An Experimentally study of the effect of hot water flow rate on solar collector systems

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ABSTRACT

Solar power is an appealing green energy source. Domestic hot water represents the second-largest consumption of household electricity. The most straightforward application of solar energy is converting it into useful heat, particularly for water heating systems. The flat plate collector is the most common device for this conversion. This paper details the design and experimental analysis of the flow rate within the collector of a natural circulation solar water heater, which was constructed and tested in Erbil, Iraq, at a latitude of 36 degrees. The collector is placed towards the south with a tilt angle of 45° with the horizontal. The results indicate that the system's performance is highly dependent on the collector's flow rate and the incident solar radiation. The maximum flow rate within the system due to natural circulation is approximately 0.207 litres per minute per square meter. During the cold season, the highest water temperature from the header pipes ranges between 50 to 56°C; in the hot season, it reaches about 80 to 90°C. Energy savings for February, March, and April are 326.6 MJ, 277.2 MJ, and 252 MJ, respectively.

Keywords: solar energy, solar collector, hot water, flow rate and efficiency

Nomenclature			
SWHs	Solar water heating system	t	Time
DHW	Domestic hot water	A_c	Collector area (m^2)
Q_{sol}	Solar thermal energy to the system (kWh)	V	Volume of storage tank (L)
E_{sol}	Irradiation onto solar collector (kWh)	L	Latitude angle (deg.)
E_{aux}	Heat Generator and electricity consumption (kWh)	**Greek symbols**	
Q_{use}	Domestic hot water energy consumption (kWh)	δ	Solar declination angle, (deg.)
Q_{int}	Heat Loss to the indoor room (kWh)	τ	Hour angle, (deg.)
Q_{ext}	Heat Loss to surrounding (kWh)	β	Solar altitude angle,(deg.)
SF	Solar Fraction of the system (%)	θ	Surface incident angle,(deg.)
Q	Flow rate (L/h)	γ	Surface-Solar azimuth angle,(deg.)
T	Temperature (°C)	ϕ	Collector plane's inclination to the horizontal(deg.)
h	hour (h)	n	Number of days
		η	Efficiency of the collector (%)

1. Introduction

Solar energy is most commonly used for residential water heating. This is made feasible by a solar water heating (SWH) system, which comprises of a solar collector and a storage tank. The collector absorbs solar radiation and converts it into heat, which is subsequently transferred to the water passing through it. Within the system, water circulates both spontaneously through buoyancy-driven circulation and by a pump. Natural circulation SWH systems are particularly intriguing since they offer a popular and easy way to harness solar power.

Due to a major increase in power use and a severe shortage that goes back more than a century, Iraq has experienced a rising energy crisis over the past thirty years. Particularly in the last 20 years, Iraq's residential sector has been a significant consumer of the nation's electricity. Water heating consumes a significant portion of this electricity, particularly during the winter. As a practical solution to the rising demand, solar water heaters (SWHs) are an affordable and simple substitute for other clean energy technologies being deployed globally (Duffie, John A.; Beckman, 2005).

Standard flat plate solar thermal collectors are designed to withstand temperatures between 40 to 70°C, making them ideal for low- to medium-temperature applications [1]. The industry standard for solar water heating is flat plate collectors. The dimensions of the thermal performance system are 125 by 110 cm with a 25 cm width. This permits fluid to flow from the input to the outlet via a 15.9-meter-long pipe that is arranged in a lope square design. Water serves as the working fluid, and two distinct flow rates 5.3 and 6.51 L/min—are assessed. Experiments were done at the Iraqi University of Technology in Baghdad. The results demonstrate that the lower flow rate of 5.3 L/min created a greater water temperature compared to 6.51 L/min, which increased collector efficiency. At 51.4°C and 49 °C, respectively, the highest recorded temperatures were accompanied by flow rates of 6.51 L/min and 5.3 L/min. This study emphasizes how well the system heats water for a range of applications, including home, business, and other uses. (Hashim *et al.*, 2018).

The sun's radiation and the transformation of thermal energy into a fluid are produced by solar collectors. Typically, solar collectors, accumulators (hot water tanks), and auxiliary sources make up solar water heating systems. (Jaisankar *et al.*, 2011).

The findings of using numerical simulation in Basra city for the solar water heating system show that the greatest tilt angle of the collector is seen to be close to 50 degrees, while the highest solar altitude angle in January is roughly 40 degrees. It is found that, given the parameter ranges used in the study, the storage water temperature ranges from 65 to 95 ^{o}C. This temperature range is suitable for residential use in Basra. (Hammadi, 2009).

to find out how employing nanofluids with enhanced thermal conductivity affects flat plate solar collector efficiency. specifically, studies on the effects of different mass flow rates on the efficiency of flat plate solar collectors based on CuO/water nanofluid. The experimental setup consists of a storage tank, a flat plate solar collector, and a ladder-type heat exchanger. The instantaneous efficiency of the solar collector was measured with and without Triton X-100 surfactant, at a reduced volume fraction of 0.01% and an average particle size of 30 nm, while the flow rate was adjusted from 1.0 l/min to 3.0 l/min under ASHRAE requirements. The experimental results show that using the nanofluid at a mass flow rate of 1.5 l/min increases collector efficiency by 19.7%..(Prakasam, Thottipalayam Vellingiri and Nataraj, 2017).

The relationship between heat gain and collector pump electricity consumption is the main topic of this study, which looks at the ideal flow rate of a collector loop in a solar hot water system in Ho Chi Minh City, Vietnam. After accounting for variables such as tank volume, collector area, and water temperature, the ideal flow rate is found to be 0.132 kg/s (Joseph Stalin, Arjunan and Sadanandam, 2017).

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The working fluid employed in the design and construction of a flat plate solar water heating system was Al2O3/water nanofluid. The solar collector's efficiency was evaluated in forced circulation mode. By using Al2O3/water nanofluid at a flow rate of 2 litres per minute, collector efficiency was increased by 14.3% as compared to using distilled water as the working medium.(Prakasam, Thottipalayam Vellingiri and Nataraj, 2017).

the design of the collector for a solar water heater that runs on natural flow and the experimental assessment of the flow dynamics inside. In Ado-Ekiti, Nigeria, a solar-powered water heater was constructed and tested at 7.5°N latitude. The system's performance through the collector and the incident solar radiation is found to be significantly reliant on the flow rate, according to the results. Analysis conducted throughout a typical day, particularly around midday when the solar collector receives its maximum energy input, shows peak collector efficiency. Testing revealed that the equipment performed optimally at 0.1 kg/s.m2, yielding a maximum collector efficiency of 68.5%. In addition, it was discovered that the system's average daily efficiency was 57.7%. The highest recorded water temperature was 83.5°C, whereas the maximum recorded ambient temperature was 34.5°C. (Bolaji, 2006).

Investigates the impact of mass flow rate on the thermal performance of a solar household water heating system (SDHW). Although it is recommended to have a specified flow rate of 50 l/h.m^2, modern advancements in motor technology suggest considering lower flow choices (7–14 l/hm2). Experimental tests show that the performance of a conventional serpentine collector increases only modestly with higher flow rates. The study models the entire system and compares the initial investment and operating costs for low-flow (20 l/h.m2) and high-flow (80 l/h.m2) configurations. Given that the low-flow system has a lower investment cost and embodied energy, it may prove to be more cost-effective over 18 years, even though the high-flow system has fewer running hours and a somewhat greater solar fraction. As a result, the study suggests backing. As a result, the study suggests backing. Consequently, the study suggests that low-flow designs for SDHW systems be encouraged while taking a number of ecological and economic factors into consideration.. (Plaza Gomariz, Cejudo López and Domínguez Muñoz, 2019).

Solar collectors are the primary and essential components of any solar thermal energy system. They can be divided into two main categories: stationary collectors and tracking collectors (Tyagi *et al.*, 2021) . The classification of these solar thermal collectors is illustrated in Figure 1.

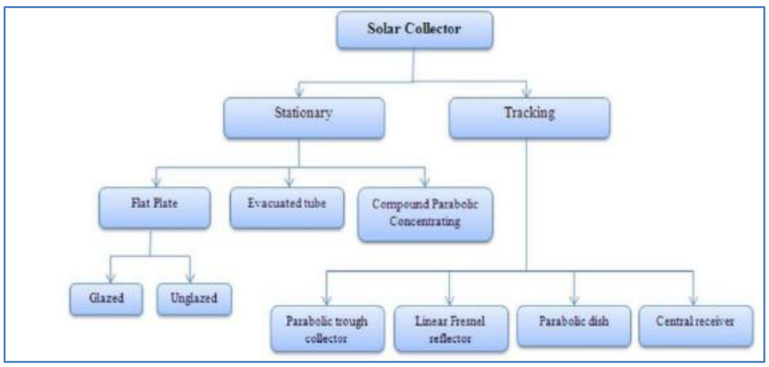

Figure 1. Types of solar collectors.(Tyagi *et al.*, 2021)

This study aims to analyses the impact of the flat plate solar water heating collector's efficiency and flow rate at the College of Engineering's mechanical engineering department in Erbil, Iraq. The system's flow rate, efficiency, and incident solar radiation are measured in this study to evaluate the effectiveness of solar thermal collectors.

2. Methodology

2.1 Description of the system

The apparatus comprises a flat-plate solar collector. Figure 2 displays the aerial perspective of this collector. Each tube measures 1.5 meters in length and possesses dimensions of 20mm x 40mm. These tubes are joined at both ends to header pipes, with the headers featuring an inner diameter of 25 mm, an outer diameter of 25.6 mm, and a length of 825mm. The flat-plate solar collector is affixed to an Aluminum casing at a 42-degree angle facing south. Additionally, the solar collector incorporates a water tank with a capacity of 50 liters for one person and 100 liters for two individuals.

Figure 2. Experimental set-up of the flat plate solar water collector system.

2.2 Solar Collector and Energy Equations

A thorough understanding of the sun's current radiation levels in each location is essential for the design and testing of an affordable solar energy system. As seen in Figure 3, the sun's surface direction and position inside the atmosphere determine how much solar energy it emits.

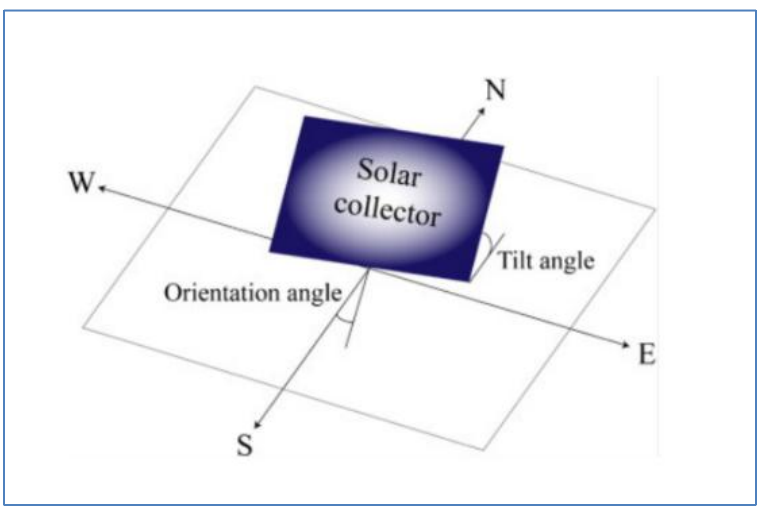

Figure 3. Solar angles for a tilted surface.

The latitude (L), solar declination (δ), and time (t) all affect the sun's location. These characteristics are derived from solar geometry fundamentals and are provided by (Saleh, Kaseb and El-Refaie, 2004).

$$\delta = 23.45\sin\left(360\,\frac{384+n}{365}\right) \quad (1)$$

$$\tau = 15(t - 12) \qquad (2)$$

$$\sin\beta = \sin L \ \sin\delta + \cos L \ \cos\delta \ \cos\tau \qquad (3)$$

The incident angle θ of solar beams on a surface tiled with the horizontal angle ϕ is given by (Standard, 2009).

$$\cos\theta = \cos\beta \cos\gamma \sin\phi + \sin\beta \cos\phi \qquad (4)$$

For the system, an estimate of the electrical resources saved by the use of SWHs must be performed using theoretical equations and solar weather data to measure the electrical resources. The usable energy of an SWH Solar Collector part is provided by (Duffie, John A.; Beckman, 2005).

$$Q = m*C.p*\Delta T \qquad (5)$$

$$T_{fo} = T_{fi} + \frac{Q_u}{\dot{m}C_{pf}} \qquad (6)$$

$$Q_u = A_c F_R[\tau\alpha I_t - U_L(T_{fi} - T_a)] \qquad (7)$$

$$F_R = \frac{\dot{m}C_{pf}}{A_c U_L}\left(1 - e^{\frac{-A_c U_L F'}{\dot{m}C_{pf}}}\right) \qquad (8)$$

$$\eta_c = \frac{Q_u}{A_c I_t} \qquad (9)$$

$$Q_{sol} = E_{sol} - Q_{ext} \qquad (10)$$

The efficiency of the collector is estimated as

$$\eta_{Collector} = \frac{Qsol}{Esol} \qquad (11)$$

The solar fraction SF is given by

$$SF = \frac{Qsol}{Qsol + Qaux} \qquad (12)$$

2.3 Experimental parts use

The descriptions of all components used in the experiment are depicted in Figure 4. A K-type thermocouple was employed for temperature measurement. The water tank temperature was gauged using a thermocouple, calibrated with a thermometer. An infrared thermometer was utilized to measure the temperature of the inlet and outlet of the header pipes of the collector, with calibration performed using the forehead or palm. Water temperature was also monitored using a standard thermometer (°C). Furthermore, a Solar Power Meter (Model: SM206) was employed to measure solar intensity across

different periods.

Figure 4 Main components of the experimental

3. Result and Discussion

The culmination of data collected from the experimental setup offers crucial insights into the functionality and efficiency of the flat plate collector in utilizing solar energy for water heating via natural circulation. This section scrutinizes the recorded temperatures at pivotal points within the system, discerning patterns and correlations. The discussion extrapolates these findings to propose potential enhancements for optimizing solar thermal systems, aiming to augment their efficacy in practical water heating applications, particularly in regions abundant in solar resources like Kurdistan. The outcome of the simulation of Erbil city in Iraq with coordinates (Latitude: 36.221° N and Longitude: 44.021° E).

Figure 5 Displays the day characterized by intermittent cloud cover and bursts of sunshine, the water temperatures at the inlet and outlet of the system exhibit notable variations. The maximum recorded outlet temperature reaches a peak of 63°C, Meanwhile, the inlet water temperature achieves a maximum of approximately 45°C. This differential between the inlet and outlet temperatures underscores the system's ability to significantly elevate the water temperature, leveraging the available solar energy even under partly cloudy conditions. Such performance highlights the resilience and effectiveness of the system in optimizing thermal gain throughout the day.

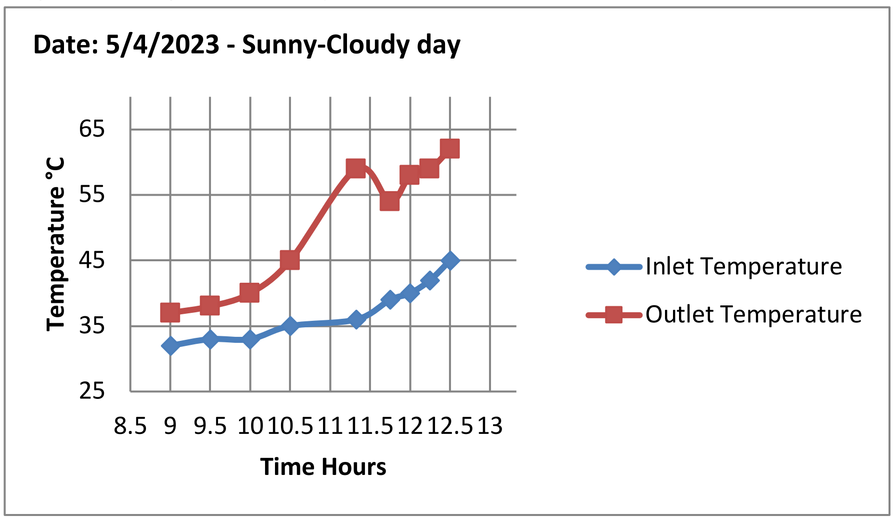

Fig. 5. Hourly inlet and outlet collector tank assembly temperature

Figure 6 depicts the same situation but for cloudy days on April 5th and it is clear that the temperatures are low as compared to the previous cases. The maximum outlet temperature is not exceeding 33 °C, and the inlet temperature is below 25 degrees.

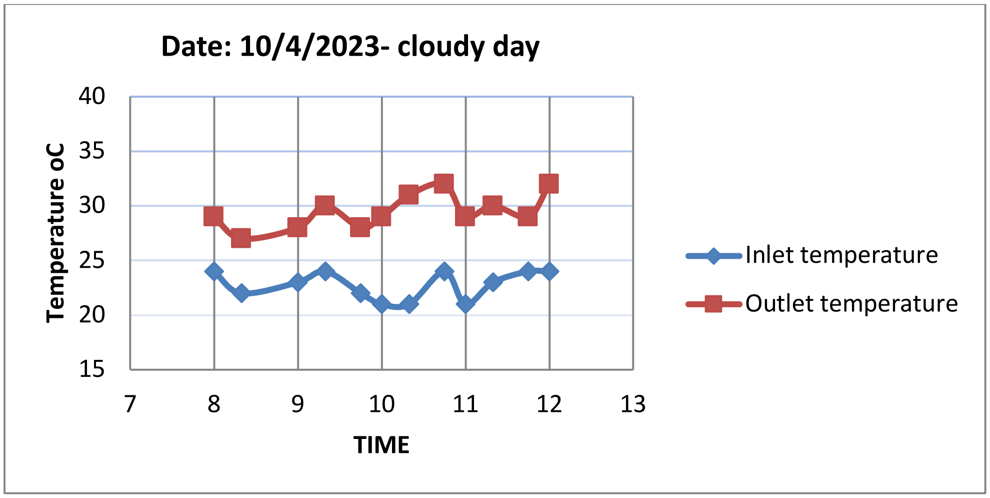

Figure 6 Hourly inlet and outlet collector tank assembly temperature variation

In the same month in **Figure 7**, the solar collector system operates at peak efficiency on a sunny day, with the outlet water temperature soaring to 72°C. This high outlet temperature reflects the optimal conditions for solar energy absorption, as the abundant sunlight maximizes the system's thermal output. Concurrently, the inlet water temperature reaches a maximum of 63°C, indicating a substantial increase in temperature as the water passes through the collector. The significant difference between the inlet and outlet temperatures demonstrates the system's capability to effectively harness solar energy, converting it into a substantial thermal gain, which is particularly evident on clear, sunlit days

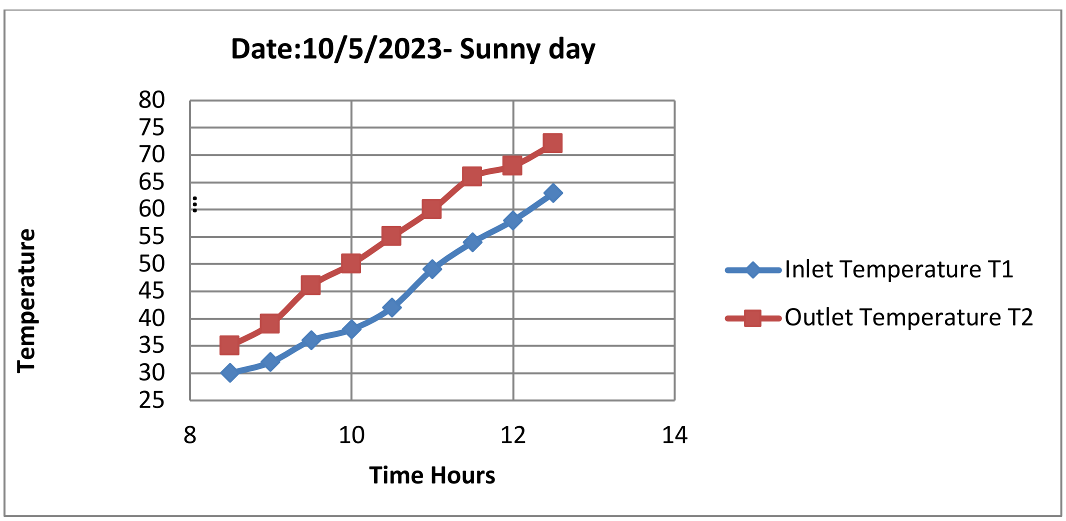

Figure 7 Hourly inlet and outlet collector tank assembly temperature variation.

Figure 8 shows the collector efficiency varies with the collector's performance coefficient (($T_{f,in}$-T_a)/q_s) the collector efficiency decreases also the collector performance coefficient increases making it reach a stagnation point, as seen in this diagram. The stagnation temperature for the collector is defined as the maximum equilibrium temperature attainable and therefore corresponds to operation at no flow when no energy is withdrawn from the collector.

The stagnation point is at the x-axis of the curve at x=$(Cg * (\tau\alpha))/U'$. The curves also show a high level of agreement between theoretical and practical results but sometimes the sudden change in the weather or the inaccuracy of the devices causes a difference between the results.

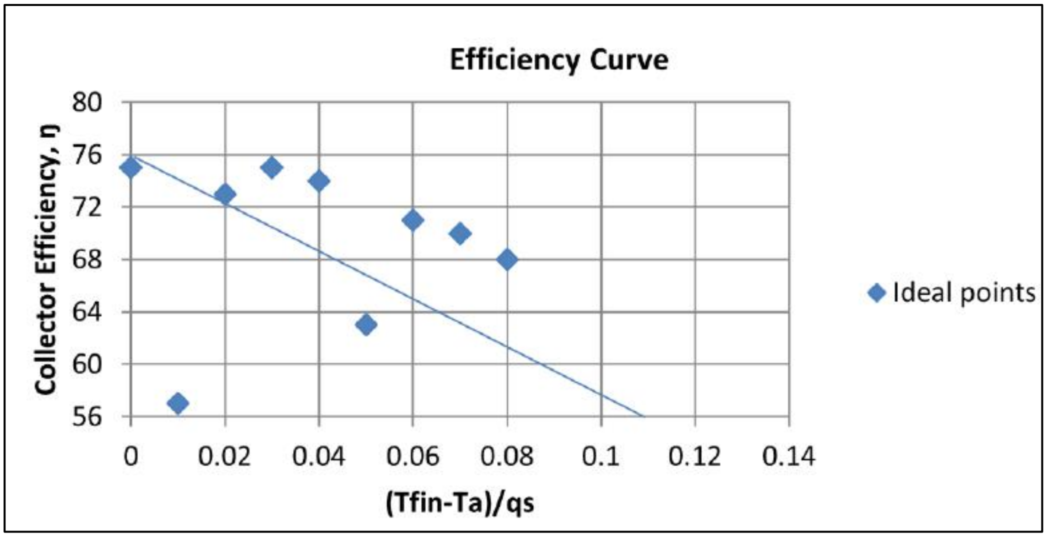

Figure 8. Correlation of predicted collator efficiency in terms of $\left(T_{f,in} - T_a\right)/q_s$.

On the other hand, the experimental connection of pipes used; the inlet and outlet from the collector as shown in **Figure 1**. The assembly was filled with water and there is a vertical transparent tube which filled with water after waiting for about two hours the level inside the vertical began to decrease which is an indication of the vaporization of water from the free surface as the temperature increased and the in the horizontal pipe the dye is applied and as the dye begins to move with water from hot outlet to the inlet portion the velocity of the propagation was determined dividing the propagation distance over the time and the velocity could be determined and the flow rate found and it was in the limit of 0.207 lit/min.m^2. the value obtained is near 0.3 lit/min.m^2 indicated by (Howell, 1982) and it is less than that adopted for forced circulation as 1 to 4 lit/min.m^2. Table 1. Displays the different temperature variations with time, including inlet and outlet temperature of the collector, ambient temperature, and solar radiation.

Table 1. Natural circulation solar water heater on February 26th 2024

Local time (hours)	Header pipe temperature (°C)		Ambient temperature (°C)	Tank temperature (°C)	Collector inlet temperature $T_{f,in}$, °C	Solar intensity W/m^2
	inlet	outlet				
8:00	25	27	3	21	18	100
9:00	26	29	5	22	19	300
10:00	30	45	8	24	22	450
11:00	38	50	13	31	25	600
12:00	44	56	16	33	27	650
13:00	45	56	17	38	30	630
14:00	42	54	15	41	32	550
15:00	41	50	12	43	31	450
16:00	37	43	9	47	30	250

Figure 9 shows the hourly temperature variation for the collector tank and the header pipes. The maximum temperature recorded in the header pipe outlet was 56 ºC while the temperature at the inlet was 45 ºC. in the collector tank assembly, the temperature from the tank entering the collector was 32 ºC at nearly two o'clock and the water in the tank was 41 ºC and this is due to heat gain from the solar rays. The energy saving for this day is equal to 10.92 MJ/ day, and if this value could be taken on average for the month the energy saving will be 327.6 MJ/month (91 kWh/month) in this month.

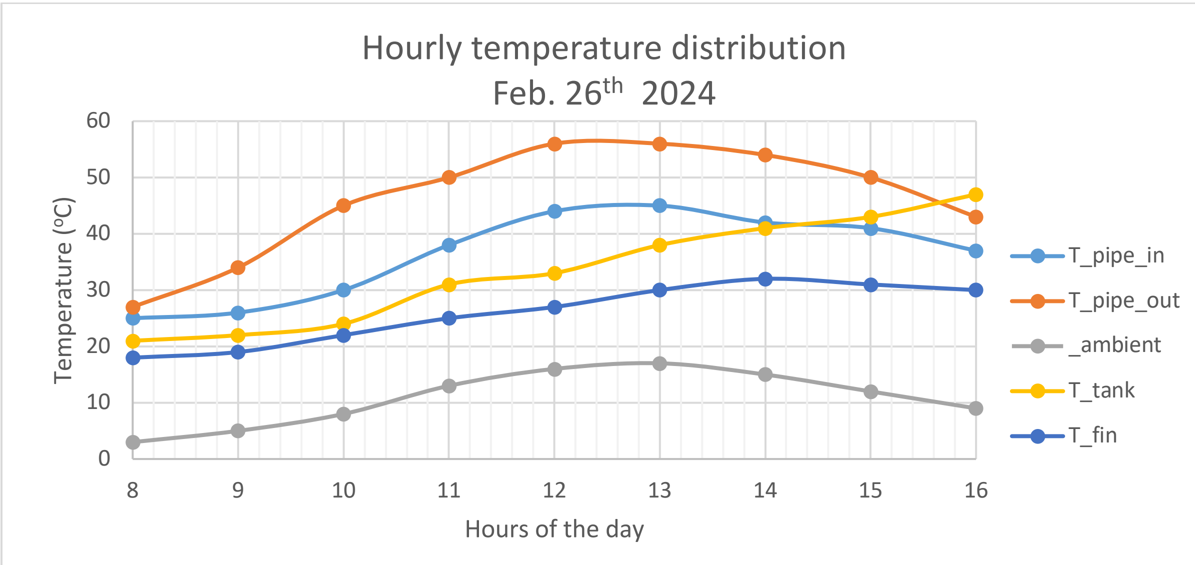

Figure 9 Hourly temperature variation in the tank collector assembly and header pipes

Figure 10 demonstrates the flow rate through the header pipes and it is clear that the maximum flow rate was observed after the solar noon and then declined due to the decrease in solar intensity.

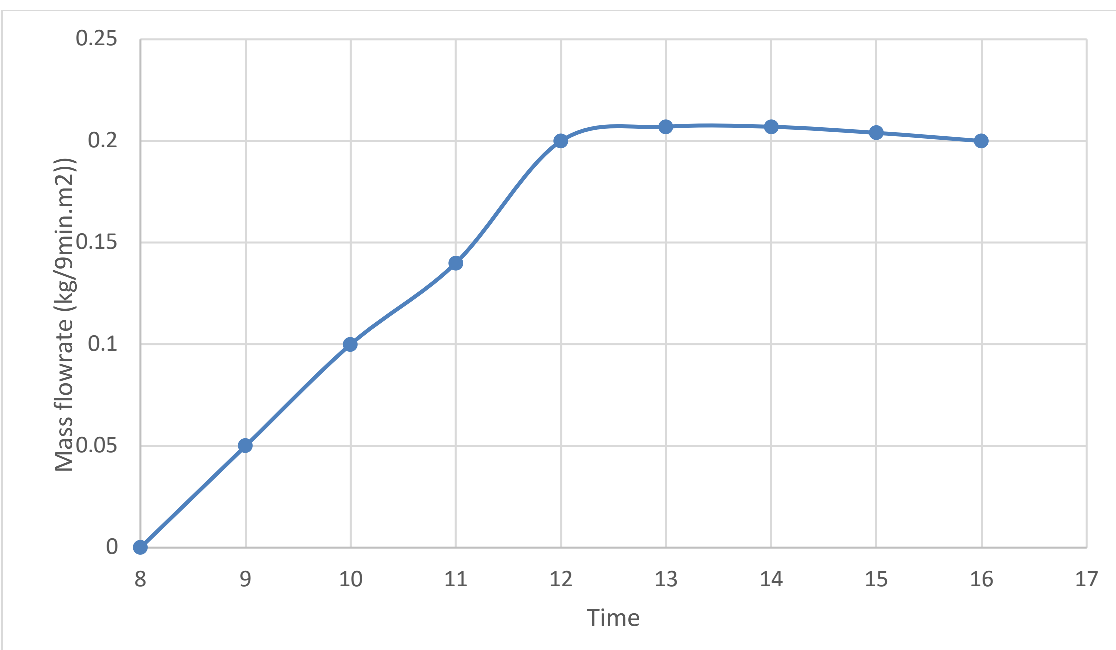

Figure 10 Hourly flow rate variation through the header pipes.

Table 2. shows the situation on March 4th 2024, the maximum head pipe temperature was 70 °C and the collector temperature was 42 °C because the outlet header pipe water will mix with raw water in the tank so that the tank temperature is the mixture temperature. The energy saving for this day is equal to 9.24 MJ/ day, and if this value could be taken on average for the month the energy saving will be 277.2 MJ/month (77 kWh/month) in this month.

Table 2. Natural circulation solar water heater on March 4th 2024

Local time (hours)	Header-pipe temperature (°C)		Ambient temperature (°C)	Tank temperature (°C)	Collector inlet temperature $T_{f,in}$, °C	Solar intensity W/m^2
	inlet	outlet				
8:00	22	29	7	20	18	200
9:00	25	32	10	21	19	450
10:00	31	44	13	22	23	600
11:00	39	55	15	32	28	750
12:00	43	65	18	32	30	800
13:00	46	68	18	36	34	760
14:00	47	70	16	38	36	700
15:00	45	64	14	42	38	550
16:00	41	56	12	40	36	350

Table 3. shows the situation on April 1st 2024, the maximum head pipe temperature was 90 °C and the collector temperature was 52 °C because the outlet header pipe water was mixed with raw water in the tank so that the tank temperature is the mixture temperature. These temperatures were recorded between one and 2 PM. In comparison with other works, the trend is the same but the differences are not large for instance (Bolaji, 2006) recorded the maximum collector outlet temperature as 83.5 °C at 2 PM. The energy saving for this day is equal to 8.4 MJ/ day, and if this value could be taken on average for the month the energy saving will be 252 MJ/month (70 kWh/month) in this month.

Table 3. Natural circulation solar water heater on April 1st, 2024

Local time (hours)	Header-pipe temperature (°C)		Ambient temperature (°C)	Tank temperature (°C)	Collector inlet temperature $T_{f,in}$, °C	Solar intensity W/m^2
	inlet	outlet				
8:00	33	40	10	32	30	500
9:00	38	45	13	36	33	600
10:00	49	69	16	39	37	750
11:00	52	75	22	41	40	800
12:00	58	82	25	43	42	900
13:00	56	90	26	48	46	850
14:00	54	87	24	52	48	750
15:00	52	80	22	47	45	600
16:00	50	71	20	44	41	550

4. Conclusion

In this study, the importance of solar water collectors shows that the water temperature should be increased and the need for water heating significantly will be reduced during cold seasons the following conclusions were obtained which are vital for environmental protection and less demand on national electricity:

1. The maximum flow inside the system due to the natural circulation is in the range of 0.207 litter/min.m^2.
2. The maximum water temperature from the header pipes was in the range of (50 to 56 ^oC) in the cold season, while it is about (80 to 90 ^oC) in the hot season.
3. The collector volume was 100 litres and this is suitable for a family of two persons.
4. The energy saving in cold weather is more than that of hot weather and this might be returned that on a hot day, the heat loss from the collector is high and this will lead to more energy loss to the surrounding by convection and radiation.
5. Energy savings in February, March, and April are 326.6, 277.2, and 252 MJ respectively.

5. Recommendation for future work

Precise flow meters were used to measure water circulation within the system driven by natural water circulation. Solar collectors with vacuum tubes were employed to determine the flow rate and investigate differences. A data logger recorded data throughout the testing period, including after sunset.

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