Design and Development of Solar Thermal-Photovoltaic Hybrid System for Cooking, Drying and Power Application

Abstract

A hybrid system has been designed and developed which comprises the principle of solar thermal and photovoltaic. Flat plate collector and concentrating trough collector were incorporated under solar thermal technology. Solar thermal device which makes the most using infrared radiation out of solar spectrum. Black copper sheet at focal point of the solar trough served as a stand for cooking pan was able to gain direct as well as high intensity reflected solar radiation to expedite the cooking process. The electric unit of the system worked on the principle of photovoltaic effect. Main components of the hybrid system were collector housing, solar trough reflector, triangular shaped glazing surfaces, copper sheet to place cooking pots and dedicated insulation to prevent heat loss. The dual concept hybrid system was found exceptionally speedier as compared to traditional box type cooker. Results revealed that cooking pot attained maximum temperature of 104.5^0 C at 12.30 pm, which was sufficient for cooking nutritious food. The experiment was conducted in winter season on 18th January, 2018. Average thermal efficiency (η_{therm}) was estimated as 35.1%, cooking power (P) was estimated 47.68 W and the overall heat loss coefficient was calculated 3.03 W/m^2°C. Average cooking time found to be just 130 minutes which was otherwise more than 3 hrs in case of traditional box type cooker. Electric power which was stored in the battery can operate 5W dc bulb for 9 hours in single charging. It also could operate smart phone charger and a dc fan (12V , 4Ah) for 60 minutes each.

Key Words: Solar thermal, photovoltaic, insolation, drying, cooking.

1.0 Introduction

Solar cooking presents an alternative energy source for cooking, which is simple, safe and convenient without consuming fuels, and polluting the environment. It is appropriate for hundreds of millions of people around the world with scarce fuel and financial resource to pay for cooking fuel. Drying is basically a simple process for removal of moisture by evaporation from a product in order to reach the desired moisture content and is an energy intensive operation. Drying of fruits, vegetables, and food are essential for keeping them for a long time without further deterioration in the quality of the product. Solar Photovoltaic System has potential to illuminate millions of homes without access to electricity. Looking to the need of a device which can be used for cooking, drying as well as for power generation for lighting and small fan, a hybrid system has been developed comprising principle of solar thermal and photovoltaic.

3.0 Material and Methods

The present study was carried out on design, development and performance evaluation of low cost solar thermal and photovoltaic (PV) hybrid system for cooking, crop drying, lighting and cooling for household usage.

3.1 Thermal Performance evaluation of hybrid solar system

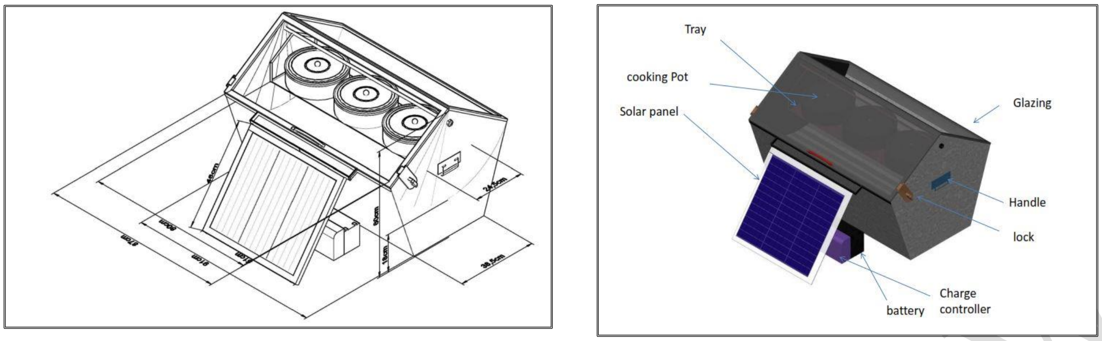

Fig.1

Fig.1: Schematic diagram and actual image of the system

The test for thermal performance of cooking system was conducted as per IS 13429 (Part 3):2000. The thermal performance tests were carried out in the form of first and second figure of merit.

3.1.1 Stagnation Temperature Test

The stagnation test (no load) for solar cooker and is giving as; the ratio of optical efficiency F_{no} to overall heat loss coefficient F_{ul} of the collector. It is represented by mathematically as (Folaranmi,2013);

$$F_1 = \frac{\eta}{l} = \frac{T_{ps} - T_a}{G} \qquad \text{.............(3.5)}$$

Where,

F_1 = Stagnation value

T_{ps} = Maximum plate surface temperature, ˚C

T_a = Average ambient temperature, ˚C

G = Average solar radiation, W/m^2

3.1.2 Sensible Heating of Water Test

The sensible heat test in which known amount of water is sensibly heated in a solar cooker. The second figure of merit is given as (Folaranmi, 2013).

$$F_2 = F'\eta_0 C_R = \frac{F_1\,(MC)w}{A\tau}\, ln\left[\frac{1-(\frac{1}{F_1})(\frac{T_{w1}-T_a}{G})}{1-(\frac{1}{F_1})(\frac{T_{w2}-T_a}{G})}\right] \qquad \text{................ (3.6)}$$

Where,

F_2 = sensible heat value

F' =Heat exchange efficiency factor

η_0 =Optical efficiency

C_R =Heat capacity ratio
F_1 =First figure of merit
$(MC)_w$= Product of the mass of water and its specific heat capacity
A = Absorber area, m^2
τ =Time interval, hr
T_{w1} =Initial temperature of water, ˚C
T_{w2} =Final temperature of water, ˚C
T_a =Average ambient temperature, ˚C
G =Average solar radiation.

3.1.3 Cooking power estimation

The cooking power was calculated in the form of average cooking power and standardized cooking power (Folaranmi, 2013). According to ASAE S580.

$$P = \frac{(T_1 - T_2) M\, C_p}{600} \qquad \text{........(3.7)}$$

Where,

p = cooking power (W)
T_1 = initial temperature , ˚C
T_2 = final temperature , ˚C
M = mass of water (kg)
C_p =Specific Heat Capacity of Water (4168 kJ/[kg-K]

3.1.4 Standardized cooking power

To determine the standardizing cooking power (P_s) from the cooking power (P) and each interval is corrected to a standard insolation of 700 W/m^2

$$P = \frac{P_S \times 700}{I_S} \qquad \text{…………..(3.8)}$$

Where,

700 = Standard Insolation , W/m^2

I_s = Average insolation , W/m^2

3.1.5 Overall thermal efficiency of solar cooker

Thermal efficiency was calculated by following equation (El-Sebaii and Ibrahim, 2005)

$$\eta = \frac{M_f\, C_f\, \Delta T_f}{I_{av}\, A_c\, \Delta t} \qquad \text{…….(3.9)}$$

Where,

η = Thermal efficiency (%)

M_f = Mass of cooking fluid (kg)
C_f = Specific heat of cooking fluid (j/kg.K)
ΔT_f = Difference between the maximum and ambient air temperature.
I_{av} = Average solar intensity (W/m^2) during the time interval.
A_c = Aperture area (m^2) of the cooker.
Δt = Time required to achieve the maximum temperature of the cooking fluid (s).

3.2 Performance Evaluation of Drying System

The performance evaluation of drying system was conducted to know the performance of developed dryer at college of Renewable Energy and Environmental Engineering. The tests were conducted from 10.00 to 17.00 hrs duration and the hourly data recorded.

3.2.1 Moisture content of product

The moisture content of product during an experiment at hourly time interval was determined by calculating the mass of dry matter of product. Moisture content (g water per 100g of sample) at various times, were calculated by the following formula;

$$Mc_{(wb)} = \frac{(W_1 - W_2) * 100}{W_1} \qquad \ldots\ldots\ldots(3.10)$$

Where,

W_1 = weight of sample before drying, (g)

W_2 = weight of dried sample, (g)

3.2.2 Dry matter

It is the matter left after complete removal of moisture from the product. The dry matter and mass of dry matter in sample was calculated by the following formula;

$$DM\ (\%) = 100.0 - IMC\ (wb)$$

$$Weight\ of\ DM = Initial\ mass\ of\ sample\ * \frac{DM\%}{100} \qquad \ldots\ldots\ldots\ldots(3.11)$$

3.2.3 Drying rate

Drying rate is gram of moisture removed per hour per 100 g of dry matter was calculated by using the following formula,

$$DR = \frac{M_M}{D_M * t} \qquad \ldots\ldots\ldots\ldots(3.12)$$

Where,

M_m = mass of moisture remove kg

D_m = dry mss in kg

T = time

3.2.4 Dry matter recovery

Dry matter recovery is defined as the ratio of final weight of dried product to the initial weight of product and was calculated by using following formula;

$$Dry\ matter\ recovery\ (\%) = \frac{D_S * 100}{F_S} \quad \ldots\ldots\ldots\ldots\ldots(3.13)$$

Where,

D_s = dry sample weight, gm

F_s = fresh sample weight , gm

3.3 Electrical Performance of Photovoltaic System

Electrical performance was evaluated based on following load requirements.

Appliances	Power rating
Bulb	5 W
Fan	12 V 4 Ah (48 W)
Mobile charger	5 V 2 Ah

$$Total\ hour = \frac{batttery\ power\ rating}{sum\ of\ applinces\ power\ rating} \quad \ldots\ldots\ldots(3.14)$$

4.0 Results and Discussion

4.1 Stagnation test

Figure 2 shows the ambient temperature, inside cooker tray temperature and solar insolation versus time on winter day of 1st December, 2018.the experiment conducted for the stagnation temperature without load condition. Test of the hybrid solar cooker at 10:00am , at this time, T_{amb} noticed was around 30.25°C, and solar insolation was 660 W/m^2. A significant effect of the ambient conditions was observed over plate temperature. Results revealed that inside temperature of cooking tray was found to be maximum at 13:35 hrs., which was 102.5^{0}C.

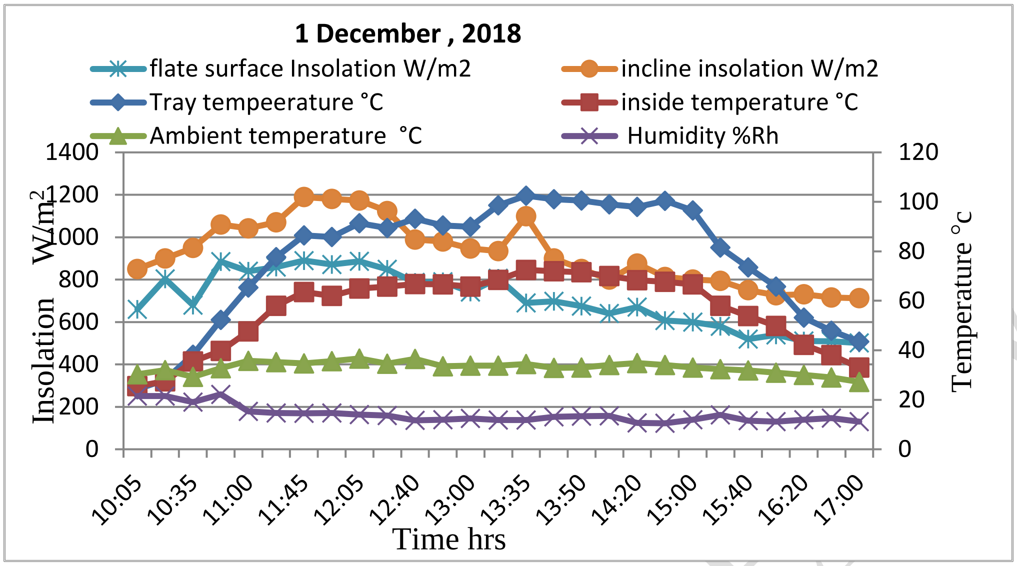

Fig.2: stagnation test

However ambient temperature at that time was 34^{0}C and insolation 690 W/m^2. Stagnation value F1 under no load of hybrid solar cooker was found to be 0.11 m^{2}°C /W .

Sensible heat test

Figure 3 shows the ambient temperature, inside pan temperature and solar insolation versus time on winter day of 3rd December ,2018. In the experiment 1.5 kg water was considered as a cooking stuff and placed into three cooking pan for an equal quantity (500 grams in each vessel). Test of the Hybrid system was commenced at 10.00 am, where, T_{amb} recorded was around 30°C, T_P (plate temperature) was around 19 °C and solar insolation was 660 W/m^2.

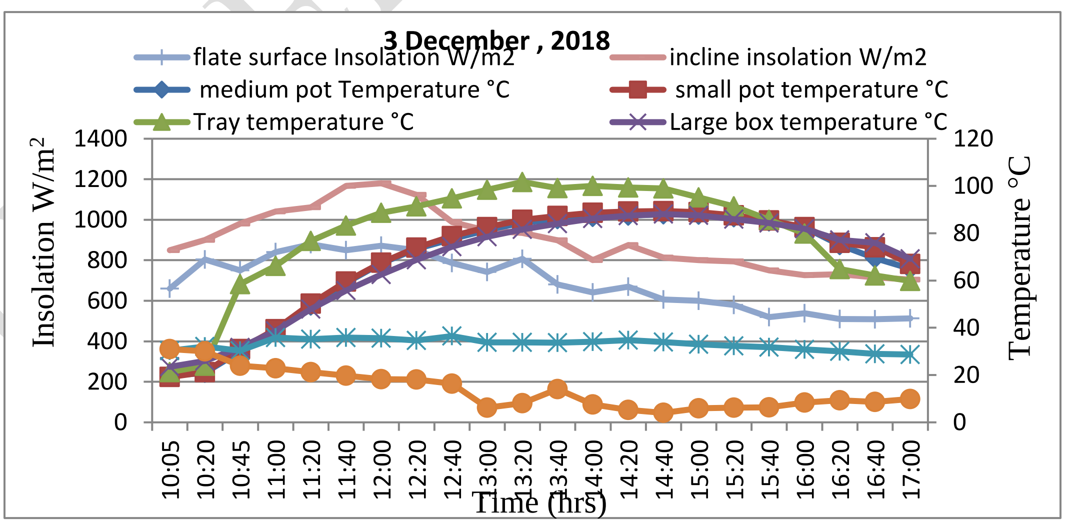

Fig.3: sensible heat test

A significant effect of the ambient conditions was observed over plate temperature. Results revealed that inside temperature of cooking pan was found to be maximum at 13:20 hrs., which was 101^0C. However cooking temperature of 98.5^0C was attained in just 100 minutes of test commenced at 12.30 pm (Lahkar, P. J. and Samdarshi S. K.,2010). The temperature showed increasing trend thereafter till 15.20 hrs. Sensible heat (F2) determined by conducting sensible heating test of known mass of water were found to be 0.42 m^2°C /W . Average thermal efficiency (η_{therm}) was estimated as 22%, cooking power (P) was estimated 47.68 W and the overall heat loss coefficient was calculated 3.03 W/m^2°C. Actual cooking time was found to be about 130 minutes which was otherwise more than 180 minutes in case of traditional box type cooker. The experiment was conducted in winter season on 3rd December ,2018 where initial, maximum and final data of horizontal insolation were observed as 879, 786 and 513 W/m^2 at 11:20,12.40 and 17.00 hrs respectively.

4.3 Drying test

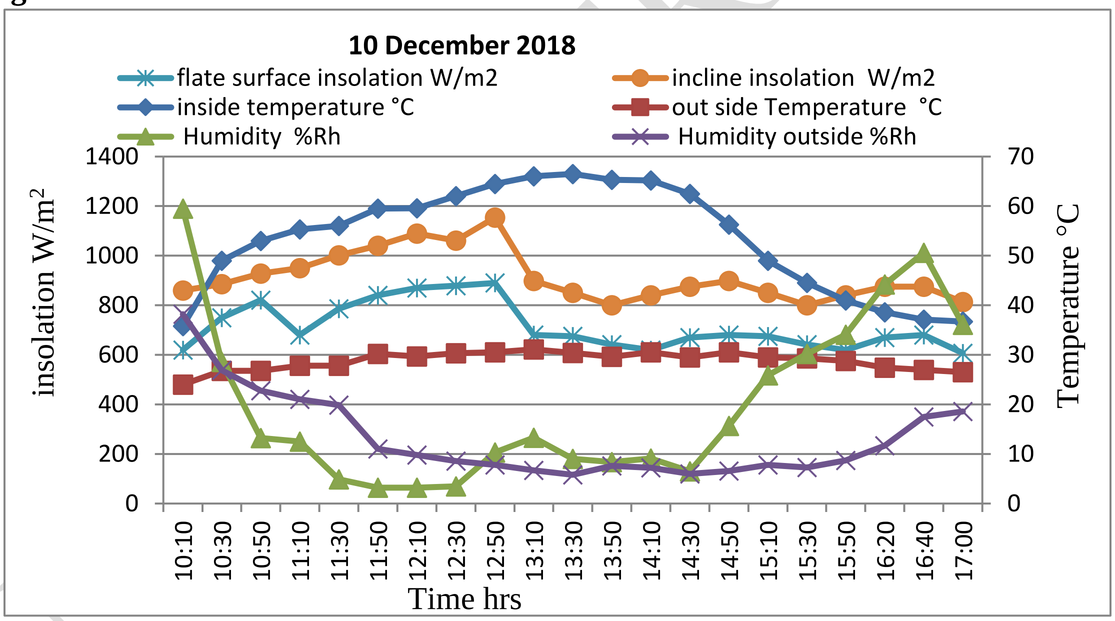

Fig.4:Drying test

The figure 4 shows the humidity, temperature inside and outside of the dryer during the process for the drying of Amla continuously for 14 hrs starting from 10:10 am from 10th to 11th December 2018. The experiment revealed that initial moisture content of Amla as 90.24% , after 14 hrs drying moisture content was 3.14%, drying rate of the hybrid solar cooker was found to be 4.99 kg /h.

4.4 Electricity Generation

30 W panel which mounted on the hybrid solar cooker generated 150W power per day, which

stored in the battery of 12 V ,7Ah . The figure shows the system can operate 5W dc bulb for 9 hours in single charging, it was sufficient to operate smart phone charger , bulb and a dc fan (12V , 4Ah) for 55 min . Battery charging and discharging performance shown below in the figure. The battery took 4 hours for full charging.

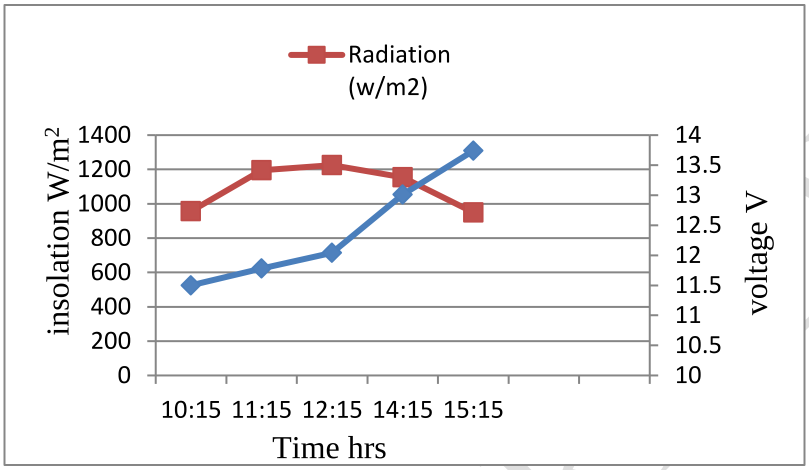

Fig.5:Battery charging test

5.0 Energy produced by the cooker

The heat energy required for cooking for a single person is 900 kJ (Singh, 2009). The solar cooker was designed to cook for a five head family but it can cook only 80% of the meal while another part of the meal is considered as frying based food. Considering cooking two meals per day. The heat energy produced by the solar cooker per day is,

= 5×2×0.8×900

The energy produce by solar cooker per day is 7200 kJ.

5.1 Energy content of an LPG cylinder

The calorific value of LPG is 49371.20 kJ per kg. For the domestic purpose, the weight of an LPG cylinder is typically 14.2 kg of gas. The total energy of a full cylinder is 49371.2 × 14.2 = 701071.04 kJ per cylinder. But only 60% of this energy is used for heating other part goes to waste, therefore useful energy is 701071.04 × 0.6 = 420642.62 kJ per cylinder (Singh, 2009).

When LPG will be replaced by solar cooker, the number of days required by solar cooker to produce equivalent energy of LPG cylinder is

$$= \frac{420642.62 \text{ KJ}}{7200 \text{ KJ/Day}}$$

= 58.42 Days

$=\frac{365}{58.42}$

=6.25 cylinders are required in a year.

A family of five members needs 6.25 LPG cylinders in a year. The cost of an LPG cylinder is ₹900 (Non-subsidized). New connection of an LPG with double bottle cylinder (two cylinders and one regulator) along with the cost of LPG is ₹4500.

So, after subtracting cost of new connection of LPG cylinder from total investment, cost of the developed solar cooker, the total cost of solar cooker is ₹6120.

$$\text{Payback period} = \frac{Cost\ of\ developed\ hybrid\ system}{Cost\ of\ energy\ saved\ per\ year}$$

$$= \frac{6120}{5.13 \times 900}$$

= 1.32 Years

The payback period was 1.32 years and this solar cooker can save 51.3 LPG cylinders in ten years of time, estimated to be the lifetime of the developed solar cooker.

6.0 Conclusion:

Average thermal efficiency (η_{therm}) of the hybrid system calculated as 22 per cent, cooking power (P) was estimated as 47.68 W and the overall heat loss coefficient was calculated to be 3.03 W/m^2°C. Actual cooking time was found to be about 130 minutes which was otherwise more than 180 minutes in case of traditional box type cooker. Drying performance of the system revealed that initial moisture content of Amla was 90.24% , after 14 hrs drying, moisture content was reduced to 3.14 per cent , drying rate of the hybrid solar cooker was found to be 4.99 kg /h. The electric unit of the system was found able to operate 5W DC bulb for 9 hours, smart phone charger and a dc fan (12V, 4Ah) for one hour each in single charging. The cost of the system was worked out as Rs. 6120.00.

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