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Mathematical Formalism to Study Energy Distribution Pattern in Solar Hot Boxes for Global Solar Radiation

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ABSTRACT: The paper presents a mathematical formalism for studying energy distribution in solar hot boxes for global solar radiation. Formalism has been developed as a general case for a flat plate tilted collector with off-south orientation considering a number of parameters. It has been applied to a hot box solar cooker kept horizontally in non-tracked south facing mode. The wall height and the wall inclination have been incorporated in the development of the mathematical model along with a number of parameters such as tilt of the collector, transmissivity-absorptivity, aperture area, base plate area, hour angle, angle of incidence, solar and surface azimuth angle, solar insolation etc. for the estimation of rate of heat absorbed by the collector considering the global solar radiation. This formalism may prove to be a simple and an efficient tool in the design and development of improved solar hot box cookers with better efficiency and cost-effectiveness.

KEYWORDS: mathematical formalism, energy distribution, solar hot box cooker, global solar radiation, wall height and inclination.

I. INTRODUCTION

The rate of heat absorbed by a collector plays a significant role in deciding the performance of the collector. The absorbing surface of a flat plate collector is in form of a tray and the energy collected by the aperture area is distributed between the absorber base plate and walls. For solar flat plate collectors the medium to be heated is in contact with the base plate and therefore the heat transfer is mainly through the base plate. In case of solar water heaters, the wall heights are very small (~ 5cm.) whereas the collector areas are quite large (~1-2 sq.m.) hence the shading of the base plate by the walls and the fraction of heat absorbed by the walls is less. In box type solar cookers the wall height is more (~10cm.) and the base plate area is small (~ 0.25 sq.m.) hence the study of energy distribution between base plate and walls becomes important as the effect of wall height and wall inclination is more pronounced on energy absorption by the base plate. The wall height and wall inclination play a major role in determining the shading effects on the base plate which is further visualized as non-uniform heating of load.

There have been studies on the estimation of energy absorption and utilizibility by the flat plate collectors for various orientations [1-3], gap spacing variation [4,5], optimization of tilt and azimuth [6-8], impact of optical and thermal properties on the performance considering length, breadth and height ratios[9], optimization of absorber plates of different geometry [10], modeling for collector under transient condition [11], modeling of solar stills with concept of solar fraction [12,13], an analysis of the energy accretion pattern of a box type solar cooker [14], a number of studies on solar thermal devices [15], solar cookers [16], but hardly any study is to be found on the distribution of energy between the walls and the base plate of the absorber tray considering the variations in wall inclination, wall height and solar radiation geometry. As a usual practice energy absorbed is considered for the aperture area only, the distribution of this energy between the walls and base plate is not studied. Therefore the present work presents a mathematical model for the estimation of energy distribution between the walls and base plate of any four walled flat plate solar collector.

II. MATERIALS AND METHODS

The formalism has been developed on the basis of the solar radiation geometry and study of shading effects on the walls and base plate of the absorber trays for local apparent motion of sun. For studying the shade lengths and useful areas experimental observations were taken for various days on commercial solar cooker and solar hot boxes developed by authors [17,18]. The shade length variations were observed from morning to evening for different days of the year and on the basis of the study various mathematical conditions and expressions have been developed leading to the development of the formalism. A computer program has been developed based on the formalism. The formalism incorporates the different angles related to solar radiation geometry and dimensions of the hot box as defined in the nomenclature section.

III. NOMENCLATURE

- $A_{1=}$ shadow area on the base plate due to any one of the walls (2 or 4)
- A_2= shadow area on the base plate due to any one of the walls (3 or 5)
- A_3 = overlap area of shadow on the base plate
- A_{gj} = the geometric area of the j^{th} surface
- A_{sj} = the shadow area on the j^{th} surface.
- A_u = total useful absorber area or total radiation receiving area
- A_{uj} = useful absorber area or radiation receiving area on the j^{th} surface
- B'= the breadth of the aperture of the tray
- B= the breadth of the base plate of the absorber tray
- d= depth of the tray
- I_b = the hourly beam radiation incident on a horizontal surface.
- I_d = the hourly diffuse radiation incident on a horizontal surface.
- j = index associated with a surface, j = 1represents the absorber base plate and j = 2 to 5 correspond to the four walls of the absorber tray.
- L = the length of the base plate of the absorber tray
- l = the slant height or the breadth of the walls
- L'= the length of the aperture of the tray
- L_j = shade length perpendicular to edges of the base plate due to any j^{th} wall
- L_x= shade lengths due to walls '3 or 5'
- L_y= shade lengths due to walls '2 or 4'
- $\mathbf{n_b}$ = unit vector along the beam radiation
- $\mathbf{n_j}$= unit vector normal to the j^{th} surface
- q_{ag} = Energy absorbed by the absorber tray of the collector without reflector for global radiation.
- r_{bj} = tilt factors for the beam radiation corresponding to the j^{th} surface.
- r_{dj} = tilt factors for the diffuse radiation corresponding to the j^{th} surface.
- r_{rj} = tilt factors for the radiation reflected by ground corresponding to the j^{th} surface.
- S_{gj} = the incident global solar flux absorbed by the j^{th} surface.
- ξ_j = absorptivity of the j^{th} absorber surface
- β =angle of inclination of the collector with the horizontal.
- γ = surface azimuth angle of the collector
- γ_j = surface azimuth angle of the j^{th} wall surface
- γ_s = solar azimuth angle
- δ = declination angle
- θ_{ij} = angle of incidence of beam radiation on the j^{th} surface

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- θ_w = the outward inclination of the walls with respect to the vertical
- τ_c = the transmissivity of the glaze.
- φ = latitude angle of the place
- ω= hour angle

IV. DEVELOPMENT OF THE FORMALISM

In the present work the relations have been developed for a general case when the collector is inclined at an angle with the horizontal and is kept non-tracked (stationary) at a surface azimuth angle. The expressions for the useful absorber area have been derived considering an absorber tray with five surfaces, i.e. base plate and four walls as shown in Fig.1. The absorber tray of the collector considered is trapezoidal in shape with the walls inclined outside the vertical at an angle θ_w (Fig. 2).

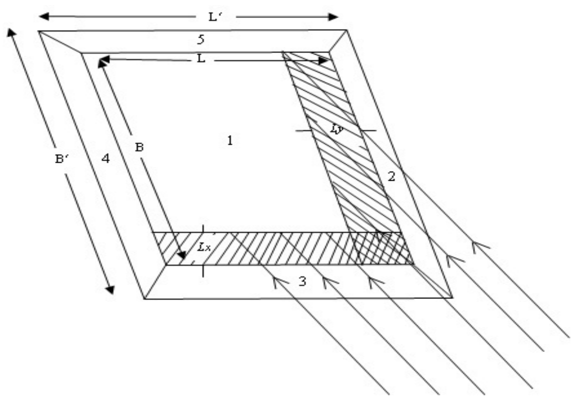

Fig. 1. View of the absorber tray with the shade lengths L_x and L_y along the front and side walls respectively

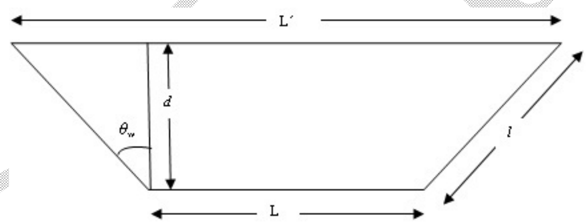

Fig. 2. Cross sectional view of the absorber tray

The energy absorbed by the absorber tray of the collector without reflector is

$$q_{ag} = \sum_{j=1}^{5} A_{uj} S_{gj} \qquad (1)$$

here

$$S_{gj} = I_b r_{bj} (\tau_c \xi_j)_b + \{I_d r_{dj} + (I_b + I_d) r_{rj}\} (\tau_c \xi_j)_d \qquad (2)$$

is the absorbed radiation according to the isotropic diffuse concept [19], the modification incorporated is that here surfaces j=1 to 5 (base plate and walls) have been considered. The tilt factors are

$$r_{bj} = \frac{\cos\theta_{ij}}{\cos\theta_z}, \quad r_{dj} = \frac{1+\cos\beta_j}{2}, \quad r_{rj} = \rho\left(\frac{1-\cos\beta_j}{2}\right) \qquad (3)$$

Following are the relations in the dimensions of the tray (Fig. 2)

$$L' = L + 2d\tan\theta_w$$
$$B' = B + 2d\tan\theta_w \qquad (4)$$
$$l = d\sec\theta_w$$

Expressions for Useful Absorber Area for Direct Radiation

The total useful absorber area or total radiation receiving area is given by

$$A_u = \sum_{j=1}^{5} A_{uj} = \sum_{j=1}^{5} (A_{gj} - A_{sj}) \qquad (5)$$

The expressions for the useful areas have been developed in the present work considering the direct radiation, and assuming that this holds for global radiation. The energy absorbed has been calculated by the product of useful area and global solar flux.

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Useful Base Plate Area

When the collector is without reflector, the shade on the base plate would be due to the walls of the tray. The unit vector normal to the absorber base plate is

$$\mathbf{n_1} = \mathbf{k} \tag{6}$$

The unit vector along the beam radiation for the absorber tray is

$$\begin{aligned}\mathbf{n_b} &= [-\sin\theta_z \cos\beta \cos(\gamma - \gamma_s) + \sin\beta \cos\theta_z]\mathbf{i} + \sin\theta_z \sin(\gamma - \gamma_s)\mathbf{j} \\ &- [\sin\theta_z \sin\beta \cos(\gamma - \gamma_s) + \cos\beta \cos\theta_z]\mathbf{k}\end{aligned} \tag{7}$$

The following are the expressions for the normal to the four walls of the absorber tray

$$\mathbf{n_2} = -\cos\theta_w \mathbf{j} + \sin\theta_w \mathbf{k}, \quad \mathbf{n_3} = -\cos\theta_w \mathbf{i} + \sin\theta_w \mathbf{k},$$

$$\mathbf{n_4} = \cos\theta_w \mathbf{j} + \sin\theta_w \mathbf{k}, \quad \mathbf{n_5} = \cos\theta_w \mathbf{i} + \sin\theta_w \mathbf{k} \tag{8}$$

and the cosine of angle of incidence of the direct radiation on the j^{th} surface is

$$\cos\theta_{ij} = -(\mathbf{n_j})(\mathbf{n_b}) \quad \text{here } j = 1 \text{ to } 5 \tag{9}$$

At any time due to the finite height of the walls of the tray, one or two walls would cast shadow on the base plate depending on the difference of the γ_j and γ_s. The surface azimuth angles of the walls in terms of γ are as follows

$$\gamma_2 = 90° + \gamma, \gamma_3 = \gamma, \gamma_4 = 90° - \gamma \text{ and } \gamma_5 = 180° - \gamma \tag{10}$$

The shade length of on the base plate along the ray direction is given by $d \tan \theta_{i1}$. The shade length perpendicular to edges of the base plate due to any j^{th} wall is expressed as

$$L_j = d \tan\theta_{i1} \cos(\gamma_j - \gamma_s) \tag{11}$$

This shade would fall on the base plate when L_j is positive and would fall outside the base plate when L_j is negative. The shade lengths of the two walls '2 or 4' may be labeled as L_y and for '3 or 5' as L_x as shown in Fig. 1.The shade lengths L_x and L_y within the base plate due to a wall inclined at an angle θ_w can be expressed as

$$\begin{aligned}L_x &= d \tan\theta_{i1} \cos|\gamma - \gamma_s| - d \tan\theta_w \\ L_y &= d \tan\theta_{i1} \sin|\gamma - \gamma_s| - d \tan\theta_w\end{aligned} \tag{12}$$

Here the second term on the R.H.S. of the eq. accounts for the shade lengths outside the base plate due to the wall inclination. These conditions and the expressions for useful base plate area with different conditions are shown in Table 1.

Table 1: Useful base plate area when collector is non-tracked oriented off-south.

Shade lengths L_x and L_y	Shadow area
$L_x = 0$ if $\tan\theta_{i1} \sin|\gamma - \gamma_s| < \tan\theta_w$ $L_x = d \tan\theta_{i1} \sin|\gamma - \gamma_s| - d \tan\theta_w$ if $0 \le L_x \le L$ $L_x = L$ if $\tan\theta_{i1} \sin|\gamma - \gamma_s| - \tan\theta_w \ge L/d$	$A_{s1} = L_x B + L_y L - L_x L_y$ $= dL(\tan\theta_{i1} \cos|\gamma - \gamma_s| - \tan\theta_w)$ $+ dB(\tan\theta_{i1} \sin|\gamma - \gamma_s| - \tan\theta_w)$ $- d^2(\tan\theta_{i1} \cos|\gamma - \gamma_s| - \tan\theta_w)$ $\times(\tan\theta_{i1} \sin|\gamma - \gamma_s| - \tan\theta_w)$
$L_y = 0$ if $\tan\theta_{i1} \cos|\gamma - \gamma_s| < \tan\theta_w$ $L_y = d \tan\theta_{i1} \cos|\gamma - \gamma_s| - d \tan\theta_w$ if $0 \le L_y \le B$ $L_y = B$ if $\tan\theta_{i1} \cos|\gamma - \gamma_s| - \tan\theta_w \ge B/d$	**Useful base plate area** $A_{u1} = LB - A_{s1}$ $= LB - dL(\tan\theta_{i1} \cos|\gamma - \gamma_s| - \tan\theta_w)$ $- dB(\tan\theta_{i1} \sin|\gamma - \gamma_s| - \tan\theta_w)$ $+ d^2(\tan\theta_{i1} \cos|\gamma - \gamma_s| - \tan\theta_w)$ $\times(\tan\theta_{i1} \sin|\gamma - \gamma_s| - \tan\theta_w)$

Useful Wall Area

For a solar collector that has walls inclined at an angle θ_w with the vertical there would be shadow on the walls partially if $\theta_{i1} \ge \theta_w$ and there would not be any shadow on the walls if $\theta_{i1} < \theta_w$. For high angle of incidence of solar

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radiation ($\theta_{i1} \rightarrow 90^o$) the system with all four walls would be completely in shade. The fraction of the wall area in shade is dependent on θ_w and $|\gamma - \gamma_s|$ if $\theta_w \le \theta_{i1} < 90^o$. When γ_s is equal to γ_j then the wall facing the sun from outside would be in shade from inside and the adjacent walls would have triangular sections of shadow. If the tray had straight walls then with even slight deviation of γ_s from γ_j two adjacent walls would be in complete shade and the other two walls would be partially in shade. If the value of θ_w is equal to or greater than 22.5^o then only one wall would be in complete shade for any value of γ_s, there would not be any situation in this case when two walls are in complete shade as shown in Fig.3.

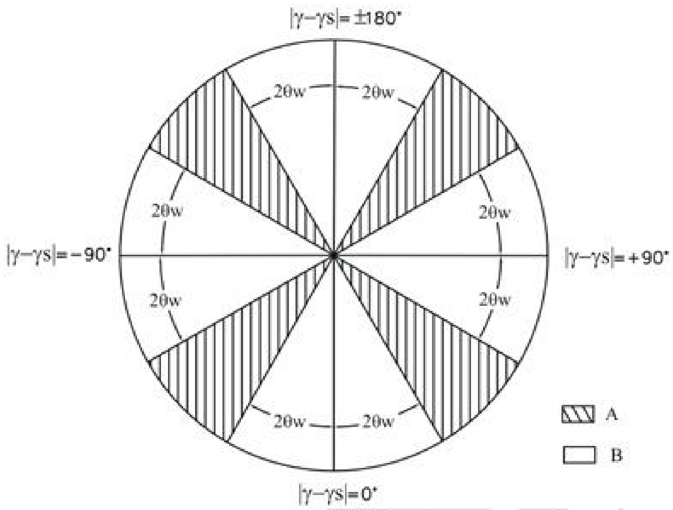

Fig. 3. Conditions of $|\gamma - \gamma_S|$ showing shading of one wall (B)/two walls (A) completely. Area 'A' in the figure represents the shading of two adjacent walls completely and partial shading of the other two walls, and the area 'B' represents the shading of one wall completely and partial shading of walls adjacent to the shaded wall.

The mathematical expressions for the useful wall area for the conditions mentioned above are given in Table 2. The subscripts in the expressions of A_{uw} represent the respective wall surface receiving the solar radiation.

Table 2: Useful wall area when collector is non-tracked oriented off-south.

Boundary Conditions		Useful wall area
$\theta_w < 22.5^\circ$	$\lvert\gamma-\gamma_s\rvert < 2\,\theta_w$	$A_{uw} = \left[\frac{1}{2}(L+L')\times l\right]_5 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_2 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_4$
	$2\theta_w < \lvert\gamma-\gamma_s\rvert < 90-2\theta_w$	$A_{uw} = \left[\frac{1}{2}(L+L'-L_y)\times l\right]_{5/5} + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_{4/2}$
	$90-2\theta_w \le \lvert\gamma-\gamma_s\rvert \le 90+2\,\theta_w$	$A_{uw} = \left[\frac{1}{2}(B+B')\times l\right]_{4/2} + \left[\frac{1}{2}(L+L'-L_y)\times l\right]_3 + \left[\frac{1}{2}(L+L'-L_y)\times l\right]_5$
	$90+2\theta_w < \lvert\gamma-\gamma_s\rvert < 180-2\,\theta_w$	$A_{uw} = \left[\frac{1}{2}(L+L'-L_y)\times l\right]_{3/3} + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_{4/2}$
$\theta_w \ge 22.5^\circ$	$\lvert\gamma-\gamma_s\rvert \le 2\,\theta_w$	$A_{uw} = \left[\frac{1}{2}(L+L')\times l\right]_5 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_2 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_4$
	$2\theta_w < \lvert\gamma-\gamma_s\rvert < 180-2\,\theta_w$	$A_{uw} = \left[\frac{1}{2}(B+B')\times l\right]_{4/2} + \left[\frac{1}{2}(L+L'-L_y)\times l\right]_3 + \left[\frac{1}{2}(L+L'-L_y)\times l\right]_5$
	$180-2\,\theta_w < \lvert\gamma-\gamma_s\rvert < 180$	$A_{uw} = \left[\frac{1}{2}(L+L')\times l\right]_3 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_2 + \left[\frac{1}{2}(B+B'-L_x)\times l\right]_4$

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Total Useful Absorber Area and Energy Absorbed

The total useful absorber area when the collector is without reflector is given as

$$A_u = \sum_{j=1}^{5} A_{uj} \tag{13}$$

Thus the energy absorbed by the base plate and walls of the absorber tray can be given by the product of respective useful area (A_{uj}) and the global solar flux absorbed by the j^{th} surface (S_{gj}).

V. COMPUTATIONS

A computer program has been prepared on the basis of developed formalism using expressions in tables 1 and 2 taking into account all the parameters viz. θ_{ij}, γ_s, γ, d, θ_w, L, B, L', B', l, β. The collector used in computations is commercial solar cooker (CSC). The extinction coefficient and refractive index of glass sheet have been taken as 15 m^{-1} and 1.52 respectively [20]. The details of the parameters used in computations are given in Table 3. 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 [20]. 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° and the absorptance would vary from 0.91 to 0.81[21], 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.

Table 3: Parameters used in computations.

S. No.	Parameters	Details			
1.	CSC (20°) dimensions	Base plate area-0.16 sq.m. (0.40 m × 0.40 m)	Aperture area-0.21 sq.m. (0.46 m × 0.46 m)	Wall height-.084 m.	Wall inclination-20°
2.	Same base plate area, different wall heights, different wall inclinations	Base plate area-0.16 sq.m. (0.40 m × 0.40 m)	Aperture area- 0.16 sq.m.(0°), 0.21sq.m. (20°) 0.29 sq.m.(40°)	Wall heights- 0.08 m. 0.10 m. 0.12 m. 0.14 m.	Wall inclinations 0° 20° 40°
3.	Location and time	Jaipur (India)	Latitude-26.55°N	Longitude-75.52°E	Solar time-8 a.m. to 4 p.m.

VI. RESULTS AND DISCUSSION

Fig. 4 presents the variation in energy absorbed by the base plate and walls of the solar cooker with θ_w=20° with the solar time for three different declinations. It can be seen from the figure that the energy absorbed is maximum for the base plate on June -21, followed by Mar-21 and Dec-21. The total energy absorbed due to global radiation over the considered day length for Jun-21 is 97% higher than on Dec-21 and 12% higher than on Mar-21. The energy absorbed by the base plate of the collector on Jun-21 is 8% more as on Mar-21 and 93% more as on Dec-21 at solar noon. It is interesting to see that minimum energy is absorbed by the walls on Jun-21 followed by Mar-21 and Dec-21. Though the total energy absorbed on Jun-21 and Mar-21 are almost the same yet the cooking performance differ in these two months as uniform heating of hard food items is obtained in a better way in June. This can be explained through the fact that the radiation received on the base plate differs significantly for these months, being higher for June.

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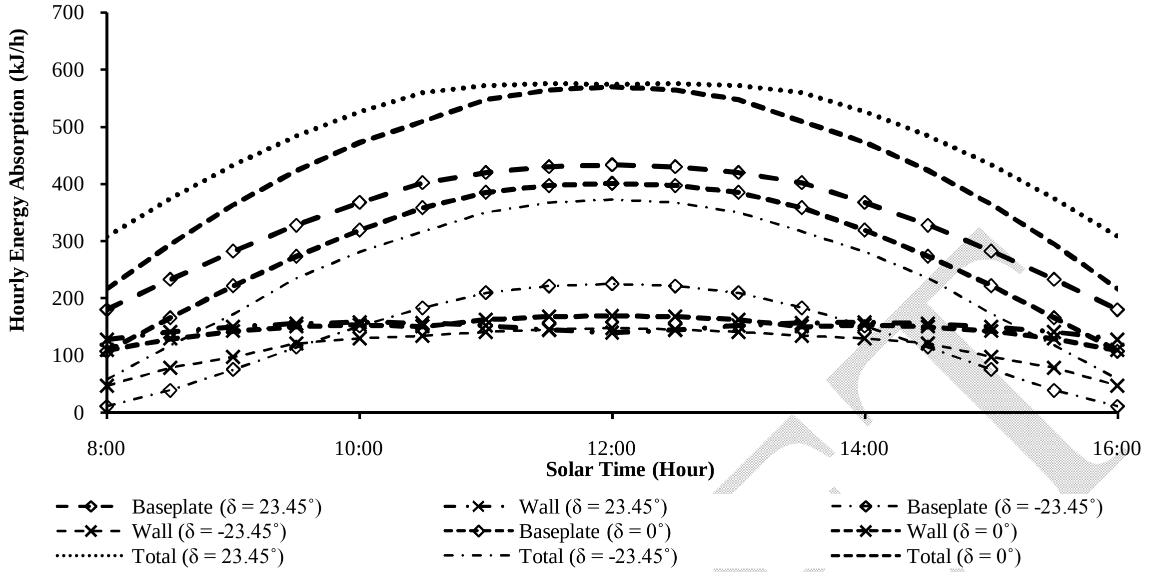

Fig. 4. Variation in hourly energy absorbed by the base plate and walls of the solar collector for global radiation for three declinations (δ)

The results for the variation in the pattern of energy absorbed by the collector with the stepwise increase in wall height (d = 8, 10, 12 and 14 c.m.) and wall inclination (0°, 20° and 40°) have been presented in fig. 5-7. Here the base plate area is assumed to be same (0.16 sq.m.) in all the cases whereas the aperture area can vary with wall inclination.

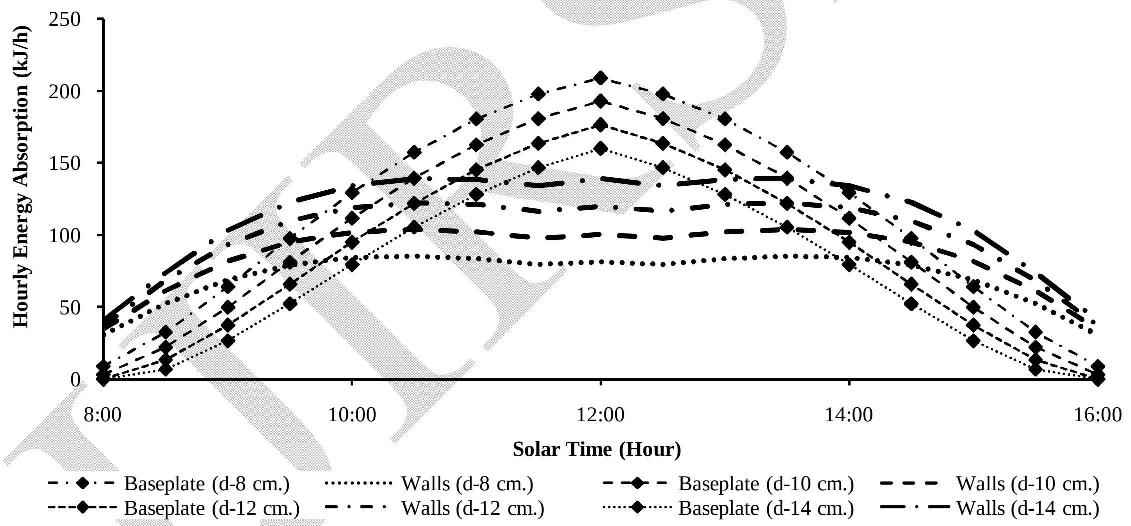

Fig. 5. Variation in hourly energy absorbed by the base plate and walls of the solar collector for different wall heights (d) but fixed wall inclination (θ_w= 0˚) for global radiation on Dec-21

From the Fig. 5 it can be seen that as the wall height is increased keeping wall inclination fixed at 0° the energy absorbed on the base plate decreases and the energy absorbed by the walls increases though the total energy absorbed remains the same. When total energy absorbed by the base plate for wall height 8 c.m. over the solar time period 8:00 a.m. to 4:00 p.m. is considered it is found to be 15%, 33% and 56% more than the corresponding values for the systems with wall heights of 10, 12 and 14 c.m. respectively. Just reverse trend is observed for the energy absorbed by the walls. Similar observations can be made from the Fig. 6and 7 for the systems with wall inclinations 20° and 40° and different wall heights.

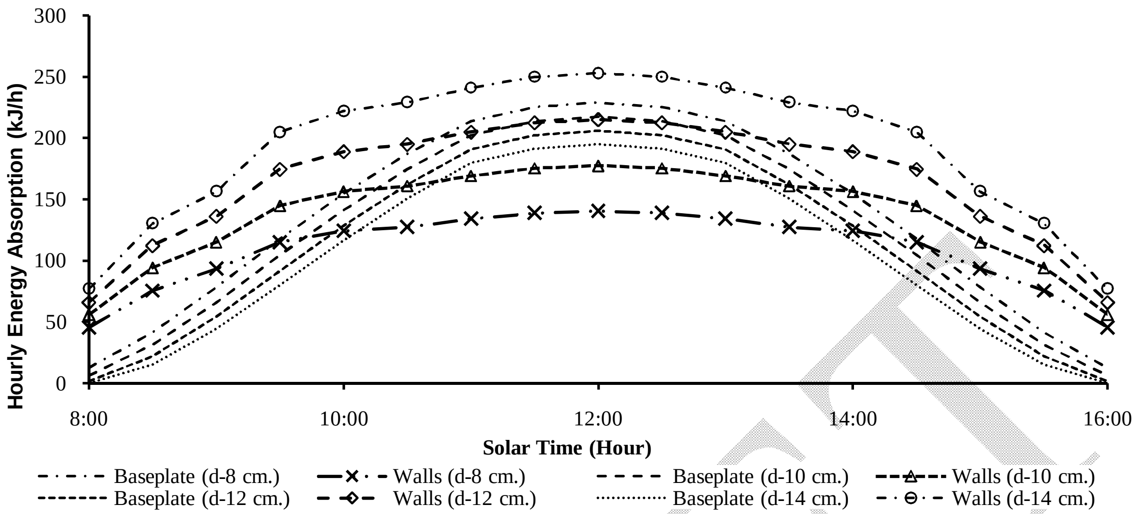

Fig. 6. Variation in hourly energy absorbed by the base plate and walls of the solar collector for different wall heights (d) but fixed wall inclination (θ_w= 20˚) for global radiation on Dec-21

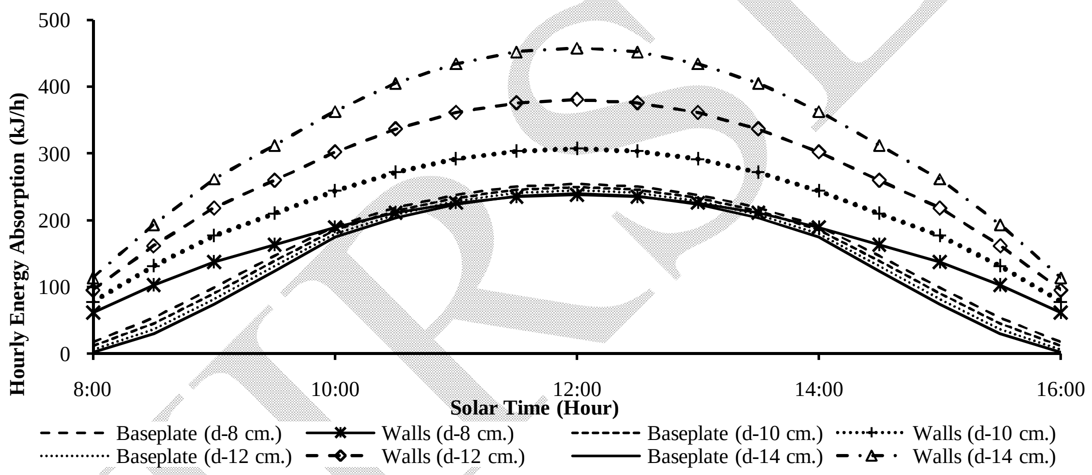

Fig. 7. Variation in hourly energy absorbed by the base plate and walls of the solar collector for different wall heights (d) but fixed wall inclination (θ_w= 40˚) for global radiation on Dec-21

It is interesting to observe the three figures (Fig.5-7) simultaneously. If the wall height of the system is changed from 8 to 12 c.m. and wall inclination is also changed from 0° to 20°, the energy absorbed by the base plate over the considered solar time interval remains almost the same but the total energy absorbed by the system increases by 50% as the energy absorbed by the walls increases by 132%. Further if the wall height is increased to 14 c.m. from 8 c.m. and wall inclination is also increased to 40° from 0° then there is 22.5% increase in the energy absorbed by the base plate over the considered day length and 151% increase in the total energy absorbed. Thus if there is requirement of increased wall height for a system it would be desirable to incline the wall outwards to save base plate from shading and to achieve higher energy absorption by the system.

To reduce the top heat loss it is desirable to increase wall height but with it the energy absorbed by the base plate decreases due to shading effects. Though the total energy absorbed remains the same as the wall height is increased (8c.m. to 10 c.m., 12 c.m., 14 c.m.), the energy absorbed on the base plate decreases (13%, 25%, 36%) and the energy absorbed by the walls increases (21%, 41%, 58%). From the study it can be also be observed that on increasing the wall inclination from 0 to 20^o the percent useful base plate area increases by almost 20% in winters and the energy absorption increases by around 30%. Therefore it is desirable to fabricate the absorber tray in trapezoidal shape though this may add to the complexity in fabrication of collector. Another option can be to increase the base plate area accordingly to compensate for the shading effects of the walls and the load should be placed in the radiation receiving area of the base plate.

VII. CONCLUSIONS

The formalism presented may prove to be highly useful in better designing of four walled flat plate collectors especially hot box solar cookers taking into account the energy distribution between walls and base plate. The study shows that the rate of energy absorption is almost same in the month of March and June but the energy absorbed by the base plate is more in June and this explains the uniform and faster solar cooking in June as compared to March. Therefore during the designing of the solar cookers/collectors the energy distribution between the base plate and walls should be considered in order to improve the performance of the system. The conditions mentioned in the present work (tables 1 and 2) may be used in computer programs or in development of softwares for study of flat plate collectors or hot box solar cookers.

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