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Application of Energy and Exergy Analyses to the Human Body

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Abstract

The aim of this study is to apply energy and exergy analyses to the human body under the different metabolic rates and outdoor air temperatures. For this aim, air temperature, relative and specific humidity, wind speed and atmospheric pressure data in the indoor and outdoor atmospheric conditions of the room were used. Radiative, convective and evaporative heat losses from the human body based on skin surface and respiration were obtained by using the energy balance equation. In addition, exergy destruction and exergy efficiency values were determined by using the entropy and exergy balance equations. According to the obtained results, human body's heat loss, exergy destruction and exergy efficiency values were considerably influenced from the change in the human metabolic rate and outdoor air temperature.

Keywords: Human body, human heat loss, entropy generation, exergy destruction, exergy efficiency.

INTRODUCTION

The heat, which is not converted into work by the metabolism of the human body, must be transferred to the environment in order to feel comfortable and survive with health. This heat, however, exchanges with the indoor and outdoor atmospheric conditions of the room due to the human body's metabolism and activity. These exchange mechanisms are of great importance for thermal comfort of the human body. In this context, exergy analysis is used to assess the quality of energy conversion processes that occur in the human body during physical exercise, which aims to implement performance indicators based on the concepts of exergy destruction rate and exergy efficiency (Mady et al., 2012).

90% of heat is released from the skin of the human body, while the remaining 10% is released via the respiratory system. Given the influence a decrease in respiratory evaporative heat loss has on gradients of temperature between the cranium and thorax, the hyperthermia-induced heat loss from the upper airways could have an impact on brain temperatures. For this reason, analysis of heat loss and exergy flow occurring through respiration of the human body is a vital concern in terms of thermal comfort and health (White and Cabanac, 1995).

Exergy analysis based on first and second laws of thermodynamics describes a complete working process of system including destruction and entropy generation considering the reference temperature (Caliskan, 2013). According to the second law of thermodynamics, minimal human body exergy destruction will coincide with relatively maximal useful work performed by the human body, in other words with optimal human performance. Hence, human body exergy destruction may be used to describe the state of human performance under different meteorological conditions (Wu et al., 2013). In this study, total heat loss from the human body was obtained by using the energy balance equation. In addition, exergy destruction and exergy efficiency values were determined by using the entropy and exergy balance equations.

MATERIALS AND METHODS

Energy Analysis

In the steady-state energy balance model developed by Fanger (1970; 1982), when the body is in a state of heat balance, the energy storage in the body is considered to be negligible. This energy balance is expressed in the equation shown below (Bilgili et al., 2015; Gebremedhin and Wu, 2002)

$$\mathrm{M-W=(C+R+E_{sk})+(C_{res}+E_{res})}$$

$$\mathrm{M-W=(C+R+E_{sk})+(C_{res}+E_{res})} \quad (1)$$

where all terms have units of W/m^2 and, M is the rate of metabolic energy production, W is the rate of mechanical work, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, Esk is the rate of total evaporative heat loss from the skin, Cres is the rate of convective heat loss from respiration and Eres is the rate of evaporative heat loss from respiration. Heat loss through clothing (conduction, convection and radiation) is defined as (Parsons, 2002);

$$\mathrm{C+R=(T_{sk}-T_0)/(R_{cl}+\frac{1}{f_{cl}.h})}$$

$$\mathrm{C+R=(T_{sk}-T_0)/(R_{cl}+\frac{1}{f_{cl}.h})} \quad (2)$$

where T_{sk} (^{o}C) is mean skin temperature, T_o (^{o}C) is operative temperature, R_{cl} (m2KW-1) is thermal resistance of clothing, f_{cl} is clothing area factor and h (Wm-2K-1) is combined heat transfer coefficient. Evaporative heat loss from the skin is calculated as (Parsons, 2002);

$$E_{sk}=w(P_{sk,s}-P_a)/(\mathrm{R_{e,cl}}+\frac{1}{\mathrm{f_{cl}}.h_e})$$

$$E_{sk}=w(P_{sk,s}-P_a)/(\mathrm{R_{e,cl}}+\frac{1}{\mathrm{f_{cl}}.h_e}) \quad (3)$$

where w is skin wettedness, $P_{sk,s}$ (kPa) is water vapor pressure at the skin, Pa (kPa) water vapor pressure in the ambient air, $R_{e,cl}$ (m2kPaW-1) is evaporative heat transfer resistance of the clothing layer and he (Wm-2kPa-1) is evaporative heat transfer coefficient. Convective and evaporative heat losses associated with respiration are represented by the following equations:

$$C_{res} = \dot{m}_{res} C_{p,a} (T_{ex} - T_a)/A_D$$

$$C_{res} = \dot{m}_{res} C_{p,a} (T_{ex} - T_a)/A_D \qquad (4)$$

$$E_{res} = \dot{m}_{res} h_{fg} (W_{ex} - W_a)/A_D$$

$$E_{res} = \dot{m}_{res} h_{fg} (W_{ex} - W_a)/A_D \qquad (5)$$

In these equations, $\dot{m}_{res}\dot{m}_{res}$ (kg/s) denotes inhaled air flow rate, W_{ex} (kg H_2O/kg dry air) is the specific humidity of exhaled air, T_{ex} (^oC) is expelled air temperature, W_a (kg H_2O/kg dry air) is specific humidity of the inhaled ambient air, $C_{p,a}$ (kJ/kg.K) is the specific heat capacity of ambient air, T_a (^oC) is the ambient air temperature and h_{fg} (kJ/kg.K) is the evaporative heat of the vaporization of water.

Exergy Analysis

The exergy balance equation of the human body can be expressed as follows (Caliskan, 2013):

$$\dot{E}x_{M,gen} + \dot{E}x_{gen,core} + \dot{E}x_{gen,shell} + \dot{E}x_{abs,rad} + \dot{E}x_{inh,air} = \dot{E}x_{disch,rad} + \dot{E}x_{conv} + \dot{E}x_{exh,air} + \dot{E}x_{sweat} + \dot{E}x_{stored,core} + \dot{E}x_{stored,shell} + \dot{E}x_{cons} \qquad (6)$$

where $\dot{E}x_{M,gen}\dot{E}x_{M,gen}$ is the metabolic exergy generation, $\dot{E}x_{gen,core}\dot{E}x_{gen,core}$ is the exergy generation of the liquid water in the core, $\dot{E}x_{gen,shell}\dot{E}x_{gen,shell}$ is the exergy generation of the liquid water/dry air in the shell, $\dot{E}x_{abs,rad}\dot{E}x_{abs,rad}$ is the absorbed radiant exergy rate by the body surface, $\dot{E}x_{inh,air}\dot{E}x_{inh,air}$ is the inhaled humid air exergy rate, $\dot{E}x_{disch,rad}\dot{E}x_{disch,rad}$ is the discharged radiant exergy rate from the body surface, $\dot{E}x_{conv}\dot{E}x_{conv}$ is the convection exergy rate to the air, $\dot{E}x_{exh,air}\dot{E}x_{exh,air}$ the exhaled humid air exergy rate, $\dot{E}x_{sweat}\dot{E}x_{sweat}$ is the water vapor/air exergy rate from the sweat, $\dot{E}x_{stored,core}\dot{E}x_{stored,core}$ is the stored exergy rate in the core, $\dot{E}x_{stored,shell}\dot{E}x_{stored,shell}$ is the stored exergy rate in the shell, and $\dot{E}x_{cons}\dot{E}x_{cons}$ is the exergy consumption rate.

The metabolic exergy generation is defined by (Caliskan, 2013)

$$\dot{E}x_{M,gen} = \dot{E}n_{M,gen}\left(1 - \frac{T_o}{T_{cr}}\right)$$

$$\dot{E}x_{M,gen} = \dot{E}n_{M,gen}\left(1 - \frac{T_o}{T_{cr}}\right) \qquad (7)$$

where T_o and T_{cr} are the outdoor air (environmental) and body core temperatures, respectively. The exergy generation of the liquid water in the core is determined from

where "$V_{w,core}V_{w,core}$", "$\rho_w\rho_w$", "$c_{p,w}c_{p,w}$", "R", "$X_w X_w$", "$P_{sv,T_o}P_{sv,T_o}$" and "$P_{vo}P_{vo}$" are the velocity of the liquid water generated in the body core, the density of the liquid water, the specific heat capacity of the liquid water, the gas constant, the molar mass of water molecules, the saturated water vapor pressure at reference temperature and the water vapor pressure of the reference air, respectively. The exergy generation of the liquid water/dry air in the shell is calculated as

$$\dot{E}x_{gen,shell} = V_{w,shell}\rho_w\left\{c_{p,w}\left[(T_{sk} - T_o) - T_o\left(\ln\frac{T_{sk}}{T_o}\right)\right] + \frac{R}{X_w}T_o\left[\left(\ln\frac{P_{sv,T_o}}{P_{vo}}\right) + \frac{P-P_{vr}}{P_{vr}}\left(\ln\frac{P-P_{vr}}{P-P_{vo}}\right)\right]\right\}$$

where "$V_{w,shell}V_{w,shell}$", "$T_{sk}T_{sk}$", "P", and "$P_{vr}P_{vr}$" are the velocity of the liquid water generated in the body shell, the skin temperature, the atmospheric air pressure and the water vapor pressure in the room space, respectively. The absorbed radiant exergy rate by the body surface is found by (Caliskan, 2013)

$$\dot{E}x_{abs,rad} = f_{ef} f_{cl} a_i \varepsilon_{cl} h_{rb}\frac{(T_i - T_o)^2}{(T_i + T_o)}$$

$$\dot{E}x_{abs,rad} = f_{ef} f_{cl} a_i \varepsilon_{cl} h_{rb}\frac{(T_i - T_o)^2}{(T_i + T_o)} \qquad (10)$$

where "$f_{ef}f_{ef}$", "f_{cl}", "a_i", "$\varepsilon_{cl}\varepsilon_{cl}$", "$h_{rb}h_{rb}$" and "$T_i$" are the ratio of the effective area of the human body, the clothing area factor, the absorption coefficient, the emittance of clothing surface, the relative heat transfer coefficient of a black surface, and the surface temperature, respectively. The inhaled humid air exergy rate is defined as

$$\dot{E}x_{inh,air} = V_{in}\left\{\left[c_{p,a}\left(\frac{X_{da}}{RT_{ra}}\right)(P - P_{vr}) + c_{p,v}\left(\frac{X_w}{RT_{ra}}\right)P_{vr}\right] x \left[(T_{ra} - T_o) - T_o\left(\ln\frac{T_{ra}}{T_o}\right)\right] + \frac{T_o}{T_{ra}}[(P - P_{vr})]\left(\ln\frac{P-P_{vr}}{P-P_{vo}}\right) + P_{vr}\left(\ln\frac{P_{vr}}{P_{vo}}\right)\right\}$$

where "$V_{in}V_{in}$", "$c_{p,a}$", "X_{da}", "$c_{p,v}c_{p,v}$", and "T_{ra}" are the velocity of inhaled air, the specific heat capacity of the dry air, the molar mass of the dry air, the specific heat capacity of the water vapor and the room air temperature, respectively. The discharged radiant exergy rate from the body surface is expressed to be

$$\dot{E}x_{disch,rad} = f_{ef} f_{cl} \varepsilon_{cl} h_{rb}\frac{(T_{cl} - T_o)^2}{(T_{cl} + T_o)}$$

$$\dot{E}x_{disch,rad} = f_{ef} f_{cl} \varepsilon_{cl} h_{rb}\frac{(T_{cl} - T_o)^2}{(T_{cl} + T_o)} \qquad (12)$$

The convection exergy rate to the air is computed as (Caliskan, 2013)

$$\dot{E}x_{conv} = f_{cl} h_{ccl} (T_{cl} - T_{ra}) \left(1 - \frac{T_o}{T_{cl}}\right)$$

$$\dot{E}x_{conv} = f_{cl} h_{ccl} (T_{cl} - T_{ra}) \left(1 - \frac{T_o}{T_{cl}}\right) \quad (13)$$

where $h_{ccl} h_{ccl}$ is the average convective heat transfer coefficient over clothed body surface. The exhaled humid air exergy rate is determined as

$$\dot{E}x_{exh,air} = V_{out} \left\{ \left[c_{p,a} \left(\frac{X_{da}}{RT_{cr}}\right) (P - P_{sv,T_{cr}}) + c_{p,v} \left(\frac{X_w}{RT_{cr}}\right) P_{sv,T_{cr}} \right] x \left[(T_{cr} - T_o) - T_o \left(\ln \frac{T_{cr}}{T_o}\right) \right] + \frac{T_o}{T_{cr}} [(P - P_{sv,T_{cr}})] \left(\ln \frac{P - P_{sv,T_{cr}}}{P - P_{vo}}\right) + P_{sv,T_{cr}} \left(\ln \frac{P_{sv,T_{cr}}}{P_{vo}}\right) \right\}$$

where $V_{out} V_{out}$ and $P_{sv,T_{cr}} P_{sv,T_{cr}}$ the velocity of the exhaled air and the saturated water vapor pressure at body core temperature, respectively. The water vapor/air exergy rate from the sweat can be determined as

$$\dot{E}x_{sweat} = V_{w,shell} \rho_w \left\{ c_{p,v} \left[(T_{cl} - T_o) - T_o \left(\ln \frac{T_{cl}}{T_o}\right) \right] + \frac{R}{X_w} T_o \left[\left(\ln \frac{P_{vr}}{P_{vo}}\right) + \frac{P - P_{vr}}{P_{vr}} \left(\ln \frac{P - P_{vr}}{P - P_{vo}}\right) \right] \right\}$$

The stored exergy rates in the core and shell are determined by (Caliskan, 2013)

$$\dot{E}x_{stored,core} = \dot{Q}_{core} \left(1 - \frac{T_o}{T_{cr}}\right)$$

$$\dot{E}x_{stored,core} = \dot{Q}_{core} \left(1 - \frac{T_o}{T_{cr}}\right) \quad (16)$$

$$\dot{E}x_{stored,shell} = \dot{Q}_{shell} \left(1 - \frac{T_o}{T_{sk}}\right)$$

$$\dot{E}x_{stored,shell} = \dot{Q}_{shell} \left(1 - \frac{T_o}{T_{sk}}\right) \quad (17)$$

where $\dot{Q}_{core} \dot{Q}_{core}$ and $\dot{Q}_{shell} \dot{Q}_{shell}$ are the heat capacities of the body core and shell, respectively.

RESULTS and DISCUSSION

The individual envisioned for the study has a mass of 70 kg and a height of 1.73 m. The individual's internal body temperature and skin temperature were fixed at 36.8 oC and 33.7 oC, respectively, in accordance with the steady-state energy balance model. The DuBois surface area of the individual was determined to be 1.8 m2. The indoor and outdoor weather data, the human body physiological characteristics, clothing properties, heat conduction and radiation coefficients, which are selected in accordance with the values recommended by ASHRAE, are given in Table 1. Required and selected parameters for exergy analysis are given in Table 2.

Figure 1 shows the variation of the human body's heat losses in the case of different metabolic heat production. As can be seen from the figure, required evaporative heat loss from the skin and, convective and evaporative heat losses from respiration are increasing with the increasing metabolic heat production. However, convective and radiative heat losses from the skin remain constant. Because the convective and radiative heat losses from the skin, which is independent of the metabolic heat production, is particularly dependent on the skin and equivalent temperatures, and clothing properties. On the other hand, required evaporative heat loss from the skin and, convective and evaporative heat losses from respiration have a property that is directly affected from the change in the metabolic heat production. Thus, especially required evaporative heat loss from the skin increases rapidly with the increase in metabolic heat production. Apart from these, respiratory heat losses are lower than evaporative, convective and radiative heat losses from the skin.

Figure 2 shows the variation of the required skin wettedness under the different level of human activity. As seen from the figure, the required skin wittedness ratio increases with the increase in the metabolic heat production. An increase in required skin wettedness also leads to an increase in the evaporative heat loss from the skin. To achieve thermal equilibrium, the temperature control mechanism enters into action with increasing the human activity level. In the control of the body temperature, the warm signals from the skin effect more the body sweating than vasodilation. For this reason, the required skin wettedness ratio and evaporative heat loss from the skin increase at a certain level. For example, when the human activity level increases from 1 Met to 2.5 Met, the required skin wettedness ratio reaches from 15% to 100%.

Table 1. Selected parameters for energy analysis

Parameter	**Symbol**	**Value**
Body mass	m	70 kg
Body height	l	1.73 m
Dubois body surface area	AD	1.8 m2
Skin temperature	Tsk	33.7 oC
Core temperature	Tcr	36.8 oC
Cloth temperature	Tcl	30.23 oC
Outdoor air temperature	Ta	4-38 oC
Room air temperature	Tra	25 oC
Operative temperature	To	25 oC
Expelled air temperature	Tex	34.57 oC
Relative humidity of outdoor air	RHa	70 %
Relative humidity of room air	RHra	50 %
Specific humidity of exhaled air	Wex	0.0313 kg H2O/kg dry air
Specific humidity of inhaled air	Wa	0.00987 kg H2O/kg dry air
Air speed	Vair	0.15 m/s
Atmospheric air pressure	P	101.325 kPa
Inhaled air flow rate	$\dot{m}_{res}$	0.00015 kg/s
Skin wettedness	w	16-100 %
Thermal resistance of clothing	Rcl	0.08835 m2K/W
Clothing area factor	fcl	1.15
Combined heat transfer coefficient	h	6.52 W/m2K
Conduction coefficient	hc	1.8195 W/m2K
Heat transfer through linear radiation coefficient	hr	4.7 W/m2K
Heat transfer through evaporation coefficient	he	30.0217 W/m2kPa
Evaporative heat transfer resistance of the clothing layer	Re,cl	0.01245 m2kPa/W
Evaporation permeability efficiency of clothing	icl	0.43
Clothing insulation	Icl	0.57 clo
Metabolic energy production	M	1-2.5 Met
Lewis rate	LR	16.5 oC/kPa

Table 2. Selected parameters for exergy analysis

Parameter	Symbol	Value
The ratio of the effective area of the human body	fef	0.725
Absorption coefficient	ai	0.42731
Radiative heat transfer coefficient of a black surface	hrb	6.3 W/m2K
Emittance of clothing surface	εcl	0.955
Average convective heat transfer coefficient over clothed body surface	hccl	3.0825 W/m2K
Temperature surface	Ti	33.7 oC
Velocity of inhaled air	Vin	6.99 x 10-5 m/s
Velocity of liquid water generated in body core	Vw,core	1.95 x 10-9 m/s
Velocity of liquid water generated in body shell as sweat	Vw,shell	4.79 x 10-9 m/s
Velocity of the exhaled air	Vout	4.28 x 10-5 m/s
Specific heat capacity of dry air	Cp,a	1.005 kJ/kgK
Molar mass of dry air	Ra	28.97 g/mol
Gas constant	R	8.314 J/molK
Specific heat capacity of water vapor	Cp,v	1.846 kJ/kgK
Molar mass of water molecules	Rw	18.05 g/mol
Specific heat capacity of liquid water	Cp,w	4.186 kJ/kgK
Density of liquid water	ρw	1000 kg/m3

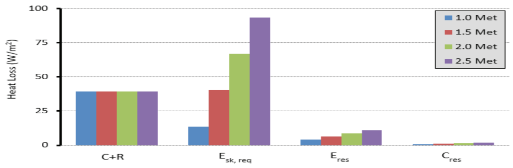

Figure 1. Variation of the human body's heat losses in the case of different metabolic heat production

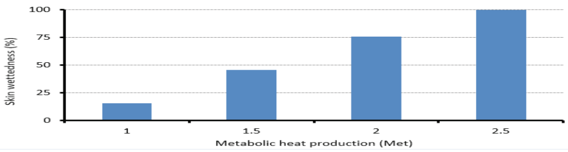

Figure 2. The variation of the required skin wettedness under the different level of human activity

Figure 3 presents the variation of the exergy destruction with respect to outdoor air temperature. As seen from the figure, the exergy destruction increases with the increase in the metabolic heat production. On the other hand, for all metabolic heat productions except 1 Met, the exergy destruction values decrease with the increase in the outdoor air temperature. Furthermore, when the outdoor air temperature is 36.8 °C, the exergy destructions for all human activity levels occur at the same value. At this temperature, which is equal to the core temperature of the body and can be expressed as a critical value, a turning point is formed. The value of exergy destruction obtained at this point is 1.5 W/m².

The variation of the exergy efficiency under the different activity levels with respect to outdoor air temperature is presented in Figure 4. As seen from the figure, firstly, the exergy efficiency values decrease with the increase in the outdoor air temperature. However, after the outdoor air temperature reaches to 32 °C, the exergy efficiency values increase. Similar to the case of the variation of the exergy destruction with respect to outdoor air temperature, when the outside air temperature is 36.8 °C, there is also a turning point in the variation of the exergy efficiency.

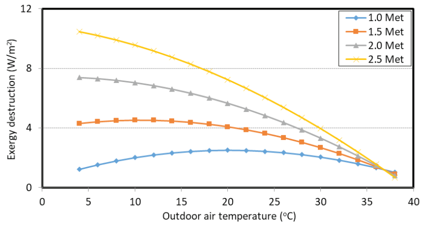

Figure 3. The variation of the exergy destruction with respect to outdoor air temperature

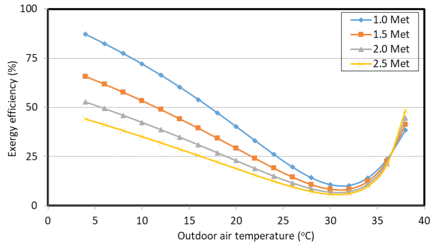

Figure 4. The variation of the exergy efficiency under the different activity levels with respect to outdoor air temperature

CONCLUSIONS

- Required evaporative heat loss from the skin and, convective and evaporative heat losses from respiration are increasing with the increasing metabolic heat production. However, convective and radiative heat losses from the skin remain constant.
- The required skin wettedness ratio increases with the increase in the metabolic heat production. When the human activity level increases from 1 Met to 2.5 Met, the required skin wettedness ratio reaches from 15% to 100%.
- The exergy destruction increases with the increase in the metabolic heat production. On the other hand, for all metabolic heat productions except 1 Met, the exergy destruction values decrease with the increase in the outdoor air temperature.
- Firstly, the exergy efficiency values decrease with the increase in the outdoor air temperature. However, after the outdoor air temperature reaches to 32 °C, the exergy efficiency values increase.

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