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Study of Energy Distribution on Absorber Tray of Cylindrical Hot-Box Solar Cooker for Global Solar Radiation

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Abstract—*This paper presents a study of energy distribution for solar hot box cooker of cylindrical shape. The rate of heat absorbed by a collector plays a significant role in deciding the performance of the collector. The absorbing surface of a solar hot box is in the form of a tray and the energy collected by the aperture area is distributed between the absorber base plate and walls. The wall height and wall inclination play a major role in determining the shading effects on the base plate which maybe further visualized as non-uniform heating of load. On the basis of the various parameters formalism has been developed to estimate theoretically the energy absorption for the developed cooker and energy distribution between base plate and walls. The paper presents the development of a formalism to study the energy distribution between the wall and base plate of a cylindrical building-material-housing solar cooker for global solar radiation. The building-material-housing solar cooker (BMHSC) is a hot box type solar cooker with housing of locally available building material. The aperture area of the structure is 0.25 sq.m. The study involves theoretical estimation of energy absorbed by the systems for global solar radiation and assessment of energy distribution between the walls and base plate of the absorber tray of the cooker. The energy absorbed by the base plate and walls of the cooker has been calculated on the basis of expressions developed for the useful base plate and wall areas. The results for the variation in useful areas and energy absorbed by the base plate and walls with solar time have been presented in the form of graphs and compared with the respective values for the commercial hot box solar cooker.*

Keywords:-*energy distribution, solar cooker, cylindrical shape, global solar radiation, useful areas*

1. INTRODUCTION

Major fraction of energy requirements in rural areas of developing countries like India is for cooking applications which is mainly met through wood, dungcakes etc. The use of solid fuel in poorly ventilated kitchens results in pollutants which place the persons exposed to them at a risk of various respiratory diseases, asthma and cancer. Solar cookers offer a promising solution for meeting the energy requirements for cooking in a clean, non-polluting manner, especially for the developing countries [1,2]. Solar cookers are of various types but the box type solar cooker being simple and convenient is specially suited for domestic and animal feed needs. There have been several developments in the design and study of box type solar cookers [3-5].

To cover a wide spectrum of users authors have developed a wide variety of user need based cooking systems ranging from light weight cardboard makes to fixed structure building material ones [6-8].

This paper presents the study of energy distribution between the base plate and walls of the absorber tray of the developed cylindrical building-material-housing solar cooker. Due to the apparent motion of sun the shades on the absorber tray keep on changing continuously and thus the useful area available to the load also varies continuously. A careful study of these shadow areas and useful areas is very important as these directly affect the performance of the solar collector. Therefore a formalism has been developed in the present work for the developed cylindrical solar cooker, which is useful in understanding theoretically the variation of performance of the system with varying solar angles and it can further prove helpful in better designing of cylindrical solar cookers in future.

Theoretical relations have been deduced for useful base plate and wall area. The energy absorbed by the aperture, base plate and walls of the cooker has been calculated on the basis of expressions developed for the useful base plate and wall areas. The results for the variation in useful areas and energy absorbed by the aperture, base plate and walls with solar time have been presented in the form of graphs for three representative days of a year and compared with the corresponding values for commercial hot box solar cooker.

2. DESIGN DETAILS AND METHODOLOGY

The building-material-housing solar cooker (BMHSC) is a hot box type solar cooker with housing of locally available building material (Fig. 1). As this solar cooker is fixed, it has been installed at an open place at the rooftop. The housing of this cooker has been built up of local masonry bricks and cement plaster, at the rooftop. This structure is cylindrical in shape with the top inclined at 10° with the horizontal and facing south. The design and inner dimensions of the structure are as follows: its diameter is 0.63 m., front wall is of height 0.08 m. The back wall is of height 0.19 m. A cylindrical blackened metal tray made of used oilcans, of diameter 0.56 m. and depth 0.076 m has been used as absorber. Around 0.35 m of insulation of thermal conductivity 0.035 W/mK is filled at the bottom and sides of the cooker. The glaze has been fabricated through two 3 mm thick transparent polymeric sheets with 13 mm air gap in between. The aperture area of the structure is 0.25 sq.m. [8].

Fig. 1: Cylindrical building material-housing solar cooker (BMHSC).

The commercial solar cooker that has been used for comparative study is a fibre reinforced polymer body hot box solar cooker. It consists of outer case of fibre and inside it is a blackened metal tray of trapezoidal shape. The bottom of the tray has dimensions 40 cm × 40 cm. The upper dimensions of the tray are 46 cm × 46 cm. Aperture area of commercial solar cooker is 0.21 sq. m.

Fig. 2 Commercial hot box solar cooker (CSC).

3. ESTIMATION OF ENERGY ABSORBED BY THE ABSORBER TRAY OF THE BMHSC FOR GLOBAL SOLAR RADIATION

3.1 Energy Absorbed by the Base Plate

The shape of the BHMSC is cylindrical and the tray is also cylindrical. The top surface of the BHMSC is inclined at an angle of 10° with the horizontal and faces South. The tray is also inclined at the same angle therefore the height of the walls all around the tray is same d. The walls of the tray are straight. As this structure is fixed the variation in the shadow area would depend on the motion of the Sun. Only a section of this structure would face Sun at any instant and that particular section would cast shade on the base plate. As the Sun moves azimuthally, the shadow would move accordingly. Hence the solar azimuth angle would determine the direction of shadow at any instant but the magnitude of the shadow area would depend on the angle of incidence of sunrays. Here expressions have been deduced for the estimation of the magnitude of the shadow area and the corresponding useful area on the base plate of the BMHSC.

It can be seen from Fig. 3 that a section of the BMHSC collector would face the Sun at an instant and as this structure is symmetrical it has been safely assumed that one-third of the perimeter (~$2R$) of the circle would face Sun at an instant. Therefore in the case of minimum shadow on the base plate, it has been taken to be $2R$ on the tray wall when Sun is almost overhead. As the angle of incidence increases, the shade length x due to the wall height d on the base plate increases and hence the shadow area is the area bounded by two arcs BDC and BEC. The length of the outer arc BDC is $2R+2x$ and inner arc BEC can be taken as half the perimeter of an ellipse.

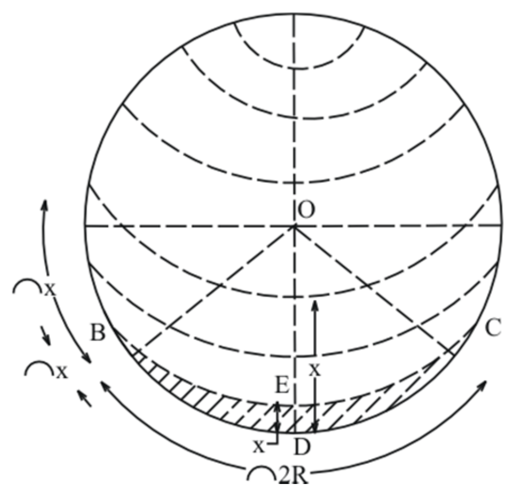

Fig. 3 Shade length x on the absorber base plate. The dashed arcs represent the increase in shade with increase in angle of incidence of sunrays.

The shade length x is given by

$$x = d \tan \theta_i \quad (1)$$

Here θ_i is the solar angle of incidence.

The angle 2ϕ subtended at the centre by the arc BDC is

$$2\phi = \frac{2(R+x)}{R} \Rightarrow \phi = \frac{R+x}{R} \quad (2)$$

The shadow area BDCEB is given by

$$\begin{aligned} A_{SB} &= \text{Area}(\text{BDCEB}) \\ &= \text{Area of the Segment BDCFB} \\ &\quad - \frac{1}{2}\text{Area of the Ellipse}(\text{BECFB}) \end{aligned} \quad (3)$$

$$\textit{Area of Segment BDCFB} = \textit{Area of Sector OBDC} - \textit{Area of Triangle OBC} \quad (4)$$

$$\text{Area of Segment BDCFB} = \frac{2\phi}{360} \times \pi R^2 - R^2 \sin\phi \cos\phi \quad (5)$$

$$\textit{Area of the Ellipse}(BECFB) = \pi a b \quad (6)$$

Here
$$\begin{aligned} a &= \textit{Semi-major axis} = R \sin\phi \\ b &= \textit{Semi-minor axis} = R - x - R\cos\phi \end{aligned} \quad (7)$$

$$\textit{Area of ellipse} = \pi R(R - x - R\cos\phi)\sin\phi \quad (8)$$

Using (5) and (8) in (3), the shadow area is

$$A_{SB} = \pi R^2\left(\frac{2\phi}{360} - \frac{\sin\phi}{2}\right) + \frac{1}{2}R^2 \sin 2\phi\left(\frac{\pi}{4} - 1\right) + \frac{1}{2}\pi R x \sin\phi \quad (9)$$

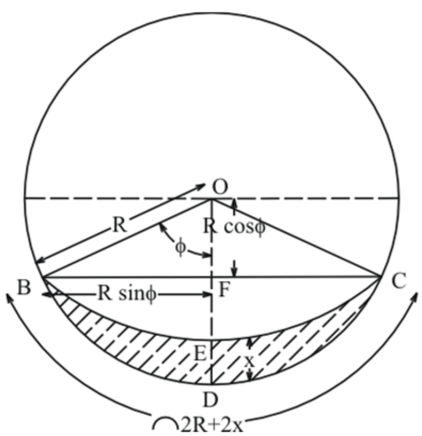

Fig. 4 Hatched portion shows the shadow area on the base plate for the condition $\phi < 90^\circ$ and R > *x*.

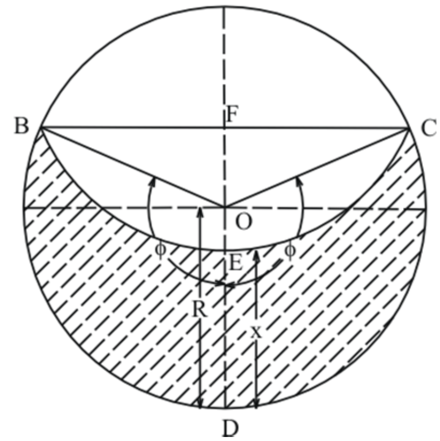

Fig. 5 Hatched portion shows the shadow area on the base plate for the condition $\phi > 90^\circ$ and R > *x*.

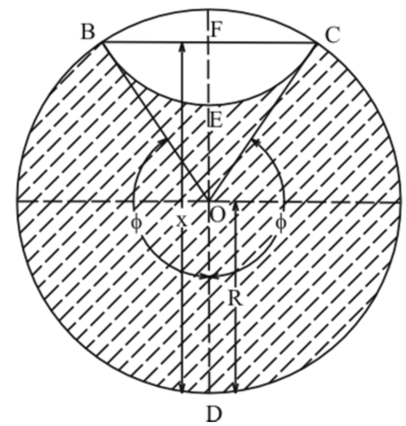

Fig. 6 Hatched portion shows the shadow area on the base plate for the condition $\phi < 90^\circ$ and R < *x*.

Fig. 4, Fig. 5 and Fig. 6 show the shadow areas on the base plate of the BMHSC for various cases. The expression for the shadow area for these cases would remain the same as deduced in eq.9.

The corresponding useful base plate area is

$$\begin{aligned} A_{UB} &= A_B - A_{SB} \\ &= \pi R^2 - A_{SB} \end{aligned} \quad (10)$$

The energy absorbed by the base plate can be calculated by multiplying the incoming solar flux (S) with the useful absorber base plate area (A_{UB}).

$$S = I_b r_b (\tau_c \alpha)_b + \left[I_d r_d + (I_b + I_d) r_r\right](\tau_c \alpha)_d \quad (11)$$

3.2 Energy Absorbed by the Walls

The shadow area on the walls of the BMHSC would be slanted in shape i.e. it would form a trapezium if the wall is straightened. The upper portion of the wall would have shade arc length equal to the inner arc length of the shadow area on the base plate if $2\phi \leq 180^\circ$ and for $2\phi > 180^\circ$ it would be equal to half the circumference. The lower portion of the wall would have shade arc length as $2R+2x$ which is equal to the outer arc length of the shadow area on the base plate. Thus shadow area on the wall of the BMHSC at any instant is given by the following expressions.

For $2\phi \leq 180^\circ$

$$A_{SW} = \frac{1}{2}\left[(2R+2x) + arc\ BEC\right]\cdot d \qquad (12)$$

The arc length BEC can be taken as half the perimeter of the ellipse BECFB.

$$A_{SW} = \frac{1}{2}\left[(2R+2x) + \pi\sqrt{\frac{1}{2}\left(a^2+b^2\right)}\right]$$

$$= \frac{1}{2}\left[(2R+2x) + \pi\sqrt{\frac{1}{2}\left[R^2\sin^2\phi + (R-x-R\cos\phi)^2\right]}\right] \qquad (13)$$

For $2\phi > 180^\circ$

$$A_{SW} = \frac{1}{2}\left[(2R+2x) + \pi R\right]\cdot d \qquad (14)$$

The corresponding useful wall area is given by

$$A_{UW} = 2\pi Rd - A_{SW} \qquad (15)$$

4. NUMERICAL SIMULATION

A computer program was prepared on the basis of the developed formalism for cylindrical solar cooker. The computer program involves various parameters related to solar angles and design of the system. The calculations have been performed for the developed cylindrical building- material -housing solar cooker

(BMHSC) and have been compared with commercial solar cooker. The value of τ_c and the tilt factors have been calculated. The values of I_b and I_d have been obtained through ASHRAE method, where the values of A, B and C used in the calculations are the revised values given by Iqbal [9]. During calculations the average value of absorptance has been taken for a day depending on the variation of incidence angle. On Dec-21 (δ=-23.45°) the angles vary from 50 to 77° (location-Jaipur, Rajasthan) and the absorptance would vary from 0.91 to 0.81[10], therefore average value of 0.86 for absorptance has been used in the program. Similarly for δ = 0° and δ = 23.45° the average values of absorptance are taken as 0.93 and 0.94 respectively. The refractive index of glass is taken as 1.52 and of the polymer sheet as 1.49, and the extinction modulus are taken as 0.925 m^{-1} and 5×10^{-2} m^{-1} respectively [11].

For calculating the energy absorbed by the walls of the cookers the useful absorber area has to be multiplied by the flux on the walls. The cylindrical wall of the BMHSC has been assumed to be divided in four parts and the corresponding value of flux on the wall sections have been calculated as Sgj as mentioned in the paper [10]. The related flux value is multiplied with the useful absorber area depending on the conditions of γ_s and ϕ. The calculations for CSC have been done on the basis of formalism in the paper [10].

5. RESULTS AND DISCUSSION

The results related to the variation in useful base plate and wall areas of the BMHSC with solar time for three representative days of a year (δ = -23.45°, 0°, 23.45°) have been presented in Fig.7. The variations in energy absorbed by the base plate and walls of the BMHSC with solar time for three representative days of a year have been plotted in Fig. 8.

Fig. 7 shows the variation in the percent useful base plate and wall areas for the BMHSC with solar time for the three representative days of a year. The figure clearly shows that the there is a difference of 9% and 4% in the values of percent useful base plate and wall areas at solar noon for the Dec-21 and Jun-21 being higher for the June. The difference in the percent useful base plate area becomes around 23% at the morning and evening. On comparison of the values for the Mar-21 and Jun-21 it is found that percent base plate areas differ by just 2% at solar noon and by 5% at the morning and evening, being higher for Jun-21.

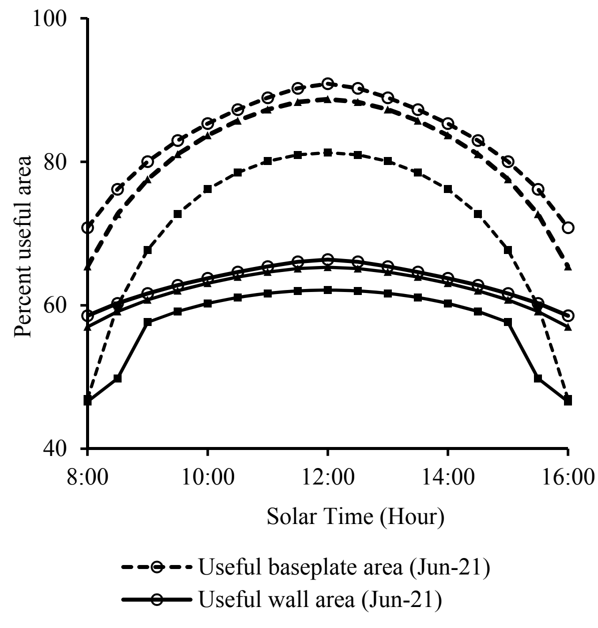

Fig. 7 Variation in useful base plate and wall areas of the BMHSC with solar time for three representative days of a year (δ = -23.45°, 0°, 23.45°)

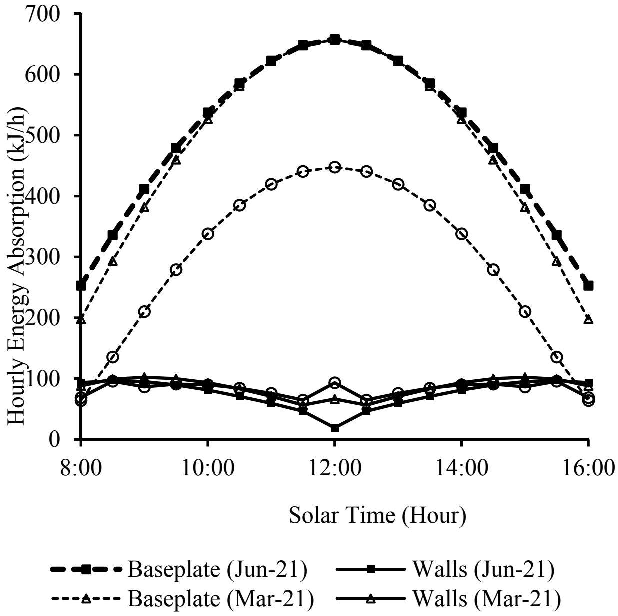

Fig.8 Variation in energy absorbed by the base plate and walls of the BMHSC with solar time for global radiation on three different declinations (δ) of a year.

Similar trends can be observed for the variation in energy absorbed by the base plate of the BMHSC with solar time for the three days (Fig. 8). The energy absorbed by the base plate over the day for Jun-21 is 68% and 4% more than the corresponding values for the Dec-21 and Mar-21. It is interesting to observe that the energy absorbed by the walls over the day for Dec-21 is 9.5% more than the corresponding value for Jun-21 and therefore the difference in total energy absorbed over the day becomes 51%. The value of the total energy absorbed over the day for Jun-21 is just 1.6% higher than the value for Mar-21 as the energy absorbed by the walls over the day for Mar-21 is 1.3% higher than Jun-21.

On comparing the values of the energy absorbed by the base plate and total energy absorbed over the day for the BMHSC and the CSC, it is found that the values are considerably higher for the BMHSC as shown in Fig. 9. The aperture area of the BMHSC is 19% more than the CSC but the energy absorbed by the base plate of the BMHSC over the day is 123% and 47% higher than the corresponding values for the CSC on Dec-21 and Jun-21, respectively. The energy absorbed by the walls of the CSC is higher than the BMHSC and therefore the total energy absorbed over the day for the BMHSC is 53% and 18% higher than the corresponding values for the CSC on Dec-21 and Jun-21, respectively. This shows that in winter months there is a gain in energy absorbed by the BMHSC over the CSC.

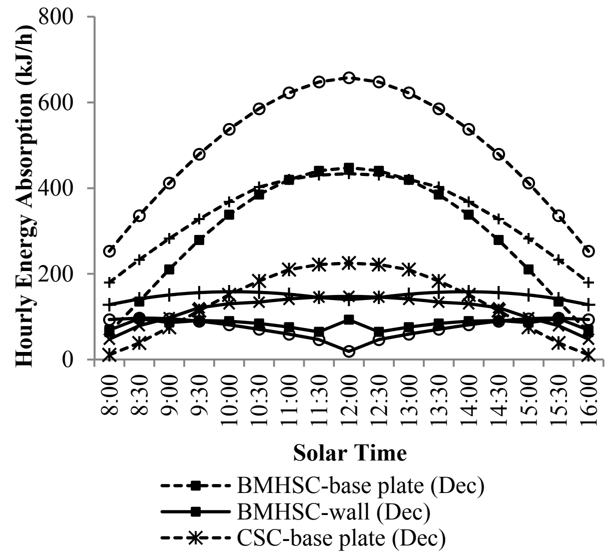

Fig. 9 Variation in energy absorbed by the base plate and walls of the BMHSC and CSC with solar time for global radiation on Dec-21 and Jun-21.

6. CONCLUSIONS

Solar cookers can provide a large population in developing countries with pollution free option for cooking. It is important to develop efficient, convenient and user-need based solar cookers. To improve the efficiency of solar cookers more studies and researches are required addressing each parameter. Increasing useful areas and enhancing energy absorption can be one way of improving efficiency. In this paper formalism has been developed and study is reported for energy absorption for cylindrical shaped building-material housing solar cooker. It has been compared with commercial solar cooker. The study reports that aperture area of the BMHSC is 19% more than the CSC but the energy absorbed by the base plate of the BMHSC over the day is 123% and 47% higher than the corresponding values for the CSC on Dec-21 and Jun-21, respectively. The total energy absorbed over the day for the BMHSC is 53% and 18% higher than the corresponding values for the CSC on Dec-21 and Jun-21, respectively. Thus it can be concluded that energy absorption increases for cylindrical shape and the effect is more pronounced in winters which is quite useful in improving the performance of the cooker in winters.

7. ACKNOWLEDGEMENTS

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