ISSN:2321-1156
International Journal of Innovative Research in Technology & Science(IJIRTS)

Evaluation of Thermal Performance of Paraboloid Concentrator Solar Cooker

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Abstract

Cooking is the prime requirement of people all over the world. Solar Energy is contributing major energy requirements of the world population. Paraboloid Concentrator is used to utilize the solar energy for heating purposes. The Experimental investigations were carried out to determine performance of solar paraboloid cooker during summer season in Hubli (15° 20' N, 75° 12' E). A paraboloid collector having aperture diameter 1.4m, depth 0.4m, focal length 0.30m was fabricated. First the paraboloid solar cooker was tested under no load condition, and then cooker filled with different volume of water viz. half, one and two liters along with the suitable quantity of rice. The solar radiation and temperatures of reflector, pot, ambient were recorded. Performance parameters of paraboloid concentrator cooker as Suggested by ASAE namely Optical efficiency factor (F'η0) and Heat loss factor (F'UL) were obtained. The cooking power, standard cooking powers are also calculated. Pressure cooker of 3 liters is used for the experiment. The solar cooker was found to be useful in cooking a variety of foods.

Keywords— Solar Cooker, Heat loss factor, Optical efficiency factor

Introduction

Solar energy is one of the most promising renewable energy resources which is available in most of the developing countries including India. Cooking in a rural area mainly depends upon conventional energy sources such as cow dung, straw, wood, coal and hence, solar cooking can play an important role in rural areas in cooking. Solar cookers are the most promising devices since firewood used for coking causes deforestation while commercial fuels such as LPG and electricity are not available besides cooking accounts for a major share of energy consumption in developing countries. As the authors know 70% population of India lives in rural areas and there are about 300 sunny days a year in India [2]. Solar thermal is being developed and disseminated in many countries around the world. The Ministry of New and Renewable Energy (MNRE), Govt. of India has been pursuing a comprehensive program in the country on the development and dissemination of renewable energy technologies. Solar cooking saves not only fossil fuels but also keeps the environment free from pollution without hampering the nutritional value of the food. PSC are low cost options for meeting the cooking energy needs as well as environmental protection. The PSC is an emerging device which has a great potential in India. However, PSC technology will have to compete with prevalent cooking devices in the country. Even though over 5, 00,000 SBCs have been sold so far, the large potential of solar cookers is yet untapped [3]. The parabolic solar cooker rests on the principle of the concentration of the rays. It is well known that the parallel beam of ray of the sun is reflected on the parabolic mirror and the rays converge in the same point, the hearth of the parabola. While running up against a dark container placed in this point, the rays are released their energy in the form of heat. Determination of the exact receiver size and the arrangement to provide insulation at the receiver are of prime importance to avoid thermal losses. One or more transparent covers are employed to reduce the convective and radiative heat losses from the absorber to the environment. Heat losses from a paraboloidal concentrator solar cooker depend on the pot water temperature, the surface area of the cooking pot, the wind speed, and the orientation of the reflectors. The heat losses are classified as Optical losses and thermal losses. Optical losses are those which occur in the path of the incident solar radiation before it is absorbed at the surface of the absorber, while thermal losses are due to convection and reradiation from the absorber [4]. The thermal and optical performance of the paraboloidal concentrator was evaluated by carrying out thermal tests by heating and cooling a known amount of water.

The Solar paraboloid cooker

The first solar parabolic cooker was developed by Ghai. The solar paraboloid cooker (SPC) is a preliminary construction for the experiment. The pot is painted black with dull black paint and water temperature is measured using Copper-constantan thermocouples. These thermocouples having low cost, acceptable accuracy and rapid response

The coordinates of parabola were obtained by the software called PARABOLA CALCULATOR which is easily available on the internet. The initial specification for the design of Paraboloid Solar Collector is obtained by considering parabolic equation

$$X^2=4fY \quad (1)$$

Where Y is Distance along vertical axis, f is the Focal length; X is Distance along horizontal axis.

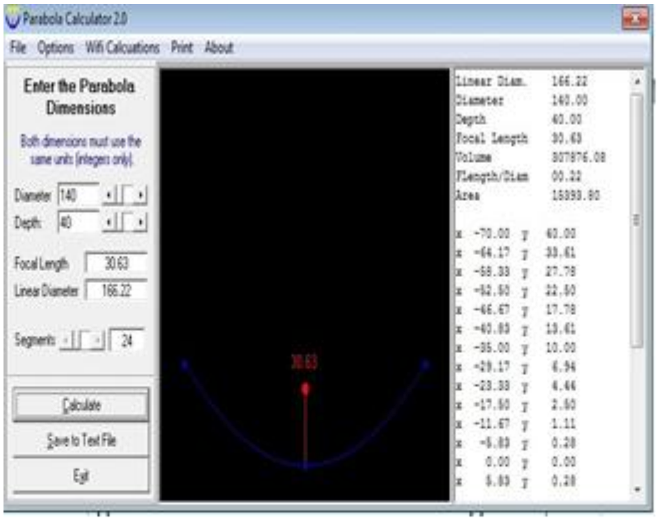

Figure 1. Parabola dimensions from Parabola Calculator 2.0 software

We get a parabolic shape at different values of x and y. The initial design of the prototype paraboloid solar collector by the use software is shown below and the values of different parameters obtained are shown in Table 1

Table 1. Co-ordinates of designed paraboloidal concentrator from parabola calculator

X(cm)	-70	-64.1	-58.3	-52.2	-46.6	-40.8	-35
Y(cm)	40	33.1	27.7	22.5	17.7	13.6	10
X(cm)	-29.1	-23.3	-17.5	-11.6	-5.83	0	-
Y(cm)	6.9	4.4	2.5	1.1	0.2	0	-
X(cm)	5.8	11.6	17.5	23.3	29.1	35	40.8
Y(cm)	0.28	1.11	2.5	4.44	6.9	10	13.6
X(cm)	46.6	52.5	58.3	64.1	70	5.8	-
Y(cm)	17.7	22.5	27.7	33.6	40.00	0.28	-

The parabola was also designed in Catia software as shown in figure (2). The cooker is designed as per dimensions mentioned in Table 2

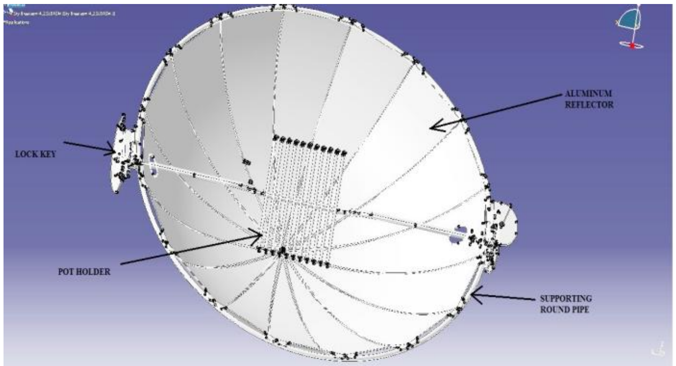

Figure 2. CAD model of Solar Paraboloid Cooker

Table 2. Main Specifications of the Paraboloid Solar Cooker and Cooking Vessel

Description	Specification
Parabolic Solar Cooker	
Aperture Diameter, Da (m)	1.4
Aperture area, A_{ap} (m^2)	1.54
Reflector material	Aluminum film (anodized)
Number of reflector sheets	24
Focal length (m)	0.30
Concentration ratio	49
Receiver diameter (m)	0.219
Receiver area (m^2)	0.037
Capacity (Watts)	600
Cooking Vessel	
Material	Aluminum (darkened surface)
Shape	Cylindrical
Capacity (Liters)	3
Inner diameter	0.236
Outer diameter (m)	0.240
Thickness (m)	0.003
Depth (m)	0.25
Mass (kg)	1.2

Modeling

We used these equations

The focal length of Parabola

$$f = \frac{h^2}{4 \times R} \quad (2)$$

The parabola surface Area

$$As = \frac{8 \times \pi \times f^2}{3}\left[\left(\left(\frac{d}{4 \times f}\right)^2 + 1\right)^{\frac{3}{2}} - 1\right] \quad (3)$$

The Concentration Ratio

$$C_R = \frac{A_{ap}}{A_{ab}} \quad (4)$$

Cooking power

$$P = \frac{Mw \times Cw \times dTw}{dt} \quad (5)$$

Standard cooking power

$$Ps = \frac{700 \times Mw \times Cpw \times \Delta T}{t \times I_b} \quad (6)$$

Thermal efficiency

$$\eta_t = \eta_0 - U_L \times \frac{A_p \times (T_w - T_a)}{A_a \times I_b} \quad (7)$$

Heat loss factor

$$F'U_L = \frac{\left(M_{POT} \times C_{POT} + M_W \times C_W\right)}{A_{POT} \times \tau_0} \quad (8)$$

Optical Efficiency Factor

$$F'\eta_0 = \frac{\frac{F'UL \times A_{pot}}{A_p}\left[\left(\frac{T_{wf} - T_a}{I_b}\right) - \left(\frac{T_{wi} - T_a}{I_b}\right) \times e^{-\frac{\tau}{\tau 0}}\right]}{1 - e^{-\frac{\tau}{\tau 0}}} \quad (9)$$

Experimental Setup

Set up consists of 1.4 m diameter Concentrator and black coated absorber in the form of cooker as shown in figure 3.. The value of the diameter is selected such that heat input available at focal area in the range of 600 watts [2]. The focal area is a white bright spot measured and found to be almost 0.2.m diameter and hence pressure cooker of 0.2m diameter, 0.25m is selected. An anodized aluminum reflector with reflectivity of 82% is fitted over to get the shape of parabola.

The paraboloid cooker should be placed facing east direction in the morning and the reflector should be tilted according to Sun angles. Lock key is provided to lock the position of reflector. The cooker will reach maximum temperature if tracking is done correctly.

Figure. 3 Experimental Setup of SPC

Performance Evaluation of Paraboloid Cooker

The performance of paraboloid cooker was evaluated by carrying out the tests suggested by Mullick Traditional methods of characterizing the performance of solar cooker are based on energy analysis[21] based on first law of thermodynamics and it provides information about quantity of energy without investigating quality of energy. Exergy analysis is based on second law of thermodynamics which not only considers the irreversibility in the system but also it is directly related to quality of available energy. Exergy is defined as the maximum work which can be produced by system.

No –Load testing

To evaluate the thermal performance of the solar cooker, a no-load test was conducted. The pot without load was kept at the focus. The temperature at various points of the pot was measured by thermocouples attached at different locations on the inner surface of the pot. Four thermocouples each were fixed at the pot bottom center, bottom side, side wall, and cover. The paraboloid was adjusted, and the bright spot was positioned at one edge of the bottom of the pot. The concentrator was lifted in this position until the “bright spot” moved across the bottom of the pot, almost to the diametrically opposite edge. The record of the temperatures at the various points obtained by a multichannel data logger at 10-minute intervals was carefully analyzed

Water Heating and Cooling Tests

The water heating and cooling tests were performed to determine the optical efficiency factor and overall heat loss factor respectively. The water heating and cooling tests were performed on a paraboloidal concentrating cooker with aperture area 1.4 m2. The pot was made of aluminum and had an outer surface area of 0.212 m2. The aperture to pot surface area ratio, C, was 49. The thermal capacity of the pot was 920 J/kg °C. During experimentation, 0.5 and l of water was heated from normal temperature to 95.1°C. The concentrator was adjusted initially so that the bright spot was positioned on the bottom of the pot near the edge.

When the water temperature reached 95–97°C, the concentrator was shaded by a large umbrella. The water temperature, ambient temperature, was recorded during the test. And solar insolation was calculated.

Cooling Curve Analysis

The test was conducted with 0.5kg of water using concentrator. The observations are tabulated as shown in table 3.

Table 3. Readings taken for 0.5kg of water

time(sec)	Tw (˚C)	Ta(˚C)	ln(Tw-Ta)	$I_b(W/m^2)$
9:00	38.7	38.7	0.00	650.56
9:05	48.8	37.3	2.44	653.98
9:10	57	38.1	2.94	657.35
9:15	66.6	38.2	3.35	660.67
9:20	72.8	38.2	3.54	663.95
9:25	81.5	39.1	3.75	667.18
9:30	89	39.3	3.91	670.37
9:35	92.1	39.4	3.96	673.50
9:40	95.1	39.4	4.02	676.59

Results and Discussions

The heating and cooling curves were plotted against time as shown below

From the cooling curve slope is calculated. The slope of the line drawn between ln (Tw-Ta) vs time gives the value of (-1/τ0). Where τ0 is time constant for cooling and τ is time interval and it is used to calculate optical efficiency factor. Slope m is calculated and τ0=1/m.

Table 4. Performance of Paraboloid cooker

Time(sec)	τ_0	$F'\eta_0$	I_b (w/m^2)	η_t
9:00-9:10	68.72	0.483	657.35	0.347
9:10-9-20	68.72	0.480	663.95	0.337
9:20-9:30	68.72	0.536	670.37	0.327
9:30-9:40	68.72	0.322	676.59	0.324

Table 5. Performance of paraboloid cooker

Time	P(W)	Ps(W)	η	Ψ (10^{-3})
9:00-9:10	63.85	67.99	6.39	1.95
9:10-9-20	55.12	58.12	5.46	4.54
9:20-9:30	56.52	59.02	5.54	7.04
9:30-9:40	21.28	22.02	2.06	3.18

Table 6. Performance of paraboloid cooker for cooking various food items

S. No	Cooking material	Quantity of material Kg+water	Solar Radia-tion	Cooking time, min
1	Rice	0.5+1	698.50	45
2	Green gram	0.25+0.5	670.70	40
3	Dal	0.25+0.5	705.23	55
4	Potato	0.25+0.5	711.40	50

Optical Effciency Factor

The optical efficiencies F'η0 were determined after analyzing the sensible heating curves shown in Figs. 4 the values were determined using the equation (9).the overall optical efficiency factors were calculated and shown in table 4

. The values were found to be nearly same. Thus, the solar insolation affects the values of the optical efficiency factor very little. The major factors influencing these values are the reflectance of the reflector and the absorptance of the cooking pot,

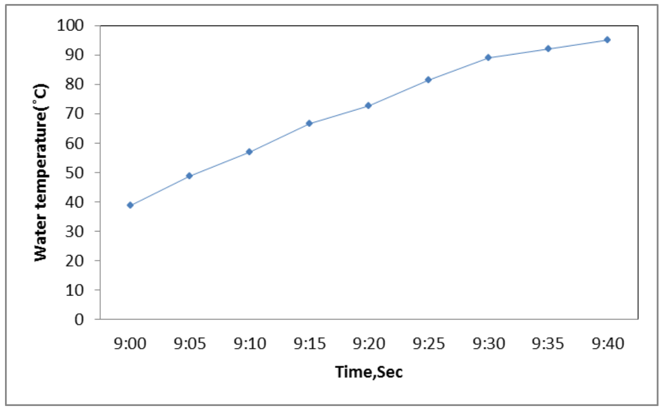

Figure 4 heating curve

Determination of Overall Heat Loss Factor

The overall heat loss factors F'UL were determined from the cooling curve as shown in figure 5. The determination of the overall heat loss factor F'UL requires the value of the cooling time constant τ0 which can be obtained by calculating slope of cooling curve. The observed value is 68.72. By using the equation (8).

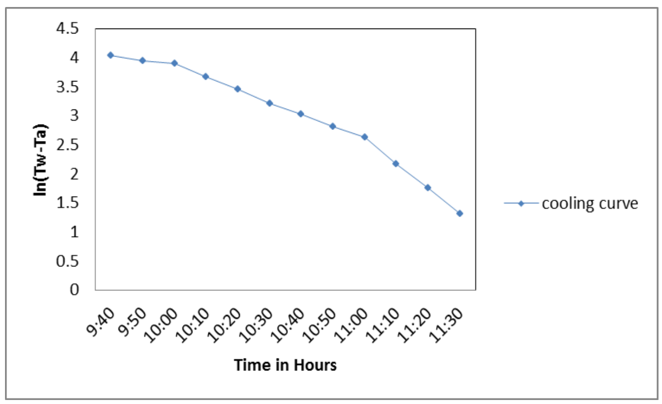

Figure 5 Cooling Curve

The maximum pot temperatures during the tests on the day were found to be 139.45'C for pot surface and 39.5'C ambient temperature, water temperature reached 95.1'C as shown in figure 6. The temperature increases as solar insolation increases. This high temperature can be utilized cooking, heating, and steaming.

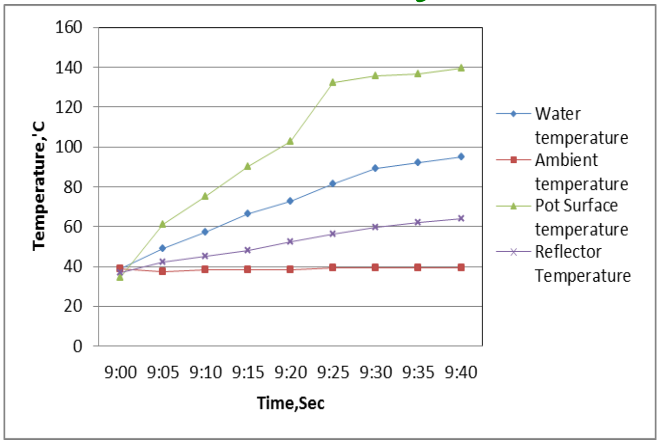

Figure 6.Variation of temperature with time

The maximum Solar beam radiation obtained during the test was 676.59 which depend on local solar time as shown in figure 7.

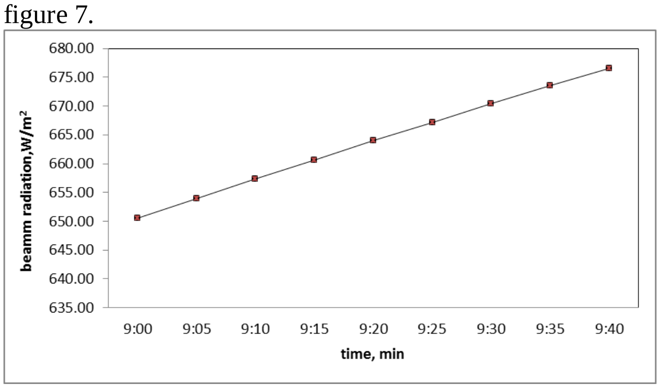

Figure 7. Variation of Solar insolation with time

.The thermal efficiencies were found to be 34, 33, and 32 percent for average solar radiations of 657.3, 663.5, and 670 W/m^2, respectively as shown in figure 8.

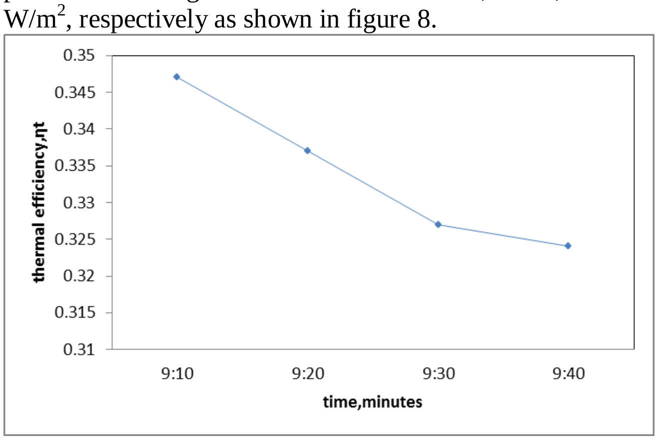

Figure 8. Variation of thermal efficiency with time

The determination of the thermal efficiency is another criterion for comparing the performance of the paraboloidal concentrator as a solar cooker under different climatic conditions.

The cooking power was initially high and then decreases gradually along time. The maximum cooking power 63.85, 55.12, 56.52, 21.28 for solar radiation of 657.35, 663.95, 670.37, and 676.59 respectively as shown in figure 9.

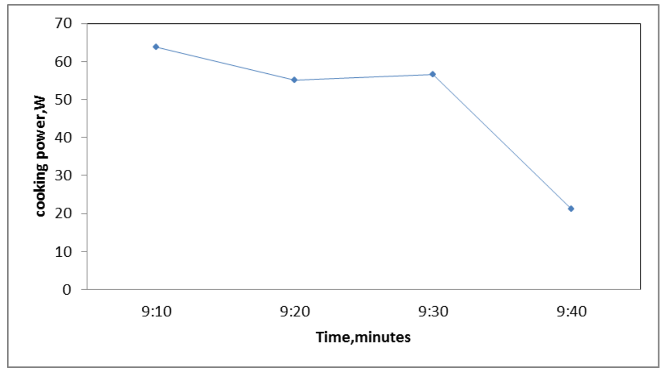

Figure 9. Variation of Cooking power with time

The Energy Efficiency was high during initial time and decreases as the solar radiation increases as it is inversely proportional to radiation. The energy efficiencies obtained are 6.39, 5.46, 5.54 and 2.06 percent for average solar insolation 657.35, 663.95 670.37 and 676.59 respectively as shown in figure 10.

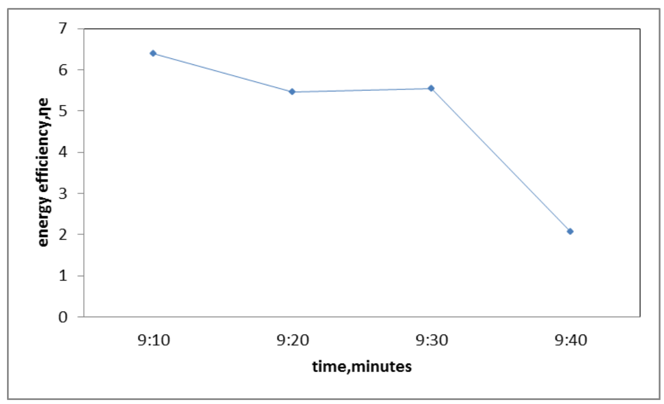

Figure 10.. Variation of Energy Efficiency with time

The exergy efficiency and solar radiation have different trend with time which are low initially then increases sharply takes peak and then decreases. The maximum exergy efficiency 1.95, 4.54,7.04, 3.18 as shown in figure 11.

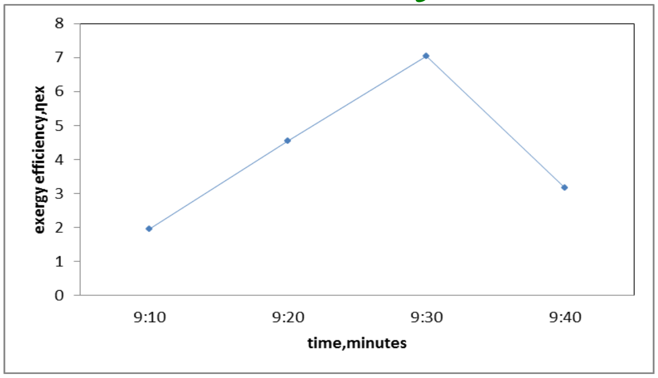

Figure 11. Variation of Exergy Efficiency with time

Future potential of solar cookers

Average cost of solar cookers decreases day by day on the contrary their power output and efficiency considerably increases. In the upcoming future, widespread use of this technology is expected hopefully not only in developing countries but also throughout the world.
Renewable energy resources will play an important role in the world's future. According to the global renewable energy scenario, proportion of the solar thermal applications will be about 480 million tons oil equivalent by 2040. Nowadays, solar cookers are also available to use in the areas with limited solar radiation depending on the developments in solar power concentrating systems and material technology. In addition, the most challenging point of solar cookers, unavailable to use when sun goes away, is overcome with thermal energy storage techniques. Briefly, it is anticipated that solar cooking technology will be demanded by a huge group of people in the near future because of its outstanding features.

Conclusion

A parabolic cooker has been built and tested. The experimental results showed that the low efficiency of the parabolic cooker is attributed to the optical and thermal losses from the reflector and the pot. The exergy efficiency of the solar cooker is very because input solar radiation is rich in exergy and being utilized in the form of heat at low temperature. The exergy efficiency can be increased only marginally by increasing the reflectivity of reflectors, proper designing of cooking place and by using a suitable cooking pot. Cylindrical shaped cooking vessels made of aluminum or copper and painted black should be preferred for a higher cooking efficiency. The parabolic cooker presents encouraging results while being compared to other types of solar cooker. Solar cooking technology is a key item in order to deal with deforestation.

Recommendations

. India has so many opportunities regarding with renewable and sustainable energy such as solar, biomass, wind and so on. It is quite important and critical since the public awareness among people is at low level. Introducing the solar energy or perhaps renewable energy subject to Students The people will be more appreciating on what are they have learned and apply it in daily life Construct parabolic concentrator with larger in diameter and minimize the focal point area as small as possible, to get higher stagnation temperature, thus increase the effectiveness of the parabolic concentrator.
The enhancement on the reflector material should be made to increase reflectivity of the reflector.

Nomenclature

A_{ap}	Area of Aperture (m^2)
A_{abs}	Area of pot (m^2)
As	Surface area of parabola (m^2)
C	Concentration Ratio
C_{pw}	Specific heat of water
C_{pot}	Specific heat of Pot
f	Focal Length (m)
$F'U_L$	heat loss Factor
F'η0	optical Effciency Factor
h	Depth of Parabola(m)
Ib	Beam Radiation (W/m^2)
Mw	Mass of Water (kg)
M_{pot}	Mass of Pot (kg)
P	Cooking Power (W)
Ps	Standard cooking Power (W)
Ta	Ambient Temperature (˚C)
T_{wf}	Final water Temperature (˚C)
T_{wi}	Initial water Temperature (˚C)
UL	Overall loss Coefficient (W/m˚k)
τ_0	Cooling time Constant
η_0	Optical Effciency
η_t	Thermal Efficiency
η	Energy Efficiency
ψ	Exergy Efficiency

Acknowledgments

I want to thank my professors for their valuable guidance during testing and analysis.

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