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Optimum Tilt Angle and Orientation for a Flat Plate Solar Water Heater under Egyptian Conditions

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Abstract Solar water heater (SWH) is a most widely used for different Agricultural and Industrial applications in Egypt. But, there are many parameters that affect solar water heater thermal performance. Tilt angle and orientation are considered as an important factors influencing, not only the thermal performance but also the heat energy acquired by the solar system. Four identical solar water heaters were situated on the roof of Agricultural Engineering Department to investigate under clear sky conditions the effect of tilt angle and orientation on solar water heater thermal performance. They were mounted individual on a movable frames which could be adjusted so that at any time the angle of incidence of the surface of the solar heater and the sun's rays could be set at zero. Water could be continually cycled through the SWH. After passing through the SWH, the heater water was stored in an insulated storage tank. The obtained result clarified that the solar heater which tracked the sun's rays once each half an hour from sunrise to sunset was more efficient than the other solar heaters. Overall thermal efficiencies for SWH1, SWH2, SWH3, and SWH4 were on average 72.83%, 65.85%, 61.60%, and 55.98%, respectively.
Key words: solar energy, solar water heater, flat plate.

INTRODUCTION

A solar water heater will not operate at its peak potential unless it is orientated to track the sun's rays from sunrise to sunset and tilted from the horizontal plane in such a way that it will minimize the angle of incidence and maximize the transmittance of the glass cover and absorptance of the absorber plate. Consequently, it will absorb the maximum amount of solar radiation. The transmittance of the solar collector cover varies with the incident angle. Transmittance of most cover materials varies little when the incident angle is less than 30°, but it decreases very rapidly as increases beyond 30° *(Chau, 1982 ; Abdellatif, 1985 ; Duffie and Beckman, 1991 ; Kalogirou, 1997 ; and Sayigh, 2001*). The annual solar fraction of the system (the fraction of energy that is supplied by solar energy) was used by *Shariah et al. (2002*). It was functioned as an indicator to find the optimum inclination angles for a thermosyphone solar water heater installed in northern and southern provinces of Jordan. The obtained results revealed that, the optimum tilt angle for the maximum solar fraction was about $\Phi + (0 \rightarrow 10°)$ for the northern province (represented by Amman city) and about $\Phi + (0 \rightarrow 20°)$ for the southern province (represented by Aqaba town). They concluded that, 1) the optimum tilt angle for maximum solar fraction is larger than any of those for the maximum solar radiation at the top of the solar collector by about 5 to 8°, 2) the optimum tilt angle of the solar collector depends on the operating strategy, and 3) the useful energy collected by the system is perceived higher than the load energy during summer especially for a collector with an area of 3 m^2 or larger. They also recommended that, further work should be carried out to analyze the effect of the latitude angle (Φ) and different climates on the optimum tilt angle. An energy efficient solar collectors absorb incident solar radiation, convert it to thermal energy and deliver the thermal energy to a heat transfer medium with minimum heat losses at each step. It is possible to achieve that, if the solar collector is continuously orientated and tilted with an optimum direction and tilt angle (*Kalogirou, 2004*).

The objective of the present research work was to determine under clear sky conditions the optimum tilt angle and orientation, and their effect on thermal performance of solar water heater.

MATERIALS AND METHODS

Four similar solar water heaters were designed and constructed in the work shop of the Agricultural Engineering Department and situated on the roof of the department as demonstrated in Fig.(1).

Fig. 1. Solar water heaters during operating the heating system.

Each solar heater having a net surface area of 2.0 m^2. It consisted of seven components (absorber plate, copper pipes, casing, insulation material, glass cover, storage tank, and water pump) The absorber plate is formed of an aluminum slab (2 m long, 1 m wide, and 2 mm thick) and painted with matt black paint in order to absorb the maximum amount of solar energy available. A copper pipes (10 pipes) 12.5 mm in diameter are arranged at an equidistance of 10 cm and attached well to the upper surface of the absorber plate using slab ties each 10 cm long throughout the length of each pipe. They were also painted matt black paint. The solar heater casing is rectangular in shape (2.1 m long, 1.1 m wide, and 0.1 m deep) made of aluminum bar 25 mm thick. A 50 mm insulation material (fiberglass wool) was placed in the bottom and around the sides of the casing to reduce the heat losses from the sides and back of the solar heater. To reduce the heat losses by convection and radiation from the absorber plate, a clear glass cover 5 mm thick was placed to cover the solar heater casing. The solar water heaters were mounted individually on a movable frames which were adjusted manually to change the orientation and the tilt angle using a quadrant and clamp. Each movable frame was carried on five small wheels (10 cm in diameter) and screwed pin (as an axial point) for orientation of solar heater, where the small wheels were moved around the axial pin. The operating fluid (water) was forced using 400 Watt water pump, so as to pass through the solar heater. After the water passes through the solar heater it was stored in a 300 liters insulated storage tank. The storage tank was connected to the solar heater by two junctions of insulated rubber hose. One junction is between the bottom of the storage tank (usually cold water) and the bottom of the solar heater (water inlet point). The other junction is between the top of the storage tank and the top of the solar heater (water outlet point). The water pumps were manually switched ON and OFF on sunny days from 5^{th} until 20^{th} March 2008 (10 days were recorded). The mass flow rate of operating fluid (15 l/min as recommended by *Abdellatif, et al., 2006*) was tested, adjusted and controlled every day using a control valve and measuring cylinder with stop watch. Four different orientations and tilt angles were used during this research work. The first solar heater (SWH1) was orientated continuously and inclined with an optimum direction and tilt angle in order to track the sun's rays once each half an hour from sunrise to sunset. The second heater (SWH2) was continuously orientated and inclined with one tilt angle (optimum at noon). The third solar heater (SWH3) was continuously orientated and inclined with one tilt angle equal the latitude angle of the place (31.045°N). The last heater (SWH4) was fixed with an optimum tilt angle at noon (stationary non-tracking). For solar heater (SWH1) the optimum tilt angle (β_o) at each hour from sunrise to sunset as a function of solar altitude angle (ψ) was determined using the following equation *(Abdellatif, 1985)*:-

$$\beta_o = 90 - \psi \quad (1)$$

For stationary non-tracking solar heater (S4), the optimum tilt angle at noon can be calculated as a function of latitude angle(Φ) and solar declination angle (δ) using the following formula:-

$$\beta = \Phi - \delta \quad (2)$$

$$\delta = 23.45 \sin (0.9863(n+284)) \quad (3)$$

The weather data from a meteorological station (Watch Dog model 550) which located above the solar heaters were used. Two thermocouples were employed to measure the inlet and outlet water temperatures of each solar heater. The water temperature in each storage tank was measured using one thermocouple installed at the center of storage tank. Four solarimeters were fixed and installed on the top frame of each solar heater in order to measure the solar radiation flux incident. These sensors were connected to a data logger system to display and record the obtained data throughout the experimental work. The parameters of thermal performance test and the relationship between them are examined and tested by *Duffie and Beckman (1991)*. The solar energy available (**Q**) can be calculated as a function of solar radiation flux incident (**R**) and solar heater surface area (**A_C**) as follows:-

$$Q = R\ A_C, \quad W\ (4)$$

The absorbed solar radiation (**Q_a**) can be computed in terms of the transmittance of glass cover (**ζ**) and the absorptance of the absorber plate (**α**) as follows:-

$$Q_a = \zeta\, \alpha\, Q \qquad W\ (5)$$

The absorption efficiency (**η_a**) can be determined as follows:

$$\eta_a = \frac{Q_a}{Q} \times 100, \%\ (6)$$

The useful heat gain to storage (**Q_C**) can be estimated as a function of the mass flow rate of water (**m**), specific heat of water (**C_p**), and temperature difference between outlet (**T_{fo}**) and inlet (**T_{fi}**) water temperatures as follows:-

$$Q_C = m\, C_P\, (T_{fo} - T_{fi}) \qquad W\ (7)$$

The heat transfer efficiency (**η_h**) can be calculated as follows:

$$\eta_h = \frac{Q_C}{Q_a} \times 100, \quad \%\ (8)$$

The total heat losses from the solar water heater can be computed as follows:-

$$Q_L = Q_a - Q_C \qquad W\ (9)$$

The overall thermal efficiency (**η_o**) can be found as follows:-

$$\eta_o = \frac{Q_C}{R\ A_C} \times 100, \quad \%\ (10)$$

The "temperature rise" (**D_T**) can be estimated in terms of the temperature difference between the inlet water (**T_{fi}**) and the ambient air (**T_a**) as follows:-

$$D_T = \frac{T_{fi} - T_a}{R}, \ °C.m^2/W \quad (11)$$

The solar energy stored in the storage tank (**Q_s**) can be computed as a function of mass of water in the storage tank per unit time (**m_s**), specific heat of water (**C_p**), and the temperature difference between mean tank at the end (**T_{k2}**) and beginning (**T_{k1}**) of each hour as follows:-

$$Q_s = m_s\, C_P\, (T_{k2} - T_{k1}) \quad W\ (12)$$

The storage system efficiency (**η_s**) can be found as follows:-

$$\eta_S = \frac{Q_S}{Q_C} \times 100, \quad \% \qquad (13)$$

RESULTS AND DISCUSSION

For the ten days duration of this experiment, the four solar water heaters were operated satisfactorily without any malfunctions. Tilt angle and orientation are probably the most important parameters affecting thermal performance of solar water heater. The daily average solar energy available for SWH1, SWH2, SWH3, and SWH4 was 19.649, 14.012, 13.009, and 12.449 kWh/day, respectively. These obvious differences in solar energy available can be attributed to the difference in tilt angle and orientation between the four solar heaters. The solar water heater (SWH1) which tracked the sun's rays from sunrise to sunset increased the solar energy available by 40.23%, 51.04%, and 57.84% as compared with SWH2, SWH3, and SWH4, respectively. The daily average absorbed solar energy for the four solar heaters was 16.800, 10.744, 9.620, and 8.573 kWh/day, which gave an average absorption efficiencies of 85.5%, 76.68%, 73.95%, and 68.87%, respectively. The differences in absorption efficiencies were due to the differences in the effective absorptance of the absorber black plate and the effective transmittance of the glass cover between the four systems, which were highly dependent upon the solar incident angle. Once each half an hour from sunrise to sunset the rays of the sun were perpendicular to the surface of SWH1 which tracked the sun's rays. Consequently the solar angle of incidence equaled zero at those times and the absorptance of absorber plate and the transmittance of glass cover were at their highest values of 0.95 and 0.9, respectively. Meanwhile, the solar incident angles for SWH2 and SWH4 equaled zero only at solar noon, and they were greater than zero particularly in the early morning and later afternoon. The solar incident angles during this experiment ranged from 78° at 7 am to 0° at solar noon. The daily average absorbed solar energy which was converted into useful heat gain to storage during this experiment for the four solar water heaters was 14.310, 9.227, 8.014, and 6.968 kWh/day which gave an average heat transfer efficiencies of 85.18%, 85.88%, 83.31% and 81.28%, respectively. There was no significant difference in heat transfer efficiency between SWH1 and SWH2 due to the water inlet temperature. The solar heater which tracked the sun's rays (SWH1) converted more energy into useful heat gain to storage particularly from sunrise to solar noon due to more energy was absorbed. After solar noon the absorbed solar energy converted into useful heat acquire to storage was reduced due to high water inlet temperature. While, the maximum amount of useful heat gain to storage for SWH2, SWH3, and SWH4 occurred at and around solar noon. At that time the water temperatures in the storage tanks were lower than that in SWH1, so the heat transfer efficiencies for SWH2, SWH3, and SWH4 were greater than SWH1 around solar noon. Because the overall thermal efficiency of the solar water heater is a combination of absorption and heat transfer efficiencies, the SWH1 was more efficient than the SWH2, SWH3, and SWH4. For the duration of this experiment the daily average overall thermal efficiencies for the four different systems were 72.83%, 65.85%, 61.60%, and 55.98%, consequently 27.17%, 34.15%, 38.40%, and 44.02% of the solar energy available were lost, respectively. If the water inlet temperature for the four different systems had been kept the same from sunrise to sunset, the solar water heater which tracked the sun's rays (SWH1) could be increased to an overall thermal efficiency greater than 72.83%. The overall thermal efficiencies (η_o) for the four different orientations and tilt angles were plotted against "temperature rise" (**D_T**) as shown in Fig.(2). Regression analysis revealed a highly significant linear relationship (R^2 = 0.998 ; P$\leq$ 0.001) between these parameters. The regression analysis also clarified that, the overall thermal efficiency of the solar water heaters can represent as:-

$$\eta_o = F_R\,(\zeta\alpha\,) - U_o\,F_R\,(D_T)$$

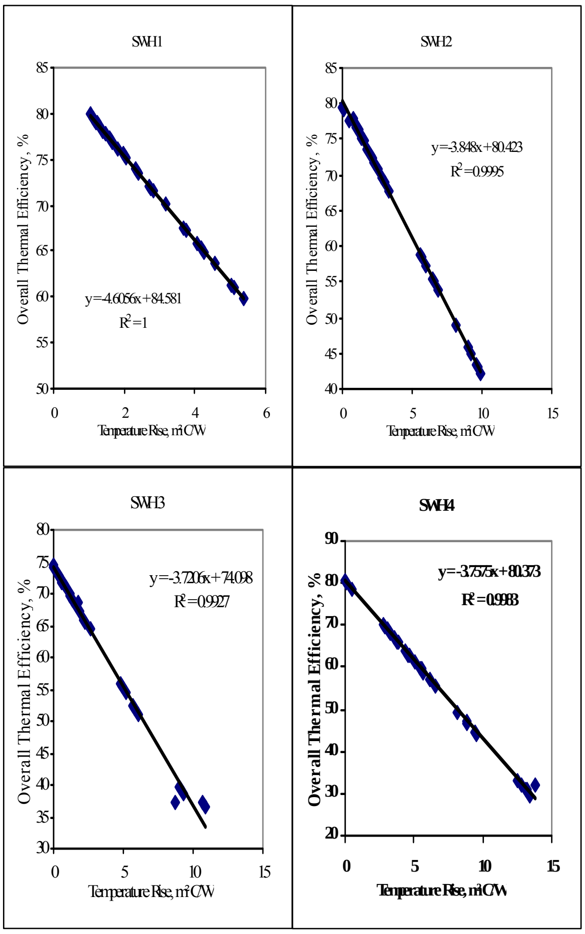

Fig 2. Overall thermal efficiency against "Temperature rise" for the four systems

$$\eta_o = \quad a \quad - U_o\,F_R\,(D_T)$$

Regression equations are definitely the numerical expression of the above two equations. The y-intercept (a) is equal to the product of heat removal factor (F_R) and the optical efficiency ($\zeta\alpha$). While, the slope is equal to the product of heat removal factor (F_R) and overall heat transfer coefficient (U_o). The plots of overall thermal efficiency (η_o) versus "temperature rise"(D_T) were straight lines with intercept F_R ($\zeta\alpha$) and slope (- F_R U_o). It is evident that U_o is a function of temperatures (difference between mean absorber plate temperature and ambient air temperature) and wind speed. Some variations of the relative proportions of beam, diffuse, and surrounding substances-reflected components of solar radiation occurred during the experimental work due to variations in angle of solar incidence. Thus scatter in the data of (SWH2, SWH3, and SWH4) were expected, because of water inlet temperature dependence, wind speed effects, solar incident angle variations. In spite of these difficulties, for purposes of estimating long-term thermal performance of many solar heating systems, solar panels can be characterized by the intercept and slope (i.e., by F_R ((ζα) and – F_R U_O). According to the previous expression of the regression equations, the daily average heat removal factors (F_R) for the four different solar heating systems were, respectively, 0.9893, 0.9412, 0.8979, and 0.9400.

They also revealed that, the daily average overall heat transfer coefficients were 4.656, 4.089, 4.144, and 3.997 $W/m^2.°C$, respectively. The daily averages solar energy stored in the storage tank for SWH1, SWH2, SWH3, and SWH4 during this research work were 11.777, 9.227, 8.014, and 6.968 kWh/day, which gave an average storage system efficiencies of 82.30% , 80.67%, 77.5%, and 67.16%, respectively. During the early morning hours just after sunrise and prior to sunset, very little amounts of useful heat were acquired by the working fluid (water) of SWH4 because of little amounts of solar energy available on the surface of that heater at those times. Thus a large amount of solar energy was required to increase the absorber plate temperature above the average water temperature passing through the heater. The solar water heater (SWH1) which tracked the sun's rays from sunrise to sunset increased the solar energy stored in the storage tank by 27.64%, 46.96%, and 69.02% as compared with SWH2, SWH3, and SWH4, respectively. The heat energy stored in the storage tank for the four solar heating systems were found to be directly proportional to useful heat gain to storage and ambient air temperature, and inversely proportional to working fluid (water) temperature in the storage tank. Therefore, at and around noon the storage system efficiency for stationary non- tracking solar heating system (SWH4) was greater than that for tracking solar heater (SWH1) at those times, because of lower water temperature in the storage tank.

CONCLUSION

The obtained data of this experimental work can be summarized and concluded as follows:-

1- The solar water heater which was continuously orientated and tilted to maintain an incident angle of zero from sunrise to sunset was attained maximum values of the absorptance of the absorber plate and transmittance of the glass cove as compared with the other solar heaters.

2- The solar heater which tracked the sun's rays once each half an hour from sunrise to sunset was more efficient than the other solar heaters. Overall thermal efficiencies for SWH1, SWH2, SWH3, and SWH4 were on average 72.83%, 65.85%, 61.60%, and 55.98%, respectively.

3- The differences in thermal performance between the four systems varied with solar time from sunrise to sunset according to the day length and water inlet temperature.

4- As the day length is increased the variation in effective absorptance and transmittance for the stationary solar heating system (SWH4) increased due to the changes in angle of solar incidence throughout the day. Therefore, the differences in thermal performance between the four systems during summer months will be greater than in winter months.

5- Also these differences depend strongly upon the water inlet temperature. As the tracking solar heating system absorbed more energy than the other solar heating systems, the water inlet temperature became greater than that in the other systems particularly at and after noon.

REFERENCES

Abdellatif, S., M. 1985. Solar energy collection, storage and utilization in protected cropping. Ph. D Thesis, Wye College. University of London.

Abdellatif, S. M., A. M. Matouk, R. E. Matouk, 2006. Effect of mass flow rate of operating fluid on solar panel thermal performance. J. Agric. Sci. Mansoura University, 31(7) :479-496.

Chau, K. V.1982. Optimum tilt angle for solar collector in clear sky conditions. J. Agric. Engng. Res. 27:321-328.

Duffie, J., W. Beckman.1991. Solar engineering of thermal processes. John Wiley and Sons, New York, ed. 762pp.

Kalogirou, S.1997. Survey of Solar desalination systems and system selection. Energy: Int J., 22:69-81

Kalogirou, S. 2004. Solar thermal collectors and applications. Energy and Combustion Science 30:231-295.

Sayigh, A. A. W.2001. Renewable energy : global progress and examples. Renewable Energy WREN, 15-17.

Shariah, A. ; M. A. Al-Akhras; and I. A. Al-Omari. 2002. Optimizing the tilt angle of solar collectors. Renewable Energy, 26:587-598.