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Performance Improvements by Introducing Solar Pump in Flat Plate Collector – Experimental Study

Hussain Sadig*, Abdullah Alghafis, Nejlaoui Mohamed, Eihab A. Raouf

Department of Mechanical Engineering, College of Engineering, Qassim University, Buraydah 51452, Saudi Arabia

Corresponding Author Email: H.SADIG@qu.edu.sa

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ABSTRACT

The kingdom of Saudi Arabia (KSA) is recognized for it is huge solar resources, where the average annual solar radiation about 2200 kWh/m^2. With the increase of global awareness on the negative impacts of burning fossil fuels, the kingdom has placed an ambitious plan on utilizing solar energy. The implementation of flat plate collectors (FPC) for water heating would decrease the domestic electric consumption. In this work, an enhancement of a FPC performance by introducing of solar pump was investigated, where, a passive locally fabricated FPC system was modified by introducing of small size solar water pump. The original FPC was characterized at the beginning, then an experimental investigation was conducted on the modified system. The performance of modified system was collected and compared with the original system based on the measurement of achieved water tank temperature, plate temperature, removal factor and system's efficiency for different operating condition and different tilt angles. For the same operating period, and for a tilt angle of 21°, 26° and 31°, the maximum achievable tank temperature for modified system were found to be 57℃, 59℃ and 60℃, respectively. The collected tank temperatures were increased by 12℃, 19℃ and 13℃ for tilt angle of 21°, 26° and 31°, respectively. In addition, as compared with the original system, the maximum achievable efficiency for the modified FPC system was found to be improved by 6%, 7% and 10% for tilt angle of 21°, 26° and 31°, respectively.

1. INTRODUCTION

Burning of fossil fuels is the main cause to many environmental issues including global warming, acid rains and draught. The rising of global demand for energy, coupled with the declining supply of fossil fuels and the associated environmental concerns, has significantly driven the global concerns on renewable energy sources [1-3]. Solar energy can be considered as a one of the most abundantly available type of renewable energy sources in developing world [4, 5]. In addition, solar energy is clean renewable energy source [1, 6], it has variable applications, including direct use for water heating, power generation, and space heating and cooling [7, 8]. Another utilization method of solar energy is by converting the electromagnetic energy of sun's light into direct electric current by using of photovoltaic cells [7]. The geographical location of the kingdom of Saudi Arabia (KSA) is in the middle of Arabian Peninsula with a latitude line between 32ºN and 17ºN and longitude lines between 56ºN and 28ºN [9, 10]. The studies conducted on KSA renewable energy potential in KSA showed a high potential in solar energy [9-11], whereas the mean value for the annual solar radiation in KSA is 2200 kWh/m^2 [9]. In addition, the annual average daily Global Horizontal Irradiation (GHI) values in Saudi Arabia is varying between 5700 Wh/m^2 and 6700 Wh/m^2 while the annual mean value of daily Direct Normal Irradiation (DNI) is varying between 4400 Wh/m^2 and 7300 Wh/m^2 with the maximum values in the northwest part of the country [9]. Solar energy research in KSA dates back several years, with initial planned investigations into solar energy systems launched by the King Abdulaziz City for Science and Technology in 1977 [12]. Recently, numerous studies on using of flat plate collectors were conducted in KSA. Nejlaoui et al. [13] developed a six sigma optimization for flat plate collector with an uncertain designing parameters for material, geometer and environment conditions for Qassim area. The collected results showed that the flat plate collector design presents 31% sensitivity based on efficiency and 27% sensitivity when considering the total cost. Khedher [8] has investigated experimentally the effect of varying water flow rates on flat plate collector efficiency. The collected results confirmed a maximum water tank temperature of 82.5℃ which was achieved at water flow rate 2.5 L/min. Another investigation on the flat plate system performance under different water flow rates was performed by Al-Ajlan et al. [14]. In this work, the investigation was focused on an active water heating system that uses flat plate solar. The collected results were derived from a simulation study, and the simulated outcomes were compared with experimental results collected from a flat plate collector in Riyadh's climate. The collected results from the simulation study and experimental investigation was with in good agreement. The effect of inlet flow condition on the efficiency of the FPCs was studied by Alobaid et al. [15]. The collected results in this work were validated from literature. Flat plate solar collectors are a widely used type of solar thermal collector that transforms solar energy into heat. FPCs are simple in design, they consist of a flat, dark-colored surface that absorbs solar radiation. This heat is then passed on to a circulating fluid, typically water or antifreeze, which can be used for various applications [16]. Flat plate collectors (FPCs) are considered as one of the cheapest and most desirable equipment for water heating for domestic use. In passive (FPCs), water circulation can be accomplished naturally where water flows due to density differences and convection current [1]. Although the relatively high efficiencies associated with passive (FPCs), high temperatures are very difficult to be achieved with such systems due to poor water circulation associated with natural convection [1], other reasons limit the system to achieving high temperature for instance, flat plate collectors have a relatively simple design, which can lead to significant heat losses. These losses which caused by conduction, convection, and radiation, decrease the overall efficiency of the collector [17, 18]. Also design limitations, the design of flat plate collectors often involves a simple absorber plate and a glazing layer, these components may not be able to withstand extremely high temperatures without degrading or failing [7, 19, 20]. Achieving of high temperature is very important parameters in several solar heating applications such as water desalination and water heating for domestic use purposes. Different methodologies can be implemented to achieve higher temperatures in FPCs such as using of concentrating techniques [21, 22], using of Nano-fluids [23, 24] and using of active FPC systems [16, 25]. As compared with FPC active systems, using of concentrating techniques and Nano-fluids to improve the FPCs performance can be considered relatively expensive, where additional materials and space may require. Active FPCs systems use an external pump to circulate the water inside the system, which would affect in improve of the heat transfer coefficient, and hence an increase in water temperature is expected. On the other hand, additional power is needed to run the pump in active FPCs, which in turn would reduce the overall efficiency. The commonly available active FPCs are use electric pump to move the water within the collector which reduce the overall system's efficiency and increase the cost. Use of small size PV solar pump to circulate water in FPCs would give an opportunity to improve the performance of such systems without consuming an electric power.

The traditional FPC that use Thermosiphoning techniques of natural water circulation suffering of a number of issues such as the big size of the system, heat loss and relatively low achievable temperature. Research into more effective FPC systems with small sizes and higher efficiency is crucial. The integrated FPC with a solar-powered water circulation pump offers a sustainable solution for water heating and circulation, particularly in regions with abundant solar resources like KSA. However, improvements in design, materials, and manufacturing processes can significantly boost efficiency, longevity, and cost-effectiveness.

The integration of FPC with low cost small size solar would provide the system with a great improvement in the efficiency since the small size solar pump is not requires big collector area and provides a quite enough water circulation which will improve the heat transfer coefficient significantly. In addition, the use of solar pump provides a sustainable solution for water circulation inside FPC system with an environmentally friendly source for water circulation. Moreover, Integrating the FPC with other renewable energy technologies, such as photovoltaic (PV) modules, can create hybrid systems that provide both heat and electricity. Combined FPC with solar-powered water pumps provides a sustainable solution for water heating in regions with abundant of solar energy like KSA. Continued research and development in these areas are crucial for realizing the full potential of such technology.

Saudi Arabia known with its huge solar resources specially in northern and northwestern parts of the country which put the utilization of solar energy as an attractive option for different applications such as space cooling, water desalination and water heating. Despite the great efforts being made in the Kingdom of Saudi Arabia to benefit from the available renewable resources, especially solar energy, all these efforts are focused on electricity generation and there are no tangible efforts to use solar energy in simple direct thermal applications. The use of small size PV pumps to circulate the water in FPCs would improve the collected water temperatures to a higher level without high cost. Additionally, the small size PV pumps are using very small areas for PV collector which will not affect too much on the required area. The collected results from this work showed that the improved FPC could be used as a promising reliable solution for water heating for domestic uses in Qassim region and northern of Saudi Arabia especially in winter seasons where a considerable amount of electricity is consumed in water heating.

2. MATERIALS AND METHODOLOGY

The objective of this study is to investigate the effect of introducing a low-cost, small-sized water pump powered by solar energy on the performance of a passive flat plate collector. The experimental setup used in this investigation is shown in Figure 1. The system used is primarily composed of three main components including the flat plate collector system's assembly, system's stand and water tank. The flat plate collector assembly is attached to a adjustable stand which can be to use to change the collector's direction into variable orientation tilt angles from ranging 0° to 90°. Riser and header tubes was made from copper tubes with different lengths and diameters.

Figure 1. Experimental rig

Table 1 provides a detailed specification of the flat plate collector system used in this study, including the materials and main dimensions. As shown in Figure 1, four thermocouples were installed at different locations in the system to measure the water temperature throughout the system. These include the inlet water temperature (T1), outlet water temperature

(T2), and plate temperature (T3). The fourth thermocouple (T4) was used to measure the water tank temperature and also to monitor the ambient temperature.

Table 1. Specifications of the used flat plate collector system

No.	Item	Material	Dimensions
1	Absorber plate	Mild steel	1250 × 600 × 3 mm^3
2	Transparent cover	Glass	1268 × 618 × 6 mm^3
3	Collector casing	Wood	1250 × 600 mm^2 18 mm thickness 100 mm height
4	Header tubes	Copper	1190 mm × ⌀ 9.53 mm
5	Riser tubes	Copper	660 mm × ⌀ 19.05 mm
6	Thermal insulation	Rockwool	1250 × 600 × 50 mm^3

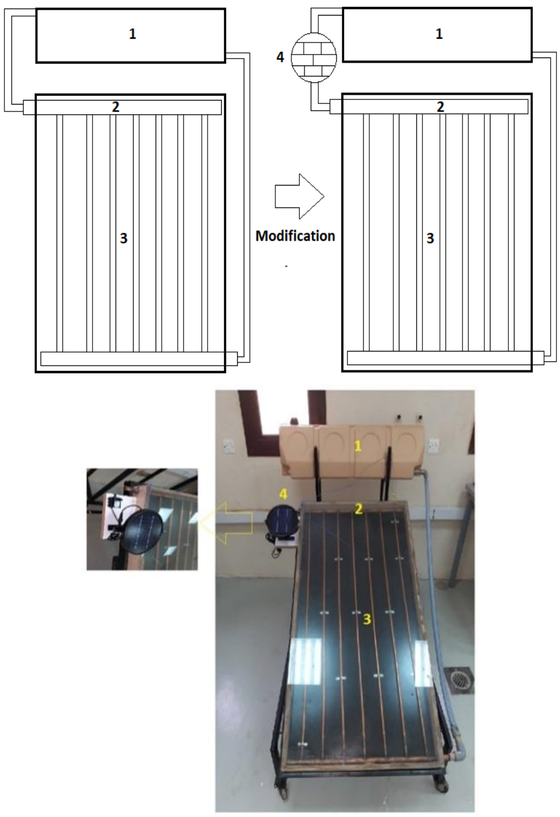

Figure 2. Modification that proposed to passive FPC available at Unaizah College of Engineering (1) Water tank (2) Header tubes (3) Riser tubes (4) Solar pump

The investigations include the following:

1. Study the effect of introduction of solar pump on the FPC's achievable temperature and efficiency.
2. Compare the performance of FPC under passive and active operation mode.

In order to achieve these objectives an experimental methodology consisting of the following phases was used:

1. Characterization of FPC passive system which available at Mechanical Engineering Department laboratory of Unaizah College of Engineering at 31° tilt angle and at operating time from 9:12 to 15:12 solar time. The characterization of the FPC system include collecting the temperature at the mentioned point and calculating of performance parameters including system's efficiency and thermal useful load.
2. Modifications were applied to the system, as shown in Figure 2, where the water flow mechanism at the exit of the upper header tube was altered by introducing a small-sized solar pump. Thus, the operation mode of FPC system was changed to be an active system and the heat transfer mechanism was consequently converted to be as forced convection type instead of free convection where the coefficient of heat transfer is expected to improve [26, 27].
3. Experimental investigation on the modified system under different operating hours and tilt angle of 31°, 26° and 21°. The operating time for the modified system was from 9:12 to 15:12 solar time.
4. The collected results of water temperature at the variable points and the system's efficiency for the modified system were collected and compared with original system's results.

3. THEORETICAL BACKGROUND OF COLLECTOR'S PARAMETERS

During conducting the experiments, there is a need to calculate different parameters related the performance of the fabricated system. These parameters include collector thermal efficiency, thermal useful load of the collector and collector losses.

3.1 Thermal useful load on the FPC

At the steady operation condition, the different heat losses in the flat plate collector can be represented as in overall heat loss coefficient. The amount of heat collected by the system for specific area (Ac) can be calculated based on Eq. (1) [1].

$$Q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] \tag{1}$$

where,

Q_u=Themal useful load

G_t=Global solar irradiance at the collector plane.

Ac=Collector area (m^2) including FPC area and solar pump collector area.

τα=Absorber transmittance.

U_L=Solar collector overall heat loss coefficient (W/m^2- °C).

T_p =Average temperature of the absorbing surface (°C).

T_a=Ambient temperature (°C).

3.2 Top loss coefficient

As in all thermal energy conversion systems which include heat transfer processes, heat losses to the surrounding by various means of heat transfer are not avoidable. The heat loss from the flat plate collector includes top loss, bottom and edge loss. Since the top part of the collector is exposed directly to atmospheric condition and cannot be insulated such as collector's bottom the majority of the collector heat loss is due to the top loss which is calculated based on Eq. (2) [1].

$$U_t = \frac{1}{\frac{N_g}{\frac{C}{T_p}\left(\frac{T_p - T_a}{N_g + f}\right)^e + \frac{1}{h_w}}} + \frac{\sigma\left(T_p^2 + T_a^2\right)\left(T_p + T_a\right)}{\frac{1}{\epsilon_p + 0.00591 N_g h_w} + \frac{2N_g + f - 1 + 0.13\epsilon_p}{\epsilon_g} - N_g} \tag{2}$$

where,

$f = (1 + 0.089h_w - 0.1166h_w\epsilon_p)(1 + 0.07866N_g)$.

$C = 520(1 - 0.000051\beta^2)$.

$e = 0.43(1 - \frac{100}{T_p})$.

N_g=Number of glass covers.

σ=Stefan - Boltzmann constant=5.67 * 10^{-8} W/m^2.K^4.

ϵ_g=Emissivity of glass covers.

ϵ_p=Absorber plate emittance.

T_p=Average temperature of the absorbing surface (°C).

T_a=Ambient temperature (°C).

h_w=Wind heat transfer coefficient (W/m^2 °C).

L=Half distance between two consecutive riser pipes (m).

V=Wind velocity (m/s).

3.3 Bottom heat loss coefficient

Collector bottom heat loss is mainly due to conduction. Since the bottom side is insulated, the temperature at the outside surface of the bottom which exposed to atmospheric condition is expected to be low and thus heat transfer due to the radiation can be neglected. Collector bottom heat transfer coefficient can be calculated based on Eq. (3) [1].

$$U_b = \frac{1}{(\frac{t_b}{k_b} + \frac{1}{h_{ce-a}})} \quad (3)$$

where,

t_b=Thickness of back insulation (m).

k_b=Conductivity of back insulation (W/m °C).

h_{ce-a} =Convection heat loss coefficient from back to ambient (W/m^2 -K).

3.4 Heat loss coefficient form the collector edges

As compared with top and bottom area, flat plate collector edges have smaller area which would affect in reducing of amount of heat loss. The heat transfer coefficient for the flat plate collector edges can be calculated based on Eq. (4) [1].

$$U_e = \frac{1}{(\frac{t_e}{k_e} + \frac{1}{h_{c,e-a}})} \quad (4)$$

where,

t_e=Thickness of edge insulation (m).

k_e=Conductivity of edge insulation (W/m °C).

$h_{c,e-a}$ =Convection heat loss coefficient from edge to ambient (W/m^2 °C).

3.5 Solar collector overall heat loss coefficient

Collector's overall heat loss coefficient was calculated based on Eq. (5).

$$U_L = U_t + U_b + U_e \quad (5)$$

3.6 Thermal efficiency

Collector's thermal efficiecny was calculated based on Eq. (6).

$$\eta = \frac{Q_u}{A_c G_t} \quad (6)$$

where, η = $collecto's\ thermal\ efficiency$.

3.7 Heat removal factor

In all flat plate collectors, heat removal factor is very important parameter since it represents to which extent the available energy es transferred to the working fluid. Heat removal factor can be defined as the ratio of the amount of useful energy gained and the amount that would result if the absorbing plate surface of the collector had been at the same local fluid temperature. The collector heat removal factor was calculated based on Eq. (7) [1].

$$F_R = \eta / \left[(\tau\alpha) - U_L \frac{(Tp - Ta)}{G_t} \right] \quad (7)$$

where,

G_t=Global solar irradiance at the collector plane.

F_R=Heat removal factor.

τα=Absorber transmittance.

U_L=Solar collector overall heat loss coefficient (W/m^2- °C).

T_p=Average temperature of the absorbing surface (°C).

3.8 Reckoning of time

Since there is a variation between the local time at specific location and the real position of the sun in the sky, apparent solar time is a suitable way express the day time with the real position of the sun. For all tested hour modes, the local noon time for Unaizah city was found to be at 12:12 PM which was calculated based on the apparent solar time based on the Eq. (8) [1].

$$AST = LST + ET \pm 4(SL - LL) \quad (8)$$

where,

$$ET = 9.87\, sin(2B) - 7.53\, cos(B) - 1.5\, sin\,(B) \quad (9)$$

where,

$B = (N - 81)\frac{360}{364}$.

N=Day Number (From table).

AST=Apparent solar time.

LST=Local standard time.

ET=Equation of time.

SL=Standard longitude.

LL=Local longitude.

4. RESULTS AND DISCUSSIONS

4.1 Variation of water tank temperatures

Figure 3 shows the variation in water tank temperatures for the original and modified FPC systems at different times of the day for tilt angles of 31°, 26°, and 31°. As observed in the figure, the water tank temperatures in the modified system were higher compared to those in the original system. This increase was due to the improved heat transfer coefficient of the system, which resulted from the higher water flow rates associated with the modified system. For the same operating period, the maximum achievable tank temperature for modified system were found to be 57°C, 59°C and 60°C for tilt angles of 31°, 26° and 31° respectively. Moreover, for all tested tilt angles, the peak temperature for the modified system was shifted towards the left which shows the capability of the modified system to transfer the heat form the collector plate to the water even after noon time where the absorber plate temperature is expected to be less at this time which is an advantage for the modified system. In addition, for the same operating hours, the rate of temperature increase was found to be higher for the modified system. As it can be seen from the Figure 3 that the modified system reached the highest achieved temperature for the original system in around 10:30 solar time. Thus, the introduction of solar pump was very effective in reducing the needed time for heating.

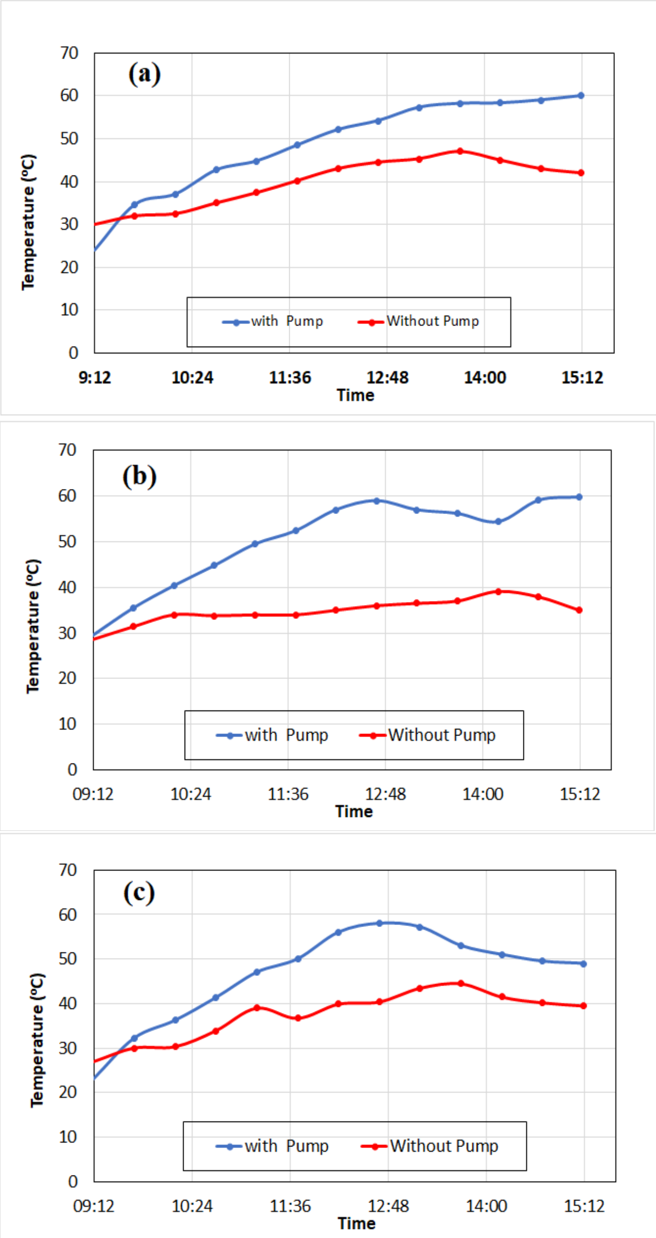

Figure 3. Tank temperature for original and modified system at: (a) 31° tilt angle (b) 26° tilt angle (c) 21° tilt angle

The absorber plate temperatures for original and modified systems for tilt angle of 31° are shown in Figure 4. As compared with modified system, the original system showed higher absorber plate temperatures trends throughout the day. The maximum plate temperature for original system was found to be 107.3℃, which was collected at noontime while for modified system it was 98°C. This was due to higher heat transfer rates associated with modified system.

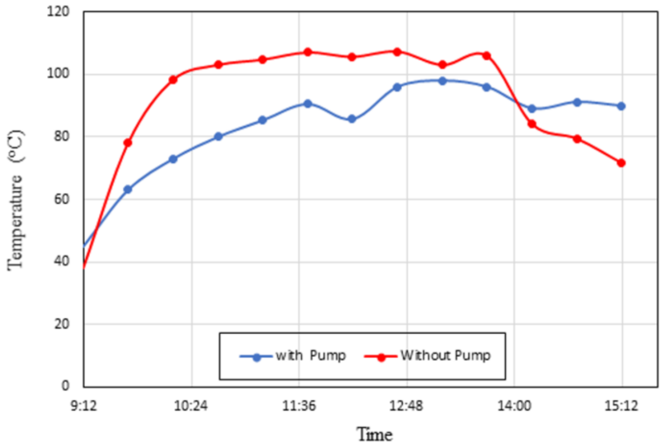

Figure 4. Plate temperature for original and modified system for tilt angle of 31°

The effect of higher heat transfer rates associated with modified system was very clear at the beginning of system operation. As it can be seen from the Figure 4, a higher plate temperature increase rate was observed for original system at the first two hours. Since the system water circulation in the original was relying on thermosiphon phenomena, the increase in water temperature was very slow at the beginning of the process. This was due to poor water circulation associated with original system at the beginning which was affected in a lower heat transfer rates and hence higher absorber plate temperatures. In addition, at afternoon time, a sudden drop in temperature were noticed for original FPC system as compared with the modified system. This may be due to the relatively higher water temperature associated with the modified system which would affect in lower heat transfer rates at afternoon time.

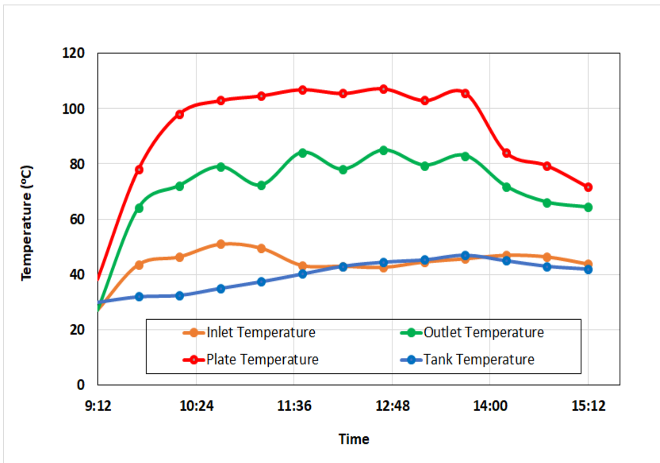

Figure 5. Temperatures at different points for the original system for tilt angle of 31°

A comparison of the collected inlet, outlet, plate and tank temperatures throughout the operating hours for the original and modified FPC systems for tilt angle of 31° are shown in Figure 5 and Figure 6, respectively. Generally, the higher temperatures differences between water inlet and outlet shows the higher need for improving of heat transfer rates inside the FPC system, since a higher heat transfer rates would lead to a closer inlet and outlet temperatures. Similarly, the higher differences between absorber plate temperature and inlet and outlet temperatures shows the higher opportunity and higher need to improve the heat transfer rates inside the collector. As it can see from Figure 5, the original FPC system temperature profile show huge variation between inlet and outlet water temperature and also between water outlet temperature and plate temperatures.

As compared with the original FPC system, the collected temperatures at inlet, outlet and tank were found to be very close to each other for modified FPC system which shows the effect of solar pump on improving of heat transfer rates. Due to the higher water flow rates associated with modified FPC system, the introduced water in the system receives higher amounts of heat during passing through the absorber plate which was affected in closer temperatures readings for water at inlet and outlet points. On the other hand, a considerable temperature difference was observed for same points for the FPC original system, which reflects the poor water circulation in passive systems. As it can be seen from Figure 6, a constant temperature different between water tank temperature and plate temperature was noticed. Thus, a further increase in water temperature are expected with the increase of water flow rate inside the system.

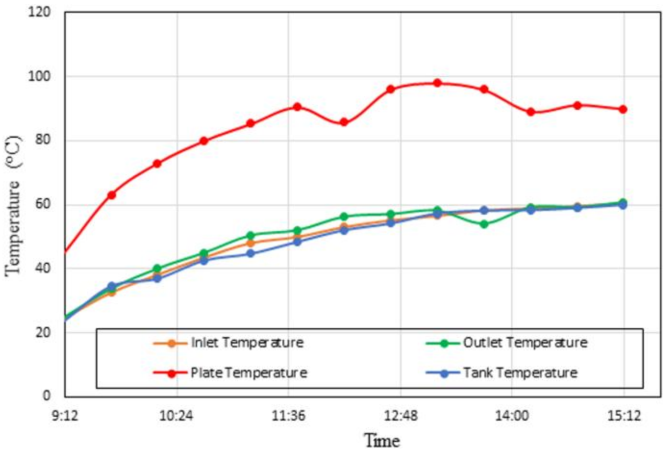

Figure 6. Temperatures at different points for the modified system for tilt angle of 31°

As compared with the original FPC system, the temperature differences between tank temperature and plate temperatures for tilt angle of 31° was found to be ranging from 20℃ to 30℃ for the modified system while it was found to ranging from 10℃ to 60℃ for the original FPC system. The higher variation in temperature between water tank temperature and plate temperature represents the higher opportunity loss to benefit from the collected heat by FPC system.

4.2 System efficiency

Figure 7 is a comparison of collector efficiencies for original and modified FPC systems at different operating hours and for tilt angles of 31°, 26° and 31°. As it shown in the Figure, for most of operating hours, the modified FPC system showed higher efficiencies as compared with the original system this is due to the higher heat transfer rates associated with modified system. After 14:00 solar time, different trend was observed where the modified FPC system showed lower efficiency as compared with the original system. This may be due to the reduction in solar radiation which in turn affected in water flow rate which inside the system. In addition, since at afternoon time the water temperature for modified system is higher as compared with the original system lower heat transfer rates are expected which would affect the system efficiency. Moreover, the efficiency of the modified FPC system showed a relatively stable values as compared with the original FPC system. In addition, the maximum achievable efficiency for the modified FPC system was found to be improved by 6%, 7% and 10% for tilt angle of 21°, 26° and 31°, respectively as compared with the original system.

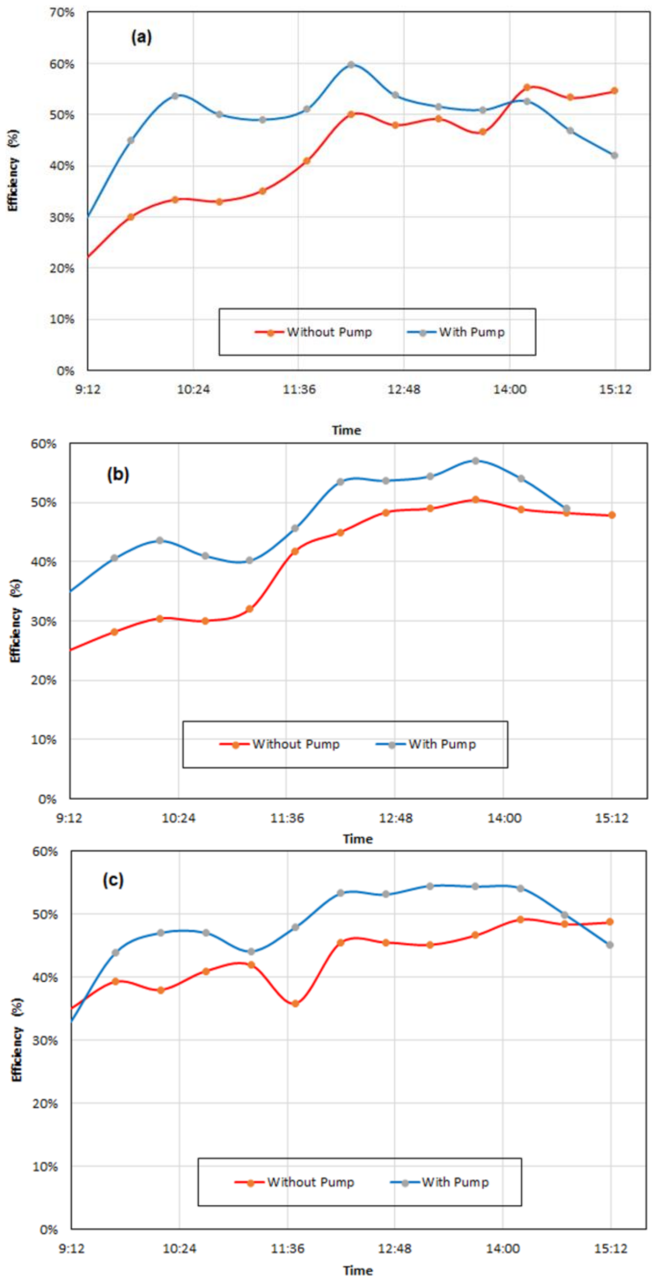

Figure 7. Variation of efficiency for original and modified system at: (a) 31° tilt angle, (b) 26° tilt angle, (c) 21° tilt angle

4.3 Thermal useful load

Figure 8 is a comparison of thermal useful load for original and modified system for tilt angle of 31°. As it can be seen from the figure, for most operating hours, the thermal useful load was higher for the modified system. The percentage increase in the thermal useful load for the modified system was ranging from 5% to 61%. It is very clear that higher percentage increase in the thermal useful load was found to be at morning hours. This is may be due to the combined effect of increasing of solar radiation for the collector and also for the solar panel which would affect in increasing of the amount of circulated water by the solar pump. A gradual reduction in the percentage increase in the thermal useful load was noticed after noon time and continued till a negative value were observed around 14:00 solar time, this also referred to the negative effect of the reduction of the amount of solar radiation on the system performance.

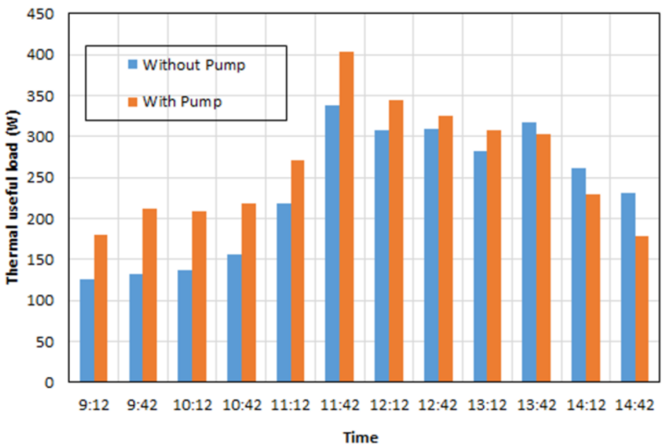

Figure 8. A comparison of thermal useful load for original and modified system for tilt angle of 31°

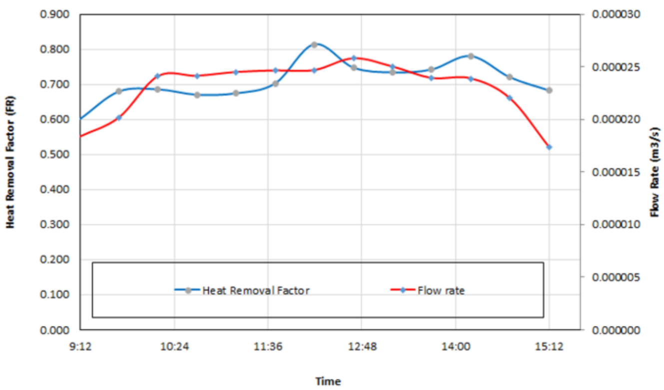

Figure 9. The effect of water flow on the collector's heat removal factor for tilt angle of 31°

4.4 Effect of water flow

Water flow inside the collector is very important parameter and has huge influence of the system's performance. During collector operating, water flow inside the system is affected by many parameters including the amount of received radiation, insulation level, water speed, water density and water temperature. The received radiation has a combined effect on the water flow since it would effect on water temperature and also on the solar pump pumping power. On the other hand, the increase of water temperature would effect of lowering of water density which in turn would increase the water circulation inside the system. Heat removal factor is an important factor that affect the overall FPCs efficiency. The heat removal factor expresses the ratio of the actual useful energy collected to the maximum potential energy gain if the collector's surface were at the fluid temperature. Heat removal factor is strongly affected by increasing of heat transfer rate between absorbing surface and working fluid. Figure 9 is the effect of water flow on the collector's heat removal factor for tilt angle of 31°. As it can be seen from the figure that the water flow increases with the increase of time till it reached it is highest value at noon then it decreases till the end of the day. From the figure it is very clear that a higher increase in water flow rate was observed at the beginning hours from 9:12 to 10:00 solar time. This may be due to the higher percentage increase in water temperature at the beginning as compared with the other operating hours where the percentage increase in the temperature is relatively less. A similar trend was observed for the collector's heat removal factor where it increases with time increase till it reaches it is maximum value at noon then falls down again.

5. CONCLUSIONS

Saudi Arabia known with it is huge solar resources throughout the year, which encourages the implementation of solar energy systems for various purposes, including domestic water heating. In this work, a locally fabricated flat plate collector was investigated experimentally at Unaizah Engineering College. The work presents the results of introducing of a solar pump in a water heating system driven by a flat plate collector. The effect of introduction of small size low cost PV solar pump in a locally fabricated passive water heating system driven by a flat plate collector was investigated experimentally. The collected results showed that the percentage increase in thermal useful load for the modified system was found to be ranging from 5% to 61%. In addition, the use of solar pump to circulate the water was affected in an improvement in achievable water temperature with 27.5%. The overall system efficiency was found to be improved by 6%, 7% and 10% for tilt angle of 21°, 26° and 31°, respectively. The collected results of this work showed the capability of using of the improved FPC systems as promising and reliable solution for domestic water heating specially in Qassim region, KSA. For further research, additional investigation on the FPC system under different climate and with different water circulation driving methods will be conducted.

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