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On the performance of a Flat Plate Collector

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Abstract – Flat plate collector with thin absorber is studied. Heat balance equation is solved to estimate the temperature of the absorber and its variation along the local day time. The same equation is used to determine the temperature of the working fluid. A published expression [20] to predict with good fitting the hourly global solar irradiance is considered as a source function for the incident solar energy. Three absorbers of different materials: Copper, Aluminum and Mica are considered. The water is considered as a working fluid. Two cooling conditions at the absorber front surface are considered. Factors affecting the efficiency are revealed.

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1. INTRODUCTION

Solar energy exploitation can be principally achieved through basic technological patterns namely:

1) Helio-chemical process (photosynthesis)
2) Helio-electrical process (photovoltaic convertors)
3) Heliothermal process (fixation of received solar energy)

The most important element of the third type is the collectors, either flat plate collectors or concentric collectors. The flat plate collectors are still among the most common devices for solar heating [1]. It absorbs solar energy and then converts it into heat and then transfers that heat to a working fluid. It consists of several basic elements such as: glazing cover (may be glass or transparent plastic), absorber plate (which may be flat), insulation (which minimizes heat loss from the back and sides of the collector), container or casing (to protect it from dust, moisture … etc.), tubes or channels or reservoir through which the working fluid circulates removing the thermal energy from the plate to a storage tank.

These collectors are useful in supplying low-grade thermal energy at temperatures generally less than 90 0c [2]. The most important part of the collector is its absorber plate.

The performance and efficiency of such collectors have aroused the interest of many investigators [3-7].

There are a variety of fluids that may be used to act on working fluid, but practically water or water ethylene glycol solutions are used in principle. There are a variety of factors that affect the collector's efficiency such as: The absorber temperature and its roughness, absorptivity, the convective heat loss and radiative heat loss from the glass cover, the kind of the working fluid, its rate of mass flow, and the variation of the received incident solar radiation along the local day time. Besides, the angle of incidence of such radiation [1-13].

The objective of the present trial is to study theoretically the performance of a flat plate collector and to evaluate quantitatively its efficiency. This may be useful to reveal the functional dependence of the efficiency on the different parameters controlling it.

2. THEORY

To study the performance of a flat plate solar collector, a simple model is considered as shown in figure 1.

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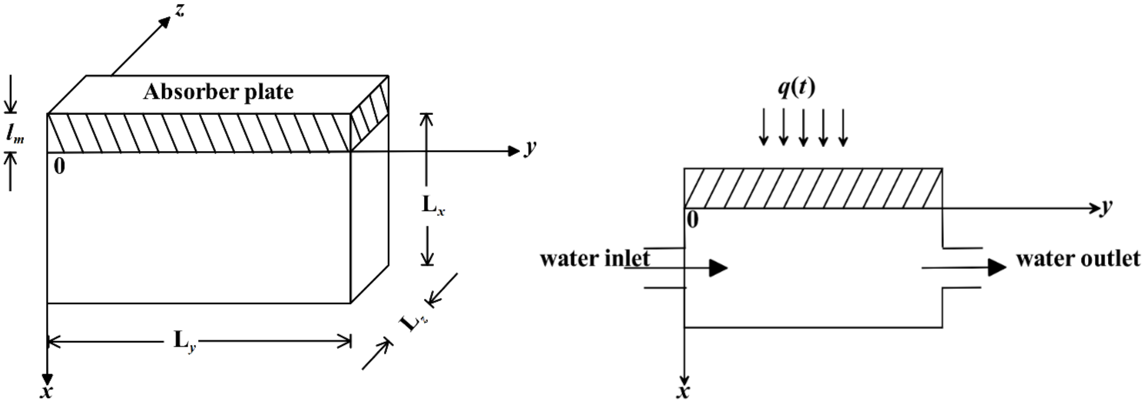


Fig 1: simple model of a flat plate collector.

It is assumed that the collector has a thin absorber plate, so as to realize a homogenous temperature field through it. Thus, no temperature gradient is found across its cross-section area. This absorber is subjected to incident to daily global solar radiation (t),W⁄m^2 . This requires information on such a function. There are a lot of trials to predict q(t) using various parameters [14-21]. In the present trial, one accepts a distribution published elsewhere [20] of the form:

$$q(t) = 4q_{max}\left(\frac{t}{t_d}\right)\left(1-\frac{t}{t_d}\right) \qquad (1)$$

It is a symmetrical distribution about the midday time $t_0 = t_{max} = \frac{t_d}{2}$ with maximum irradiance q_{max} ,W/m^2 at $t = t_{max}$, where t_d is the length of the solar day. The value of "t_d" is given in terms of the latitude "L" and the solar declination "δ" [22] as follows:

$$t_d = \frac{24hr}{180}\cos^{-1}(-\tan\delta\tan L) \qquad (2)$$

Where, $$\delta = 23.45\sin 360\frac{284+n}{365} \qquad (3)$$

And "n" is the day of the year $(1 \le n \le 365)$ starting from 1 January.
The distribution eq. (1) satisfies the following conditions

i) At $t = 0$ (sunrise), $q(0) = 0$
ii) At $t = t_s = t_d$ (sunset), $q(t_s) = 0$
iii) At $t = t_{max}$, $q(t) = q_{max}$

$$\left.\frac{\partial q}{\partial t}\right|_{t=t_{max}} = 0$$

2.1. *Determination of the temperature of the absorber*

To find the temperature absorber, let us write the heat balance equation in the form:

$$(1-R)q(t) - h\Theta(t) = l\rho c_p\frac{d\theta}{dt} \qquad (4)$$

The first term represents the heat energy absorbed by the absorber, "R" is the reflectance of the front surface,"h",(W/m^2K) is the heat transfer by convection, "ρ",(kg/m^3) is the density of the absorber material, "l",(m) is thickness of the absorber, and $\Theta(t) = (T - T_0)$ is the excess temperature relative to the ambient temperature "T_0".
Heat losses due to radiation (infrared emission) are neglected. Equation (4) has an integrating factor:

$$The\ integrating\ factor = e^{\int\frac{h}{l\rho c_p}dt} \qquad (5)$$

The solution is obtained in the form:

$$\theta_m = e^{-\int \frac{h}{l\rho c_p}dt}\left[\int_0^t \frac{(1-R)}{l\rho c_p} q(t) e^{\int \frac{h}{l\rho c_p}dt}\, dt + C\right] \tag{6}$$

at $t = 0$, $\theta(0) = 0$, one gets $C = 0$

Substituting the distribution $q(t)$ equation (1) in equation (6) and performing the included integration, one gets the solution for $\theta(t)$ expressed as follows:

$$\theta_m(t) = e^{-at}\left[Nt_d\left\{e^{at}\left[\frac{t}{a}-\frac{1}{a^2}\right]+\frac{1}{a^2}\right\} - N\left\{e^{at}\left[\frac{t^2}{a}-\frac{2t}{a^2}+\frac{2}{a^3}\right]-\frac{2}{a^3}\right\}\right] \tag{7}$$

Where,

$$a = \frac{h}{l\rho c_p}, \quad N = \frac{4\alpha q_{max}}{{t_d}^2}, \quad \alpha = \frac{(1-R)}{l\rho c_p} \tag{8}$$

2.2. *Determination of the working fluid temperature*

Let the thin absorber of thickness "l", (m) represents the upper ceiling for a reservoir of dimensions L_x, L_y and L_z ,(m). The upper surface of the thin absorber of area$S_x = L_y L_z$, (m^2) is subjected to the incident solar radiation$q(t), W/m^2$.

The x-axis is taken vertically downwards. It is coincident with the direction of the incident radiation. The volume of the absorber material is$V_{abs} = l_m L_y L_z, m^3$. The volume of the reservoir is$V_{res} = L_x L_y L_z, m^3$.

The sides of the reservoir are assumed to be thermally insulated. The working fluid enters the reservoir from the face$dS_y = L_z L_x$, (m^2) and emerges from the opposite sides. For simplicity, let $L_y = L_z = 1m$.

The fluid flows along the y-direction with velocityv_y,$\left(\frac{m}{s}\right)$, and volumetric rate :

$$G_y = L_z L_x v_y, \ (m^3/s) \tag{9}$$

Let $\bar{\theta}_w$ represents the average temperature of the working fluid within an interval of timeΔt.

The value of which is gives as:

$$\bar{\theta}_w(t) = \frac{\int_0^t \theta_w(t)\, dt}{\int_0^t dt} \tag{10}$$

Thus, the heat balance equation concerning the working fluid within an interval of time Δt is written in the form:

$$\int_0^t l_m L_y L_z \rho_m c_{p_m} \frac{\partial \theta_m}{\partial t} dt = V_{res}\rho_w c_{p_w}\bar{\theta}_w(t) + \rho_w c_{p_w}\bar{\theta}_w \int_0^t G_w dt \tag{11}$$

If the volumetric rate of working fluid is constant, i.e. $G_w = const.$ one gets:

$$\bar{\theta}_w(t) = \frac{1 \cdot l_m \rho_m c_{p_m} \theta_m(t)}{V_{res}\rho_w c_{p_w} + \rho_w c_{p_w}\int_0^t G_w dt} \tag{12}$$

$$\bar{\theta}_w = \frac{1\cdot l_m \rho_m c_{p_m} e^{-at}\left[Nt_d\left\{e^{at}\left[\frac{t}{a}-\frac{1}{a^2}\right]+\frac{1}{a^2}\right\}-N\left\{e^{at}\left[\frac{t^2}{a}-\frac{2t}{a^2}+\frac{2}{a^3}\right]-\frac{2}{a^3}\right\}\right]}{\rho_w c_{p_w}(V_{res}+G_w t)} \tag{12}$$

The first term on the right-hand side of equation (11) represents the heat energy stored in the working fluid within the reservoir. In an interval of time$\int_0^t dt$, s. The second term represents the heat energy gained by the flow during the same intervalΔt, s.

2.3. *The efficiencyη*

The efficiency of the flat plate collector within a certain interval of time $\Delta t = \int_0^t dt$, s. defined through the equation:

$$\eta = \frac{\textit{The heat energy gained by the fluid within "t"}}{\textit{The incident solar energy within the same interval "t"}}$$

$$\eta = \frac{V_{res}\rho_w c_{p_w}\bar{\theta}_w + \rho_w c_{p_w}\bar{\theta}_w \int_0^t G_w dt}{1 \cdot \int_0^t q(t)dt} \qquad (13)$$

Substituting the distribution $q(t)$ equation (1) in equation (13) and performing the included integration, one gets the effciency expressed as follows
Then,

$$\eta = \frac{\rho_w c_{p_w}\bar{\theta}_w (V_{res} + G_w t)}{4q_{max}t_d\left[\frac{1}{2}\left(\frac{t}{t_d}\right)^2 - \frac{1}{3}\left(\frac{t}{t_d}\right)^3\right]} \qquad (14)$$

Where $\bar{\theta}_w$ is evaluated within the same interval of time according to equation (12).

3. COMPUTATIONS

The incident solar irradiance received per unit area in Makah (1983) [20] is considered with parameters: $q_{max} = 938\ W/m^2$, $t_d = 12\ hr$, and is predicted using equation (1) with fitting 8% [20]. The dimensions of the absorber are: $l_m = 0.01m$ (its thickness).
Two cooling conditions are considered for $h = 3\ \ W/m^2K$ and $h = 10\ \ W/m^2K$ the reflection coefficient $R = 0.2$. Three materials are considered. These are Copper (Cu), Aluminum (Al) and Mica. The physical parameters of which are given in table 1.

Table 1. The physical parameters of the considered absorber materials.

Element	$\rho, kg/m^3$	$c_p, J/kg.K$
Cu	8954	383.1
Al	2710	910
Mica	2883	880

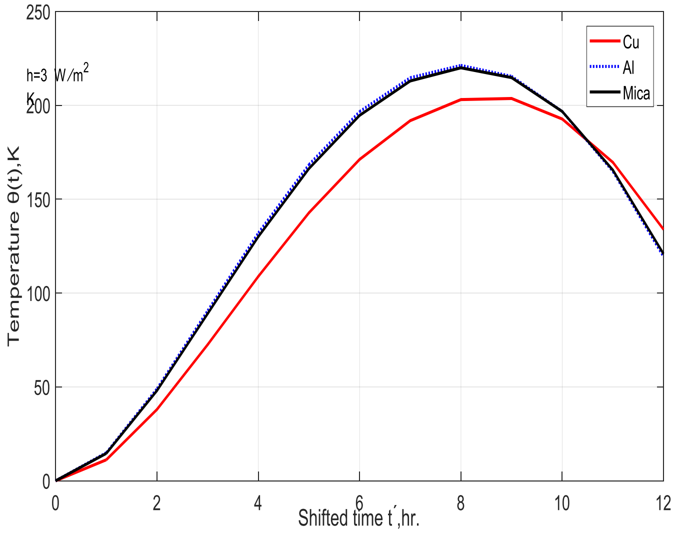
For water as the working fluid: $\rho_w = 1000\ kg/m^3$, $c_{p_w} = 4.1818 \times 10^{3} J/kg\ K$ The volumetric water rate $G_{w_y} = 10^{-7}\ m^3/s$ and the volume of the reservoir $V_{res} = 0.05\ m^3$

3.1. *The temperature $\theta(t)$ of the absorber plate*

The temperature of the three elements subjected to the incident solar radiation $q(t)$ is computed along the local day time according to equation (7). Shifted time is considered according to which the sunrise time "t_r" is taken as zero, i.e. $t_r = 0$ the obtained results are given in table 2 and table 3 for $h = 3\ \ W/m^2K$ and$h = 10\ \ W/m^2K$. These data are illustrated graphically in figures 2 and 3 respectively.

Table 2. The variation of the temperature of the absorber of different materials subjected to incident solar radiation with local day time [Eq. (7)] for [$h = 3\ \ W/m^2K$].

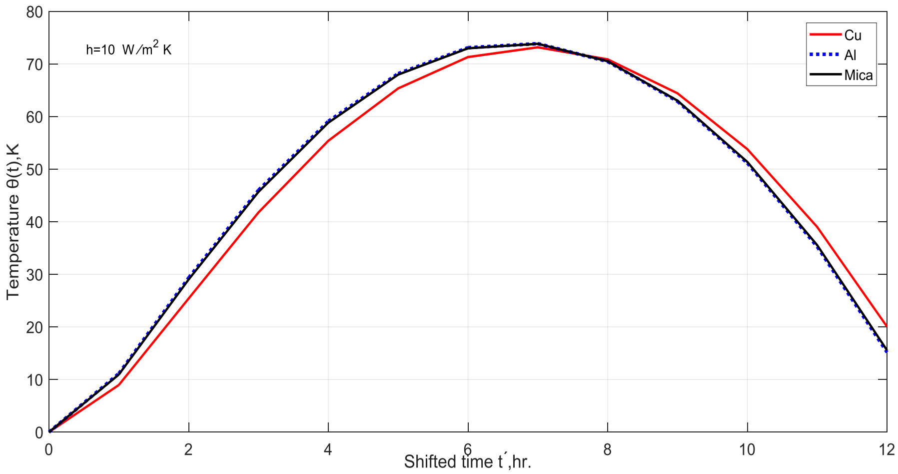
Shifted time $\acute{t}, hr.$	$\theta_m(t), K$		
	Cu	**Al**	**Mica**
0	0	0	0
1	11.1747	14.9477	14.5858
2	37.9995	49.0557	48.0327
3	72.4942	90.6009	88.9841
4	108.8336	132.0178	130.0208
5	142.7663	168.4238	166.2956
6	171.1888	196.6678	194.6418
7	191.8363	214.7162	212.9904
8	203.0552	221.2567	219.9899
9	203.6390	215.4422	214.7572
10	192.7067	196.7261	196.7153
11	169.6155	164.7557	165.4875
12	133.8962	119.3033	120.8273



Fig(2): The variation of the temperature of the absorber of different materials subjected to incident solar radiation with local day time.

Table 3. The variation of the Temperature of the absorber of different materials subjected to incident solar radiation with local day time [Eq. (7)] for $[h = 10 \ \ W/m^2K]$.

Shifted time $\acute{t}, hr.$	$\theta_m(t), K$		
	Cu	**Al**	**Mica**
0	0	0	0
1	8.9521	11.1281	10.9348
2	25.4001	29.3394	29.0198
3	41.7633	45.9956	45.6747
4	55.3875	59.0899	58.8234
5	65.3435	68.1564	67.9635
6	71.3058	73.0867	72.9735
7	73.1606	73.8558	73.8240
8	70.8681	70.4577	70.5079
9	64.4142	62.8911	63.0234
10	53.7940	51.1558	51.3702
11	39.0058	35.2516	35.5482
12	20.0491	15.1785	15.5573



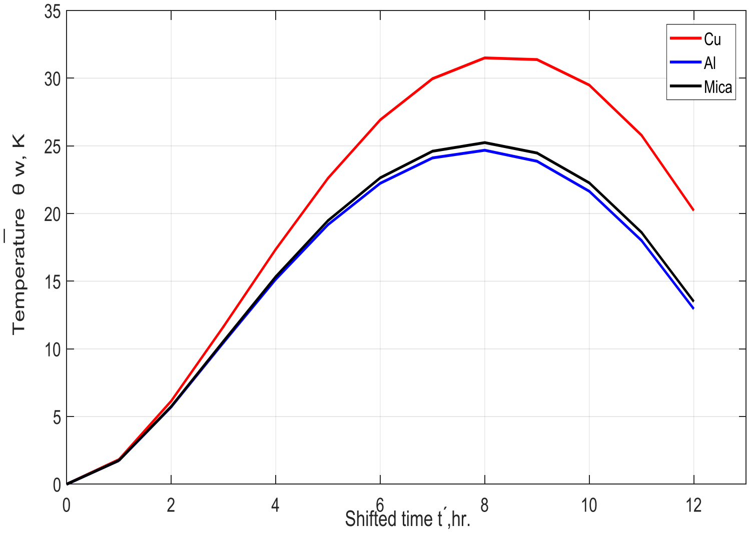
Fig(3): The variation of the temperature ofthe absorber of different materials subjected to incident solar with local day time

3.2. *The temperature of the working fluid*

The temperature of the working fluid (water) is computed as an average value $\bar{\theta}_w$ within a certain interval of time according equation (12). The heat transfer coefficient for convection "h" is taken equal to3 W/m^2K. The obtained results for considered three elements Cu, Al and Mica are given in table 4. And are illustrated graphically in figure 4.

Table 4. The variation of the temperature of the working fluid$\bar{\theta}_w$, ${}^0K$ with local day time [Eq. (12)] for [$h = 3\ \ W/m^2K$].

Shifted time $\acute{t}, hr.$	$\bar{\theta}_w,\ {}^0K$		
	Cu	**Al**	**Mica**
0	0	0	0
1	1.8202	1.7504	1.7571
2	6.1456	5.7037	5.7454
3	11.6418	10.4599	10.5688
4	17.3551	15.1349	15.3347
5	22.6080	19.1744	19.4767
6	26.9218	22.2353	22.6393
7	29.9621	24.1095	24.6036
8	31.4984	24.6747	25.2392
9	31.3754	23.8638	24.4722
10	29.4916	21.6444	22.2658
11	25.7846	18.0059	18.6062
12	20.2197	12.9521	13.4949



Fig(4): The variation of the temperature of the working fluid with local day time

3.3. *The efficiency (η) computations*

The efficiency "η" is computed according to equation (14) for the three elements for different time intervals along the local day time. The obtained results are given in table 5 and are presented graphically in figure 5.

Table 5. The variation of the efficiency η with local day time [Eq. (14)] for [$h = 3\,W/m^2K$].

Shifted time $\acute{t}, hr.$	η,%		
	Cu	**Al**	**Mica**
1	72.1170	69.3515	69.6169
2	65.1396	60.4558	60.8977
3	58.9141	52.9330	53.4841
4	53.3042	46.4851	47.0988
5	48.1937	40.8743	41.5187
6	43.4750	35.9069	36.5594
7	39.0472	31.4200	32.0639

8	34.8082	27.2675	27.8913
9	30.6465	23.3094	23.9037
10	26.4274	19.3955	19.9524
11	21.9700	15.3421	15.8536
12	17.0021	10.8910	11.3474

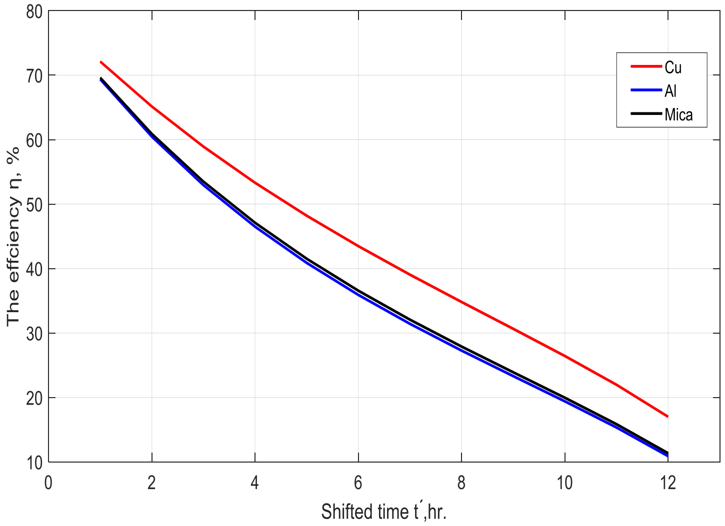


Fig (5): The variation of the effciency η,% with local day time [Eq. (14)] for [h=3 W ⁄(m^2 K)]

4. CONCLUSIONS

The obtained results make it possible to formulate a set of conclusions:

The temperature of the thin absorber $\theta(t)$ does depend linearly on the maximum value of the received incident solar irradiance$q_{max}, W/m^2$.

The function $\theta(t)$ changes with the local exposure time and passes through a maximum value.
The value of $\theta(t)$ weakly depends on the physical parameters of the absorber material. This result is a vital economical importance. The curves of $\theta(t)$ for the three elements are nearly coincident, especially for Aluminum and Mica. Such a result is in coincidence with that obtained by other authors [10]. Moreover, it depends principally on cooling conditions.

The temperature of the working fluid varies with local day time, volume of the reservoir, the volumetric rate of the working fluid, and the geometrical and physical properties of the absorber plate.

The efficiency of the collector as given through eq (14) is inversely proportional to the maximum value of the incident solar irradiance, and it does depend also on all other operating conditions as shown in equation (14).

All such factors are well known, nevertheless, our study represents a quantitative analysis of the flat plate collector dealing with its performance and this may be useful for further analysis.

REFERENCES

[1] G. N. Tiwari, S. Suneja, Solar thermal engineering systems, *Narosa publishing house*, London, (1997) Ch. 3 P. 82.

[2] A. A. M. Sayigh, Solar energy engineering, *Academic press*, London, (1977), Ch. **6** P.106.

[3] G. M. Nouidu, J. P. Agrawal, A theoretical study of heat transfer in a flat plate collector, *Solar energy* **26**, pp.313 (1981).

[4] S. P. Chow, G. L. Harding, Effect of antireflection coating on the transmittance of glass tubular and plane double glazed covers for flat plate collectors, *Solar energy*, **34**(2) pp.183 (1985).

[5] L. Jianmin, X. Wenhua, Analysis of thermal performance of a new type of flat-plate collector with a black ceramic absorber, *Int. Energy Journal* **12** (2) (1990).

[6] H. Ming and T. Tolin, Efficiency improvement of flat-plate solar air heaters, *Energy* vol.**21**, No.6, pp.435-443 (1996).

[7] S. A. Kalogiron, Solar thermal collectors and applications, *Progress in energy and combustion science* **30**, 231-295 (2004)

[8] J. F. Kreider and F. Kreith, Solar heating and cooling, McGraw-Hill, New York, (1977)

[9] W. E. Buckles, S. A. Klein, *Solar energy*, vol.**35**, p417 (1980)

[10] M. K. El-Adawi, M. M. Al-Nicklawy, G. G. Al-Barakati and A. A. Kutub, Bulletin Faculty of education (Umm Alqura University) vol.**1** No.3, 9(1984).

[11] S. A. Shalaby, A study on flat plate collector, *Indian J. Physics* **69B** (5), pp. 373-388 (1995).

[12] S. K. Samdarshi, S. C. Mullick, Analysis of the top heat loss factor of flat plate solar collector with single and double glazing. *Int. J. Energy Res.* Vol.**14**, p975 (1990).

[13] D. Gupta, S. C. Solanki, J. S. Saini, Effect of artificial roughness on performance of solar air heaters, New Delhi: Solar Energy society of India/Tata McGraw Hill: (1990) p.14.

[14] B. Y. Liu, R. C. Jordan, The interrelationship and characteristic distribution of direct, diffuse and total radiation, *Solar energy* vol.**4** (1), (1960).

[15] S. I. Reddy, An empirical method for estimation of the total solar radiation, *Solar Energy*, vol. **13**, pp.289 (1971).

[16] M. M. Munroe, Estimation of irradiance on a horizontal surface from U.K. average meteorological data, *Solar Energy* vol. **24** , pp.235(1980).

[17] C. T. Leung, The fluctuation of solar irradiance in Hong Kong, *Solar Energy* vol. **25**, pp. 485 (1980).

[18] M. K. El-Adawi, M. M. Al-Nicklawi, A. A. Kutub, G. G. Al-Barakati, Estimation of the hourly solar irradiance on a horizontal surface, vol.**36** (2), pp.129(1986).

[19] S. A. Shalaby, Estimation of global solar irradiance on a horizontal surface – New Approach, *Indian J. Phys.* **68B** (6), pp 503-513(1994).

[20] M. K. El-Adawi, New approach to modelling a flat plate collector Fourier transform technique, *Renewable Energy* **26**, pp.489-506 (2002).

[21] M. K. El-Adawi, S. A. Shalaby, S. E. S. Abd El-Ghany, F. E. Salman and M. A. Attallah, prediction of the daily global solar irradiance received on a horizontal surface – New approach, *Int. Refereed J. of Engineering and Science (IRJES)*, vol.**4** issue 6, pp.85-93, (2015).

[22] J. A. Duffiee, W. A. Beckman, Solar Energy Thermal processes, Wiley-Interscience, New York (1974).