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EXPERIMENTAL INVESTIGATION OF EFFECT OF OIL MASS FLOW CHANGES ON PARABOLIC TROUGH COLLECTOR EFFICIENCY IN A SOLAR WATER HEATER SYSTEM

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Abstract- Collectors, as the heart of solar systems, are in reality special types of heat exchangers that convert the solar radiation to applicable thermal energy. Parabolic trough collectors (PTC) have great ability to produce hot water, steam and other various industrial and domestic applications. Therefore, the present system includes PTC, heat exchanger and two tanks, which are used to store warm water for subsequent water consumption. Collector efficiency is influenced by variations in the mass flow rate, solar radiation, fluid heat capacity and gradient temperature of the output-input fluid. The PTC efficiency depends on these parameters which, in turn, cause the dependence of the water heater system on them. Therefore, the aim of this paper is to achieve the best possible efficiency of the PTC by changing the oil mass flow rates. Consequently, by increasing the oil flow rate, the efficiency of the collector gets enhanced; this fact concurs well with the results of the studies of other researchers. Water temperatures of the two tanks and the gradient temperature of the output-input fluid are improved by rapidly decreasing the oil flow rate.

Keywords: Solar Water Heater, Parabolic Trough Collector, Collector Efficiency, Oil, Mass Flow.

I. INTRODUCTION

The most original crisis of today's world is energy crisis. Fossil fuels are no longer the answer to the increasing human demand for fuel needs. To meet this crucial need, energy networks alone will be insufficient. Therefore, appropriate substitutes for natural energy sources should be found for the future, and this continues to be one of world's greatest challenges [1]. Besides these problems, the fossil fuels generate greenhouse gases which irreparably damage the earth's atmosphere. Renewable and clean energies can thus reduce these damages and prevent global warming and climate changes across the globe [2]. In this respect, many countries in the world have a high potential to utilize solar energy which does not produce any environmental pollution. Therefore, the use of solar energy appears completely reasonable. Batidzirai et al. investigated the solar water heater and explained that the Solar Water Heating System (SWHS) offered many environmental and economic advantages [3].

To employ solar energy in a domestic heater system, extensive researches have been conducted. Luo et al. have constructed a new dual-function collector which involved tiles covered with Polymeric Methyl Methacrylate material. This new design was used to increase the instantaneous efficiency from 53 to 69% [4]. Mozafari et al. heve used Paraffin and commercial wax as PMC to enhance the performance of the collector [5].

Parabolic collectors provide a lot of heat that is used to generate steam, hot water or electric power, desalination of sea water, air conditioning, refrigeration, etc. PTCs can track the sun in the sky and concentrate the radiation beams on the focal tube and transfer the high thermal energy to the working fluid. As they generate a greenhouse effect due to the Pyrex cover of the absorber tube, the PTCs can be employed in cold seasons. Therefore, the PTCs are powerful solar instruments which can produce an extensive temperature range for various applications in the rural areas [6].

As cited earlier, some researchers have applied PTC in the domestic SWHS. Devanarayanan and Murugavel compared performance of various designs of the compound parabolic collector with that of SWHS. They described the advantages and disadvantages of the various types of integrated collector storage SWHS. They understood the performances of each type of system and the manner they change during the day [7].

In order to maintain long-term hot water consumption, the energy storage tank is utilized within the SWHS by some scientists and its temperature was evaluated during 'time' (days or seasons) [1]. Javier et al. have been investigated the effect of tank water temperature on the performance of a SWHS that water can be withdrawn from it. Their research illustrated that as the water discharge from the storage tank increased, the thermal efficiency reduced [8].

Issa and Kodah determined the water tank temperatures along the vertical axis versus position. They observed a linear relationship between the temperature and position. After verifying it experimentally, they concluded that the linear relationship was adapted for high inflow velocities of the hot water into the storage tank [9].

To improve the SWHS performance, an attempt to enhance the performance and thermal efficiency of the PTC is very necessary. Several parameters are found to affect the thermal efficiency of the PTC, including the heat capacity of the fluid, ambient temperature, solar radiation and working fluid flow rate, etc. Among the parameters mentioned fluid flow is controllable. Therefore, by changing the flow rate, the thermal efficiency can be improved.

Venkataramaiah et al. have conducted a comprehensive study on the effects of various parameters on the conversion efficiency using a numerical method called the desirability functional analysis. They investigated the conversion efficiency versus the width of the collector aperture, radiation and concentration ratio and absorber tube diameter at various temperatures. Their research showed that the collector performance decreased as the aperture width of the collector increased. They demonstrated that to whatever degree the aperture area increased, there was a corresponding increase in the conversion efficiency. However, with increasing the temperature, it decreased [10].

However, not many studies have been done on the effect of the fluid flow on the PTC efficiency of the SWHS. Dagdougui et al has done extensive study on the effect of a number of different covers on the flat plate collector in the SWHS. They had also evaluated variations in the collector efficiency versus water flow rate for different kinds of covers. However, their study showed that the flat collector efficiency improved when the water flow rate was increased up to 0.02 kg/s; however, the efficiency became constant after 0.02 kg/s of flow rate values [11].

Goudarzi et al. have improved thermal performance of the solar collector using new design. They used a helical copper tube in center of the cylindrical solar collector. Also, they investigated the collector efficiency versus mass flow rate. Consequently, increasing flow rate can enhance the collector efficiency [12]. Hussain and Lee predicted the thermal output and efficiency of a U-shaped collector in the water heater system by varying the rates of water flow [13].

Sagade constructed a new kind of receiver for the parabolic dish thermal energy system. He designed the SWHS using two tanks and a parabolic dish collector and demonstrated improved efficiency of the SWHS apparatus. He determined the collector's efficiency, heat losses and the useful heat gained by the water for two water mass flows. His research detected that water with a high mass flow could obtain more thermal energy while with the low mass flow it showed more total heat loss [14]. Gao et al. studied the effects of the water mass flow rate and thermal mass on forced-circulation SWHS. He compared the collected energy of water in glass- and U-pipe-evacuated solar collectors [15].

Kerman (a province in Iran), due to its hot and dry climate, has a high solar energy potential (5.85 kW/m^2 day) to generate warm water for building consumption at low cost [16].

This article presents an attempt to improve the SWHS with a parabolic trough collector. The thermal behavior of the PTC was evaluated under conditions of three variations in oil mass flow rates. Effective parameters (such as time, mass flow rate) on thermal efficiency were investigated. This presents a simple method of improving the SWHS efficiency without additional cost, simply by selecting a suitable oil flow rate [15]. The system is able to produce and store warm water up to 45 L, too.

In most of the SWHSs the water flows into the collector and accumulates the heat from the solar rays, directly. But the PTC can achieve the temperature of a working fluid to more than 100°C, which causes the water to evaporate at this temperature. Besides, the water in Sirjan has a high degree of hardness that generates corrosion and deposition in the SWHS hoses. Therefore, to prevent the failure of the device and minimize additional costs, Behran oil was utilized instead of water [17]. Thus, this study illustrates that oil is a more suitable choice than water for the PTCs.

II. MATERIALS AND METHODS

A. Measuring System and Experimental Procedure

Generally, all solar SWHSs include a solar collector, water storage tank and water pump, to circulate the water. Some researchers designed an SWHS with two water tanks. The advantage of an SWHS with two tanks is its ability to withdraw the water and store hot water, instantaneously [18]. The experimental SWHS included two cylindrical tanks, a PTC device, heat exchanger, water and oil pumps, tubes and valves as shown in Figure 1. It was trialed in Sirjan city (Iran) (29°28′ N, 55°34′E; altitude 1743 m).

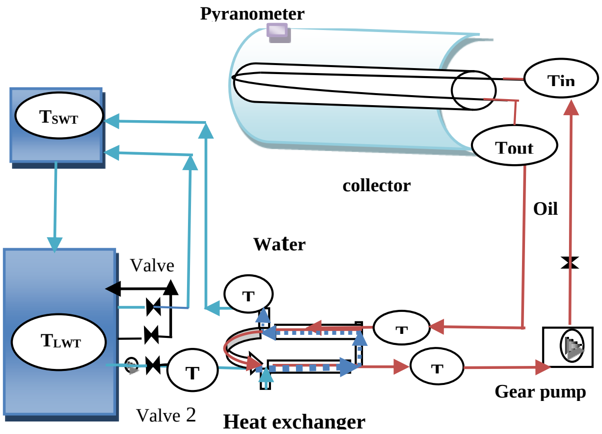

Figure 1. Schematic shape of SWHS

The volumes of the small water tank (SWT) and the large water tank (LWT) were 2.5 L and 45 L, respectively. Both tanks were made of galvanized iron. The SWT was used to harvest the warm water and the LWT was to store warm water as the storage tank for the next consumption. As mentioned, the fresh water in Sirjan city is rather hard and when it passes through the tubes of the collector it tends to cause deposition inside the tubes.

These depositions get accumulated in the absorber tube of the PTC by enhancing the temperature and reducing the velocity fluid. As a result of the deposition by the water in Sirjan, which is a type of porous deposition, problems are created including (1) reducing the heat transfer rate. (2) Reducing the pressure of the water in the system. With reduced pressure, the water can move only with difficulty. (3) Generating corrosion in the tubes of the collector. (4) A drop in the performance of the SWHS. In addition, as the freezing point of water is 0°C, it makes the water freeze faster with the hydrocarbon fluids in the cold seasons [19].

This leads to bursting tubes and incurs additional expense for system fixing. For solving these problems, Behran oil was selected as the working fluid in the absorber tube of the PTC (German Standards DIN 51515). This oil is actually engine oil, which after being refined well has chemical materials added to it. Besides, this oil does not cause deposition, due to the presence of the additional material, which itself resolves the depositions. Therefore, it prevents deposition, corrosion and oxidation and reduces the heat transfer rate [17].

The maximum temperature that the fluid can often be achieved, depends on the suitable designs of the collector components such as: the right choice of fluid type, diameter of the absorber tube, reflection coefficient of the material that covers the parabolic collector surface, etc. [20].

Therefore, designers are trying to construct PTCs by employing the best and low-cost materials. In this study, the PTC device was fabricated a supply structure, with a reflector surface, absorber tube and two handy levers. That these levers can rotate the PTC apparatus, two axes north-south and east-west to track the direction of the sun, alternatively. To accumulate useful solar energy, solar collectors have to incline towards the south in the northern hemisphere [21].

Effective accumulation of the radiation beams occurred when the incident beams radiate directly on the focal line of the reflector surface that the absorber tube was placed on. The absorber tube of the collector was made of copper and the reflector was an anodized aluminum sheet. The characteristics of the PTC are listed in Table 1. To reduce heat loss, a Pyrex cylindrical pipe was used to cover the absorber tube (outlet diameter: 0.06 m, inlet diameter: 0.05 m).

One pyranometer was installed on the aperture of the PTC and was inclined as the PTC device was positioned. (The pyranometer used was model TES-1333, with range up to 2000 Wm^{-2}, and accuracy of 1 Wm^{-2}) Four valves were placed at various locations in the system (as shown in Figure 1). At first, in the experiment, Behran oil was circulated into the absorber tube of the collector using an oil pump (that was placed inside small oil tank). It used the valve (1) in that part of the outlet oil tank. To reach various flow rates, the valve was used (1) and it modified the oil pump revolution.

The PTC absorber tube accumulated the thermal energy from the solar radiation and transferred it to the oil. Then the hot oil was passed inside the horizontal cylindrical heat exchanger that was one type of two tube heat exchangers. It had four inlets/outlets, two for oil and two for water [22].

The cold water of the LWT entered the heat exchanger through the valve (2). The flow rate of the water was adapted equal to 35 L/h. The heat exchanger transferred the thermal energy from the oil to the water. It was designed so that the water and oil have the most contact together (Figure. 1). Then the warm water was passed from the heat exchanger, where it entered the SWT. When there is a need for instantaneous warm water valves (3) and (4) will be closed. By closing these valves, the temperature of the SWT increases rapidly, and water withdrawal can be done. If not the warm water will get stored in the LWT.

The oil cycle was a closed one. To reduce heat loss, all the oil transfer tubes were covered by glass wool (conduction coefficient: 0.048 $Wm^{-1}{}^{\circ}C^{-1}$), with an insulation thickness of 0.02m. Data loggers determined the temperatures of both the water tanks, input/output oil of the collector, the input/output water and oil of the heat exchanger. (TES-1384, 4 channels thermometer, percentage of accuracy 0.05±1°C, range -100~ +1370 °C). The picture of the system is represented in Figure 2.

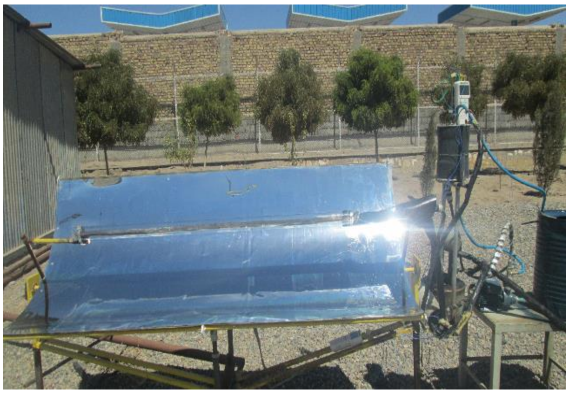

Figure 2. Image of the solar water heater system

B. The Theoretical Relationships

The total thermal efficiency of the collector describes the performance of the solar collectors. It explains the ratio of the useful energy to the total energy which the collector receiver tube absorbs from the sun over a specified time period. It is expressed by [23]:

$$\eta_c = \frac{\int \dot{Q}_c \, dt}{A_c \int I(t)\, dt} \tag{1}$$

where, A_c is the area of the reflector surface of the collector, $I(t)$ and $\dot{Q}_c$ are, respectively, solar radiation and the collector power. Instantaneous thermal efficiency is defined as equation (2) [23]:

$$\eta_c = \frac{\dot{Q}_c}{\dot{Q}_s} \times 100 \tag{2}$$

The solar energy received for the surface area of the collector is determined by [23]:

$$\dot{Q}_s = I A_c \tag{3}$$

The power produced that is converted using the PTC, is explained by equation (4) [23]:

$$\dot{Q}_c = \dot{m}_o \, C_o \, (T_{out} - T_{in}) \tag{4}$$

where, $\dot{m}_o$ and C_o are, respectively, oil mass flow and the specific thermal capacity of the oil. T_{out} and T_{in} are the temperatures of the outlet oil and inlet oil. Therefore [23]:

$$\eta_c = \frac{\dot{m}_o C_o (T_{out} - T_{in})}{I A_c} \quad (5)$$

III. RESULTS AND DISCUSSION

The data measured were collected for three days under similar weather conditions (15, 17& 23 June, 2015). To investigate the performance of the SWHS over the 8-hour period, all the tests were done between 8:00 am and 16:00 pm and the temperatures were measured at half-hour intervals. The time given is the effective radiation interval. Solar radiation is insufficient to heat the water, before and after that time.

It is worth mentioning that the temperature data were evaluated for eight days (15 June to 23 June). But the information on the days with similar climates (sunny days) alone was selected. This was because when the solar radiation is at a constant value during that interval of time, the examiner can compare the effects of the oil mass flow rates. The geometrical characteristics of the PTC are cited in Table 1.

Table 1. Characteristics of parabolic collector

Components of collector	Value
Rim angle	99
Diameter of absorber tube	0.008 m
The length of the collector (*L*)	1.32 m
Focal length (*f*)	0.25 m
Reflectivity of reflector surface	89%
Surface area of PTC	1.31 m^2
Surface area of receiver	0.033 m^2
Aperture with	0.89 m
Concentrating ratio	39.5

By tracking the sun, the receiver of collector absorbs more thermal energy. Direction of tracking the sun has a strong effect on all of the measured temperatures [24]. Figure 3 shows solar radiation versus time. Maximum values of the solar radiation changes from 700 Wm^{-2} up to 925 Wm^{-2} for all three days. All the temperatures (15 June, 2015) are shown in Table 2.

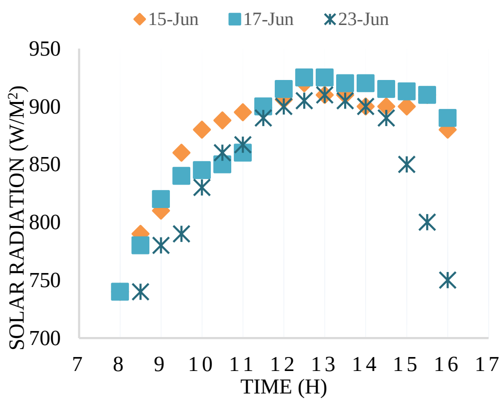

Figure 3. Solar radiations versus time (for 15, 17 & 23 June 2015)

Table 2. Temperatures of the solar water heater system

T_{in}(°C)	T_{out}(°C)	T_{SWT}(°C)	T_{LWT}(°C)	*Time(h)*
40	40	24	24	8
50	73	26	26	8:30
61	92	30	30	9:00
67	99	34	34	9:30
72	107	37	37	10
75	110	40	40	10:30
80	115	42	42	11:00
82	120	45	45	11:30
83	124	47	46	12:00
85	127	49	49	12:30
83	125	52	52	13:00
84	126	55	55	13:30
82	120	57	57	14:00
83	120	59	59	14:30
82	115	61	61	15:00
79	116	62	62	15:30
76	115	63	63	16:00

In Figure 4 the temperatures of the outlet oil in the collector versus time are shown for the three oil flow rates of 0.0012 kg/s, 0.0017 kg/s, and 0.0036 kg/s; whichever fluid moved slower, it could gain greater heat from the solar rays. Therefore, for the lowest oil mass flow, the outlet oil temperature revealed the highest value [14].
The diagram of the oil temperatures for the oil flow of 0.0017 kg/s, 0.0036 kg/s increased up to 12:30, and then it dropped in the afternoon. This was because the solar radiation on 17 June and 15 June had the maximum power at 12:30 pm. Differences in the temperatures between the inlet and outlet oils are shown in Figure 5.

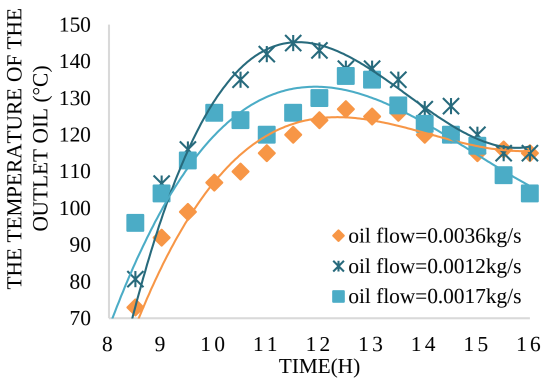

Figure 4. Changes in Outlet oil temperatures of collector during 'time'

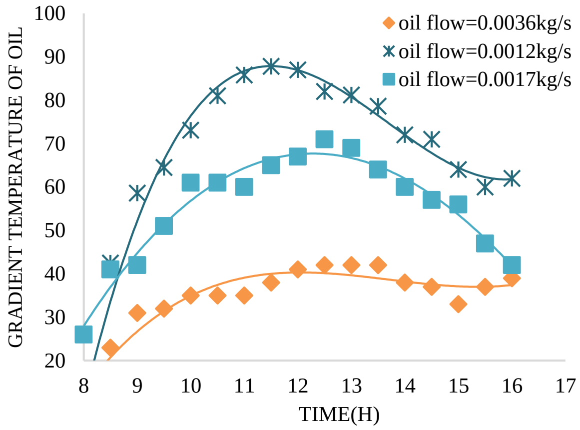

Figure 5. Gradient temperatures of oil in terms of time

As seen, the data measured in the three curves as seen in Figures 4, 5 follow a similar process. As the radiation power increased, the oil that passed inside the absorber tube could collect more heat and, therefore, the oil temperature and its gradient improved [14]. The powers of the collector in the three different flow plots are given in Figure 6.

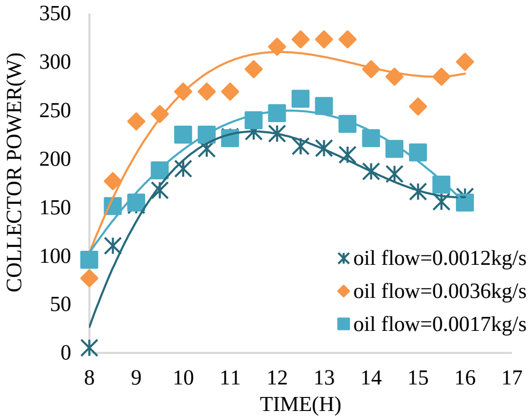

Figure 6. Power of the collector versus time

The diagrams of the power collector show specific arrangement. According to Equation (4), there are three effective parameters of collector power: mass flow rate, thermal capacity, and the oil gradient temperature [23]. These parameters change power, simultaneously. Therefore, even though the higher mass flow can cause a greater gradient temperature, this flow will decrease the power of the PTC [14]. The relationship of the collector efficiency is calculated equation (2), and depicted for three mass flows of oil in Figure 7.

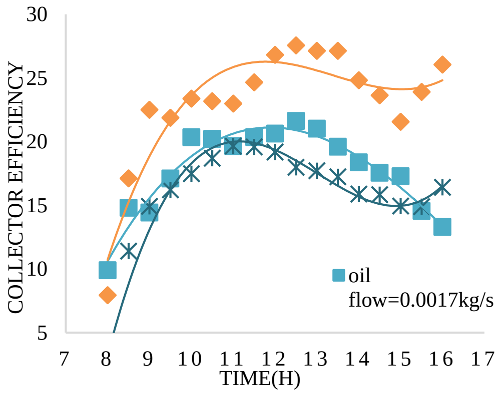

Figure 7. Instantaneous efficiency of the PTC

The efficiency and power of the PTC diagram fit degree 3 of the polynomial with a regression coefficient of about 0.9. The diagrams in Figure 7 represent the best efficiency achieved by the PTC, which is a boost for the oil mass flow rate [14]. Temperatures of the water of the LWT and SWT are displayed in Figures. 8 & 9. These temperatures follow similar patterns. A similar work has been done by Valan Arasu and Sornakumar [25]. They measured the temperature of the storage tank for various sunny days.

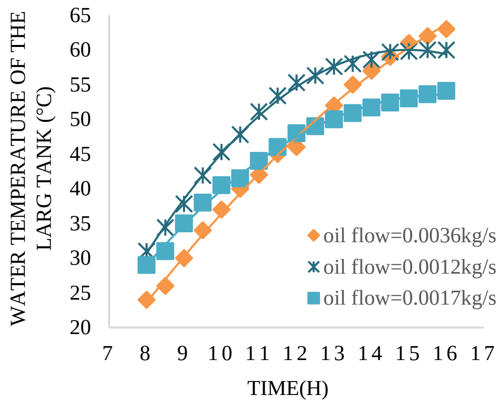

Figure 8. Water temperature of the large tank at different times

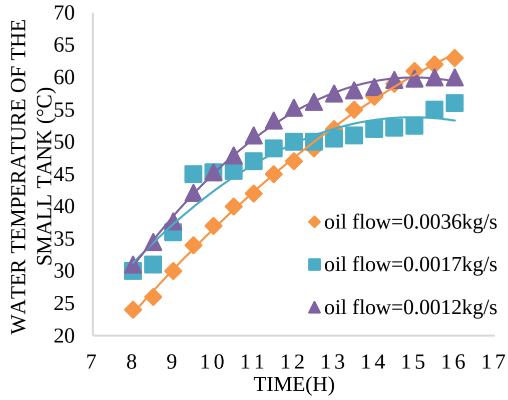

Figure 9. Temperature of small tank in terms of time

The maximum temperatures of the LWT and SWT were 63 °C beginning from a primary value of 24°C at 8:00 am on 15 June (with oil flow of 0.0036 kg/s). The water temperatures of the two tanks show equal values. This detects which of the heat losses between them is ignorable. The temperature of the LWT shows a sharp incline up to 12 and the lowest mass flow of oil resulted in the production of the highest heat to water. After this time, the arrangement of the curves changed. An increase in both the temperature (LWT and SWT) curves with the oil mass flows at 0.0012 kg/s and 0.0017 kg/s are slow and show mild slopes but the temperature curve of 0.0036kg/s has a sharp slope. Figure 10 shows that the collector's efficiency is enhanced by raising the oil mass flow rate [14, 15].

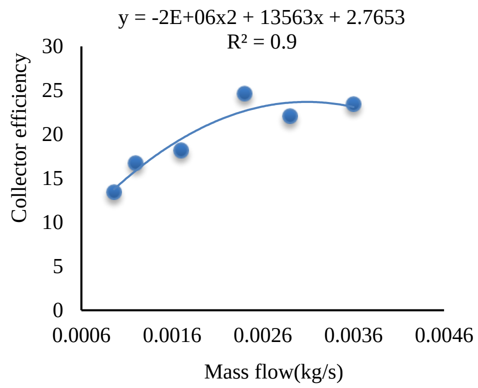

Figure 10. Variation in the collector efficiency as a function of mass flow

Figure 10 is accordance with the results of Gao et al. [15]. They investigated the effects of the water mass flow rate on the efficiency of the energy collection. They recorded a diagram similar to our study diagram [15].

IV. CONCLUSION

In all the solar experiments, radiation is the most effective parameter that changes the outlet oil temperature of the collector, tank temperature and other recorded data. Due to climate changes, solar radiation has different values in daily measurements. However, one of the parameters which the designer can modify to gain more useful energy is the fluid flow rate. The velocity of passing oil within the tubes switches the amount of heat transfer to the water. The flow rate influenced the thermal energy absorbed from the solar radiation and transferred the heat from the oil to the water in the heat exchanger. Our results show good agreement with the results recorded in the literature available

1. The temperature of the outlet heat transfer fluid (oil) increases when the oil mass flow is decreased. Whenever the velocity of the oil diminishes, the fluid has more time to gain more heat radiation. Thus, the temperature gradient of the oil (collector) rises as well.
2. The power and thermal capacity of the parabolic collector is enhanced with the higher mass flow rate. This is because the mass flow affects the collector power, directly.
3. The collector efficiency improves by increasing the flow rate. When there is the greatest flow of oil, it has the maximum efficiency.
4. The temperature of the large tank for all oil flow rates rises over time and is accompanied by solar radiation, but it drops in the afternoon. For oil flow 0.0036 kg/s the temperature of LWT is at its highest value (63°C) rather than at any other.
5. As considered, the curve of the LWT temperature of the oil flow of 0.0036 kg/s has a sharp tilt and grows faster in comparison with the lower oil flow rates.

Consequently, to improve the solar water heating systems efficiency (using PTC) the flow rate of the fluid should be increased.

NOMENCLATURES

C : Specific heat capacity of fluid, J/kg.°C
I : Solar radiation, W/m^2
$\dot{m}$: Mass flow rate, kg/s
O: Oil
$\dot{Q}$: Power, W
T: Temperature, °C
W: water
η : Collector efficiency
a: Ambient
c: Collector
t: Tank

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BIOGRAPHY

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