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Experimental Investigation of Thermal Performance in an Advanced Solar Collector with Helical Tube

K. Goudarzi* [a], S. K. Asadi Yousef-abad [b], E. Shojaeizadeh [c], A. Hajipour [b]

[a] *Department of Mechanical Engineering, Yasuj University, Yasuj, Iran.*
[b] *Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.*
[c] *Mechanical Engineering Department, Razi University, Kermanshah, Iran*

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ABSTRACT

This paper reports the thermal performance of a new cylindrical solar collector based on an experimental investigation with the difference that instead of the collector tube with absorbent coating, coil into a helical copper tube is placed in the center of the collector. Because of the helical shape of the tube, without any change in the heat transfer area, heat transfer increases. In this case, the centrifugal forces generated secondary flow, increases the coefficient of the convection heat transfer. Another advantage of this type of collector with respect to the flat plate collector, is its circular shape that is constantly exposed to sunlight. Inlet and outlet temperatures of the cylindrical solar collector was measured, during September 6-8, 2012 from 10 AM to 14 PM, and the thermal efficiency was between 43.5 and 58.7 percent. The results of this article can be useful for analysis of the solar energy systems.

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1. INTRODUCTION

Due to the limited fossil energy and heated up emissions debates, more attention has been paid to solar energy as a clean and limitless resource. Non-complex technology, pollutionless energy and most importantly, capability of saving fossil fuels for the future generations are of the main reasons necessitating the use of solar energy in our country. Worthy to note that solar electric energy demand has grown by an average 30% per annum over the past 20 years against a backdrop of rapidly declining costs and prices.

One of the applications of solar energy is in heating processes; for this means, mostly, water-heaters are in use. The main part of solar water-heaters is its absorbent which is utilized for collecting and then transferring the sun's energy to the storage tank. In solar absorbers, solar energy will be absorbed by their relatively extensive as well as black surface, and by conduction and convection mechanisms, it will be transferred to the fluid through the attached tube to the surface. Then, the heated fluid will transmit the energy to the storage tank. Worthy to note that for heating purposes, the energy received from sun is utilized in two different ways, direct and indirect methods. In this study, we employ indirect method in which thermal energy absorbed by collector fluid in a heat exchanger will be transferred to another fluid. This part of the water-heaters, which is considered as the most important part of it, is called the collector. The collectors used in the industry are divided into three categories: flat-plate collector, evacuated-tube collector and concentrating collector. Cylindrical solar collector is a type of tubed collector; however, instead of a pipe coated with absorbent material, in these collectors, a coil in the form of copper helical tubes is placed in the center of a transparent tube. Substantial work has been done in the area of designing, as well as optimizing the solar collectors. For example, Gupta et al. [1] proposed a computer model to predict the thermal performance of domestic solar water heaters. In their model, they used thermosyphon circulation between the collector and the insulated storage tank. For the first time, they

*Corresponding Author Email: Kgoudarzi@yu.ac.ir (K. Goudarzi).

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incorporated factor of absorber plate efficiency and the solar radiation intensity as well. Khalifa [2] conducted an investigation on a locally-made natural circulation domestic hot water system to present the relevant variables on the performance of the solar system. They carried out this by finding the temperature fields along the fin between the absorber tubes in the flow direction and the thermosyphonic mass flow rate. Alongside with the optimization of collector designs, Kalogirou et al. [3], emphasizing high complex and ill-defined nature of collector designs, employed artificial neural networks (ANN) for the performance prediction of a thermosyphon solar water heater. Experimental measurements of heat loss in an advanced solar collector have been carried out by Groenhout et al. [4]. Riffat et al. [5] showed that hybrid solar collector is the best option for collector/CHP system. They described the process of optimizing, selecting and designing, the major components, especially the solar collector, of a hybrid solar collector/CHP system. Bari [6] showed that the regular orientations of solar collectors of domestic solar water heaters for the low latitude countries are not good angles. Solar thermal applications in the West Indies has been done by Headley [7] and finally, theoretical approach of a flat plate solar collector with clear and low-iron glass covers taking into account the spectral absorption and emission within glass cover layer has been investigated by Khoukhi et al. [8]. They have presented the optimum orientation for these countries. In this paper, a novel kind of technique is utilized to enhance the thermal performance of solar collector. This technique consists of employing a coil in the form of a set of helical copper tubes located in the center of the collector. In this kind of collector, instead of coating the tube with absorbent, a coil in form of a set of helical copper tubes is placed in the center of the collector. This solar collector consists of a glass tube and a copper helical coil in which working fluid flows through. Employing a helical tube, the heat transfer increases due to increasing effective heat transfer area without disturbing the flow. In this case, the centrifugal forces generating the secondary flow, which consists of a pair of longitudinal vortices, will increase the coefficient of the convection heat transfer. Another advantage of this collector over the flat plate one is its circular shape, which is constantly exposed to sunlight.

2. CYLINDRICAL SOLAR COLLECTOR DESIGN

The Cylindrical solar collector consists of a glass tube and a copper helical coil. The copper helical coil works as the collector (absorber or receiver) and working fluid is water; the schematic of the experimental setup is shown in Figure 1.

2. 1. Glass Tube Geometrical dimensions of the glass cylinder are: the outer diameter, length and thickness 15.0 mm, 6.0 mm and 5.0 mm, respectively. Glass cylinder is open at both ends; so, two transparent plastic flanges are sealed at both ends. The space between the glass rods and copper coil is evacuated. The glass, in this investigation has two main properties; having minimum reflection coefficient to avoid reflecting the solar radiation received by a cylindrical glass, and maximum transmission coefficient in order to transmit solar radiation from the glass to the copper coil. Utilizing this high quality glass, we are sure that cylindrical solar thermal efficiency will be improved.

2. 2. Copper Helical Coil The copper coil is made in the form of a cylindrical spring. The external diameter of the copper tube is 10 mm and its thickness is 1 mm. To have the maximum absorbed solar energy eradiating to the glass tube walls, black color is used for copper coil. According to the foregoing description of the solar collector, as Figure 2 shows, a solar collector with copper helical tube has been manufactured. A shown in this figure, the collector consists of a storage tank, a pump and water heating systems. The solar water-heater in this study used a closed forced circulation system. Besides, an electric pump is employed for flowing water in the system. Figure 2 presents a schematic of the solar collector. According to this figure, the collector and the storage tank are installed separately. The schematic of the experimental is shown in Figure 2. Cylindrical solar collector that was experimentally investigated at the University of Yasuj, Iran was designed and constructed. Solar collector consists of a cylindrical glass tube (1 in Figure 2) as receiver and a copper helical pipe as absorber through which the water flows (2 in Figure 2). These sensors were connected to a 4-channel data logger (ET-7018Z) (3 in Figure 2). Four K Thermocouples were used to measure the fluid temperatures in the inlet and outlet (4 in Figure 2) of solar collector. Also, two K thermocouples were used to measure the inlet temperature of heat exchanger (11 in Figure 2) and air temperature (12 in Figure 2). The collector is placed horizontally. According to the solar system, an electrical pump is used (6 in Figure 2). The electrical pump is used with a valve flow sensor (7 in Figure 2). It is connected to the water pipe line before the electric pump. The rotameter which measures flow rate is of type ACA03 (8 in Figure 2). The copper coil with 1 mm inner diameter, and 10 mm outer diameter, painted black to absorb the maximum possible radiation to raise the water temperature. As shown in this study, in the solar water heating system, in addition to the solar collector has a tank (9 in Figure 2) for absorbing the heat load from the collector cycle. In the system, the maximum capacity of this tank according to the absorbed heat load, the heat needed and hot water required is about 40 liters and used as supplement cycle (second cycle). A heat exchanger (10 in Figure 2) used inside the tank transmits the heat load of the solar cycle to the tap water. Copper wire coil with the length of 10 meter is used in the heat exchanger. The total solar radiation was recorded by a CM21 solar meter. In the present study, in order to measure the fluid pressure in the inlet and outlet, two pressure gages are used. Calibration of measuring instruments was undertaken before, during, and after the experimental data collection.

Thermocouples were calibrated using an independently calibrated platinum resistance thermometer; flow meter using a data logging sub-routine for water draw off from the systems into a container and measuring the mass with accuracy scales.

3. COLLECTOR CORRESPONDING EQUATIONS

To estimate the thermal performance of the cylindrical solar water heater, the instantaneous efficiency will be calculated to determine the hourly beam radiation and the useful energy gained.

3. 1. Instantaneous Efficiency The instantaneous efficiency of collector is given by the ratio of useful absorbed energy to the total absorbed energy by cylindrical wall (collector) [7-9], as follow:

$$\eta_i = \frac{Q_u}{A_c I_b}, \tag{1}$$

where, Q_u is the useful absorbed energy, A_c is the collector surface area and I_b is the direct solar radiation.

3. 2. Useful Absorbed Energy In steady state condition, the useful energy absorption can be obtained by the following equation:

$$Q_u = A_c F_R \left[S - U_L \left(T_i - T_a \right) \right], \tag{2}$$

where, F_R is the multiplicative factor, S the absorbed solar radiation, U_L the total heat transfer coefficient, T_i the inlet fluid temperature to collector and T_a the ambient temperature.

3. 3. Total Heat Loss Factor Total heat loss factor, depending on the type of glass and dielectric properties of materials, could be selected. Thus, the total heat loss coefficient is calculated as follows:

$$U_L = \frac{1}{\left[\begin{array}{l} \dfrac{1}{h_{rad} + h_{wind}} + \dfrac{r_1}{k_{glass}} \ln\left(\dfrac{r_2}{r_1}\right) + \cdots \\ \cdots + \dfrac{1}{h_{air}} + \dfrac{r_1}{k_{pipe}} \ln\left(\dfrac{r_2}{r_1}\right) + \dfrac{1}{h_{fluid}} \end{array} \right]}, \tag{3}$$

where, h_{rad}, h_{wind} and h_{air} are the coefficient of convection heat transfer of the radiation, wind and water, respectively. k_{glass} and k_{pipe} are the conductively of the glass and the copper coil respectively; and therefore:

$$U_b = \frac{k}{L}, \tag{4}$$

where, k and L are the thermal conductivity and thickness of the insulation respectively.

3. 4. Collector Heat Removal Factor Since the heat loss occurs on all the cylindrical walls of the copper tube, the temperature of the system will increase significantly. The quantity F_R is the equivalent to the effectiveness of a conventional heat exchanger, which is ratio of the actual heat transfer to the maximum possible heat transfer. The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collector is at the inlet fluid temperature; heat losses to the surroundings are then minimized. Thus, for reduction of the obtained useful energy in a direct current, coefficient multiplier F_R can be used as following:

$$F_R = F'' F', \tag{5}$$

where,

$$F' = \frac{\dfrac{1}{U_L}}{W\left[\dfrac{1}{U_L \left(D \left(W - D \right) F \right)} + \dfrac{1}{C_b} + \dfrac{1}{\pi D h_{fi}} \right]}, \tag{6}$$

where, D is the diameter of copper helical coil, W the distances between successive helical copper tubes, and C_b the weld conductivity coefficient. In our study, since there is no boundary, C_b is considered infinite. h_{fi} is the heat transfer coefficient of the inlet fluid to the collector. In addition, F is the coefficient of the wind heat transfer, which has been calculated as follows:

$$F = \frac{\tanh\left[\dfrac{m\left(W - D \right)}{2} \right]}{\left[\dfrac{m\left(W - D \right)}{2} \right]}, \tag{7}$$

where,

$$m^2 = \frac{U_L}{k t_{glass}}, \tag{8}$$

where, k and t_{glass} are the conductivity and the thickness of the glass cylinder, respectively.

$$F'' = \frac{\dot{m} C_p}{A_c U_L F'} \left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m} C_p} \right) \right], \tag{9}$$

In Equation (9), $\dot{m}C_p$ is the multiplied of the inlet flow rate to the collector and the specific heat capacity of the working fluid.

3. 5. Absorbed Solar Radiation Absorbed solar radiation can be calculated as following:

$$S = I_b R_b (\tau a)_b, \tag{10}$$

where, $(\tau a)_b$ is the transmission coefficient multiplied by the absorption coefficient of the direct solar radiation. Moreover, R_b is defined as follow:

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\cos\omega + \sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta}, \tag{11}$$

where, φ is the latitude, δ the deviation angle, β the plane angle with the horizon (slope angle), and ω the hour angle proportional to the sun at noon which is 15 degrees per hour. In this study, the cylinder is considered without deviation, so parameter β is zero.

$$\omega = \frac{(t-12)}{15}, \tag{12}$$

where, parameter t is the time in hour. In the solar collector, due to the setup of the collector, the slope angle, β, can be considered zero. Thus, according to Equations (1), (2) and (10), the thermal efficiency of the solar collector can be expressed as:

$$\eta_i = F_R(\tau a)_e - F_R U_L \frac{T_i - T_a}{I_b}, \tag{13}$$

where, the following values for the solar collector are presented in the Table 1. In Table 1, parameters $F_R(\tau\alpha)_e$ and F_RU_L describe the collector performance. In Table 1, the parameter $F_R(\tau\alpha)_e$ shows the absorbed energy and the parameter F_RU_L the lost energy. Substituting the given values in the Table 1 in Equation (13), it can be shown that the thermal performance of the cylindrical solar collector is higher than other types of collectors. So, the use of these collectors is suggested.

4. RESULTS AND DISCUSSIONS

So far, several tests have been done to analyze the solar collector performance. Therefore, we need to investigate the effects of inlet, outlet and ambient temperatures on the thermal performance of the collector over the time. For this purpose, Figure 5 shows the variation of different system temperatures with local time. Accordingly, the inlet, outlet temperatures of the cylindrical solar collector of working fluid (e.g. water), and ambient temperatures, are shown in Figure 5. The solar radiation data measured at Yasuj weather station is shown in Figure 6. As expected, the solar radiation peak occurrs at 12:00. Figure 7 shows the thermal efficiency of the cylindrical solar collector for water flow rates of 45, 60 and 90 liters per minute during the test period of 11 AM to 13 PM. Irradiation measurement device (CM21) can be mounted in all latitudes. This device has three sensors for measuring various type of radiation is from KIPP & ZONEN Inc. Differences in solar collector efficiency for different flow rates of water are clearly evident in Figure 7. Based on this figure, approximately, by passing time from 11 AM to 13 PM, we could have a higher efficiency. According to Figure 8, increasing the water flow rate results a substantial increment in the thermal efficiency of the cylindrical solar collector. In other words, by increasing the flow rate, convection heat transfer will be improved, and, as a result, the efficiency will increase. The tests for cylindrical solar collector are carried out for several values of flow rates. The parameters $F_R(\tau\alpha)_e$ and F_RU_L are the maximum possible efficiency of the collector and the energy loss, respectively. According to this table, for 90 (Lit/hr) flow rate, the parameters $F_R(\tau\alpha)_e$ and F_RU_L are the maximum and minimum values, respectively. In other words, in this flow rate, we have maximum efficiency and minimum heat loss.

TABLE 1. The values of $F_R(\tau\alpha)_e$ and F_RU_L for the solar collector.

Solar collector type	$F_R(\tau\alpha)_e$	F_RU_L ($W.m^{-2}.K^{-1}$)
Flat plate, selective surfaces: single-layer transparent glass	0.8	5
Flat plate, selective surfaces: double-layer transparent glass	0.8	3.5
Vacuum tube collectors	0.8	1-2
Parabolic concentrating solar collector	0.7	2.5

TABLE 2. The values of $F_R(\tau\alpha)_e$ and F_RU_L for the solar collector

Flow (Lit/hr)	$F_R(\tau\alpha)_e$	F_RU_L
45	0.2929	3.01745
60	0.3874	2.9545
90	0.4099	3.0661

Figure 1. Cylindrical solar collector with copper helical tube receiver.

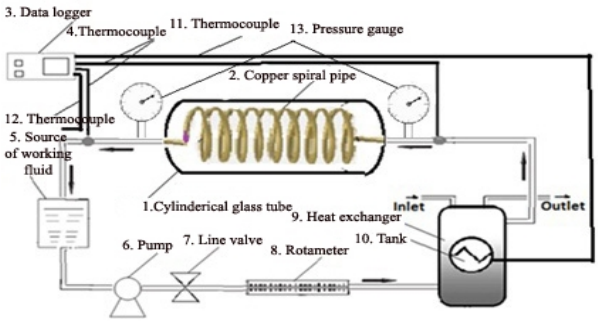

Figure 2. A solar water-heating system.

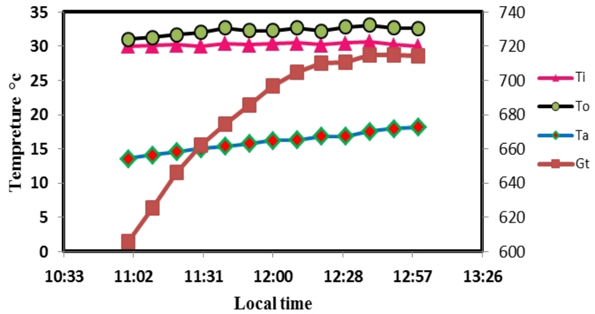

Figure 3. Time variation for the inlet, outlet and ambient temperatures of a cylindrical solar collector.

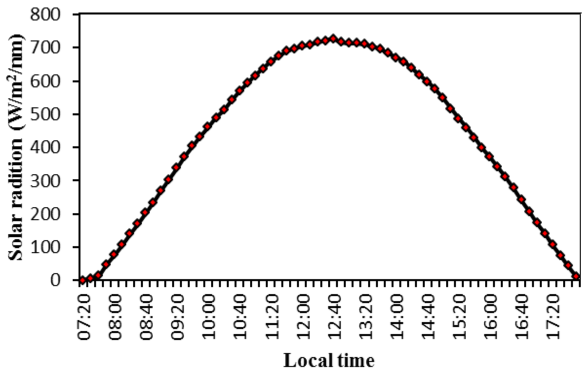

Figure 4. The solar radiation on a test day.

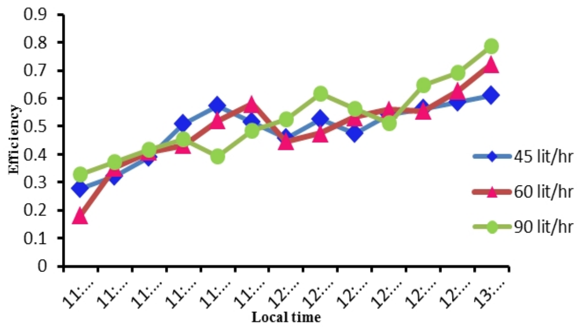

Figure 5. Time variation of the solar collector efficiency for several flow rate during the day.

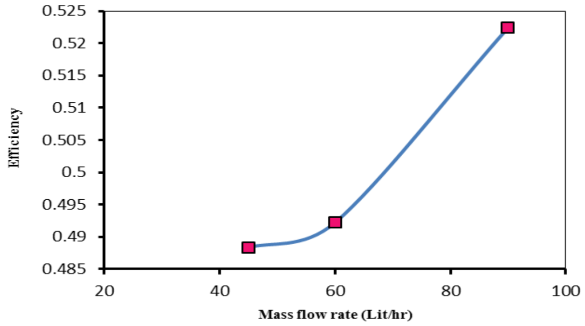

Figure 6. The efficiency of the solar collector for several values of flow rate and at different times of day.

5. CONCLUSION

Employing experimental tests, we presented the thermal performance of the cylindrical solar collector for several flow rates of working fluid. It was shown that having an increment in flow rate, we could enhance the heat transfer. Another important conclusion of this paper is that, in a fixed flow rate, the average of collector efficiency is improved over the time. This improvement in thermal efficiency which is due to employing copper helical tubes could be a result of two main factors: the centrifugal forces with a secondary flow generated by the longitudinal vortices, and the circular shape that is constantly exposed to sunlight.

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K. Goudarzi [a], S. K. Asadi Yousef-abad [b], E. Shojaeizadeh [c], A. Hajipour [b]

[a] *Department of Mechanical Engineering, Yasuj University, Yasuj, Iran.*
[b] *Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.*
[c] *Mechanical Engineering Department, Razi University, Kermanshah, Iran*

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چکیده

در این مقاله، گزارش آزمایشگاهی عملکرد حرارتی یک کلکتور خورشیدی که در آن به جای لوله به عنوان پوشش جاذب، از یک کویل به صورت لوله‌های مسی مارپیچی در مرکز کلکتور استفاده شده است، ارائه شده است. مارپیچ بودن لوله باعث افزایش سطح انتقال حرارت بدون ایجاد اغتشاش در جریان و افزایش سطح می‌شود. در این حالت، نیروهای گریز از مرکز با ایجاد یک جریان ثانویه باعث افزایش ضریب انتقال حرارت جابجایی می‌شوند. یکی دیگر از مزایای این نوع کلکتور نسبت به کلکتور صفحه تخت، شکل دایره‌ای آن است که همواره در معرض تابش مستقیم خورشید قرار دارد. با توجه به اندازه‌گیری مقادیر دمای ورودی و خروجی کلکتور خورشیدی استوانه‌ای ساخته شده، کارایی حرارتی در روز ٦تا ٨ سپتامبر ٢٠١٢ (پانزدهم مرداد ماه سال٩١) از ساعت ١٠ تا ١٤ بین ٤٣/٥ درصد و ٥٨/٧ درصد می‌باشد. نتایج به دست آمده این مقاله می‌تواند برای تجزیه و تحلیل سیستم‌های انرژی خورشیدی مفید باشد.

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