



The Performance and Efficiency of Flat Plate Collectors with Different Absorbers and Different Convection Heat Loss Levels

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Abstract

The performance of a flat plate solar collector with thin absorber is studied. The temperature of the absorber and its variation along the local day time is obtained by solving a heat balance equation. The temperature of the working fluid is also estimated. A published solar source function to predict the hourly daily incident solar irradiance on horizontal surface is considered. Five absorbers of different materials: Copper, Aluminum, Stainless steel, Glass and Mica are treated. Two cooling conditions at the absorber front irradiated surface are also taken into consideration. Factors affecting its efficiency are revealed.



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Introduction

The flat plate collectors are still among the most popular devices to intercept and exploit solar energy. The absorbed solar energy is transferred to a fluid passing in contact with its absorber plate.

Increasing the efficiency of such a device has aroused the interest of many investigators.¹⁻⁸

The main part of such a system is its absorber plate whose thermal performance affects essentially its efficiency.

To study the thermal response of the collector one has to get information on the incident global solar irradiance $q(t)$, W/m^2 and its variation along the local day time.

This represents an essential input parameter to study the performance theoretically.

Several trials are made to predict the function $q(t)$.⁹⁻¹⁷

In the present study $q(t)$ ⁹ is considered.

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Absorbers of different material such as: Copper, Aluminum, Steel, Glass and Mica are treated.

Water is considered in the present study as the working fluid.

Other factors affect the efficiency of the collector as the water rate of flow, selective coatings of the front surface of the absorber, heat losses by convection and radiation, the surface absorptivity of the surface.

Heating Problem

In setting up the problem it is assumed that the solar insolation $q(t)$ W/m² is received on the upper surface

of the absorber plate, where it will be partly reflected and partly absorbed $(1-R) q(t)$ W/m². The absorbed energy will induce heating effects within the absorber. This part of heat energy will be transferred to the working fluid glazing its near surface.

A thin absorber is considered in this study thus neglecting any temperature gradient across its thickness.

A simple device for the collector is shown in fig. (1). The absorber is kept in a horizontal position. The problem is thus treated as one dimensional problem.^{16,18}

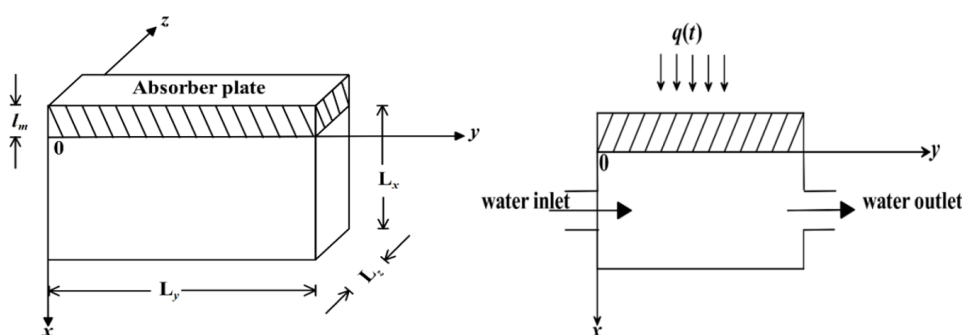


Fig. 1: simple model of a flat plate collector

The accepted distribution $q(t)$ ⁹ has the form:

$$q(t) = q_{max} \left(\frac{t}{t_0} \right)^2 \left(\frac{t_d - t}{t_d - t_0} \right)^2 \quad \dots(1)$$

It is a symmetrical distribution about the midday time $t_0 = t_{max} = t_d/2$ with maximum irradiance q_{max} , W/m² 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 "¹⁹ as follows:

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

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

And " n " is the day of the year ($1 \leq n \leq 365$) starting from 1 January.

The distribution eq. (1) satisfies the following conditions

$$\begin{aligned} \text{At } t=0 \text{ (sunrise),} & \quad q(0) = 0 \\ \text{At } t=t_s=t_d \text{ (sunset),} & \quad q(t_s) = 0 \end{aligned}$$

$$\text{At } t=t_{max}, \quad q(t) = q_{max}$$

$$\frac{\partial q}{\partial t} \bigg|_{t=t_{max}} = 0$$

Determination of the Temperature of the Absorber

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

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

The first term represents the heat energy absorbed by the absorber, " R " is the reflectance of the front surface, " h ", (W/(m² K)) is the heat transfer by convection at the front surface, " ρ ", (kg/(m³)) 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:

$$\text{The integrating factor} = e^{\int \frac{h}{\rho c_p} dt} \quad \dots(5)$$

The solution is thus obtained in the form:

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

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:

$$\theta_m(t) = Bt_d^2 \left[\left(\frac{t^2}{a} - \frac{2t}{a^2} + \frac{2}{a^3} \right) - \frac{2}{a^3} e^{-at} \right] - 2Bt_d \left[\left(\frac{t^3}{a} - \frac{3t^2}{a^2} + \frac{6t}{a^3} - \frac{6}{a^4} \right) + \frac{6}{a^4} e^{-at} \right] + B \left[\left(\frac{t^4}{a} - \frac{4t^3}{a^2} + \frac{12t^2}{a^3} - \frac{24t}{a^4} + \frac{24}{a^5} \right) - \frac{24}{a^5} e^{-at} \right] \quad \dots(7)$$

Where,

$$a = \frac{h}{l\rho c_p}, \quad B = \left\{ \frac{Aq_{max}}{(t_0^2 t_d^2 - 2t_0 t_d^3 + t_0^4)} \right\}, \quad A = \frac{(1-R)}{l\rho c_p} \quad \dots(8)$$

Determination of the Temperature 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 $V_{abs} = l L_y L_z, m^3$. 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 faced $S_y = L_z L_x, m^2$ and emerges from the opposite sides. For simplicity, let $L_y = L_z = 1m$.

The fluid flows along the y-direction with velocity v_y , (m/s), and volumetric rate:

$$G_y = L_z L_x L_y, (m^3 / s) \quad \dots(9)$$

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

The value of which is given as:

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

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

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

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

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

$$\bar{\theta}_w = \frac{1 \cdot l_m \rho_m c_{p_m} \left\{ Bt_d^2 \left[\left(\frac{t^2}{a} - \frac{2t}{a^2} + \frac{2}{a^3} \right) - \frac{2}{a^3} e^{-at} \right] - 2Bt_d \left[\left(\frac{t^3}{a} - \frac{3t^2}{a^2} + \frac{6t}{a^3} - \frac{6}{a^4} \right) + \frac{6}{a^4} e^{-at} \right] \right\}}{\rho_w c_{p_w} (V_{res} + G_w t)} + \frac{1 \cdot l_m \rho_m c_{p_m} \left\{ B \left[\left(\frac{t^4}{a} - \frac{4t^3}{a^2} + \frac{12t^2}{a^3} - \frac{24t}{a^4} + \frac{24}{a^5} \right) - \frac{24}{a^5} e^{-at} \right] \right\}}{\rho_w c_{p_w} (V_{res} + G_w t)} \quad \dots(13)$$

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 Δt . The second term represents the heat energy gained by the flowing fluid during the same interval Δt , s.

The Efficiency η

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

$\eta = (\text{The heat energy gained by the fluid within an interval } \Delta t) / (\text{The incident solar energy within the same interval } \Delta t)$

$$\eta = \frac{V_{res} \rho_w c_{p_w} \bar{\theta}_w + \rho_w c_{p_w} \bar{\theta}_w \int_0^t G_w dt}{1 \cdot \int_0^t q(t) dt} \quad \dots(14)$$

Substituting the distribution $q(t)$ equation (1) in equation (14) and performing the included integration, one gets the efficiency expressed as follows :

$$\eta = \frac{\rho_w c_{p_w} \bar{\theta}_w (V_{res} + G_w t)}{K \left[\frac{1}{3} t^3 t_d^2 - \frac{1}{2} t^4 t_d + \frac{1}{5} t^5 \right]} \quad \dots(15)$$

Where, $K = q_{max} (1/t_0)^2 (1/(t_d - t_0))^2$,

$\bar{\theta}_w$ is evaluated within the same interval of time according to equation (13).

Computations

The experimental values of the incident solar irradiance received per unit area in Makah⁹ with parameters: $q_{max} = 938 \text{ W/m}^2$, $t_d = 12 \text{ hr}$, These values

are computed according to our model (eq.1). The obtained fitting between them is revealed to be 92%.

Two cooling conditions are considered $h=3 \text{ W}/(\text{m}^2 \text{ K})$ and $h=10 \text{ W}/(\text{m}^2 \text{ K})$ the reflection coefficient $R=0.2$. Five materials are considered. These are Copper (Cu), Aluminum (Al), Steel, Crown glass and Mica. The physical parameters of which are given in table (1).

Table 1: The physical parameters of the considered absorber materials.²⁰

Element	$\rho, \text{kg/m}^3$	$c_p, \text{J/kg.K}$
Cu	8954	383.1
Al	2710	910
Mica	2883	880
Steel	7833	465
Crown glass	2500	670

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

The Temperature $\theta(t)$ of the Absorber Plate

The temperature of the five elements subjected to the incident solar radiation $q(t)^9$ 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 thickness of the absorber for each case is taken as $l_m=0.01 \text{ m}$. The obtained results are given in table (2) and table (3) for $h=3 \text{ W}/(\text{m}^2 \text{ K})$ and $h=10 \text{ W}/(\text{m}^2 \text{ K})$, respectively. These data are illustrated graphically in figures (2) and (3) respectively.

The Temperature of the Working Fluid

The temperature of the working fluid (water) θ_w is computed according to equation (13). The heat transfer coefficient for convection " h " is taken equal to $3 \text{ W}/(\text{m}^2 \text{ K})$. The obtained results for the considered five elements Cu, Al, Steel, Crown glass and Mica are given in table (4). And are illustrated graphically in figure (4).

The Efficiency (η) Computations:

The efficiency " η " is computed according to equation (15) for the five elements for different time intervals along the local day time. The obtained results are given in table (5) and table (6) for $h=3 \text{ W}/(\text{m}^2 \text{ K})$ and $h=10 \text{ W}/(\text{m}^2 \text{ K})$, respectively. These data are illustrated graphically in figures (5) and (6) respectively.

Conclusions

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

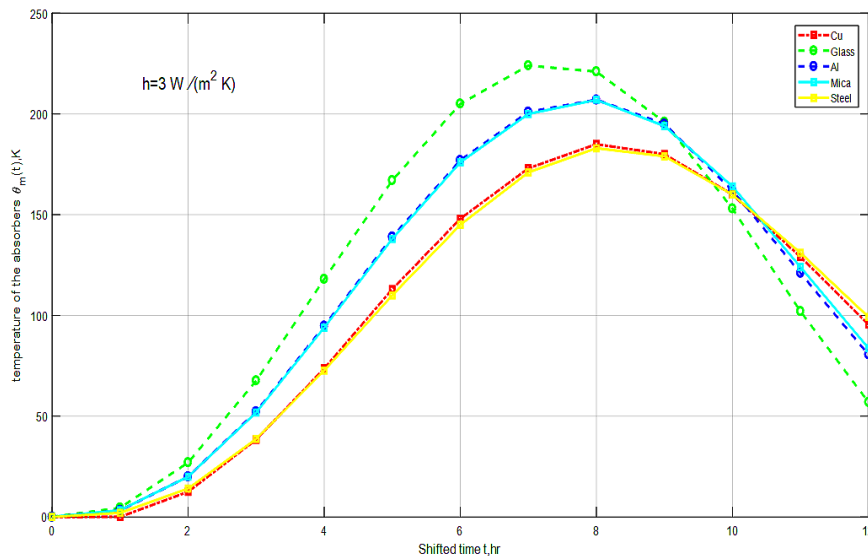


Fig. 2: The temperature of the absorbers of different materials subjected to incident solar irradiances with local day time for, $h=3 \text{ W}/\text{m}^2 \text{ K}$

Table 2: The variation of the temperature of the absorbers of different materials subjected to incident solar radiation for [$h=3 \text{ W/(m}^2 \text{ K)}$]

Local time, hr	Shifted time (t,) hr.	$\theta_m(t), K$				
		Cu	Al	Mica	Steel	Crown glass
6.5	0	0	0	0	0	0
7.5	1	0.5	3.27	3.36	2.03	4.54
8.5	2	12.5	20	20	14.1	27
9.9	3	38.4	52.3	51.9	38.7	67.7
10.5	4	73.7	94.8	94	72.7	118
11.5	5	113	139	138	110	167
12.5	6	148	177	176	145	205
13.5	7	173	201	200	171	224
14.5	8	185	207	207	183	221
15.5	9	180	193	194	179	196
16.5	10	160	162	164	160	153
17.5	11	129	121	124	131	102
18.5	12	95.2	80.5	83.7	99.2	56.9

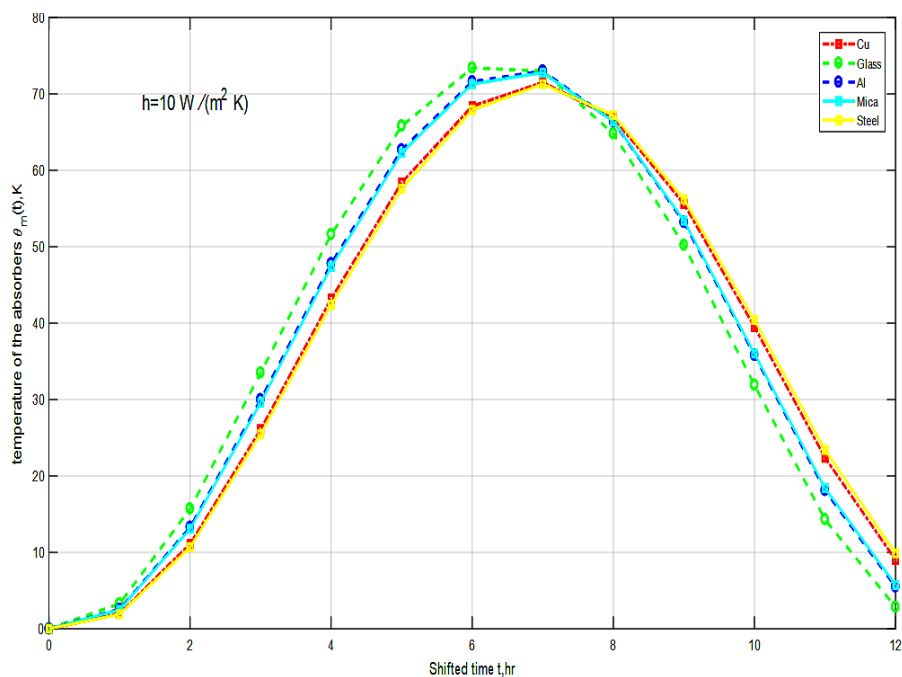
**Fig. 3: The variation of the temperature of the absorbers of different materials subjected to incident solar radiation for [$h=10 \text{ W/(m}^2 \text{ K)}$]**

Table 3: The variation of the temperature of the absorbers of different materials subjected to incident solar radiation for [$h=10 \text{ W/(m}^2 \text{ K)}$]

Local time, hr	Shifted time (t_s)'hr.	$\theta_m(t), K$				
		Cu	Al	Mica	Steel	Crown glass
6.5	0	0	0	0	0	0
7.5	1	1.99	2.55	2.5	1.91	3.28
8.5	2	11.1	13.3	13.1	10.7	15.7
9.5	3	26.1	30	29.6	25.5	33.5
10.5	4	43.2	47.8	47.4	42.4	51.6
11.5	5	58.4	62.7	62.3	57.6	65.8
12.5	6	68.4	71.6	71.3	67.9	73.4
13.5	7	71.5	73	72.8	71.3	73
14.5	8	66.9	66.4	66.4	67.2	64.8
15.5	9	55.6	53.2	53.4	56.2	50.2
16.5	10	39.5	35.8	36	40.4	31.9
17.5	11	22.4	18.1	18.4	23.4	14.3
18.5	12	9.02	5.48	5.7	9.87	2.84

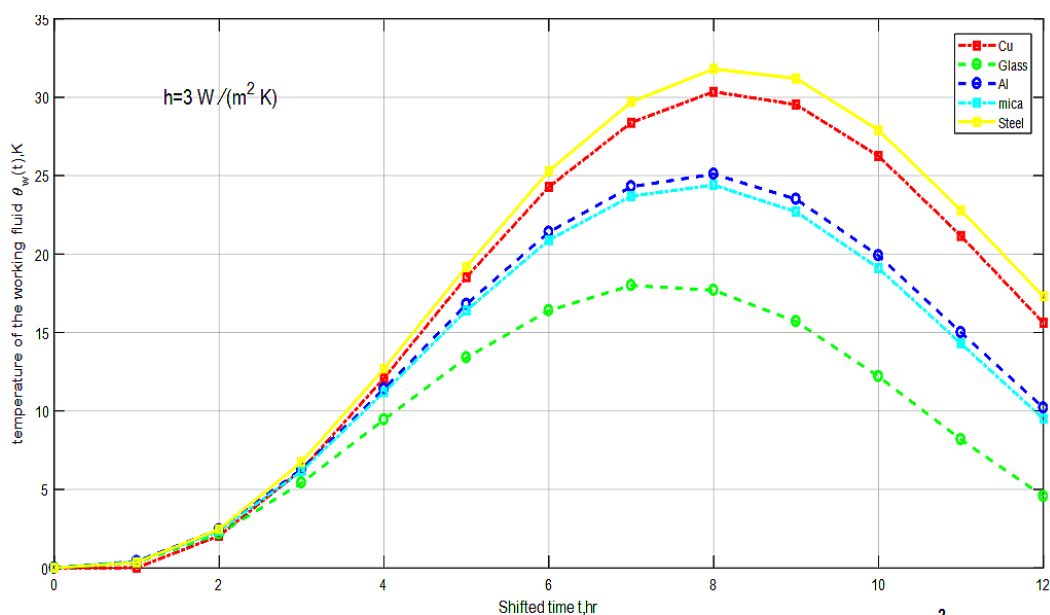
**Fig. 4: The variation of the temperature of the working fluid $\theta_w(t), K$, with local day time for [$h=3 \text{ W/(m}^2 \text{ K)}$]**

Table 4: The variation of the temperature of the working fluid θ_w , °K with local day time for [$h=3 \text{ W/(m}^2 \text{ K)}$]

Local time, hr	Shifted time (t,) hr.	θ_w , °K				
		Cu	Al	Mica	Steel	Crown glass
6.5	0	0	0	0	0	0
7.5	1	0.08	0.39	0.41	0.39	0.36
8.5	2	2.05	2.36	2.43	2.46	2.16
9.5	3	6.2	9.17	6.30	6.74	5.42
10.5	4	12.09	11.2	11.40	12.70	9.45
11.5	5	18.54	16.40	16.80	19.20	13.40
12.5	6	24.28	20.90	21.40	25.30	16.4
13.5	7	28.38	23.70	24.30	29.70	18.00
14.5	8	30.35	24.40	25.10	31.80	17.70
15.5	9	29.53	22.70	23.50	31.20	15.70
16.5	10	26.25	19.10	19.90	27.90	12.20
17.5	11	21.16	14.30	150	22.80	8.18
18.5	12	15.62	9.50	10.20	17.30	4.56

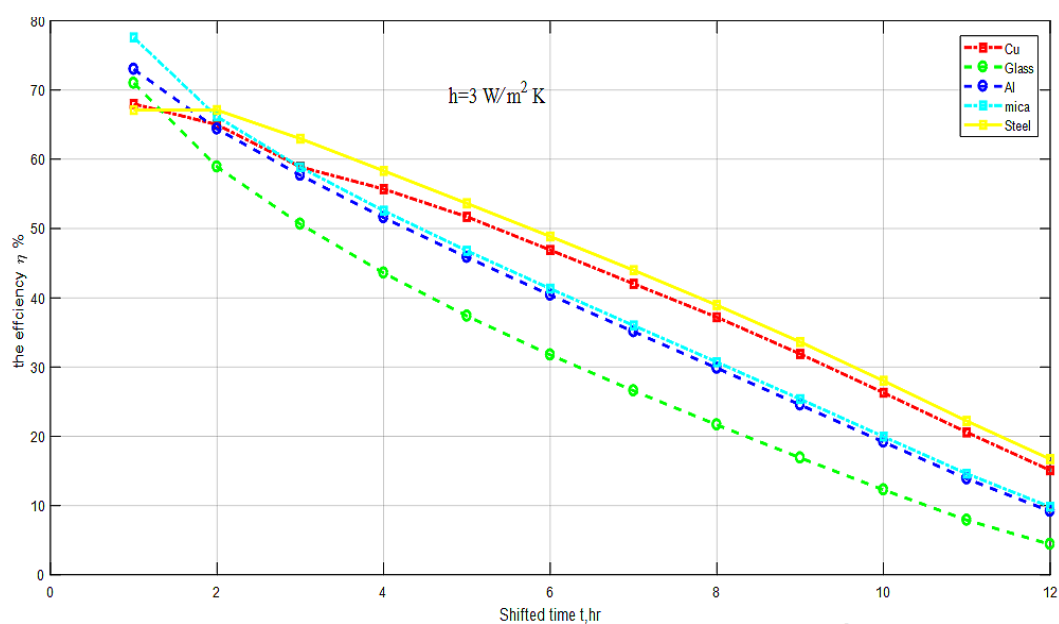
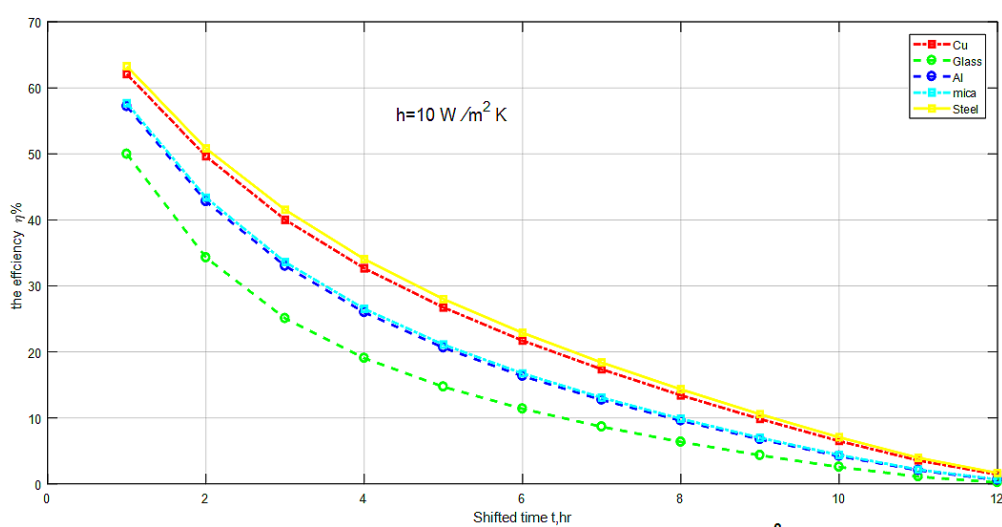


Fig. 5: The variation of the efficiency η with local day time for $h=3 \text{ W/(m}^2 \text{ K)}$

Table 5: The variation of the efficiency η with local day time for [$h=3 \text{ W/(m}^2 \text{ K)}$]

Shifted time (t,) thr.	$\eta, \%$				
	Cu	Al	Mica	Steel	Crown glass
1	68	73	77.58	67.1	70.89
2	65	64.38	66.15	67.1	58.9
3	58.9	57.7	58.85	62.98	50.64
4	55.7	51.57	52.57	58.34	43.58
5	51.7	5.85	46.79	53.63	37.37
6	46.9	40.40	41.32	48.86	31.76
7	42.03	35.11	6	43.99	26.58
8	37.2	29.85	30.72	38.94	21.66
9	31.9	4.55	25.38	33.63	16.90
10	26.3	19.18	9.96	28.01	12.28
11	20.58	13.88	14.6	22.21	7.95
12	15.1	9.19	9.82	16.72	4.41

**Fig. 6: The variation of the efficiency η with local day time for $h=10 \text{ W/(m}^2 \text{ K)}$** **Table 6: The variation of the efficiency η with local day time for [$h=10 \text{ W/(m}^2 \text{ K)}$]**

Shifted time (t,) thr.	$\eta, \%$				
	Cu	Al	Mica	Steel	Crown glass
1	62.08	73	7.58	63.27	70.89
2	49.63	4.38	66.15	50.81	58.9
3	40.02	57.7	58.85	41.52	50.64

4	32.67	51.57	52.57	34.05	43.58
5	6.74	45.85	46.79	28	37.37
6	21.71	0.40	41.32	22.89	31.76
7	17.37	35.11	36	18.39	26.58
8	13.43	29.85	30.72	14.33	21.66
9	9.84	24.55	25.38	10.56	16.90
10	6.5	19.18	19.96	7.06	12.28
11	3.57	13.88	4.6	3.96	7.95
12	1.43	9.19	9.82	1.66	4.41

- 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 at critical time that differs with cooling conditions.
 - The value of $\theta(t)$ depends on the physical parameters of the absorber material. The curves of $\theta(t)$ for the two elements Al, Mica are nearly coincident also for Cu & steel. This indicates that the dependence on the physical parameter is not the same for all elements higher values of $\theta(t)$ is obtained for glass element. This result is of a vital economical importance if one considers the price of the raw materials in relation to the obtained relative efficiencies. 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. (15) 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 (15).
- 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.

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Conflict of Interest

The author has no conflicts of interest to disclose.

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