Experimental Evaluation of a Flat Plate Solar Collector Under Hail City Climate

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Abstract—**Flat plate solar water heaters are widely used for water heating in low-temperature residential applications. In this paper the thermal performance of a solar flat plate water heater under Hail weather conditions (latitude 27°52´N longitude 41°69´E) was experimentally investigated. Fluid was circulated through the imbedded copper tubes in the flat plate collector and inlet and outlet temperatures of the fluid were noted at five minute intervals. The experimental-time was between 9:00AM-15:00PM. A study was carried out experimentally to present the efficiency curves of a flat plate solar collector at different flow rates. ASHRAE standard 93-2003 was followed for calculation of instantaneous efficiency of solar collector. Result shows that the flow rate of the circulating fluid highly influence the thermal efficiency of the solar collector. Optimum flow rate of 2.5L/min leads to maximum collector efficiency.**

Keywords-flat plate solar collector; low rate; thermal efficiency; ASHRAE standard 93-2003

I. INTRODUCTION

Solar energy is becoming an alternative for the limited fossil fuel resources. The recent increased interest in renewable energy has created a need for research in the area of solar technology. One of the simplest and most direct applications of this energy is the conversion of solar radiation into heat. Solar radiation can be widely used for water heating in hot water systems, as well as a supporting energy source for central heating installations. The energy of the solar radiation is in this case converted to heat with the use of solar panels. Using the sun's energy to heat water is not a new idea. More than one hundred years ago, black painted water tanks were used as simple solar water heaters in a number of countries. However, the solar water heating technology has greatly improved during the past century. Today there are more than 30 million square meters of solar collectors installed around the globe. Most solar water heating systems for buildings have two main parts: a solar collector and a storage tank. A flat plate solar collector [1-3] is the most popular solar energy based device which absorbs the heat of sun rays through its body (usually with black color for maximum absorption) and then transfers the absorbed heat to the working fluid for raising its temperature. The efficiency of flat plate solar collectors as a group of water heaters depends on many factors such as climate conditions (especially solar radiation intensity), materials and design of collector as well as the working fluid type and mass flux rate. Authors in [4] reviewed applications of nanofluid in evacuated tube and flat plate solar collectors from efficiency, economic and environmental considerations and concluded that nanofluids offer a better alternative to conventional fluid. Authors in [5] presented theoretically and experimentally the enhancement of heat transfer to the working fluid with a metal porous medium placed inside pipes. The metallic mesh inserted in the collector, provided a higher water temperature compared to the conventional collector and it is the presence of the aluminum mesh inside the channels that distributes heat more evenly. Author in [6] investigated experimentally the design of flat-plate solar collector system. In [7], authors presented an experimental analysis and a thermal and hydrodynamic modelling of a newly designed flat-plate solar collector characterized by its corrugated channel and by the high surface area directly in contact with the heat transport fluid. Authors in [8] studied the effect of nanofluids on the performance of solar collector and solar water heater from efficiency, economy and environmental points of view. Authors in [2] reviewed advancements made in the field of solar thermal technology with emphasis on techniques employed for performance augmentation. For a sunny country like Saudi Arabia it is very important to use the sun as main source of energy in many ways such as heating applications and generating electricity. In our study we will evaluate the thermal efficiency of a flat plate solar collector during winter season at four flow rates. The collector is working in closed loop where the water is stored in a tank and it is controlled to evaluate the stored heat.

II. EXPERIMENTATION AND METHODOLOGICAL APPROACH

A. Experiments on Solar Collector

The experiments on the flat plate solar collector were carried out in Hail city (latitude 27°52'N longitude 41°69'E).

The collector type is TE39 collector provided by TecQuipment. Figures 1 and 2 illustrate a schematic of the experimental set-up, and a photograph of the flat plate solar collector, respectively. The collector specifications are given in Table I. The main part of the TE39 flat plate solar energy collector is a modern solar collector panel, it is two sheets of preformed stainless steel welded together to form integral parallel water channels. An airtight box with a clear acrylic cover encloses the surface of the panel. A thick layer of insulating material on the back of the panel reduces heat loss to the rear.

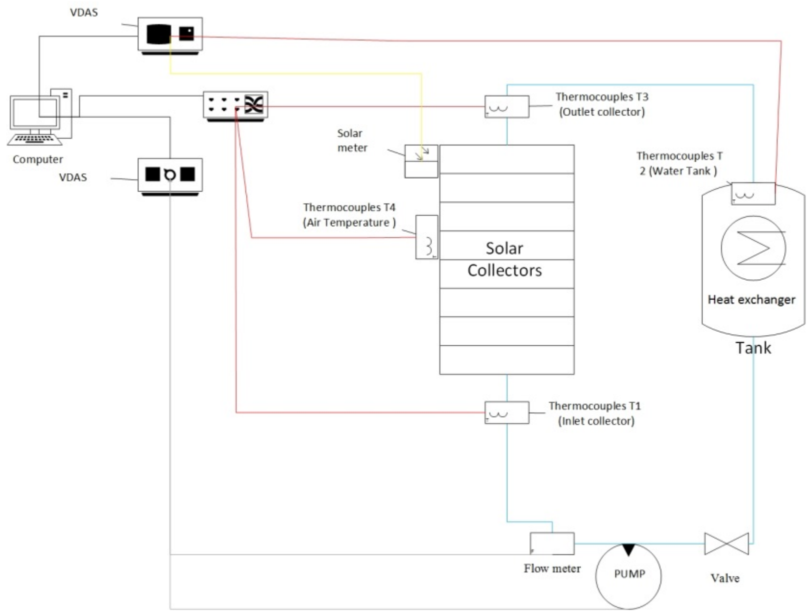

Fig. 1. Schematic of the experimental set-up.

TABLE I. EXPERIMENTAL SETUP DESCRIPTION

Item	Details
Type	Single pass flat plate solar energy heat absorber
Overall Size	Maximum 1500mm Height x 2400mm Length x 110mm Depth
Collector	
Cover	Acrylic -1
Overall Dimensions	$1.8m^2$
Effective Surface Area	$1.6m^2$
Maximum Water Inlet Pressure	3bar
Pump Type	Mains powered, centrifugal Energy Input to Water 55W

In order to determine the performance of the prototype under various conditions, the apparatus was equipped with the necessary instrumentation. A schematic diagram of the apparatus is shown in Figure 1, demonstrating the positioning of the instrumentation within the prototype. An electrical pump circulates the working fluid. A heat exchanger transfers heat energy from the solar collector to the tank which has a capacity of 30L. A flow sensor measures the fluid flow rate. A simple valve was installed to control the flow rate. A series of thermocouples type K were fitted on the collector (with accuracy of ±0.1°C), measuring the temperature of the working fluid in the collector at the inlet T_i and outlet T_o, the ambient temperature T_a and the stored water temperature T_h. The solar radiation G was measured by a solar meter with accuracy of ±2%. The solar collector was set to angle of inclination equal to that of Hail.

Fig. 2. Picture of the set-up.

In the current study, the instruction given in ASHRAE standard 93-2003 [9] has been implemented to evaluate the thermal performance of the solar collector. The purpose of this standard is to test the thermal performance of solar collectors that use single-phase fluids. The experiments were performed from 9AM to 3PM (local time) on several days in January 2018. The best data satisfying conditions of ASHRAE standard have been taken. Experimental results are expressed in the form of graphs that indicate the collector efficiency against a reduced temperature parameter $[(T_i–T_a)/G]$. The efficiency of solar collector was examined at various flow rates of 1.5, 2, 2.5

and 3L/min. All the tested runs were collected using acquisition card system (Figure 3). Moreover, we designed the coil tank to store the hot water and to evaluate the solar collector working in a closed loop (Figure 4). The coil heat exchanger is made from copper.

Fig. 3. Data acquisition of the experimental setup.

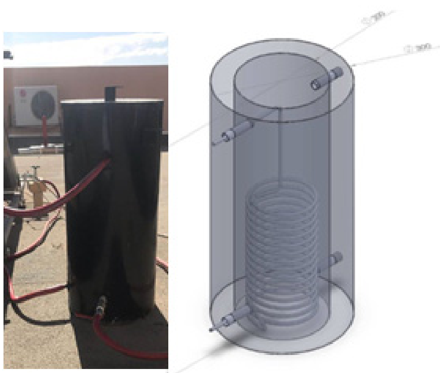

Fig. 4. The designed coil tank.

B. Testing Method

Based on the ASHRAE standard 93-2003 [9], the thermal performance of the solar collector is evaluated. If G is the intensity of solar radiation, in W/m^2, incident on the aperture plane of the solar collector having a collector surface area of Am^2, then the amount of solar radiation received by the collector is:

$$Q_i = G \cdot A \quad (1)$$

However, a part of this radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation. Therefore the conversion factor indicates the percentage of the solar rays penetrating the transparent cover of the collector (transmission) and the percentage being absorbed. Basically, it is the product of the rate of transmission τ of the cover and the absorption rate α of the absorber. Thus,

$$Q_i = G\tau\alpha \cdot A \quad (2)$$

As the collector absorbs heat its temperature is getting higher than that of the surrounding and heat is lost to the atmosphere by convection and radiation. The rate of heat loss (Qo) depends on the collector overall heat transfer coefficient (UL) and the collector temperature.

$$Q_0 = U_L A(T_c - T_a) \quad (3)$$

Thus, the rate of useful energy extracted by the collector (Qu), expressed as a rate of extraction under steady state conditions, is proportional to the rate of useful energy absorbed by the collector, minus the amount lost by the collector to its surroundings. This is expressed as follows:

$$Q_u = Q_i - Q_0 = G\tau\alpha A - U_L(T_c - T_a) \quad (4)$$

It is also known that the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through it, that is:

$$Q_u = m\, C_p(T_o - T_i) \quad (5)$$

Equation (4) proves to be somewhat inconvenient because of the difficulty in defining the collector average temperature. It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is known as "the collector heat removal factor (FR)" and is expressed as:

$$F_R = \frac{m\, C_p(T_o - T_i)}{G\tau\alpha A - U_L A(T_i - T_a)} \quad (6)$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. The actual useful energy gain Q_u, is found by multiplying the collector heat removal factor F_R by the maximum possible useful energy gain. This allows the rewriting of (4):

$$Q_u = F_R A[G\tau\alpha - U_L(T_i - T_a)] \quad (7)$$

Equation (7) is a widely used relationship for measuring collector energy gain and is generally known as the "Hottel-Whillier-Bliss equation". The collector efficiency η is defined as the ratio of the useful energy gain Q_u to the incident solar energy over a particular time period:

The thermal performance of the solar collector is checked by determining the values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature. The instantaneous efficiency is defined as the ratio of useful energy gain to the solar energy received by absorber plate of the collector. The instantaneous thermal efficiency of the collector is:

$$\eta = \frac{Q_u}{GA} \quad (8)$$

$$\eta = \frac{F_R A[G\tau\alpha - U_L(T_i - T_a)]}{GA} \quad (9)$$

$$\eta = F_R\tau\alpha - F_R U_L \frac{(T_i - T_a)}{G} \quad (10)$$

If it is assumed that FR, τ, α, U_L are constants for a given collector and flow rate, then the efficiency is a linear function of the three parameters defining the operating condition: Solar irradiance (G), fluid inlet temperature (T_i) and ambient air temperature (T_a). Thus, the performance of a flat-plate collector can be approximated by measuring these three parameters in experiments.

III. RESULTS AND DISCUSSION

Experiments were carried out at the roof top of mechanical engineering department of the college of engineering of Hail. From Figure 5 it is not so easy to judge which flow rate ensuring the highest outlet temperature, because outlet temperature is highly influenced by the outdoor conditions (solar radiation, air temperature, wind speed). Moreover, a solar collector working in a closed loop it is dependent to the initial hot water tank temperature. As shown in Figure 6 the initial outlet temperatures (at 9:00AM) are different. For example for the case of 1.5L/min flow rate the outlet temperature starts from 34°C. However, it starts from 18°C for the case of 2.5L/min. This behavior is justified by the variability of weather conditions which leads to different initial hot water tank temperatures. The temperature of the hot water in the thermal storage tank depends on the effectiveness of the heat exchanger and the temperature difference between the outlet and inlet fluid. The flow rate equals to 2.5L/min produced the highest storage tank temperature of 82.5°C as shown in Figure 6. Figure 7 shows the variation of collector efficiency versus the reduced temperature parameter for water and different mass flux rates. The experimental data are fitted with linear equations to obtain the characteristic parameters of the collector and having better judgment about the effect of flow rate on the thermal efficiency. As it can be seen, at a given value of reduced temperature parameter, with increasing flow rate, the efficiency increases till reaching an optimum value corresponding to the Flow rate 2.5L/min. Based on (5) and (6), the useful heat energy rate increases with an increase in mass flux, on the other hand, useful heat energy rate is directly proportional to efficiency. Therefore, the efficiency increases with increasing mass flux. With increasing Vol. flow rate from 1.5L/min to 2.5L/min the maximum enhancement in efficiency was found to be about 15%.

Table II provides more details regarding Figure 5 and the solar collector performance when the working fluid is water. This table shows the values of the removed energy parameter F_RU_L and the absorbed energy parameter $F_R(\tau\alpha)$ for the four flow rates (1.5L/min, 2L/min, 2.5L/min, 3L/min). It is seen that both removed energy and absorbed energy parameters have an optimum value corresponding to Vol. flow rate of 2.5L/min. The collector efficiency η is plotted against $(T_i–T_a)/G$. The slope of this line ($-F_R U_L$) represents the rate of heat loss from the collector. For example, collectors with cover sheets will have less of a slope than those without cover sheets.

TABLE II. VALUES OF F_RU_L AND $F_R(\tau\alpha)$ FOR DIFFERENT FLOW RATES

Vol. Flow rate (L/min)	$F_R(\tau\alpha)$	$-F_RU_L$
1.5	0.779228	-7.7476
2	0.666701	-3.2787
2.5	0.952	-13.6875
3	0.921	-12.2477

There are two interesting operating points on Figure 7. The first is the maximum collection efficiency, called the optical efficiency. This occurs when the fluid inlet temperature equals ambient temperature (T_i=T_a). For this condition, the ΔT/G value is zero and the intercept is FR(τ α). The other point of interest is the intercept with the ΔT/G axis. This point of operation can be reached when useful energy is no longer removed from the collector, a condition that can happen if fluid flow through the collector stops (power failure). In this case, the optical energy coming in must be equal to the heat loss, requiring that the temperature of the absorber increase until this balance occurs. This maximum temperature difference or "stagnation temperature" is defined by this point. For well-insulated collectors the stagnation temperature can reach very high levels causing fluid boiling.

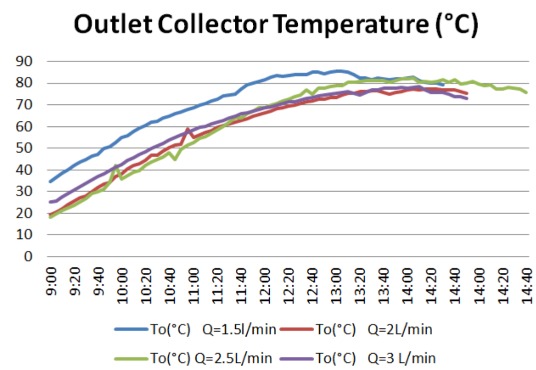

Fig. 5. Outlet Temperature at different flow rates.

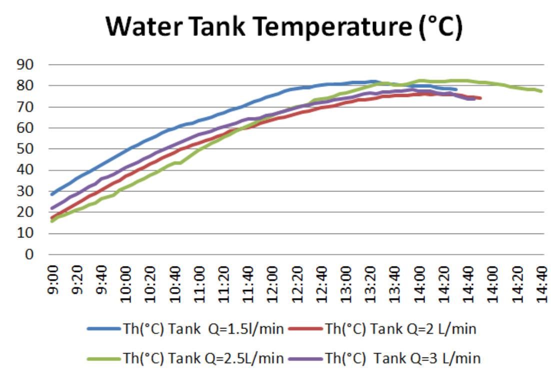

Fig. 6. Hot stored water at different flow rates.

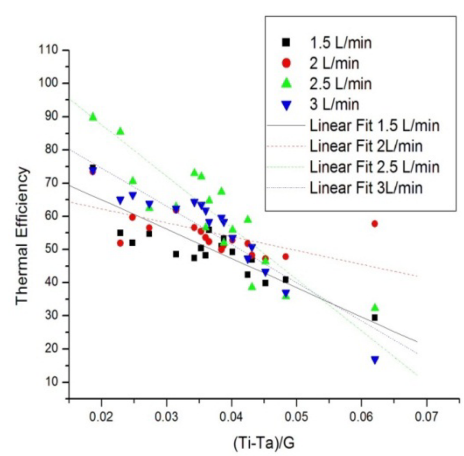

Fig. 7. Solar collector efficiency curve at four flow rates for water.

From the optimum flow rate (2.5L/min) corresponding to the highest efficiency we presented in Figure 8 the solar radiation, ambient temperature, hot water temperature, the inlet and the outlet temperatures. From this figure we can notice that the stagnation of outlet and hot water temperatures is reached at 1:30 PM.

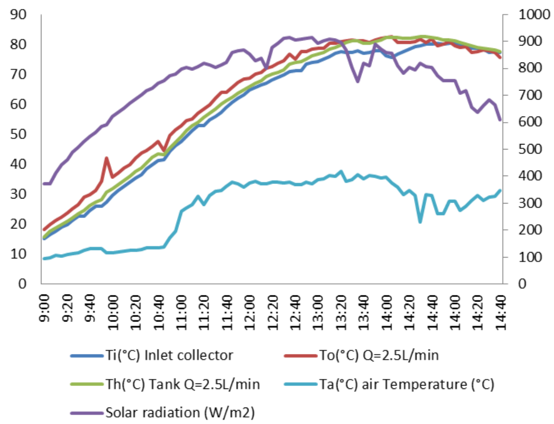

Fig. 8. Hot Solar intensity and various temperatures of solar collector at flow rate 2.5L/min.

IV. CONCLUSION

ASHRAE standard 93-2003 was detailed, then followed for calculation of the efficiency of a flat plate solar collector. A more precise and detailed analysis should include the fact, that the overall heat loss coefficient (U_L) and other factors as the heat removal factor (F_R) are not constant values and they are tightly dependent on fluid flow rate. The present experiment focused on a comparative analysis of a four different flow rates (1.5 L/min, 2L/min, 2.5L/min, 3L/min) and their effect on the performance of flat plate solar collector. The experiment findings established that maximum efficiency, when reduced temperature parameter $[(T_i–T_a)/G]$ equals to zero, was 95% for flow rate 2.5L/min.

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