AN EXPERIMENTAL STUDY OF THE THERMAL PERFORMANCE OF THE SQUARE AND RHOMBIC SOLAR COLLECTORS

by

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Solar collectors are the key part of solar water heating systems. The most widely produced solar collectors are flat plate solar collectors. In the present study, two types of flat plate collectors, namely square and rhombic collectors are experimentally tested and compared and the thermal performance of both collectors is investigated. The results show both collectors have the same performance around noon (≈61%), but the rhombic collector has better performance in the morning and afternoon. The values for rhombic and square collectors are approximately 56.2% and 53.5% in the morning and 56.1% and 54% in the afternoon, respectively. The effect of flow rate is also studied. The thermal efficiency of rhombic and square flat plate collectors increases in proportion to the flow rate. The results indicated the rhombic collector had better performance in comparison with the square collector with respect to the mass-flow rate.

Key words: *flat plate solar collector, efficiency, rhombic collector, square collector, flow rate effect*

Introduction

The most important benefit of renewable energy is the reduction of environment pollution. Solar energy as one of the most significant kinds of renewable energy sources has always been a viable option for the energy problems faced by the world. This form of energy is the radiation which results from nuclear fusion reaction in the sun [1, 2]. Solar radiation can be converted to other form of energy such as heat, electricity and etc. Many different kinds of equipment are available for this conversion. Among the solar thermal technologies, the flat plate solar collector has been widely used as air heater or water heater [3]. A simple flat plate collector consists of an absorber plate in an insulated box covered by transparent sheets. The most important part of a collector is the absorber, which usually consist of a metal plate with several pipes to convert energy from solar radiation to working fluid.

The color, shape, kind, and quality of absorber play important roles in the performance of flat plate solar collectors [4]. Thermal quality of solar collectors such as a flat plate solar collector can be measured by the common quantity called efficiency. The efficiency of a solar collector depends on the ratio of useful energy received from the heated working fluid to solar irradiance. There are so many investigations about the methods of increasing the efficien-

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cy of solar collectors all over the world [5-7]. The absorbent surface of the solar collector is the more effective on the efficiency value [8]. The color, the configuration factor and the heat transfer between the absorbent and the working fluid are also important [9]. The amount of heat transfer depends on the kind of working fluid, the kind of contact between the absorbent and the working fluid and the geometry of absorbent [10]. Many of the studies carried out on heat transfer between absorbent and working fluid and the others focus on the geometry of the absorbent and the collector. These studies propose the use of gas-particle suspension, the use of fluid-film and introduce metal-foam to increase the amount of heat transfer [11-13]. Other studies deal with the geometry of solar collectors in order to increase incident radiation. To maximize the incident global radiation for a surface, solar tracking mechanisms can be used. This can increase the yearly solar radiation gain up to 1.45 times more compared with an optimal tilted solar collector [14]. Such tracking mechanisms are complicated and costly to operate and their use in solar water heating is not economically justified. Eliminating the tracking mechanism and keeping its benefits can be made possible by using suitable and symmetric surfaces such as a spherical collector [15]. A number of long term experimental researches have been conducted to evaluate the performance of flat plate solar collectors with solar tracking systems in a low latitude region [16, 17].

In the present work, two kinds of flat plate solar collectors with square rectangle and rhombic geometry are experimentally investigated. The reasons for this work are manifold. One main reason is that due attention has not been given to the study of flat plate solar collectors in both rhombic and square geometries though it is of immense importance in installation and efficiency of collectors. Accordingly, thermal efficiencies of both collectors *vs*. Sun radiation, time and flow rate will be studied.

Materials and methods

Materials and measurement

Both square and rhombic flat plate collector are made by authors in Shahid Chamran University of Ahvaz. The specifications of these collectors are shown in tab. 1. According to tab. 1. both collectors have same size and same specifications.

Table 1. Specifications of square and rhombic collector

Specifications	Rhombic collector	Square collector	Unit
Dimensions of frame	151×151(length)×15	151×151(length)×15	[cm]
Absorber area	1.0	1.0	[m$^{2]}$
Cover (flat glass)	$t = 6$	$t = 6$	[mm]
Absorber thickness	1.5	1.5	[mm]
Frame (aluminum)	–	–	–
Piping	$D = 6.2$, $t = 1.1$	$D = 6.2$, $t = 1.1$	[mm]
Weight	31.3	31.3	[kg]
Insulation (Polystyrene and wood)	$t = 20$	$t = 20$	[mm]
Solar Absorption	89.1%	89.1%	–

To measure the thermal efficiency of the solar collectors, two K type thermocouples are placed at the inlet and outlet of the collector. Thermocouples are connected to a two-channel data logger (ktt 310-kimo data logger). A diaphragm pump is used for circulating the fluid (water) inside the system. The accuracy of thermometer data logger is 0.1 ^{o}C and accuracy of flow meter is 0.05 kg/min, respectively. Tracking of total solar radiation was implemented by a TES 132 solar meter type with 1 W/m^2 accuracy.

Experimental procedure

The solar collectors were experimentally investigated at Shahid Chamran University of Ahvaz, Iran (latitude is 31^{o} 19' 16" N and longitude is 48^{o} 40' 16" E). The relative collector positions are shown in figs. 1 and 2. The schematic of experimental set-up is shown in fig. 3 and some of the measurement dives that were used in this study, is shown in fig. 4.

Figure 1. The experiment set-up for square collector

Figure 2. The experiment set-up for rhombic collector

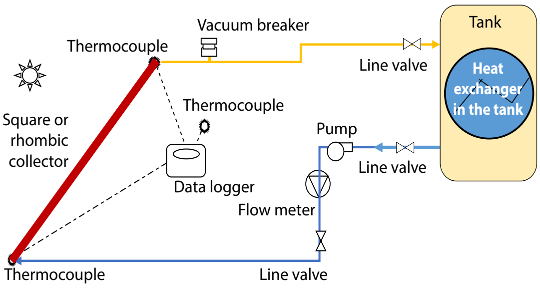

Figure 3. The schematic of experiment

Figure 4. The actual photo of the solar meter and data logger that were used in this study

The experiments consist of two positions. At the first, they are tested in horizontal position without any tilted angle and in the second position both collectors are tested with 45^{o} tilt angle. The solar system in both collectors is a forced convection system with an electrical pump that is shown in fig. 5. The nominal max pressure of this pump is 12.4 bar its flow rate is between 0-4 liter per minute.

Figure 5. The electrical pump

Calculation of the collector efficiency

According to the ASHRAE standard, inlet temperature of the collector should perform in various values [18]. In steady-state conditions, the data for each test period should be averaged and used in calculation and other data should be rejected. To evaluate the efficiency of the collector, the inlet, outlet, and ambient temperatures and mass-flow rate should be measured. First, the useful energy can be calculated by using eqs. (1) and (2). Useful energy expresses how much energy is received by the working fluid as its temperature increases [2, 3].

$$Q_u = \dot{m} C_p \left(T_\mathrm{o} - T_\mathrm{i}\right) \tag{1}$$

$$Q_u = A_c F_R \left[G_T \left(\tau\alpha\right) - U_L \left(T_\mathrm{i} - T_\mathrm{a}\right)\right] \tag{2}$$

where C_p is the heat capacity of water, $\dot{m}$ – the mass-flow rate of the working fluid, T_i and T_o are the inlet and outlet fluid temperature, respectively, G_T – the incident solar irradiation on the front glazing per unit collector surface area, and A_c – the surface area of the collector. The instantaneous collector efficiency is the ratio of useful energy to the total radiation incidents on the collector surface that is achieved by eqs. (3) or (4) [2, 3].

$$\eta_i = \frac{Q_u}{A_c G_T} = \frac{\dot{m} C_p \left(T_\mathrm{o} - T_\mathrm{i}\right)}{G_T} \tag{3}$$

$$\eta_i = F_R \left(\tau\alpha\right) - F_R U_L \left(\frac{T_\mathrm{i} - T_\mathrm{a}}{G_T}\right) \tag{4}$$

When the thermal efficiency of flat-plate solar collector is tested, $F_R(\tau\alpha)$ and $F_R U_L$ can be calculated from the results data [2, 3, 19]. Both $F_R(\tau\alpha)$ and $F_R U_L$ will be constant if the efficiency tests are performed near the normal incidence conditions. According to eq. (4), if the data of efficiency tests are plotted, it will be a straight line with vertical axis as efficiency against $(T_\mathrm{i} - T_\mathrm{a})/G_T$ as the horizontal axis. The intersection point of this line with the vertical axis shows the maximum of collector efficiency, when the inlet temperature of the collector is near to the ambient temperature. Also, the intersection of this line with horizontal axis is called, stagnation point. In this point the collector efficiency is zero and usually occurs when the working fluid dose not flow in the collector. Also, the storage tank reaches the maximum temperature or the collector loop pump is switched of [3].

Experimental uncertainty analysis

According to ASME guidelines, there exist no absolute measurements and errors in every experimental measurement [18]. Some of the usual sources of error are: calibration errors, data recording errors, and unsuitable instruments. The uncertainty of the experimental results was calculated via ASME guidelines on reporting uncertainties in experimental measurements based on the deviation in the experimental parameters [18, 20]. Errors in the flow rate measurement, temperature measurement, and solar radiation measurement are the main components of uncertainty in the collector efficiency. The uncertainty results of the measurements including all the sources of errors are revealed in tab. 2.

Table 2. The uncertainty results of the study measurements

Parameter	Uncertainty, [%]
Volumetric flow rate	±1.6
Solar radiation	±6.5
Difference between inlet-outlet temperatures	±1.2

The combined uncertainty to calculate the collector efficiency, S_η, was determined by the root sum square (RSS) method, based on eq. (3). This analysis is as eq. (5). The errors in C_p and A_c are assumed negligible.

$$(S_\eta)^2 = \left\{ \left(\frac{\Delta \dot{m}}{\dot{m}} \right)^2 + \left[\frac{\Delta (T_\mathrm{o} - T_\mathrm{i})}{T_\mathrm{o} - T_\mathrm{i}} \right]^2 + \left(\frac{\Delta G}{G} \right)^2 \right\} \tag{5}$$

In the calculation of the collector efficiency, the maximum uncertainty was approximately 6.8% at several tests.

Results and discussions

Collector performance

The experiment tests were done at 8:00 a. m. to 5:00 p. m. on spring 2015. Water was used as working fluid and its mass flow rate was 1.4 kg per minute. The experimental results are shown in the form of graphs to describe the collector efficiency. All the presented data were obtained from many experimental tests measured into several test periods in quasi-state condition. The tests conditions are according to the ASHRAE standard 93-86 because the maximum variations in inlet, outlet, and ambient temperatures in each period of test was about 0.9 °C, 0.8 °C, and 0.9 °C, respectively, and the maximum variation in Sun radiation was about 33 W/m^2. At first, square and rhombic collectors were tested in the horizontal position. The results of the tests show both collectors have the same efficiency because in this position, their area and shape factor are equal. Also the incident radiation in the both square and rhombic collectors in this position is equal. When the square and rhombic collectors are tested in the vertical or angled positions, the shape factor of both collectors will be changed. In the second position, both collectors were tested in 45 tilt angle in order to investigate the effect of geometries on the collector efficiency. The results are shown in the fig. 6.

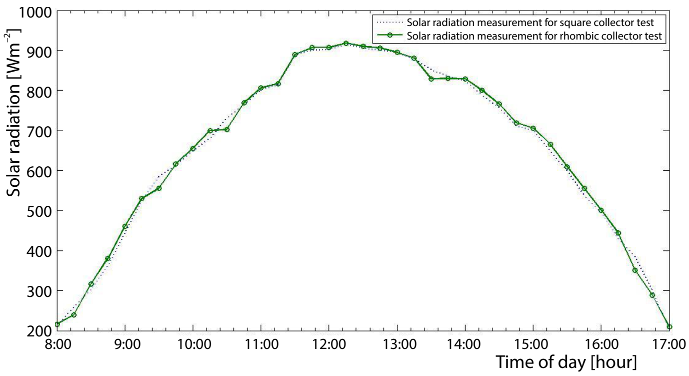

Figure 6. Sun radiation on the day for square collector and rhombic collector test (selected data is from March 25, 2015)

This figure illustrates the Sun radiation in the typical test and fig. 7 shows the temperature variations in that test. In figs. 8 and 9 the efficiency comparison of square collector and rhombic collector is shown. This chart describes the efficiency values for both collectors. According to this chart, there is a difference between the efficiency of rhombic and square collectors. This chart shows the rhombic collector has better efficiency, specially, in the morning and afternoon. This phenomenon occurs because the rhombic geometry is better than the square geometry in

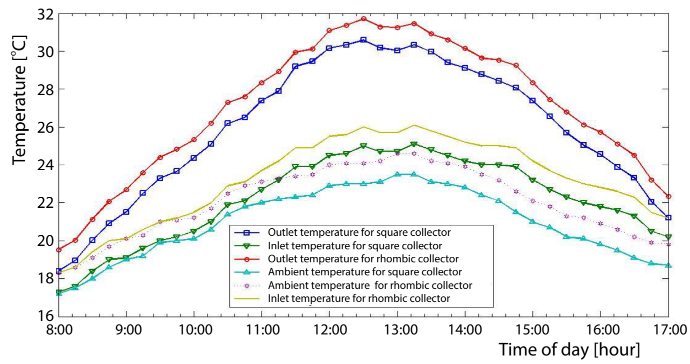

Figure 7. Temperature variations in square collector and rhombic collector tests (*for colour image see journal web site*)

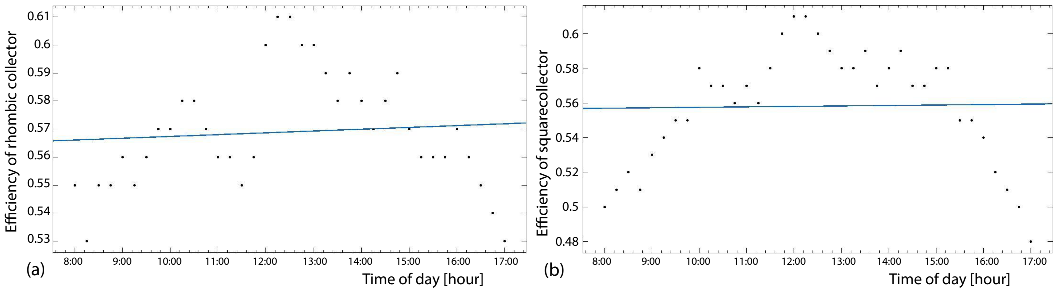

Figure 8. Efficiency comparison of collectors based on time; (a) rhombic collector, (b) square collector

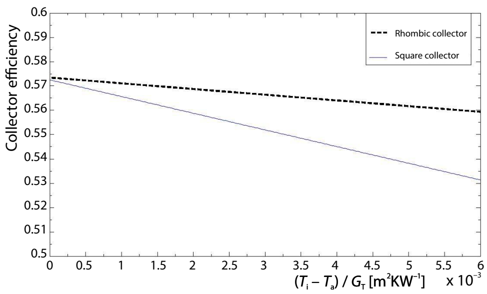

Figure 9. Efficiency comparison of rhombic and square collectors based on reduced temperature

collecting diffuse radiation in the morning and evening. The values for rhombic and square collectors are approximately 56.2% and 53.5% in the morning and 56.1% and 54% in the afternoon, respectively. These results are similar to Khatib *et al*. [21] study.

According to the investigations conducted and the fact that Reynols numbers being more than 2300 in all tests, heat transfer model will be turbulent in very tube. Moreover, the flow regime, the length of tubes and heat transfer model are same in both square and rhombic collectors. The type of fluid-flow within the solar system is forced. In this flow, buoyancy force impact is negligible. Also because of the aforementioned reason there is no matter difference in vertical, horizontal and tilt angled position.

The effect of mass-flow rate

In this section, the influence of mass-flow rate of the working fluid on the square and rhombic solar collectors is investigated. Both collectors are tested for different mass-flow rates to evaluate their performances. To control the flow rate of the working fluid (water), a regulating valve was used. The range of mass-flow rate was 0.35 to 2.8 L/min. To find the effect of flow rates on the efficiencies of both collectors, several tests were performed and the best experimental data was chosen. The variation of efficiency *vs*. mass-flow rate is presented in fig. 10. According to this figure, the efficiency of both collectors increases in proportion to the mass-flow rates. This trend is similar to previous works [19, 22, 23] where they had investigated the effect of mass flow-rate on the flat plate collector.

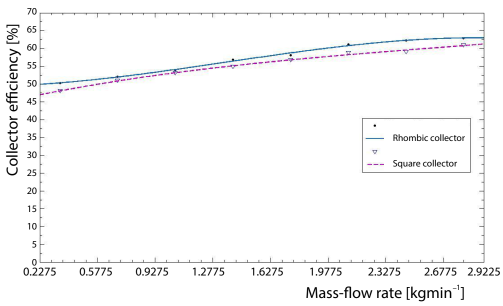

Figure 10. Efficiency comparison of both collectors *vs.* mass-flow rates

Figure 10 shows in the whole range of mass-flow rate, the efficiency of rhombic collector is better than that of the square collector and trends of efficiency of both collectors *vs*. mass-flow rates is approximately polynomial. Also this figure shows the thermal efficiency of rhombic and square flat plate collectors in 2.5 kg/min mass-flow rate are 62.1% and 59%, respectively.

Conclusion

In this paper the efficiency and temperature variations of two solar collectors, namely, the square and rhombic solar collectors are experimentally investigated. The results show that by using the same specifications for square and rhombic collectors, both collectors have the same efficiency around noon, but due to the fact that the diffused radiation is more important than beam radiation in the morning and afternoon, the rhombic collector has better efficiency at that time. The values for rhombic and square are approximately 56.2% and 53.5% in the morning and 56.1% and 54% in the afternoon, respectively. The rhombic collector has more altitude than he square collector, so it will be able to collect more diffused sunshine. According to the experimental data, the efficiency of both collectors increases by increasing the mass-flow rate. Thermal efficiency of rhombic and square flat plate collectors in 2.5 kg/min mass-flow rate are 62.1% and 59%, respectively.

Nomenclature

A_c – surface area of solar collector, [m^2]
C_p – heat capacity, [Jkg^{-1}K^{-1}]
F_R – heat removal factor
G_T – global solar radiation, [Wm^{-2}]
$\dot{m}$ – mass-flow rate, [Ls^{-1}]
Q_u – rate of useful energy gained, [W]
S_η – uncertainty of efficiency, [%]
T_a – ambient temperature, [K]
T_i – inlet fluid temperature of solar collector, [K]
T_o – outlet fluid temperature of solar collector, [K]
U_L – overall loss coefficient of solar collector, [Wm^{-2}K^{-1}]

Greek symbols

η_i – instantaneous collector efficiency
$\tau\alpha$ – absorbance-transmittance product

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