The Effect of Using Hot and Cold Water Separator Plates in Evacuated Tubes of a Solar Water Heaters

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Abstract-Different methods have been proposed to increase the efficiency and the temperature of hot water from evacuated tube solar collectors. In this article, the impact of a separator plate between the hot and cold fluids in the evacuated tube water heater on the temperature changes and the efficiency of hot water produced by the evacuated tube solar water heater (SWH) is investigated. Experiments were conducted on a thermosyphon evacuated tube solar water heater (Solar Polar, E180) with eighteen evacuated glass tubes with a length of 1800 mm and a diameter of 58 mm with a 180-liter tank made of isolated stainless steel (SUS304). The experiments were performed in four different modes: in the absence of separator plates and with separator plates with a length of 1.2 m, 1.4 m and 1.6 m. To validate the results, the experiments were repeated three times. The solar water heater in the absence of the separator plates was modelled and simulated with the help of energy relations. The simulation results were consistent with experimental results. After validation of the results, the other cases were investigated experimentally. The use of separator plates in the evacuated tube solar water heater distinguishes this article from previous studies. According to the results, the length of stagnation region at the end of the evacuated tube is about 0.6 m. By placing a separator plate between the hot and cold fluids, the length of stagnation region can be reduced and consequently the efficiency can be increased. According to the results, the use of 1.6 m separator plates led to 5% increase in the overall thermal efficiency.

Keywords Keywords- Solar water heater, evacuated tube collector, thermosyphon system, stagnation region.

1. Introduction

Electrical energy is one of the most popular types of energy in today's world and can be achieved from different sources of energy. Fossil fuels such as oil, gas and coal are among the most important sources of electrical energy with a high negative impact on the planet due to greenhouse gas emissions resulting from the burning of fossil fuels. Due to the limited sources of fossil fuels, it is important to find alternative energy sources. Solar energy is one of the energy sources that many countries have attempted to invest in and take advantage of. Solar energy is very clean and does not produce any pollution. It is readily available in many regions of the Earth and can be used for a variety of purposes including in air conditioners and the production of electrical energy, hot water, hot air and so on [1].Evacuated tube water heaters have two coaxial glass tubes, the both ends of which have been completely blocked. The air between the two tubes is removed as much as possible to reduce heat conduction between the fluid inside the tube and environment. Working fluid flows within the inner tube. The surface of the inner tube is covered by a special coating to absorb the solar energy. The fluid enters and leaves the inner tube through the open end of the tube which is connected to the water heater tank or working fluid transfer system [2]. Applied research on evacuated tubes with absorber surface began in 1976 [3,4] . China is a country that produces and consumes a vast amount of energy, and with its rapid economic growth, it is anticipated that its energy consumption will increase similar to the situation in countries including Jordan and Tunisia[5,6].The emission of greenhouse gases from China has also increased, and its dependence on imported crude oil increased from 32% in 2000 to 57% in 2012 [7]. Many researchers have undertaken significant studies investigating and evaluating the performance of SWHs both experimentally and theoretically [8-16]. comakl et al. optimized the size of solar collectors and storage tanks to design more economic and efficient solar water heating systems, according to Turkish conditions and relevant Turkish standards, with experiments and simulations [9]. Govind et al. identified possible and feasible designs on collector area vs. storage volume using a methodology called the design space approach [10] .The work done by Comakl and Govind implies the collector area and storage volume affect the thermal performance of a forced circulation solar water heating system with flat plate solar collectors. A report from IEA gives the performance of 11 evacuated solar heating and cooling systems. The heat extraction methods from the evacuated tubes were heat-pipes, U-tube inserts or integrated collector/storage in the tube [17]; however, the most successful method was the simple water-in-glass concept [11]. A case study by Hazami et al., in the Tunisian market, shows that a forced circulation system with evacuated tube solar collectors had a better performance and cost benefits than a system with flat plate solar collectors [12] . The experimental work by Sakhrieh and Al-Ghadoor in the Jordanian market indicated that evacuated solar collectors had the highest efficiency of five types of solar collectors [6] Various factors including the solar radiation intensity, inner and outer diameters of evacuated tubes, and the distance between two adjacent evacuated tubes, latitude, and environmental conditions and so on affect the efficiency of solar water heaters. According to experimental studies, since the end of the evacuated tubes are completely blocked and mass transfer does not happen in those regions, the working fluid is stagnant in this area. Consequently, heat transfer does not happen at the end of evacuated tubes leading to reduced thermal efficiency of the evacuated tube collectors compared to the flat plate collectors, because both ends of tubes in the flat collectors are open and the fluid flows throughout the tube[12,18]. According to experimental studies, since the end of the evacuated tubes are completely blocked and mass transfer does not happen in those regions, the working fluid is stagnant in this area. Consequently, heat transfer does not happen at the end of evacuated tubes leading to reduced thermal efficiency of the evacuated tube collectors compared to the flat plate collectors, because both ends of tubes in the flat collectors are open and the fluid flows throughout the tube [18]. This has been confirmed by theoretical calculations. [19]

Zhang et al. concluded in their experimental study that the proper ratio of tank volume to the surface area of the evacuated tube solar collectors was 57-72 l/m2. In this case, the efficiency of system was approximately 49-57 percent. They also mentioned that shorter evacuated tubes led to a higher efficiency [17].The outer diameter of the evacuated tubes was 47, 58, 70, 84, 100, 102 and 125 mm. In total, about 94.3 percent of the evacuated tube collectors had an outer diameter of 58 mm, 84.4% had an outer diameter of 58 mm with a length of 1800 mm, 5.7 percent had a length of 2100 mm and 4.5 percent had a length of 1600 mm [17]. Tang et al. found that in the event of a change in the tilt angle of evacuated tube water heater collectors, the hot and cold fluid flow path in the evacuated tube solar water heaters is naturally organized and a higher efficiency can be achieved. They found that the water heater collectors tilt angle should be 22° in reference to the horizon instead of 46° [20]. The tilt angel of the tube collectors on the left and right hands is 46° and 22°, respectively. Figure 2 shows the fluid flow and the stagnation region in the evacuated tube. According to literature, evacuated tube solar collectors with a heat pipe have a higher efficiency than convectional evacuated tube collectors. However, the payback period of conventional evacuated tube collectors is much less than the evacuated tube with a heat pipe and thus are more affordable [21].The comparison of these two types of evacuated tube collectors in Hong Kong showed similar results. According to Chow et al., the use of evacuated tube collectors is more cost-effective than flat plate collectors. Morrison et al. conducted extensive research on evacuated tube solar collectors. They simulated evacuated tubes without solar radiation reflectors under the tubes. They also provided a numerical model to estimate the heat transfer coefficient inside the evacuated tubes. They also have shown that the circulating flow rate within the solar water heater system is significantly affected by the solar radiation received by the collector surface and the temperature of the fluid in the tank [22, 23]. In this paper, the impact of the hot and cold water separator plates on the thermal efficiency of evacuated tube solar water heater is investigated. The use of separator plates in the evacuated tube solar water heaters distinguishes this paper from previous research.

Behina and Morrison shows that For uniform heating of a single-ended thermosyphon tube, a significant stable stagnant region exists near the closed end of the tube, the length of which decreases with increasing heating fluid temperature. The stagnant region length varies nonmonotonicaily with the angle of inclination and shows a minimum at 45 ° [18] Y.He in an experimental investigation to observe the effect of using fluids which contain Nano particles in the evacuated tubes of solar collector under cloudy and sunny environmental conditions showed that using of Nano fluids increases the temperature of working fluids inside the collector [19].

2. The Experimental Setup

2.1. Test equipment

The evacuated tube solar water heater used in this experiment is a thermosyphon solar water heater (E180, Solar Polar) with eighteen evacuated glass tubes with a length of 1800 mm and a diameter of 58 mm with a 180-liter tank made of stainless steel (SUS304). The tank is isolated with injected polyurethane foam with a density of 35 kg/m^3 and a thickness of 5 mm. The water heater has an auxiliary tank equipped with floats to control the water level in the main tank. A solar radiometer (TES-1333, TES, Taiwan) was used to measure the solar radiation in these experiments. The solar radiometer is able to display and save the instantaneous radiated power or the radiant energy in a given period. The radiometer is installed on a tripod with a gauge to measure the tilt angle in reference to the horizon the evacuated tube solar water heater was assembled on the roof of a house and its tank was filled with the municipal water. A thermometer was placed inside the tank to transmit the water temperature to the water heater control system. The water heater control system is connected to an element inside the tank with the ability to activate it to increase the water temperature inside the tank to the desired temperature. At the beginning of measurements, an electric heating element was used to raise the water temperature to a certain temperature in all experiments to examine the results more accurately. A thick fabric cover was used to cover the surface of the absorber tubes to prevent solar radiation reaching the collector surface At the beginning of the experiment, the water temperature inside the tank was set at a specific temperature using the control system and the electrical heating element in the tank at 7:30 AM while the absorber tubes were covered with a fabric cover. Then the heating element was turned off and the fabric cover was removed to increase the water temperature in the tank naturally using solar radiation. Simultaneously, the solar radiometer was activated to record radiation data. The water temperature in the tank was recorded using an intelligent control system on the water heater. The test was stopped at 16:00 and all data were collected and stored.

On the next day, the hot and cold fluid flow separator plates were placed inside the water heater absorber tubes and all experiments were repeated. At the end of experiments, the results were stored and collected. The tests on the solar water heater in different modes were repeated at least twice and in some cases three times due to significant differences of results to examine the independence of experiments. To investigate the effect of separator plates, eight experiments were conducted in successive days. Two tests were conducted on the solar water heater without separator plates, two tests with a 1.2 m separator plate with a thickness of 2 mm, two experiments with a 1.4 m separator plate and two tests with a 1.6 m separator plate. Figure 1 is a view of the experiment location.when required. Plexiglas separator plates were used to separate the hot and cold fluids inside the evacuated tubes.

Fig.2. Radiometer TES-1333 for calculate the solar radiation

Table 1. Technical data of experimental solar water heater system

Heat transfer fluid in tubes	water
Length of tube	1.8 m
Inner/outer diameter of tube	47 mm/58 mm
Number of tube	18
Collector angle	45 Degree
Absorbing efficiency of collector	93 %
Collector direction	South
Collector Area	1.8 m^2
Volume of tank	150 Liter

Figure 3 shows a cross section of evacuated tube that is divided into two part that is separated cold and hot flows.

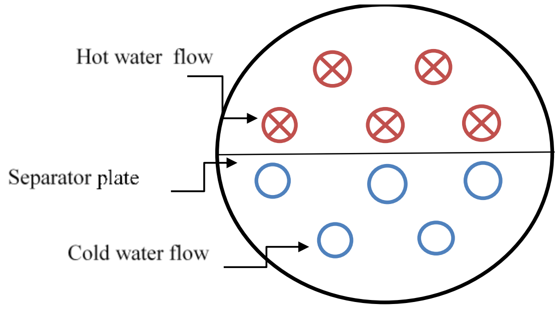


Fig. 3.cross section of evacuated tube with separator plate

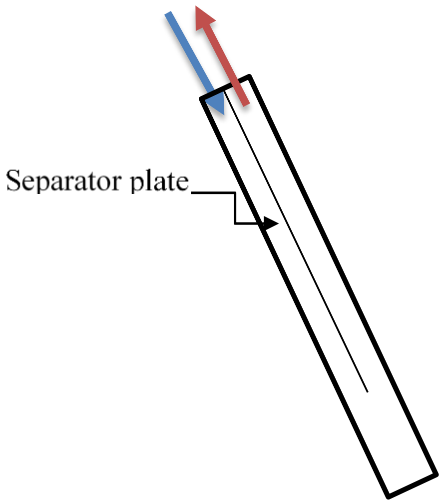


Fig.4.scheme of evacuated tube with separator plate

3. Governing Equations

The governing energy equations of the system are as follows [16]:

$$\dot{Q}_{tank} = \dot{Q}_{col} - \dot{Q}_{loss} \quad (1)$$

$$\dot{Q}_{col} = N_{tub}.\dot{m}.c_p(T_{out} - T_{in}) \quad (2)$$

$$\dot{Q}_{col} = A_{sys}.U_{loss}(\bar{T} - T_a) \quad (3)$$

where $\dot{\boldsymbol{Q}}_{\boldsymbol{tank}}$ is the energy stored in the tank, $\dot{\boldsymbol{Q}}_{\boldsymbol{col}}$ is the energy received by the collector, $\dot{Q}_{loss}$ is the energy loss from the tank,N_{tub} is the number of evacuated tubes of the water heater, $\dot{m}$ is the flow rate per tube, $C_p$is the specific heat of water,T_{out} and T_{in} are the respectively the outlet and inlet temperature of water, $A_{sys}.U_{loss}$ is the system loss factor, $\bar{T}$ is the average temperature of the tank and T_a is the ambient temperature, η is the collector efficiency, I is the solar radiation, T_i is the initial temperature of the water in the collector and T_a is ambient temperature. The useful received energy is calculated as follows:

$$\dot{Q}_{col} = \eta.A_a.I \quad (4)$$

In the eq.4 η is the absorbing efficiency of collector which obtained from manufacture catalog of the collector and the value is 93% [24].

$$\dot{Q}_{col} = N_{tub}.\dot{m}.c_p\frac{dT}{dt} \quad (5)$$

$$T_f - T_i = \int_{t0}^{t1}\frac{dT}{dt}dt \quad (6)$$

The eq.5 and eq.6 has been used to simulate temperature changes of water tank during the experiment.

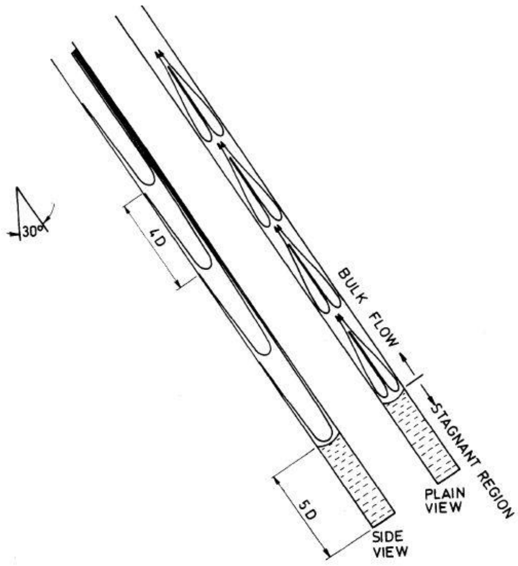


Fig. 5. The fluid flow and the stagnant region in the evacuated tube

Figure 5 shows the fluid flow and the stagnant region in the evacuated tube. [18]

4. Experiment Validation

The experiments in the absence of hot and cold water separator plates in the evacuated tubes were validated using the equations (1) to (7). Figure 5 shows the simulated and experimental water temperature variations. As can be seen, the simulated temperatures are consistent with the experimental results. In addition, the experimental thermal efficiency is consistent with the simulated efficiency as shown in Figure 8. Accordingly, the results are acceptable for other modes. Figure 6 shows the simulated and experimental water temperature changes in the tank. The two charts well overlap from 07:30 to 09:30 AM. From 09:30 to 15:30, the simulated graph shows a higher temperature and finally reaches a higher temperature. Given the greater changes of the simulation temperature of the tank, the thermal efficiency is slightly higher in this case. The experimental and simulated thermal efficiency is 29.68% and 32.60%, respectively. Figure 8 shows the thermal efficiency in different scenarios.

During the test, the temperature at different times of day was almost the same (figure 9). It can be concluded that the effect of heat transfer from the solar water heater tank to the environment in different days and different tests is almost identical. Thus, its effect on the results was neglected, because the aim was to evaluate the changes in the tank temperature throughout the day in various experiments relative to the evacuated tube water heater without separator plates. The solar water heater was installed in such a way that it was inclined towards the east of the main directions.

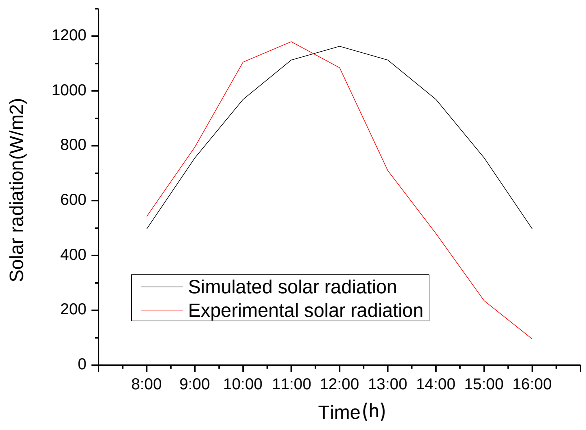


Fig.7. The simulated and experimental solar radiation

There was also a tall building in the west which reduced the solar radiation received by the solar water heater in the afternoon, that's the reason that experimental and simulated solar radiation is not the same (figure7).

As the measurement instruments always has errors, the 5% error is chosen according to the manufacturer catalog.

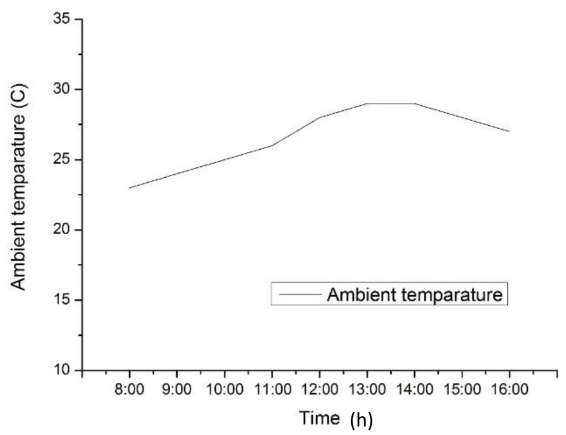


Fig.9. The ambient temperature variation in experiment days

The first experiment without the use of separator plates began from 07:30 when the water temperature in the tank was 31 °C and the data on solar radiation and water temperature was recorded until 16:00. It should be noted that the experiment was conducted on two successive days in the same weather conditions and the average results were reported. As clear from Table 3, the temperature variation is 17 °C in the absence of separator plates. At 11:00 AM, the solar radiation reached its maximum value and then was reduced. From 09:30 AM, the water was warming at a good rate until 13:00. Figure 4 shows the evacuated tube and the separator plate schematically. Figure 10 shows the changes in the water temperature in the experiments with hot and cold fluid separator plates.

The second experiment was performed using a separator plate made of Plexiglas with a length of 1.2 m. Since the evacuated tube length was 1.8 m, to prevent the separator plate movement inside the evacuated tube, the separator plate was temporarily attached to the evacuated tube using the aquarium glue.

5. Results

The experiments were performed without separator plates and with separator plates with a length of 1.2, 1.4, 1.6 m and the results were analyzed. Weather forecasts were used to select the sunny days to perform the tests. Accordingly, eight successive days were selected when the weather conditions and temperature and the amount of solar radiation were without much change to assess and compare the results more accurately.

Four series of experiments were repeated three times in eight days with the same weather conditions. Table 2 shows the results of three series of experiments in the absence of separator plates. Experiments were conducted on clear and sunny days of November 2015. Figure 10 shows the change in solar radiation throughout the day in different dates. Since each series of tests was performed on two successive days, no large variation is observed in the amount of solar radiation received by the collector of solar water heater.

That is why the average results of experiments are shown. According to solar energy calculations and experimental results of previous research, the amount of solar radiation received by the solar collector during the day is symmetrical with respect to the solar noon hour. However, as shown in Figure 7, the amount of solar radiation in the early hours of the morning and afternoon hours is not symmetrical. This asymmetry in solar radiation chart is due to local conditions of the solar collector.

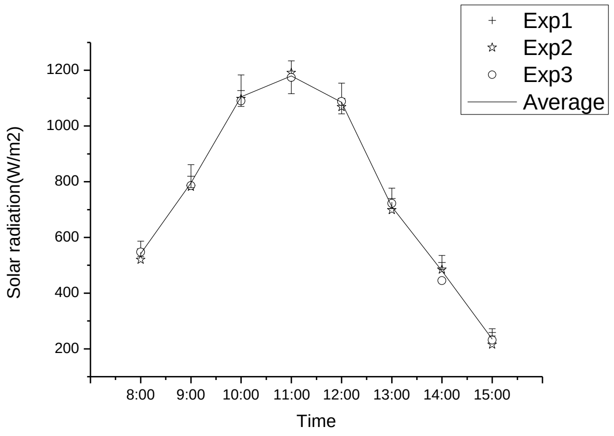
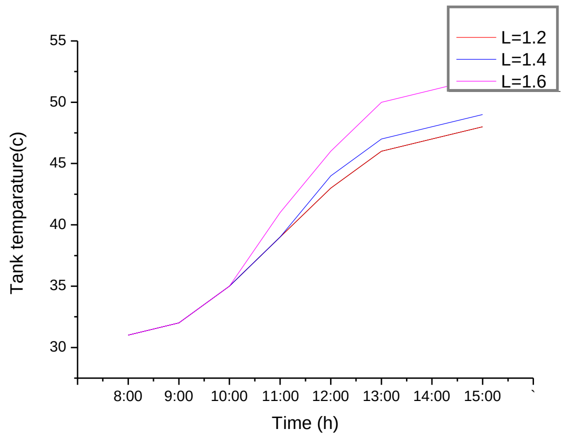


Fig.10. Solar radiation in 3 experiment

As clear from Table 3 and Figure 8, the water temperature variation was 17 °C (from 31 °C to 48 °C). The change in the water temperature in the absence and presence of separator plate with a length of 1.2 m was identical. The change in the water temperature in the presence of 1.4 m separator plates was 18 °C. Figure 9 shows the experimental water temperature variations in different modes. The average results for various tests are shown in Table 3.



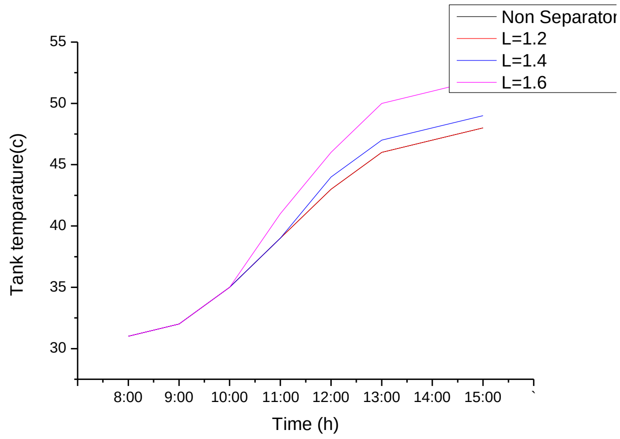


Fig.11. Experimental water temperature variations.

Table 2. Experiment result that repeated in absence of separator plate

Number of experiment	Inlet water temperature (°c)	Outlet water temperature (°c)	Total absorbed solar radiation (KJ)	Heat gain (KJ)	Efficiency (%)
1	31	48	42700	12798	30
2	31	48	42861	12944	30.2
3	31	48	42821	12642	29.5

It was observed that the increase in the water temperature inside the tank without separator plates was about 17 °C. On the other hand, the increase in the water temperature in the presence of separator plates with 1.2 m length was also 17 °C. The reason lied in the lack of change in the stagnation region of the evacuated tube.

As shown in table 3 that shows the thermal efficiency in different modes, the use of 1.2 m separator plates had no effect on the thermal efficiency of the system, but 1.4 m separator plates increased the thermal efficiency. The increase in the thermal efficiency was significant with the use of 1.6 m separator plates.

6. Discussion and Conclusion

In this article, the effect of hot and cold water separator plates in evacuated tubes was investigated with the aim of increasing the thermal efficiency of conventional evacuated tube solar water heaters. For this purpose, the conventional evacuated tube solar water heater was first modeled and studied experimentally. The results were in good agreement. After validation of the results, the effect of 1.2, 1.4 and 1.6 m separator plates in the evacuated tubes was investigated. To reduce the dependence on environmental conditions, the tests were repeated several times for each length of the separator plates. The input parameter, the solar radiation, and the output, the water temperature in the tank, were continuously measured. The final results obtained in this paper are summarized as follows. As seen in Figure 11, the water temperature inside the tank is steadily rising during the day. The increase in the water temperature in the tank is higher in noon because of the higher solar radiation reaching the surface of the solar collector (As seen in Figure 6). Considering that the total length of the evacuated tube of the solar collector is 1.8 m and given that two experiments on the solar collector without the separator plates and with 1.2 m separator plate showed no significant changes, the stagnation region is estimated to be about 0.6 m.

As shown in Tables 3 and 4, the thermal efficiency of the solar water heater steadily increases by reducing the length of stagnation region at the end of the evacuated tube so that the efficiency can be increased about 5% with the use of 1.6 m separator plates (efficiency: 36.8%) in comparison with the conventional solar water heater without separator plates (efficiency: 30%).

Table 3.Experiment result of November 2015

Length of separator plates (m)	Inlet water temperature (°c)	Outlet water temperature (°c)	Total absorbed solar radiation (KJ)	Heat gain (KJ)	Efficiency (%)
Non plate	31	48	42794	12794	29.9
1.2	31	48	42959	12794	29.8
1.4	31	49	42953	13547	31.5
1.6	31	52	42963	15805	36.8

Table 4. Experiment Results of December 2015

Length of separator plates (m)	Inlet water temperature (°c)	Outlet water temperature (°c)	Total absorbed solar radiation (KJ)	Heat gain (KJ)	Efficiency (%)
Non plate	31	47	42520	12018	28.2
1.2	31	47	42370	12018	28.3
1.4	31	48	42468	12769	30.0
1.6	31	51	42600	15022	33.2

According to the results, the use of hot and cold fluid separator plates in the evacuated tubes is optimal leading to an increase in the hot water temperature compared with conventional evacuated tube solar water heaters. Also as this Plexiglas separator plates is not expensive the use of these separator plates is recommended. Determining the stagnation region in this article, other researchers will be able to find other ways to increase the efficiency of solar water heater systems.

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