Design, Develop and Analysis of Laboratory Model of Indoor Solar Cooker

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Abstract - *A laboratory model of indoor solar cooker was constructed using a parabolic dish concentrator of 100 cm diameter to concentrate the radiations on mirror tube of size 10cm × 10cm and length 1m to transfer the concentrated solar radiations. Reflective mirrors of size 1 inch × 1 inch were used to cover the interior of the concave surface of the parabolic dish. Mirror tube was constructed using 4mm thick glass mirrors such that reflective effect will be inside the tube. One end of mirror tube stainless steel mirror was placed at an angle of 45° such that it diverts the concentrated solar radiations inside the tube which undergo continuous reflections and emerge out at other end of tube. Mirror tube was laid horizontally in east-west direction, such that opening of mirror tube was made to face north direction and concentrator was made to face south. Concentrator was adjusted to focus the solar radiations on the opening of mirror tube. The average efficiency of concentrator to concentrate radiations on opening of mirror tube was found to be 39.09%. Efficiency of transfer of solar radiations through mirror tube was found to be 8.6%. At the end of mirror tube, arrangements to hold the vessel and divert solar radiations towards the vessel were done. Thermal efficiency of the model was found to be 0.6455% and average cooking power was found to be 2.787W.*

Key Words: indoor solar cooker, parabolic dish concentrator, solar radiations, mirror tube, thermal efficiency, cooking power

1. INTRODUCTION

As demand for energy is increasing, energy sources like fossil fuels, coal and wood are destroyed. For sustainable development of the world, more use of renewable resources for energy is important. Use of solar energy can reduce burning of fossil fuels, wood, gas, etc. for generation of heat for cooking purpose. This in turn help in reducing indoor pollution. The solar cooking is the simplest, safest, clean, environment-friendly, and most convenient way to cook food without consuming fuels or heating the kitchen [1]. Still solar cooking is not established as a user friendly and economic technology. Scientists all over the world have made large number of efforts in developing different types of solar cookers for many decades. Although it can be one of the best alternative for cooking, it is hardly accepted by the society. There are many reasons for that like lack of awareness, large size, bulky models, slow cooking, highly dependent on weather conditions, fixed cooking time etc. [2].

The available solar cookers are broadly categorized under two groups as solar cookers with and without storage [3]. Solar cookers without storage are classified into direct and indirect depending upon the heat transfer mechanism to the cooking pot [4]. Box type cookers and concentrating type cookers are included in direct category. In indirect type solar cookers, the pot is physically displaced from the collector and a heat transferring medium is required to convey the heat to the cooking pot. Solar cookers with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category [4].

When cooking with a reflective solar collector, people are often close to a strong and concentrated sunlight, which may cause considerable safety issues involving both burns and blinding. There are very less technologies to use the solar energy to generate heat at indoor locations. The goal of this project was to develop safer and user-friendly model of indoor solar cooker to be generally used for food cooking and heating purpose at indoor and outdoor locations. Solar radiations are concentrated using concentrator and these concentrated radiations are made to enter a mirror tube in which they undergo continuous reflections and emerge out at side of the mirror tube. A laboratory model was developed using a concentrator 1m diameter and mirror tube of 1m length. Experiments are conducted on the model to know efficiency of concentrator, efficiency of mirror tube to transfer the solar radiations and to analyse the cooking power of the model. These indoor solar cookers can be used not only for cooking purposes it can also be used in industrial applications like energy generation, product manufacturing where there is demand for heat energy.

2. ESTIMATION OF SOLAR RADIATION

2.1 Hourly global and diffuse radiation on horizontal surface

Before The hourly global radiation I_g on a horizontal surface is the sum of hourly beam radiation, I_b and hourly diffuse radiation I_d thus

$$I_g = I_b + I_d \quad (1)$$

If I_{bn} is the beam radiation on a surface normal to the direction of sun rays, the beam radiation received on a horizontal surface may be given as

$$I_b = I_{bn} \cos \theta_z \quad (2)$$

Where θ_z = surface azimuth angle

$$\text{Thus } I_b = I_{bn} \cos \theta_z + I_d \quad (3)$$

I_{bn} and I_d are estimated as follows

$$I_{bn} = A\, e^{(-B/\cos \theta z)} \quad (4)$$

$$I_d = C\, I_{bn} \quad (5)$$

Where A, B, and C are constants whose values have been determined month-wise based on measurements carried out in the USA. These constants change during the year because of seasonal changes in dust and moisture contents of the atmosphere and also because of variation in the sun-earth distance. The values of constants A, B and C are tabulated in the table 1 [5]

Table -1: Constants A, B and C for predicting hourly solar radiation on clear days

Month	A (W/m^2)	B	C
January	1202	0.141	0.103
February	1187	0.142	0.104
March	1164	0.149	0.109
April	1130	0.164	0.120
May	1106	0.177	0.130
June	1092	0.185	0.137
July	1093	0.186	0.138
August	1107	0.182	0.134
September	1136	0.165	0.121
October	1136	0.152	0.111
November	1190	0.144	0.106
December	1204	0.141	0.103

2.2 Solar radiation on inclined surface

Solar radiation incident on an inclined surface can be given by [6]

$$I_T = I_b r_b + I_d r_d + (I_b + I_d)\, r_r \quad (6)$$

r_b it is defined as the ratio of flux of beam radiation on an inclined surface (I_b') to that on a horizontal surface (I_b)

$$I_b' = I_{bn} \cos \theta_i \quad (7)$$

$$I_b = I_{bn} \cos \theta_z \quad (8)$$

Where I_{bn} is the beam radiation on a surface normal to the direction of sun's rays

$$\text{Thus } r_b = (I_b'/ I_b) = (\cos \theta_i / \cos \theta_z) \quad (9)$$

Second term in equation (6) represent diffused radiation and third term represent radiation reflected from ground and surrounding objects incident on inclined surface. While using a solar concentrator only beam radiation incident on the concentrator surface is diverted towards the focus of concentrator. The intensity of beam radiation incident on inclined surface is given by

$$I_{br} = I_b r_b \quad (10)$$

3. MATERIALS AND METHODS

Components of the model like solar concentrator, mirror tube and vessel arrangements were designed and constructed for the laboratory scale

3.1 Designing of concentrator

To develop a laboratory scale model of indoor solar cooker a concentrator was designed to have capacity to increase temperature of 1litre of from 20°C to 100°C in 20 minutes assuming specific heat capacity of water as 4168 J/kg° C and density of water as 1kg/litre. Assuming efficiency of concentrator as 50%[7], angle of tilt of concentrator as 60° and surface azimuth angle as 0° for the location for which solar radiation incident on the concentrator surface calculated surface area of concentrator required was found to be 0.747m^2. From analysing available materials from market a parabolic dish of 100cm diameter was found suitable. A reflective mirror of 2 mm thickness was cut using a glass cutter into small square pieces of size 1 inch × 1 inch, these small reflective mirrors were used to cover the interior of the concave surface of the satellite dish by using a glue which form the parabolic concentrator as shown in figure 1

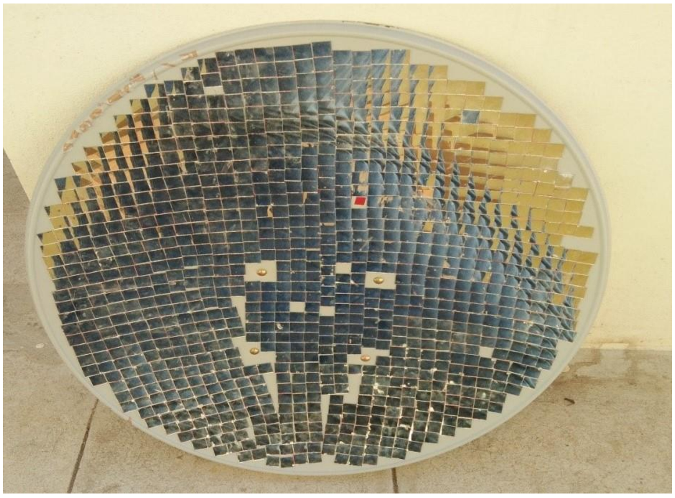

Fig -1: Parabolic dish concentrator

3.2 Construction of mirror tube

To design mirror tube, the minimum area on which solar radiations can be concentrated by concentrator was analyzed by placing the concentrator at inclination angle of 60° and solar azimuth angle of 0° (facing south). A sheet of paper was placed vertically at the focus of concentrator the minimum area on which radiation can be focused was found to be 6cm × 6cm. Hence, a mirror tube of internal dimension 10cm × 10cm and length 1m was constructed using 4mm thick glass mirrors. At one end of mirror tube stainless steel mirror was placed at an angle of 45º to the opening of mirror tube such that it directs incoming concentrated solar radiations to pass through the tube as shown in figure 3.

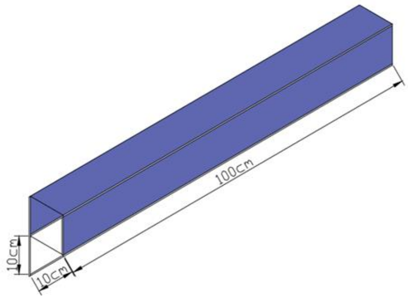

Fig-1: mirror tube

3.3 Arrangements to hold vessel

At the end of the mirror tube, modifications were done to hold a cylindrical vessel of 11cm diameter and 5cm height, as shown in figure 4 such that the light rays travelling through the tube were reflected towards the cylindrical vessel. Vessel was painted black at outer surface to absorb the solar radiations. The temperature variation of cylindrical vessel was measured using thermometer

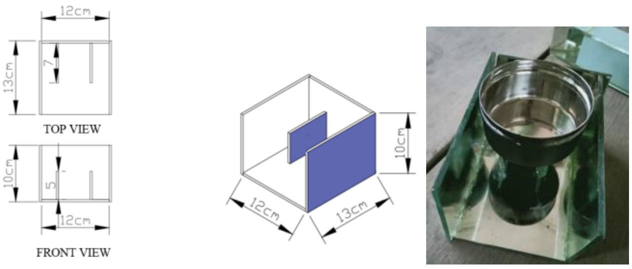

Fig-3: arrangements to hold vessel

4. RESULTS AND DISCUSSION

Experiments were conducted on the roof of Department of Civil Engineering, Bangalore University, Bengaluru. The latitude and longitude of the location were 12°57'0.591"N and 77°28'43.074" E respectively. Experiments were conducted when clear sky was available on the location

4.1 Analysis of efficiency of concentrator and mirror tube

This experiment was carried out to analyze the efficiency of concentrator to concentrate solar radiations on opening of mirror tube and to find efficiency of the mirror tube to transfer the solar radiation. The experiments were carried out on 16th October 2020, 22nd October 2020 and 20th December 2020.

4.1.1 Thin plate method for measurement of concentrated solar radiation

This method is based on the sudden change of temperature in unsteady mode. A metal plate is held at the focus of the concentrator where solar radiations are concentrated. Temperature variation of the plate is noted to measure the concentrated energy [8].

The heat equation in a plate is written as follows

$$mC_p\,(dT/dt) = Q_u + Q_a - Q_{p\text{-}cv} - Q_{p\text{-}r} \qquad (11)$$

Where Q_u , Q_a ,Q_{p-cv} and Q_{p-r} are the useful concentrated solar flux, the absorbed flux, the heat losses by convection and the heat losses by radiation, respectively. Hypothesis used in this part are the heat losses by convection and radiation are neglected because at time (t=0), the plate temperature is equal to ambient therefore the above equation can be written as

$$mC_p\,(dT/dt) = Q_u \qquad (12)$$

$a = (dT/dt)_{(t=0)}$, is the slope in the beginning of the temporary plate temperature variation and C_p is the heat capacity. At time t = 0 the thin plate temperature varies linearly according to the time so to determine the slope in the beginning.

$$T = at + T_a \qquad (13)$$

Where T is the thin plate temperature and T_a is the ambient temperature

4.1.2 Experimental analysis of efficiency of solar radiation transfer by mirror tube

Experimental setup were made as shown in figure 5 Concentrated solar radiations at the opening of mirror tube and radiations transferred by the mirror tube were measured using two different metal plates made of mild steel and stainless steel of size 10cm × 10cm. During experiment concentrator is adjusted manually to concentrate solar radiations on the opening of mirror tube and tilt angle (β) and solar azimuth angle (ϒ) of the concentrator were noted. The metal plate was held at the opening of mirror tube where mirror tube gets concentrated solar radiations and its temperature variation was noted then metal plate was cooled and fixed at end of mirror tube and its temperature variations were noted again. Solar radiations incident on the concentrator surface experiment are calculated using equation (10).

(a) mild steel plate

(b) stainless steel plate

Fig-4: experimental setup for Analysis of efficiency of concentrator and mirror tube

Table 2: Properties of metal plates used

Plate material	Cp J/(g°C)	Weight (grams)	Thickness mm
Mild steel	0.51	105	2
Stainless steel	0.46	119	2

Efficiency of concentrator(nc) was calculated as
n_c = (energy at focus of concentrator)/(energy incident on concentrator)

Efficiency of mirror tube to transfer solar radiations($n_{transfer}$) was calculated as
$n_{transfer}$ =(energy transferred by the tube) / (energy incident on mirror tube)

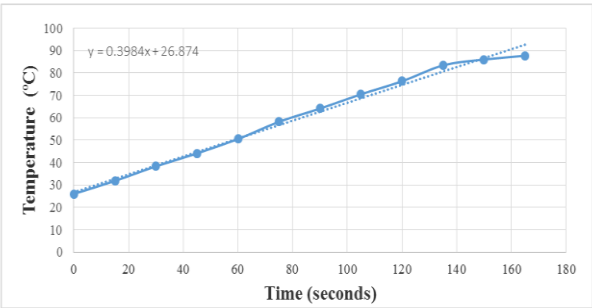

Fig-5 :Temperature variation measurement of mild steel plate when placed at the end of mirror tube during experiment on 16th October 2020 at 11:30AM

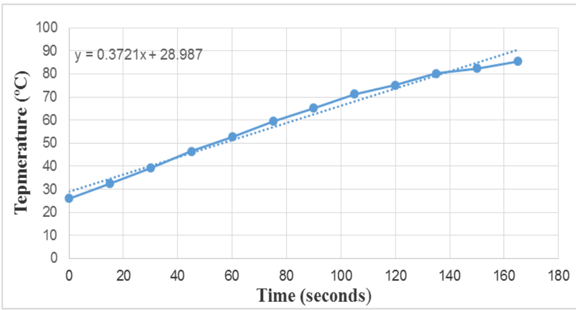

Fig-6: Temperature variation measurement of mild steel plate when placed at the end of mirror tube during experiment on 16th October 2020 at 12:05 PM

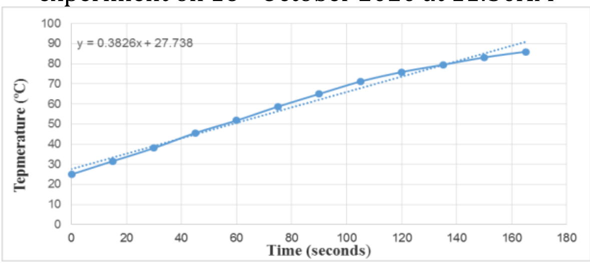

Fig-7: Temperature variation measurement of mild steel plate when placed at the end of mirror tube on 22nd October 2020 at 11:30 AM

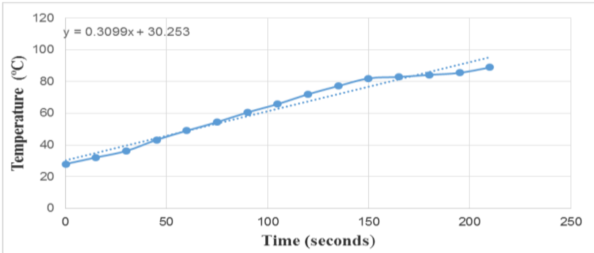

Fig-8: Temperature variation measurement of mild steel plate when placed at the end of mirror tube on 22nd October 2020 at 1:17 PM

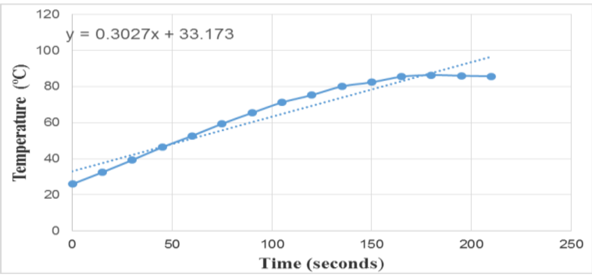

Fig-9: Temperature variation measurement of stainless steel plate when placed at the end of mirror tube on 20th December 2020 at 10:30 AM

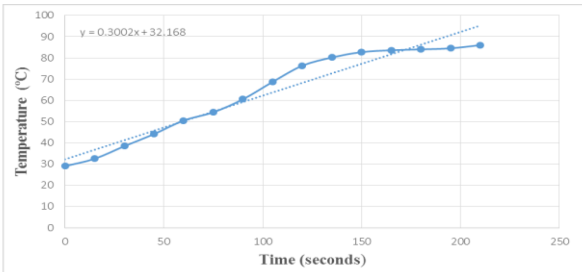

Fig-10: Temperature variation of stainless steel plate when placed at the end of mirror tube on 20th December 2020 at 11:30 AM

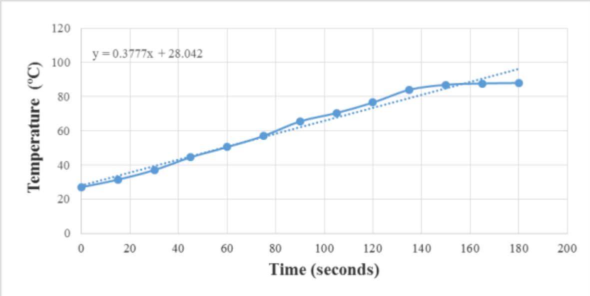

Fig-11: Temperature variation measurement of stainless steel plate when placed at the end of mirror tube on 20th December 2020 at 12:15 PM

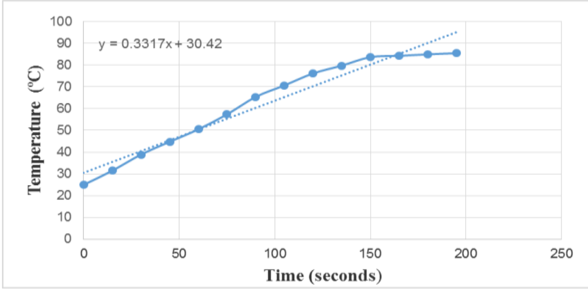

Fig-12: Temperature variation measurement of stainless steel plate when placed at the end of mirror tube on 20th December 2020 at 1:30 PM

Date	Time	Plate material	β	ϒ	I_c	Temperature variation of plate placed at entrance of mirror tube			I_{in}	(dT/dt)	I_t	η_c (%)	$\eta_{transfer}$ (%)
						T_i	T_f	Δt					
16/10/2020	11:30 AM	Mild steel	57°	17°	463.54	26	105	20	211.52	0.39	20.8	**45.63**	**9.83**
16/10/2020	12:05 PM	Mild steel	52°	10°	550.77	27	110	20	222.23	0.37	19.92	**40.34**	**8.96**
22/10/2020	11:30 AM	Mild steel	55°	17°	494.13	26	107	20	216.87	0.38	20.48	**43.88**	**9.46**
22/10/2020	01:17PM	Mild steel	61°	23°	565.09	26	110	21	218.96	0.30	15.52	**38.75**	**7.08**
20/12/2020	10:30 AM	Stainless steel	66°	22°	537.38	27	112	22	211.96	0.30	16.58	**39.44**	**7.82**
20/12/2020	11:30 AM	Stainless steel	58°	18°	574.20	25	104	19	227.60	0.30	17.5	**39.6**	**7.68**
20/12/2020	12:15 PM	Stainless steel	56°	8°	630.04	26	108	20	224.43	0.37	20.69	**35.5**	**9.21**
20/12/2020	01:30 PM	Stainless steel	60°	23°	668.92	26	110	23	199.92	0.33	18.17	**29.88**	**9.08**

Note: Ti = Initial temperature of plate T_f = final temperature of plate achieved dT/dt = slope of curve of temperature variation plate when placed at end of mirror tube ϒ = solar azimuth angle β = tilt angle I_c = radiation incident on collector surface $\eta_{transfer}$ = Efficiency of transfer radiations through mirror tube I_{in} = Radiation energy incident on mirror tube or radiation energy at focus of concentrator I_t = Energy transmitted by mirror tube

4.2 Water boiling test

Arrangements to hold vessel were attached to mirror tube. Experiments were conducted on the laboratory model of indoor solar cooker with load of 250ml water on 22 December 2020 and 5 January 2021. Following parameters were analyzed from these experiments

4.2.1 Calculation of instantaneous energy, exergy output

Energy analysis based on the first law of thermodynamics, i.e., net heat supplied converted in order to work. Energy analysis thus ignores reductions of energy potential. Its analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Thus, energy analysis is suitable for the sizing and analyzing of the systems using only one form of energy [9].

Fig-13: Experimental setup for water boiling tests

Instantaneous Energy output = M×C (Twf-Twi)/dt

The term exergy is defined as the maximum amount of work that can be obtained from a system. The rational efficiency based on the concept of exergy is a true measure of the performance of a thermal system. The thermal exergy content of water at temperature Ti can be calculated by

Instantaneous Exergy output = M×C× [(Twi-Twf)-Ta ln(Twf/Twi)]/dt

Where,

M = mass of water (kg)

C = heat capacity of water (4.168 kJ kg^{-1} K^{-1})

Twf = final water temperature (K)

Twi = initial water temperature (K)

dt = time interval (sec)

Ta = ambient temperature (K)

4.2.2 Calculation of overall cooking power and overall thermal efficiency

Overall thermal efficiency of the cooker were calculated using following formula [10].

Overall thermal efficiency = $M_f \times C_f \times \Delta T / (I_{av}\ A\ \Delta t)$

Where,

M_f = mass of cooking fluid (kg)

C_f = specific heat capacity of cooking fluid water (4.168 kJ kg^{-1} K^{-1})

ΔT = difference between the maximum and ambient air temperature

Δt = time required to reach maximum temperature (sec)

A= aperture area of concentrator

I_{av} = average solar intensity (W/m²) during the time interval

Cooking power was calculated using equation [11] as follows

Cooking power = $M_w \times C_w\ (Tw_2 - Tw_1)/t$

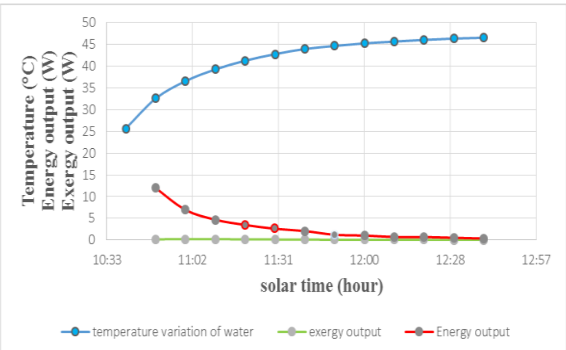

Fig-14 : Temperature variation of water, exergy output and energy output with solar time measured on 23rd december 2020

Where,

M_w = mass of water (kg)

C_w = water heat capacity (4.168 kJ/kg K)

Tw_2 = final water temperature

Tw_1= initial water temperature

t= time (sec)

Table 4: Results of parameters obtained from water boiling tests

Sl No	Parameter	23/12/2020	5/1/2021
1	Maximum temperature of water in vessel	46.6°C	48.1°C
2	Maximum Energy output of cooker	11.98 W	10.59 W
3	Maximum Exergy output of cooker	0.2166 W	0.123 W
4	Overall cooking power	3.024 W	2.55 W
5	Overall thermal efficiency	0.7048%	0.5863%

5. CONCLUSIONS

A laboratory model for indoor solar cooker was successfully developed. The model has two separate parts cooking vessel and collector. The cooking section was placed 1m far from focus of concentrator, mirror tube conveys concentrated radiations to cooking vessel. This arrangement can help to cook indoors or shaded area like the conventional cooking style. Experiments to check the efficiency of mirror tube to transfer the radiations were conducted. Maximum energy output through the mirror tube achieved was 20.8W. The overall efficiency of energy transfer achieved was 8.6 %. Average efficiency of the collector to focus the radiations on opening of mirror tube was found to be 39.09%. Through water boiling tests the maximum energy output of the model was found to be 11.98 W. Average overall cooking power of the model developed was found to be 2.787 W and overall thermal efficiency of the cooker was found to be 0.6455%. The most of the energy was lost when radiation travels through the mirror tube as it was absorbed by mirror tube, the energy of the radiation was absorbed by the mirrors

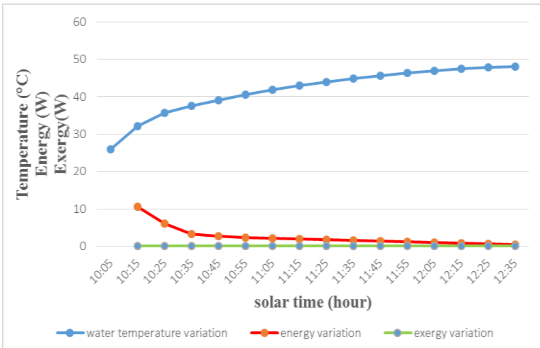

Fig-15: Temperature variation of water, exergy output and energy output with solar time measured on 5th January 2021 when they undergo multiple reflections. The determined values of energy, exergy and efficiency of indoor solar cooker were very low compared to outdoor solar cookers. Material of mirror tube, arrangements to hold vessel, variation of transmitted energy with length of mirror tube provide further areas of research.

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