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Design and Performance Analysis of Spiral Solar Water Heater Using Iron Plate/Sand Absorber for Domestic Use

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Abstract
In this study, water was heated using solar energy . This research presents the design and experimental analysis for using Spiral Flow Solar Water Heater (SFSWH) to enhance thermal efficiency of a flat plate solar collector. A solar water heater consisting of a copper tube in the shape of a spiral was fixed on an iron flat plate as an absorber. The experiment also included the selection quality of the paint used to dye the absorbent surface. In May at Fallujah (33.34ºN, 43.8ºE), the thermal performance was calculated. The maximum temperature difference in the storage tank of about 18 ℃ for (SFSWH) during the experimental time was obtained. The obtained efficiency of the collector was about (80.11%). The SFSWH gave an increase of (40 %) in its efficiency compared to published values.

Keywords: Solar radiation, Spiral Flow Solar Water Heater, Flat plate solar collector, solar energy, black paint

تصميم وتحليل الأداء الحراري لسخان المياه بالطاقة الشمسية الحلزوني للأستخدام المنزلي باستخدام لوح امتصاص من الحديد مضاف له الرمل لزيادة الامتصاصية

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الخلاصة
في هذه الدراسة توصلنا إلى تسخين المياه باستخدام الطاقة الشمسية. يقدم هذا البحث التصميم والتحليل التجريبي لاستخدام سخان المياه الشمسي الحلزوني (SFSWH) لتعزيز الكفاءة الحرارية لمجمع الطاقة الشمسية المسطح. حيث يتكون سخان المياه الشمسي من أنبوب نحاسي على شكل لولب يتم تثبيته على لوح حديد مسطح كممتص. تتضمن التجربة أيضًا جودة اختيار الطلاء المستخدم لصبغ السطح الماص. تم حساب الأداء الحراري في الفلوجة في مايو (33.34 درجة شمالاً ، 43.8 درجة شرقاً). تم الحصول على أقصى فرق درجات الحرارة في خزان التخزين بقيمة حوالي 18 ℃ لـ (SFSWH) خلال فترة التجربة. بلغت كفاءة المجمع حوالي (80.11٪). حيث يعطي زيادة (40٪) في كفاءته مقارنة بالقيم المنشورة.

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1. Introduction

In several countries, the standard of living development and industrial growth are dramatically increasing the energy demand, and the new potential gap between energy supply and demand is estimated to be significant [1]. Thus, the matter of sustainable development is steadily acquiring more attention. Renewable energy sources that are fundamentally renewable and eco sustainable are getting noticed. Most advanced states and many industrial states have included renewable energy sources as important sources of energy in their energy generation [2]. Solar energy is a source of energy that has become the biggest part of the world attention due to its great importance in providing high levels of conventional energy as well as clean technology that does not pollute the environment. Basically, in the solar water heating system, the most essential component is the solar water heating collector, converting the energy coming from the sun into thermal energy and eventually transferring that energy to a flowing fluid inside the pipes. There are two main types of solar water heater collectors: concentrated and flat-plate solar collectors. Based on the specific temperature range, the concentrating collector might be a tracking type or a non-tracking type. They operate with direct sun solar irradiation and are only functional at clear daylights. The flat-plate collector has the benefit of transferring both beam and scattered radiation, even when the radiation is blocked by clouds [3, 4]. A flat-plate welded on heat pipes is the most popular format of a domestic solar hot water system with heat pipes, where cooled water flows through and gains heat from the collector. Water gets recycled between the collector and the thermal tank where the collected heat is deposited in the flat-plate collector [5]. The flat-plates are fitted with transparent glass inside a box cover at the bottom. This arrangement is for reducing heat loss. Domestic solar water heaters (SWH) with flat-plate collectors have been commonly built in household and service buildings for heating water and space heating due to their consistent efficiency, low cost, minimal maintenance requirements and simple integration with building frontages [6]. The economic benefits of using SWH can be noticed mainly by having saved on the cost of fuel for water heating and environmental problems. SWH systems have become common and are now contributing significantly in many countries to both the households and industry. Today, China dominates the global solar energy market. In 2009, Chinese companies manufactured 28 million square meters of system which was about 80% of the global solar hot water / heating production [7]. Various research on flat plate solar water heating systems have been conducted. Ismail and Abogderah [8] performed comparable analysis between theoretical predictions and experimental results of a flat-plate heat-pipe solar collector. Their findings showed that the heat pipe solar collectors' instantaneous efficiencies are least in the morning than the traditional collector, and greater when the heat pipes exceed their operating temperatures. El-Sebaii and Al-Snani [9] investigated the effect of different selective coatings on the absorber on the efficiency of the solar heating system so as to improve its performance. The best performance was obtained using nickel – tin as a selective surface coating with an extremely rapid efficiency average of 0.4 per day. Ogie et al. [10] designed and built solar water heater based on the thermo-syphon concept. Solar energy is collected through a flat-plate collector made of thin absorber plate combined with fluid carrying tubes underneath grids and mounted in an insulated network The temperature of the absorber plate increases by the radiation emitted from it since it cannot escape through the glass. The water heats up and flows by thermo- syphon principle into a storage tank. The system designed in this work required little or no maintenance and was made basically from locally available raw materials with no mechanical components, and the system also worked automatically. A new solar water heater technique using black colored sands immersed in the water storage tank was designed and constructed by Taheri et al. [11], who developed the major parts of the collector absorber component. Wide storage space per unit volume, an adequate operating temperature range, high storage performance, long life, and low cost are the most important characteristics of conventional solar water heater systems. In this study, thermal daily efficiency reached greater than 70 percent in all experiment results. Amin et al. [12] studied numerical and experimental investigation on heat transfer enhancement of flat plate collector using three types of twisted tapes. They found, from the experimental results, that the outlet temperature of mixed twisted tape collector is higher by 10°C than that from the other type of plain tube collector. Selvadhurai. el al. [13] carried out, experimentally and with built-in TRNSYS simulation program, a study on the flow mechanism of a flat plate collector with the parallel flow and spiral flow, They concluded, that at noon, the output of the SFSWH is greater than that of the parallel flow SWH. The SFSWH was recommended for the kovilpatti area in Tamilnadu than the parallel flow SWH. From this, it can be noted that the numerical simulation SFSWH TRNSYS predicted the results in software without experimentation in real-time. Thus, in TRNSYS, the model method is as accurate as in experimentation. The Impact of various device absorbers models on heat flux and efficiency of the solar collector have been shown in the numerous studies discussed above.

In this paper, a spiral tube solar water heater was designed and its thermal performance was evaluated. Fine red sand was added to the black coating to increase absorption. Theoretical equations were used to determine collector thermal performance, out water temperature, and various device heat losses. The device was designed using SolidWorks software to show the true dimensions of the collector. The simplicity of its manufacturing and having no moving objects make it an important technical heating method solution development in the agricultural region

2. Theoretical Methods

A schematic diagram of a typical solar system that uses a flat plate solar collector and a storage tank is shown in Figure 1. The solar energy absorbed by the solar collector is distributed through the top, bottom and edges as heat losses and heat gains by the working fluid. These energies can be calculated by the following procedures.

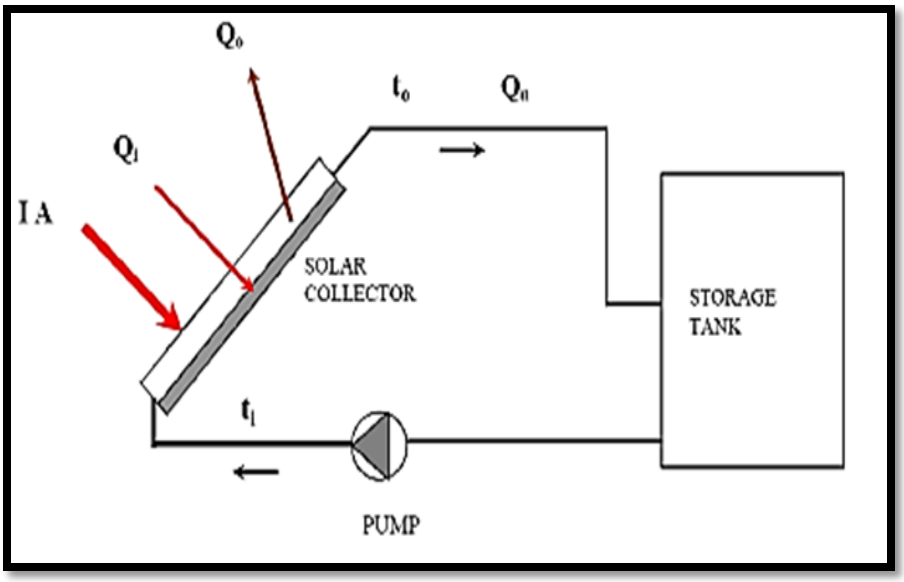

Figure 1- Schematic diagram of a typical solar energy collection system.

2.1. Heat losses of the collector.

Thermal losses from the collector include losses from the top of the glass cover, losses from the bottom and losses from the edges. So the collector total heat loss can be expressed as [13]:

$$Q_{loss} = U_L A(T_c - T_a) \quad (1)$$

where Q_{loss}=The heat rate of loss, W; U_L= Overall heat loss coefficient, W/$m^2.K$; A= Gross

Collector area, m^2; T_c = The collector temperature, °C;T_a = The ambient temperature, °C.
The heat rate of loss (Q_{loss}) depends on the overall heat transfer coefficient (U_L) and the temperature of the collector.

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

Where U_t=Heat loss factor from top, $W/m^2.K$; U_b=Heat loss factor from bottom, $W/m^2.K$; U_e=Heat loss factor from edge, $W/m^2.K$.

The energy loss across the top is the product of convection between parallel plates and radiation through them [14]. So the factor of heat loss from above is given by:

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}}\left(\frac{T_{pm}-T_a}{N+f}\right)^e} + \frac{1}{h_w}\right)^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{\frac{1}{\varepsilon p+0.00591Nh_w} + \frac{2N+f-1+0.133\varepsilon p}{\varepsilon p} - N} \quad (3)$$

Where N=Number of glass cover; C= 520(1 - 0.0051β^2) for 0°<β < 70°. For 70°<β < 90°, use β = 70°. β= Collector slope; T_{Pm}=Mean plate temperature, °C; f= (1+ 0.089h_w _ 0.1166$h_w \varepsilon_p$) (1 + 0.07866N); h_w= Wind heat transfer coefficient ,$W/m^2.K$; ε_p= Emittance of the absorber plate for infrared radiation.
The heat loss from the bottom of the device is because of heat flow resistance through the insulation [15]. U_b, therefore:

$$U_b = \frac{k}{z} \quad (4)$$

Where k=Thermal conductivity, W/m.K.; z= insulation thickness, m
The edge losses are then calculated, based on the collector field, by assuming one-dimensional heat flow around the edge loss coefficient [14]

$$U_S = \frac{2L_3(L_1+L_2)\lambda}{L_1 L_2 \delta s} \quad (5)$$

Where L_1=length of casing, m; L_2=width of casing, m; L_3=height of casing; λ= thermal conductivity of insulation, W/m.K; δs= thickness of insulated side, m.
2.2. The heat gained by the collector
The equation for the energy balance is given by the equation Hotel-Whillier-Bliss. The heat gained by the collector, Q_c is measured by multiplying the collector heat removal factor (F_R) by the total energy gain possible [16].

$$Q_c = F_R A\,[I_T(\alpha\tau) - U_L(T_i - T_a)] \quad (6)$$

F_R= heat removal factor = $F_R = \frac{\dot{m}c_p}{A_c U_L}\left[1 - exp\left(-\frac{A_c U_L}{m\,c_p}\right)\right]$

Where Q_c=the heat gained by the collector, W; I_T= Incident solar radiation, W/m^2; T_i= The inlet temperature, °C; $\dot{m}$=mass flow rate, Kg/s; c_p=Specific heat (J/kg.k); τα = Transmittance- absorbance product

3. The efficiency of solar water heating systems

The efficiency of Solar heating systems (η_C) is the ratio of the collector usable heat gain to solar radiation incident on the solar collector's adsorbent [17].

$$\eta_C = \frac{Q_C}{IA_C}$$

$$\eta_C = F_R[\alpha\tau - U_L \frac{(T_{ci} - T_a}{I}] \quad (7)$$

4. Experimental work

An experimental setup and operational procedure employed to achieve the experimental work is given. Accordingly, this section begins with the description of the experimental equipment with its design plus the experimental procedure to achieve experimental measurements.
4.1. Experimental setup.
The followings were used in the present experimental design.
1. (5⁄8) Inch copper tube with (1.5 mm) thickness and (13.35 m) length.

2. Iron plate sheet of (2mm) thickness with (1m*1m) dimension.
3. Wooden box of dimensions (1.02 m * 1.02 m*0.11m).
4. 4 mm thick cover glass with a wooden box size.
5. rock wool
6. K-type thermocouple, thermometer and Infrared thermometer.
7. Solar meter device for the measurement of solar radiation beam.
8. Storage tank of (50L) volume.

Figure 2-Spiral tube solar water heater front view.

Solidworks program was used for the design of the spiral solar collector which was constructed (with its dimensions in mm) (as shown in Figure 2) . Its schematic diagram is shown in Figure 3.

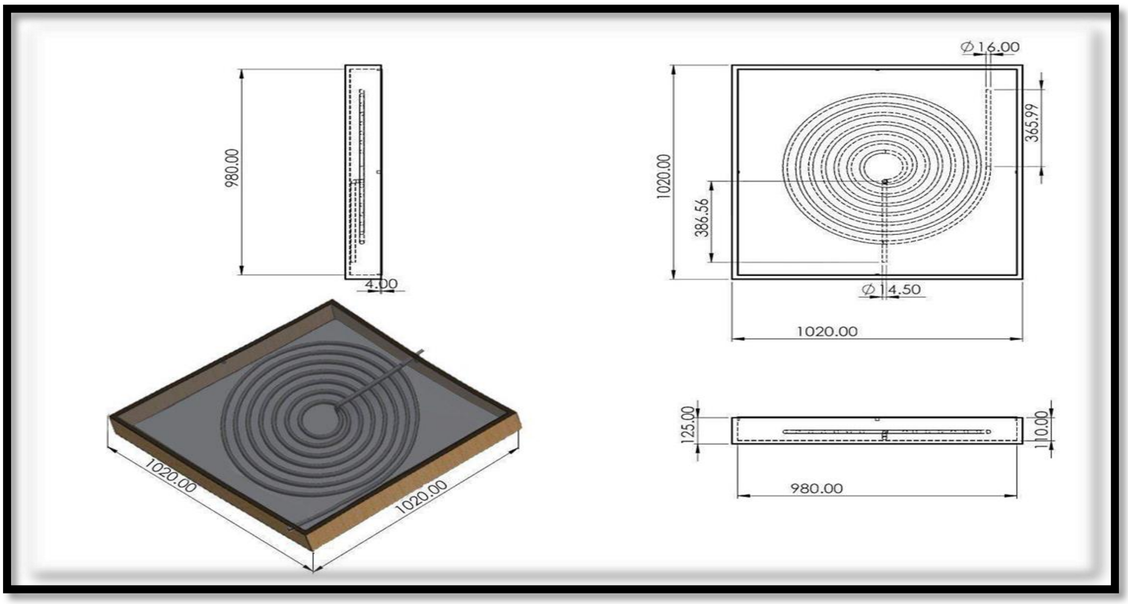

Figure 3- Spiral design of solar heater on sold works

4.2. Experimental Procedure

Our tests were conducted on the (SFSWH) system on different clear days of May at Fallujah city (33.34ºN, 43.8ºE). Experiments were done between 10:30 a.m. and 11:30 a.m. Initially, the mass flow rate was calculated from outside the collector. Every (10 min) for a period of (1 hr.) all data, which are the inlet temperature, outlet temperature, storage tank temperature, ambient temperature and the solar radiation beam, were recorded During this hour, the solar radiation was measured with a solar power meter device (model:SPM-1116SD). Also, thermocouples (Type k) and infrared thermometers were used to measure different temperature nodes at inlet, outlet and storage tank

4.3. The process of selecting the type of additive coating.

The aim was to choose a compound to be added to black paint to increase the absorbency of the absorbent surface and to reduce its emission. In our project, red and black sand was chosen to test the compounds mixed with black paint to increase its absorbency. First, the red and black sand was washed with water to remove any mud present. The sand was, then, dried in an oven at 60^{O} C for one hour. The sand (red and black) was sieved to get specification measurements. After this, it was grinded to 75 and 200micrometer particles size. Finally, the red or black sand was proportionally blended with the black paint.

5. Results and Discussion

Table 1 gives the readings of the spiral tube solar water heater on the 15^{th} and $the\ 16^{th}$ of May, 2020, from 10:30 am to 11.30 am**.**

Table 1-Observation table for (SFSWH)

Date	Mass flow rate (kgs^{-1})	Time	T_{in} (°C)	$T_{wall\ 1}$ (°C)	$T_{wall\ 2}$ (°C)	T_{out} (°C)	T_{storge} (°C)	T_{∞} (°C)	Solar Radiation (Wm^{-2})
15/05/2020	0.08	10:30	26	58.9	55.9	35	26	34	1024
		10:40	31.4	55.7	48.6	36.4	32.5	34	1025
		10:50	34	55.4	48.1	38.2	35	34	1025
		11:00	37	54	48.4	40	38.8	34	1015
		11:10	40.3	54.5	48.2	42	41	35	1014
		11:20	41	53.9	47.7	43	42.2	35	1003
		11:30	43.6	56.8	48.3	46.3	44.3	36.4	998
16/05/2020	0.09	10:30	23	53.7	52.4	32	28	34	1024
		10:40	28.3	54.5	50.9	33.5	30	34	1025
		10:50	30.6	52.3	49	35.3	32.8	34	1029
		11:00	32.9	53.2	47.3	37.9	33.3	34	1015
		11:10	35.4	39.5	44.4	40.7	37.9	35	1016
		11:20	38	49.1	45.5	41.5	39.1	35	1007
		11:30	39.3	50.9	48.1	43	41.2	36	995

Table 2-Results of Study the Effect of Mass Flow Rate

Data	Mass flow rate (kgs^{-1})	useful energy gained (W) Eq. (6)	Maximum outlet temperature °C (Collector Time constant)	Efficiency (%) Eq.(7)	Solar Radiation (Wm^{-2})
13/5/20	0.03	672.865	51.63	67.22	1000.7
15/5/20	0.08	782.371	47.66	78.803	1015
16/5/20	0.09	805.31	46.24	80.112	1017.66

Spiral tube solar water heater efficiency and testing were performed during 13/5/15, 15/5/2020, and 16/5/2020. Variation of the spiral tube solar water heater inlet and outlet temperatures also the variability of the solar radiation with time are shown in Table 1. The efficiency of the solar water heater with the spiral tube is shown in Table 2.

Results showed that the maximum water temperature collected depends on irradiation and air temperature. The energy obtained by the collector during high solar radiation was high at nearly the period 10:30 am -10:40 am. This is confirmed by Figure 4, as it is clear that the highest radiation received by the device was at the mentioned period. The energy of the collector obtained during high solar irradiance was large at about midday but was weak in the morning and early evening due to low sun energy.

Figure 5 shows the effect of the mass flow rate on the efficiency of the solar collector. The collector efficiency is highly dependent on the flow rate; it increases with flow rate. Figure 5 shows that the efficiency was 67.22% when the flow rate was 0.03 kg/s and that at 0.09 kg/s flow rate ,the efficiency reached 80.11%, meaning that the efficiency increased by 12.89 percent.

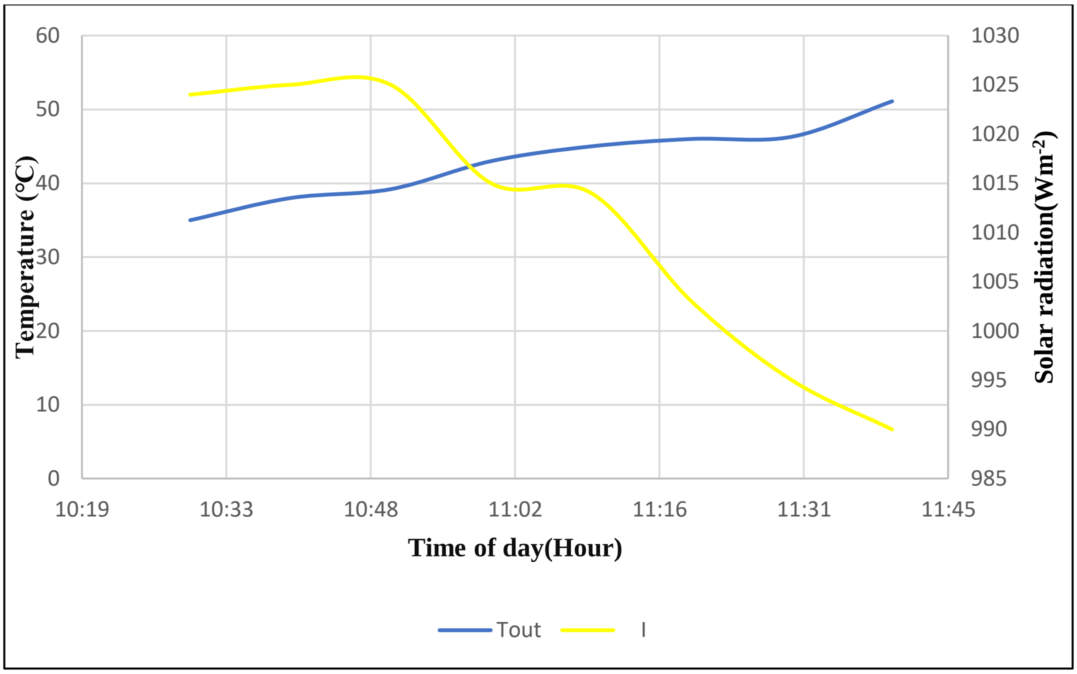

Figure 4-A typical difference in temperature of the collector-solar radiation and temperature of water outlet in 15/5/2020.

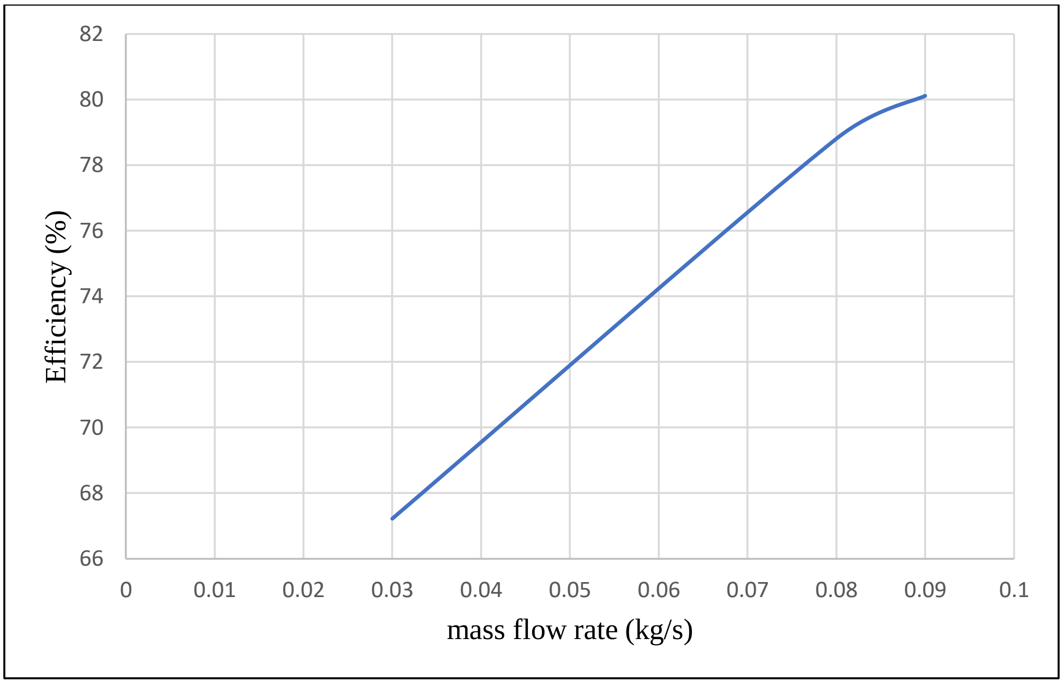

Figure 5- Mass Rate vs Efficiency.

Experimental results of the differences in the useful heat rate with the time of the experiment are clearly shown in Figure 6. It is obvious from the figure that when the solar collector received the highest solar radiation (as we have noted in the period between 10:30-10:40 am), the useful heat rate was at its maximum.

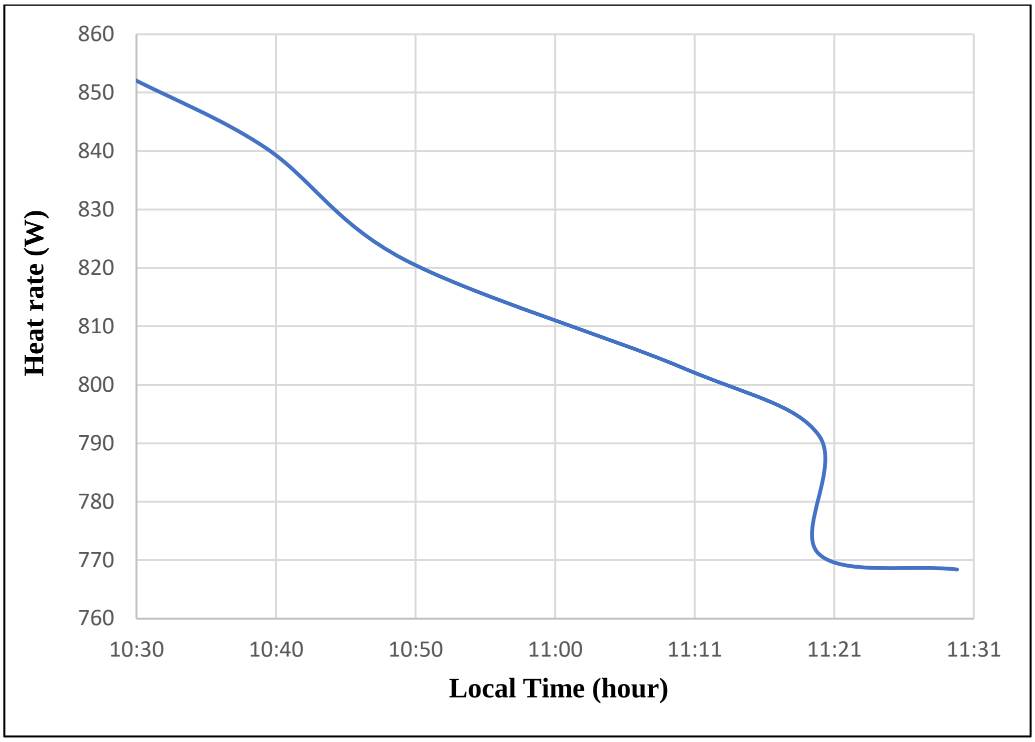

Figure 6-Changes of solar collector's useful heat rate with time

The curves also display a strong correlation between the theoretical findings and the experimental results. Figure 7 illustrates the solar collector experimental efficiency as a factor of the amount of heat. Thermal efficiency of the collector increased with the increase of the rate of heat, until its full value was reached after which any further changes in the rate of heat had no impact at all on the solar collector efficiency.

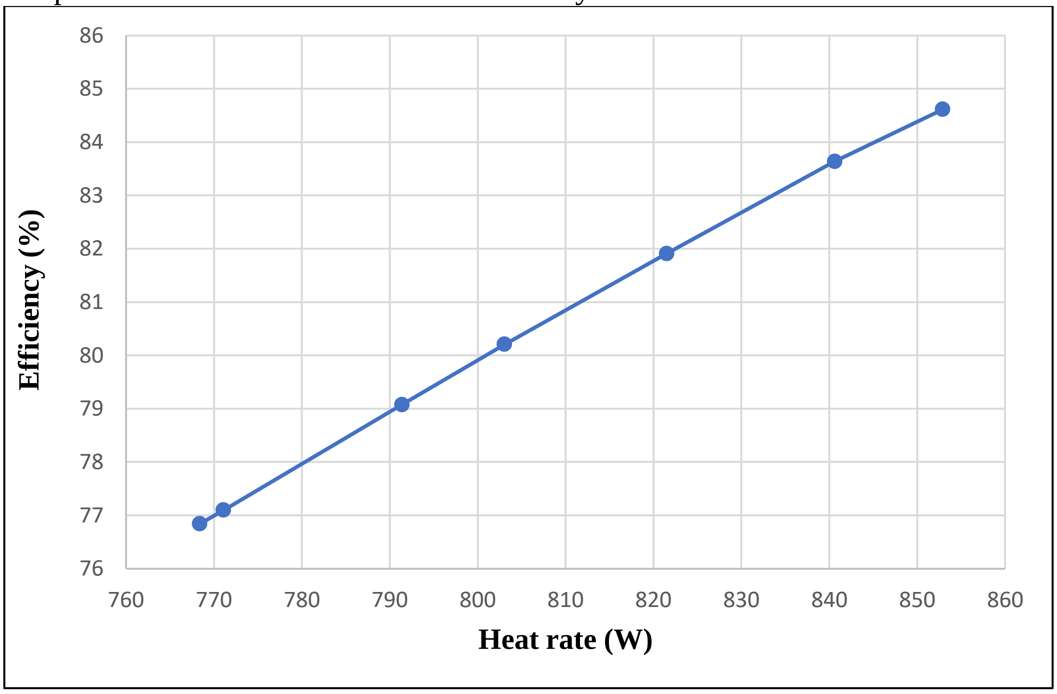

Figure 7- Efficiency variance with solar collector heat rate on 16/5/2020

As for the paint selection process, Table 3 shows that red sand has higher absorbency values than black sand, and that the higher the proportion of red sand added to the black dye, the higher the absorbency. Absorbency was tested with a UV spectrophotometer. .

Table 3-Results of process selecting of additives for coating

Simple	Absorption	transmission	Reflection
Black paint	0.91919	0.04539	0.02542
Black paint with 10% red sand	0.89362	0.04307	0.06331
Black paint with 20% red sand	**0.93494**	**0.042899**	**0.02216**
Black paint with 10% black sand	0.88793	0.04278	0.06929
Black paint with 20% black sand	0.85136	0.04751	0.10113

6. Conclusion

In this study, the thermal efficiency of the heat transfer in spiral tube solar water heater was evaluated. A spiral tube solar water heater was designed and assessed for efficiency to be compared with previous research of conventional solar water heater for the same solar radiation average. Maximum temperature difference of 18 ℃ was obtained between inlet and outlet water temperatures which is more than that obtained with the conventional solar water heater. Also, SFSWH takes less time to fill a 50-liter tank compared to a conventional heater. The thermal efficiency and the outlet temperature is higher in the case of spiral tube solar water heater than that of straight tube solar water heater. As the heat rate increased, the efficiency of the collector grew until maximum value was obtained. The overall efficiency obtained during the test at an optimum heat rate of 805.31 W was 80.112 per cent. This work also focused on the quality of the black paint additive, the tests showed that red sand delivered 0.934 absorbency.

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