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An Approach of Exergy Analysis of Human Physiological Response in the Outdoor Conditions during Blocklaying in Ogun State, Nigeria

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Authors' contributions

This work was borne out due to the fact that little or no research has been done on the outdoor condition of Nigeria workers most especially the mason activities during blocklaying. Author AIM made substantial contribution researching into the potential energy which is the exergy needed to perform a physical job of blocklaying in outdoor environment. Author AIM equally developed a model which is a modification of Fanger (1970) which has been in existence over 40 years ago. The co-authors contributed by initiating the project research, verifying every step of the research and monitoring the field work in a view to collect a very accurate environmental and physiological response data. The co-authors also developed part of the draft, proof read the complete draft and issued an approval for the submission. This work was carried out between author AIM and co-authors. Author and co-authors read and approved the final manuscript.

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ABSTRACT

Exergy is a property of a system and its environment and it is defined as the maximum available energy that could be converted into a useful work. This study determined an approach to analyse exergy of human physiological response of the outdoor conditions during blocklaying. Total of 204 masons were investigated on the average of seventeen (17) masons every month. The study was conducted between May, 2013 and April, 2014 between the hour of 8.00 am and 5.00 pm with environmental and physiological were recorded. The data collected were analysed with SPSS 17

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version. The mean air temperature was at maximum in November 2013 (36,1ºC) and March 2014 (36.1ºC) while maximum relative humidity occurred in July 2013 (69%). Similarly, the radiant temperature was at maximum in June 2013 (36.9ºC) and the peak value for the solar radiation occurs in December 2013 (806w/m^2). Furthermore, the maximum average mean skin temperature occurs in March 2014 (34.8ºC) and the core temperature in September 2013 (35.2ºC). The addition of stored exergy and the output exergy gives the differences between the input and exergy consumed by the mason. This approach was used to develop a model for the stored exergy of the mason during blocklaying. The stored exergy was model named AI Model for the exergy of the mason working in an outdoor environment. This model was a modification of Fanger model of thermal comfort.

Keywords: Exergy; physiological; environment; subjective; human; model; mason; equation.

1. INTRODUCTION

The application of the exergy analysis for human body may be used to assess the quality of the energy conversion processes that takes place in several systems, organs and even cells. Several authors [1-4] applied the exergy analysis for the human body to assess the quality of the energy conversion processes but Simone et al. [5] revised the method. To perform the exergy analysis, it is necessary to determine the metabolic exergy in human body.

Several human comfort models has been developed to predict how human feel in a particular environment such as Fanger model and Gagge two-node model which are from simple, one-dimensional, steady state, unsteady state to complex [6]. The most current model that are available now includes ComFA model [7], Givoni model [8], Munich energy balance model for individual [9], ENVI-Met [10], Rayman Model [11] and SOLWEIG model [12]. Huizenga et al. [13] reported that the human comfort models have not considered the individual variation which was a basis for this study. This present study developed a model, AIModel which has to take care of the anomalies and variation indicated by Huizenga et al. [13].

However, the scope of this paper is to actually derive an exergy model which can best be the modification of the Fanger model. The most well-validated heat balance models were Fanger model [14] and Gagge model [15] which was developed for indoor conditions not for outdoor conditions [13]. These are not good for measuring and determined the heat stress and outdoor conditions of any individual [16].

Pellegrini et al. [17] presented an exergy of the human body under physical activity by developing a model that considered the heat and mass transfer between the lungs, tissues and blood. The exergy analysed by Pellegrini et al. [17] was based on the results generated by models of human respiratory and thermal systems which was developed in the laboratory as against the present study which was performed and analysed within the outdoor conditions. Prek et al. [18] described the similarity of most models as the application of energy balance to a person and use of energy exchange mechanisms along with experimentally derived physiological responses to predict the thermal sensation. The models differ in the physiological models (human passive heat transfer system and environment) and the criteria used to predict thermal sensation [7-15,17].

Simone et al. [5] performed the exergy analysis for the human body to obtain a relation of exergy destruction with thermal comfort and thermal sensation conditions. Exergy is a constant property of a system and its environment because unlike energy, it depends on the state of both the system and the environment [19]. Shukuya et al. [20] and Saito and Shukuya [21] investigated extensively the human-body exergy balance model has been developed and its relation to thermal comfort in the built environment. Isawa et al. [22] and Simone et al. [5] found that there was a thermal environmental condition that the smallest human-body exergy consumption rate emerges together with rational thermal comfort, but so far all of the analysis was done with an assumption of steady-state conditions.

However, exergy measure the work potentials between a system and its environment, the specification of the environment remain the important factor. To combine the human body heat and mass transfer processes with outdoor conditions, the system can be divided into two distinct parts, the outdoor and the human body. The human body works to converts energy, the metabolism into the necessary forms, taking into account the clothing and the metabolic activity, and thereby provides the desires thermal comfort level.

Gavin [23] recommended that further research on outdoor environment should be conducted where higher work rates, wind speed and humidities will have drastic impact on thermoregulation and this give rise to this present study where the measurement of skin temperature and core temperature were considered as a key to the thermoregulation of any individual. The aim of this study was to examine the exergy approach method of physiological responses in the outdoor environment during physical activity such as blocklaying through thermal indices which can be used to consider the thermal physiology, energy balance of the human body with a specific task/purpose of deriving and formulate a very suitable mathematical model of human exergy budget for mason performing physical activity outdoor in various meteorological conditions. Prek et al. [18] presented an approach for an extended quantitative and qualitative method to characterise the processes between human body and environment. The analysis was applied to different indoor conditions [18].

This present study is limited to any individual performing physical activities in an outdoor environment. This study was borne out due to the fact that little or no study has been conducted in the area of outdoor environmental-physiological human relationship in Nigeria.

The comfort assessment in outdoor environment entails a typical six parameter that cannot be over emphasized in one way or the other. The parameters include four outdoor climatic conditions and two parameters that are related to the human behaviour. The interaction between all the climatic parameters of air temperature, radiant temperature, wind speed and relative humidity determine the human physiological responses to the outdoor conditions [24]. The two parameters that relates to the human being are the metabolic activity and the type of clothing.

For a given metabolic activity, the skin temperature and sweat production rate are seen to be only physiological variables that influence the heat balance [14]. Outdoor conditions are very complex with the energy stream being metabolic heat production within the body (M), convective heat loss, (C), evaporative heat loss, (E), conductive heat loss, (K), and radiative condition, (R) [7].

The energy balance equation developed from the principle of heat transfer and human physiology may be written as:

$$\Delta S = M + R - C - K - E$$

Where, ΔS is the change in heat storage (W/m^2). The above equation has been displayed and used in many different forms [25,26].

2. METHODOLOGY

Two hundred and four (204) masons performing blocklaying in outdoor environment were randomly selected in different locations in Ogun State, Nigeria for investigation. The study was conducted between 8.00am and 5.00pm from May 2013 to April 2014 to cover necessary environmental seasons.

The Masons thermal environments were assessed by measuring the environmental and physiological parameters as well as using the thermal indices. The description of the environmental parameters includes the values of air temperature, wind speed, relative humidity, radiant temperature and solar radiation. Metabolic heat production (activity) and clothing insulation was also noted in the analysis of heat transfer between the body and the environment.

Environmental conditions were recorded around the mason. The air temperature was recorded using GM013-Thermo-Hygro indoor/outdoor, Max/Min thermometer-Hygrometer with external sensor (Shenzhen Kai Heng Jie technology Ltd, China) respectively placed a height equally spaced from 0.2 to 1.2 m. The radiant temperature was also recorded at 1m to 1.6m in the sun with infrared thermometer. Solar radiation was also measured using solar power meter SM 206 (Shenzhen Sanpo Instrument Co. Ltd, China) with resolution of $0.1 W/m^2$, 0.1 Btu/ft^2h while the wind speeds using vane probe anemometers, Am-4201 microprocessor digital anemometer (Lutron Electronics Enterprise co Ltd, Taiwan).

The physiology of human thermo-regulation involves the measurement of body (core) temperature and skin temperature because human body responds to thermal conditions through physiological system of thermo-regulation. The Masons were weighed before every two hours using Detecto PD300MDHR column scale (Cardinal Scale manufacturing company, USA) with digital height to measure body mass (kg) and height (cm) simultaneously. The skin temperature was measured using Smart sensor AR872D, (Shenzhen Kai Heng Jie technology Ltd, China) number 00505613 with thermometric range of -50ºC to 1050ºC pointing to the forehead of the subject at 1.2m distance while Oral temperature was measured before every two hours using a Dx-101 water resistant digital clinical thermometer (Hicks thermometer Ltd, Indian).

The data collected was analysed statistically with SPSS 17 version and Microsoft excel (2010) program descriptively.

3. RESULTS AND DISCUSSION

The data were collected between May, 2013 and April, 2014 at a latitude 7º.00N and a longitude 03º.31[1]E (Ogun State, Nigeria) between 8.00am and 5.00pm. Below were the average mean values of the environmental (Table 1) and physiological parameters (Table 2).

3.1 HUMAN EXERGY ANALYSIS

Available energy is the maximum energy that could be converted into useful work by ideal processes which reduced the system to a dead state (state of equilibrium with the atmosphere and earth). This available energy is the exergy which, unlike energy can be transferred to or from a system in three form; heat, work and mass flow. Exergy transferred is recognized at the system boundary as exergy crosses it and it represents the exergy gain or lost by a system during a process.

Exergy transfer by heat, $X_{heat} = (1-T_a/T_c)\ Q$ ---- 2

The heat transfer, Q is the heat rejected to the medium (waste heat). The exergy transferred by heat is zero when $T_a = T_c$ at the point of transfer [19].

The combine thermal comfort within environment can be divided into two parts,

- Environment (space)
- Human Body

The human body works to convert energy to provide desired thermal comfort level. The exergy measure the ability of energy to do work.

Table 1. Average mean values of the environmental parameters

Parameter	May '13	Jun '13	Jul '13	Aug '13	Sep '13	Oct '13	Nov '13	Dec '13	Jan '14	Feb '14	Mar '14	Apr '14
Air temp	31.6	33.3	27.9	30.5	33.1	32.8	36.1	32.8	34.2	35.0	36.1	34.4
RH	58	58	69	56	55	56	58	53	57	42	54	48
Wind Speed	0.5	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Solar Radiation	571	583	551	779	668	771	725	806	648	484	706	660
Radiant Temp	34.6	36.9	29.5	31.6	33.9	32.5	33.4	32.9	35.6	35.6	35.8	35.6

Table 2. Average mean values of the physiological parameters

Parameter	May '13	Jun '13	Jul '13	Aug '13	Sep '13	Oct '13	Nov '13	Dec '13	Jan '14	Feb '14	Mar '14	Apr '14
Height (cm)	170.0	170.0	168.0	166.2	166.7	168.3	166.8	165.9	171.7	168.2	169.4	168.6
Body mass (kg)	63.4	60.7	64.1	62.9	62.8	61.2	61.2	62.5	62.6	64.1	63.0	63.3
Skin temp (ºC)	33.1	33.2	34.4	33.5	34.0	33.9	33.9	34.1	34.3	34.5	34.8	34.6
Core temp (ºC)	35.0	34.8	34.3	33.4	35.2	34.5	34.8	34.4	33.2	33.5	33.3	33.1

3.1.1 Exergy balance equation

The concept of exergy which is derived by combining the energy and entropy balance equations together with environmental temperature, indicates the ability of energy or matter within a system in question to disperse themselves or to make the energy and matter in the environment disperse. The general form of the exergy balance equation [19] regardless of the system is:

Input exergy – Exergy consumption = Stored exergy + Output exergy

The feature of this equation above is that there is the “exergy consumption”. The other terms, are warm, wet or dry exergies depending on the outdoor conditions of temperature and water vapour pressure. The detail of the equation terms above is described in [20]. The heat transfer through a finite temperature difference is irreversible and it is accompany by exergy destruction. The exergy of a body at a specified state depends on the condition of the environment as well as the properties of the body.

The decrease of exergy principle can be expressed [19] as;

Exergy entering – Exergy leaving – Exergy Consumed = Change in the exergy of the body

$$X_{in} - X_{out} - X_{consumed} = \Delta X_{body}$$

The human body is considered as a closed system (Fig. 1) in which no masses cross the system boundary during the process.

Decreased exergy principle can be deduced as

$$X_{in} - X_{out} - X_{consumed} = 0 \quad \text{-------------} \ 3$$

Though the body is steady (close system) where the heat is transferred, the rate of change in exergy = 0.

The exergy destruction/consumed is due to the irreversible heat transfer through a finite temperature difference [19].

Where,

Exergy consumed, $X_{consumed}$ = Exergy destroyed, $X_{destroyed}$ = Exergy irreversible, $X_{irreversible}$

Reference to the 2nd law of thermodynamics,

$$X_{in} = (1-T_a/T_c)\ M \quad \text{-----------------} \ 4$$

$$X_{out} = (1-T_a/T_{sk})\ M \quad \text{------------------}5$$

Where, Q = M is the metabolic heat transfer

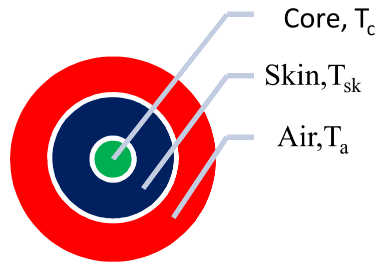

Fig. 1. Illustrations of body structure and environment

The human body derives heat from ingesting food while the energy value of food is turned over to producing heat and energy for work. The human body produces heat from food when combined with oxygen in the cell.

Therefore,

The exergy balance equation regardless of the system is as follows [19]:

Input exergy – Exergy consumption = Stored exergy + Output exergy

$$X_{supplied} = X_{expended}$$

Where,

$$X_{supplied} = X_{input} - X_{consumed}$$

and

$$X_{expended} = X_{stored} - X_{lost\ to\ environment}$$

From the equation 4 and 5 above, X_{in} and X_{out} can be substituted as

$$(1-T_a/T_c)\ M - (1-T_a/T_{sk})\ M = X_{consumed} \quad \text{------} \ 6$$

$$X_{input} = \text{metabolic rate, M (ingested food.)} \quad \text{-----} \ 7$$

$$X_{supplied} = X_{input} - X_{consumed}$$

Therefore, Exergy supplied, $X_{supplied}$ will be reduced to

$$X_{supplied} = M – [(1\text{-}T_a/T_c) M - (1\text{-}T_a/T_{sk}) M] \text{-----}8$$

Similarly, Exergy expended is also to consider the stored exergy and exergy lost to the environment,

$$X_{expended} = X_{stored} - X_{lost\ to\ environment}$$
$$= X_{stored} – [X_C + X_{Esk} + X_{Cres} + X_{Eres}] \text{----} 9$$

When the temperature T_a and T_{sk} at the location where heat transfer is taking place is not constant, the exergy transfer accompany heat transfer is determined by integration [19].

Exergy lost by convention through dry air can be determined by integration as

$$X_{c,\ dry\ air} = {}_{Tsk}\int^{Ta} dQ/Tdt = m\ C_a(T_a - T_{sk}) – mC_aT_a\ln(T_a/T_{sk}) \text{--------------}10$$

Where, C_a is the specific heat capacity of air

3.1.2 Exergy lost through skin

Exergy lost through the skin, which is the heat due to sweating can also be determined from exergy of the evaporation required and the exergy diffused through the body.

$$X_{Esk} = X_{Ereq} + X_{Ediff} \qquad \text{-------------}11$$

With no regulatory sweating, skin wettedness due to diffusion is approximately 0.06 for normal conditions [24]. For large values of E_{max} or long exposures to low humidities, the value may drop to as low as 0.02, since dehydration of the outer skin layers alters its diffusive characteristics. With regulatory sweating, the 0.06 value applies only to the portion of skin not covered with sweat (1 − *w*) [24].

The exergy of the evaporative heat loss by diffusion [23] is

$$X_{Ediff} = (1 – w)\ 0.06X_{Emax} \qquad \text{------------}12$$

The skin wettedness fraction is the ratio of the actual evaporative heat loss to the maximum possible evaporative heat loss E_{max} with the same conditions and a completely wet skin (w=1) [23]. Skin wettedness is important in determining evaporative heat loss. Maximum evaporative potential E_{max} occurs when w = 1 [24].
The portion w of a body that must be wetted to evaporate the regulatory sweat is;

$$w = X_{Ereq} / X_{Emax}$$

The exergy skin wettedness is determined and exergy of the evaporative heat loss from the skin is calculated as,

$$X_{Ereq} = wX_{Emax} \text{------------------------}13$$

Hence, from equation 12, exergy lost through the skin, which is the heat due to sweating can be calculated as;

$$X_{Esk} = X_{Ereq} + X_{Ediff}$$
$$= wX_{Emax} + 0.06(1\text{-}w)\ X_{Emax} \text{-------}14$$

3.1.3 Exergy lost by respiration

Similarly, the exergy of the convective heat loss by respiration, X_{Cres} can be determined from ASHRAE [24].

$$X_{Cres} = 0.0014M\ (T_{sk} – T_a) \text{----------}15$$

Also, exergy of the evaporative heat loss due to respiration, X_{Eres} can also be determined from [24] as,

$$X_{Eres} = 0.0173M\ (P_{sk} – P_a) \text{---------}\ 16$$

Therefore, from equations 9 above

$$X_{expended} = X_{stored} - X_{lost\ to\ environment}$$
$$= X_{stored} – [X_C + X_{Esk} + X_{Cres} + X_{Eres}]$$

The exergy balance equation regardless of the system is as follows [18]:

Input exergy – Exergy consumption = Stored exergy + Output exergy

$$X_{supplied} = X_{expended}$$

$$X_{input} - X_{consumed} = X_{stored} - X_{lost\ to\ environment}$$

Substitute for all variables,

Therefore,

$$M – [(1\text{-}T_a/T_c) M - (1\text{-}T_a/T_{sk}) M] = X_{stored} – [mC_a(T_a - T_{sk}) - mC_aT_a\ln(T_a/T_{sk}) + wX_{Emax} + 0.06(1\text{-}w)\ X_{Emax} + 0.0014M\ (T_{sk} - T_a) + 0.0173M\ (P_{sk} – P_a)]$$

$$\boxed{\mathbf{X_{stored}} = M – [(1\text{-}T_a/T_c) M - (1\text{-}T_a/T_{sk})M] + [mC_a(T_a - T_{sk}) - mC_aT_a\ln(T_a/T_{sk}) + wX_{Emax} + 0.06(1 - w)\ X_{Emax} + 0.0014M\ (T_{sk} - T_a) + 0.0173M\ (P_{sk} – P_a)] \text{---------}\ 17}$$

Equation 17 is the derived exergy model named AlMusa model for the exergy of mason working in an outdoor condition.

The relation is referred to as the exergy balance and this is referred to as the change of a body during a process which is equal to the difference between the net exergy heat transfer through the body system and the exergy consumed within the body system as a result of irreversibilities.

Exergy of a person at a given time and a place can be viewed as the maximum amount of work he or she can do at the time and place. Exergy is certainly difficult to quantify because of the interdependence of physical and intellectual capabilities of a person. Exergy of human being is a function of time and physical and or intellectual exergy of a person goes to waste if it is not utilised at that time.

The mean air temperature was at maximum in November 2013(36,1ºC) and March 2014 (36.1ºC) and maximum relative humidity also occurred in July 2013 (69%). Similarly, the radiant temperature was at maximum in June 2013 (36.9ºC) and the peak value of the solar radiation occurs in December 2013 (806w/m^2).In addition, the maximum average mean skin temperature of the mason occurs in March 2014 (34.8ºC) and the core temperature in September 2013 (35.2°C). In July 2013, it was discovered that the air, radiant temperature (27.9 and 29.5ºC) were very low and relative humidity (69%) was higher compared with the other months. The outdoor humidity seems to have a major effect on the result. At high humidity, too much skin moisture tends to increase discomfort [24]. The discomfort appears due to the feeling of moisture itself which increases between skin and clothing with skin moisture [24]. A person may feel thermally neutral as a whole but still feel uncomfortable if one or more parts of the body are too warm or too cold. This condition greatly affects the work output of the mason due to the climatic change in the month of July, 2013. ASHRAE [24] recommend that the warm side of the comfort zone of the relative humidity should not exceed 60%. The subjective response rating from the thermal sensation, comfort, preference, pleasantness, acceptance and satisfactory responses of the masons were analysed. The body structure and environment was illustrated which relate the approach to the exergy balance equation and this deduced that exergy of a body at a specified state depends on the condition of the environment as well as the properties of the body. The thermal sensation alone is not reliable predictor of thermal comfort for the mason in high humidity [24].

The exergy of a person in a daily life can be viewed as the best job that a person can do under the most favourable conditions. The reversible work in daily life on the other hand can be viewed as the best job a person can do under some specified conditions. Then, the difference between the reversible work and the actual work done under these conditions can be viewed as the irreversible or the exergy destroyed. In engineering system, to identify the major sources of irreversibility and minimized them in order to maximized performance.

Pellegrini et al. [17] result agreed that the increase in the overall exergy destruction is proportional to the internal energy variable due to the metabolism and the exergy analysis of the body will be improved as the physiological model become more accurate. This was also accepted in this present study for outdoor condition during blocklaying.

Hardworking mason for example may make full use of his physical exergy but very little use of his intellectual exergy. Exergy can also be viewed as the opportunities that we have and the exergy destruction as the opportunities wasted. The energy content of the universe is constant just as its mass content is. Yet at times of crisis we are bombard with speeches and articles on how to “conserve” energy. As engineers, we know that energy is already conserved. What is not conserved is exergy which is the useful work potential of the energy.

Once the exergy is wasted, it can be never be recovered. Exergy is a property and is associated with the state of the system and the environment. A body that is in equilibrium with its surrounding has zero exergy and is said to be at the dead state. The exergy of heat supplied by thermal energy body is equivalent to the work output of a Carnot heat engine operating between the body and the environment.

The heat transfer between the human body and the environment depends on the air temperature and the skin. The increase in exergy depends on the initial and the final exergy of the surrounding while the loss in exergy takes place in human body and it depends on the initial and the final exergy generated within the body. Work done during the process depends on the initial state, the final state and the process path.

Work done = f(initial state, process path, final state).

4. CONCLUSION

In conclusion, the stored exergy is the available energy for the work and this can be increased by actually working on the exergy lost to the surrounding. This exergy depends on the temperature of the skin (X_{Tsk}) and the temperature of the environment (T_a). Similarly, the maximum exergy (X_{Emax}) which also depends on the relative density of the environment do play a major role in determine the stored exergy due to the pressure of the environment and the saturation vapour pressure of the reference state.

The system at a specified state depends on the condition of the environment as well as the properties of the system. Exergy is a property of the system-environment combination and not of the system alone. Altering the environment is another way of increasing the exergy.

The exergy stored of the mason under physical activity was determined. The variables used in the exergy analysis were generated by two physiological attributes, one for the thermal system and the other for the respiratory system. The aim of this study was to examine the exergy approach method of physiological responses in the outdoor environment during physical activity such as blocklaying through thermal indices which can be used to consider the thermal physiology, energy balance and the sweat production rate of the human body with a purpose of deriving and formulate a very suitable thermal comfort model of human exergy budget for mason performing physical activity outdoor in various meteorological conditions which was achieved as AImodel and predict their thermal sensation.

COMPETING INTERESTS

Author and co-authors declared that no competing interests exist.

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