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RESEARCH ARTICLE

Renewable Energy

A novel approach for energy and exergy analysis of a flat plate solar collector with energy storage

M Hanif, MK Khattak, I Ul Haq, R Uddin and K Ullah

Department of Agricultural Mechanization and Renewable Eneryy Technologies,Facalty of Crop Prodction Sciences, The University of Agriculture Peshawar, Peshawar, Pakistan - 25130.

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Abstract: Experiments were conducted to evaluate the performance of a flat plate solar collector in terms of its energy, exergy, and efficiency. The data were analyzed using three factors in a Completely Randomized Design. The first factor was tilt angle with three levels, the second was air mass flow rates with four levels, and the third was heat storage fluid with four levels, making a 4 x 3 x 4 factorial experiment. The least significant difference between means was calculated with Alfa (α) < 0.01. The results showed that the maximum energy of 1509.74 kJ hr^{-1} was gained by the flat plate solar collector when a polyethylene glycol solution was used in head raised pipes at 11.76 kg min^{-1} air flow rates with a 30^o collector tilt. The maximum exergy of 46.0 % was gained by the flat plate solar collector when air was used in head raised pipes at 4.67 kg min^{-1} air flow rates, with 30^o collector tilt angle, while the minimum exergy gain of 32.67 % was recorded for a polyethylene glycol solution in the solar collector at 1.78 kg min^{-1} air flow rates with collector tilting at 30^o. The maximum efficiency of 39.71 % was gained by the flat plate solar collector when a polyethylene glycol solution was used in head raised pipes at 9.69 kg min^{-1} air flow rates with 40^o collector tilt angle. The storage medium showed that the maximum energy of 40,207 kJ day^{-1}was stored in the energy storage unit per day, followed by 33,291 kJ day^{-1} stored in salt solution while minimum energy of 29,640 kJ day^{-1} was stored with water.

Keywords: Efficiency, energy storage, exergy, flat plate, solar collector, solar energy

INTRODUCTION

Energy is the engine of economic growth and social development. The increasing demand for energy and depletion of fossil fuel reservoirs is a serious global issue. An increase in the demand for energy production and the adverse impact of fossil fuels on the global environment has led to a significantly enhanced interest in acquiring environment-friendly renewable energy resources. Renewable energy sources have the potential to fulfill energy demand and alleviate environment destruction by greenhouse gases emitted *via* the use of fossil fuels. It is therefore widely realized that renewable energy can play a vital role in any field where energy is a primary source. Renewable energy resources have the potential to replace the non-renewable energy resources if properly planned and installed according to the demand, with all the engineering aspects needed for their maximum output (Bellos *et al.*, 2016).

Renewable energy has many sources; among them, solar energy is a clean, abundant, and environment-friendly source which has received considerable attention for generating heat and electricity. It is playing a vital role in maintaining the environment of this green planet. This energy from the sun reaches the earth in the form of solar irradiance. Solar irradiance is the energy given by sunlight per unit area in unit time. It can be converted into heat and electricity using different solar conversion technologies, namely flat plate solar collectors, concentrating solar collectors and photovoltaic technologies. Flat plate and parabolic trough solar collectors are the main types of solar thermal heating systems. The flat plate solar collectors are used mainly for low thermal systems for agricultural and domestic

* Corresponding author (hanif_mechanization@aup.edu.pk; https://orcid.org/0000-0003-1698-8802)

heating requirements. Alternately the parabolic trough concentrating solar collector technology is used for high thermal systems like steam and power generation (Soteris *et al.*, 2016).

The efficiency of a solar thermal system is critical to its maximum performance. However, the efficiency equation alone does not determine the internal losses from the solar collectors. For this purpose, an analysis based on the second law of thermodynamics is best to determine the exergy analysis or potential energy of the solar collector system. Exergy analysis is both vital and the most important parameter for optimization of design and the future operation of solar thermal collectors. Solar thermal collectors must have been examined in terms of their energy and exergy, efficiency, and entropy generation for peak performance (Boukelia *et al.*, 2015). Fahad *et al.* (2013) discussed the optimal and critical operations of different solar collectors by means of energy and exergy analysis. They concluded that an optimal operational model at any state is not useful for performance analysis because it is not a complete setup for generalizing and optimizing the solar collector performance. Therefore, an advanced model incorporating solutions to common errors for energy and exergy analysis is required for computing efficiencies of solar collectors.

Farhat *et al.* (2009) and Frances *et al.* (2012) studied the performance of a thermal solar collector. They stated that the performance must be tested in dynamic models, and energy and exergy analysis must be carried out in transient states. Many authors reported their work on optimizing the performance of solar collectors and they have concluded that solar collectors showed multiple difficulties under steady state conditions. Thus, it is recommended to develop and test the solar thermal collectors in transient states for achieving better results of energy and exergy analysis.

Air turbidity is playing a significant role in energy and exergy analysis of solar collectors. To carry out energy and exergy analysis of a solar collector, it is necessary to keep in mind that the sky must be clear, the flow rate must be constant, the assumption must be made that the properties of the material of construction of the solar collector are constant, the glazing must have more than 85% transmittance, the fluid velocity must be uniform, the losses by reflection are assumed to be negligible, and the air gap between the absorber and glazing must be transparent (Jafarkazmi & Ahmadifard, 2013). The aim of the study was to evaluate the energy, exergy, and efficiency of a flat plate solar collector as affected by both the sole and the combined or interaction effect of air mass flow rate, tilt angle, and heat storing fluid in the flat plate solar collector, and to study the role of the energy storage unit in enhancing the solar collector performance.

MATERIALS AND METHODS

Site selection

The collector was installed on the roof of the Department of Agricultural Mechanization, The University of Agriculture Peshawar, Khyber Pakhtunkhwa, Pakistan. The latitude, longitude and elevation of the site are 34.02^o, 71.48^o and 448.36 m, respectively. The site is ideal for this purpose as it receives maximum solar irradiance from dawn to dusk without the interference of any shadow of a structure (Francesco *et al.*, 2016).

The thermal solar collector

The flat plate solar collector that was used in the experiment is shown in Figure 1. The solar collector was developed in the Department of Agricultural Mechanization, The University of Agriculture Peshawar. The design and other parameters of construction are given in Table 1.

Figure 1: Design specifications of the flat plate solar collector

Recording solar irradiance

The data of daily solar irradiance were recorded with the help of a digital Pyranometer (Solar Power Meter, TES-1333, Taiwan)

Energy and exergy analysis

When the solar collector is in equilibrium with the surroundings, then the general form of the energy balance equation (1) given by Govindaraj *et al.* (2012), can be applied:

Table 1: Design specifications of the flat plate solar collector

Parameters/Conditions	Value
Collector's length, width and depth	3.40, 2.46 & 0.66 m respectively
Area	8.365 m^2
Volume of the solar collector	5.520 m^3
Absorber	V-corrugated, black painted galvanized steel with header raiser pipes
Absorber area	8.360 m^2
Absorbance and transmittance of absorber	0.92 and 0.88
Glazing (single glass)	0.008 m (8 mm)
Agent fluids	Air, Water, salt solution and polyethylene glycol solution
Air velocity range	0.1 – 3.31 m s^{-1}
Collector tilt angles	30^o, 35^o and 40^o
Ambient temperature range	275 – 315 K
Apparent sun temperature	5777 K (Yadav *et al*., 2014)
Absorber thickness	0.0024 m (2.4 mm)
Optical efficiency	0.88
Transmittance of glazing	0.89
Thickness of insulation (Wood of deodar + polystyrene)	0.15 m
Thermal conductivity of absorber	380 W m^{-1}. $^o C^{-1}$
Solar irradiance range	0 – 950 W m^{-2}
Tubes/ pipes diameter (steel)	0.025 m
Air mass flow rates	3.56 – 12.46 kg min^{-1}
Volume of storage tank	0.12 m^3
Mass of water in storage tank	120 kg
Volume of the head raised pipes	0.086 m^3
Mass of water in pipes	86 kg
Total volume of water in solar collector	206 kg
Parts of the the solar collector/materials Used for construction	Cost
Insulation box	$ 500
Absorber	$ 120
Glazing	$ 110
Water pipes, fluids and storage tank	$ 130
Total cost	$ 860

$$E_{in} - E_s - E_{L1} - E_{L2} - E_{ex} = 0 \quad ...(1)$$

Where E_{in} is energy input to the solar collector (kJ), E_s is the energy stored by the solar collector (kJ), E_{ex} is the exergy of the solar collector (kJ), E_{L1} is the heat lost by glazing due to transmittance and absorbance of the absorber plate (kJ), and E_{L2} is heat lost due to insulation characteristics of the solar collector (kJ). Now we have to calculate each and every component of equation (1) in detail to develop an equation for finding the efficiency of the solar collector.

Energy analysis of a thermal solar collector

The Energy available to the solar collector is the amount of solar irradiance per unit area of the collector. It is the energy given by sun radiation to the solar collector and can be calculated using equation (2) given by Hanif *et al.* (2015),

$$E_{in} = IA_c\,(1- \frac{Ta}{Ts}) \qquad ...(2)$$

where E_{in} is the rate of energy given by sunlight to the solar collector (kJ hr^{-1}), I is solar irradiance (kJ m^{-2}), A_c is area of the solar collector (m^2), T_a is ambient air temperature (^oC), T_s is the apparent the sun surface temperature, which is 4077 (^oC). Since both I and Ta changes with time of the day, the total energy should be calculated by integrating solar irradiance over small time intervals.

Exergy analysis of a thermal solar collector

Exergy is defined as the heat energy that can be used from the solar collector with the help of the fluids (air, water) flowing inside the solar collector. Before calculating the exergy we have to calculate the energy stored and lost in the process.

Energy stored in the solar collector

The energy stored in solar collector will be the energy gained by the absorber plate, energy gained by the water present in the storage tanks and energy gained by the air present inside the solar collector. The stored energy can be calculated using equation (3) given by Hanif *et al.* (2018).

$$E_s = E_{abs} + E_w + E_a \qquad ...(3)$$

Where E_s represents the energy stored in solar collector(kJ), E_{abs} represents the energy stored by the absorber plate (kJ), E_w represents the energy stored by the water (kJ), and E_a represents the energy stored in the air inside the solar collector (kJ). Now we can determine each component in detail using a separate equation for the energy gained at each place. Firstly, we determine the energy gained by the absorber which can be calculated using equation (4) (Hanif *et al*., 2015)

$$E_{abs} = m_{abs}C_{abs}\Delta T \qquad ...(4)$$

where E_{abs} represents the energy stored by the absorber plate (kJ), m_{abs} represents the mass of the absorber plate (kg), C_{abs} represents the specific heat of the absorber plate (kJ $^oC^{-1}$ kg^{-1}), and ΔT is the difference between ambient and absorber temperature (^oC).

Secondly, the energy gained by the water is calculated using equation (5), given by Hanif *et al.* (2016),

$$E_w = m_wC_{pw}\Delta T \qquad ...(5)$$

where E_w represents the energy stored by water (kJ), m_w represents the mass of water (kg), C_w represents the specific heat of water (kJ $^oC^{-1}$ kg^{-1}), and $\Delta T$is the temperature rise of the water inside the solar collector (^oC).

Thirdly, the energy gained by the air inside the solar collector is given by equation (6) given by Islam *et al.* (2015),

$$E_a = m_aC_a\Delta T \qquad ...(6)$$

where E_a represents the energy stored by air (kJ), m_a represents the mass of air (kg), C_a represents the specific heat of air (kJ $^oC^{-1}$ kg^{-1}), and $\Delta T$is the temperature difference between ambient air and the air inside the solar collector (^oC).

Energy lost from the solar collector

Energy is lost from the solar collector in two ways. The first is due to the optical efficiency of the glazing and acceptance of the absorber plate and can be calculated using equation (7), given by Hanif *et al.* (2018),

$$E_{L1} = (\tau\alpha)\, IA_cT_a\,(\frac{1}{Ta} - \frac{1}{Tabs}) \qquad ...(7)$$

where E_{L1} is the energy lost by glazing due to transmittance and absorbance of the absorber plate (kJ), τ is the transmittance of the glazing, α is the absorbance of the absorber plate, I is solar irradiance (kJ. m^{-2}), A_c is area of the solar collector (m^2), T_a is the ambient air temperature (^oC), and T_{abs} is absorber temperature (^oC).

The second factor that affects the heat lost is the insulation characteristic. The heat lost through insulation can be calculated using equation (8) given by Jafarkazemi *et al.* (2013),

$$E_{L2} = \{U_lA_{abs}(T_{abs} - T_a)\,(1 - \frac{Ta}{Tabs})\} \qquad ...(8)$$

where E_{L2} is energy lost by the solar collector due to insulation characteristics (kJ), U_l is the coefficient of the rate of energy lost from the insulation to the surroundings (kJ $m^{-2o}C^{-1}$), A_{abs} is an area of the absorber

(m^2), T_a is ambient air temperature (^oC), and T_{abs} is absorber temperature (^oC)

Exergy of the solar collector

The exergy of a solar collector can be calculated using equation (9) given by Koca *et al.* (2008),

$$E_{ex} = m_f C_{pa} \Delta T \quad ...(9)$$

where E_{ex} is the rate of exergy of the solar collector (kJ hr^{-1}), m_f is the mass flow rate of air delivered by the blower (kg hr^{-1}), C_{pa} is the specific heat of air (kJ $^oC^{-1}$ kg^{-1}), and T is the difference in the temperatures of ambient air and air at the outlet (^oC).

Mass flow rates were determined using the continuity equation as used by Hanif *et al*., (2018). Mass flow rates are obtained by taking the product of air velocity at outlet, density of air and outlet area. To find the mass flow rate (m_f), an anemometer (Extech, AN100, USA) will be used to find the velocity of air at the outlet.

Efficiency of a thermal solar collector

The Performance of the solar collector is measured in terms of its energy and exergy. It is the ratio of energy and exergy of the solar collector. Equation (10) is used to find the efficiency of the solar collector and is given by Hanif *et al.*. (2018),

$$\eta = \text{x } 100 \quad ...(10)$$

where η represents the efficiency of the solar collector (%), m_f is the mass flow rate of air (kg hr^{-1}), C_{pa} is the specific heat of air (kJ $^oC^{-1}$ kg^{-1}), DT is the difference between the temperatures of ambient air and air at the outlet, (^oC), I is solar irradiance (kJ m^{-2} hr^{-1}), A_c is the area of the solar collector (m^2), T_a is the ambient air temperature (^oC), and T_s is the apparent surface temperature of the Sun, which is 4077 ^oC.

Data loggers

Data loggers (Mastech, MS6514, USA) that will record the air temperature at the inlet, outlet, and absorber plate were installed on the solar collector. The water temperature in the storage tank and drying chamber tank was measured with the help of mercury thermometers. The data were collected during a clear sky having a C.S.I (Clear Sky Index) of more than 70000 Lux at the time of data recording, with the help of a Luxmeter (Extech, 401025, USA). After evaluating the optimum combination of all the factors for maximum efficiency of the solar collector, the setup was installed and tested.

Statistical analysis

The data were analyzed using three factors in a completely randomized design. The first factor was tilt angle with three levels, second factor was air mass flow rates with four levels and third was heat storage fluid with four levels, making a 4 x 3 x 4 factorial experiment. All the treatments were replicated three times. Least significant difference between means was calculated with $\alpha < 0.01$. The experimental factor and their levels are as given below.

a. *Factor 1:* *Flow rates* (F)
   F1(natural or passive) 0.1 $m.s^{-1}$, F2 1.31 $m.s^{-1}$, F3 2.72 $m.s^{-1}$ and F4 3.31 $m.s^{-1}$
b. *Factor 2:* *Tilt angles* (T)
   T1 (30^o), T2 (35^o), and T3 (40^o)
c. *Factor 3:* *Heat storage fluid* (H)
   H1 (air or control), H2 (water), H3 (concentrated salt solution), and H4 (polyethylene glycol)

RESULTS AND DISCUSSIONS

Diffused daily solar irradiance

Mean daily diffused solar irradiance at the site for the experimental period is shown in Figure 2. During day time, maximum solar irradiance was recorded at noon. The data show that mean maximum solar irradiance of 902 W m^{-2} were recorded at noon followed by 891 W m^{-2} at 1:00 pm while the minimum solar irradiance of 209 W m^{-2} was recorded at 6:00 pm followed by 212 W m^{-2} at 6:00 am. From the mean values of solar irradiance, the solar noon was found to be around 12:35 to 12:37 pm. The correlation equation showed a positive correlation with R^2 = 0.950. The R^2 showed that there is a strong relationship of solar irradiance with time of the day. The reduced Chi Square test showed that there is a perfect correlation found between solar irradiance and time of the day. The test also showed that the shape of the solar irradiance is nearly a bell shaped structure having a σ (sigma) value of 0.91. The results are in line with the findings of Mouna *et al.* (2014). The results are 1.1% less than the findings of Hanif *et al.* (2018). This may be due to air turbidity which increased in 2017 and 2018 as reported by Mamata *et al.* (2017).

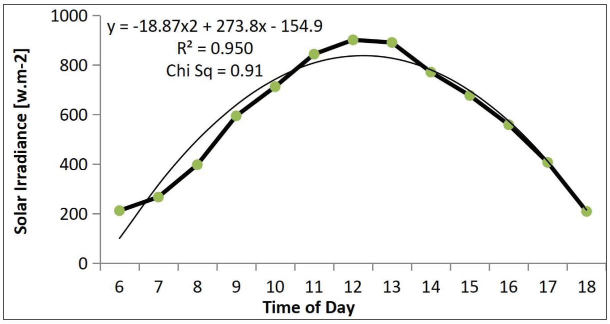

Figure 2: Daily diffused solar irradiance at the site

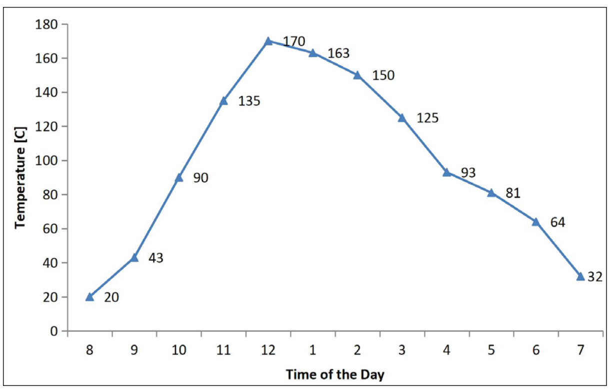

Figure 3: Average temperature of the absorber plate

Temperature of absorber plate

The average temperature data of the absorber plate and the dryer assembly is given in Figure 3. The minimum absorber plate temperature of 20 °C was recorded at 8:00 am followed by 32 °C at 7:00 pm while a maximum temperature of 170 °C was recorded at 12:00 noon followed by 163 °C recorded at 1:00 pm. Hanif *et al.* (2018) reported the same increase in temperature of the absorber plate. Hanif *et al.* (2016; 2018) reported 33 and 30% less values of absorber temperature. The fact is that they used small collectors having absorber area of 3.1 and 4.23 m^2.

Energy gained by the flat plate solar collector

Statistical analysis of the data showed that all three factors, *i.e.*, tilt angle, collector air flow rates, and collector fluid used as medium, have a significant ($\alpha \leq 0.05$) effect on the energy gained by the flat plate solar collector. All the interaction between the tilt angle and air flow rates, tilt angle and collector fluids, air flow rates and collector fluids, and tilt angle, air flow rates, and collector fluids also significantly affected the energy gained by the flat plate solar collector.

The results of the energy gained (kJ hr^{-1}) by the flat plate solar collector as affected by tilt angles (degrees), air flow rates (kg min^{-1}), collector fluids and all the interaction between these factors is given in Table 2. The results of the means of tilt angle showed that the maximum energy of 1156.02 kJ hr^{-1} was recorded at a tilt of 35° followed by 1153.20 kJ hr^{-1} at 30° while the minimum energy of 1150.33 kJ hr^{-1} was recorded at tilting the collector at 40°. The results of the means of air flow rates showed that the maximum energy of 1325.02 kJ hr^{-1} was recorded for an air flow rate of 11.76 kg min^{-1} followed by 1292.81 kJ hr^{-1} of energy at 9.69 kg min^{-1} while the minimum energy gained of 950.17 kJ hr^{-1} was recorded for an air flow rate of 1.78 kg min^{-1}. The results of means of fluids flowing in the raiser head pipes of the flat plate solar collector showed that the maximum energy gained by the collector of 1297.31 kJ hr^{-1} was recorded for polyethylene glycol, followed by 1233.61 kJ hr^{-1} for salt solution, while the minimum energy gained of 941.93 kJ hr^{-1} was recorded for air as the flowing medium without any fluid in the head riser pipes.

With regard to interaction effects, the means of interaction between tilt angles and air flow rates (T x F) showed that the maximum energy of 1331.11 kJ hr^{-1} was gained by the flat plate solar collector at 11.76 kg min^{-1} air flow rate with a 35° collector tilt angle, while the minimum energy gained of 947.63 kJ hr^{-1}was recorded at 1.78 kg min^{-1} air flow rate with the collector tilting at 35°. The means of interaction between air flow rates and collector fluid (F x H) showed that the maximum energy of 1500.33 kJ hr^{-1}was gained by the flat plate solar collector at 11.76 kg min^{-1} air flow rate with polyethylene glycol solution used as collector fluid while the minimum energy gained of 756.07 kJ hr^{-1}was recorded at 1.78 kg min^{-1} air flow rate with no fluids in the collector head rised pipe. The means of interaction between tilt angles and collector fluid (T x H) showed that the maximum energy of 1301.99 kJ hr^{-1}was gained by the collector when polyethylene glycol solution was used in head rised pipes with a 30° collector tilt angle, while the minimum energy gained of 938.38 kJ hr^{-1} was recorded with air only flowing in the solar collector without any fluids in head raised pipes, and with the collector tilting at 40°. The means of overall interaction between tilt angles, flow rates and collector fluid (T x F x H) showed that the maximum energy of 1509.74 kJ hr^{-1} was gained by the collector when polyethylene glycol solution was used in head raised pipes at 11.76 kg min^{-1} air flow rates with a 30° collector tilt angle, while the minimum energy gained of 751.39 kJ hr^{-1} was recorded with air only flowing in the solar collector, without any fluids in head raised pipes, at 1.78 kg min^{-1} with the collector tilting at 35°. Hanif *et al.* (2018) reported results in line with the findings of this research. Sabet *et al.* (2014) also reported results in line with the findings of this research. Hanif *et al.* (2016) reported results of energy less than the findings of this research because of the fact that they have not used any energy storage medium.

Table 2: Energy gained (kJ hr^{-1}) by the flat plate solar collector as affected by tilt angles (degrees), air flow rates (kg min^{-1}) and collector fluids.

		Collector fluids				
		Air/control	Water	Salt solution	Polyethileneglycol	Mean
Tilt Angles	Flow rates		T x F x H		T x F	
30°	1.78	760.07	964.05	1001.52	1082.97	952.15
	4.67	839.64	1020.47	1145.18	1162.25	1041.88
	9.69	1091.22	1249.05	1370.57	1453.02	1290.96
	11.76	1077.04	1315.02	1409.34	1509.74	1327.78
35°	1.78	751.39	985.03	1007.02	1047.09	947.63
	4.67	871.03	1011.65	1145.90	1169.05	1049.41
	9.69	1075.59	1275.67	1366.52	1465.90	1295.92
	11.76	1083.55	1325.14	1417.44	1498.31	1331.11
40°	1.78	756.75	936.71	1030.75	1078.63	950.71
	4.67	868.28	1017.4	1122.03	1163.84	1042.90
	9.69	1070.67	1253.97	1397.62	1443.91	1291.54
	11.76	1057.80	1324.56	1389.37	1492.96	1316.17
Tilt Angles				T x H		
	30°	941.99	1137.15	1231.65	1301.99	1153.20b
	35°	945.39	1149.37	1234.22	1295.09	1156.02a
	40°	938.38	1133.17	1234.94	1294.83	1150.33c
Flow rates (kg min^{-1})				F x H		
	1.78	756.07	961.93	1013.10	1069.56	950.17d
	4.67	859.65	1016.52	1137.70	1165.04	1044.73c
	9.69	1079.16	1259.56	1378.23	1454.28	1292.81b
	11.76	1072.81	1321.57	1405.38	1500.33	1325.02a
	Mean	941.93d	1139.90c	1233.61 b	1297.31a	

Means followed by different letter (s) within each category are significantly ($\alpha \leq 0.05$) different using the LSD test

$LSD_{(0.05)}$ for T = 1.09, $LSD_{(0.05)}$ for F = 45.61, $LSD_{(0.05)}$ for H = 43.21

T x F = * ; T x H = *; F x H = *; T x F x H = *

* Significant at 1% level of probability

Exergy analysis of the flat plate solar collector

Statistical analysis of the datashowed that all three factors, *i.e.,* tilt angle, collector air flow rates, and collector fluid used as medium, have a significant ($\alpha \leq 0.05$) effect on the total potential or exergy efficiency of the flat plate solar collector. All the interactions, between the tilt angle and air flow rates, tilt angle and collector fluids, air flow rates and collector fluids, and tilt angle, air flow rates, and collector fluids—also significantly affected the exergetic efficiency of the flat plate solar collector.

Table 3: Exergy efficiency (%) of flat plate solar collector as affected by tilt angles (degrees), air flow rates (kg min^{-1}) and collector fluids

		Collector fluids				
		Air/Control	Water	Salt solution	Polyethylene glycol	Mean
Tilt angles	Flow rates	T x F x H				T x F
30°	1.78	42.33	36.07	33.94	32.67	36.25
	4.67	46.00	45.00	37.33	35.67	41.00
	9.69	44.17	40.53	35.64	34.17	38.63
	11.76	44.17	40.53	35.64	34.17	38.63
35°	1.78	44.78	42.02	36.20	34.67	39.42
	4.67	44.37	41.03	35.83	34.33	38.89
	9.69	44.44	41.20	35.89	34.39	38.98
	11.76	44.53	41.42	35.97	34.46	39.09
40°	1.78	44.45	41.21	35.90	34.40	38.99
	4.67	44.47	41.27	35.92	34.42	39.02
	9.69	44.48	41.30	35.93	34.42	39.03
	11.76	44.47	41.26	35.91	34.41	39.01
Tilt angles		T x H				
	30°	44.17	40.53	35.64	34.17	38.63c
	35°	44.53	41.42	35.97	34.46	39.09a
	40°	44.47	41.26	35.91	34.41	39.01b
Flow rates (kg min^{-1})		F x H				
	1.78	43.85	39.77	35.35	33.91	38.22c
	4.67	44.95	42.43	36.36	34.81	39.64a
	9.69	44.36	41.01	35.82	34.33	38.88b
	11.76	44.37	41.11	35.84	34.35	38.91ab
Mean		44.39 a	41.07b	35.81c	34.32d	

Means followed by different letter (s) within each category are significantly ($\alpha \leq 0.05$) different using the LSD test

$LSD_{(0.05)}$ for T = 0.03, $LSD_{(0.05)}$ for F = 0.16, $LSD_{(0.05)}$ for H = 3.01

T x F = *; T x H = *; F x H = *; T x F x H = *; T x F x H = *

* Significant at 1% level of probability

The results of the exergy analysis of the flat plate solar collector as affected by tilt angles (degrees), air flow rates (kg min^{-1}), collector fluids and all the interaction between these factors is given in Table 3. The results of the means of tilt angle showed that the maximum exergy efficiency of 39.09 % was recorded at the tilt of 35^o followed by 39.01 % at 40^o, while the minimum exergy efficiency of 38.63 % was recorded at tilting the collector at 30^o. The results of the means of air flow rates showed that the maximum exergy efficiency of 39.64 % was recorded for an air flow rate of 4.67 kg min^{-1} followed by 38.91% at 11.76 kg min^{-1},while the minimum exergy efficiency of 38.22 % was recorded for an air flow rate of 1.78 kg min^{-1}. The results of means of fluids flowing in the head riser pipes of the collector showed that the maximum exergy efficiency gained by the collector was 44.39 % recorded for air without any medium in the pipes, followed by 41.07 % for water, while the minimum exergy efficiency of 38.22 % was recorded for polyethylene glycol solution as a flowing medium in the head riser pipes.

With regard to interaction effects, the means of interaction between tilt angles and air flow rates (T x F) showed that the maximum exergy of 41.0 % was gained by the flat plate solar collector at a 4.67 kg min^{-1} air flow rate with a 30^o collector tilt angle, while the minimum exergy gained of 36.25 % was recorded at a 1.78 kg min^{-1} air flow rate with the collector tilting at 30^o. The means of interaction between air flow rates and collector fluid (F x H) showed that the maximum exergy of 44.95 % was gained by the flat plate solar collector at a 4.67 kg min^{-1} air flow rate with air used as the collector fluid while the minimum exergy efficiency gained of 33.91 % was recorded at 1.78 kg min^{-1} air flow rate with polyethylene glycol used as the fluid in the flat plate solar collector head riser pipe. The means of interaction between tilt angles and collector fluid (T x H) showed that the maximum exergy of 44.53 % was gained by the flat plate solar collector when air was used with a 35^o collector tilt angle, while the minimum exergy efficiency gained of 34.17 % was recorded for polyethylene glycol flowing in the solar collector head riser pipes with the collector tilting at 30^o. The means of overall interaction between tilt angles, flow rates and collector fluid (T x F x H) showed that maximum exergy of 46.0 % was gained by the flat plate solar collector when air was used in the head riser pipes at 4.67 kg min^{-1} air flow rates with a 30^o collector tilt angle, while the minimum exergy gained of 32.67% was recorded for a polyethylene glycol solution in the solar collector at 1.78 kg min^{-1} with the collector tilting at 30^o. Silva *et al.* (2013) reported results in line with the findings of this research. Soteris *et al.* (2016) reported that exergy increase was a function of collector fluids, which was confirmed by the results of the solar collector exergy gained in this research. Siva *et al.* (2012) reported less exergy gained by the flat plate solar collector. This was due to the smaller size of the solar collector used in their experiment.

Efficiency of the flat plate solar collector

Statistical analysis of the data showed that all three factors, *i.e.,* tilt angle, collector air flow rates, and collector fluid used as medium, have a significant ($\alpha \leq 0.05$) effect on the efficiency of the flat plate solar collector. All the interactions between the tilt angle and air flow rates, tilt angle and collector fluids, air flow rates and collector fluids, and tilt angle, air flow rates, and collector fluids also significantly affected the efficiency of the flat plate solar collector.

The results of the performance evaluation of the flat plate solar collector as affected by tilt angles (degrees), air flow rates (kg min^{-1}), collector fluids, and all the interaction between these factors are given in Table 4. The results of the means of tilt angle showed that the maximum efficiency of 29.74 % was recorded at the tilt of 40^o followed by 28.16 % at 35^o tilt while the minimum efficiency of 21.77 % was recorded when tilting the collector at 30^o. The results of the means of air flow rates showed that the maximum efficiency of 28.28% was recorded for air flow rate of 11.76 kg min^{-1} followed by 27.64 % at 9.69 kg min^{-1}, while the minimum efficiency of 25.01 % was recorded for air flow rates of 1.78 kg min^{-1}. The results of means for fluids flowing in the head riser pipes of the collector showed that the maximum efficiency obtained by the collector was 29.90 % recorded for polyethylene glycol solution used as a medium in the pipes, followed by an efficiency of 28.36 % for salt solution, while the minimum efficiency of 21.70 % was recorded for air or without any medium in the head riser pipes.

With regard to interaction effects, the means of interaction between tilt angles and air flow rates (T x F) showed that the maximum efficiency of 36.17 % was gained by the flat plate solar collector at a 11.76 kg min^{-1} air flow rate with 35^o collector tilt angle while the minimum efficiency gained of 18.54 % was recorded at 1.78 kg min^{-1} air flow rate with the collector tilting at 30^o. The means of interaction between air flow rates and collector fluid (F x H) showed that the maximum efficiency of 31.08% was recorded by the flat plate solar collector at 11.76 kg min^{-1} air flow rate when polyethylene glycol solution was used as the collector fluid, while the minimum efficiency gained of 18.61% was recorded at a 1.78 kg min^{-1} air flow rate when air was used as the fluid in the flat plate solar collector. The means of interaction between tilt angles and collector fluid (T x H) showed that maximum efficiency of 34.14 % was gained by the flat plate solar collector when polyethylene glycol solution was used with a 40° collector tilt angle, while the minimum efficiency gained of 17.92 % was recorded for air flowing in the solar collector with the collector tilting at 30°. The means of overall interaction between tilt angles, flow rates and collector fluid (T x F x H) showed that the maximum efficiency of 39.71% was gained by the flat plate solar collector when polyethylene glycol solution was used in the head riser pipes at a 9.69 kg min^{-1} air flow rate, with a 40° collector tilt angle, while the minimum efficiency gained of 13.71 % was recorded for air in the solar collector at 1.78 kg min^{-1} with the collector tilting at 30°. Tian *et al.* (2013) and Wang *et al.* (2008) reported results in line with the findings of this research. However, Hanif *et al.* (2018) reported efficiency results with the fluids used in contradiction of the results obtained in this research. The fact was that they used a lower concentration of salt in the solution, while using tap water with high impurities.

Table 4: Overall efficiency (%) of flat plate solar collector as affected by tilt angles (degree), air flow rates (kg min^{-1}) and collector fluids

		Collector Fluids				
		Air/control	Water	Salt solution	Polyethyleneglycol	Mean
Tilt angles	Flow rates		T x F x H			T x F
30°	1.78	13.71	19.18	19.39	21.89	18.54
	4.67	19.18	24.84	27.6	28.63	25.06
	9.69	19.38	22.47	23.04	23.53	22.10
	11.76	19.41	20.97	22.09	23.12	21.39
35°	1.78	20.49	28.22	33.27	33.89	28.96
	4.67	19.52	21.02	23.28	23.53	21.83
	9.69	23.18	22.44	28.77	28.31	25.67
	11.76	29.78	37.42	38.13	39.36	36.17
40°	1.78	21.63	27.24	28.37	32.85	27.52
	4.67	23.26	29.66	29.9	33.25	29.01
	9.69	28.86	33.71	38.28	39.71	35.14
	11.76	22.04	28.00	28.27	30.75	27.26
	Tilt Angles			T x H		
	30°	17.92	21.86	23.03	24.29	21.77 c
	35°	23.24	27.27	30.86	31.27	28.16 b
	40°	23.94	29.65	31.21	34.14	29.74 a
	Flow rates (kgmin^{-1})			F x H		
	1.78	18.61	24.88	27.01	29.54	25.01 d
	4.67	20.65	25.17	26.93	28.47	25.31 c
	9.69	23.81	26.21	30.03	30.52	27.64 b
	11.76	23.74	28.80	29.49	31.08	28.28 a
Mean		21.70d	26.26c	28.36b	29.90a	

Means followed by different letter(s) within each category are significantly ($\alpha \leq 0.05$) different using the LSD test

$LSD_{(0.05)}$ for T = 0.023, $LSD_{(0.05)}$ for F = 0.011, $LSD_{(0.05)}$ for H = 0.021

T x F = * ; T x H = *; F x H = *; T x F x H = *

* Significant at 1% level of probability

The role of the energy storage unit in storing energy in the solar collector

The role of the energy storage unit to store energy in the flat plate solar collector is shown in Figure 4. The statistical analysis of the data (Tables 2 - 4) showed that there is significant ($\alpha \leq 0.05$) difference found in the values of energy stored by different fluids. The results showed that the maximum energy of 40,207 kJ day^{-1} was stored in the energy storage unit followed by 33,291 kJ day^{-1} stored by the salt solution, while the minimum energy of 29,640 kJ day^{-1} was stored with water. Energy storing ability varies for each fluid used in the solar collector. They play a vital role in increasing the efficiency and exergy. This energy stored by the energy storage unit helped the solar collector to achieve higher performance, less energy loss, and more drying time. The results are in accordance with the findings of Zhong *et al.* (2014). The results are more significant than those of Yahya *et al.* (2000) and Hanif *et al.* (2018), because of the fact that a larger collector absorber was used as compared to the size of their solar collectors. Tian *et al.* (2013) reported results in accordance with the findings of this research. They stated that energy storage can be increased with increasing flow rates of the solar collectors.

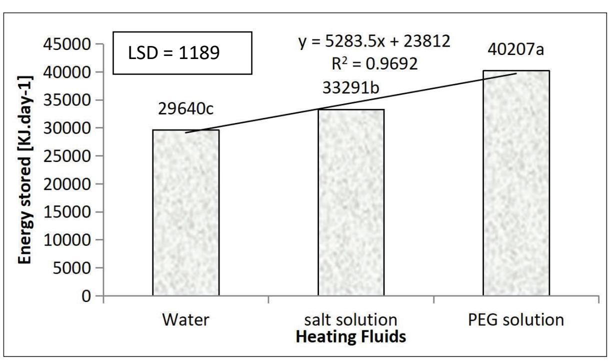

Figure 4: The energy stored by the fluids in the flat plate solar collector

CONCLUSIONS

From the results of the research study it was concluded that

1. Tilt angle, air mass flow rates and heat storage fluid played a vital role in increasing the efficiency of the solar collector when analyzed as factors in three factors in a completely randomized design.
2. A solar collector with fluids used as a medium of storage gives higher efficiencies of energy and exergy as compared to air used as a medium.
3. Polyethylene glycol is the best solution to increase performance of a solar collector.
4. The flat plate solar collector must be operated at higher air flow rates with 40^{o} tilt to achieve maximum performance with higher exergetic values.
5. More energy is stored by polyethylene glycol when used as fluid in the flat plate solar collector.

REFERENCES

Bellos E., Christos T. & Antonopolus A. (2016). Exergetic, energetic and financial evaluation of a solar driven absorption cooling system with various collector types. *Journal of Applied Thermal Engineering* **102**(3): 749–759. DOI: https://doi.org/10.1016/j.applthermaleng.2016.04.032

Boukelia T., Macibah M. & Reddy S. (2015). Investigation of solar parabolic trough power plants with and without integrated TES (thermal energy storage) and FBS (fuel backup system) using thermic oil and solar salt. *Energy* **88**(1): 292–303.
DOI: https://doi.org/10.1016/j.energy.2015.05.038

Fahad A & Sulaiman A.L. (2013). Exergy analysis of parabolic trough solar collectors integrated with combine steam and organic Rankine cycle. *Energy Conversion and Management* **77**(2): 441–449.
DOI: https://doi.org/10.1016/j.enconman.2013.10.013

Farhat S., Sarhadi F. & Ajam. H. (2009). Exergetic optimization of flat plate solar collectors. *Renewable Energy* **34**(3): 1169–1174.
DOI: https://doi.org/10.1016/j.renene.2008.06.014

Frances C., Polombo A. & Vanoli L. (2012). A finite-volume model of a parabolic trough photovoltaic/thermal collector: Energetic and exergetic analyses. *Energy* **46**(1): 283–294.
DOI: https://doi.org/10.1016/j.energy.2012.08.021

Francesco D., Massimo D. & Adriano M. (2016). Exergetic and exergoeconomic analysis of a novel hybrid solar-geothermal poly generation system producing energy and water. *Energy Conversion and Management* **115**(1) : 200–220.
DOI: https://doi.org/10.1016/j.enconman.2016.02.029

Govindaraj K., Rahulram S. & Vilraj R. (2012). Performance studies of a solar parabolic trough collector with a thermal energy storage system. *Energy* **47**(2): 395–402.
DOI: https://doi.org/10.1016/j.energy.2012.09.036

Hanif M., Khattak M.K., Ali S.A., Khan M., Ramzan M., Amin M. & Aamir M. (2015). Impact of drying temperature and slice thickness on retention of vitamin C in persimmons (*Diospyros Kaki*. L) Dried by a flat plate solar collector. *Pakistan Journal of Food Sciences* **25**(2): 66–70.

Hanif M., Khattak M.K., Amin M., Ramzan M., Zakir S., Ullah S. & Khan Z. (2016). Developing a flat plate solar collector for drying and water heating purposes. *Sains Malaysiana* **45**(3): 89–497.

Hanif M., Khattak M.K., Ramzan M. & Maazullah K. (2018). Energy, exergy and efficiency analysis of a flat plate solar collector. *Sains Malaysiana* **47**(6): 1061–1067.
DOI: https://doi.org/10.17576/jsm-2018-4705-24

Islam S., Ibrahim D. & Sami Y. (2015). Energetic and exergetic performance analyses of a solar energy-based integrated system for multi generation including thermoelectric generators. *Energy* **93**(6): 1246–1258.
DOI: https://doi.org/10.1016/j.energy.2015.09.111

Jafarkazemi F. & Ahmadifard E. (2013). Energetic and exergetic evaluation of flat plate solar collectors. *Renewable Energy*. **56**(1): 55–63.
DOI: https://doi.org/10.1016/j.renene.2012.10.031

Koca A., Hakan F., Koyun T. & Varol Y. (2008). Energy and exergy analysis of a latent heat storage system with phase change material for a solar collector. *Renewable Energy* **33**(4): 567–574.
DOI: https://doi.org/10.1016/j.renene.2007.03.012

Mamta S., Singha G.K. and Sainib R.P. (2017). Effects of air pollution for estimating global solar radiation in India. Effects of air pollution for estimating global solar radiation in India. *International Journal of Sustainable Energy* **36**(1): 20–27.
DOI: https://doi.org/10.1080/14786451.2014.979348

Mouna H., Snoussi A. & Brahim A.B. (2014). Energy and exergy analysis of flat plate solar collectors in transient behaviors. *The fifth International Renewable Energy Congress IREC*. 2014. March 25-27, Hammamet, Tunisia. Applied Thermodynamic Research Unit, Engineers National School of Gabes, University of Gabes, 6072 Gabes, Tunisia.

Sabet A., Rahini A. & Hatamipour M.S. (2014). An experimental study on drying characteristics and kinetics of figs. *Polish Journal of Chemical Technology* **16**(1): 60–65.
DOI: https://doi.org/10.2478/pjct-2014-0071

Silva R., Berenguel M., Perez M. & Fernandez A. (2013). Thermo-economic design optimization of parabolic trough solar plants for industrial process heat applications with memetic algorithms. *Applied Energy* **113**(3): 603–614.
DOI: https://doi.org/10.1016/j.apenergy.2013.08.017

Siva V., Kaushik S.C. & Tyagi S.K. (2012). Exergetic analysis and performance evaluation of parabolic trough concentrating solar thermal power plant. *Energy* **39**(1): 258–273.
DOI: https://doi.org/10.1016/j.energy.2012.01.023

Soteris A.K., Karellas S., Badescu V. & Braimakis K. (2016). Exergy analysis on solar thermal systems: A better understanding of their sustainability. *Renewable Energy* **85**(6): 1328–1333.
DOI: https://doi.org/10.1016/j.renene.2015.05.037

Tian Y. & Zhao C.Y. (2013). A review of solar collectors and thermal energy storage in solar thermal applications. *Applied Energy* **104**(3): 538–553.
DOI: https://doi.org/10.1016/j.apenergy.2012.11.051

Wang Z., Sun J., LiaoX., Chen F., Zhao G., Wu J. & Hu X. (2008). Mathematical modeling of hot air drying of thin layer apple. *Food Research International* **40**(1): 39–46.
DOI: https://doi.org/10.1016/j.foodres.2006.07.017

Yadav S., Kaushal M., Varun M. & Siddhartha S. (2014). Exergetic performance evaluation of solar air heater having arc shape oriented protrusions as roughness element. *Solar Energy* **105**(1): 181–189.
DOI: https://doi.org/10.1016/j.solener.2014.04.001

Yahya M.G., Yahya S.A. & Faiz K.B. (2000). Preservation of fruits and vegetables using solar drier. *Renewable Energy* **19**(1): 203–212.
DOI: https://doi.org/10.1016/S0960-1481(99)00032-4

Zhong G., Wang H., Hua W., Zhang S. & Guan X. (2014). Exergy analysis of flat plate solar collectors. *Entropy* **16**(6): 2549–2567.
DOI: https://doi.org/10.3390/e16052549