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DEVELOPMENT OF AN AUTOMATED TRACKER FOR THE ENHANCEMENT OF ENERGY AVAILABILITY IN A SOLAR BOX OVEN

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ABSTRACT

The study focuses on the enhancement of the energy available in a solar box oven, by designing and testing an automated pendulum system to efficiently track the sun's position during the course of the day; using locally available material. The pendulum mechanism is made of a support stand of mild steel rods and steel pipes, bearings fixed on the stand as fulcrum, string connecting the pendulum with the reflectors, buckets and water. The pendulum mechanism pulls on strings to move the reflectors on the solar box cooker slowly tracking the sun. A drain device is attached to one of the bucket while the other bucket is filled with water; allowing the water to drip out of the bucket while the other bucket was half filled. The tracker performance was evaluated by comparing the expected theoretical angle of tilt over the operational period with the measured angles of tilt of the reflectors during experimentation. Results obtained revealed that the maximum tilt angle deviation was 2^o. No significant difference between the theoretical and experimental results was observed using the Chi-square statistical analysis method. The performance level is a good approximation to the expected results. Based on the simplicity of the developed solar tracker and the construction costs, this type of solar box cooker with tracker will address the issue of energy sustainability in the rural areas as well provide the much needed technology for the less privileged people.

Keywords: *solar tracker, solar box oven, rural dwellers, Chi-square method, low cost, sustainability.*

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I. INTRODUCTION

Solar energy is the energy received by the earth from the sun, and solar radiation has been identified as the largest renewable resource on earth [1]. Solar energy can be applied in different ways and there are also many different methods for collecting the solar energy from incident radiation. Solar oven is one device that is used to collect solar energy from incident radiation to heat things up such as in cooking, roasting, frying, baking etc. The heat input causes the temperature inside of the solar box oven to rise, so it cooks because the interior of the box is heated by the energy collected from the sun. Solar ovens or cookers are simple and effective way to provide the energy needed for cooking to people with less access to other energy sources.

External reflectors are fixed on the topsides of solar oven so that the solar radiation that falls outside the aperture area of the solar box oven can be redirected to oven interior and utilized to increase the intensity of solar radiation reaching the oven plane. This additional input of solar energy results in higher cooker temperature there by increasing the cooking performance. Solar box with adjustable reflectors need tracking device to be able to shift the position of the reflectors in order to maximize the amount of sunlight concentration on the solar box receiver.

Tracking collectors are either single-axis or double-axis [2, 3, 4, 5]. Both manual and mechanized systems are used for continuous tracking. Mechanized systems used for continuous tracking could be categorized in two: the first is the automated electronic system that used electric motor and other related components, while the second category is the automated mechanical system that uses clock mechanism or suitable weight reduction device to operate a pendulum mechanism that pulls on a string which in turn moves the reflector in other to track the sun.

Though several tracker technologies and methods are available but they differ in their characteristics, operational conditions, applications and level of performance. Therefore, the present study focuses on the needs of the rural dwellers; hence the weight and cost reductions, supported by appropriate structure using water under steady flow rate of draining were considered appropriate and adopted in this study.

II. METHODOLOGY

2.1 Theoretical Background

Pressure in a fluid at rest is independent of the shape or cross section of the container. It changes with the vertical distance or direction in a gravity field but remains constant in the other directions. This is the principle behind the gravity driven flows [6]. This principle has been applied by researchers in developing techniques for solar tracker. The ideas proposed by both Von Oppen and Thomasson W. James in line with this principle have been considered useful in the development of this work. While Von Oppen system [7, 8] uses a half filled bottle to act as a floating piston, which drops when the water is slowly drained from a reservoir and caused a string pulls that rotates the solar cooker, Thomasson W. James [9] proposed a pendulum mechanism that pulls on a string that moves the reflectors on a cooking solar box for the purpose of tracking the sun. The configuration he proposed consisted of a pendulum mechanism suspended on a fulcrum above the ground. The pendulum supports a rigid platform that buckets (to hold water) were fasten to its opposite ends. Water is to be drain from one of the buckets at a steady regulated rate. It was suggested that a location should be found on the pendulum mechanism that moves in 6 hours through a distance that is equal to the size of the reflector; such location should be connected to one of the reflectors. As the water drains out of the bucket, it pulls the reflectors and tracks the sun automatically.

2.2 Design Considerations and Procedure

i.) Type and Geometry of Solar Oven: The Solar Oven used in this study is similar to that reported by Suharta et al. [10] as fourth generation oven, with the following major external dimensions; Height, H_o = 0.33 m, Length, L_o = 0.70 m, Width, W_o = 0.70 m, Aperture Length, AL= 0.52 m, Aperture Width, AW = 0.52 m

ii.) 2 numbers plane glass mirrors were selected as the reflectors. Considering the solar oven aperture dimensions, the sizes of the reflective mirrors were taken to be equal to the solar oven window size, the aperture area. The reflective mirrors were put in ply wood frames to serve as supports for the glasses as well as protector.

iii.) The weights of the 2 number reflectors with the support frames were measured.

iv.) In order to lift the weights of the reflectors, water inside 2 number buckets have been selected to provide the needed force. Appropriate weight of water needed was estimated using equations 1 and 2 [6, 11]:

$$Mass, M = density(\rho) \times Volume\ (V) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$Weight, W = Mass(M) \times Acceleration\ due\ to\ gravity\ (g) \ldots\ldots\ldots\ldots\ldots \quad (2)$$

v.) In order to achieve effective tracking of the sun by the reflectors, pendulum mechanism suspended on a structural support capable of carrying the weights of the water in the buckets, while the full water inside one of the bucket is draining at a steady flow rate in order to induce continuous weight reduction, was developed. The pendulum assembly was connected to the edges of the reflectors at one of the sides.

vi.) The procedure specified by the American Institute of Steel Construction (AISC) as presented by Shigley and Mischke [12] was applied in the design of the structural support for the pendulum system.

2.3 Design Analysis

1. Calculation of the Reflectors Parameters:

Mass of individual reflector and frame, MR = 3.7kg
Length of reflectors, HR = 0.7m
Width of reflectors, WR = 0.7m

$$Area\ of\ reflector\ and\ frame, A_{RF} = H_R \times W_R$$
$$A_{RF} = 0.7\ m \times 0.7\ m = 0.49m^2$$
$$Maximum\ Height\ attainable\ by\ reflectors, H_{RM}$$
$$H_{RM} = H_O + H_R = 0.7\ m = 0.33m = 1.03m$$

Reflectors rotation range is between 0^o to 90^o.

2. Force required to lift the Reflectors:

The force required to lift the 2 number reflectors should be greater than the total weight of the reflectors and their frames with some magnitude in order to take care of likely wind effect and other frictional effect within the whole system.

$$Total\ Mass\ of\ Reflectors\ and\ Frames, M_{TR} = 2 \times M_R$$
$$= 2 \times 3.7 = 7.4\ kg$$

$$Design\ Force\ to\ lift\ the\ refrectors\ with\ frames, F_{RF}$$
$$= W_{TR} + \sum W_i$$

where W_{TR} is the weight of the reflectors and frames

W_i, represents the forces to be overcome from other contributors such as wind load, etc

W_i is taken as 40% of W_{TR}

Hence, required mass for W_i, denoted by M_i is 40 % of M_{TR} will be equal to 2.96 kg. Since this weight is to be overcome by the weight of water inside containers, then the minimum weight of water with the containers should be equal to the Design Force.

$$Weight\ of\ water\ with\ the\ container, W_{WC} = F_{RF}$$

$$Total\ mass\ required\ of\ water\ and\ containers, M_{TWCR} = M_{TR} + M_i = 7.4 + 2.96 = 10.34\ kg$$

2.4 Material Selection

For this study, plastic bucket of 13 litres capacity was selected as the water container. 2 number Buckets were used as water containers, one filled up with water that is to be drain over the operational period while the second was half filled and to maintained constant weight during the operational period.

Mass of plastic bucket, M_b=0.4 kg

If the bucket is filled with 10 litres of water, it will amount to a mass, M_w= 10 kg;

Total Mass available from Full container, M_{FWCA}=10+0.4=10.4 kg

Total Mass available from half-Full container, M_{HFWCA}=5+0.4=5.4 kg

This Mass will provide enough force to lift the reflectors by pulling on a string connecting the reflector and the pendulum system together.

3. Computing the required drops of water during draining for appropriate tracking: Expected operation period of tracking was taken as 8 hours; Volume of Water to be drained in 8 hours is 10 litres. Since 20 drops is per millilitre (i.e 1 drop per 0.05 millilitres [13]), therefore 10 litres will equals 200,000 drops. To drain 10 litres in 8 hours, about 7 drops per second is required.
4. Selection of the Drip Device:
   The water to be drain is to be hanged at a height or desired elevation above the ground level thereby making it a gravity driven flow. Though the height of the water reservoir can be used to control the flow rate in gravity driven flows, for this study, Danal Flow Set, a Non Vented Intravenous Administration Set was adopted by connecting it to the bucket, in order to achieve accurate drops of the water draining out of the Full-bucket of Water. It is a reliably device with roller clap to adjust flow rate to any desired, specified or required flow rate, and it is available as it is been commonly used for intravenous infusion.
5. Structural Support for the Pendulum Water Assembly: The configuration of a proposed structural support has four major members. Member A is the Hanger expected to carry the 2 number buckets with water. Member B connects the hanger with the shaft incited in a cylindrical pipe (Member C) suspended by bearings that provide rotary motion of the whole pendulum assembly. Member D represent the stem of the structural support.

Considering the variable load on member A at one of its end due to the drain water from mass 10kg to 0kg, maximum Moment obtained was 0.033kNm, Axial Load computed was 0.17kN and shearing force of 0.11kN was obtained; for member B, maximum Moment obtained was 0.015kNm, Axial Load computed was 0.17kN and shearing force of 0.194kN was obtained; for member C, maximum Moment obtained was 0.107kNm, Axial Load computed was 0.37kN and shearing force of 0.194kN was obtained; member D, maximum Moment obtained was 0.107kNm while the Axial Load computed was 0.5kN.

In selecting the dimensions of the structural support members, care was taken to ensure that they were sized such that the design stresses computed from the forces does not exceed the allowable stresses. For Members A, B, and C, mild steel rod of 15mm diameter with *Z* value of 331.3 mm^3 and *A* value of 172.72 mm^2 was selected. For the cylindrical part of member C housing the bearing and the shaft, a circular pipe of 38mm with 1.5mm thickness having *Z* value of 1510 mm^3 and *A* of 172mm^2 was selected. For the structural stem, square pipe of 38mm and 1.5 mm thickness with *Z* value of 2361mm^3 and *A* of 208 mm^2 have been selected.

III. CONSTRUCTION AND ASSEMBLY OF AUTOMATED TRACKING SYSTEM

The major parts of the tracking system are: Support structure, Pendulum members, Buckets filled with water, Flow set and Strings. Processes involved in the construction of the support structure and pendulum members of the tracking system which are made of mild steel rod, circular pipe, square pipe and 2 number bearings include metal cutting and joining process, metal finishing and painting work. Equipment and tools used for the construction include the following: measuring tape, marking tool, punch, hammer, hack saw and welding machine. Two number plastic buckets were bought in the market, one which is expected to hold a full – bucket of water to be drained was connected with the local Dana Flow Set as follows; a hole was drilled at bottom of the bucket and the spike heading of the local Dana Flow Set was connected to the drilled bottom centre of the bucket.

It was joined and made leakage free by using strong adhesive glue. Two number strings were cut to the required lengths using a knife and each was tight to the hook on the edges of the hanger member A of the pendulum assembly. The buckets filled with water were hanged on these hooks at the edges of member A.

The square pipe was cut to the required length using hack saw to formed member D and welded to the support base made of mild steel square pipes. The mild steel circular pipe was cut to the required dimension and fitted with bearings at each end to accommodate the rotating shaft that formed the pendulum. The Hanger rod regarded as member A was welded to the connecting rod member B and welded to the rotating shaft that formed member C. This was fitted into the bearing inside the circular pipe welded to stem support. All these component parts after assembled formed the mechanically automated tracking system for the solar oven as shown in Fig. 1. The total cost of production is =N=3,000.00 which is equivalent to $15.15 at an exchange rate of $1 to =N= 198.00.

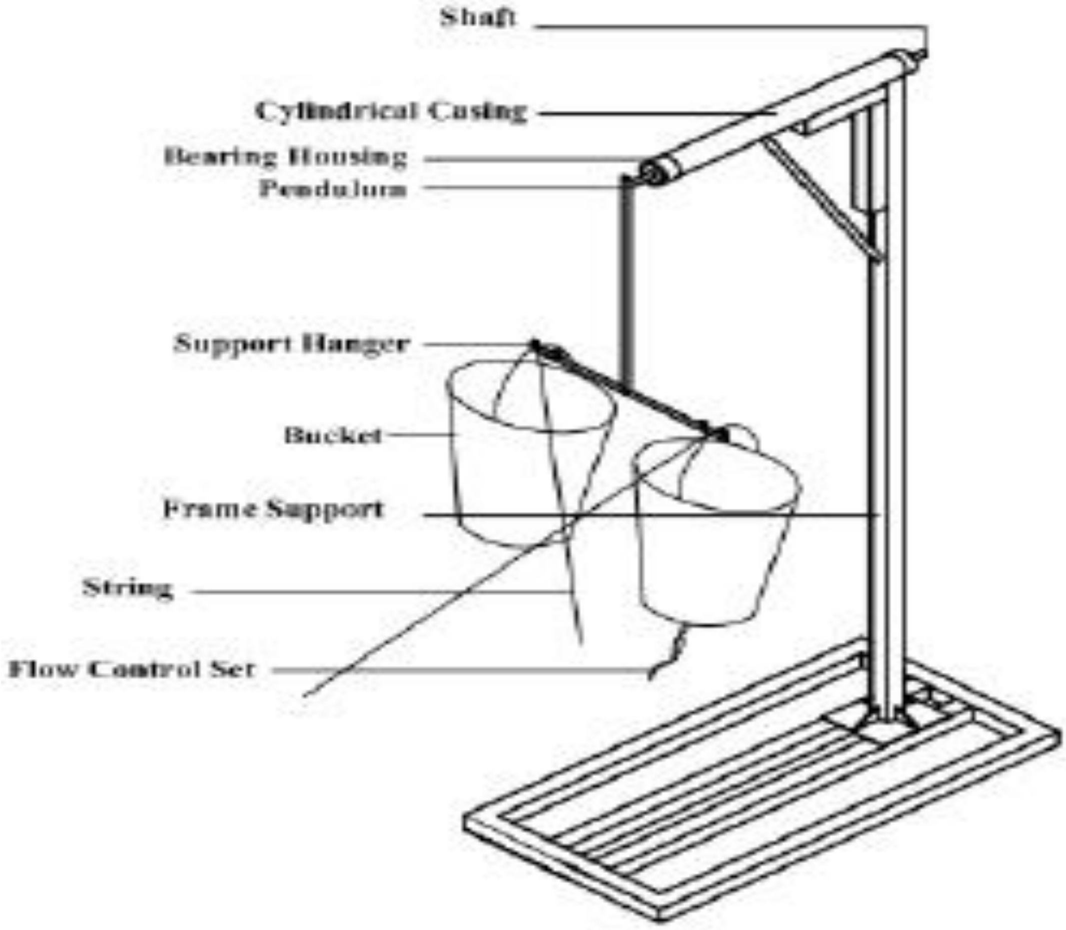

Figure 1: Pendulum system assembly

IV. OPERATION AND PERFORMATION EVALUATION

The system was put into operation at the test site as follows: the full-water bucket (10 litres) was hanging on one side of the hanger (member A) and the half-full -water bucket (5 litres) on the other side of the hanger, and the whole connecting the reflectors on the solar oven to the hooks at the edges of the hangers using string as shown in Fig. 2.

The tracking system was designed to operate for 8 hours (from 8a.m to 4p.m) and while the sun moves 15 degrees per hour, the reflectors rotate 10 degree per hour. The sun is assumed to be at 30 degrees on the horizon at 8 a.m. and to have rotated to 50 degrees at 4 p.m. Plate 1 shows the developed Automated Solar Tracker for Solar Box Oven during operation.

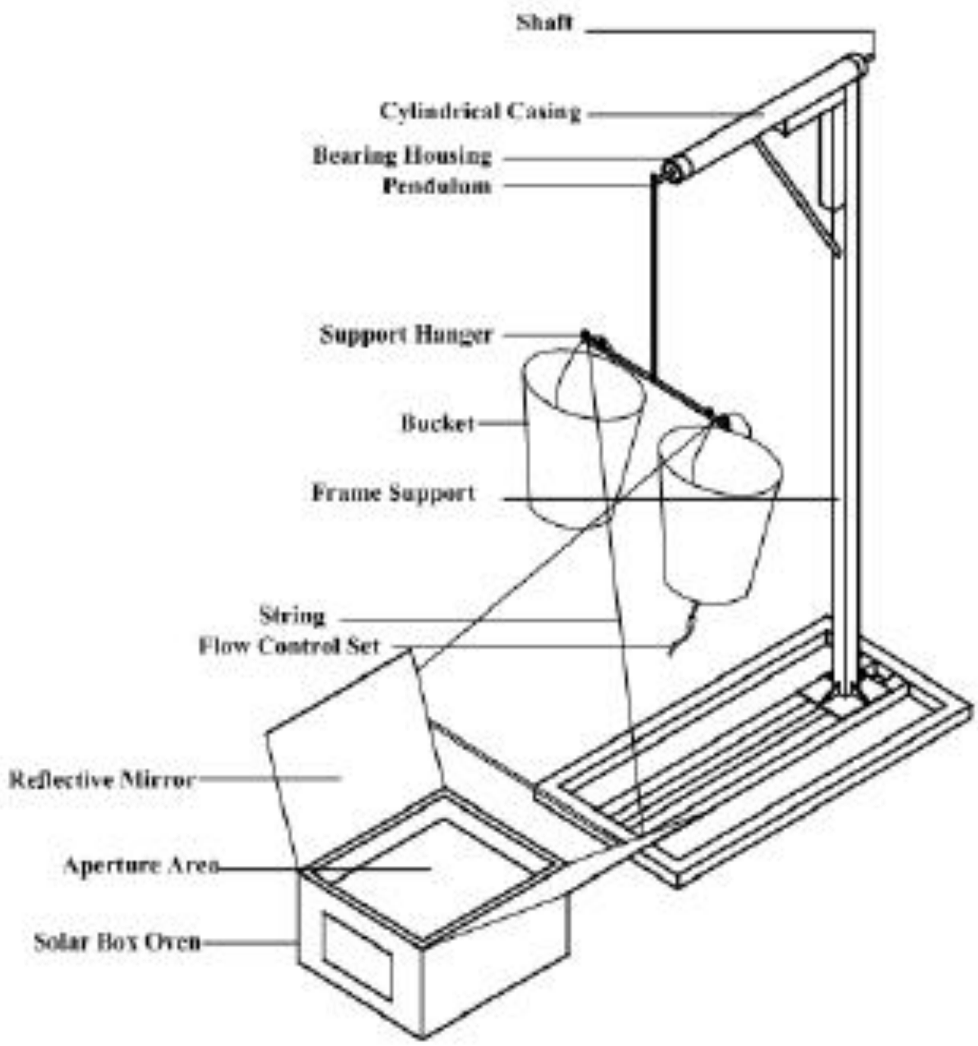

Figure 2: Assembled solar tracking oven

By 8 a.m. in the morning at the starting period of operation, the reflectors on the solar oven were manually oriented so that one of the reflectors formed an angle of 20^o when measured to the horizontal surface of the solar oven aperture area while the other one was inclined at an angle of 80^o facing the sun. The strings on the hooks of the hanger were connected to the appropriate position at the top edge of each alternate reflector. The roller clap on the tube of the flow set connected to the full-water bucket was adjusted to achieve 8 drops per second for the water dripping from the full-bucket.

As water continues to drip out of the bucket, the reflectors rotate. The rotation of the reflectors in degree was read from the degree scaled metal plates attached to the solar oven at one hour interval.

Measured values of the reflectors rotation angles were recorded over the period of operation. The performance of the tracking system was evaluated by comparing the measured values with the theoretical values expected.

The results obtained were statistically analyzed by computing the percentage error and standard deviation using equations 3 and 4 respectively. Chi-square as expressed in equation 5 was used to determine the significance differences between theoretical results and the experimental results while the standard deviation was found using equation 6.

$$Percentage\ error = \left(\frac{Expected - Observed}{Expected}\right) \times 100\% \quad \ldots\ldots\ldots\ldots 3$$

$$Standard\ deviation = \sqrt{\frac{\sum(Expected - observed)^2}{degree\ of\ freedom}} \quad \ldots\ldots\ldots\ldots 4$$

$$Calculated\ Chi - square; \sum \frac{(Observed - Expected)^2}{Expected} \quad \ldots\ldots\ldots\ldots 5$$

$$Degree\ of\ freedom, df = (c-1)(r-1) \quad \ldots\ldots\ldots\ldots 6$$

Plate 1: Pictorial view of Automated Solar tracker for Solar Oven

The theoretical as well as the measured results are presented in Table 1.

Table 1: Reflectors angles of rotation with respect to time of the day.

Time(hours)	Reflectors Angle of Rotation (^{o})			
	Theoretical Results		Measured Angle of Rotation	
	Reflector 1	Reflector 2	Reflector 1	Reflector 2
8:00	20	80	20	80
9:00	30	90	29.5	89.5
10:00	40	100	39	99
11:00	50	110	49	109
12:00	60	120	58	118
1:00	70	130	69	129
2:00	80	140	80	140
3:00	90	150	90	150
4:00	100	160	101	161

In this study, the expected are the theoretical results while the observed are the measured results.

where c is the number of variables (i.e.: which is 2 in this study), and r is the numbers times in which readings were taken (i.e.: which is 9 in this study).

The results of the analysis show that there was no significant difference between the measured results and theoretical results. They both fitted each other. The maximum reflector rotation angle deviation recorded was 2^o, the maximum percentage error was found to be 3.3%, while the standard deviation was found to be 1.01.

Since trackers that have accuracies of $\pm 5^o$ can deliver greater than 99.6% of the energy delivered by direct beam plus 100% of the diffuse light, then the performance of the developed tracker could be regarded as good and satisfactory.

V. CONCLUSION

This research paper has demonstrated a simple way of developing an automated tracking device for a solar box oven especially for use in the developing countries of the world with abundant solar energy. Materials used as well as the technology involved are those available in most of these developing countries and as well promote sustainability. The performance of the solar tracker is quite appreciable with a maximum reflectors rotation angle deviation of 2^o and maximum percentage error of 3.3%. The simplicity of the design as well as the operation of the automated solar tracker for a solar box oven will go a long way in assisting to meet the basic energy needs of the less privileged people across the globe. It is believed that the device has the potential to provide the domestic energy for heating and cooking.

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NOMENCLATURE

A = Area, cm^2
c = number of variables
F= Force, N
H = Height, m
L = Length, m
M = Mass, kg
r = Number of times in which readings were taken
V = Volume, cm^3
W = Weight, N
ρ = Density, kg/m^3

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