Design Fabrication and Performance Evaluation of Solar Oven

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Abstract— Solar oven is a device which uses the energy of sunlight for cooking, heating, roasting, pasteurizing etc., Different types of solar ovens and cookers are developed over years, mainly box type ovens, panel type and parabolic dish types. Among all the types box type is more popular because of its simplicity of handling and operation. Referring to the different collector design, it has been concluded that box type is better when compared to cost and compound parabolic collectors are better when compared with cooking time. Here a new design of a solar oven has been developed using a parabolic trough collector and an evacuated borosilicate glass tube. It has a wide range of application such as cooking, distillation, roasting etc., due to its unique property of producing a very high temperature of around 250°C. The parabolic glass tube type solar oven was designed, fabricated using locally available materials and the thermal performance was evaluated. The solar oven was tested for different conditions such as under load condition of 2.5Kg of water for with and without reflectors and under no load condition with an empty tube for with and without reflectors. Temperature of 90-95°C was obtained within 90 minutes under loading condition and a maximum temperature of around 234°C was achieved under no load condition in 60 minutes. Cooking power, Stagnation temperature, and the thermal efficiency of the solar oven was determined.

Key words: Solar Ovens, Parabolic Trough Collector, Evacuated Glass Tube, Thermal Performance

I. Introduction

Solar cooker is a device that cooks food using only sun energy in the form of solar radiation. The solar cooking saves a significant amount of conventional fuels. The solar cooking is the simplest, safest, clean, environment friendly, and most convenient way to cook food without consuming fuels or heating up the kitchen. [1]

Solar cookers have a long history dating back almost 18th century when Nicholas-de-Saussure built first ever Solar Box Cooker. Today there is about more than 60 major designs however the solar cooking has not caught the imagination of peoples, except in places where shortage of conventional fuel like fire wood and the solar cookers have attracted the attention of many researchers so far. Different types of solar cookers have been developed and tested all over the world. Today, there is challenge to manufacturing and evaluation of efficient and cheap solar cookers. There has been a considerable interest recently in the design, development and testing of various types of solar cookers. [1]

Different designs of solar cookers that exists are solar box cooker, panel solar cooker, collector cooker, concentrating type solar cooker, SK-14 Parabolic concentrator, PRINCE-15 parabolic concentrator, community parabolic dish cooker, Scheffler solar cooker – direct cooking model etc., [1]

II. Literature Survey

Solar cookers have a long history dating back almost 18th century when Nicholas-de-Saussure built first ever Solar Box Cooker. Today there is about more than 60 major designs however the solar cooking has not caught the imagination of peoples, except in places where shortage of conventional fuel like fire wood and the solar cookers have attracted the attention of many researchers so far. Different types of solar cookers have been developed and tested all over the world. Today, there is challenge to manufacturing and evaluation of efficient and cheap solar cookers. There has been a considerable interest recently in the design, development and testing of various types of solar cookers. [1]

A. Solar box cooker or solar oven

It is the most common type of solar cooker made for personal use. It is very simple in construction, consists of a box in the shape of square, rectangular or cylindrical which is painted black from inside and insulated from all sides except window side which is double glazed is used. Up to four black painted vessels are placed inside the box with the food to be cooked. The cooker takes 1 ½ to 2 hours to cook items such as rice, vegetables. Refer figure 1 [1]

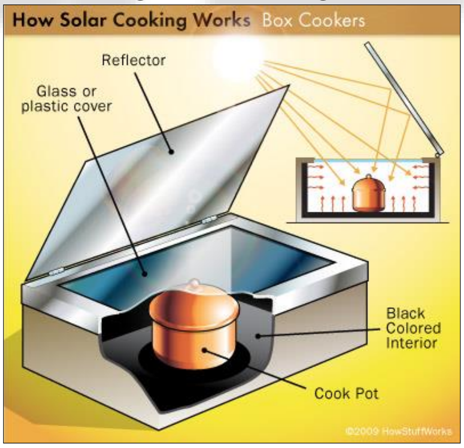

Fig. 1: Box Solar Cooker.

B. Panel Solar Cooker

The panel cooker is quite similar in operation to the solar box cooker. The same principles are employed but instead of an insulated box only, the panel cooker typically relies on large (often multifaceted) reflective panels, which focus the sunlight on a cooking vessel. Panel cookers are the easiest and least costly to make, requiring just four reflective panels and a cooking vessel, but they are unstable in high winds and do not retain as much heat when the sun is hidden behind clouds. Refer figure 2 [1]

Fig. 2: Panel Solar Cooker.

C. SK-14 parabolic concentrator

SK 14 is a solar concentrator developed by Dr. Ing. Dieter Siefert. It is a concentrating type parabolic dish solar cooker useful for households and small establishments. A typical dish solar cooker has an aperture diameter of 1.4 meter and focal length 0.28 meter. The reflecting material used for fabrication of this cooker is anodized aluminum sheet which has a reflectivity of over 80%. The tracking of the cooker is manual and thus has to be adjusted in 15 to 20 minutes during cooking time. It has a delivering power of about 0.4 kW. The cooker can meet the needs of around 4-8 peoples and can be used from one hour after sunrise to one hour before sunset on clear days. Refer figure 3 [1]

Fig. 3: SK-14 Domestic Solar Cooker

D. PRINCE-15 Parabolic concentrator

It is a concentrating type parabolic dish solar cooker with square geometry and useful for households and autoclaving. A typical dish solar cooker has dimension of 1250 mm × 1250 mm and focal length 0.460 meter. The reflecting material used for fabrication of this cooker is anodized aluminum sheet which has a reflectivity of over 80%. The tracking of the cooker is manual and thus must be adjusted in 15 to 20 minutes during cooking time. The cooker having a thermal efficiency of around 50% can meet the needs of around 8 peoples. PRINCE-15 is a concentrator with square or rectangular dish shape. This shape permits use of same sized strips of steel to make bowl. This makes the bowl sturdy. As the members of the dish have same geometric shape this reflector is easy to assemble even by novice people with the help of construction manual. Refer figure 4 [1]

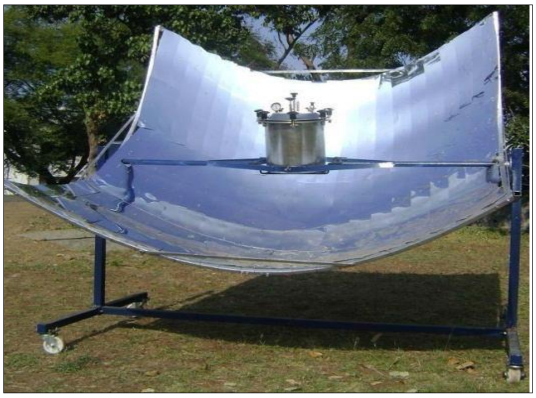

Fig. 4: PRINCE-15 Solar Cooker

III. DESIGN DETAILS

A. Solar Collector Tube

Evacuated tubes absorb solar energy and convert it into heat for use in water heating. There are several types of evacuated tubes used in solar thermal collectors. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass. The outer tube is transparent and allows sunlight to pass through with minimal reflection. The inner tube is coated with an aluminum nitride (Al-N/Al) coating.

This selective surface is excellent at absorbing solar radiation with minimal reflection losses. During the manufacturing process, the air contained in the space between the two layers of glass is pumped out, while the top of the tubes is exposed to high temperatures. This fuse the two tubes together into a single evacuated tube. This "evacuation" of the gasses forms a vacuum, which is the most important factor in achieving the high performance of the evacuated tubes. The vacuum eliminates a physical connection between the two glass layers of the tube which means there is nothing to transfer thermal energy so the heat cannot escape. This is important because once the evacuated tube absorbs the radiation from the sun and converts it to heat, we don't want to lose it. The vacuum helps to achieve this. The insulation properties are so good that while the inside of the tube may be 150°C, the outer tube remains within a few degrees of the ambient air temperature.

Sl.No	Components	Specification
1.	Tube material	Borosilicate glass tube
2.	Coating	Copper/aluminium nitrile
3.	Length of the tube	1500mm
4.	Outer diameter	58mm
5.	Inner diameter	47mm
6.	Emission after evacuating	ε=0.96
7.	Average heat loss coefficient	U_L = 0.4-0.6 W/m^2
8.	Transmittance	τ = 0.92

Table 1: Specifications of the solar collector tube

B. Stand

Stand is a structure which supports reflectors, and solar glass tube. It is fabricated using rectangular cross section tube of mild steel material. The frame can be tilted to an angle such as 45°, 30°, 20°. This helps in tracking the sun at different angles.

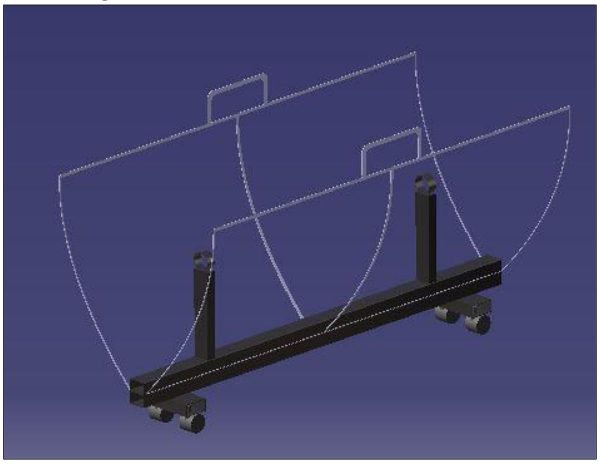

Fig. 5: CAD Model of the frame

C. Reflectors

The CPC reflector to increase the efficiency of evacuated tube collectors, a highly reflective, weather-proof CPC (Compound Parabolic Concentrator) is fitted behind the evacuated tubes. The reflector geometry guarantees that direct and diffuse sunlight strikes the absorber, even when the angles of irradiation are unfavorable. This significantly improves the energy yield of a solar collector. Unfavorable angles of irradiation are caused by light striking the collector at an angle (azimuth angle).

Equation to parabola is given by,

$$y^2 = 4fx, \qquad (3.1)$$

Where f is the focal point of the parabola.

y is the vertical distance from x axis.

x is the horizontal distance from the y axis.

Therefore, $y^2 = 4 * 0.3 * x$

$y^2 = 1.2x$

where focal length is taken as 300mm.

D. Concentration ratio

Concentration ratio also called geometric concentration ratio is the ratio of area of reflector to the area of absorber. Parabolic trough type of reflectors will have concentration ratio between 1 to 100.The more the area of the absorber tube less will be the concentration ratio.

$$\text{Concentration Ratio(CR)} = \frac{\textit{Area of the reflectors}}{\textit{area of the absorber}} \qquad (3.2)$$

$$CR = \frac{1.8}{0.273} = 6.5$$

Where,

Area of the reflector = $0.6 \times 1.5 \times 2 = 1.8\ m^2$

Area of the absorber(collector), $A_c = \pi \times d \times l$

$= \pi \times .058 \times 1.5$

$A_c = 0.273\ m^2$

E. Tray

The tray is semicircular in cross section. Aluminium sheets are used to make tray. These have a very good thermal conductivity when compared with other metals such as MS and SS. It has a thermal conductivity of 249 w/m-K. whereas the conductivity of SS is just 50w/m-K. Also, the weight of the aluminium is less and the sheets of various thickness are easily available.

IV. Working Principle

Solar oven works purely on solar radiation emitted by the sun. It consists of an evacuated tube which is literally the cooking chamber and parabolic trough reflectors. A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned directly above the middle of the parabolic mirror. The tube is constructed with two layers of glass in the shape of a sealed tube, where the air has been removed between the layers. It is coated with special coatings such as aluminium nitrile which catches and absorbs light, stainless steel which conducts heat and copper traps infrared radiation. Heat loss happens primarily by conduction and convection through a medium. With no air gap between the layers of glass the chamber is nicely insulated, well suited for retaining cooking heat. The ends of the tube are open so a slender cooking tray can be inserted. The figures shown below are the different types of solar radiation that are incident on the earth which are either normal to the surface or at an angle.

V. Performance Testing

A. Temperature reading under loading condition with 2.5 liters of water.

The set up was set under the sun for the following days. The tube was filled with 2.5 litres of water. The temperature reading was taken at an interval of 10 min and this was done up to two hours. The readings are noted in the tabular column.

Date	5-5-17	6-5-17	12-5-17
Time	2:30 pm	12:15 pm	2:40 pm
Initial	35°C	31°C	38°C
10 min	41°C	43°C	51°C
20 min	52°C	56°C	59°C
30 min	65°C	67°C	68°C
40 min	69°C	74°C	73°C
50 min	74°C	79°C	78°C
60 min	79°C	85°C	80°C
70 min	83°C	89°C	87°C
80 min	87°C	93°C	91°C
90 min	92°C	97°C	95°C
100 min	92.5°C	97°3C	96°C
110 min	93°C	97.5°C	97°C
120 min	94°C	98°C	97°C

Table 2: Temperature reading under loading condition with reflectors.

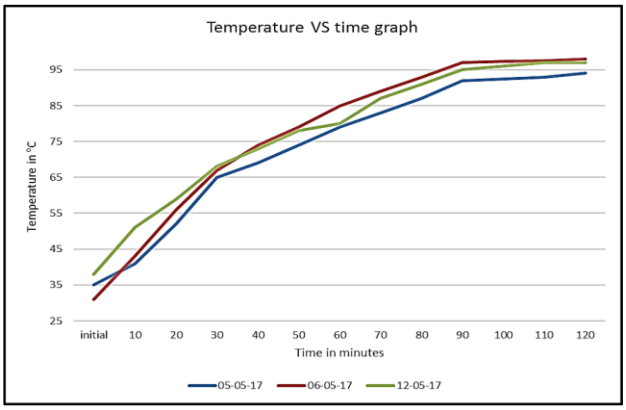

Fig. 6: Temperature Vs Time graph under loading condition.

B. Comparing under loading condition for with and without reflectors.

The tube was filled with 2.5 litres of water and kept under the sun. The reflectors were removed during this test and the temperature reading were noted down for every 10 minutes. This was done up to two hours and the readings are tabulated below.

Condition.	Without reflectors.	With reflectors.
Time	12:00 noon (4-6-17)	12:15 pm (6-5-17)
Initial	30°C	31°C
10 min	36.5°C	43°C
20 min	41°C	56°C
30 min	44°C	67°C
40 min	48°C	74°C
50 min	50°C	79°C
60 min	51°C	85°C
70 min	52°C	89°C
80 min	54°C	93°C
90 min	56°C	97°C
100 min	58°C	97°3C
110 min	61.5°C	97.5°C
120 min	64°C	98°C

Table 3: Temperature reading under loading condition without reflectors.

The above table is a comparison of temperatures under loading condition for with and without reflectors. The maximum temperature reached was around 64°C at the end of 120 minutes for the case of without using reflectors Whereas a maximum temperature of 98°C was reached at the end of 120 minutes for the case of with using reflectors. The use of reflectors will help in achieving a maximum temperature with a faster rate. The amount of average solar radiation on both the days during testing were almost same and it was between 900w/m² to 800w/m².

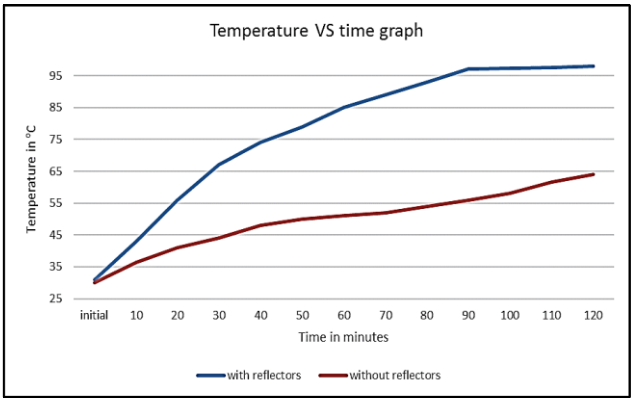

Fig. 7: Temperature Vs Time graph (comparing between with and without reflectors under loading condition)

C. Under no load condition (Empty tube with tray).

The set up was set under sun for the following days. The temperature readings were taken at an interval of 5min and this was done up to one hours. The readings are noted in the tabular column.

Date	19-5-17	19-5-17
Time	12:00 noon	1:30 pm
Initial	30°C	34.5°C
5 min	90°C	86°C
10 min	134°C	127°C
15 min	152°C	143°C
20 min	165°C	170°C
25 min	178°C	198°C
30 min	184°C	206°C
35 min	198°C	212°C
40 min	213°C	223°C
45 min	215°C	226°C
50 min	222°C	227°C
55 min	228°C	230°C
60 min	231°C	234°C

Table 4: Temperature reading under no load condition with reflectors.

From the above table, it can be noted that the temperature of about 200°C was achieved within 30 minutes and a temperature of 234°C was achieved within next 30 minutes. The temperature rise decreases from this point of time and it reaches a constant value.

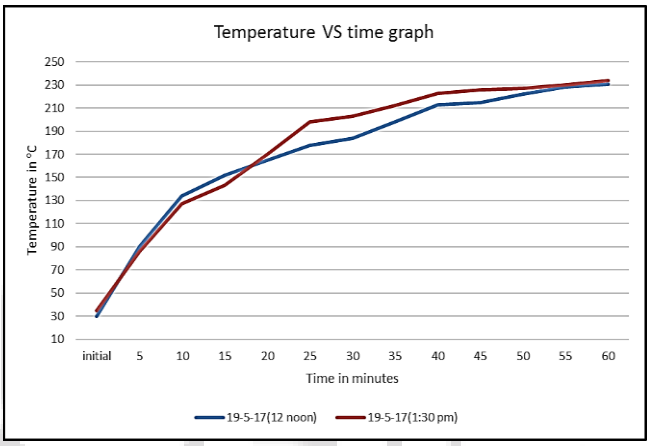

Fig. 8: Temperature Vs Time under no load condition.

D. Comparing under no load condition for with and without reflectors.

The set up was set under sun for the following days. The temperature readings were taken at an interval of 5min and this was done up to one hour. The readings are noted in the tabular column.

Date	Without reflectors (8-5-17)	With reflectors (19-5-17)
Time	2:30 pm	1:30 pm
Initial	33°C	34.5°C
5	40°C	86°C
10	47°C	127°C
15	55°C	143°C
20	67°C	170°C
25	76°C	198°C
30	85°C	206°C
35	93°C	212°C
40	101°C	223°C
45	112°C	226°C
50	125°C	227°C
55	134°C	230°C
60	145°C	234°C

Table 5: Temperature reading taken without reflectors.

The above table is a comparison of temperatures under no condition for with and without reflectors. The maximum temperature reached was around 145°C at the end of 60 minutes under the case of without reflectors. Whereas a maximum temperature of 234°C was reached at the end of 60 minutes under the case of with reflectors. The use of reflectors will help in achieving a maximum temperature with a faster rate.

The amount of average solar radiation on both the days during testing were almost same of about 850 w/m^2.

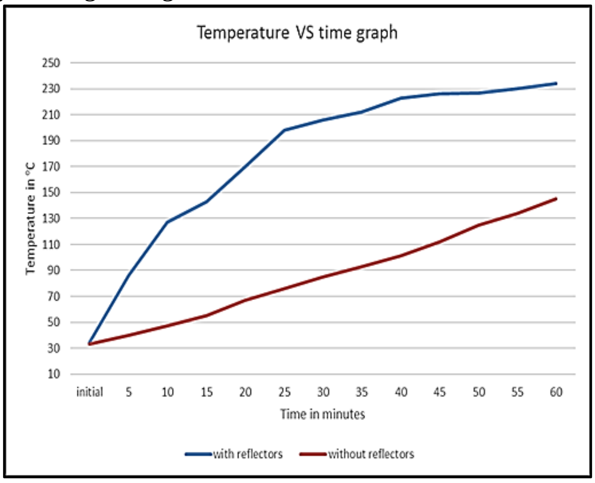

Fig. 9: Temperature Vs Time graph (comparing between with and without reflectors under no load condition)

E. *Equations*

1) *Useful energy*

Under steady condition, the rate of useful energy available with evacuated tube solar collector can be represented by the equation. [2]

$$Q = A_C[I - U_L(T_2 - T_1)] \quad (5.1)$$

Where, Q = Useful energy in watts

A_c = Area of the collector, m^2

I = Average solar insolation, w/m^2

U_L= Average heat loss co efficient, w/m^2

T_2 = inner wall temperature of tube at the end of interval, °C

T_1 = inner wall temperature at beginning of interval,°C

2) *Cooking Power*

The cooking power is given by [3]

$$P = \frac{M_W C_W (T_2 - T_1)}{\Delta t} \quad (5.2)$$

Where, M_w = Mass of water in cooking vessel, kg

C_w = Specific heat of water, kJ/kg K

T_2 = Water temperature at end of interval, °C

T_1 = Water temperature at beginning of interval, °C

Δt= time interval

3) *Stagnation Temperature*

The stagnation temperature gives an understandable figure for the maximum possible temperature achievable by a cooker

The Stagnation Temperature is simply given by:

$$ST = (T_2 - T_1) \quad (5.3)$$

Where, T_2 = Highest water temperature reached, °C

T_1 = Ambient temperature, averaged over testing period, °C

4) *Measurement of thermal efficiency of solar cooking unit*

The cooking power and sensible efficiency can represent the thermal efficiency of the solar cooking unit. The sensible or heating-up power represents the rate of sensible energy used to heat up a certain mass of water [3]

$$\eta = \frac{M_W C_W \Delta T}{A_C * I * t} = \frac{Q}{I A_C} \quad (5.4)$$

Where, M_w = Mass of water in cooking vessel

C_w = Specific heat of water.

ΔT = change in temperature.

A_c = Area of the collector.

I = Average solar insolation.

t = time taken for temperature rise.

5) *Total Solar Radiation*

The incident solar beam radiation on the horizontal surface can be calculated by [4]

$$I_b = I_{bn} \cos \theta_z \quad (5.5)$$

$$I_{bn} = A e^{\left[\frac{-B}{\cos \theta_z}\right]}$$

The values of extraterrestrial solar intensity A, the atmospheric extinction coefficient B, for any day of the month by the following equations

$$B = 0.175[1 - 0.2 \cos(0.93 \times ND)] - 0.0045(1 - \cos(1.86 \times ND))$$

$$A = 1158\left[1 + 0.066 \cos\left(360 \times \frac{ND}{365}\right)\right]$$

Declination angle,

$$\delta = 23.45 \sin\left\{\frac{360(284 + ND)}{365}\right\}$$

Where, ND is the number of days from Jan 1st

Hour angle is calculated as shown by the equation

w =15*[12 - LST]

Where, LST is local solar time.

The general definition of the incident angle θz for any surface orientation can be expressed as

Cos q_Z = (Sind × Sinf × Cosb) - (Sind × Cosf × Sinb × Cosg) +(Cosd× Cosb × Cosf ×Cosω) + (Cosd × Sinf × Sinb × Cosg × Cosw)+ (Cosd × Sinb × Sinw × Sing)

Where,

γ = surface azimuth angle. That is, the deviation of projection on a horizontal plane of the normal to the surface from local meridian with zero due to south facing.

ϕ =Latitude angle

θz = Zenith angle It is the vertical angle between the sun's rays and a line perpendicular to the horizontal plane through point.

β = Slope The angle between the horizontal and the plane.

ω = Hour angle

δ = Declination angle

VI. RESULTS AND DISCUSSION

Performance testing was done for different conditions and in different days at different times through the day time. The following observations were made

A. *For empty tube with cooking tray*

The useful energy was 0.2kw and the stagnation temperature was 201°C. The maximum temperature achieved in an hour was 234°C. The average solar isolation during testing was 886 w/m^2.

Comparison was done using with and without reflectors. The time taken to reach 200°C was about 25 to 30 minutes while using the reflectors whereas the time taken to reach the same temperature was more than 1 hour for without using reflectors.

B. With 2.5kg of water

The power obtained for this condition was 0.13kw and the stagnation temperature was 67°C. The maximum temperature achieved was 98°C. The average solar isolation during testing was 852 w/m^2. The thermal efficiency of the cooking unit obtained was about 61%

Comparison was done using with and without reflectors. The time taken to reach 97°C was about 80 to 90 minutes while using the reflectors whereas the time taken to reach the same temperature was more than 120 minutes for without using reflectors.

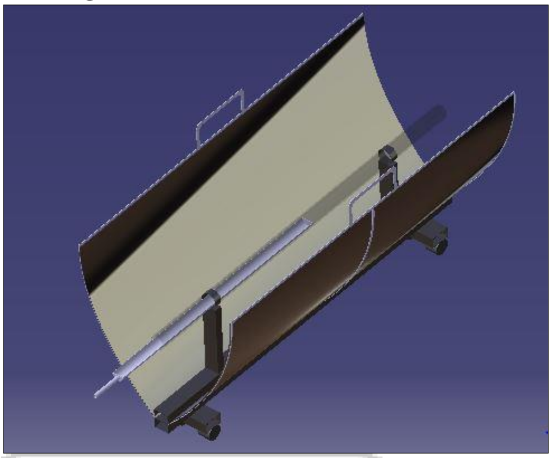

Fig. 10: 3D view of the model

Fig. 11: Actual model

VII. ADVANTAGES AND LIMITATIONS

A. Advantages

- Parabolic solar oven can attain temperatures of about 230 °C. Whereas conventional solar box oven attains temperatures up to 165 °C.
- The greatly enhanced heat collecting capacity due to relatively large collector area allows frequent interaction with the food during the cooking process without fear of losing performance.
- Evacuated tube absorbs heat very efficiently from all directions supported by reflector to absorb maximum of solar heat.
- These do not use fuel. This save cost as well as reducing environmental damage caused by fuel use.
- These could have large economic and environmental benefits by reducing deforestation.
- Less attention is needed during cooking.

B. Limitations

- Food cannot be cooked at night.
- Poor performance on Cloudy Conditions.
- The availability of different standard sizes of the evacuated tube is very less.
- Evacuated tube is made from glass. So, it must be handled carefully.

VIII. CONCLUSION

The following conclusions are drawn based on the experimental study:

1) The non-tracking Compound Parabolic Collector(CPC) system can absorb maximum amount of solar radiation throughout the day.
2) By redesigning the CPC system, the stored energy level can be raised.
3) The initial investment is high, but this type of systems can be encouraged due to its clean and green nature.
4) Thermal energy obtained from glass tube type solar oven can be transported to any comfortable place or cooking as its assembly is foldable and very easy to assemble for use. The reasonably high insulation decreases the cooking time to a very minimum value.

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