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Comparative Evaluation of Parabolic Collector and Scheffler Reflector For Solar Cooking

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ABSTRACT

Solar energy is transforming to be the promising renewable energy resource that could be used efficiently for human basic needs like cooking. This study presents the performance analysis of solar cooking instruments based on their geometrical aspects. The main aim is to find the best solar cooking device that can efficiently absorb heat reflecting from its surface. Here we evaluated the performance of parabolic type solar reflector and Scheffler type solar reflector in terms of its thermal efficiency and losses. The main dependent factor for this comparative analysis is the geometry of the reflectors with a diameter of 1.5 m and the radiation of the sun. For better reflectivity in both receiver and concentrator or reflector medium, stainless steel material is used. Depending on these factors, we have evaluated performance of both the reflectors and found satisfactory results. Theoretical and simulated results over various conditions prove that the Scheffler reflector performs well compared to parabolic collector.

Keywords: Parabolic Collector, Solar insolation, Thermal Efficiency, Scheffler Reflector, Efficiency

I. INTRODUCTION

In urban areas, the cooking is concentrated on LPG or electric cooking devices [1]. Solar cookers can play a major role both in rural and in urban areas such that use of conventional resources and commercial fuels can be reduced to a certain extent. This could help in improving the economy of the individual as well as the nation. India is surrounded by 70% of the families living in rural areas with 300 sunny days. So utilizing the solar power could be regarded as a best option that could serve in power consumption aspects in India [2]. To safeguard the environment from pollution and without reducing the nutritional value of food, solar cooking is used. Additionally, solar cooking can reduce the consumption or extinction of fossil fuels [3]. Electricity through alternative resources is an alluring thing that could incorporate techniques for concentrating solar energy that includes solar parabolic collector and scheffler reflector [4]. This solar power is concentrated to a particular focal point and that should sufficiently generate power without much wastage. The main drawbacks to get energy from solar radiations are its installation cost, maintenance and operation cost, and reduced efficiency of solar energy conversion rate [5]. Proper placement of cooking devices at the focal point could increase the efficiency, since the solar energy is used efficiently. The preliminary strategy that can use efficiently the solar energy is the geometry of both these instruments with a proper focal point. To make this technology best use for cooking purpose, certain changes needs to be done by setting up an azimuth axis for tracking the solar power. Devising reflector surface with least imperfection that could help in attaining better efficiency with best tracking as well [6]. Most of the study concentrates on a single solar reflector type, out of which José Ruelas et al. [7] developed a new mathematical model that estimates the scheffler reflector based on optical and geometric behaviour. Solar parabolic collector was analyzed by Harris and Lenz [8] for finding out its thermal behaviour based upon its geometry and amount of radiation that reaches the reflector. Other researches that concentrated on geometrical shapes includes Shuai et al. [9] and Badescu [10] determined the thermal irradiance on parabolic solar reflector depending on various geometries. Optimal size for determining the aperture area of parabolic spherical cavity is done through software implementation by Kumar and Reddy [11]. Chin-Hsiang and Hang-Suin [12] studied optimal parameters related to geometry of the parabolic dish for modelling efficiently the thermal parameters. Solar power transmitted from transmitter to receiver is studied theoretically using Duffie and Beckman [13]. Optical and thermal conversion factor for optimizing the solar parabolic collector geometry is studied using Jaffe [14] and Badescu [15]. From the above researches, it is found that to improve efficiency geometry of the dish is concentrated and several theoretical analyses are made to improve the efficiency of the solar instrument.

The literature that concentrated on scheffler reflectors are determined here and the performance of solar parabolic trough collector was improved by Qibin et al. [16] using a solar ray trace method. Fresnel concentrator with ray tracing was studied by Lara et al. [17]. Linear Fresnel solar reflector was studied by Ya-Ling et al. [18] for analyzing the optical and thermal performance through heat transfer fluid. Sunlight is concentrated using a immobile mirror and receiver that was studied by Rogers et al. [19] for analyzing the ray tracing performance of the system. [20-22] studied the receiver design using a parabolic dish though ray tracing software, which is simulated to analyze the efficiency of the system. An experiment is conducted with three parabolic collectors with various aperture entrances was tested and simulated [23] and finally scheffler reflector was designed by Munir et al. [24] for low temperature applications. Soon after reviewing all the literature, it is found that none of the studies concentrated particularly on cooking system. These studies duly concentrated on performance by changing its geometry. Using this, we can compare the geometrical parameters of parabolic scheffler and reflector to find its computational efficiency. In this study a comparative analysis of thermal efficiency and radiation losses is studied by comparing both the solar cooking reflectors. Here the geometry and the parameters required for simulation is kept constant and finally the results were compared for finding out the best cooking solar instrument.

This paper focuses on comparing the performance of both solar parabolic and scheffler reflector in terms of efficiency and loss. Cooking is a major phenomenon, so this paper concentrates on the instrument with best thermal efficiency. The device with best performance is suited for cooking purpose such that it could use the maximum resources available from the sun. Here, the geometry along with radiation of sun is regarded as a major factor that suitably tracked could help in attaining better thermal efficiency and least losses. Since the entire research is based on comparative analysis, performance is compared in terms of various parameters to find the best suited device for cooking in rural areas of India.

II. MATERIALS AND METHOD

This section deals mainly with the geometry of solar cooking instrument namely parabolic collectors and scheffler reflector. This gives the primary outline of the efficient cooking instrument through the major geometrical factor with fixed measurement for both the instruments. Initially the geometry of solar parabolic collector with misalignments is discussed and that is followed by its competitor.

2.1 Solar parabolic collector

The parabolic collector considered for analysis consists of a concentrator with an opening diameter of 1.5 m in a parabolic shape. A reflecting layer is placed over the interior surface and the sun rays falling on the reflecting layer, gets reflected on a receiver plate. The reflection over the plate is placed accurately using the focal point made at the concentrator. The reflective material that is used to cover the parabola is taken as steel. The reflective co-efficient of which is taken as 0.85. This concentrator could be defined as a directional medium that provides a best follow up for the sun rays based on axis, z.

2.1.1 Geometry of Parabolic Collector

The geometry of collector is assumed to have parabolic shape for better reflectivity, which is defined as:

$$z = {x^2}/{4F} \qquad (1)$$

The parabolic surface with an opening diameter, D along with focal distance is given by:

$$S = \frac{8}{3}\pi F^2\left[\left(1+\left(\frac{D}{4F}\right)^2\right)^{1.5} - 1\right] \qquad (2)$$

Where the focal distance as a depth of dish, H could be give as:

$$F = {x^2}/{16H} \qquad (3)$$

2.1.2 Receiver of Parabola Collector

The receiver that collects the sun rays directed from concentrator is taken to be stainless steel material with a diameter of 0.12 m and thickness with 0.02 m. A very thin coating of Bakelite material is poured over the receiver medium for reducing the solar ray reflection, which is placed at the parabola's focal point. Thus the absorber or the receiver with an absorption coefficient of 0.9 can be modelled geometrically using parabola's surface opening S_0.

$$F = {S_0}/{S_a} \quad (4)$$

Where S_a is the absorption area or the receiver area and S_0 can be given as:

$$S_0 = \frac{\pi D^2}{4} \quad (5)$$

Considering, sun as a source at an infinite distance and these rays are assumed to parallel to z-axis. So the rays' incident on the collector can be determined using slope of the concentrator as shown in fig. 1.

$$\tan\theta = \frac{R}{4F}\ ;\ \theta = \tan^{-1}\left(\frac{R}{4F}\right) \quad (6)$$

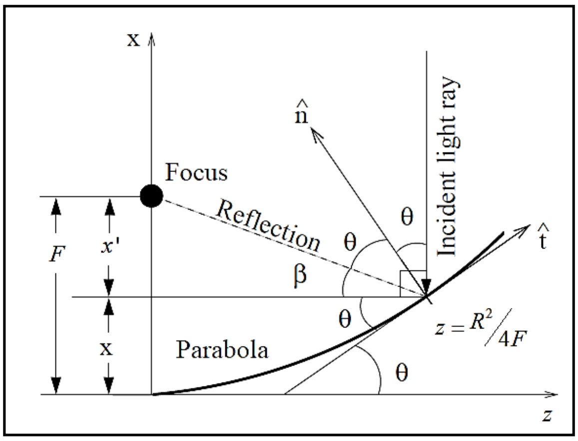

Fig.1. Geometry of Parabolic Solar Collector reflected at focal point

2.1.3 Misalignment in Parabolic Geometry

An arbitrary value normal to R bisects reflection emitted from incident ray. This could be treated as perpendicular to z-axis and the definition for x axis is defined as:

$$x' = F' - x = z\tan\beta \rightarrow F' = z\tan\beta + x \quad (7)$$

F' is treated as a co-ordinate of x axis where the incident ray is mathematically given as $\beta = -\left[\frac{\pi - 4\theta}{4}\right]$. Thus, along with misalignment (fig. 2) in the geometry with respect to equ 7, the x' can be realigned using $\psi = \theta - \phi$ and $\beta' = \beta + \phi$

$$x' = z\tan(\beta + \phi) = \frac{z}{2}\tan\left[\pi - \tan^{-1}\left(\frac{R}{F}\right) + \phi\right] \quad (8)$$

This could give well the correcting balancing solution since we consider misalignment as one of the main constituent in the geometric design of parabolic collector. Thus depending on the geometry of parabolic solar collector, an efficient cooking strategy could be achieved with this design.

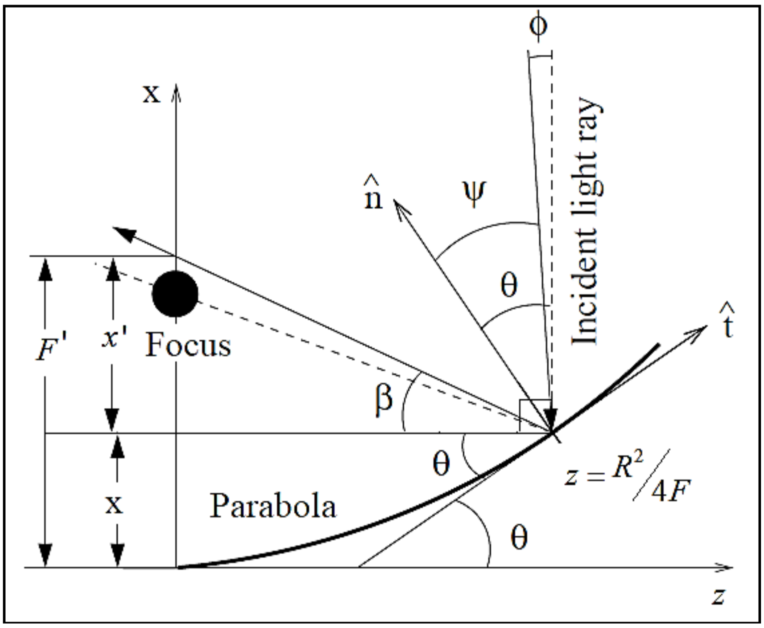

Fig.2. Geometry of Parabolic Solar Collector reflected at focal point with misalignment

2.2 Solar Scheffler Reflector

Scheffler reflector is designed to operate at high temperature because of its frequent variation in focal point and improved handling of its receiver. The main advantage is that it can shift its receiver based upon the reflection from the elliptical cavity. In order to balance the earth's rotation, reflector rotates with an angular velocity along polar axis from east to west. Thus the reflector's relative position remains stationary with respect to sun that provides fixed focal axis along the axis of rotation. Advantage of scheffler is that it can also provide seasonal tracking with same focus over rapid changing in solar declination. The following section includes the geometry of scheffler with crossbar reflector.

2.2.1 Geometry of Scheffler collector

Unlike traditional parabolic collector, the scheffler reflector is considered to be the lateral part of the parabolic surface. Using equinox with solar declination as null value, calculations for the scheffler reflector with parabolic surface is made. Lateral view of the parabola is taken as a medium of reflection for calculation purpose. This representing both the parabola and reflector as parabolic curve and a linear line that passes through x axis.

$$P(z) = mz^2 + C \qquad (9)$$

Where m is the slope of the parabola and C is is the x-intercept. By taking first derivative for the above eq. 9, we could obtain $P'(z) = 2mz$. The focal area of scheffler reflector with respect to parabolic diameter could be calculated using $z=(x^2+y^2)/4F$. Starting from parabolic curve P_a, the solar radiation reflected at positive coordinate axis at 90° is shown in fig. 3. At this parabolic point, tangent is made at 45° and value at x is half the value of z axis.

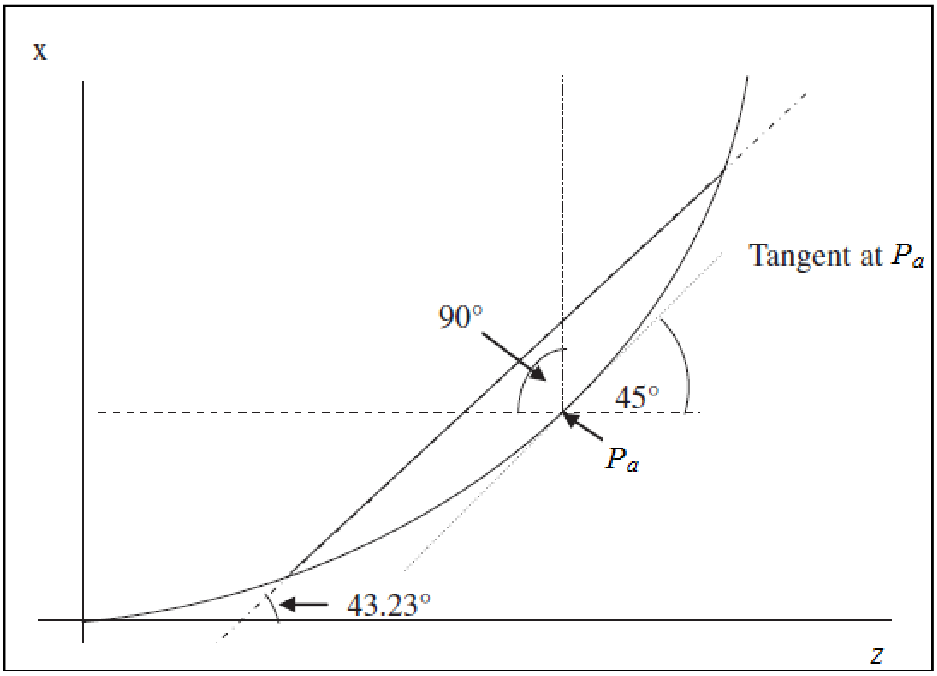

Fig.3. Parabolic Reflective Surface of Scheffler

Where $P'(z)=\tan\left(\frac{86.22+a}{2}\right)$, thus the first order derivative could be represented using $2mz=\tan\left(\frac{86.22+a}{2}\right)$ with a as solar declination. The diameter for scheffler reflector could be calculated using:

$$D=2\left[\left(m_g/2m_p\right)-\left(C_p-C_g\right)/m_p\right]^{0.5} \quad (10)$$

The intersection points for balanced placing of the reflectors are given using a quadratic equation (Eq. 11 & 12) between the parabola and linear line.

$$z_1=\frac{m_g}{2m_p}+D \quad (11)$$

$$z_2=\frac{m_g}{2m_p}-D \quad (12)$$

Where m_g and C_g are the slope and z-intercept of a straight line $G(z)=m_g z+C_g$ and m_p and C_p represents the slope and z-intercept of $G(z)=m_p z+C_p$.

2.2.2 Calculation of Crossbar

Crossbar in a scheffler reflector is required to exactly fix the scheffler reflector over it. Here to fix the scheffler relector, seven crossbar is been taken into account and the construction of the scheffler reflector with respect to crossbar is represented in the following section:

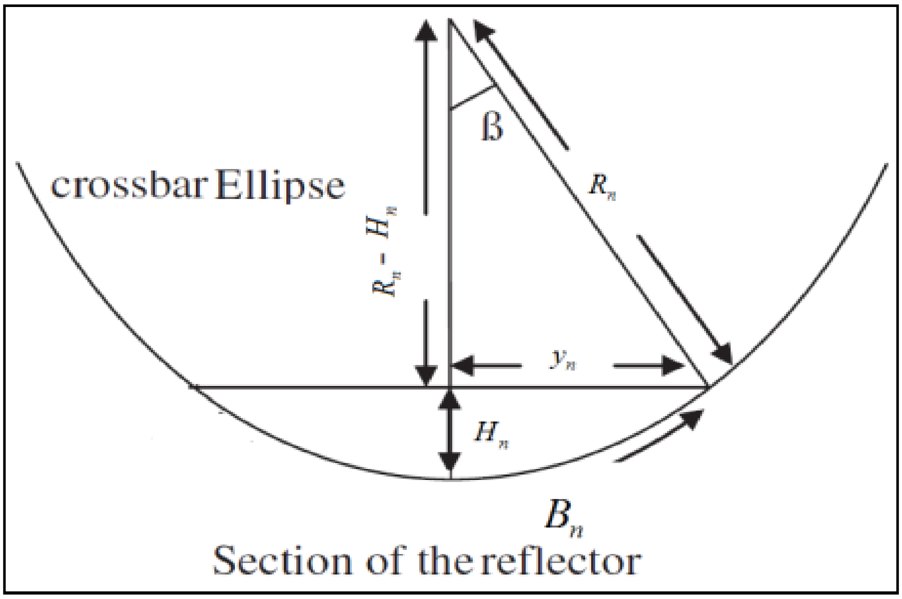

Fig.4. Section of Crossbar with the shape of Ellipse

For constructing a scheffler reflector, positioning of crossbars over reflective frame is a major task. Assume the frame is elliptical (fig. 4) and that is given by:

$$\left(\frac{x}{b}\right)^2+\left(\frac{y}{a}\right)^2=1 \qquad (13)$$

Where a and b corresponds to semi- minor and semi-major axis and x_n can be located w.r.t z_n over elliptical frame using:

$$x_n = 0.73(b^2 - z_n^2)^{0.5} \qquad (14)$$

The eq. 11 calculates the crossbar position over elliptical frame placed over a scheffler reflector. After the calculation for placing the crossbar, the depth of the scheffler reflector using n[th] crossbar can be calculated using:

$$H_n = -D/(0.938+Z) \qquad (15)$$

Where $Z=-1.066\left[(D-y_n)^{0.5}\right]$ and finally calculating the depth using basic ellipse equation as:

$$H_n = 1.066\left[(D-y_n)^{0.5}-D\right] \qquad (16)$$

Also, arc length B_n and radius R_n using depth H_n could be calculated as:

$$B_n = 2R_n\left[\pi\beta/180\right] \qquad (17)$$

$$R_n = (H_n^2 + y_n^2)/2H_n \quad (18)$$

Where $\beta = \sin^{-1}(y_n / R_n)$ and after calculating all the above parameters

2.2.3 Misalignment in Scheffler Geometry

Similar to Parabolic reflector, misalignments is one of the major criteria that could affect the performance of the scheffler. To avoid such deviations in the results, misalignments are added in the scheffler reflector. Thus β can be re-written as $\sin\beta = y_n / R_n$ and the misalignment factor could be added with this and thus calculating the value as:

$$y_n / R_n = \sin\beta' \quad (19)$$

Where $\beta' = \beta + \phi$ and next step is to implement it over standard temperature condition that could help us in finding the efficient system for cooking purpose.

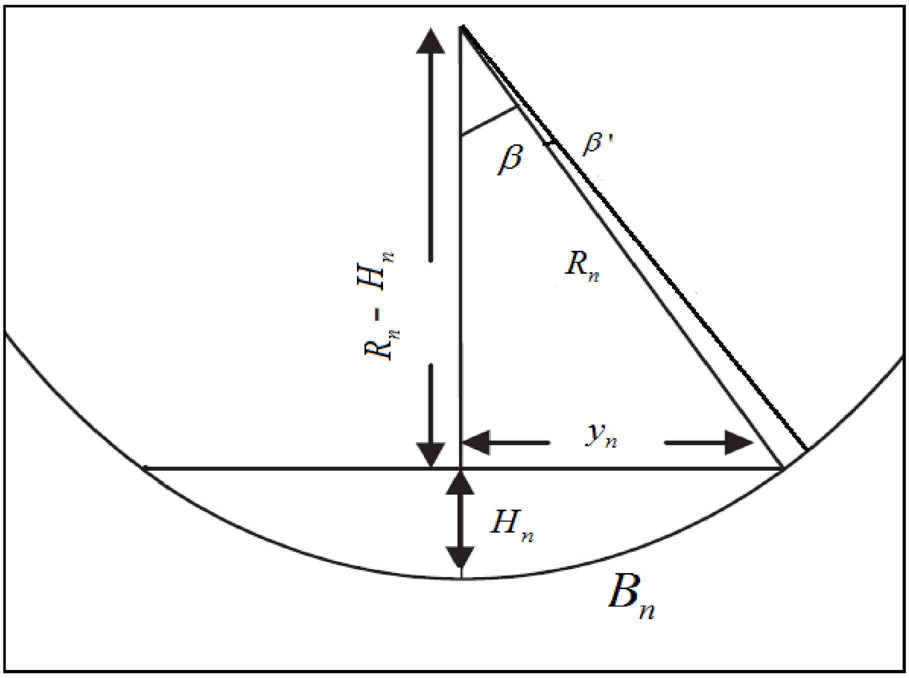

Fig.4. Section of Crossbar with the shape of Ellipse with misalignment

III. RESULTS AND DISCUSSION

Both the instruments were modeled in Simulink and tested with STP conditions. To calculate all the resultant output parameters, the equations that are defined above are used for modelling blocks in Simulink. The experimental conditions are observed in terms of values generated in a range using the equations defined above. Here parabolic collector (fig. 5) is tested without tracking and scheffler reflector (fig. 6.) is tested such that it tracks the sun. The parameters like aperture area, radiation of sun and other coefficients are maintained with same values for both the instruments.

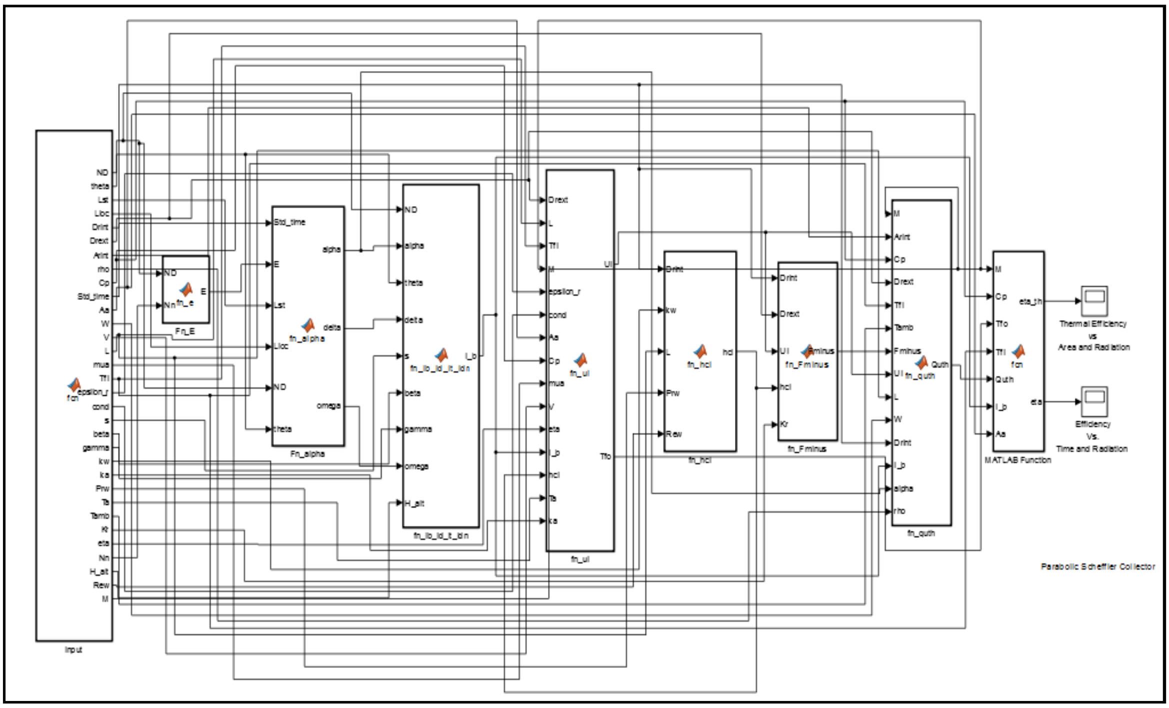

Fig.5. Simulink model for Parabolic Collector

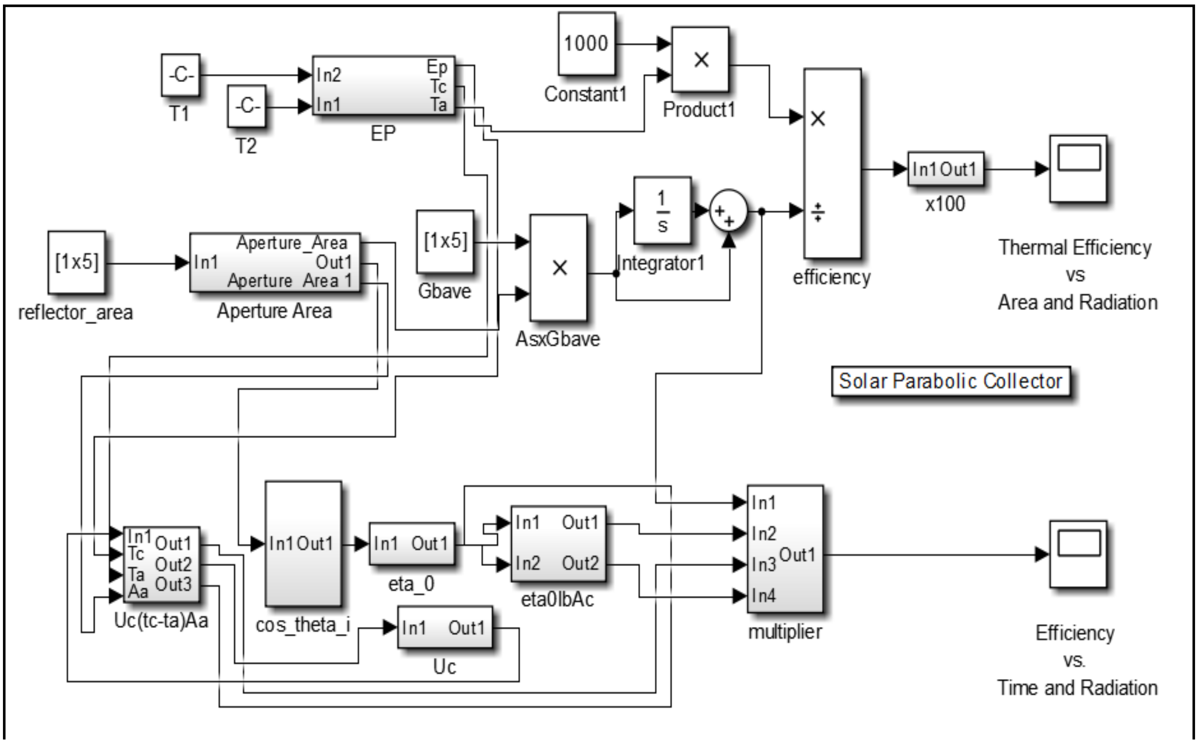

Fig.6. Simulink model for Scheffler Reflector

Stainless steel material is used as a concentrator for both the instrument with same diameter, thickness and reflection coefficient as stated in previous section. Diameter of both parabola and scheffler is taken as 2 m, depth of both parabola and scheffler is taken as 0.5 m and the focal distance as 0.75 m.

Different thermal efficiency formula is needed to calculate both parabolic collector and scheffler reflector. Thermal efficiency of solar parabolic collector is calculated in terms of the geometry and temperature of the sun:

$$E_{th\_p} = E_o - U_L \frac{A_p(T_w - T)}{I_b A_a} \times 100 \tag{20}$$

Where, T_w is the temperature of the fluid and T is the ambient temperature, A_a is aperture area, I_b is the radiation of the beam, U_L represents loss coefficient, A_p represents the area of aperture opening and E_o is the energy efficiency.

For parabolic scheffler the overall efficiency is calculated in terms of heat gain along with the area of the aperture:

$$E_{ovl\_s} = \frac{(H_g)e^3}{\int (I_b \times Aa)dt} \times 100 \tag{21}$$

Where, $H_g = \frac{m_w c_w \Delta t}{3600}$ is the heat gain, Aa is the aperture area and the E_{ovl_s} is the thermal efficiency over time period t. m_w is the total mass of the fluid, c_w is the specific heat constant of fluid at constant pressure and Δt is the difference between the temperature of the fluid. The aperture area, Aa is calculated in terms of the geometry of the reflector that is defined as follows:

$$A_a = E_a \times A \times (\cos(43.23 - a)/2) \tag{22}$$

Ea is the area efficiency, A is the area of the reflector and a is the solar declination of the sun. Thus with the above parameters, the thermal efficiency is calculated between the time interval of 9.30 am to 10.30 am and the parameters used for simulation is shown in the table below. Also the optical efficiency for both the instruments is calculated using:

$$Eopt = \frac{A_{po} F_c \left[\frac{(T_{wf} - T_a) - (T_{wi} - T_a)}{I_b} e^{-\frac{\tau}{\tau_0}} \right]}{A_p \left(1 - e^{-\frac{\tau}{\tau_0}} \right)} \tag{23}$$

Where A_{po} is the mass of the pot, T_{wf} is the final water temperature and T_{wi} is the initial water temperature, τ_0 cooling temperature constant.

Table.1. Simulation parameters for Test Conditions with steel as reflecting medium

Time *(s)*	Tw *(°C)*	T *(°C)*	H_g	U_L
9.05	39	37	0	4.21
9.10	49	37	250	4.23
9.15	57	38	460	4.27
9.20	67	38	540	4.31
9.25	73	39	880	4.35
9.30	82	39	1000	4.40
9.35	90	39	1210	4.44
9.40	92	40	1250	4.46
9.45	95	40	1340	4.47
9.50	96	40	1354	4.49
9.55	97	41	1359	4.51
10.00	99	41	1364	4.52

From the above analysis, we could able to find that as the radiation increases the temperature of the concentrator of the reflector increases proportionally. The major drawback is that due to misalignment in the reflector or collector geometry, the heat or the radiation is not properly concentrated at the receiver medium. This further reduces the heat gain parameters thus reducing the efficiency of the cooking instruments. Since in our research, the geometry is maintained well in terms of theoretical value that helps in maintaining the efficiency of both the cooking instruments. With careful consideration of parameters, it could be found that the efficiency is maintained without less loss. Thus the beam radiation of solar collector and the scheffler reflector varies in accordance with its geometry keeping the sun's radiation as constant (fig. 7.).

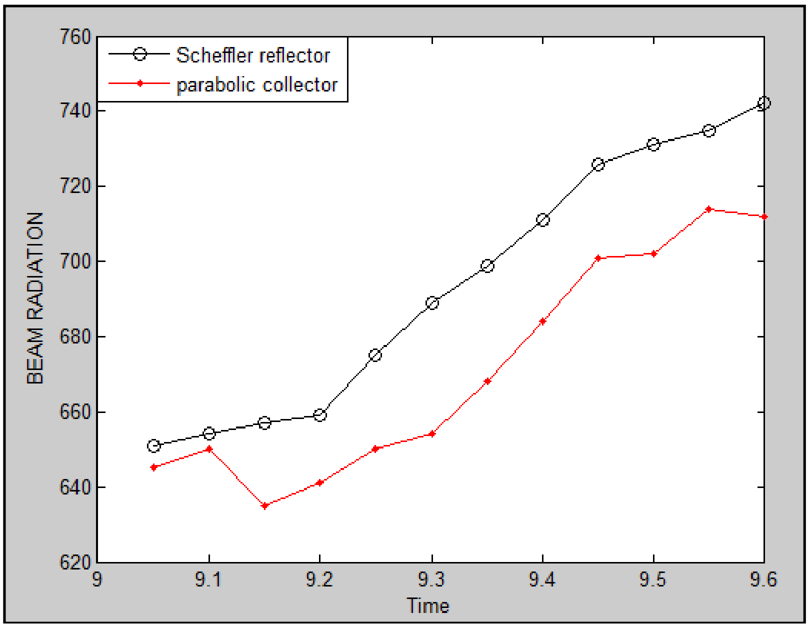

Fig.7. Beam Radiation versus time for solar parabolic collector and scheffler reflector

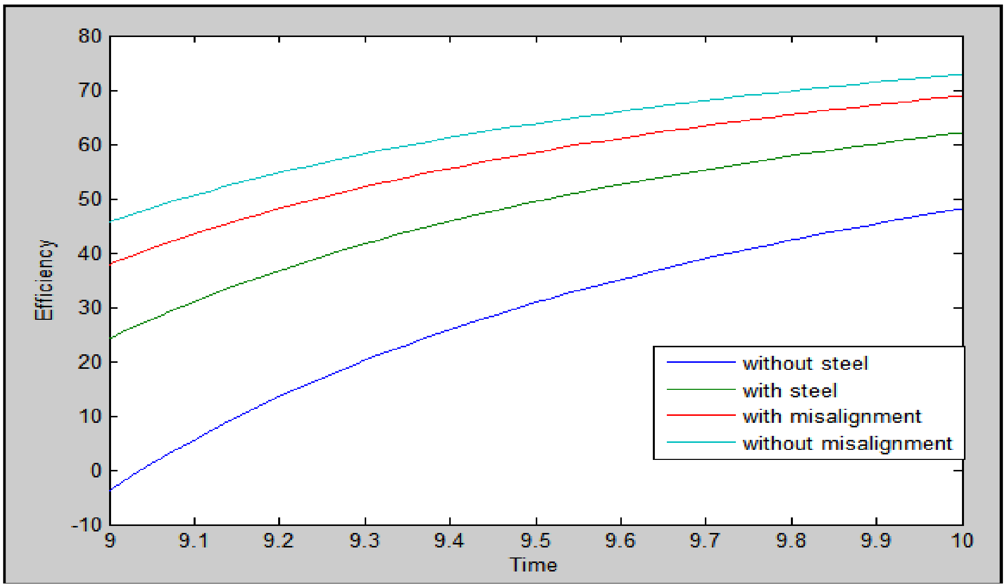

Fig.8. Calculated overall efficiency of Parabolic Collector with area and radiation as Prime Parameters

The overall efficiency of the parabolic collector is calculated in terms of its aperture area and radiation from the sun as shown in fig. 8. From the above graph it could be concluded that the efficiency of the instrument without misalignment attains better efficiency than compared with misalignment. Also, the misalignment is made over the stainless steel reflector interface and the system is tested over this condition. The collector medium or the concentrator medium without steel performs poor when compared with stainless steel parameters.

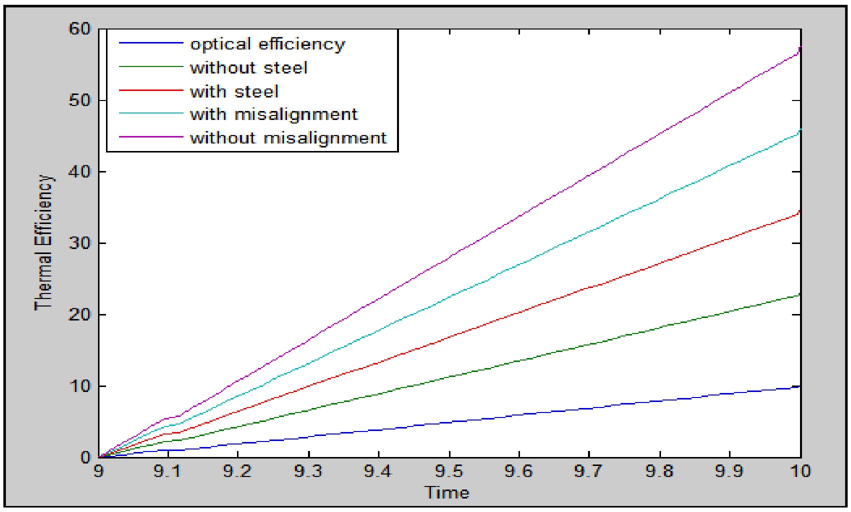

Fig.9. Calculated Thermal efficiency of Parabolic Scheffler Reflector with aperture area and radiation as prime parameters

Fig. 9 shows the calculated thermal efficiency with constant aperture area and varying solar radiation. From the above graph we could able to conclude that the instrument performs well when stainless steel is used as a reflecting medium. The system without misalignment gives better efficiency when solar radiation reflected over steel surface than with misalignment. Also steel performs well as it provides high conductivity compared to other materials as shown in graph.

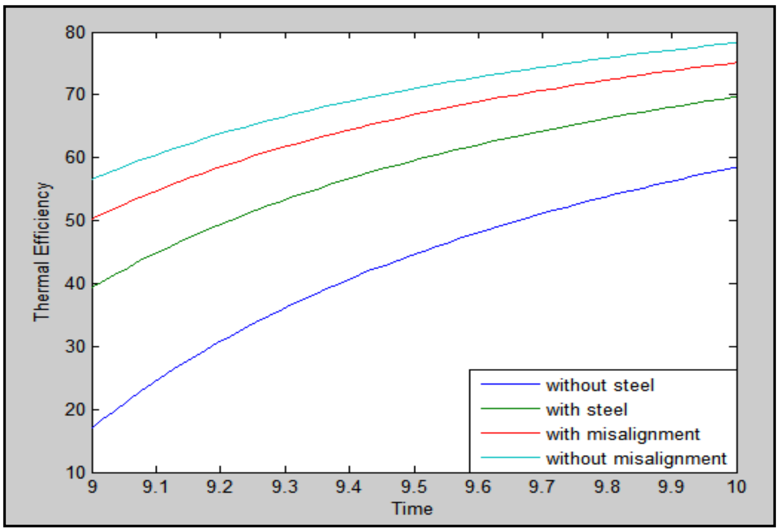

Fig.10. Calculated overall efficiency of Parabolic Scheffler Reflector with aperture area and radiation as prime parameters

From the simulated result, it could be found that scheffler reflector gives maximum efficiency when it is been applied with steel as a reflecting medium (fig. 10). Also, without misalignment the scheffler reflector performs well with maximum efficiency than with misalignment.

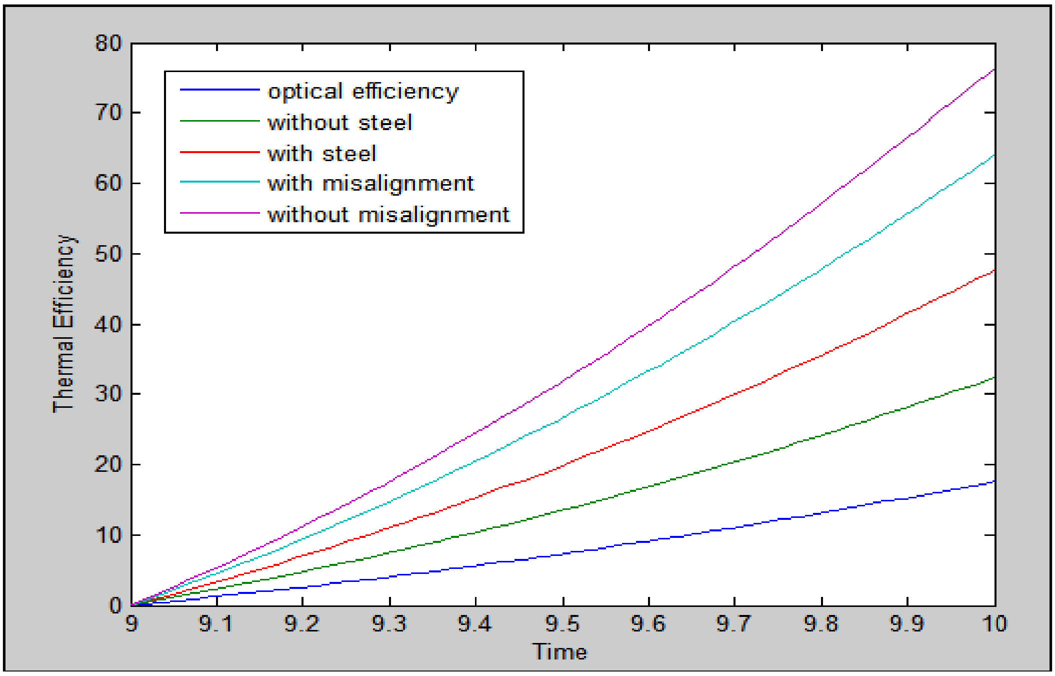

Fig.11. Calculated Thermal efficiency of Parabolic Scheffler Reflector with aperture area and radiation as prime parameters

Similar to parabolic collector, scheffler also performs the same in terms of medium and material. The thermal efficiency of the steel material without misalignment attains maximum efficiency than compared with other efficiencies (fig. 11). Optical efficiency of the scheffler is high when compared with parabolic collector and also other thermal efficiencies are found to be relatively high when compared with parabolic collector. From the above results, it could be found that scheffler reflector attains maximum efficiency when compared with parabolic reflector as radiation over the reflector increases. It is seen from the fig. 8 and 10 that the overall efficiency of the scheffler reflector is found to be 79% with steel as reflecting medium and geometry is considered without misalignment. Similarity the efficiency of parabolic collector seems to possess an efficiency of 72% at 10:00 am without considering the misalignment. When misalignment is considered as a factor, it could be found that efficiency of both the scheffler reflector and parabolic collector seems to get reduced by a factor of β'. The results from the above graph (fig. 9 and 11) for both instruments proved that with steel as a reflecting instrument, the efficiency of the devices increases. The thermal efficiency at 10:00am for scheffler reflector is found to be 48% with steel as reflector and 31% efficiency without steel. Likewise for parabolic collector, the thermal efficiency is found to be 34% with steel as collecting medium and 22% without steel. From the simulated results, it could be obtained that scheffler reflector performs well in terms of thermal efficiency and overall efficiency.

IV. CONCLUSION

This research clearly demonstrates the effectiveness of the scheffler reflector and proved its efficiency in terms of heat gain with water as absorbing medium to make it suitable for cooking heat conditions. Thus the scheffler reflector attains maximum efficiency of 79% at 10:00am compared with parabolic collector with 72%. Also, it is observed that the geometry of the device plays a major role in concentrating the heat to the reflector object. Slight misalignment in geometry reduces the obtained efficiency, since the heat is concentrated to uneven space. From the simulations, we could conclude that scheffler reflector outperforms well when compared with solar parabolic collector. This could be proved in terms of scheffler reflector's tracking ability than fixed parabolic collector. Also, we found that reflectivity of the concentrator plays a major role in improving the efficiency such that the concentrator or reflector with better heat coefficient can improve the design. Improvements could be further done by changing the geometric design of both parabolic collector and scheffler reflector with better design for improving its efficiency. Also use of other reflective material can further improve the thermal efficiency and reduced cost design could make it suitable for people to use it for daily use.

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