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Prototype Design and Performance Analysis of Solar Clothes Dryer

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Abstract – **The current state of the laundry industry in Nigeria has created an opportunity to capture a significant market segment that has rejected conventional dryers as expensive, energy consuming and damaging to clothing. Clothes lines and other hang drying methods subject those users to a lack of privacy, extremely long drying times and great dependency on weather. A solar clothes dryer was designed and developed to provide a compromise solution, with faster dry times, low cost and superior energy efficiency. The unit consists of two parts, an inclined flow chamber (solar collector) and the drying box. A performance- analysis was conducted employing a two stage nested design and two way Anova. The two stage nested design had a total number of 24 observations (6 clothe materials x 2solar radiation modes x 2 replications), using six clothing materials as the test material at an average drying chamber temperature of 50 ºC for safe drying of the clothes. The results of the experimental design shows that the number of clothes, solar radiation mode has highly significant ($P<0.05$) effect on the drying time. The two way Anova design had a total number of 12 observations (6 clothe materials x moisture remove {%}). The test reveals that the number of clothes, percentage of moisture removed has highly significant ($P<0.05$) effect on the drying time. Graphical analyses of residuals reveal adequacy of models employed. The normality assumption check conducted on the models revealed nonconstant variance defect which validated the conclusions of the two-staged nested design and two way Anova. The normal probability plots and the standardized residual plots also gave no indication of outliers, which shows that experimental designs took into consideration proper randomization of the experimental runs. The main advantage of this dryer is that it can work all round the year, with a built-in auxiliary heating system. it consumes less power than conventional dryers in washing machines(800.64kJ). It can easily be built with commonly available materials.**

Keywords: **Proto type Design, Performance Analysis, Solar Clothers Dryer**

I. Introduction

According to Hall (1980) drying is a dual process of heat and mass transfer of moisture from the interior of the product to the surrounding air. Drying involves the abstraction of moisture from the product by heating and the passage of air mass around it to carry away the released vapor (Mclean1980). The basic essence of drying is to reduce the moisture content of a given product. Solar drying can be a feasible alternative for sun drying because it provides the most cost effective drying technique. Since the material is enclosed there is less contamination and it is less susceptible to adverse weather conditions. A substantial amount of theoretical and experimental work has been reported on solar as well as open sun drying. The natural convection (passive) solar drying system appears to have a good potential in many developing countries. According the work of Bala and Woods (1994) this system is only suitable for a limited capacity and owing to low buoyancy induced airflow inside the dryer, the drying rate is very low and highly dependent on weather conditions which may reduce the quality of the drying products especially in adverse weather conditions.

Schirmer et al(1996),Maskan *et al* (2002)and Lutz *et al* (1989) had conducted studies on force convection(active) solar dryers for fruit and vegetables. Their findings revealed that forced convection reduced the drying time as well as improved the quality of the dried products. A compendium of works have been performed on solar dryers. Zomorodion *et al*(2009) employing active indirect and mixed-mode thin layer solar drying using a combination of solar air heater and a cabinet dryer ,established a model for determining the moisture ratio and moisture content at any drying time for each mode. Ahmed (2011) design and fabricated a solar dryer for drying of bean crop. In Nigeria Medugu(2010) conducted a study of the drying properties of a chimney and cabinet type dryer on tomatoes ,pepper and bitter leaf. A survey of these studies reveals the application of solar technology as preservative techniques in agriculture application. The literature on solar dryers shows that there is a dearth of work pertaining to the application of solar drying to the laundry sub sector. Conventionally, clothe drying is done on a string and is allow to dry for more than two to three hours at least because of humidity. These clothes do not enhance the exterior look of the apartment/house and hence people are trying to banish this practice. Most modern dryers (electric and gas dryers) are fast, yet they are expensive, energy consuming and damaging to clothing. Indoor hang-dryers are exceptionally slow drying. Even drying cabinets, which better balance these competing priorities, are so expensive and bulky that they are not an option for most people. As detailed above, there remains a clear need for innovation in the laundry drying space. No solution yet exists that balances speed of drying, protection of clothing, energy efficiency and cost. In pursuit of these underlying variables, a solar clothes dryer that would evaporate water from an object by using energy from the sun, removing water vapour through a system of vents and air circulation was design and fabricated. Its envisage to work employing the use of radiation, ambient temperature, relative humidity and a small amount of maintenance for use in diverse situations.

II. Materials and Design Methods

The design concept for the solar clothes consists of two major components; the drying cabinet unit and the solar collector unit.

A. Drying cabinet unit

This is a rectangular unit approximately 122cm high and 60cm x60cm in width and depth. The structure is of double wall with air gap between to act as heat insulator. The cabinet has an air tight door on one side opposite the solar collector. The top of the cabinet unit tappers into square opening which has a 12volts direct current (D.C) exhaust fan attached. Rack for hanging of clothes is located at the top within the cabinet. At the bottom opposite the door is created an opening through which the solar collector is attached to the cabinet; from this point air current can enter the cabinet for drying clothes.

B. Solar Collector Unit

The solar collector consist of a panel box made 122cm long,30cm wide and 15cm high.its sides are made of steel plates which the bottom consist of plywood of sufficient thickness. Also fixed on top of the collector is a transparent glass across which solar radiation can pass to fall on the black painted aluminium plate positioned below the glass inside the box. The solar collector unit has its front and back opened and the unit is coupled to the cabinet on one end and the other end is opened to the atmosphere.

C. Components list and machine specifications

The ancillary components of the solar clothes dryer are as follows:

(i) Hanging rack (ii) Exhaust fan (12v D.C motor) (iii) Transparent glass (iv) Solar collector plate (v) Temperature Gauge (vi) Six bulbs of 100W each.

The following machine specifications were outlined, which are required for analysis and design.

1. Temperature range of 60-80^{0}C.
2. Ambient temperature of 30^{0}C-40^{0}C.
3. Active solar dryer for the tropics an air gap of 5cm is usually chosen for sufficient air vent and air passage.
4. 4cm solar collector glass covering.
5. Collector plate-1mm thick aluminium plate.
6. Latitude of location-6^0 35 N(Ekpoma).

The materials used for the construction of solar clothes dryer are cheap and easily obtainable in the local market. The following materials were used for the construction of the domestic solar clothes dryer as shown in Table 1.50cm x 120cm of glass, as the solar collector cover and the cover for the drying chamber. It permits the solar radiation into the system but resists the flow of heat energy out of the systems. Mild steel sheet of thickness 1mm and aluminium painted black for absorption of solar radiation. 60cm galvanize pipe, which serve as the cloth hanger.50cm x 120cm of plywood which serve as the solar collector.

Table I Part List and Material Selection

S. No.	Part	Material	Basis For Selection
1	Cabinet unit	Mild steel plate	Easily fabricated
2	Exhaust unit	12V D.C fan	Low cost and minimal energy consumption
3	Hanging Rack	Aluminium pipe	Resistance to corrosion, lightweight and easily machinable
4	Solar Absorber	Aluminium plate	Good conductor of heat,
5	Solar collector top cover	Glass	Transparent and allows 80% of solar radiation to pass through
6	Solar collector base	Plywood	Low thermal conductivity, rigid and cheap

III. Operating Principle

The machine is position in the open such that the solar collector is orientated at an angle of latitude to face the rays from the sun. The air enters the unit via the solar collector. The solar radiation pass through the transparent glass and falls on the black painted aluminium plate which absorbs much of the solar heat. Thus heat is transferred to the air flowing through the solar collector by conduction, convection and radiation. The fan attached to the drying cabinet sets up air current that moves from the base to the top and out of the cabinet. The state of the air within the cabinet which is relatively dry, hot and fast flowing ensures that the clothes hung on the rack dries at faster rate than outdoor clothes

The hot air act as drying medium, it extracts and conveys the moisture from the clothes to the atmosphere under force convection, thus the system is an active solar system and a mechanical device such as the exhaust fan is required to control the intake of air into the dryer. The orthographic view of the constructed solar dryer is shown figure 1 below..

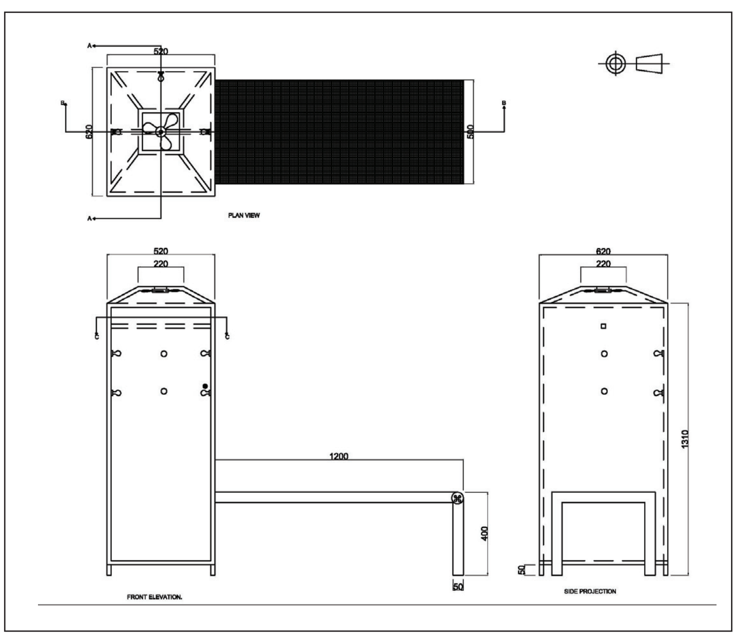

Fig. 1 Orthographic view of Solar Clothes Dryer

IV. Design Consideration

(i) Temperature : The minimum temperature for drying of clothes is 40^0c and the maximum temperature is 70^0c therefore, 55^0c and above is considered average and normal for drying clothes. The design was made for the optimum temperature for the dryer of 70^0c and the air inlet temperature or ambient temperature T_1=40^0c (approximately outdoor temperature).

(ii) Meteorological data collection.

(iii) The physical features of the dryer were considered i.e., type, shape, collector area, air gap and material of construction.Transparent glass covering 4mm thick was used , mild steel-sheet of 1.0mm thickness was used and glass cover for the collector was 50x50 cm^3

(iv) The solar radiation of a location was considered.

V. Design Calculation

A. Angle of Tilt (B) of Solar Collector

The angle of tilt (β) of the solar collector is given by equation (1) below.

$$\beta = 10^0 + \text{Lat } \varphi \tag{1}$$

Where lat φ is the latitude of the collector location, the latitude of Ekpoma where the dryer was designed is latitude 6.742N.Hence the suitable value of β use for the collector is β =10^0+ 6.74=16.74^{0}N which according to Adegoke and Bolaji (2000), is the best recommended orientation for stationary absorbers.

B. Insolation on the Collector Surface

The value of solar isolation for Edo i.e. average daily radiation(H)on horizontal surface and average effective ratio of solar energy on tilted surface to that on the horizontal surface R are 678.59W/M^2 and 1.0002 respectively, thus insolation on the collector surface was obtained as

$$IC = HR = 678.59X1.0002 = 678.72W/M^2 \tag{2}$$

C. Determination of Collection Area and Dimension:

The air gap height was taken as 4.6cm = 0.046m and the width of the collector assumed to be 50cm = 0.50m.

Thus, volumetric flow rate of air

Va_1 = Va x 0.046 x 0.37 ; Where Va = 0.15

Va_1 = 0.15x 0.046 x0.37 = 2.256x10^{-3} m^3/s

Thus mass flow rate of air Ma = Vaρa (3)

Density of air ρa is taken as 1.2252kg/m^3 at s.t.p

Ma = 2.55x 10^{-3} x 1.2252 = 3.13 x 10^{-3}kg/s

Therefore, area of the collector Ac

Ac = 2.55 x 10^{-3}x1000 x50/0.5 x 678.59 = 0.376m^2

The length of the solar collector L was taken as L = Ac/β = 0.12/0.50 = 0.24m. (4)

Thus length of the solar collector was taken approximately as 0.3m therefore, collector area was taken as 0.376m^2

D. Determination of the Base Insulator Thickness for the Collector

For the design, the thickness of the insulator was taken as 6cm, the side of the collector was made of aluminium, the loss through the side of the collector will be considered negligible.

The moisture content of the clothes can be determined from Equation (5) (Chung *et al.,* 2010):

$$M_D = 100\% \frac{W - D}{W} \tag{5}$$

Where, M_D= Percentage moisture content, W= Wet weight and D= Dry weight

E. Clothes Dryer Efficiency

This is given as,

$$Efficiency(\%) = work\ output/work\ input\ \ x\ ^{1000}/_{1} \tag{6}$$

(Ezekoye, 2006)

Where (work output) is the mass of clothing after drying and (work input) is the mass of the clothing before drying.

VI. Fabrication and Testing of The Prototype Clothe Dryer

The dryer components were measured, machined, welded, bolted and assembled as shown in the sectional view Figure 2 according to the design specification. The dryer was then test run to effect all necessary adjustment, alignment, tensioning, greasing etc. where necessary.

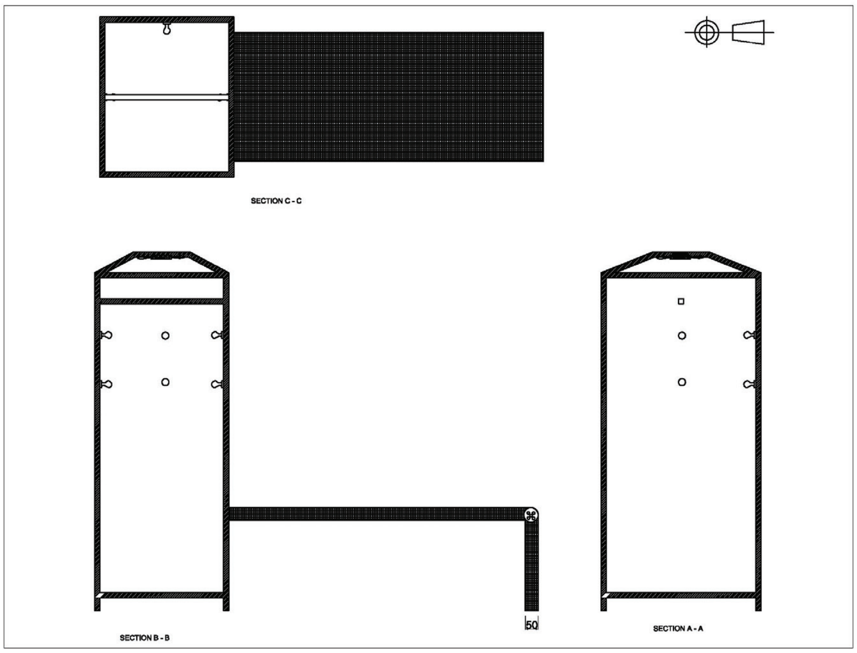

Figure2: Sectional view of Solar Clothes Dryer

VII. Performance Analysis Test

A series of test was conducted on the solar clothes dryer machine to evaluate its performance in operation with respect to certain parameters. The materials used for testing of the machine include clothe material, mercury-in-bulb thermometer, hydrometer and weighing balance. Temperature measurements was done using thermometer, a stop clock was used for timing and relative humidity was measured employing a hydrometer. Moisture content was determined by weighing the clothes before drying and after drying.The test was conducted using two stage -nested design examine the effect of number of clothes and solar radiation mode on drying time. Similarly a two way Anova was conducted to determine the effect of moisture removed (%) on drying time for different solar radiation mode.

VIII. Results

The effect of the application of solar radiation mode on time to dry with variation in the number of clothes employing a two-stage nested experimental design is presented below as Table II, while Figure 3,4,5 and 6 represented diagnostic checks carry on the model. The analysis of variance (ANOVA) is summarized in Table II along with figures representing the model validation. The analysis of variance shows highly significant size, air flow rate and drying time effect ($P<0.05$) while interaction between size and air flow was found to be significant ($P<0.05$).

Final Equation in Terms of Coded Factors :TIME TO DRY =+29.38 -9.77* A[1] -6.55 * A[2] -2.59* A[3] +2.24 * A[4] +6.63* A[5] +4.23* B (5)

TABLE II COMPUTER PROGRAM OUTPUT FOR TWO –STAGE NESTED EXPERIMENTAL DESIGN

Response 1 TIME TO DRY

ANOVA for selected factorial model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1607.28	6	267.88	39.06	< 0.0001
significant					
A-NO OF CLOTHES	*1178.18*	*5*	*235.64*	*34.36*	*< 0.0001*
B-SOLAR RADIATION	*429.09*	*1*	*429.09*	*62.57*	*< 0.0001*
Residual	116.59	17	6.86		
Lack of Fit	*14.56*	*5*	*2.91*	*0.34*	*0.8774*
not significant					
Pure Error	*102.03*	*12*	*8.50*		
Cor Total	1723.86	23			
Std. Dev.	2.62		R-Squared	0.9324	
Mean	29.38		Adj R-Squared	0.9085	
C.V. %	8.91		Pred R-Squared	0.8652	
PRESS	232.37		Adeq Precision	19.975	

Final Equation in Terms of Coded Factors:

TIME TO DRY =+29.38 -9.77* A[1] -6.55 * A[2] -2.59* A[3] +2.24 * A[4] +6.63* A[5] +4.23* B ...(5)

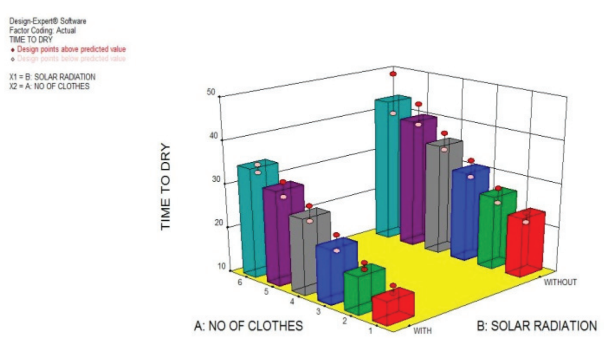

Fig.3 Plot of time to dry against no of clothes and solar radiation

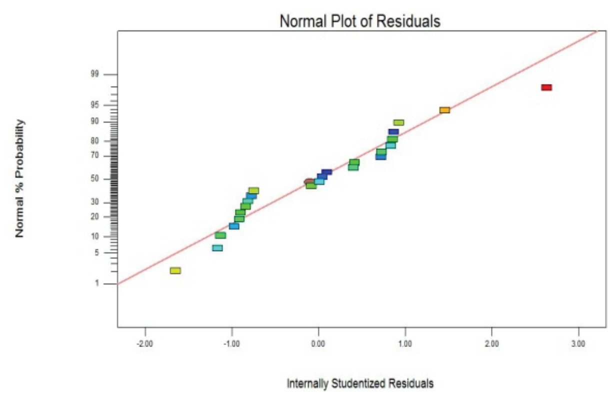

Fig.4. Normal probability plot of the studentized residuals

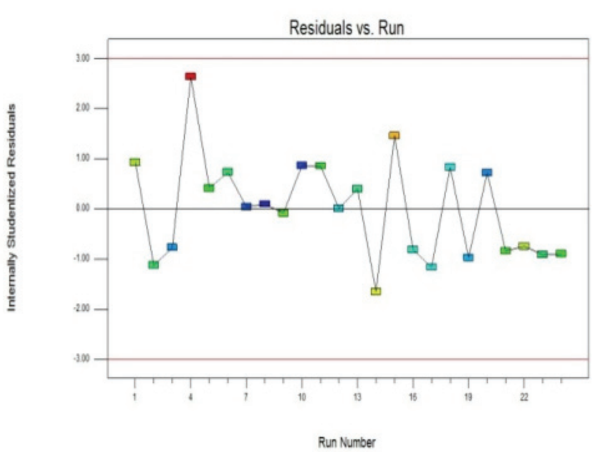

Fig.5. Plot of studentized residuals versus predicted values

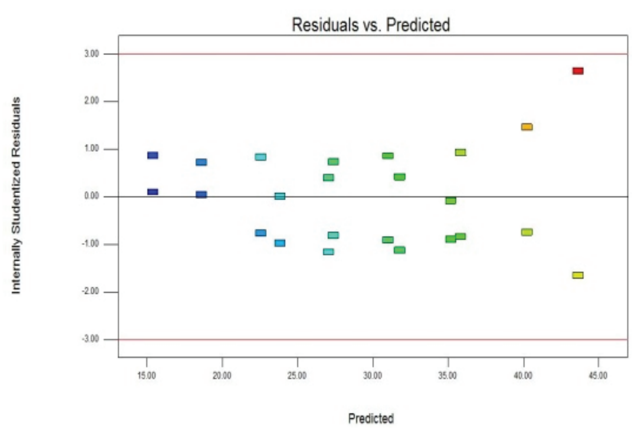

Fig.6 Plot of externally studentized residuals

Table III Computer Program Output For Two Way Anova Experimental Design

Response 1 TIME TO DRY

ANOVA for selected factorial model

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	759.90	6	126.65	30.20	0.0009
significant					
A- NO OF CLOTHES	714.97	5	142.99	34.10	0.0007
B- MOISTURE REMOVAL %	44.93	1	44.93	10.72	0.0221
Residual	20.97	5	4.19		
Cor Total	780.87	11			

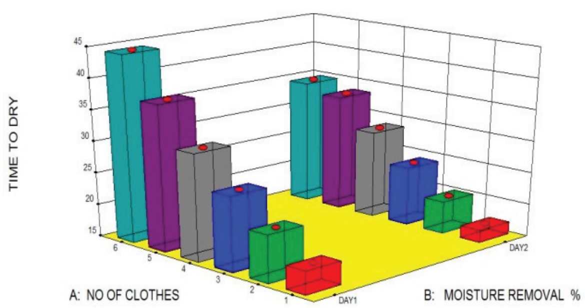

Fig.7. Plot of time to dry against no of clothes and moisture removal (%)

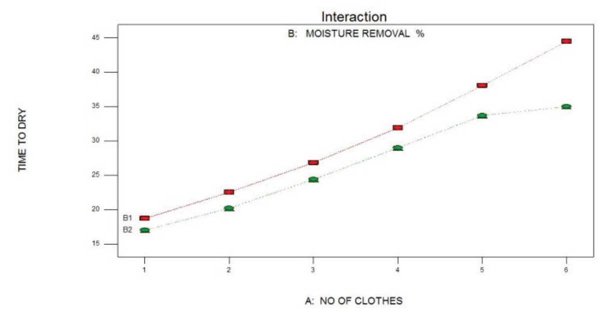

Fig.8. Plot of interaction between no of clothes and moisture removal (%)

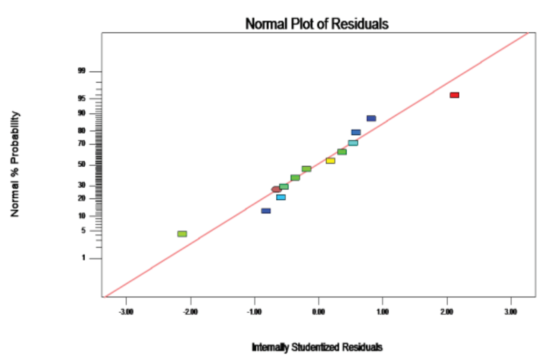

Fig.9. Normal probability plot of the studentized residuals

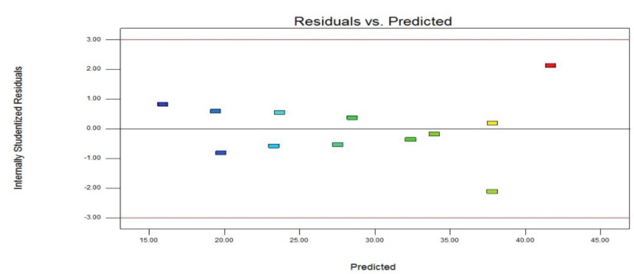

Fig.10. Plot of studentized residuals versus predicted values

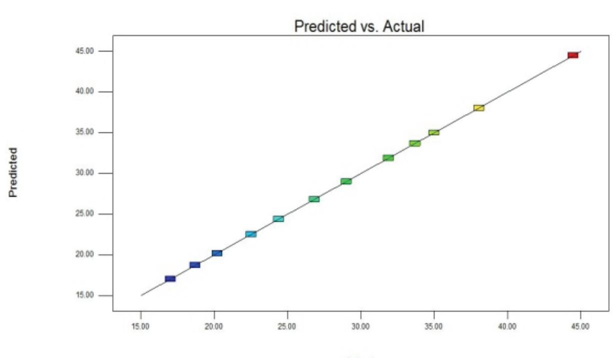

Fig.11. Plot of predicted against actual

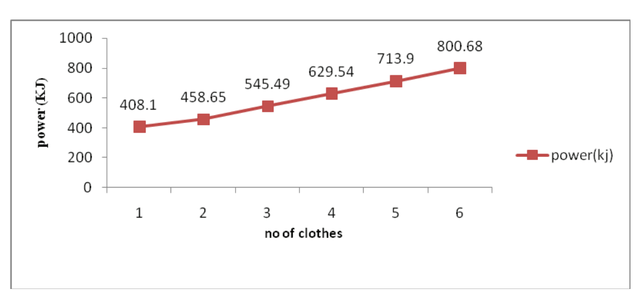

Fig.12. Plot of power consumption versus no of clothes

IX. Discussion

The computer output for the two stage nested experimental design employing Design –Expert program revealed from the analysis of variance summary that the number of clothes as well as the application of solar radiation has a significant effect ("probability>F" less than 0.05) on the time to dry for a given number of clothes. Figure 3 further shows that the application solar radiation emanating from the sun significantly reduces the drying time when compared without solar radiation emanating from the heating element (six incandescent bulbs). In addition to the basic analysis of variance summary, the program displays some additional useful information (Montgomery 2010). The "lack of fit F-value" of 0.34 is not significant relative to the pure error. This implies a significant degree of model fit. The quantity R-Square reveals that the variable number of clothes and solar radiation from sun explains 93.24% variability in the drying time obtained. The predictive capability of the model equation (5) in predicting the response (time to dry) in new experiment is significant given a value of 0.8652.

Considering the computer program output for the experimental Anova design, the analysis of variance summary shows that the percentage of moisture remove and number of clothes has a significant effect on the drying time. An evaluation of figure 8, reveal that there is no interaction between these factors in determining the drying time obtained.

Model adequacy can be investigated by the examination of residuals(Montgomery 2001).Taking into account figure 4 and figure 9 respectively the normal probability plot of the residuals, shows that error distribution is normal, given that the plot depicts a straight line. Assessment of the plot of residuals versus predicted values for figure 5 and figure 10 respectively reveal that no usual structure is apparent. Plotting of the residual in time order of data collection is helpful in detecting correlation between residuals. Hence examining figure 6, there seems no apparent tendency to have runs of positive and negative residuals indicating positive correlation. This implies that the independence assumption on errors has not been violated. The plot of predicted versus actual figure 11 shows that the model predicts over the range of data .This is indicated by the line going through the middle of the data over the whole range of the data. Finally, considering figure 12 it was found that the maximum power consume is about 800.64kJ.

X. Conclusion

Solar clothes drying device was designed and developed using low price materials that can easily be assessed and maintained. The dryer were inclined to the angle of latitude of Ekpoma,16.74^{0}N , to ensure maximum transmission of solar radiation into the dryers. The dryer performance evaluation shows that number of clothes, mode of solar radiation applied and percentage of moisture remove has significant effect on the time to dry a given quantity of clothes. The tests also reveal a maximum power consumption of 800.64kJ.

Graphical analyses of residuals were evaluated to determine adequacy of models employed. The normality assumption check conducted on the models revealed nonconstant variance defect and hence a variance stabilizing transformation is not required. Therefore the conclusions of the two-staged nested design and two way Anova were valid. The normal probability plots and the standardized residual plots also gave no indication of outliers. Also the independence assumption of error was not violated which shows that experimental designs took into consideration proper randomization of the experimental runs.

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