

Modelling of Box Type Solar Cooker Performance in a Tropical Environment

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Abstract

Thermal performance model of box type solar cooker with loaded water is presented. The model was developed using the method of Funk to estimate cooking power in terms of climatic and design parameters for box type solar cooker in a tropical environment. Coefficients for each term used in the model were determined by regression analysis of experimental data. The coefficient of determination of the models established was found to have a range of 0.64 – 0.91 ($P < 0.05$) which indicates their validity.

Keywords: Solar cookers, maize cob, maize husk, coconut fiber and efficiency

Introduction

In most developing countries, part of the energy consumption goes to the domestic sector out of which a major part goes for cooking (Nandwani, 1992). It has been estimated that cooking accounts for as much as 80% of all energy used in the domestic sector in Nigeria (Adegoke and Akintunde, 1999). The usual sources of energy used for cooking in Nigeria include electricity, charcoal, firewood, gas and kerosene. All these are beset with one problem or the other. It is estimated that only about 40% of the country's population have access to electricity with its distribution in favour of the urban areas (Ige, 1999). Even at this, its epileptic supply does not encourage its use. The supply of petroleum products in the country falls below demand and also has its availability in favour of urban dwellers that constitute about 30% of the country's population (Umar, 2000). In

addition, the escalating cost alongside erratic supplies has also gradually drawn some urban consumers away from these petroleum products back to local wood stoves for cooking their foods.

Energy is essential if adequate food supplies are to be converted into adequate diets. The technology of solar heating involves the conversion of solar energy to heat energy. Solar heating systems could be box-type, concentrating type or a hybrid of the two. Box-type solar cooker makes use of both diffused and direct radiation, while the concentrating type depends on its ability to make use of direct radiation only (Aremu, 2004; Aremu and Akinoso, 2013). The first experiment reported by Meinel and Meinel (1977) on the use of solar energy for cooking was by Nicholas de Saussure (1740 – 1799) when he came up with a solar oven for food preparation. His oven consisted of spaced glass blocks on top of a blackened surface enclosed by an insulated box. Sunlight entered the box through the glass and was absorbed by the black surface. A temperature of 88°C (191°F) was achieved and this is adequate for cooking. In order to curtail impending environmental disaster and harness other sources of energy for cooking, an investigation was carried out to develop a mathematical model for predicting the thermal performance of the box solar cooker systems from the climatic and collector parameters.

Methodology

Notations

Q_u is Useful energy collected by solar cooker in W

q_u is Energy per unit absorber area in W/m²

T is Transmissivity of glass

α is Absorptivity of plate

I is Solar intensity in W/m²

U_L is Overall heat loss coefficient in W/m²

U_t is Top heat loss coefficient in W/m²

U_b is Back heat loss coefficient in W/m²

U_e is Edge heat loss coefficient in W/m²

T_c is Temperature of collector absorber in °C

T_a is Ambient temperature in °C

$A_{\text{collector}}$ is area of the whole collector (m²)

P_c = Cooking power in W

A_i = Intercept area in m²

I_T = Solar insolation in W/m^2
 U_L = Heat loss coefficient in $W/m^2/^\circ C$
 R = Ratio of pot to absorber plate areas (dimensionless)
 N is the number of glass covers
 T_p is the plate temperature in $^\circ C$
 T_a is the ambient temperature in $^\circ C$
 f is a factor which depends on h_w and N
 h_w is wind heat transfer coefficient
 ϵ_p is the emittance of the absorber plate
 ϵ_g is the emittance of glass (0.88)
 K is the thermal conductivity of insulation material
 L is the thickness of insulation material
 U_e is edges heat loss coefficient
 U_{edge} is an edge heat loss coefficient
 A_{edge} is area of the edge in m^2
 dT = Temperature difference in $^\circ C$
 K = Thermal conductivity of the absorber plate in $W/m^2/^\circ C$
 t = Thickness of plate in m

Modeling of Box Type Solar Cooker Performance

Five box solar cookers fabricated from various insulating materials such as maize cob, maize husk, coconut fiber, polyurethane foam, and air (control) were set up as shown in figure 1. Cooking pot containing 1kg of water was placed on each of the cookers. Thermo couples were used to sense the temperature at the centre of mass of the water. The water temperature on each of the cookers was taken every ten minutes and recorded.



Figure 1: Box type solar cookers

Trials were conducted for six days per week over a two-month period each in the dry season (between November and December) and in the rainy season (between April and May) to compare performance in both rainy and dry season. Useful cooking power was determined using ASAE standard. The ambient air temperatures and solar insulation were also monitored and recorded. Once the water on all the cookers had reached about 90°C the trial was concluded. Wind speed was also monitored from a weather station not far from the test site. Data from the experiments were then used to develop some regression models.

Theory and Model Development

The following sets of simplifying assumptions were made to model the thermal performance of the box cooker:

- The transient nature of the batch heating process obviates steady state concepts, so the cooker operates under quasi-static conditions.
- The temperature at the center of mass of a quantity of water represents the whole; water being taken as representative of many foods.
- The sunlight energy converted to heat energy in the closed system of the solar cooker will either contribute to cooking power or be lost through various heat transfer mechanisms.
- Thermal losses are driven by the difference in temperature between the ambient and the cooker interior, which is related to the temperature of the pot contents.
- The objective being to heat food; internal surface and air temperatures are irrelevant.

With due considerations of the various heat transfer processes and loss mechanisms, the effective cooking power inside a solar box cooker can be described by an energy balance equation utilizing the Hottel-Whillier-Bliss equation as presented by Duffie and Beckman (1991). The energy per unit absorber area of the collector is therefore given as follows in equations 1 to 12.

$$\frac{q_u}{A_c} = [\tau\alpha I - U_L(T_c - T_a)] \quad (1)$$

The useful energy collected by the solar cooker in W

$$Q_u = A_c [\tau\alpha I - U_L(T_c - T_a)] \quad (2)$$

Since the losses are distributed to the top, bottom and edges

$$U_L = U_t + U_b + U_e \quad (3)$$

According to Duffie and Beckman (1991)

$$U_t = \left[\left(\frac{N}{(344 / TP[(Tp - Ta)/(N + f)]0.31} + \frac{1}{hw} \right) \right]_{-1} + \frac{\sigma(Tp + Ta)(Tp^2 + Ta^2)}{[\varepsilon p + 0.0425N(1 - \varepsilon p)] - 1 + [2N + f - 1]/\varepsilon g] - N} \quad (4)$$

Where

$$h_w = 5.7 + 3.8V \quad (5)$$

$$f = (1.0 - 0.04h_w + 5.0 \times 10^{-4}h_w^2) (1 + 0.058N) \quad (6)$$

$$U_b = \frac{K}{L} \quad (7)$$

$$U_e = \frac{U_{edge} A_{edge}}{A_{collector}} \quad (8)$$

Previous solar cooker testing and performance evaluation identified solar input and overall heat loss coefficient as the two primary parameters affecting cooker performance (Funk and Larson, 1994). But a third parameter, internal heat transfer efficiency, will have to be included after analysing the results of some preliminary experiments. In the experiments, the solar concentration varied only slightly and the heat loss was nearly constant. Yet the response of the ovens tested varied significantly with the thermal conductivity of the absorber plate.

From the foregoing, with the Hottel-Whillier-Bliss equation as the basis for predicting energy available from a flat plate collector at steady state (Duffie and Beckman, 1991), some slight modifications will have to be made to the equation. The fluid inlet temperature will have to be replaced by the mean plate temperature, which drives heat loss and the internal heat transfer variable will be added. Also it should be noted that the developed equation will be estimating cooking power instead of available energy.

Therefore cooking power will be considered in greater detail in this present analysis. a_i ($i = 0$ to 3) are constants to be evaluated by multiple regression analysis.

$$P_c = a_0 + a_1 A_i I_T - a_2 U_L dT + a_3 ktR \quad (9)$$

To facilitate further discussion equation (9) is written in the form

$$Y = a_0 + \sum_{j=1}^{n-1} a_j x_j \quad (10)$$

$$\text{Where } Y = P_c, X_1 = A_i I_T \quad (11)$$

$$X_2 = U_L dT \text{ and } X_3 = ktR \quad (12)$$

Results and Discussion

Modelling Findings

Solar cooker test data were used to mathematically relate cooker performance to cooker parameters and environmental factors. The mathematical model thus determined were validated using the other four box-type cookers. The term ktR was statistically insignificant, so it was dropped from the model. The simplified model that was developed contained only two variables that pertain to the energy conservation equation ($A_i I_T$ and $U_L dT$). The simplified model is:

$$P_u = 7.75 + 0.16 A_i I_T - 0.12 U_L dT$$

F_{ratio} 38.6 6.2

This equation from the statistical analysis explained 64% of the variance in cooking power response to different values for the oven parameters. From the regression analysis, the regression coefficient associated with intercept area and insolation, 0.164 is close to the expected value, the nominal efficiency of a solar cooker being about 20% (Funk and Larson 1998). The area-insolation coefficient has the strongest influence on the useful cooking power as indicated by the high F-ratio. The regression coefficient associated with the overall heat loss coefficient is 0.12. According to Funk and Larson (1998), the expected value is 1.0. Sources of error might be due to evaporation losses from the cooking fluid or water which was not included in the theoretical model and the non-availability of a data logger which prevented the recording of data on a continuous basis but at intervals which was a major source of error.

Modelling Validation

The cooking power prediction model was validated by comparing observation from tests of the four other box cookers with model performance predictions to determine how well statistically the model simulated the cooker's performance. The coefficient of determination (r^2) denotes the percentage of variation in the observed cooking power explained by the variation in the predicted cooking power. A visual representation of these correlations are straight-line plots of the predicted values of the cooking power versus the observed cooking powers. An exact fit of the predicted values to the observed values would be represented by a line with a positive slope of unity and passing through the origin (Butts and Vaughan, 1987). However, due to inaccuracies of both the input parameters and the model, the points are scattered closely about the lines. The different r^2 values, intercepts and slopes obtained are shown on Table 1 and Figures 2 - 5. The model was judged to adequately predict the thermal performance in terms of cooking power of all the tested box type cookers based on the statistical analysis carried out.

Table 1: Correlation of Predicted and Observed Cooking Power for the Cookers

Cooker Number	r^2 values	Intercept values	Slope values
Cooker 1	0.91	8.25	0.74
Cooker 2	0.70	5.32	0.89
Cooker 3	0.64	13.07	0.64
Cooker 4	0.69	12.00	0.67
Cooker 5	0.69	11.03	0.69

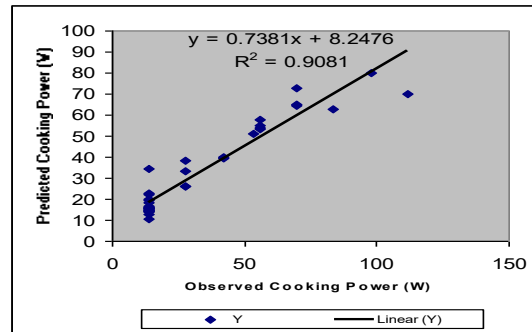


Figure 2: Correlation of predicted and observed cooking power for box cooker 1

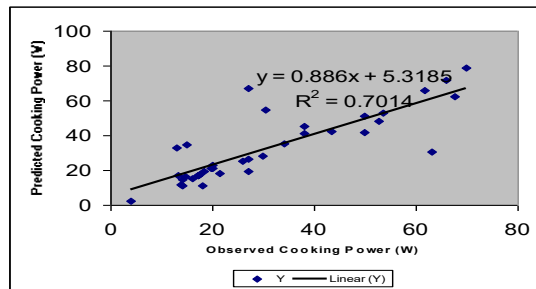


Figure 3: Correlation of predicted and observed cooking power for box cooker 2

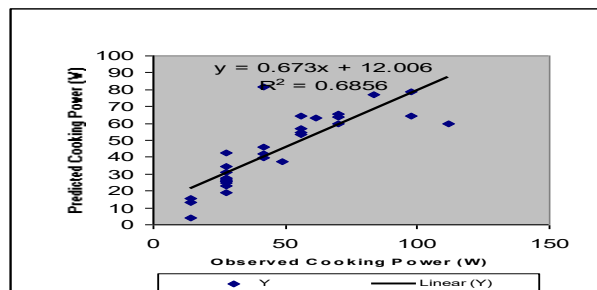


Figure 4: Correlation of predicted and observed cooking power for box cooker 4

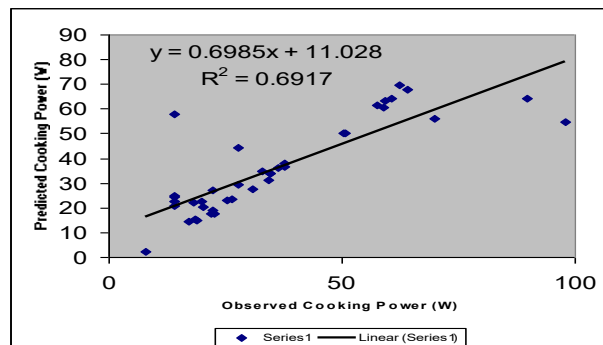


Figure 5: Correlation of predicted and observed cooking power for box cooker 5

The thermal efficiencies of all the cookers as given in Table 2, ranged between 28% - 37%. This compared well with estimation found in

literatures. Kunkhe *et al.* (1989) measured thermal efficiency of box solar cookers and found it is normally between 30 and 50%. Another estimation by Currin *et al.* (1994) says the thermal efficiency was about 20%. Also El-Sebaili *et al.* (1994) found an efficiency of 30% for his multi-step inner reflectors box-type solar cooker and the same author in 1997 also developed an outer-inner reflectors box-type solar cooker and determined its efficiency to be 31%. The coconut coir insulated box cooker had the highest thermal efficiency as shown on Table 2, which means this cooker has better heat retention ability. The control cooker had the least thermal efficiency, justifying the importance of using insulation materials in box solar cookers.

Table 2: Thermal Efficiency of the Box Solar Cookers

Cooker	Efficiency (%)
Husk	30.80
Cob	30.30
Coconut coir	37.00
Polyurethane Foam	36.40
Air (Control)	28.03

Conclusion

The model satisfactorily predicted the cooking power of the box cookers. The analysis of the model revealed that the product of intercept area and insolation has the greatest influence on the cooking power developed by the cooker. It is instructive to note that the design and testing of these box solar cookers has proved worthwhile and interesting. It reinforced the views that these devices can play a major role in solving Nigerian's domestic energy problem especially in the rural areas rather than being just a novelty demonstration of solar energy use. The thermal efficiencies of the cookers obtained were 30.8%, 28.0%, 30.3%, 37.0% and 36.4% respectively. These compared very well with efficiencies published in several literature. Comparatively, the order of performance are: cooker 4 > 5 > 1 > 3 > 2. It could be seen that cooker 2 (with no insulation materials) performed least. The evidence from performance evaluation indicates that agricultural bye-products like *maize husk*, *maize cob* and *coconut coir* can perform as well and even better than some manufactured or imported insulating materials. The employment of these local materials can lead to a substantial reduction in the initial cost of box solar cookers.

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