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ENERGY EXCHANGE DURING EMBALMMENT OF A CADAVER: A THERMODYNAMIC EXPOSĚ

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ABSTRACT

This study examined the energy exchange throughout a cadaver's embalming process while taking thermodynamic exposure into account. The embalmed cadaver's head, neck, torso, arms, forearms, hands, thighs, legs, and feet were all included in the thermal model. Skin, fat, muscle, bone, brain, viscera, lung, and heart were among the tissues that were taken into consideration for each cylinder. For every cylinder, the heat conduction equation with constant heat generation is solved. This model made it feasible to determine how radiation, convection, and evaporation move heat and mass through the skin to the surroundings. As a result, the body's temporary reaction to changes in the surroundings was accomplished. The exergy fluxes resulting from heat and mass exchange on skin (radiation, convection, and evaporation) had to be obtained because the exergy analysis was used. The findings showed that when the model is exposed to ambient temperatures below those taken into account for the thermal neutrality condition, the destroyed exergy alone is adequate to assess the thermal experience. Additionally, the constant that produced comparable experiment behavior was the consequence of the minimal exergy destruction and highest second law efficiency. However, to accurately assess thermal comfort in situations with temperatures greater than those determined for thermal neutrality, the rate of exergy delivered to the environment with the amount of exergy lost should be combined.

KEYWORDS: Embalmment, Cadaver, Thermodynamics, Exergy Analysis, Human Thermal Model.

1.0 INTRODUCTION

The art and science of temporarily preserving human remains to prevent decomposition and make them appropriate for display at a funeral is known as embalming in the majority of contemporary civilizations [1]. In order to stop autolysis and putrefaction, fixative is utilized (embalming fluid is injected or perfused into the cadavers through the vascular system). In order to stop decomposition and restore the physical appearance of dead human remains, the procedure of embalming involves chemically treating them to lessen the presence of microbes[1]. In order to sterilize the environment, it is also the process of maintaining a corpse to stop microbiological activity, disinfect the body, and stop putrefaction [2].In order to prepare a body for long-distance transportation, forensic analysis, or burial, embalming is also necessary to stop decomposition [3]. Various embalming agents and techniques have been developed over time to preserve cadavers. Additionally, the choice of embalming chemical and technique is determined by the embalming goal [3-5]. The body can be preserved for many years with proper embalming [3]. Additionally, the human organism is made up of both matter and energy. Energy interacting with dead body is both chemical (reactions) and electrical (impulses and signals). However, the human energy-generating mechanism is far more intricate. Surprisingly, your body uses about 20 watts of energy at any given time, which is sufficient to run a light-bulb. This energy is obtained in a variety of ways. We mostly obtain it from eating, which provides us with chemical energy. Our muscles are eventually powered by the kinetic energy that is created from that chemical energy. Thermodynamics has taught us that energy cannot be generated or destroyed. It merely shifts states. An isolated system's total energy cannot and does not change [23]. We also know that matter and energy are two rungs on the same ladder because of Einstein. The entire cosmos is closed. However, ecosystems, including human beings, are open systems rather than closed ones. Our environment and we both exchange energy. Energy can be gained (again, through chemical reactions) or lost (either by releasing heat or waste). The collection of atoms that make you up—a world inside a cosmos—is put to new use when you die. The energy and those atoms that were created during the Big Bang will never go away.

In addition, a variety of occurrences in several fields of study are described by the Laws of Thermodynamics. Chemistry, astrophysics, materials science, and engineering are common examples [6–9]. Everywhere there is a non-equilibrium, the environment must be affected, as shown by the Second Law of Thermodynamics. According to [10], life is ensured by this imbalance. A few decades later [11-15] demonstrated that all living beings tend to a minimum entropy production level. In recent decades, a number of thermodynamic methods to biological systems have been carried out. Studies of a single malignant cell [16], protocols in hypothermia techniques [17], and an examination of physical activities [18–21] are a few examples. As in Ozilgen [22], a review paper compiles these new uses. The assessment of thermal comfort conditions is one potential use of thermodynamics in mechanical engineering [23–28]. In a review of thermal comfort in the built environment, Ruppetal [29] noted that the exergy analysis could provide fresh insights into this area of study. Regarding the relationship between the destroyed energy and thermal comfort conditions, there are three primary methods. Only a specific set of environmental factors, which also happen to coincide with areas of thermal comfort, result in minimally destroyed energy, according to some writers [30–34]. The impact of internal and external environmental factors on the body's destroyed energy and building energy consumption was assessed by other authors [35–38] (connecting these results with the body exergy consumption). In the end, [39–42] evaluated the body's exergy efficiency and destroyed exergy. Their findings suggest that in locations that do not suggest thermal comfort, the destroyed exergy can be negligible. However, there is very little energy transmission to the surroundings at these sites, hence it makes sense to utilize these two physical variables to evaluate thermal comfort levels. It is crucial to note that the destroyed energy values for various references vary by an order of magnitude because of the disparity in the methods used. Depending on the type of irreversibility selected for evaluation, this discrepancy could be explained by the model's exergy input, which is seen as a reaction rate (in energy and exergy basis) [43], or only the impact of heat transfer. Consequently, the energy linked to this physical quantity leads to lower values of lost energy when the metabolism is solely seen as a heat transfer rate. To generalize the relationship between the exergy rates and thermal comfort, it is usual practice to divide the exergy rates by the area of the skin. Although this is the best normalization for physiological parameters related to heat transfer, the human body does not always respond linearly with its area because its tissues have very unique characteristics, such as the high metabolism of muscles and the low metabolism of fat. Because tissues alter the body's reaction even when their surface area remains constant, their impacts must be taken into account for a thorough examination of the human body. Thus, this study will examine the thermodynamic exposure of the human body as well as the energy exchange that occurs during cadaver embalming.

MATERIALS AND METHODS

2.1 Thermodynamic Model

The passive and thermoregulatory systems make up the human thermal model created by[44]. Sweating, shivering, and vasodilation or constriction are physiological reactions to variations in the temperature or degree of activity. The second involves mass and heat transfer between the body and the environment, heat transfer by convection due to the flowing fluid, and heat conduction within the body. According to [44], the anatomic model's global data are as follows: height 1.76 m, weight 67 kg, surface area 1.8 m^2, and volume 0.0627 m^3.The human body was broken up into 15 cylinders, each of which represented a realistic-sized model of the head, neck, trunk, arms, forearms, hands, thighs, legs, and feet. Skin, fat, muscle, bone, brain, viscera, lung, and heart are among the tissues that are mixed together in each cylinder. All cylinders have composition independent of cross section, except for the head and trunk, which have composition as a function of cross section. For every tissue, the heat conduction equation is solved with constant density, specific heat, and internal heat generation (metabolism). A coordinate transformation that converts an elliptical cylinder in Cartesian space into a parallelepiped in the new coordinate system is used to obtain the numerical solution. Two classes of vessels had to be distinguished in order to compute the heat transfer between the fluid and tissues in the embalmed cadaver: the large vessels and the small ones, which can be thought of as belonging to a continuum. With the exception of the fluid temperature being dependent on the position inside the tissue and not being equal to the body core temperature, the model is comparable to the one put out by [45].With the exception of the trunk, which is modeled with a single reservoir, the large vessels can be modeled using two reservoirs, one of which is filled with fluid and the other with venous blood, as suggested by [46]. This model can be used to determine mass fluxes from respiration (difference in the temperature and humidity of inspired and expired air) as well as heat and mass transfer to the environment through the skin as a result of radiation, convection, and evaporation. Additionally, the body's temporary reaction to changes in the environment (temperature dependency with time) can be obtained.

2.2 ENERGY AND EXERGY METABOLISMS

The enthalpy and exergy variations of the nutrients' reaction of oxidation during cellular respiration were assessed by Mady and Oliveira Junior [47]. The authors selected the following nutrients: palmitic acid, which represented fats; glucose, which represented carbohydrates; and an average-composition amino acid ($C_{4.98}H_{9.8}N_{1.4}O_{2.5}$), which represented proteins. It was once thought that the body completely oxidizes glucose and palmitic acid, but merely oxidizes amino acids up until urea is formed. Equation (1) can be used to compute the energy metabolism, and Equation (2) can be used to determine the exergy metabolism. The body composition is used in this study to determine the energy metabolism.

$$\dot{M} = -(\dot{m}_{carb}\Delta h_{carb} + \dot{m}_{prot}\Delta h_{prot} + \dot{m}_{lip}\Delta h_{lip} \quad (1)$$

$$\dot{B}_M = -(\dot{m}_{carb}\Delta b_{carb} + \dot{m}_{prot}\Delta b_{prot} + \dot{m}_{lip}\Delta b_{lip} \quad (2)$$

The mass of amino acids consumed in a day and its rate, which is assumed to be constant, can be calculated using the equations of the reactions of oxidation and the hypothesis put out by[48] that there is a daily excretion of 12 g of nitrogen in urea created by amino acid oxidation. The remaining system, which is made up of Equation (3), the respiratory coefficient, RQ, and the oxidation reaction equations, must be solved in order to determine the rates of consumption of carbohydrates and fats. The RQ is the volumetric (or molar, if using the ideal gas model) ratio of the carbon dioxide production to the oxygen intake during respiration. According to [49], a person engaged in daily tasks typically has an RQ of 0.83.

2.3. ENERGY TRANSFER TO ENVIRONMENT

Convection heat transfer, radiation heat transfer, sweat vaporization (and water diffusion) enthalpy transfer, and respiratory enthalpy variation are the ways in which the cadaver body interacts with its surroundings. The formulas utilized to derive these terms have been thoroughly examined in the literature and are located in [49, 50]. Since the cadaver is regarded as being nude, the operative temperature (To) would be the same in a hypothetical setting where the mean radiant temperature (Tmr) and the air temperature (Ta) are equal.

2.4. EXERGY TRANSFER TO ENVIRONMENT

The exergy transfer to the environment is calculated using the environmental circumstances as a reference. As a result, the reference values for atmospheric pressure (P0), relative humidity (0), and operating temperature (T0 = To) are established for a particular environment. Equations (3) and (4) are used to evaluate the exergy transfer rates related to convection and radiation heat transfers, respectively. Equation (5) provides the evaporative exergy flow rate to the environment. Equation (6) is used to compute the exergy of the expired air. However, because the ambient conditions (T0) were used as a reference, = 0.

$$\dot{B}_{Conv} = (1 - \frac{T_0}{T_s})\dot{Q}_{Conv} \quad (3)$$

$$\dot{B}_{rad} = (1 - \frac{T_0}{T_s})\dot{Q}_{rad} \quad (4)$$

$$\dot{B}_e = \dot{m}_e \left[h_{fg} - T_0 s_{fg} + T_0 R_g \ln(\frac{P_{g,skin}}{P_{g,o}})\right] \quad (5)$$

$$\dot{B}_{exp} = \sum_{i=1}^{4} \dot{m}_i \left[C_{p,i}(T_i - T_0 - T_0 \ln\left(\frac{T_i}{T_0}\right)) + T_0 R_i \ln(\frac{P_{exp,i}}{P_{0,i}})\right] \quad (6)$$

These equations are analyzed in [47]. In them, T_o represents the reference environmental temperature, T_s represents the skin temperature, hfg represents the enthalpy of vaporization of water at the skin temperature, sfg represents the entropy of vaporization of water at the skin temperature, Rg represents the water's gas constant, ˙ me represents the rate of fluid elimination through the skin, pg,skin represents the partial pressure of water vapor in the skin, and $pg,_o$ is the partial pressure of water vapor in the environment.The gases of respiration—oxygen, carbon dioxide, water vapor, and nitrogen—are denoted by the index i for Equation (6). The partial pressure of the gas I in the atmosphere is denoted by p0,i, while the partial pressure of the gas I that has expired is denoted by pexp,i.

2.5 EXERGY ANALYSIS

The environment/reference conditions, such as temperature (Ta and T0), pressure (Pa and P0), and relative humidity ($\emptyset a$ and Ø0), are required to establish the exergy balance. A history of the temperature of the tissues and blood or fluid at each compartment node must also be known. The model was seen as nude. The energy balance is shown by Equation (7), and the application to the human body is shown by Equation (8). However, the total variation rate of the body's energy is expressed as dB/dt, and the temperature-dependent variation of the body's energy is expressed as dB/dt│ΔT, both in W.

$$\frac{dB}{dt} = \sum B_e - \sum B_s + \sum Q_i \left(1 - \frac{T_0}{T_i}\right) - W - B_{dest} \quad (7)$$

$$B_{dest} = B_c + B_r + B_E + B_{res} + (B_M - \frac{dB}{dt} /_{AT}) - W \quad (8)$$

Where dB/dt│ΔT is the temporal variation of the body's energy, Bdest is the rate of energy destruction, BM is the metabolic energy rate, W is the work done by the body, and BQr, BQc, BE, and BR are the energy contributions of radiation, convection, evaporation, and respiration, respectively. All levels are attained where the gap between the metabolic exergy and internal energy is less than 3%. Therefore, it is possible to utilize the approximation BM

≈ M. It is crucial to remember that dB/dt includes metabolic exergy. The energy involved in heat exchange with the environment as a result of radiation is seen in equation (9). Tsk is the skin temperature (K) in Equation (9).

$$B_r = Q_r(1 - \frac{T_0}{T_{sk}}) \quad (9)$$

The exergy contribution of convection can be calculated as indicated by Equation (10).

$$B_c = Q_c(1 - \frac{T_0}{T_{sk}}) \quad (10)$$

Equation (11) can be used to compute the diffusion of vapor through the skin. The vaporization of perspiration on the skin is the first term in this equation, and the difference between the concentration of saturated vapor close to the skin and the concentration of vapor in the surrounding air is the second term.

$$B_E = -(m_w\left(h_{fg} - T_0 S_{fg}\right) + m_w R_w T_0 In\left(\frac{P_{w,sk}}{P_{w,o}}\right)) \quad (11)$$

Where Rw is the universal gas constant of water in kJ/(kgK), mw is the mass flow rate of water that evaporates and diffuses through skin, hfg and sfg are the enthalpy and entropy of vaporization, respectively, and Pw,sk, and Pw,0 are the partial pressures of water vapor at skin temperature and in the environment, both in Pa.

RESULTS AND DISCUSSION

The thermal neutrality temperature (Tn) for each age (metabolism) must be known in order to mimic scenarios other than thermal neutrality. A thermally neutral situation is provided by the operating temperature range of 29 to 31°C, per [49]. For a 50% relative humidity and a 0.15 m/s air current, Figure 1 shows the computed Tn (for each metabolism) as a function of age.The naked model was examined while standing. According to this statistic, thermal neutrality tends to rise across life, reaching its lowest value at the age of 19, when metabolism is at its highest. According to some authors, the lowest entropy generation concept applies to an adult (in this case, the destroyed exergy—Bdest). Over time, the effectiveness of the second rule (η) similarly tends to decline (Fig. 1).

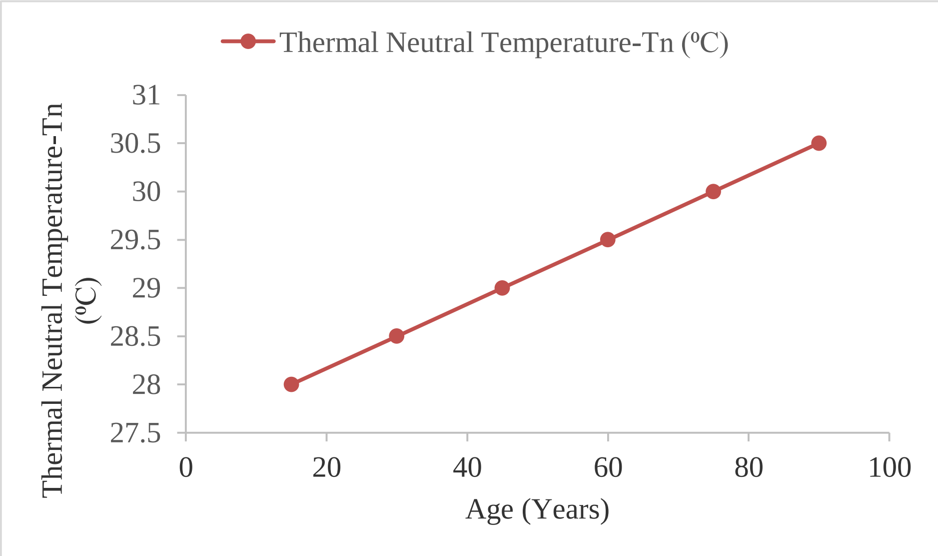

Fig. 1: Thermal neutrality temperature.

Therefore, 19-year-old guys achieved the largest exergy destruction. 32°C and φ=70% were the environmental parameters taken into account. Additionally, the exergy analysis can be a useful tool for modifying the constants, which are either derived from ways to modify these constants to the particular anatomical features of the model or from experimental results (whose values are difficult to discover and specific to a person). Exergy destruction and Second Law efficiency as a function of the thermoregulatory system are shown in Fig. 2.The vasomotor mechanism's constants in Fig. (2) for a temperature of 30°C have no discernible effect on the overall amount of energy destruction; nonetheless, it is evident that the constants employed in the model are near the smallest amount of energy destruction and near the maximum amount of energy efficiency.

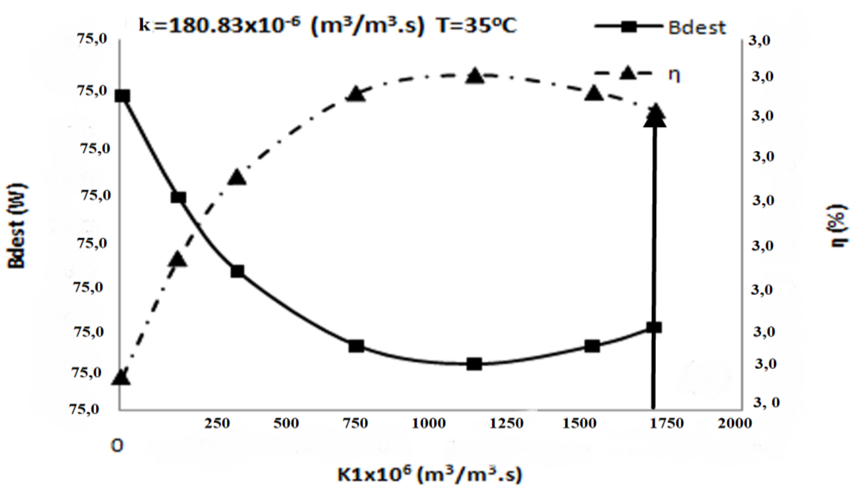

Fig. 2: Exergy destruction and exergy efficiency as function of constant.

Additionally, Fig. 3 demonstrates that, while the body's overall mass remains constant, there is no discernible change in the exergy behavior. For larger (or smaller) body masses, this might not be the case because the effects of fat and muscle might not be balanced.

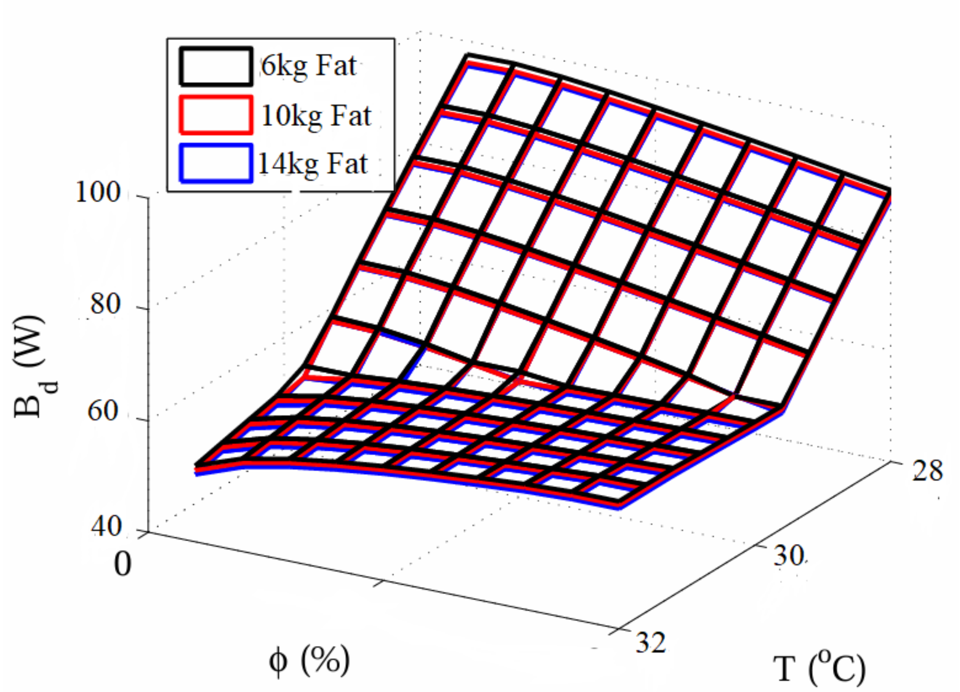

Figure 4: Exergy rates for the embalmed Cadaver.

CONCLUSION

This study examined the energy exchange that occurs during corpse embalming while taking thermodynamic exposure into account. The body's exergy behavior was examined using a thermal model. Although the exergy fluxes are essentially insignificant, the energy contribution of the heat and mass fluxes is significant based on the range examined. Furthermore, every portion of the human body expels more energy than it uses for metabolism, with the exception of the head and trunk, which house the majority of metabolic reactions.The constants of the thermoregulatory system for particular anatomical situations can be found using the exergy analysis. Exergy measures were successfully linked to the impacts of body composition. It has been shown that the metabolism of the body affects both the destruction of energy and the transmission of energy to the environment, increasing both parameters.

REFERENCES

1. Bernard E.E., Amaza D.S., Zirahei J.V., Attah M., Amaike I.A.O., Efiong O.E. (2013). The Basic Determinants of Commercial Embalmment in Ogoni Ethnic Group. Niger J Dent Sci., 3 (5): 24 27
2. Onyejike D., Ukoha U., Aladeyelu S. (2018). Evaluating the Embalming Procedures ofPutrefying Bodies in Relation to Gender in Anambra State, Nigeria. IISJ, 2 (6): 213 222
3. Brenner E. (2014). Human body preservationold and new techniques. *J. Anat.*, 224 (3): 316 344
4. Curtis D. (2001). The Basics of Funeral Services: History of Embalming. New York, USA: McGraw-Hill, pp. 332
5. Ezugworie J., Anibeze C., Akpuaka F. (2008). Critical appraisal of reasons for traditional embalming among Igbos in the Southeast Nigeria. *Internet J Altern Med.*, 7 (2): 1 4
6. Shonza J. (2015). The role of church in averting mob justice in Tanzania: a case of Kibaigwa Township [dissertation on the internet]. Dodoma: The University of Dodoma; 2015. Available from: http://hdl.handle.net/20.500.12661/110.
7. Madu, K. E. (2018). Performance Analysis of a Hot Water Driven 5 Tons Capacity Absorption Refrigeration System for Nigerian Application. *J. Indust. Techn.*, 3 (1): 33-44
8. Madu, K. E. (2018). Weibull and Cauchy Distribution Analyses of Wind Parameters in the Eastern Part of Anambra State", Nigeria. *J. Indust Tech.*, 3 (1): 23- 32
9. Madu, K.E. (2018). Evaluation of the Behaviour of Steam Expanded in a Set of Nozzles, in a Given Temperature. *Equ. J.* Eng., 9-13
10. Schrödinger,E.WhatIsLife?ThePhysicalAspectoftheLivingCell;With,MindandMatter;&A utobiographical Sketches;CambridgeUniversityPress:Cambridge,UK,1944
11. Prigogine,I., Wiame,J. (1946). Biologieetthermodynamiquedesphénomènesirréversibles. Cell.*Mol. Life Sci.*,19, 2,451–453.
12. Mady, C.E.K., Henriques, I.B., de Oliveira, S. (2015). A thermodynamic assessment of therapeutic hypothermia techniques. *Energy,* 85, 392–402.
13. Mady, C.E.K., Albuquerque, C., Fernandes, T.L., Hernandez, A.J., Saldiva, P.H.N., Yanagihara, J.I., de Oliveira, S. (2013). Exergy performance of human body under physical activities. *Energy,* 62, 370–378.
14. Spanghero, G.M., Albuquerque, C.,Lazzaretti Fernandes, T., Hernandez, A.J., Keutenedjian Mady, C.E. (2018). Exergy Analysis of the Musculoskeletal System Efficiency during Aerobic and Anaerobic Activities. *Entropy,* 20, 119

15. Madu, K. E. (2018). Prospects of Improved Power Efficiency and Operational Performance of Kainji-Dam, Nigeria. *Int. J. Innov. Sustain.*, 2: 41- 49
16. Çatak, J.,Özilgen, M., Olcay, A.B., Yılmaz, B. (2018). Assessment of the work efficiency with exergy method in ageing muscles and healthy and enlarged hearts. *Int. J. Exergy,* 25, 1–33.
17. Prek, M., Butala, V. (2010). Principles of exergy analysis of human heat and mass exchange with the indoor environment. *Int. J. Heat Mass Transf.*, 53, 5806–5814. 14. Prek, M.; Butala, V. Comparison between Fanger's thermal comfort model and human exergy loss. Energy 2017, 138, 228–237.
18. Madu, K. E. (2018). Design of a 10 Ton Capacity Standard Vapour Compression AirConditioning Plant for Application in a Mini Auditorium, in Nigeria. Int. *J Innov. Sustain,* 2: 26-33
19. Spanghero, G.M., Albuquerque, C.,Lazzaretti Fernandes, T., Hernandez, A.J.,Keutenedjian Mady, C.E. (2018). Exergy Analysis of the Musculoskeletal System Efficiency during Aerobic and Anaerobic Activities. *Entropy,* 20, 119.
20. Madu, K. E. (2018). Adaptation of an Air-Conditioning System for use in a 100-Seater Capacity Auditorium, in Nigeria. *Equ.J. Eng.*, 1-8
21. Çatak, J.,Özilgen, M., Olcay, A.B., Yılmaz, B. (2018). Assessment of the work efficiency with exergy method in ageing muscles and healthy and enlarged hearts. *Int. J. Exergy,* 25, 1–33.
22. Özilgen, M. (2017). Review on biothermoydnamics applications: Timeline, challenges, and opportunities. *Int. J. Energy Res.*, doi:10.1002/er.3712
23. N. E Nwanze, K. E. Madu, E. J. Igbagbon, & D. F. Ikikiru (2025). Thermal Energy Storage System: Overview of Sources, Classification, and Characterization, International Journal of Science, Architecture, Technology, and Environment, Volume 02, Issue 05, 1510-1526
24. Orhorhoro, E.K,Orhorhoro, W.O. (2016). Simulation of Air Inlet Cooling System of a Gas Turbine Power Plant. *Asia Pacific Journal of Applied Thermal Engineering,* 1(2)
25. Zhai, X.Q., Wang, X.L., Wang, T., Wang R.Z. (2012). A review on phase change cold storage in air- conditioning system: Materials and applications. *Renewable and Sustainable Energy Reviews,* 22: 108–120
26. G. I. Nwaeze, K.E. Madu, F. A. Nwafor, & O. N. Akpenyi-Aboh (2025). Exergetic Performance of Reversible Heat Pump, International Journal of Progressive Research in Engineering, Management and Sciences, Volume 5, Issue 01, 940-946

27. Pintaldi, S., Perfumo, R.,Sethuvenkatraman, S., White, S., Rosengarten G. (2015). A review of thermal energy storage technologies and control approaches for solar cooling. *Renewable and Sustainable Energy Reviews,* 41: 975–995
28. Okafor A. M. & Madu, K.E. (2025). Thermal Properties of Composites: A Systematic Review of Experimental and Theoretical Models, International Journal of Research Publication and Reviews, Volume 06, Issue 04, 11018-11038
29. Madu, K.E. (2018). Performance Analysis of a Steam Power Plant Operating Under Superheated and Isentropic Conditions. *Equ. J.* Eng., 22 – 28
30. Rupp, R.F., Vásquez, N.G., Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy Build.,* 105, 178–205.
31. Prek, M. (2004). Exergy analysis of thermal comfort. *Int. J. Exergy,* 1, 303–315
32. Prek, M. (2006). Thermodynamical analysis of human thermal comfort. *Energy,* 31, 732–743.
33. Prek, M. (2005). Thermodynamic analysis of human heat and mass transfer and their impact on thermal comfort. *Int. J. Heat Mass Transf.,* 48, 731–739
34. Prek, M., Butala, V. (2010). Principles of exergy analysis of human heat and mass exchange with the indoor environment. *Int. J. Heat Mass Transf.,* 53, 5806–5814
35. Prek, M., Butala, V. (2017). Comparison between Fanger's thermal comfort model and human exergy loss. *Energy,* 138, 228–237
36. Saito, M., Shukuya, M. (2001). The human body consumes exergy for thermal comfort. IEA-ECBCS-Annex 37 LOWEXNEWS2001,2: 6–7
37. Isawa, K.,Komizo, T.,Shukuya, M. (2002). Low exergy systems will provide us with the lowest human-body exergy consumption and thermal comfort. IEA-ECBCS-Annex 37 LOWEX NEWS, 37: 5–6
38. Shukuya,M (2009). Exergyconceptandits application to the built environment. *Build. Environ.,* 44, 1545–1550
39. Schweiker, M.,Shukuya, M. (2012). Adaptive comfort from the viewpoint of human body exergy consumption. *Build. Environ.,* 51, 351–360
40. Ala-Juusela, M., Shukuya, M. (2014). Human body exergy consumption and thermal comfort of an office worker in typical and extreme weather conditions in Finland. *Energy Build.,* 76, 249–257
41. Dovjak, M.,Shukuya, M., Krainer, A. (2015). Connective thinking on building envelope–Human body exergy analysis. *Int. J. Heat Mass Transf.,* 90, 1015–1025

42. Isawa, K.,Shukuya, M. (2016). Sensitivity Numerical Analysis of Human Body Exergy Balance under an Unsteady-State Thermal Environment—Behavioral Adaptation Induced by Undesirable Cold Storage by Building Envelope in Winter. *Health,* 8, 737–748.
43. Gordon, R.G., Roemer, R.B., Horvath, S.M. (1976). A mathematical model of the human temperature regulatory system-transient cold exposure response. IEEE Trans. *Biomed. Eng.,* 23, 434–444.
44. Ferreira, M.S. and Yanagihara, J.I. (2009). A Transient Three-Dimensional Heat Transfer Model of the Human Body. *International Communications in Heat and Mass Transfer*, 36(7): 718–724
45. Pennes, H.H. (1948). Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm. *Journal of Applied Physiology,* 1(2): 93–122
46. Wissler, E.H, Shitzer, A. and Eberhart, R.C. (1985). Mathematical Simulation of Human Thermal Behavior Using Hole Body Models.*Heat Transfer in Medicine and Biology, Analysis and Applications,* Vol. 1, Ed. Plenum Press, New York, U.S, pp. 325-373.
47. Mady, C.E.K., Oliveira Junior, S. (2013). Human body exergy metabolism. *Int. J. Thermodyn.,* 16: 73–80.
48. Diener, J. (1997). Calorimetriaindireta. Revista da Associação Médica Brasileira, 43, 245–253.
49. ASHRAE. Handbook of Fundamentals; American Society of Heating Refrigerating and Air Conditioning Engineers: Atlanta, GA, USA, 2005
50. Ferreira, M., Yanagihara, J.I. (2009). A transient three-dimensional heat transfer model of the human body. Int. Commun. *Heat Mass Transf.,* 36, 718–724.