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RESEARCH ARTICLE OPEN ACCESS

Flat Plate Solar Collector for Water Heating in Benghazi City: A Theoretical Analysis

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ABSTRACT
This study presents the extent of benefitusingof one of the clean energy sources"Solar Energy"available in Benghazi City, which is resented in the use of a heat exchanger (Flat Solar Panel Collector FPC) with a simple design that is easy to operate and low in maintenance. The energy absorbed from the sunlight that falls on the Solar Panels to internal energy through the working medium (water) integrated with absorption panels (water heating).

This study seeks to ensure the quality of renewable energy obtained to a pioneer in replacing traditional energy sources.

Keywords: Energy, Solar Collector, and Heating Water

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I. INTRODUCTION

The use and cost of energy affect each of us every day of our lives. Many issues arise from the use of energy, greenhouse gas emissions, acid rain,climate change, and dependency on fossil fuels-especially from politically unstable regions of the world. Today, 80% of the world's electrical production comes from fossil and nuclear fuels, and virtually all transportation is fueled by liquid petroleum (gasoline). The World Energy Council projects primary energy demand will triple by 2050, as the population grows to 8-9 billion and developing nations elevate living standards. Fossil fuels are nonrenewable and destined to run out, so economies will be forced to change as these fuels are depleted. Rich nations will be insulated a bit longer, yet scarcity will surely create geopolitical tensions. The emissions from burning fossil and nuclear fuels create atmospheric, water, and land pollution and toxic waste. The United Nations Intergovernmental Panel on Climate Change (IPCC) says this combustion is causing a discernible change in the global weather and climate patterns that will affect all humanity in decades to come.

Renewable energy

Renewable energy is produced from sources that are not depleted or replenished within a human's lifetime. The most common examples include wind, solar, geothermal, biomass, and hydropower. This is in contrast to non-renewable sources such as fossil fuels. Most renewable energies are derived directly or indirectly from the sun. Not all renewable energy sources rely on the sun. For example, geothermal energy utilizes the Earth's internal heat, tidal energy relies on the gravitational pull of the moon, and hydropower relies on the flow.

Flat Plate Collector

. Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating.
. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate, the main components of a typical flat-plate solar collector:

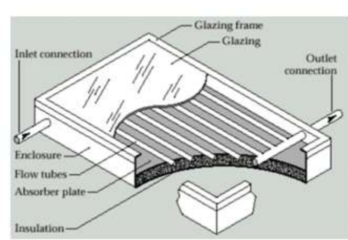

Fig.1. solar flat plate collector [1]

. Black surface absorbent of the incident solarenergy.
. Glazing covers a transparent layer that transmits radiation to the absorber but prevents radiative and convective heat loss from the surface.
. Tubes containing heating fluid transfer the heat from the collector.
. Support structure to protect the components and hold them in place.
. Insulation covers the sides and bottom of the collector to reduce heat losses.

This study is focusing on the analysis of flat plate solar collectors using water as a working fluid at a different mass flow rate. This study covered the calculation of the efficiency, the outlet temperature, and the useful heat gain of the collector.

II. MATHEMATICAL MODEL

In steady state, the performance of a flat-plate solar collector is described by the useful gain from the collector $\mathbf{Q_u}$, which is defined as the difference between the absorbed solar radiation and the thermal loss or the useful energy output of a collector [2]:

$$Qu = A_c FR\left[I(\tau\alpha) - U_l(T_{fi} - T_a)\right] \quad (1)$$

Where$I$is the intensity of radiation on a horizontal surface, $(\tau\alpha)$ is the transmittance absorbance product that represents the effective absorptance of the cover-plate system.

The overall heat losses (U_l)

$$U_l = U_b + U_e + U_t \quad (2)$$

In this study, the edges of the collector are assumed to be insulated.$U_e = Zero$

Coefficient of heat loss from the bottom:

$$Ub = \frac{k}{x} \quad (3)$$

Where the heat losses from the top of collectors $\boldsymbol{U_t}$ can calculate by:

$$U_t = \left\{\frac{N}{\frac{C}{Tpm}\left[\frac{Tpm-Ta}{N+f}\right]^e} + \frac{1}{h_w}\right\}^{-1} + \frac{\sigma(Tpm+Ta)(Tpm^2+Ta^2)}{(\epsilon_p+0.0059hw)^{-1} + \frac{2N+f-1+0.133\epsilon_p}{\epsilon_g} - N} \quad (4)$$

$$f = \left(1 + 0.08hw - 0.1166hw * \varepsilon_p\right)(1 + 0.07866N) \quad (5)$$

$$C = constant = 520(1 - 0.000051\beta^2) \quad (6)$$

70 > β > Zero
90 > 70 > use β = 70

$$e = 0.43\left(1 - {}^{100}/_{Tpm}\right) \quad (7)$$

$$\sigma = 5.6667 * 10^{-8}({}^{W}/_{m^2.k^4}) \quad (8)$$

$$hw = 5.7 + 3.8V \quad (9)$$

The collector heat removal factor (FR), is the ratio of a collector's actual useful energy gain to the maximum possible useful gain if the whole collector surface wereat the fluid inlet temperature. It is defined as:

$$FR = \frac{GC_p}{A_c U_L}\left[1 - exp - \left({}^{A_c U_L F'}/_{GC_p}\right)\right] \quad (10)$$

Where the Collector efficiency factor $\boldsymbol{F'}$given by:

$$F' = \frac{1}{\frac{wu_l}{\pi D_i hfi} + \frac{w}{D-(w-D)F}} \quad (11)$$

Where $\boldsymbol{F}$is the fin efficiency for straight fins with a rectangular cross-section, which describe as:

$$F = \frac{[\tanh m(w-D)/2]}{m(w-D)/2} \quad (12)$$

Where $\boldsymbol{m}$is a parameter of the fin-air arrangement defined as:

$$m = \sqrt{\frac{u_t}{k_p \delta_p}} \quad (13)$$

The heat transfer coefficient of the fluid

$$h_{fi} = \frac{k}{Di} N_u \quad (14)$$

The Nestle number:

$$N_u = \left\{4.36 + \frac{0.067\left[\left({}^{Di}/_{L}\right)Re\ Pr\right]}{1+0.04\left[\left({}^{Di}/_{L}\right)Re\ Pr\right]}\right\} \quad (15)$$

The Reynolds number:

$$R_e = \frac{4m}{vp} Di \quad (16)$$

The Prandtl number:

$$Pr = cp.v\ ({}^{p}/_{k}) \quad (17)$$

The mass flow rate per square meter:

$$G = {}^{m^{\cdot}}/_{A_c} \quad (18)$$

The value of the temperature can be obtained by:

$$Q_u = m^{\cdot} * C_p(T_{out} - T_{in}) \quad (19)$$

The solar collector efficiency is defined as:

$$\boldsymbol{\eta} = \frac{\boldsymbol{Q_u}}{\boldsymbol{A_c I}} \quad (20)$$

The analysis of flat plate solar collectors depends on different parameters. This research, focusing on the efficiency, useful heat gain, and outlet temperature of the collector. So, the data for the flat plate collector assuming as follows:

Table 1. Constant parameters of the collector [3]

Constant parameters	
εp	0.92
α	0.95
τ	0.92
σ	5.6669 x 10^{-8}
E_g	0.88

Measurements have been taken for the solar collector at Benghazi instated of technology and we found dimensions as the following:

Table 2. Collector dimension

Collector Dimension	
Length	1.45 m
Width	1.17 m
Thickness	0.07 m
Absorber thickness	0.001 m
Distance between the tubes	0.105 m
Length of tube	1.15 m
Diameter of tube	0.01 m
Number of tubes	13

Within this study, the specifications of the medium used (water) at different temperatures must be given:

Table 3. The viscosity of water at different ambient temperatures [3]

Kinematic viscosity	Dynamic viscosity			emperature
[$m^2/s*10^{-6}$], [cSt])	[lbf s/ft^2 *10^{-5}]	[cP], [mPa s]	[Pa s], [N s/m2]	[°C]
1.0035	2.0919	1.0016	0.0010016	20
0.8927	1.8589	0.89004	0.00089	25
0.8007	1.665	0.79722	0.0007972	30
0.6579	1.3632	0.65272	0.0006527	40

The type of material used in this research is copper, which is more common due to its high thermal conductivity.
The thermal conductivity of water and copper as follows:

Table 4. Thermal conductivity of water and copper [3]

Thermal conductivity	Temperature	State
[W/m K]	[°C]	
0.57864	10	Water
0.59803	20	
0.6145	30	
0.62856	40	
400 W/m.k	25 - 125 °C	Copper

A different glass layers in solar collectors in terms of number; our solar collector contains one layer (single regular plate).

The glass has transmission and emissivity as follows:

Table 5. Solar heat transmission and emissivity coefficient of the glass [3]

Solar Heat Transmission Type of glass		Emissivity Coefficient	
Single regular plate	0.92	Glass smooth	0.92 - 0.94

The earlier study [4] in Benghazi City measured the intensity of solar radiation using a radiation-measuring device and obtained the results as presented in table 5. In this case, taken the maximum and the minimum value of solar radiation for calculations.

Table 6. Solar radiation for Benghazi city on (Sep 1st, 2017) [4]

SOLAR RADIATION	
Friday	September Month
2017/09/01	
Time	Solat Radiation
AM 07:00	683
08:00	905
09:00	988
10:00	1043
11:00	1061
12:00PM	1069
02:00	1041
04:00	973
06:00	734

IV. RESULTS AND DISCUSSION

The collector is designed to operate in a temperature interval between 40°C and 90°C.[5]. From equations (1) to (20), the results were as following:

Table 7. Shows the calculation at Tpm = 40°C

T_{pm} (Min 40°C)					
$\dot{m}$ (kg/s)	0.03	0.05	0.07	0.09	0.1
U_b (W/m². K)	0.685	0.685	0.685	0.685	0.685
T_{fi} (°C)	28	28	28	28	28
T_a (°C)	23	23	23	23	23
e	0.2926198	0.2926198	0.2926198	0.2926198	0.2926198
U_t (W/m². K)	5.9276275	5.9276275	5.9276275	5.9276275	5.9276275
U_L (W/m². K)	6.6126275	6.6126275	6.6126275	6.6126275	6.6126275
m	3.8495543	3.8495543	3.8495543	3.8495543	3.8495543
F	0.9890019	0.9890019	0.9890019	0.9890019	0.9890019
F'	0.9118282	0.9118282	0.9118282	0.9118282	0.9118282
G (kg/m²)	0.0176835	0.0294724	0.0412614	0.0530504	0.0589449
K_{fi} (W/m. K)	0.585	0.585	0.585	0.585	0.585
h_{fi} (W/m². K)	255.06585	255.06585	255.06585	255.06585	255.06585
F_R	0.851644	0.8750587	0.8853586	0.891151	0.8931904
I (W/m²)	683	683	683	683	683
Q_u (W)	814.70014	837.09912	846.95218	852.49334	854.44421
η (%)	70.310992	72.244089	73.094437	73.572655	73.741021
T_{out} (°C)	34.48595	31.998563	30.889734	30.262276	30.040707

Table 8. Shows the calculation at T_{pm} = 65°C

T_{pm} (Mean 65°C)					
$\dot{m}$ (kg)	0.03	0.05	0.07	0.09	0.1
U_b (W/m². K)	0.685	0.685	0.685	0.685	0.685
T_{fi} (°C)	33.5	33.5	33.5	33.5	33.5
T_a (°C)	28.5	28.5	28.5	28.5	28.5
e	0.302781065	0.302781065	0.302781065	0.302781065	0.302781065
U_t (W/m². K)	6.893865609	6.893865609	6.893865609	6.893865609	6.893865609
U_L (W/m². K)	7.578865609	7.578865609	7.578865609	7.578865609	7.578865609
m	4.151465286	4.151465286	4.151465286	4.151465286	4.151465286
F	0.987236586	0.987236586	0.987236586	0.987236586	0.987236586
F'	0.900644205	0.900644205	0.900644205	0.900644205	0.900644205
K_{fi} (W/m. K)	0.589	0.589	0.589	0.589	0.589
G (kg/m²)	0.017683466	0.029472443	0.041261421	0.053050398	0.058944887
h_{fi} W/m². K)	256.80989	256.80989	256.80989	256.80989	256.80989
F_R	0.833745791	0.859676993	0.871122733	0.877569905	0.879841512
I (W/m²)	876	876	876	876	876
Q_u (W)	1029.337041	1061.351531	1075.482366	1083.442002	1086.246514
η (%)	69.2627341	71.41694702	72.36779229	72.9033857	73.0920976
T_{out} (°C)	41.69470616	38.56974699	37.16946114	36.37514795	36.0943313

Tpm (Max 90°C)					
$\dot{m}$ (kg)	0.03	0.05	0.07	0.09	0.1
U_b (W/m². K)	0.685	0.685	0.685	0.685	0.685
T_{fi} (°C)	39	39	39	39	39
T_a (°C)	34	34	34	34	34
e	0.3115427	0.3115427	0.3115427	0.3115427	0.3115427
U_t (W/m². K)	7.716912662	7.716912662	7.716912662	7.716912662	7.716912662
U_L (W/m². K)	8.401912662	8.401912662	8.401912662	8.401912662	8.401912662
m	4.392297992	4.392297992	4.392297992	4.392297992	4.392297992
F	0.98573885	0.98573885	0.98573885	0.98573885	0.98573885
F'	0.891810898	0.891810898	0.891810898	0.891810898	0.891810898
K_{fi} (W/m. K)	0.595	0.595	0.595	0.595	0.595
G (kg/m²)	0.017683466	0.029472443	0.041261421	0.053050398	0.058944887
h_{fi} W/m². K)	259.42595	259.42595	259.42595	259.42595	259.42595
F_R	0.819454654	0.847414937	0.859791453	0.86677226	0.869233484
I (W/m²)	1069	1069	1069	1069	1069
Q_u (W)	1240.474808	1282.800549	1301.535883	1312.103296	1315.82905
η (%)	68.4000438	70.73389414	71.76696441	72.34965379	72.55509263
T_{out} (°C)	48.87560551	45.12754024	43.44073794	42.48195021	42.14265357

Table 9. Shows the calculation at Tpm = 90oC

In Figures (2,5 and 8) the results show that the flow rate increases the useful heat gain increase too, in figures (3,6 and 9) the results show that the flow rate increases the useful heat gain increase too and in Figures (4,7, and 10) the result shows that the flow rate increase.

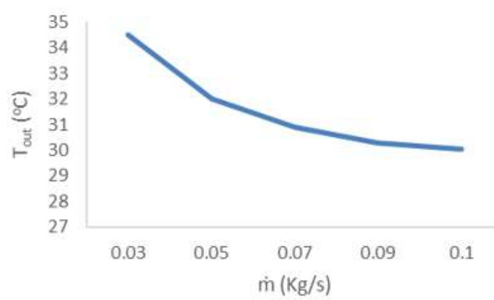

Fig.2. shows the effect of water mass flow rate on the useful heat gain at T_{pm}=40°C

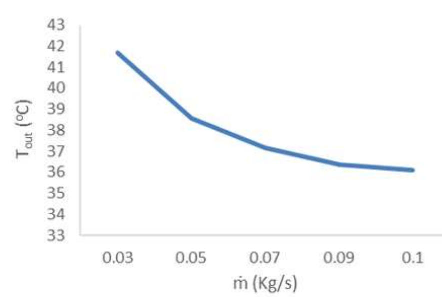

Fig.3. shows the effect of water mass flow rate on the temperature outlet at T_{pm}=40°C

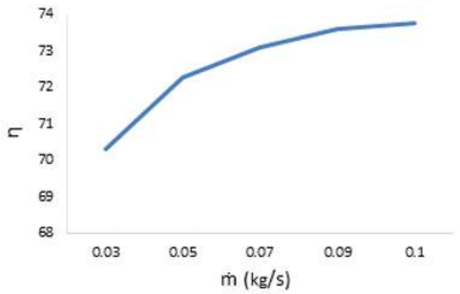

Fig.4 shows the effect of water mass flow rate on the efficiency at T_{pm}= 40ºC

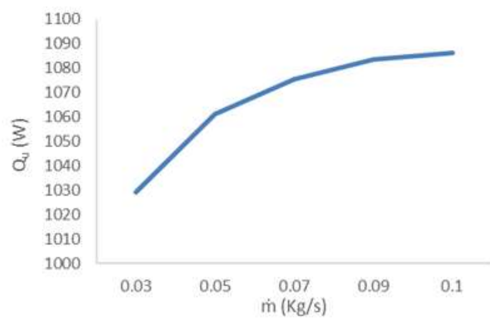

Fig.5. shows the effect of water mass flow rate on the useful heat gain at T_{pm}= 65ºC

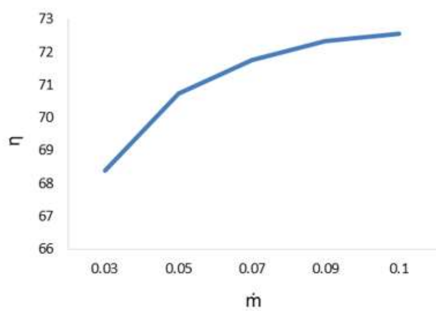

Fig.6. shows the effect of water mass flow rate on the useful heat gain at T_{pm}= 65ºC

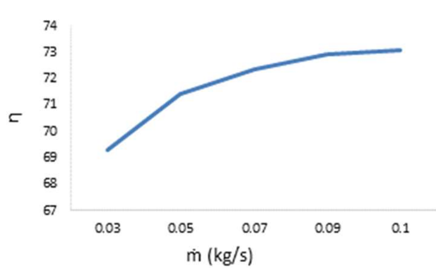

Fig.7. shows the effect of water mass flow rate on the efficiency at T_{pm}= 65ºC the

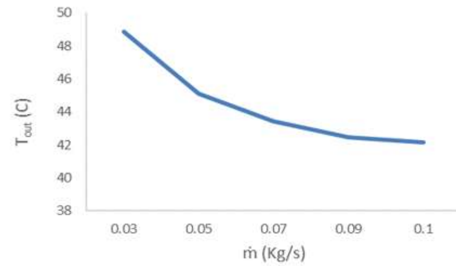

Fig.8. shows the effect of water mass flow rate on the useful heat gain at T_{pm}= 90ºC

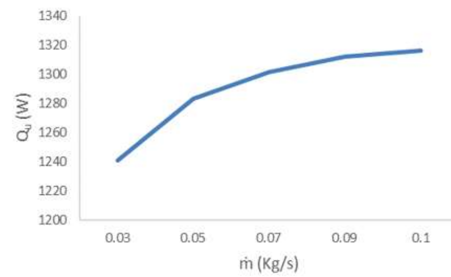

Fig.9. shows the effect of water mass flow rate on the useful heat gain at Tpm=90ºC

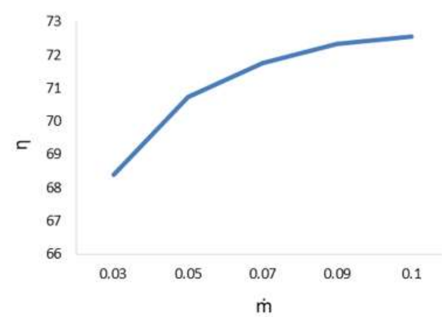

Fig.10. shows the effect of water mass flow rate on the efficiency at Tpm= 90ºC

V. CONCLUSION

The flat-plate solar collectors are probably the most fundamental and most studied technology for solar-powered domestic hot water systems. The overall idea behind this technology is simple. The Sun heats a dark flat surface, which collects as much energy as possible, and then the energy is transferred to water, air, or other fluid for further use.

In this study, a theoretical analysis of flat plate solar collectors has been studied for different parameters. More attention was paid to the outlet temperature, useful heat gain, and efficiency of the collector using water as a working fluid at a different mass flow rate. The results show that; the useful heat gain increases when the mass flow rate increases, Also the efficiency increase when the mass flow rate increases, while the outlet temperature decreases when the mass flow rate increases. After we made the calculations at the plate temperatures (40°C, 65°C, 90°C) and different values of mass we get the highest efficiency when the mass value was 0.1 at 40°C we get 73.4%, at 65°C we get 73.09% and at 90°C we get 72.5%.

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Nomenclature

A_c	Solar collector area (m^2)
D	Outer diameter of tube (m)
D_i	Inner diameter (m)
W	Distance between the tubes (m)
x	Insulation thickness (m)
$\dot{m}$	Total collector mass flow rate (kg/s)
m	Parameter of the fin-air arrangement
T_a	Ambient temperature (°C)
T_i	Fluid temperature at collector inlet (°C)
T_o	Fluid temperature at collector exit (°C)
T_{pm}	Mean plate temperature (°C)
Q_u	Useful gain from a collector (Watt)
I	Intensity of incident radiation (W/m^2)
C_p	Specific heat (kJ/kg.K)
U_L	Overall loss coefficient of the collector (W/m^2.K)
U_e	Side Heat Loss (W/m^2.K)
U_t	Heat loss factor from the top (W/m^2.K)
U_b	Heat loss factor from the bottom (W/m^2.K)
F_R	Collector heat removal factor
F	Fins efficiency coefficient
F′	Collector efficiency factor
G	Heat flow rate of the liquid for the square meter (kg/m^2)
h_{fi}	Forced convection heat transfer coefficient inside of tubes (W/m^2.K)
h_w	Air Heat Transfer Factor.V3.8+5.7
K	Thermal conductivity (W/m.K)
K_{fi}	Conductivity factor for liquid (W/m.K)
v	Liquid viscosity (m^2/s)
V	Wind speed (m/s)
N	Transparent Covers the number of glass
Re	Reynolds number
Pr	Prandtl number
E_g	The softest of the transparent plank.

Greek symbols

δ_p	Absorber thickness (m)
ε_p	Emissivity of the absorbant board
α	Absorptance
β	Collector slope (degree)
ρ	Fluid density (kg/m^3)
τ	Transmission coefficient of glazing.
η	Instantaneous efficiency of solar collector