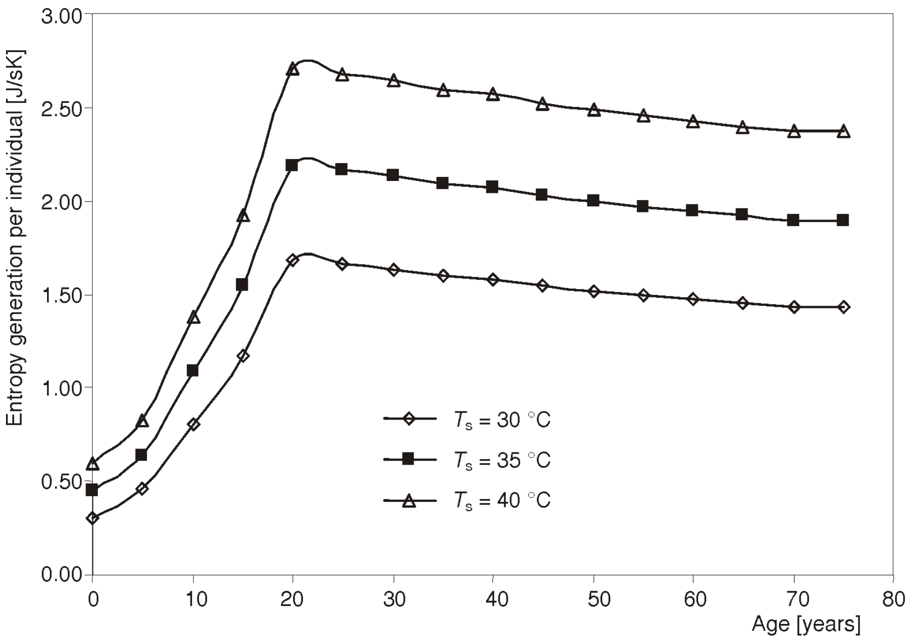

Figure 4. Consequences of the T_s on entropz generation in human life

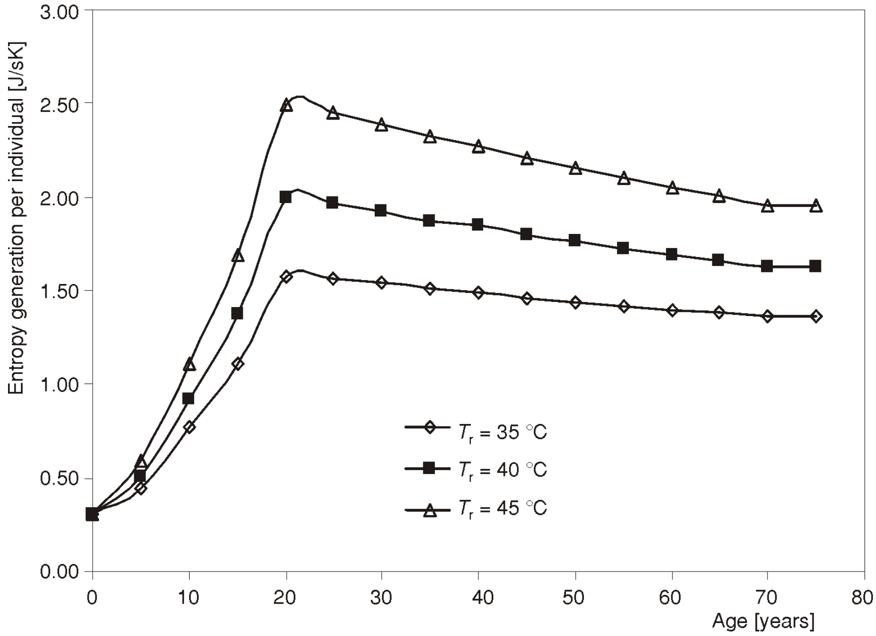

Figure 5. Consequences of the T_r on entropy generation in human life

entropy change in a human body and the entropy lost by evaporation largely depends on the T_b and consequently on the T_r of a human body.

Marsh [25] found that human body is highly responsive to changes in the *MRT*. As shown in fig. 6, the S_{gen} value decreases as the *MRT* value increases. At the age of 25 years, decrease in the S_{gen} is 55% due to 12% increase in the *MRT*. Similarly at the age of 60 years, decrease in the S_{gen} is 55% due to 12% increase in the *MRT* and at the age of 5 years, decrease in the S_{gen} is 53% due to 12% increase in *MRT*. The *MRT* plays an important role in entropy flow associated with infrared radiation emitted by surrounding surface area in which a human body resides.

As evidence of the importance of radiant heat exchange to the body's thermal equilibrium, physiologists have discovered that living human skin has extraordinarily high absorptivity and emissivity (0.97), greater than almost any other known substance [25]. Aoki [19] assumed the ε and η of the human skin to infrared radiation is equal to one. The S_{gen} increases as the value of the ε increases. At the age of 25 years, increase in the S_{gen} is 62% due to 12% increase in the ε. Similarly at the age of 60 years, increase in the S_{gen} is 62% due to 12% increase in the ε and at the age of 5 years, increase in the S_{gen} is 88% due to 12% increase in the ε. The ε plays an important role in entropy flow associated with infrared radiation emitted by the A_r area of a human body. Results indicate that, if the rate of the S_{out} value increases, the overall S_{gen} value also increases. It is noticed that 20% increase in the S_{gen} is occurred due to 1 J/sK value of the S_{out} increment.

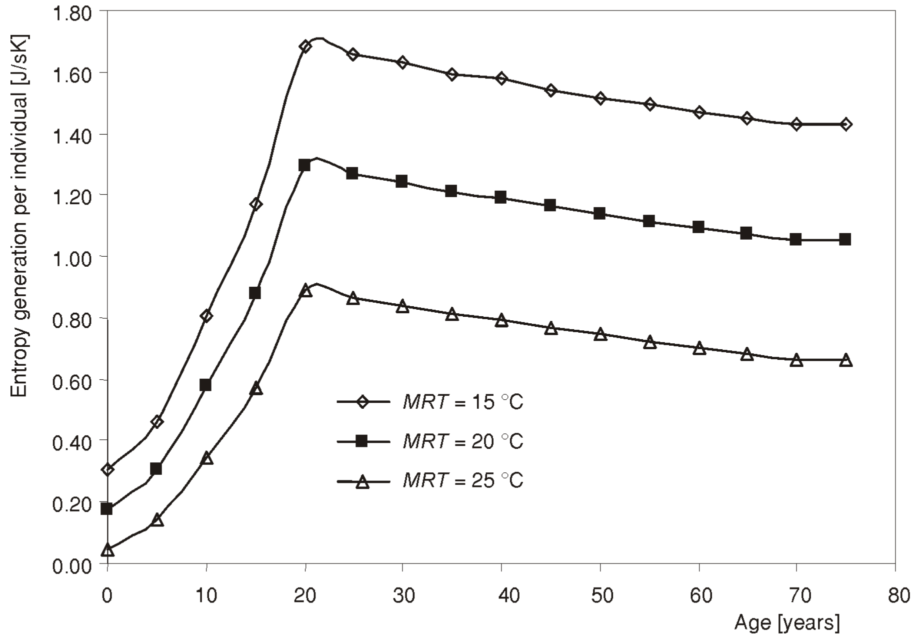

Figure 6. Consequences the *MRT* on entropy generation in human life

The S_{out} value depends on the T_s, A_r, and ε. Additionally, results show that the S_{gen} decreases as the η value increases. At the age of 25 years, decrease in the S_{gen} is 52% due to 12% increase in the η. Similarly at the age of 60 years, decrease in the S_{gen} is 52% due to 12% increase in the η and at the age of 5 years, decrease in the S_{gen} is 72% due to 12% increase in the η. The η plays an important role in entropy flow associated with infrared radiation emitted by surrounding surface area in which a human body resides. Results indicate that if the S_{in} value increases, the overall the S_{gen} value decreases. It is noticed that there is 47% decrease in the S_{gen} due to 1 J/sK increase in S_{in} value. The S_{in} value depends on the T_a, MRT, A_r, and η. Results also show that if the rate of the S_{cnv} increases the overall S_{gen} also increases. It is noticed that 10% increase in the S_{gen} is occurred due to 0.18 J/sK in the S_{cnv}. The S_{cnv} depends on the T_b, T_s, V_a, H, d, and μ. It also revealed that if the rate of the S_{evp} increases the overall S_{gen} also increases. It is noticed that 12% increase in the S_{gen} is occurred due to 0.18 J/sK increase in the S_{evp}. The S_{evp} depends on the T_b, T_s, corresponding vapor pressure, V_a, H, d, and μ. The S_{gen} decreases as water and oxygen intake into a human body increases. Similarly, the S_{gen} increases as water and oxygen outflow from a human body increases. It is noticed that 15% decrease in the S_{gen} is occurred due to 0.99 kmol/s increase in water intake and 34% decrease in the S_{gen} is occurred due to 1.98 kmol/s increase in oxygen intake. The amount of oxygen and water intake and outflow values were assumed constant throughout the calculation and the values were taken from Walker [26]. These values principally depend on the a, w, h, activity of human body, and the T_a and T_b. In this paper the entropy content of water and oxygen was varied due change in the T_a value. The Q_e and Q_p values were taken from Hardy *et al*. [3]. As shown in fig. 7 as the Q_e value increases, the S_{gen} decreases. At the age of 25 years, decrease in the S_{gen} is 6% due to 12% increase in the Q_e. Similarly at the age of 60 years, decrease in the S_{gen} is 6% due to 12% increase in the Q_e and at the age of 5 years, decrease in the S_{gen} is 13% due to 12% increase in the Q_e. As shown in fig. 8, if the Q_p increases the S_{gen} also increases. At the age of 25 years, increase in the S_{gen} is 0.70% due to 12% increase in the Q_p. Similarly at the age of 60 years, increase in the S_{gen} is 0.70% due to 12% increase in the Q_p and at the age of 5 years, increase in the S_{gen} is 4% due to 12% increase in the Q_p. The Q_e and Q_p values mainly depend on the T_r and corresponding T_b. The effects of the Q_e is more significant than that of the Q_p.

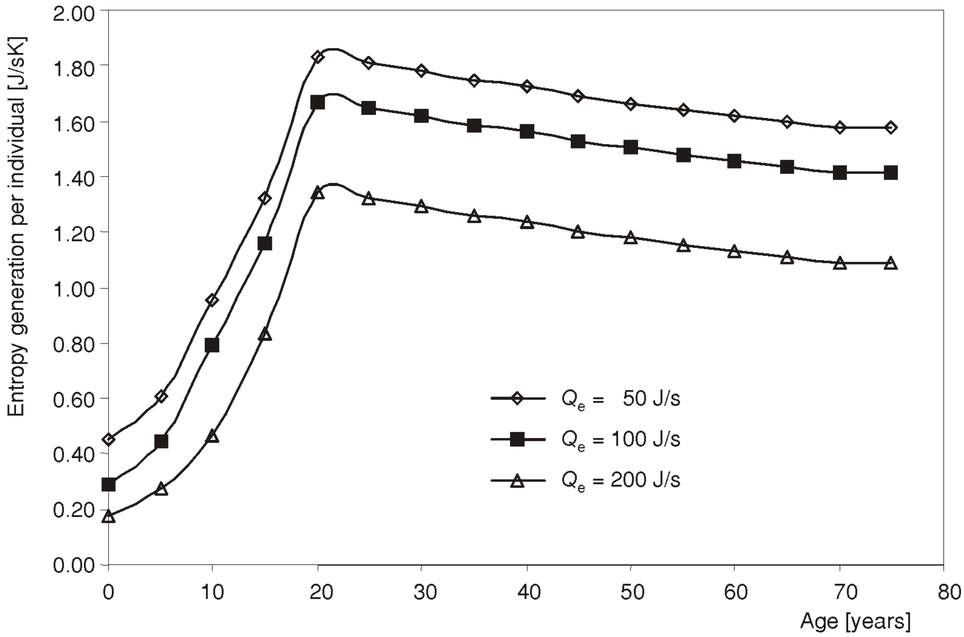

Figure 7. Consequences of the internal heat elimination on entropy generation in human life

Clo value is a numerical representation of a clothing ensembles the thermal resistance (1 *Clo* = 0.155 m^2K/W). In addition, clothing affects the latent heat transfer from the skin through the clothing layer and affects evaporative heat loss from skin surface. *Clo* values for different clothing conditions and the equations for *Clo* or i_m/Clo can be found out at [15] and [27]. As shown in fig. 9, at the age of 25 years, increase in the S_{gen} is 0.03% due to 12% increase in the *Clo* value. Similarly at the age of 60 years, increase in the S_{gen} is 0.03% due to 12% increase in the *Clo* value and at the age of 5 years, increase in

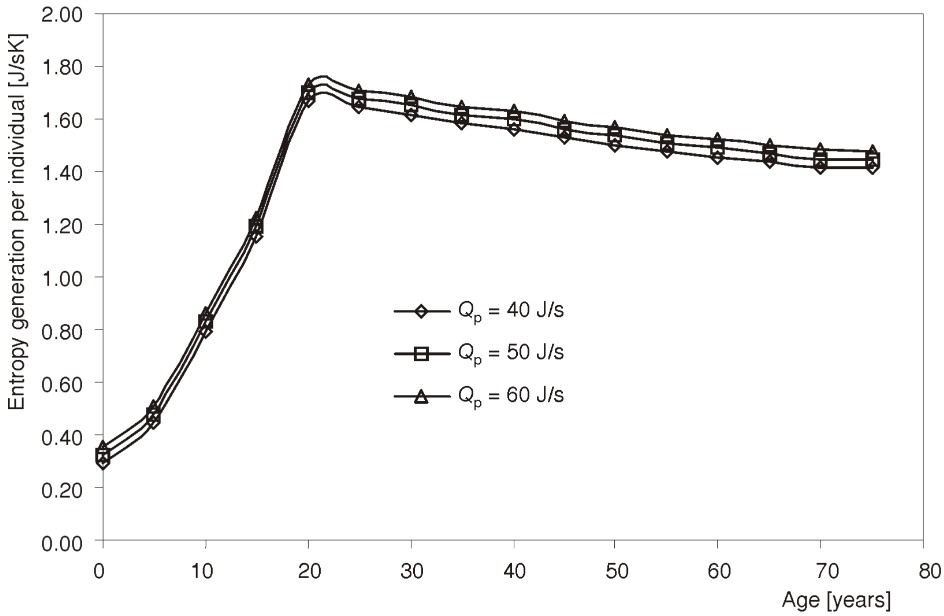

Figure 8. Consequences of internal heat production on entropy generation in human life

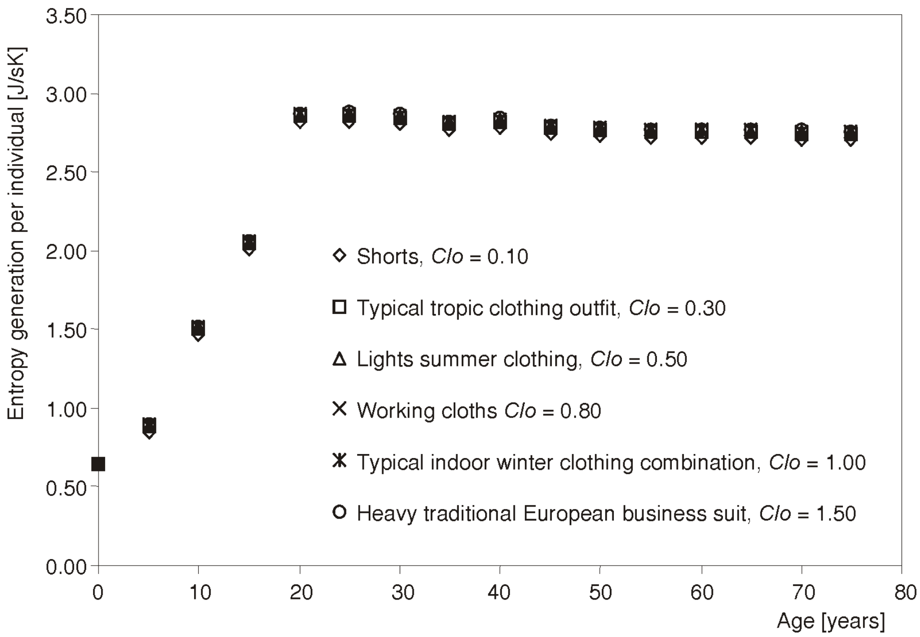

Figure 9. Consequence of clothing on entropy generation in human life

the S_{gen} is 0.3% due to 12% increase in the *Clo* value. Thus, the S_{gen} does not significantly change by clothing.

In fig. 10, it is evident that the effect of entropy flow due mass exchange of water and oxygen provides insignificant effect on the total S_{gen}. One the average of one day, water, oxygen, and food inflow and outflow and the corresponding entropy change (ΔS_{mass}) in a body will be very small. Similarly, one the average of one day the change of entropy content (ΔS) of a body will be near zero. Thus, the body is at steady-state in the long-term viewpoint (one the average of one day). In this investigation, it is found that the overall S_{gen} significantly depends on the entropy flow (ΔS_{energy}) due to heat transfer (radiation, convection, and evaporation) between a body and its surroundings. In fig. 10, it is noticed that the net entropy flow (ΔS_{energy}) into the human body due to heat transfer is negative. This means that the human body absorbs "negative entropy" from its surroundings. That is just the physical basis for the ordered structures and functions in the human body to be maintained [8]. Finally, the overall S_{gen} in a human body is positive. Thus, the SLT is valid in the human body.

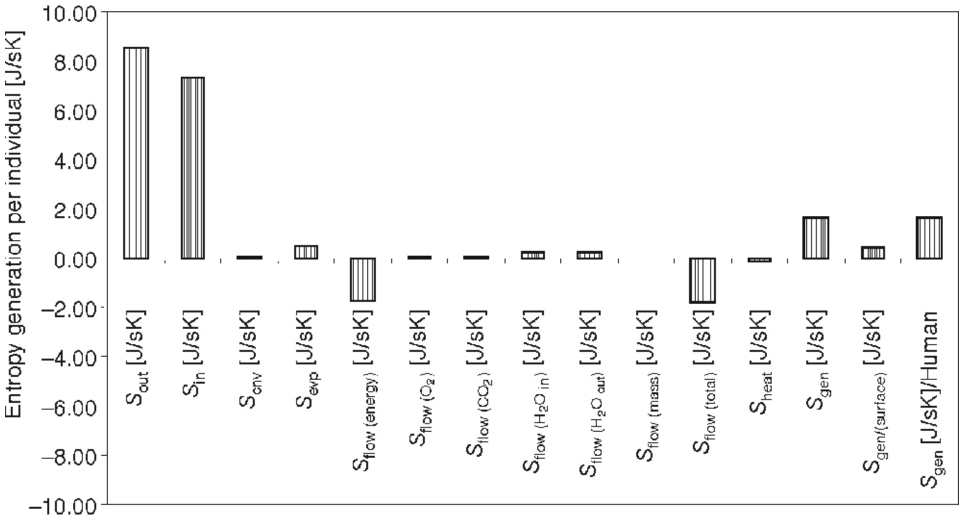

Figure 10. Influence of different parameters on entropy generation in a human body

Conclusions

At age of 30 years, men generate 11% more the S_{gen} compared to women for the particular conditions described in this paper. The rate of S_{gen} at first stage of life (0-20 years) increases rapidly. At the later stage (20+ years) the S_{gen} decreases gradually.

Activity increases the S_{gen} significantly due higher heat transfer from and to a body. As for example, at the violent exercise the S_{gen} is 40% higher compared to the rest condition. At death the S_{gen} is zero. In malarial chill, increase in the S_{gen} is 20%. In addition, at sweating and shivering increase in the S_{gen} is 60 and 40%, respectively.

At normal T_b (37 °C) the S_{gen} from a body is the least amount. At the T_b of 28 °C the muscle failure occurs and the corresponding S_{gen} is lager than the normal condition. Similarly, if the T_b exceeds 42 °C a human face death and the corresponding S_{gen} is higher than an optimum value.

Due to 12% increase in the T_s, T_r, MRT, η, and ε the corresponding S_{gen} increases is 19, 20, 55, 52, and 62%, respectively.

The effects of internal heat elimination (Q_e) and internal heat generation (Q_p) have considerable effects on the S_{gen}.

The effects of different clothing do not play a significant role in the S_{gen}. Only 0.03% increase in the S_{gen} due to 12% increase of the *Clo* value.

The overall S_{gen} in a human body is positive. Thus, the Second law of thermodynamics is valid in the human body.

Nomenclature

A_r – effective radiating surface area, [m^2]
A_s – average surface area of a human body, [m^2]
a – age, [years]
Clo – clothing coefficient
d – diameter of the body, [m]
E_{cnv} – energy loss by convection, [Js^{-1}]
E_{evp} – energy loss by evaporation, [Js^{-1}]
E_{max} – maximum evaporative capacity, [Js^{-1}]
E_{req} – required evaporative capacity [Js^{-1}]
E_{R+C} – required evaporative capacity due to *Clo* value, [Js^{-1}]
H – elevation, [m]
h – height, [m]
h_c – convective heat transfer coefficient, [$Wm^{-2}K^{-1}$]
h_e – evaporative heat transfer coefficient, [$Wm^{-2}K^{-1}$]
i_m – permeability index of clothing
M_{net} – net metabolic rate, [Js^{-1}]
$M(CO_2)$ – amount of CO_2 liberation, [$mols^{-1}$]
$M(O_2)$ – amount of O_2 uptake, [$mols^{-1}$]
$M(H_2O_{in})$ – amount of H_2O uptake, [$mols^{-1}$]
$M(H_2O_{out})$ – amount of H_2O liberation, [$mols^{-1}$]
P – atmospheric pressure, [hPa]
P_0 – atmospheric pressure at sea level, [hPa]
ΔP – pressure difference, [hPa]
Q_e – heat eliminated from the body, [Js^{-1}]
Q_p – heat produced in the body, [Js^{-1}]
ΔQ – change of (internal) energy of the body, [Js^{-1}]
S_{cnv} – entropy generation rate loss by convection, [$Js^{-1}K^{-1}$]

S_{evp} – entropy generation rate loss by evaporation, [$Js^{-1}K^{-1}$]
S_{flow} – total entropy generation rate flow into body due to energy and mass exchange, [$Js^{-1}K^{-1}$]
$S_{flow\ (energy)}$ – net entropy generation rate flow into body due to energy exchange, [$Js^{-1}K^{-1}$]
$S_{flow\ (mass)}$ – net entropy generation rate flow into body due to mass exchange, [$Js^{-1}K^{-1}$]
S_{gen} – entropy generation rate from a human body, [$Js^{-1}K^{-1}$]
$S_{gen\ (human)}$ – entropy generation rate within the body per human individual, [$Js^{-1}K^{-1}$]
S_{in} – entropy generation rate flow associated with infrared radiation emitted by the surrounding walls and absorbed by the human body, [$Js^{-1}K^{-1}$]
S_{mtb} – metabolic entropy generation rate, [$Js^{-1}K^{-1}$]
S_{out} – entropy generation rate flow associated with infrared radiation emitted by the human body, [$Js^{-1}K^{-1}$]
$S(CO_2)$ – entropy content rate of CO_2 liberation, [$Js^{-1}mol^{-1}$]
$S(H_2O)$ – entropy content rate of H_2O, [$Js^{-1}mol^{-1}$]
$S(O_2)$ – entropy content rate of O_2 uptake, [$Js^{-1}mol^{-1}$]
ΔS – change in the entropy content in the body, [$Js^{-1}K^{-1}$]
T_a – ambient temperature, [°C]
T_b – body temperature, [°C]
T_s – average skin temperature, [°C]
T_r – rectal temperature, [°C]
T_1 – head temperature, [°C]
T_2 – arms temperature, [°C]
T_3 – hands temperature, [°C]
T_4 – feet temperature, [°C]
T_5 – legs temperature, [°C]
T_6 – thighs temperature, [°C]
T_7 – trunk temperature, [°C]
ΔT – temperature difference, [°C]
V_a – air speed, [ms^{-1}]
v – wind velocity, [ms^{-1}]
w – body mass, [kg]

Greek symbols

ε – emissivity of the human skin for infrared radiation
η – absorbity of the human skin for infrared radiation
μ – dynamic viscosity, [$kgm^{-1}s^{-1}$]
σ – Stefan-Boltzmann constant, [$5.67 \cdot 10^{-8}$ $Jm^{-2}s^{-1}K^{-4}$]
ϕ – relative humidity, [%]

Abbreviations

FLT – First law of thermodynamics
MRT – mean radiant temperature, [°C]
SLT – Second law of thermodynamics
TNZ – thermally neutral zone

References

[1] Fanger, O. P., Conditions for Thermal Comfort – Introduction of a General Comfort Equation, in: Physiological and Behavioural Temperature Regulation (Eds. J. D. Hardy, A. P. Gagge, J. A. J. Stolwijk), Thomas, Springfield, III., 1970, pp. 152-176
[2] Kandjov, I. M., Heat and Mass Exchange Processes between the Surface of the Human Body and Ambient Air at Various Altitudes, *Int. J. Biometeorol, 43* (1999), 1, pp. 38-44
[3] Hardy, J. D., DuBois, E. F., Differences between Men and Women in Their Response to Heat and Cold, *Proceedings Nat. Acad. Sci.*, USA, 26, 1940, pp. 389-398
[4] Hardy, J. D., DuBois, E. F., Basal Metabolism, Radiation, Convection and Vaporization at Temperatures of 22-35 °C, *J. Nutr. 15* (1938), 5, pp. 477-497
[5] Aoki, I., Entropy Principle for Human Development, Growth and Aging, *J. Theor. Biol., 150* (1991), 2, pp. 215-223
[6] Aoki, I., Effects of Exercise and Chills on Entropy Production in Human body, *J. Theor. Biol., 145* (1990), 3, pp. 421-428
[7] Aoki, I., Entropy Balance of White-Tailed Deer during a Winter Night, *Bull. Math. Biol., 49* (1987), 3, pp. 321-327
[8] Aoki, I., Entropy Flow and Entropy Production in the Human Body in Basal Conditions, *J. Theor. Biol., 141* (1989), 1, pp. 11-21
[9] Nicolis, G., Prigogine, I., Self-Organization in Nonequilibrium Systems, John Wiley and Sons – Interscience, NewYork, USA, 1977
[10] Bauman, F., ASHRAE, Standard 55-2004, Thermal Environmental Conditions for Human Occupancy, http://www.cbe.berkeley.edu/underfloorair/thermalcomfort.htm
[11] Hardy, J. D., Milhorat, A. T., DuBois, E. F., The Effect of Forced Air Currents and Clothing on Radiation and Convection, *J. Nutr., 15* (1938), 6, pp. 583-595
[12] Aoki, I., Entropy Production in Human Life Span: A Thermodynamical Measure for Aging, *AGE: Journal of the American Aging Association, 17* (1994), 1, pp. 29-31
[13] Hardy, J. D., Milhorat, A. T., Basal Heat Loss and Production in Woman at Temperatures from 23 to 36, *Proceedings Soc. Exp. Biol. Med., 41* (1939), 1, pp. 94-98
[14] Hardy, J. D., The Radiation of Heat from the Human Body, *J. Clin. Invest., 13* (1934), 4, pp. 615-620
[15] Givoni, B., Goldlman, R. F., Predicting Rectal Temperature Response to Work, Environment, and Clothing, *Journal of Applied Physiology, 32* (1972), 6, pp. 812-822
[16] Burton, A. C., The Application of the Theory of Heat Flow to the Study of Energy Metabolism, *J. Nutrition, 7* (1934), 5, pp. 497-533
[17] DuBois, D., DuBois, E. F., A Formula to Estimate the Approximate Surface Area if Height and Weight be Known, *Arch Int. Med., 17* (1916), 6, pp. 863-871
[18] DuBois, E. F., Ebaugh, F. G., Hardy, J. D., Basal Heat Production and Elimination of Thirteen Normal Women at Temperatures from 22 Degrees C, to 35 Degrees C, *J. Nutr., 48* (1952), 2, pp. 257-293
[19] Aoki, I., Entropy Production in Living Systems: From Organisms to Ecosystems, *Thermochimica ACTA, 250* (1995), 2, pp. 359-370
[20] Moran, M. J., Availability Analysis: A Guide to Efficient Energy Use, Prentice Hall, Englewood Cliffs, NJ, USA,1982
[21] Bejan, A., Entropy Generation through Heat and Fluid Flow, John Wiley and Sons, New York, USA, 1982
[22] Koehler, K. R., Body Temperature Regulation, 1996, http://www.rwc.uc.edu/koehler/biophys/8d.html
[23] Hardy, J. D., Milhorat, A. T., DuBois, E. F., The Effect of Exercise and Chills on Heat Loss from the Nude Body, *J. Nutr., 16* (1938), 5, pp. 477-492
[24] Hardy, J. D., Soderstorm, G. F., Heat Loss from the Nude Body and Peripheral Blood Flow at Temperatures of 22 Degrees C, to 32 Degrees C, *J. Nutr., 16* (1938), 5, pp. 493-510

[25] Marsh, A., Raines, C., Human Comfort, Square One, Welsh School of Architecture, Cardiff University, 2004, http://www.squ1.com/comfort/comfort.html
[26] Walker, J., Input/Output, Sausalito, Cal., USA, 1991 http://www.fourmilab.ch/hackdiet/www/tableofcontents1_6.html
[27] Pezzagno, G., Heat Exchange between the Human Body and the Environment, *Giornale italiano di medicina del lavoro ed ergonomia, 21* (1999), 3, pp. 159-205

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