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The Comparison between the Effects of Using Two Plane Mirrors Concentrator and that without Mirror on the Flat-Plate Collector

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ABSTRACT: The aim of the study is to compare between the effects of using two planes mirror concentrator and that without mirror on the flat plate collector. The work is performed on solar water heating system with flat plate collector installed in it. Measuring of the data are taken between 9.00 to 16.00 h over a day. Based on the global and diffuse radiations with the average of 594 and 119 W/m^2, the average efficiencies of the system over a day are 41.90 % and 22.80 % for collector with and without mirror respectively

Keywords: plate collector, mirrors concentrator

NOMENCLATURE

A_p - absorbing area [m^2]
I_b - hourly beam radiation [W/m^2]
I_d - hourly diffuse radiation [W/m^2]
I_g - hourly global radiation [W/m^2]
I_{bM} - reflected beam radiation [W/m^2]
I_T - flux falling on the surface of collector [W/m^2]
r - tilt factor [-]
S - incident solar flux absorbed in the absorber plat[W/m^2]
T - temperature [^{o}C]
U - loss coefficient [W/m^2-K]

Greek letters

α - solar altitude angle [^{o}], absorptivity [-]
β - slope angle of collector [^{o}]
δ - declination angle [^{o}]
ϕ - latitude angle [^{o}]
η - incidence angle of reflected radiation on collector surface [^{o}]
θ - incidence angle on collector surface [^{o}]
$(\tau\alpha)$ - transmissivity-absorptivity product [-]
ω - hour angle [^{o}]
ξ - azimuth angle [^{o}]
ψ - mirror inclination angle [^{o}]

Subscripts

a	- absorption
b	- beam
d	- diffuse
g	- global
l	- overall coefficient
p	- absorber plate
r	- reflection and refraction
u	- useful
w	- wall,
E	- East
M	- mirror
W	- West

1. INTRODUCTION

From many studies, it has been proved that a flat-plate collector for heating liquids and gasses gives only to a maximum temperature around 100 ^{o}C. When higher temperatures are required, it becomes necessary to concentrate the incoming solar radiation. Concentrating collectors are of various types and can be classified in many ways i.e.: reflecting type utilizing mirrors and of the reflecting type utilizing Fresnel lenses. The reflecting surfaces used may be flat, parabolic or spherical. In this paper we analyzed the performance a flat-plate collector with adjustable mirrors at the edges of collector to reflect radiation to the absorber plate. An advantage associated with this type of concentrating collector is that the diffuse component of the incoming solar radiation is not entirely wasted. A flat-plate collector with plane reflectors is a simple non-imaging concentrating collector and represents an effective means of getting slightly higher temperatures than are obtainable with a flat-plate collector alone.

2. EXPERIMENTAL APPARATUS AND PROCEDURES:

The major components that make the flat-plate collector are: (1) absorber plate made of Al-sheet metal painted black, 0.4 mm thickness, size 1.6×0.9 m, (2) tubes fixed to absorber plate with nine tubes ½ inch diameter with spacing 9.9 cm, made of brass. (3) two transparent cover glasses 4 mm thick with spacing 4 cm. The spacing between absorber plate and first cover glass is 4 cm, (4) collector box made of plywood. The bottom and sides of the box are insulated by foam cork 4 cm thick. A schematic diagram of the test set-up is shown in Fig.1. It is a closed lop consisting of the solar water heater is to be tested. Water can be circulated by lowering the outlet pipe from collector 10 cm below the water surface in the tank. The experiments were performed for collector with mirror and that without mirror, during 8 hours over a day, from 9.00 AM to 16.00 PM. The solar radiations in two days give nearly the same value. The collector is equipped by two mirror-reflectors (mirrors), one of which facing West and the other East.

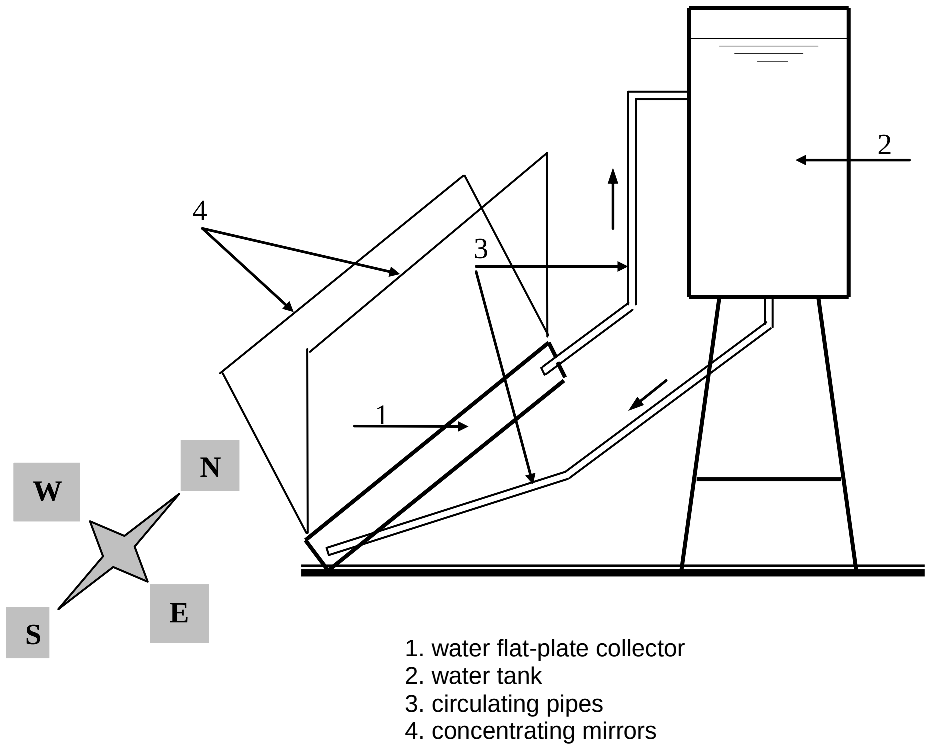

Figure 1 Schematic diagram of a closed loop set-up for testing flat-plate collector with concentrating mirror

3. ANALYSIS:

From Figure 2 and 3, the angle of incidence θ of direct solar radiation on the collector can be related by a general equation by 3 position angles of the sun in the sky i.e.: declination angle δ, latitude angle ϕ, hour angle ω and 2 orientation angles of the plane of the collector: slope of the collector β, and surface azimuth angle ξ_w.

The governing equation of incidence angle θ on the surface is given by:

$$\begin{aligned} \cos\theta &= \sin\phi\left(\sin\delta\cos\beta + \cos\delta\cos\xi_w\cos\omega\sin\beta\right) \\ &+ \cos\phi\left(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\xi_w\sin\beta\right) \\ &+ \cos\delta\sin\xi_w\sin\omega\sin\beta \end{aligned} \quad (1)$$

The flat-plate collector is facing due south and is inclined at an angle $\beta = 0^o$. Since Makassar located at latitude 5.1^o *S* and longitude 119.42^o *E*. The angle of incidence on the collector, based on equation (1) becomes:

$$\cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (2)$$

The inclination angle of the reflector ψ is adjusted manually every hour. In order to get the optimum solar radiation reflected in to collector, the reflector mirrors are adjusted in such a way that the sun's rays striking the top edge of the mirrors are reflected to the top edge of the collector. This needs the reflecting mirrors have the same length *L* as the collector in order to boost the output, Fig. 4. The inclination angle ψ can be calculated from equation (1) by changing β to ψ, the incident angle on top edge of the reflector by changing θ to θ_r, see Fig. 5. The incident angle on top edge of the reflector is given by:

$$\cos\theta_r = \sin\phi\left(\sin\delta\cos\psi + \cos\delta\cos\xi_w\cos\omega\sin\psi\right) + \cos\phi\left(\cos\delta\cos\omega\cos\psi - \sin\delta\cos\xi_w\sin\psi\right) + \cos\delta\sin\xi_w\sin\omega\sin\psi \quad (3)$$

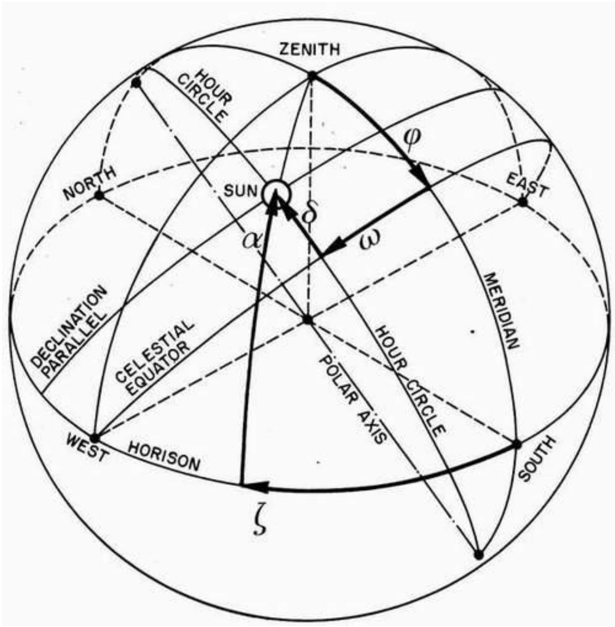

Figure 2 The celestial sphere

α = solar altitude; δ = declination angle; ϕ = latitude angle; ω = hour angle; ζ = solar azimuth angle

Latitude for Makassar: $\phi = -5.1^o$

Declination: $\delta^o = 23.45\sin\left[\frac{360}{365}(284 + N)\right]$

Day of the year on 24 October 2009, N = 298 days, gives declination angle $\delta = -12.786^o$

Surface azimuth angle: $\xi_w = 0^o$ for facing south; $\xi_w = 180^o$ for facing north

Hour angle: $\omega^0 = (12 - t)\times 15^o$, t = local apparent time

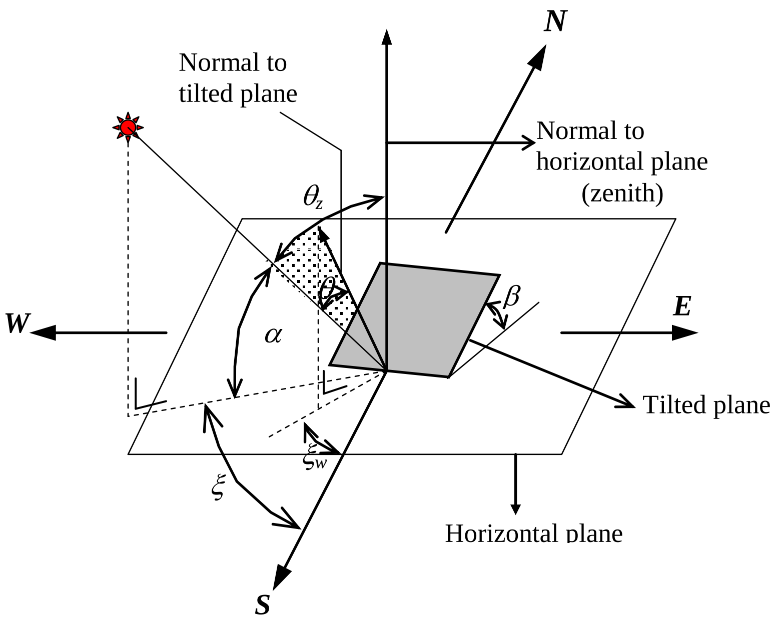

Figure 3 Diagram illustrating the angle of incidence θ

θ_z=zenith angle, α =solar altitude angle, β = slope of the plane, ξ= solar azimuth angle, ξ_w = wall azimut angle

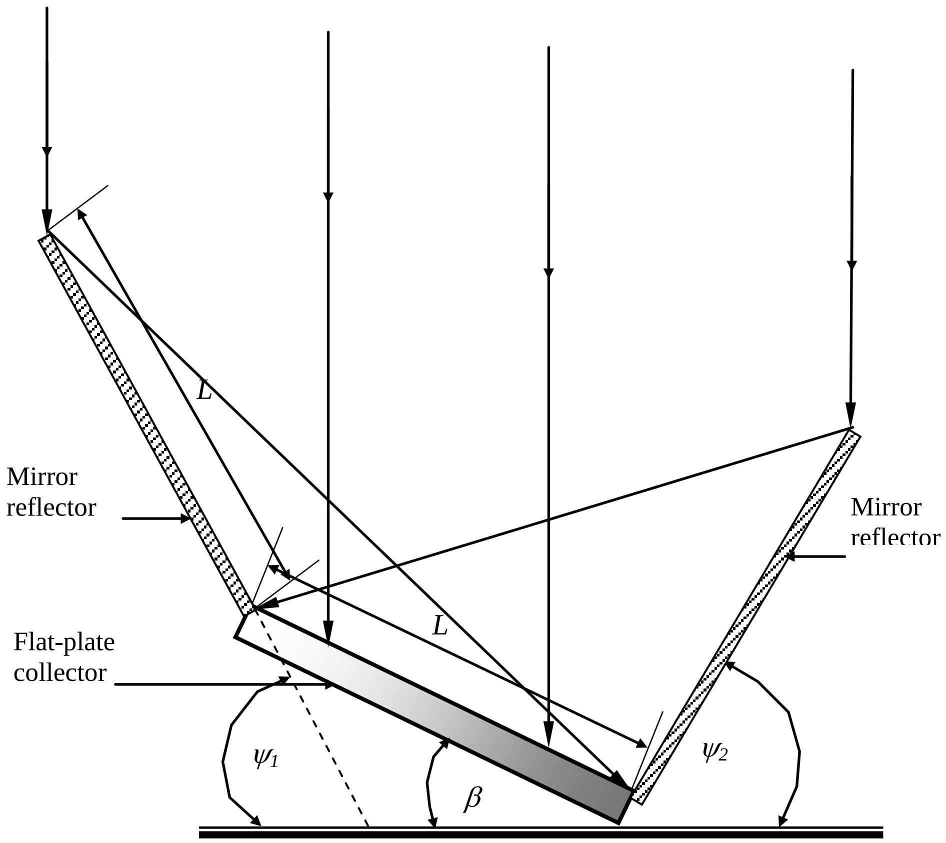

Figure 4 Flate-plate collector with reflectors

Based on equation (3) and F on reflector θ_r are given by :

for reflector facing West, surface azimuth angle: $\xi_w = -90^o$

$$\cos\theta_{rW} = \sin\phi\sin\delta\cos\psi_W + \cos\phi\cos\delta\cos\omega\cos\psi_W - \cos\delta\sin\omega\sin\psi_W \quad \text{.................(4.a)}$$

for reflector facing East, surface azimuth angle: $\xi_w = 90^o$

$$\cos\theta_{rE} = \sin\phi\sin\delta\cos\psi_E + \cos\phi\cos\delta\cos\omega\cos\psi_E + \cos\delta\sin\omega\sin\psi_E \quad \text{........... .... (4.b)}$$

From Fig: 5, we found the relations for η, ψ, θ_r are:

$$\left.\begin{array}{l}\eta = 90^o - \theta_r \\ \psi = 2\times\eta\end{array}\right]$$

Then: $\psi = \pi - 2\theta_r$ (5)

From equations (4.a), (4.b) and (5), we found by trial-and-error, the inclination angle of the reflector ψ_W and ψ_E for facing West and East respectively.

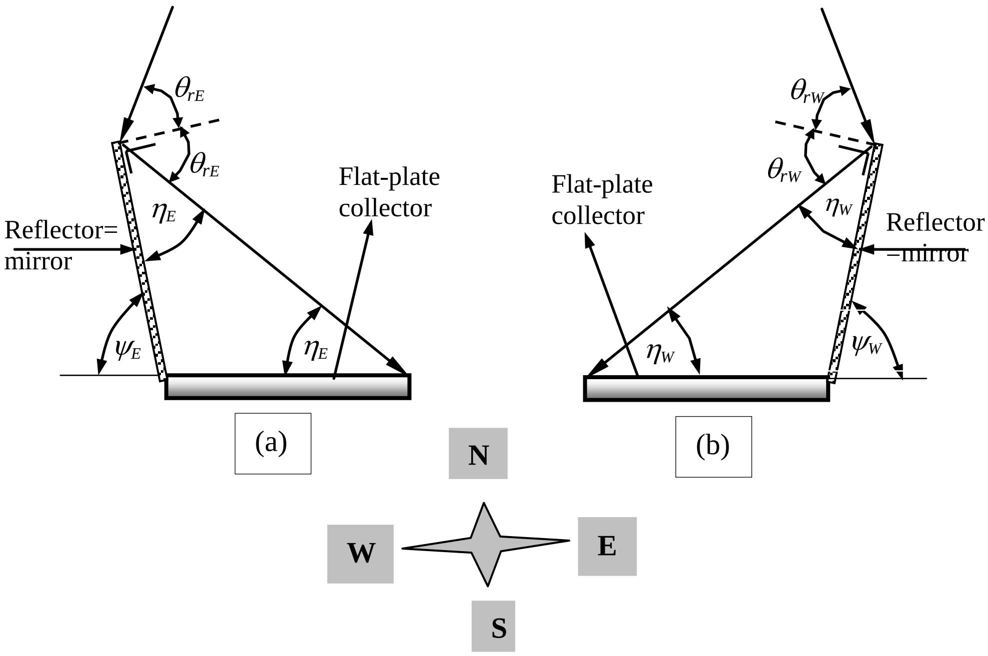

Figure 5 Flat-plate collector and reflectors facing due West and East, $\beta = 0^o$

The flux incident on the top cover of collector I_T and the flux absorber in the absorber plate S are:

Solar radiation flux incident on the top cover of flat-plate collector I_T and flux absorbed in the absorber plate S are sum of the beam and diffuse radiation falling directly on the surface and the radiation reflected onto the surface from the surrounding with the factors r_b, r_d, and r_r. Fluxes I_T and S are given by:

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

$S = I_b r_b (\tau\alpha)_b + \{I_d r_d + (I_b + I_d) r_r\}(\tau\alpha)_b$ (7)

Tilt factor r_b, diffuse radiation factor r_d and reflected radiation factor r_r are given as:

$r_b = \cos\theta/\theta_z$, $r_d = (1+\cos\beta)/2$, and $r_r = \rho(1-\cos\beta)/2$ respectively.

Where θ, θ_z, β, ρ are incidence angle on the surface, zenith angle, surface slope angle, reflectivity respectively. Since $\beta = 0^o$, then r_b and $r_d = 1$, and $r_r = 0$.

Based on equations (6) and (7), solar radiation incidents on the existing flat-plat collector become:
(i). Incident flux on the top of the collector:

Without mirror:

$$I_T = I_b r_b + I_d r_d \tag{6.a}$$

With mirror:

$$I_{Tm} = (I_b + I_{bM})r_b + I_d r_d \tag{6.b}$$

I_{bM} = beam radiation reflected by the two-mirrors = $I_{bW} + I_{bE}$

$$I_{bW} = \frac{I_b}{\cos\theta}\sin\eta_W\ ,\ I_{bE} = \frac{I_b}{\cos\theta}\sin\eta_E$$

(ii). Flux S absorbed on the absorber plate:
Without mirror:

$$S = I_b\, r_b\, (\tau\alpha)_b + (I_d\, r_d)(\tau\alpha)_d \tag{7.a}$$

With mirror:
Since the reflected radiations are not influenced by r_b and r_d then,

$$S_M = (I_b + I_{bM})r_b(\tau\alpha)_b + (I_d\, r_d)(\tau\alpha)_d \tag{7.b}$$

The factors $(\tau\alpha)_b$ and $(\tau\alpha)_d$ are transmisivity-absorptivity product for beam and diffuse radiations. The procedures to calculate $(\tau\alpha)$ can be found in Ref. [2].

The useful heat gain = the rate of heat transfer to the working fluid:

$$q_u = A_p S - q_l \tag{8}$$

The instantaneous collection efficiency is given by:

$$\eta = \frac{\text{Useful heat gain}}{\text{Radiation incident on the collector}} = \frac{q_u}{A_p\, I_T} \tag{9}$$

4. RESULTS AND DISCUSSIONS

The global (I_g) and diffuse (I_d) solar radiations were measured by using digital pyranometer over a day from 9.00 to 16.00 h and the variations are as shown on Fig.6. For performing the calculations, data are taken for the temperatures at: plate-absorber surface, two glass cover surfaces, and water at the inlet and outlet ports of the collector. The ambient temperature and the hourly wind speed over the surface of the collector are also measured. Based on the equations (1) to (5) , we can find the variation of hour angle ω, incident angle on the collector surface θ, incident angle on mirror facing west θ_{rW} and facing east θ_{rE}, inclinations of the mirrors facing west ψ_W and facing east ψ_E. The results obtained are given in Table 1. By considering the calculated inclination angles ψ_W and ψ_E for every hour during the day, the slopes of the two mirrors are adjusted. All the data calculated are available in the files. Figure 6 shows the variations of global I_g and diffuse I_d radiations during a day. It is seen that the values increase a little bit sharp from 0900 to 1100 h, touch a peak around noon and then drop sharply to 1600.

It is also interest to study the performance of collector h for collector with and without mirrors over a day. The variation of the important items are tabulated and presented on graphs are shown in Table 2 and Figures 7, 8, and 9. The variation obtained indicates the strong independence of these items on the radiation incident on the collector. From Figure 7, it seen that the flux incident I_T for collector increase from 0900 to 1100 h and has a maximum value at noon then decrease to 1600 h. It is also shown that collector using mirrors give higher value compared to that without mirrors. The flux incident I_T using mirror facing West has higher values at the 0900 h and the decrease to 1600 h and inversely for collector with mirror facing East gives lower values at 0900 h and higher at afternoon 1600 h. The overall heat loss coefficients do not vary much during the day but have a higher value for collector with mirrors compared to that without mirrors.

The average efficiencies over a whole period, during which considering the useful energy q_u, flux absorbed S , heat loss from collector q_l, flux incident on the top cover I_T, could also be calculated. Making the approximation, then the efficiencies average over 8 hours from 0900 to 1600 h for collector with and without mirrors work out to be 41.9 % and 22.8 % respectively.

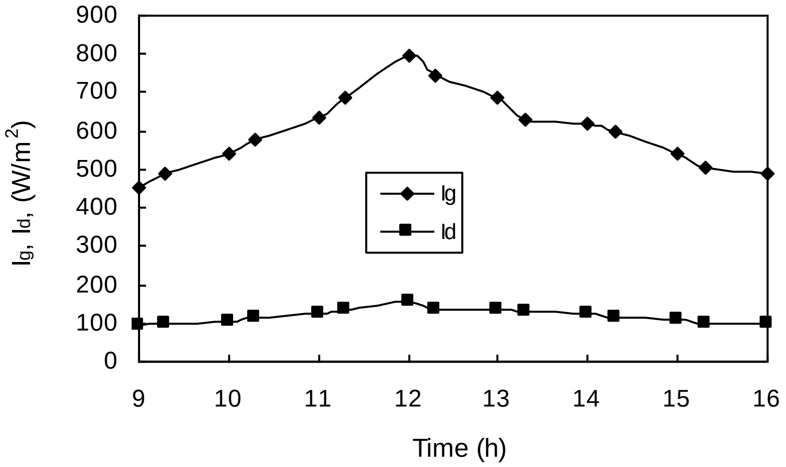

Figure 6 Variations of global I_g and diffuse I_d radiations over a day

Table 1 The variation of the inclination angles over a day on 24 October. N = 297, $\delta = -12.79^o$, $\xi_{w.W} = -90^o$, $\xi_{w.E} = +90^o$

Time	***09.00***	***10.00***	***11.00***	***12.00***	***13.00***	***14.00***	***15.00***	16.00
$\omega(^o)$	45	30	15	0	-15	-30	-45	-60
$\theta(^o)$	45.74	31.27	17.57	9.25	17.57	31.27	45.74	60.43
$\theta_{rw}(^o)$	74.829	69.904	64.978	60.054	55.133	50.220	45.320	40.447
$\theta_{rE}(^o)$	45.475	50.328	55.208	60.10	65.007	69.918	74.835	79.758
$\psi_W(^o)$	30.342	40.193	50.044	59.893	69.734	79.561	89.360	99.106
$\psi_E(^o)$	89.050	79.345	69.585	59.801	49.987	40.164	30.330	20.485

Table 2 Performance of a flat-plate collector with and without mirrors over a day, $T_a \approx 32$ °C

LST(h)	*09.00*	*10.00*	*11.00*	*12.00*	*13.00*	*14.00*	*15.00*	**16.00**
I_b (W/m^2)	382.2	403.4	509.8	613	544.2	496.4	427.4	388.6
I_d (W/m^2)	90.8	108.6	127.2	159.0	137.8	123.6	108.6	97.4
I_{bM} (W/m^2)	543.58	461.26	523.86	608.86	599.21	567.60	595.50	757.07
I_T (W/m^2)	473.00	512.00	637.00	772	692	620.00	536.00	486.00
I_{TM} (W/m^2)	891.74	930.21	1010.10	1130.11	1100.21	1066.46	1060.12	1054.60
S (W/m^2)	300.0	345.0	380.0	430.0	404.54	376.0	345.0	294.0
S_M (W/m^2)	563.05	644.44	699.58	790.0	751.03	720.0	685.0	615.0
T_p (°C)	65.2	70.6	76.1	80	77	74	71.5	65
T_{pM} (°C)	68.0	73.5	83.0	95.0	87.0	83.0	74.5	66.0
U_l(W/m^2-K)	4.96	5.55	5.62	5.67	5.45	5.34	5.33	5.04
$U_{l\text{-}M}$ (W/m^2-K)	5.60	5.77	5.85	5.91	5.87	5.76	5.73	5.38
q_u (W)	170.5	188.0	235	288.86	255	226	194	172
$q_{u.M}$ (W)	552.00	570.00	633.00	715.58	685.65	655.00	620.12	571.23
η (%)	22.50	22.92	23.03	23.36	23.00	22.75	22.59	22.10
η_M **(%)**	38.25	38.64	39.12	39.53	38.56	38.34	36.52	33.81

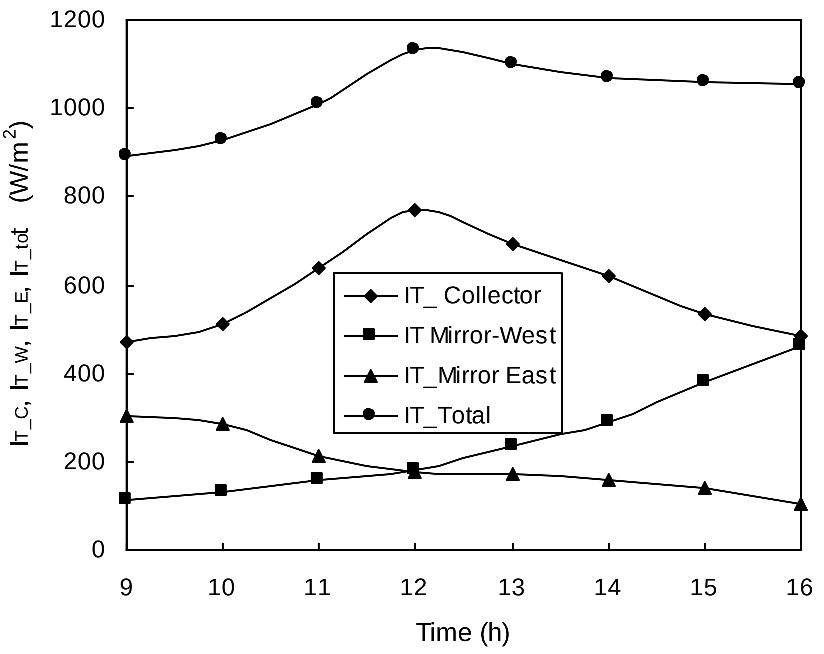

Figure 7 Variations of flux incident on the top cover of the collector over a day

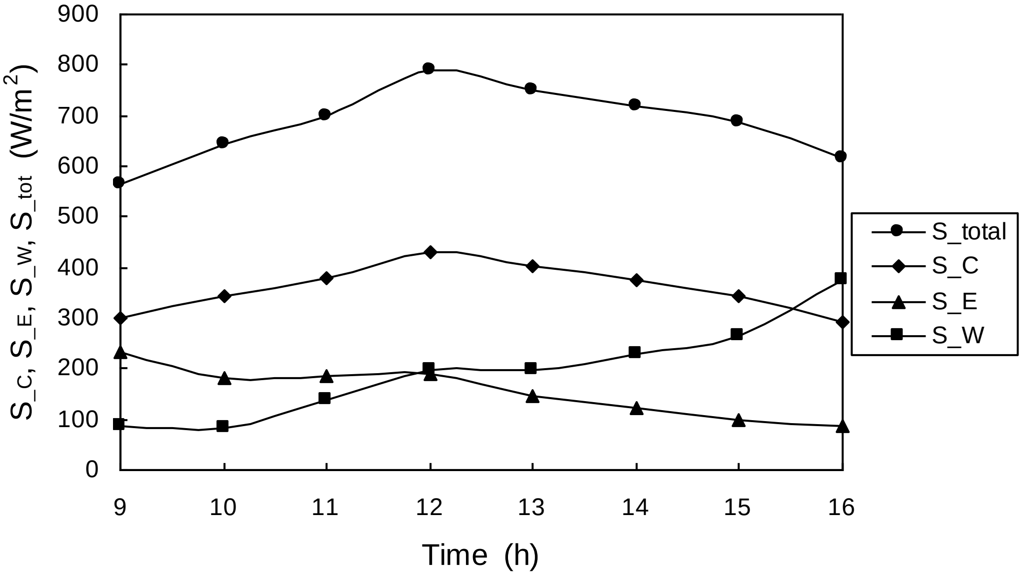

Figure 8 Variations of Insident solar flux in the absorber plate over a day

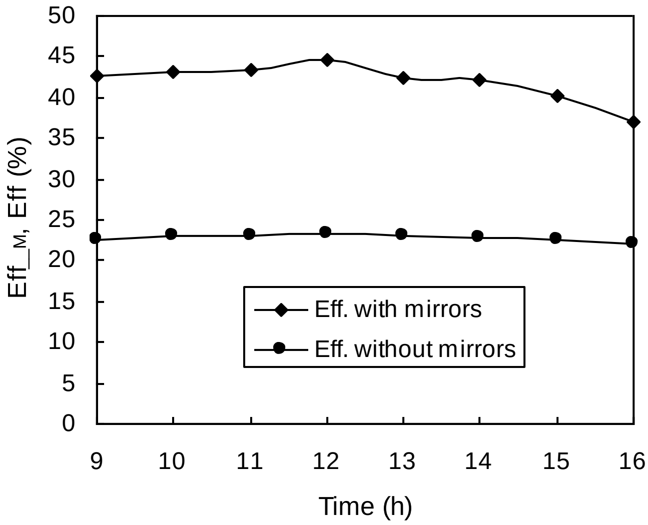

Figure 9 Variation of efficiencies with mirror and without mirror over a day

5.CONCLUSIONS

From the calculations of useful energy q_u, flux absorbed S , heat loss from collector q_l, flux incident on the top cover I_T, and making approximation, the efficiencies average over 8 hours from 0900 to 1600 h for collector with and without mirrors work out to be 41.9 % and 22.8 % respectively.

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