Exergy analysis

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EXERGY ANALYSIS: THE EFFECT OF RELATIVE HUMIDITY, AIR TEMPERATURE AND EFFECTIVE CLOTHING INSULATION ON THERMAL COMFORT

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Abstract

Exergy analysis enables us to make connections among processes inside the human body and processes in a building. So far, only the effect of different combinations of air temperatures and mean radiant temperatures have been studied, with constant relative humidity in experimental conditions. The objective of this study is to determine the effects of different levels of relative humidity (RH), air temperature (T_a) and effective clothing insulation on thermal comfort conditions from the exergy point of view. The performed analyses take into consideration the available data from the study by Toftum et al. (1998). The effect of different levels of RH, T_a and effective clothing insulation on human body exergy balance chain, changes in human body exergy consumption rate (hbExCr) and predicted mean vote (PMV) index were analyzed. The results show that thermal comfort conditions do not always results in lower hbExCr as it was proven in previous studies.Variations in effective clothing insulation, T_a and RH affect individual parts of human body exergy balance chain with an important effect on hbExCr. At hot and dry conditions the hbExCr is the largest while at hot and humid conditions it is the minimal. Hot and dry and cold and dry conditions have similar hbExCr. The difference appears, if the whole human body exergy balance chain is taken into consideration. To maintain comfortable conditions it is important that exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

Keywords: *relative humidity, air temperature, effective clothing insulation, human body exergy consumption rate, PMV index.*

Introduction

All natural or human processes and any technological process present exergy-entropy processes. Their main characteristics are generation of exergy, consumption of exergy, entropy generation and entropy disposal. The use of the exergy concept in the built environment in relation to thermal comfort is relatively new. Exergy analysis enables us to make connections among processes inside the human body and processes in a building [1]. Finally, it helps to create optimal thermal comfort conditions for everyone with a rational combination of passive and active technologies.

The relationship between the human-body exergy consumption rate, room air temperature (T_a) and mean radiant temperature (T_{mr}) was first explored by Isawa et.al [2], Shukuya [3] and furthermore elaborated by Prek [4]. Previous studies [2-4] show that the exergy consumption of the human body is lower if the subject is exposed to thermally comfortable conditions equal to thermal neutrality at T_a of 18-20ºC and T_{mr} of 23-25ºC, especially under winter conditions (0 °C, 40% of relative humidity). The whole human-body exergy balance under typical summer conditions in hot and humid regions was analysed by Iwamatsu and Asada [5], Shukuya [6] and Shukuya et al. [7]. The relation between the human-body exergy consumption rate and the human thermal sensation was first investigated by Simone and et al. [8]. So far, only the effect of different combinations of T_a and T_{mr} has been studied, with constant relative humidity (RH) in experimental conditions. However, ASHRAE Standard 55: 2004 [9] recommends that the RH in the occupied spaces has to be controlled in the ranges from 30% up to 60% and at T_a between 20°C and 25°C. In hot and humid environment the values could differ from the recommended conditions. In some cases much lower or higher levels are defined. For example, air conditioning could be an important factor in patient therapy or in some instances also major treatment [10].

The objective of the work presented in this paper is to determine the effects of different levels of clothing resistance, RH, T_a on thermal comfort conditions from the exergy point of view. On the level of thermal comfort human body exergy balance chain, human body exergy consumption rate and predicted mean vote (PMV) index were analyzed.

Methodologies

The performed analyses take into consideration the available data from the study by Toftum et al. [11]. Toftum et al. [11] studied the effect of different fabric materials (cotton, microfiber, nylon, GoreTex) on the skin and of environmental temperature/clothing insulation together with perceived discomfort at a high level of skin humidity. The experiment was carried out in a climate chamber (45 m^3) in which the T_a and RH were controlled. In total, 40 sitting subjects were exposed to different experimental conditions with different combination of temperature and relative humidity, and constant air velocity at 0.1 m/s (see Table 1). Subjective characteristics are reported in table…

Sex	Age	A_{du}	Activity	Clothing insulation
20 male	[-]	[m^2]	[met]	[clo]

20 female	22.8 ±2.6	1.89±0.14	1	0.63-0.9

Table 1….

Skin humidity was evaluated in relation at the combination of vapour permeability of clothing and the thermal environment parameters. The relative skin humidity was in a range of 32-75%, the skin wettedness within 0.09-0.48, and the moisture permeability from 0.12 to 0.40.

Experimental set up for human-body exergy analyses

In Cases A-E the effect of effective clothing insulation, T_a and RH on human body exergy balance were considered (Table 2). Human body exergy calculation was performed for test subjects assuming that they are exposed to the same conditions inside the test space as in the experimental study conducted by Toftum et al. [11].

Case	**A**	**B**	**C**	**D**	**E**
Clo.insulation [Clo]	0.89	0.63	0.90	0.89	0.89
Fabric material	Cotton+ PU naylon	Cotton+ GoreTex	Cotton+ Micro fibre	Cotton+ PU naylon	Cotton+ PU naylon
T_a [°C]	25.0	25.5	25.0	25.0	25.5
T_{mr} [°C]	25.0	25.5	25.0	25.0	25.5
RH [%]	50.0	50.0	80.0	80.0	80.0

Table 2: *Experimental conditions for case analyses A-E.*

Table 3 presents the additional cases (F-G-H-I), where the effect of RH and T_a with constant effective clothing insulation was further analysed. The human body exergy consumption rate and PMV index were calculated for test subjects, assuming that they are exposed to experimental conditions, where T_a and T_{mr} varied from 15°C-35°C, RH from 30-96% and air velocity was constant at 0.1 m/s. For all calculations, the reference environmental temperature (the outdoor environmental temperature) and the outdoor RH were assumed to be equal to the indoor T_a and indoor RH. This assumption was made because no data were available regarding the outdoor conditions in the analyzed data . Furthermore, to assume the same conditions as in the Toftum et al. [11], T_a was equal to T_{mr}.

Case	**F**	**G**	**H**	**I**
Clo.resistance [Clo]	0.63	0.63	0.63	0.63
Fabric material	Cotton+GoreTex	Cotton+GoreTex	Cotton+GoreTex	Cotton+GoreTex
T_a [°C]	15.0-35.0	15.0-35.0	15.0-35.0	15.0-35.0
T_{mr} [°C]	15.0-35.0	15.0-35.0	15.0-35.0	15.0-35.0
RH [%]	30.0-96.0	30.0-96.0	30.0-96.0	30.0-96.0

Table 3: *Experimental conditions for case analyses F-I.*

Calculation of human body exergy consumption rate

Human body is treated as a thermodynamic system based on exergy-entropy processes. The system consists of a core and shell and is situated in a test room with an environmental temperature. Thermal comfort conditions are analysed by calculated human body exergy consumption rates and predicted mean votes (PMV) index. Human body exergy consumption rates and PMV index were calculated with spread sheet based software developed by Asada [5]. The calculation procedures follow the human body exergy balance model by Shukuya et al. [7].

Human body as and exergy-entropy process

The general form of the exergy balance equation for a human body as a system is represented in Equation (1) [7]:

$$[Exergy\,input]-[Exergy\,consumption]=[Exergy\,stored]+[Exergy\,output] \tag{1}$$

To maintain healthy conditions it is important that the exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output. The exergy input consists of five components: 1) warm exergy generated by metabolism; 2) warm/cool and wet/dry exergies of the inhaled humid air; 3) warm and wet exergies of the liquid water generated in the core by metabolism; 4) warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse; 5) warm/cool radiant exergy absorbed by the whole skin and clothing surfaces. The exergy output consists of four components: 1) warm and wet exergy contained in the exhaled humid air; 2) warm/cool and wet/dry exergy contained in resultant humid air containing the evaporated sweat; 3) warm/cool radiant exergy discharged from the whole skin and clothing surfaces; and 4) warm/cool exergy transferred by convection from the whole skin and clothing surfaces into surrounding air [7].

The effect of effective clothing insulation, T_a and RH on human body exergy balance chain

Figure 1 shows the numerical example of the whole human body exergy balance chain in the following conditions of Case A (0.89 Clo, 25.0 °C, 50%). Input exergy presents thermal radiative exergy exchange between the human body and the surrounding surfaces and it influences on thermal comfort. Cool/warm radiant exergy absorbed by the whole skin and clothing surfaces is zero, because T_a is equal to T_{mr}. Exergy of the inhaled humid air is also zero, because room RH and T_a are equal to outside conditions. The main input exergy is presented by warm exergy generated by metabolism. This means that 3.07 W/m^2 of thermal exergy is generated by bio-chemical reactions inside the human body. It is influenced by the difference between body core temperature and T_a. It is important to keep the body structure and function and to get rid of the generated entropy. Thus, 3.07 W/m^2 have to be released into ambient by radiation, convection, evaporation and conduction and present output exergy. Because the moisture contained in the room air is not saturated, the water secreted from sweat glands evaporates into the ambient environmental space. Warm/cool and wet/dry exergy contained by resultant humid air containing the evaporated sweat is 0.18 W/m^2. In our case it appears as warm and wet exergy, because skin temperature is higher than T_a and skin RH is higher than room RH. Warm radiant exergy discharged from the whole skin and clothing surfaces emerges because of higher clothing temperature than T_a and presents 0.14 W/m^2. Exergy of

0.20 W/m^2 is transferred by convection from the whole skin and clothing surfaces into surrounding air, mainly due to the difference between clothing temperature and T_a. In case A, the exergy consumption that presents the difference between exergy input, exergy stored and exergy output is equal to 2.55 W/m^2 .

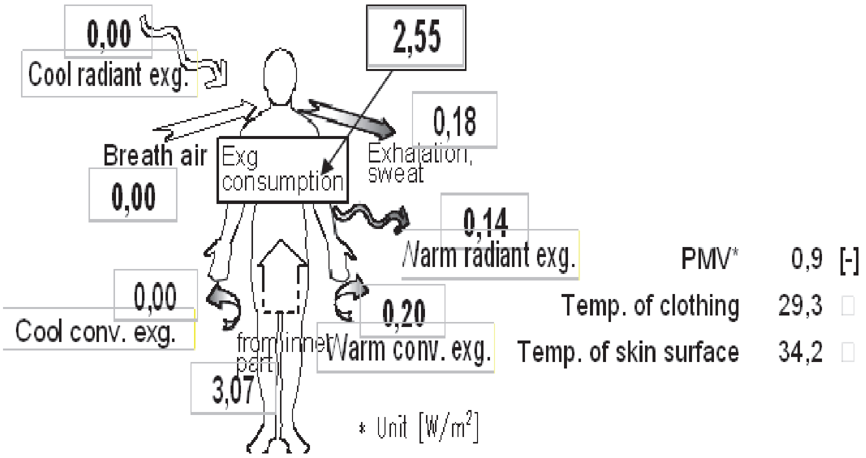

Figure 1: *Human body exergy balance for Case A (0.89 Clo, 25.0 °C, 50%).*

Exposure to different experimental conditions (Cases B, C, D and E) affects individual parts of human body exergy balance due to variations in effective clothing insulation, T_a and RH (see Table 4). If a test subject was exposed to Case B, the input and output exergies would differ. Lower effective clothing insulation with a little higher T_a causes lower internal metabolic production (2.86 W/m^2) and higher warm radiation (0.18 W/m^2) and warm convection (0.25 W/m^2). However, higher output exergies and lower inner part consequently result in lower exergy consumption rates equal to 2.26 W/m^2.

Metabolic exergy production presents the only exergy input in all cases and varies from 2.42 W/m^2 in Case E to 3.07 W/m^2 in Case A. The exergy consumption rate presents the highest amount of output and stored exergy in all cases. In general, the smaller one is the difference in temperature between the core and the shell of the human body, while the lower one is the exergy consumption rate. The lowest exergy consumption rate appears in Case E (2.02 W/m^2) due to low metabolic production and output exergies. The highest human body exergy consumption rate results in Case A (2.55 W/m^2), where metabolic exergy production and output exergies are higher due to higher effective clothing insulation.

Previous studies [2-4], where only the effect of temperature is taken into consideration, show that the exergy consumption of the human body is lower if the subject is exposed to thermally comfortable conditions, especially in winter conditions. Results of our study show that a combination of RH and T_a with subject characteristics such as clothing residence have an important effect on whole human body exergy balance chain and also on human body exergy consumption rate and as well PMV index. For example conditions in Case B are more comfortable (PMV index=0.5) with lower exergy consumption rate than in Case A where PMV index is 0.9.

The comparison between case A and case D, which present same air temperature and different relative humidity, results in lower exergy consumption rate and less acceptable comfortable environment (PMV=1.4) in case D than in Case A

(PMV=0.9). Cases A, B, C and D results with higher warm radiant exergy emission (0.14-0.18 W/m^2) and convective warm exergy transfer (0.20-0.25 W/m^2) than Case E (0.13 W/m^2) because of a larger difference between clothes temperatures and T_a. Exhalation of sweat is the highest in Cases A and B (0.18 W/m^2) and in the lowest in Cases C, D and E (0.09 W/m^2). Higher humidity in Cases C, D and E causes that the test subject cannot easily remove the resultant entropy by the evaporation of sweat, which leads to lower values.

By taking those results into consideration, it is very important to make in-depth analysis the whole chain of human body exergy balance and to include the effect of RH, temperature conditions and subject characteristics (i.e. effective clothing insulation etc.) in the calculation of human body exergy balance, as it is analysed in the following paragraph.

Case	**PMV index**	**C, W radiant exergy**	**Breath air**	**Exergy consumption**	**Inner part**	**Exhalation sweat [W/m^2]**	**C, W radiation**	**W convection**	**C convection**
A	0.9	W,C=0	0	2.55	3.07	0.18	0.14	0.20	0
B	0.5	W,C=0	0	2.26	2.86	0.18	0.18	0.25	0
C	1.4	W,C=0	0	2.06	2.50	0.09	W0.14	0.20	0
D	1.4	W,C=0	0	2.06	2.50	0.09	W0.14	0.20	0
E	1.4	W,C=0	0	2.02	2.42	0.09	W0.13	0.13	0

C-cool, W-warm exergy. *Exergy inputs and exergy outputs and exergy consumption rates* are in W/m^2.

Table 4: *Human body exergy balance for Case A-E.*

The effect of RH and T_a on human body exergy consumption rates and PMV index

In the Cases F-I (Table 5), the influence of different levels of relative humidity (30%-96%) and T_a=T_{mr} (15°C-35°C) on human body exergy consumption rates and PMV index was analysed. Respectively 0.09 and 0.48 of skin wettedness were assumed for the conditions with RH equal to 30% and 96%.

Figure 2 represents the relation between the exergy consumption rate and the PMV index with T_a=T_{mr} and RH for Case F. At cold and dry environment conditions (case F) the human body exergy consumption rate is the largest (4.23 W/m^2) due to the higher metabolic production, exhalation of sweat, radiation and convection. At hot and humid environment conditions (case I) the human body exergy rate is minimal (0.288 W/m^2), mainly because of lower metabolic production, evaporation by sweat, warm and cool convection.

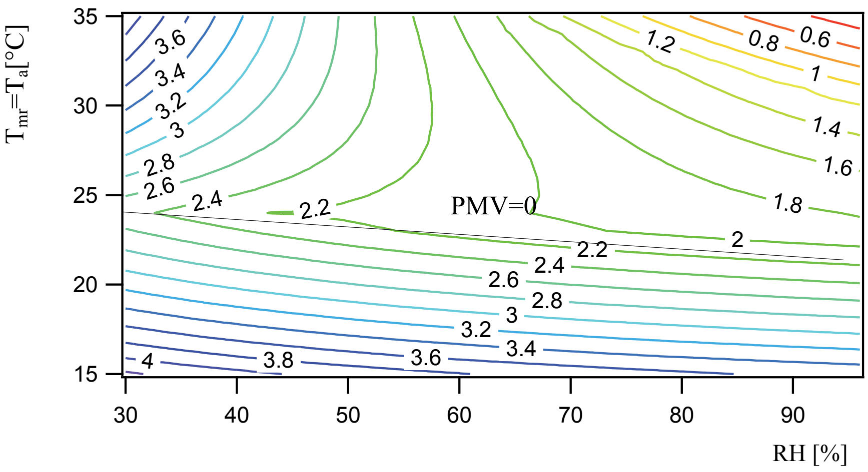

Figure 2: *Human body exergy consumption rate [W/m^2] and predicted mean vote index in relation to T_a (=T_{mr}) [°C] and RH [%], Case F.*

High relative humidity causes higher skin wettedness (0.48) and enables the release of sweat from skin surface. Hot and dry conditions (case G) and cold and dry conditions (case F), result in similar exergy consumption rates. The difference appears, if the whole human-body exergy is taken into consideration. High temperature and low RH causes lower internal production by metabolism. It should be emphasised that at higher temperatures lower values of sweat losses, warm radiation and cool convection result, even if RH is the same. In cold and humid environment conditions (case H) the results show higher internal production by metabolism and higher amount of output exergy by sweat, warm radiation and cool convection.

Table 5 presents the results of human body exergy balance and PMV index in hot/cold and humid/dry conditions. Earlier studies [2,3,4] show that in the framework of thermal comfort conditions of human body, where only the effect of temperature is taken into consideration, human body exergy consumption rate is minimal. While, when also the effect of relative humidity was taken into consideration, the present study results in higher human body exergy consumption rate at neutral thermal comfort conditions (PMV index close to 0), see Figure 2.

The result is explained by the chemical exergy consumption inside the human body, which causes the generation of quite a large amount of entropy that has to be discarded. Otherwise the human body cannot maintain its health.

The Koch et al.[12] study concluded that the relative humidity had negligible effect on thermal comfort up to 60% RH and 18°C, and T_a alone was the governing. In extreme conditions, such as hot and dry environment (case G) and cold and dry environment (caseF), the values of exergy consumption are very similar (4.230 W/m^2 and 4.137 W/m^2). The difference appears, if the whole chain of exergy balance is taken into consideration. From this point of view, it is very important to make an in-depth analysis of all exergy inputs and outputs.

Case	**Condition**	**PMV index**	**C,W radiant exergy**	**Breath air**	**Exergy .consumption.**	**Inner part**	**Exhalation sweat**	**C,W radiation**	**W Convection**	**C convection**

F	15°C, 30%	-1.4	C,W= 0	0	4.230	6.070	0.518	W 0.524	0	0.800
G	35°C, 30%	2.4	C,W= 0	0	4.137	4.295	0.155	W 0.000732	0	0.001
H	15°C 96%	-1.2	C,W= 0	0	3.526	5.103	0.222	W 0.539	0	0.816
I	35°C 96%	3.0	C,W= 0	0	0.288	0.521	0.002	W 0.012	0	0.015

C-cool, W-warm exergy. *Exergy inputs and exergy outputs and exergy consumption rates* are in W/m^2.

Table 5: *Human body exergy consumption rate and PMV index for Case F-I.*

Conclusions

Calculations of human body exergy balance enable us to see more precisely how a subject produces and gives away the heat depending on different environmental conditions. Past studies showed that in the framework of thermal comfort conditions only the effect of temperature was taken into consideration, while exergy consumption was minimal. The present study shows that the effective clothing insulation, T_a and RH had an important effect on individual parts of human body exergy balance chain and leaded to lower or higher levels of human body exergy consumption rate. RH in combination with air temperature had an important effect on thermal comfort conditions and human body exergy consumption rate. At hot and dry conditions the human body exergy rate was the largest, while at hot and humid conditions it was the minimal. Hot and dry and cold and dry environment conditions had similar exergy consumptions rates with differences in the whole human body exergy balance chain. To maintain comfortable conditions it is important that exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

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