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CONCEPTUAL DESIGN AND ANALYSIS OF A TRICYCLE MOUNTED SOLAR-POWERED PHOTOVOLTAIC COLD ROOM SYSTEM

AUTHORS:
A. Akinsade[1], J. F. Eiche[2], A. O. Akinola[3,*] and M. O. Famodun[4]

AFFILIATIONS:
[1,2,3,4]Department of Mechanical Engineering Olusegun Agagu University of Science and Technology, Okitipupa, Nigeria
[3]The Federal University of Technology, Akure, Nigeria.

***CORRESPONDING AUTHOR:**
Email: ao.akinola@oaustech.edu.ng

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Abstract

Energy crisis in developing countries is worrisome, and this has made the preservation and transportation of medical and perishable food items a common problem. Most conventional refrigeration systems operate with electricity; however, there are regions where it is difficult or not cost efficient to provide electric service. Therefore, this research seeks to solve the problems of inconsistent, irregular and complete non availability of power supply required to keep food products and drugs refrigerated over a long period of time by designing a tricycle mounted solar-powered cold room. The tricycle mounted solar-powered cold room designed consists of a refrigeration system having a compressor, a condenser, an expansion valve and an evaporator; a solar system having a photovoltaic (PV) module, charge regulator, storage battery and DC to AC inverter; and a tricycle for easy distribution and safe delivery of refrigerated items. A comprehensive analytical design was performed on each of the systems and the design results showed that the solar-powered cold room has refrigerating cooling load, PV array size, battery cap, and inverter power of 986 W, 275 W, 94 kWh, and 8000 W respectively. A structural analysis was also carried out on the tricycle chassis using the finite element method on Autodesk Inventor software. The results showed that the maximum von misses stress experienced by tricycle chassis was 56.96 MPa which is significantly lower than the yield strength of the chassis material used in the design, indicating a robust structural integrity and can therefore be used to carry the loads that it will be subjected to without deformation.

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1.0 INTRODUCTION

Energy is the ability to do work and it is essential to humanity as he makes use of it in his daily life. It is one of the indispensable tools for continuous economic growth and development. The demand for energy is increasing rapidly in developing countries due to automation, industrialization, and urbanization [1]. The present sources of energy in use nowadays are not adequate as a result of increasing population and technological development. The world population has increased at an explosive rate from 1.65 billion to just over 6 billion people in the 20th century and continues to increase. In the same century, mankind has consumed over 875 billion barrels of oil and it is very likely that even more oil will be consumed in the present century. Annual energy use in developing countries has risen from 55 to 212 kg of oil equivalent over the last thirty years, while developed countries use as much as 650 kg of oil equivalent per person [2]. Relatedly, the prevalent hot weather throughout the year in the tropics, coupled with poor storage facilities has brought about a heavy demand for refrigeration and air conditioning. However, if kept below -30℃, most food will deteriorate, often with changes in texture, taste, and smell. More important still, poisonous products may be produced. These changes can be due to micro-organisms such as bacteria and yeast. Food preservation is essentially based on methods that kill microorganisms (such as bacteria) or at least inhibit the growth of such micro-organisms that make food unsuitable for human consumption. Refrigeration is a method of lowering the temperature of substances below that of the surroundings in order to preserve or make them suitable for consumption in the near future [3; 4; 5; 6].

The shortfall of energy supply in developing countries is worrisome, and this has made the preservation and transportation of medical and perishable food items a common problem [2]. Most conventional refrigeration systems operate with electricity; however, there are regions where it is difficult or not cost-efficient to provide electric service. In addition, the cost of generating electricity is high economically and ecologically. Electricity where available is epileptic; and some villages had never enjoyed electricity supply for once, making the development of a small economy difficult. One of the ways out of these energy problems is the use of alternative energy sources – Renewable energy. The most preferred choice of renewable energy considering the prevalent hot weather is solar energy. Solar energy can be transformed either to electricity or to heat, to power a refrigeration cycle through photovoltaic system applications.

According to [7], the most preferred solar system for cooling is photovoltaic system applications. [8], experimentally investigated a solar photovoltaic powered ice-maker that operates without the use of batteries. It was reported that the study results showed very good ice-making capability and reliable operation, as well as a great improvement in the startup characteristics of the compressors. The compressor remains operational even during days with low solar irradiation and operates with improved utilization of the available photovoltaic power. [9], published a paper on a review of solar absorption refrigeration technologies, development, and applications, and pointed out that solar refrigeration technologies have the advantage of removing the majority of harmful effects of traditional refrigeration machines and that the peaks of requirements in cold, most of the time coincide with the availability of solar radiation.

This research seeks to solve the problems of inconsistent, irregular, and complete non- availability of power supply (as in the case of the Southern Senatorial District of Ondo State) required to keep food products and drugs refrigerated over a long period of time by replacing electricity from grid with the solar power harnessed from the sun.

2.0 MATERIALS AND METHOD

2.1 Materials

The tricycle mounted solar-powered cold room consists of a refrigeration system having a compressor, a condenser, an expansion valve, and an evaporator; a solar system having a photovoltaic (PV) module, charge regulator, storage battery and DC to AC inverter; and a tricycle for easy distribution and safe delivery of refrigerated items.

2.2 Design Criteria

The following criteria were considered for the design of the machine:

1. Design capacity of 80 kg;
2. Density of the refrigerating feedstock as 1000 kg/m^3;
3. Initial temperature of the feedstock as 30 ℃;
4. Condensing temperature of the working fluid (refrigerant, R134a) is 40 ℃.
5. Design desired temperature to be attained by the refrigerating sample in +2^{o}C
6. Sunlight availability in Okitipupa, Nigeria is taken to be 6 hours per day

2.2.1 Design analysis of the refrigerating components

Standard equations were used for the design of the components of the refrigerating system.

(i) Refrigerating Space: The area and volume of the refrigerating space was determined using Equations (1) and (2) [10]

$$A_s = 2\{(LB) + (LH) + (BH)\} \quad (1)$$

$$V_t = \{(L - 2t) + (H - 2t) + (B - 2t)\} \quad (2)$$

Where; A_s is the area of the refrigerating space (m^2), L is the length of the refrigerating space (m), B is the breath of the refrigerating space in (m), H is the height of the refrigerating space in (m), V_t is the volume of the refrigerating space (m) and t is the thickness of the plate (m).

(ii) Cooling Load Capacity: The cooling load capacity which consists of product load, Wall gain load, and Infiltration load was obtained from Equations (3) to (5) [10, 11]

Product Load;

$$Qproduct = \frac{m\left(c_{p\times w}(T_i - T_0) + h_{latent} + c_{p.ice}(T_0 - T_f)\right)}{\Delta t_p} \quad (3)$$

Wall gain load;

$$Q_{wall} = A_s U \Delta t \quad (4)$$

Infiltration Load;

$$Q = m h_f \quad (5)$$

Therefore, the total cooling load in the refrigerating space was obtained from Equation (6) [10].

Total Cooling Load;

$$Q_{tcl} = Q_{product} + Q_{wall} + Q_{infiltration} \quad (6)$$

Where; m is the mass of the product (kg), Cp is the specific heat of product to be refrigerated (kJ/kgK), $C_{p.ice}$ is the specific heat of ice (kJ/kgK), Q_{latent} is the latent heat of fusion (kJ/kg), Δtp is the desired production time (secs), T_i is the initial temperature of water (°C); T_0 is the freezing temperature (°C), and T_f is the final temperature of ice (°C), U is the overall heat transfer coefficient (W/m^2 K), and Δt is the temperature differential across the wall (°C) and h_f is the product latent heat of fusion (kJ/kg).

(iii) Compressor Design: The compressor capacity was evaluated from the theoretical power required; P_R, given by Equation (7) [12].

Theoretical Power Required;

$$P_R = \frac{Q_{tcl}}{3600} \quad (7)$$

(iv) Evaporator Design: The internal diameter and the length of the evaporator tube were estimated using Equations (8) and (9) respectively [16], and the evaporator cooling area was calculated using Equation 10 [15]. The number of loops of copper tube used for the evaporator tube was determined using Equation (11) [17].

$$d_{ic} = d_{oc} - 2t_w \quad (8)$$

$$L = \frac{Q_{tcl}}{\rho d_{ic} U \Delta T} \quad (9)$$

$$A_e = \frac{Q_{tcl}}{U \Delta t_m} \quad (10)$$

$$n_c = \frac{4 m_v}{\rho \pi d_{ic}^2 v_r} \quad (11)$$

Where; d_{ic} is the internal diameter of tube (m), d_{oc} is the outside diameter of tube (m), t_w is the tube wall thickness (m), A_e is the cooling area of the evaporator (m3), Δt_m is the log mean temperature difference (°C), m_v is the mass flow rate of the refrigerant (kg/s) and n_c is the number of loop of copper tube.

2.2.2 Design of the PV system

The photovoltaic (PV) system for the cold-room was designed using the following standard equations:

(i) Refrigerator Energy demand: the energy required in Watt-hour/day by the refrigerator is given in Equation (12) [17] and the total energy to be delivered by the PV panel is estimated using Equation (13) [17]. The size of the PV array needed to provide the total energy required to bring the cooling effect was estimated using Equation (14) [17].

$$R_e = P_t \times H_d \quad (12)$$

$$T_e = R_e + (20\%\ of\ load) \quad (13)$$

$$PV_a = \frac{T_e}{availability\ of\ sun/day} \quad (14)$$

Where; R_e is the Refrigerator Energy Requirement (Wh/day), P_t is the power required (W), T_e is the Total Energy to be delivered by the PV panel per Day (Wh/day) and PV_a is the PV array size needed (W).

(ii) Sizing of the Battery: The capacity of the battery used was estimated using Equation (15) [18] and the total battery pack in Watt-hour per day was determined using Equation (16) [18].

$$Cap = NVA \quad (15)$$

$$E_b = T_e \times 10 hours/day \quad (16)$$

Where; Cap is the battery pack capacity (Wh/day), N is the number of battery, V is the voltage for each battery (V) and A is the amp drawn (Ah) and E_b is the total battery pack (Wh/day).

(iii) Sizing of the Inverter: The sizing of the inverter was done based on the size of the PV array. The actual power of the inverter was estimated using Equation (17) [16], the drain current and the full load output current of the inverter were estimated using Equations (18) and (19) respectively [18].

$$P = VAcos\theta \quad (17)$$

$$drain\ current = \frac{output\ power}{battery\ voltage} \quad (18)$$

$$load\ output\ current = \frac{output\ power}{output\ voltage} \quad (19)$$

Where; P is the actual power of the inverter (W) and $cos\theta$ is the power factor.

The end elevation and circuit diagram of the conceptual tricycle mounted solar-powered cold room are shown in Figures 1 and 2 respectively.

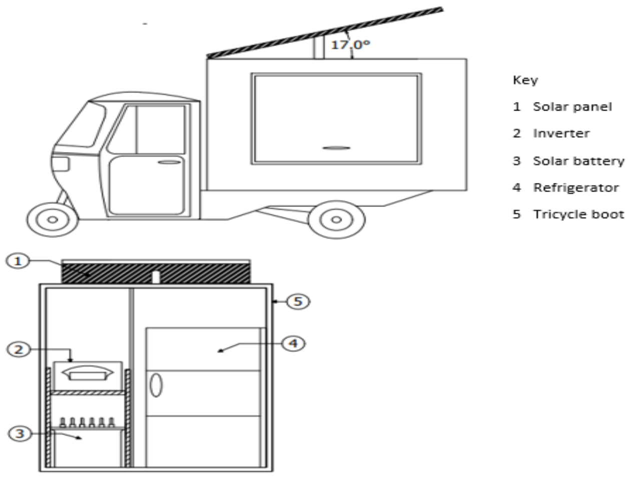

Figure 1: End elevation of the conceptual tricycle mounted solar-powered cold room

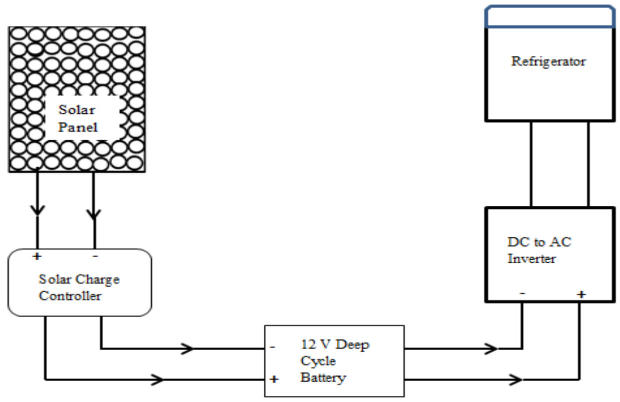

Figure 2: The circuit diagram of the solar-powered cold room

2.3 Stress Analysis of the Tricycle Used

The structural analysis was carried out by designing the 3D CAD model of the tricycle chassis on Autodesk Inventor software which was then moved to the Structural Analysis domain of Inventor, enabling the generation of a 3D solid mesh of the model using finite element method (FEA). In order to improve the accuracy of the results, mesh control setting was applied to produce a refined and improved mesh quality of an average size of 0.1 mm and a grading factor of 1.5 as shown in Table 1. This produced a discretized chassis 3D model of 69915 elements with 123878 nodes. To accurately simulate the operating condition of the tricycle, loads of 8565 N, 2450 N and 784 N, representing the engine block, tricycle body and the combined load of the refrigerator, batteries, solar panel and inverter respectively, were located and acting normally on the chassis and all forces applied are as shown in Table 2 with their selected faces shown in Figures 2 to 4 respectively.

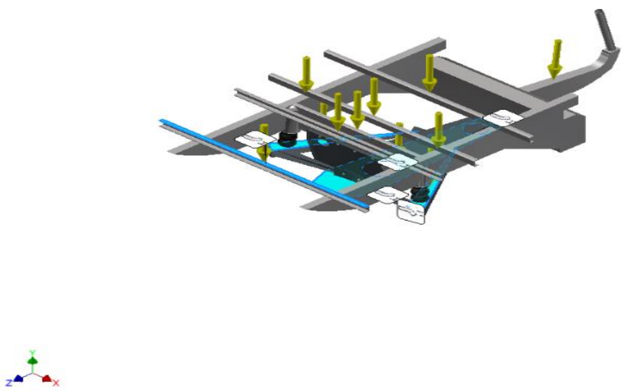

Figure 3: Selected faces for load 1

The chassis was securely fixed and prevented from moving by applying fixed supports boundary conditions as shown in Figure 5 and 6. The chassis material is mild steel with its mechanical properties given in Table 3. Other boundary conditions such as the physical values used for finite element analysis and the general setting and are shown in Tables 4 and 5 respectively.

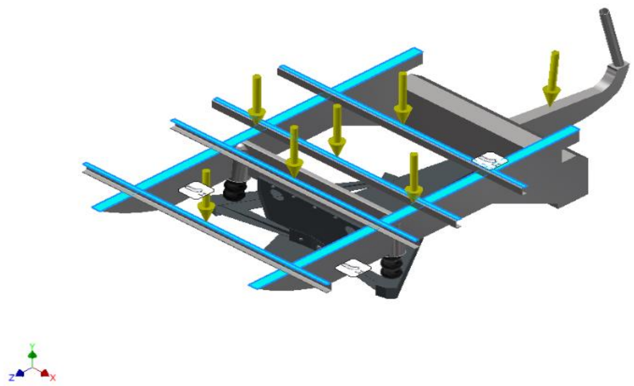

Figure 4: Selected faces for load 2

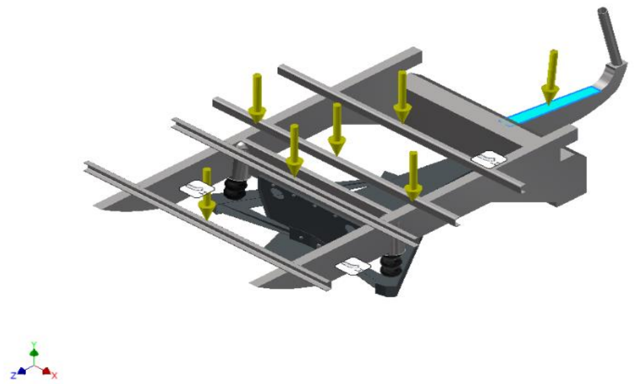

Figure 5: Selected faces for load 3

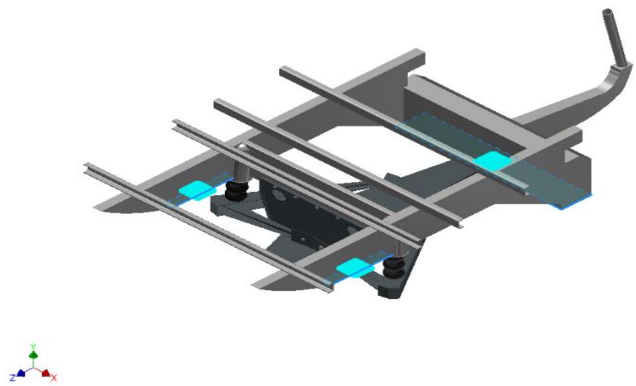

Figure 6: Fixed constraint

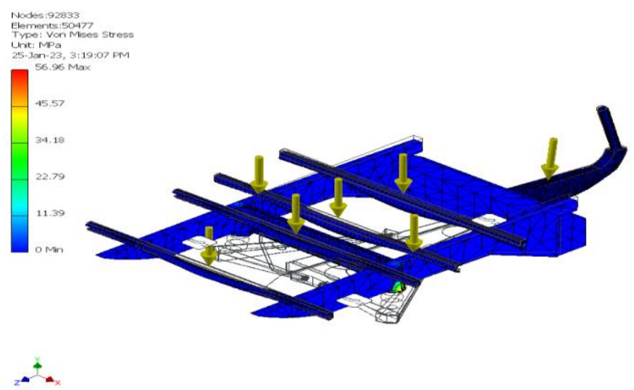

Figure 7: Von misses stress

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Table 1: Mesh setting

Average Element Size (fraction of model diameter)	0.1
Minimum Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Maximum Turn Angle	60°
Create Curved Mesh Elements	No
Use part based measure for Assembly mesh	Yes

Table 2: Applied load

Force 1		Force 2		Force 3	
Magnitude	8565.000N	Magnitude	2450.000N	Magnitude	784.000N
Vector X	-108.920N	Vector X	0.000N	Vector X	-0.000N
Vector Y	-8562.566N	Vector Y	-2450.000N	Vector Y	-779.115N
Vector Z	172.675N	Vector Z	-0.000N	Vector Z	87.384N

Table 3: Mechanical properties

Name	Steel, Mild	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0.275 ul
	Shear Modulus	86.2745 GPa
Part Name(s)	Hex Flange Head Tapping Screw - Type BF - Metric 9.5x2.1 x 25 Hex Flange Head Tapping Screw - Type BF - Metric 9.5x2.1 x 25 AS 1427 - Metric M8 x 16 AS 1427 - Metric M8 x 16 AS 1427 - Metric M8 x 16 AS 1427 - Metric M8 x 16 ANSI B18.2.3.4M M16 x 2x35 ANSI B18.2.3.4M M8 x 1.25x30	

Table 4: Physical values used for finite element analysis

Mass	604.178 kg
Area	7257680 mm^2
Volume	81309200 mm^3
Center of Gravity	$x = -801.02\ mm$ $y = 303.015\ mm$ $z = 101.185\ mm$

Table 5: General setting and objectives

Design Objective	Single Point
Study Type	Static Analysis
Detect and Eliminate Rigid Body Modes	No
Separate Stresses Across Contact Surfaces	Yes
Motion Loads Analysis	No

3.0 FINITE ELEMENT ANALYSIS (FEA) RESULTS AND DISCUSSION

3.1 Results

Structural analysis was carried out on the chassis of a tricycle to be used for distribution and delivery of refrigerated items. The modal parameters were determined and then used to validate the finite element model. The analysis model of the tricycle chassis produced a discretized chassis 3D model of 69915 elements with 123878 nodes. The element used was quadrilateral dominant and the load acting was 8565 N, 2450 N and 784 N, representing the engine block, tricycle body and the combined load of the refrigerator, batteries, solar panel and inverter respectively. The simulation was based on the condition of the tricycle being stationary.

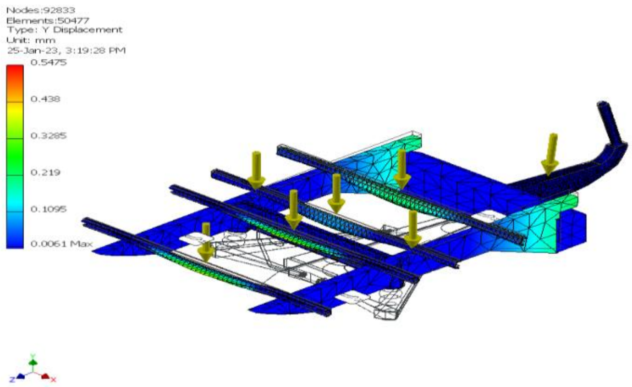

Figure 8: Equivalent Strain

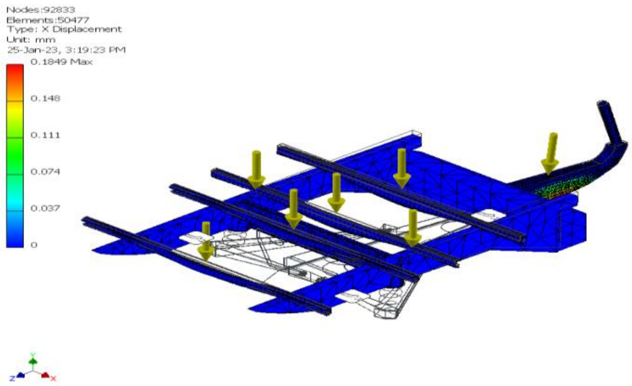

Figure 9: X Displacement

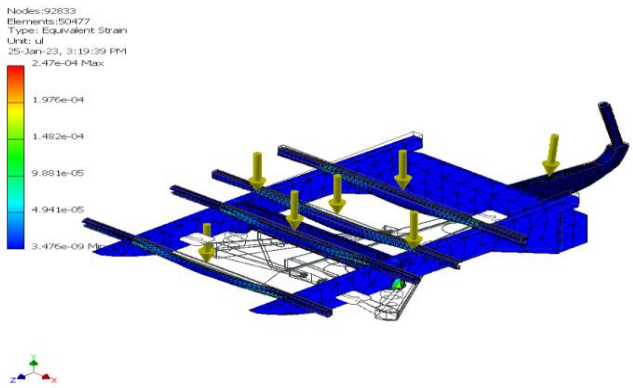

Figure 10: Y Displacement

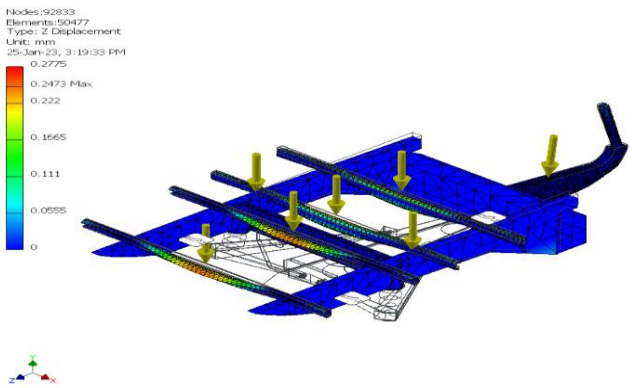

Figure 11: Z Displacement

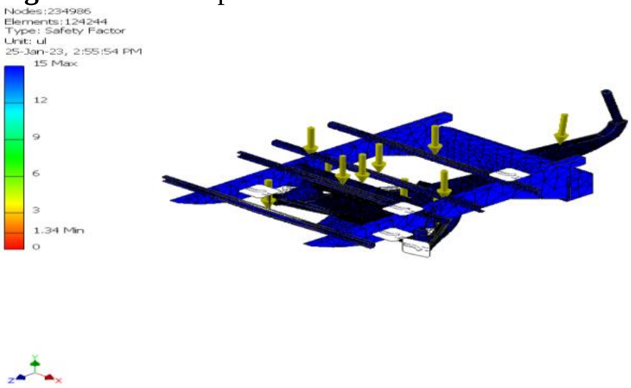

Figure 12: Factor of safety

The FEA results from the modal analysis of the tricycle are presented in Figures 7 to 12 respectively.

3.2 Discussion

From the finite element analysis (FEA) results conducted, the von misses stress and equivalent strain distribution in the chassis are shown in Figures 7 and 8 respectively. The results showed that the tricycle chassis experienced maximum von misses stress of 56.96 MPa and equivalent strain of 2.47. It can be observed that the value of von misses stress is less than the yield strength of tricycle chassis material which is 207 MPa. This implies that the loads are not enough to cause permanent plastic deformation in the chassis structure. Also, the action of the loads on the chassis with respect to its resultant displacement were assessed and presented in Figures 9, 10 and 11 respectively, and a maximum resultant displacement of 0.1849, 0.5475 and 0.2473 mm were indicated along XYZ distribution directions for the tricycle chassis. Due to the low von misses stress and strain experienced by the chassis, the maximum displacement values are therefore negligible and have no effect on the stability of the chassis as these values are still within the elastic limit of the chassis material. The minimum factor of safety 1.34 obtained as shown in Figure 12 for the entire chassis analyzed also show that the tricycle chassis is of high structural integrity and can therefore be used to carry the loads that it will be subjected to without deformation.

4.0 CONCLUSION

The conceptual design and structural analysis of a tricycle mounted solar-powered cold room for easy distribution and safe delivery of medical drugs and other refrigerated items is presented in this paper. The tricycle mounted solar-powered cold room consists of refrigeration system, solar system and a tricycle. A comprehensive analytical design was performed on each of the systems and a structural analysis was carried out on the tricycle chassis using finite element method on Autodesk Inventor software. The results showed that the maximum von misses stress experienced by tricycle chassis was 56.96 MPa which is significantly lowered than the yield strength of the chassis material used in the design, indicating a solid structural integrity and can therefore be used to carry the loads that it will be subjected to without deformation. The tricycle mounted solar-powered cold room, when constructed, can suitably be used in many rural regions where electricity is unreliable or non-existent.

5.0 ACKNOWLEDGEMENT

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