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Energy, Exergy and Efficiency Analysis of a Flat Plate Solar Collector Used as Air Heater

(Analisis Tenaga, Eksergi dan Kecekapan Pengukur Solar Plat Rata yang Digunakan sebagai Pemanas Air)

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ABSTRACT

Air heating by solar collectors is renewable technology providing hot air for different purposes. The present research emphasizes on analysis of energy, exergy and efficiency of a flat plate solar air heater. The analysis model was tested on five different air mass flow rates of 0.5 (Natural), 1.31, 2.11, 2.72 and 3.03 kgs^{-1} under three different tilt angles of 25, 35 (Recommended) and 50^o. The data was replicated three times making a total of 45 treatments. A two factorial completely randomized design was used to find if there is any significant difference among the treatments. The results showed that the solar collector gave better performance at air mass flow of 3.03 kgs^{-1} under tilt of 35^o. At maximum air mass flow rate of 3.03 kgs^{-1}and optimum tilt angle of 35^o the maximum energetic efficiency of 51%, while minimum exergetic efficiency of 24% and maximum overall efficiency of 71% were recorded. It was concluded that to get maximum thermal efficiencies of 71% from flat plate solar collector used as an air heater must be operated at high air mass flow rates of 3.03 kgs^{-1}under 35^o tilt angle at Peshawar, Pakistan.

Keywords: Efficiency; energy; exergy; flat plate solar collector

ABSTRAK

Pemanasan udara oleh pengumpul suria merupakan teknologi yang boleh diperbaharui yang menyediakan udara panas untuk tujuan berbeza. Penyelidikan yang terkini menekankan tentang analisis tenaga, eksergi dan kecekapan plat rata pemanas udara solar. Model analisis diuji pada lima kadar aliran jisim udara yang berbeza iaitu 0.5 (semula jadi), 1.31, 2.11, 2.72 dan 3.03 kgs^{-1} di bawah tiga sudut kecondongan 25, 35 (disyorkan) dan 50^o. Data uji kaji diulang sebanyak tiga kali merangkumi 45 rawatan secara total. Reka bentuk dua rawak faktorial digunakan untuk mencari perbezaan yang signifikan antara rawatan. Keputusan uji kaji menunjukkan bahawa pengumpul suria memberikan prestasi yang lebih baik pada aliran jisim udara 3.03 kgs^{-1} di bawah kecondongan 35^o. Pada kadar aliran jisim maksimum udara 3.03 kgs^{-1} dan sudut kecondongan optimum 35^o, keputusan kecekapan energetik maksimum ialah 51%, manakala kecekapan eksergi ialah minimum 24% dan kecekapan keseluruhan maksimum pula ialah 71%. Kesimpulannya, untuk mendapatkan kecekapan terma maksimum 71% daripada pengumpul suria plat rata yang digunakan sebagai pemanas udara, ia mesti dikendalikan pada kadar aliran jisim udara tinggi 3.03 kgs^{-1} di bawah kecondongan 35^o di Peshawar, Pakistan.

Kata kunci: Eksergi; kecekapan; pengumpul plat rata; tenaga

INTRODUCTION

Energy is the base of economic and social development. The timely increasing demand of energy and limitations of fossil fuels reservoirs is a serious issue for the world particularly in Pakistan. Increase in the demand of fossil fuels for energy production and their impact on the environment is now a global problem which led to a significant enhanced trend of acquiring renewable energy sources. Renewable energy sources have the potential to overcome the problems of energy demand and environment destruction by greenhouse gases emitting by the using fossil fuels. It is thus widely investigated that renewable energy can play a vital role in any field where energy is a primary source. Renewable energy resources have a potential to replace the non-renewable energy resources if properly worked out and installed according to the demand with all the engineering aspects needed for their maximum output (Koca et al. 2014). 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 can be converted into heat and electricity using different solar conversion technologies namely flat plate solar collector, concentration solar collector and photovoltaic technologies. For heating purposes flat plate solar collectors and parabolic trough solar collectors are the main component for solar thermal heating. The flat plate solar collectors are used mainly for low thermal systems of agricultural and domestic heating requirements while the parabolic trough concentrating solar collector technology is used for high thermal systems like steam and power generation (Hanif et al. 2014; Kalogirou et al. 2016).

Before installing a thermal solar system for a specific purpose, it is most important to analyse the performance of these collectors. The efficiency for a solar thermal system is the key for its maximum thermal performance. But to determine the performance of the system the efficiency equation alone does not determines the internal losses by the solar collectors. Only calculating efficiency is not the sufficient criteria for finding optimum performance of a solar collector. For this, an analysis based on second law of thermodynamics is best to determine the exergy analysis of the solar system. Exergy analysis is a vital and most necessary parameter for optimization of design and future operation of the solar thermal collectors. Solar thermal collectors must have been examined in terms of their energy and exergy, efficiency and entropy generation for optimal performance (Ge et al. 2014; Farahat et al. 2009), 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. It's not a complete setup of generalizing and optimizing the solar collector performance. Hence an advanced model with solving common errors for energy and exergy analysis is required for computing efficiencies of solar collectors. The performance must be tested at dynamic models and energy and exergy analysis must be carried out at transient states. Many authors reported their work on optimizing the performance of solar collectors and they have concluded that solar collectors showed a lot of difficulties at steady state conditions. Thus, it is recommended to develop and test the solar thermal collectors at transient states for achieving better results of energy and exergy analysis (Hamed et al. 2014).

To test a solar collector like concentrating dish or parabolic trough type solar collectors for energy and exergy analysis, it is necessary to keep in mind that the sky must be clear, the flow rate must be constant, assume the properties of material of construction of the solar collector as 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. Keeping in view these energy and exergy analysis for solar collectors must be carried out (Jafarkazmi & Ahmadifard 2013).

Keeping in view the above-mentioned facts in the literature, the present research study is designed to investigate the energy and exergy analysis of flat plate solar collector used as an air heater. The objective of the research was to investigate the sole and interaction effects of air mass flow rates and tilt angles of the solar collector energy, exergy and efficiency.

MATERIALS AND METHODS

SITE SELECTION

The solar collector assembly 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 34.0204°, 71.4822° and 448.3608 m respectively. The site is said to be perfect because it receives maximum solar irradiance from dawn to dusk without interference of any shadow of a structure.

THE THERMAL SOLAR COLLECTOR

The environmental and design conditions and parameters of the solar collector that will be used in the experiment are given in Table. 1. The flat plate solar collector that was used in the experiment is shown in Figure 1 and drawing of the flat plate solar collector assembly is given in Figures 2, 3 and 4.

RECORDING SOLAR IRRADIANCE

The data of daily diffused solar irradiance was recorded by the help of digital Pyranometer (Solar Power Meter, TES-1333, Taiwan) as shown in Figure 1. The environmental conditions of the site were as given in Table 1.

TABLE 1. Average meteorological data of the site during the time of recording of solar irradiance

Local time (h)	Ambient temperature (°C)	Air velocity ($m.s^{-1}$)
9:00	30.6	2.1
10:30	36.7	2.5
11:00	40.1	2.4
12:00 (Noon)	40.5	2.7
1:00 pm	40.2	2.1
2:00	38.3	2.6
3:00	37.5	2.2
4:00	36.6	3.1
5:00	31.5	3.3

FIGURE 1. Pyranometer used in the experiment

ENERGY AND EXERGY ANALYSIS

When the solar collector is at equilibrium with the environment then the general form of energy and exergy balance equation of the system is given by Bellos et al. (2016),

$$E_{in} + E_s + E_{out} + E_l + E_d = 0 \tag{1}$$

TABLE 2. Design and environmental conditions of the flat plate solar collector

Parameters	Value
Collector's length, width and depth	3.40, 2.46 & 0.66m
Area	8.365 m^2
Volume of the solar collector	5.520 m^3
Absorber	V-corrugated, Black painted 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 and water
Wind speed range	0.1 - 35 m s^{-1}
Collector tilt angles	25°, 35° and 50°
Ambient temperature range	283 - 810°C
Apparent sun temperature	4320 to 4350°C
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}.°C^{-1}
Solar irradiance range	0-850 W.m^{-2}
Tubes/ Pipes diameter (steel)	0.025 m
Flow rates	0.1- 3.5 m s^{-1}
Volume of storage tank	0.12 m^3
Mass of water in storage tank	120 kg
Volume of head raised pipes	0.086 m^3
Mass of water in pipes	86 kg
Total volume of water in solar collector	206 kg

Now we have to calculate each and every component of the (1). In detail to develop a model from the equation.

FIGURE 2. The flat plate solar collector assembly

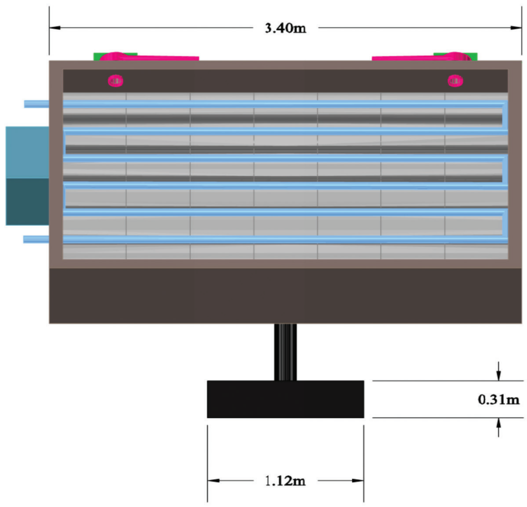

FIGURE 3. Front view of the flat plate solar collector

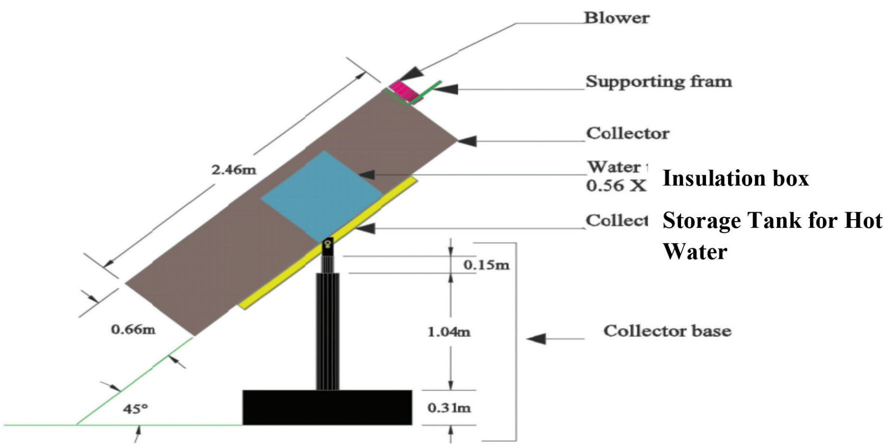

FIGURE 4. Side view of the flat plate solar collector

ENERGY ANALYSIS OF A THERMAL SOLAR COLLECTOR

To calculate energy available to the solar collector, it is important to consider the energy gained equation by the working fluid. The equation is given by Al-Sulaiman (2013),

$$Q_{use} = m_a C_p \Delta T \quad \text{here } \Delta T = Tout - Ta \tag{2}$$

Now expending the equation for considering heat losses form the collector during the fluid flowing inside the solar collector to the atmosphere is given by Hotted–Whillies as (Calise et al. 2016),

$$Q_{use} = A_{abs} Q_r \, [S_i - U_l \, (\Delta T)] \quad \text{here } \Delta T = T_{in} - T_a \tag{3}$$

where S_i is the optical absorbed solar flux and U_l is the heat lost by reflection, emittance and optical efficiency of glazing given by formula Farahat et al. (2009),

$$Si = T\alpha IT$$

$$Q_R = \frac{maCp}{U_l A_{abs}} \left[1 - \exp\left\{ \frac{-F\phi U_l A_{abs}}{maCp} \right\} \right] \tag{4}$$

Now putting (3) in (2), we get the overall equation of energy given to the collector and yielded by the absorber plate and is given by Islam et al. (2015),

$$Q_{use} = A_{abs} S_i - U_l A_{abs} (\Delta T) \quad \text{here } \Delta T = T_{abs} - T_a \tag{5}$$

EXERGY ANALYSIS OF A THERMAL SOLAR COLLECTOR

Exergy is defined as the maximum amount of heat energy the solar collectors provide to driers by the help of fluid (air, water) flowing inside the solar collector.

Before calculating the exergy, we have to calculate the losses, stored or destroyed in the system.

ENERGY STORED BY FLUIDS FLOWING IN THE SOLAR COLLECTOR

The energy stored by the solar collector fluids is given by Jafarkazmi and Ahmadifard (2013),

$$E_s = m_w C_p \Delta T \; (\Delta T = T_w - T_a) \tag{6}$$

where E_s represents the energy stored by the fluids for a specific period of time. In the solar collectors used in the experiment the E_s is only for the water to be heated and stored in the water tank.

ENERGY LEAKED BY THE SOLAR COLLECTOR

The energy leaked from the solar collector is given by Jafarkazmi and Ahmadifard (2013)

$$E_l = \{U_l A_{abs} \, (T_{abs} - T_a) \, (1 - \frac{Ta}{Tabs})\} \tag{7}$$

where E_l represents the energy leaked by the solar collectors due to the material characteristics to lost heat.

ENERGY DESTROYED BY THE SOLAR COLLECTOR

The energy destroyed by the solar collector is given by Islam et al. (2015),

$$E_d = - mC_p T_a \frac{Tout}{Tin} E_d = - mC_p T_a \left\{ \ln\left(\frac{Tout}{Tin} \right) - \left(\frac{T_{out} - T_{in}}{T_{abs}} \right) \right\} \tag{8}$$

where E_d is the lost heat energy caused by the difference in temperature of absorber plate and fluids. It is the latent heat absorbed by the fluids in phase change.

EXERGY OF THE SOLAR COLLECTOR

Now the exergy of a solar collector is given by Kalogirou et al. (2016),

$$E_{out} = \left[\left\{ \left(maCp \left(T_{out} - T_a T_a l_n \frac{T_{out}}{T_a} \right) - \frac{m\Delta P_{out}}{\rho} \right) + mwCp \left(T_w - T_a \right) \right\} \right] \tag{9}$$

where E_{out} represent the energy to be loaded to the fluids and is the exergy of the system. It is also called as entropy of the solar collectors.

EFFICIENCY OF A THERMAL SOLAR COLLECTOR

It is ratio of energy output and useful energy available to the solar collectors. Now from (10). The second law of heat exchange efficiency equation of the solar collectors is by taking the ratio of (4) and (7). The overall equation is given by Ge et al. (2014),

$$\eta = \frac{\text{Aabs Si– UIAabs } (\Delta T)}{\left[\left\{ (maCp \, (Tout - TaTa \ln \Delta T) - \frac{m\Delta P}{\rho}) + mwCp\Delta T \right\} \right]} \times 100 \tag{10}$$

DATA LOGGERS

Data loggers were installed on the solar collectors that recorded the solar irradiance, temperature of inlet and outlet, temperature inside the collector for 24 h.

STATISTICAL ANALYSIS

The data was analyzed using two factorial Completely Randomized Design (C.R.D). The first factor was air mass flow rates with five levels and second was tilt angle of the solar collector with three levels. Both the factors were replicated three times (Hanif et al. 2016). The statistics were applied on energy, exergy and efficiency of the solar collector.

Results and Discussions

SOLAR RADIATION

The data regarding the solar irradiation on the site and other meteorological conditions that affected the performance of the solar collector are shown in Figure 5. The data showed that during the experimental period the site received more than 5000 kW.m^{-2} per month of solar irradiance at an average. This accounts more than 600 W.m^{-2} of solar power availability at the site. The data also shows that during the experimental period there was 50% relative humidity and 38^{o}C ambient temperature which is far more best for drying different fruits and vegetables.

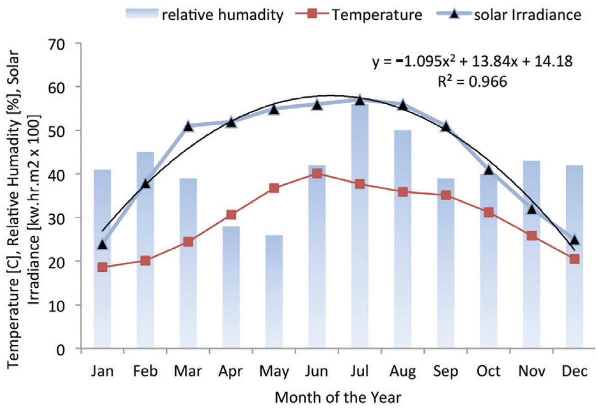

FIGURE 5. Relative humidity, temperature and solar irradiance of the site

ENERGY EFFICIENCY

Experimental data regarding the energy as affected by different air mass flow rates and tilt angles is given in Figure 6. The data in Figure 6 shows that increase in air mass flow rates will increase the energy efficiency of the solar collector. The increase in energetic efficiencies is due to improvement in convective heat transfer at higher flow rates. At natural or passive flow more, heat leaked from the collector as a result more energy is lost and solar collector was having low energetic efficiencies but as soon as the flow rates are made forced or convective, therefore, the solar collector energy improved by reducing leakage and loss of energy from the absorber through glazing to the environment. On the other hand, in collector tilt, an angle of 35^{o} gave maximum energy gained by the solar collector as compared to 25 or 50^{o} tilt. At natural flow the recorded energetic efficiencies were 33.3, 37.5 and 30.1% for 25, 35 and 50^{o} tilt angles. As flow rates are increased and reached to maximum of 3.03 kgs^{-1} therefore, the energetic efficiencies reached to 67.0, 72.0 and 61.5% for 25, 35 and 50^{o} tilt angles. The results are in accordance with the findings of Al-Sulaiman (2014) and Bellos et al. (2016) who reported increase in energetic efficiency with increase in air mass flow through the solar collector. The efficiency of the present study is almost 10% higher than the finds of these authors. It is due to the size of the collector. They used 1.4 and 2.1 m^{2} collector which is 5 and 4 times smaller than the collector used in the present study having an area of 8.34 m^{2}. The results are also in accordance with findings of Calise et al. (2016), Farahat et al. (2009) and Hanif et al. (2016) who reported the exergy increase with increase in air mass flow at tilt angle of 28 to 35^{o}.

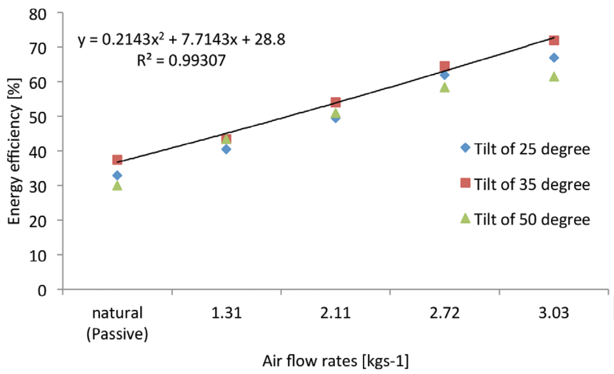

FIGURE 6. Energetic efficiencies of the flat plate solar collector as affected by air mass flow rates and tilt at different tilts of the solar collector

EXERGY EFFICIENCY

Experimental data regarding the exergy as affected by different air mass flow rates and tilt angles is given in Figure 7. The data shows that the exegetic efficiencies of the flat plate solar collector decreased by increasing air mass flow rates. Maximum efficiency of 51% was recorded for a tilt angle of 35^{o} at natural flow rate which decreased 24% by optimizing the flow to 3.03 kgs^{-1}. The minimum efficiency of 43% was recorded for tilt of 50^{o} at natural flow which decreased to 19% at maximum flow rate of 3.03 kgs^{-1}. The exergy decrease is due the heat flowing towards the dryer and storage tank by agent fluids. Exergy was maximum at 35^{o} tilt angle because of the normality of solar irradiance at this angle on the absorber plate of the solar collector. The results are in argument of Farahat et al. (2009) who reported decrease in exergetic efficiencies

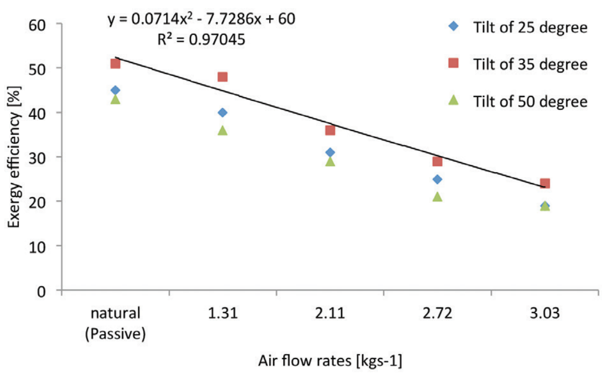

FIGURE 7. Exergetic efficiencies of the flat plate solar collector as affected by air mass flow rates and tilt at different tilts of the solar collector

of a flat plate solar collector with increase in tilt angle and increase in air mass flow rates. Ge et al. (2014) and Hanif et al. (2016) also reported in their results that exergy decreased with increased in air mass flow rates.

OVERALL EFFICIENCY

Experimental data regarding the efficiency of flat plate solar collector to convert energy to useful exergy is given in Figure 8. The data shows that the efficiencies of the flat plate solar collector increased by increasing air mass flow rates. Minimum efficiency of 59% was recorded for a tilt angle of 35° at natural flow rate which increased to 71% by optimizing the flow to 3.03 kg. s^{-1}. The minimum efficiency of 56% was recorded for tilt of 50° at natural flow which increased to 64% at maximum flow rate of 3.03 kgs^{-1}. The increase in overall efficiency is due the heat uptake by the flowing air towards the dryer and as a working agent fluid. Less heat was leaked and lost at higher air mass flow rates. Efficiency was maximum at 35° tilt angle because the solar irradiance was normal at this tilt at the site, receiving maximum solar energy. The results of efficiency as affected by different air mass flow rates and tilt angles is are in accordance with the findings of Hanif et al. (2016) and Koca et al. (2014) who reported increase in efficiencies of a flat plate solar collector with increase in air mass flow rates. Calise et al. (2016) and Hamed et al. (2014) also reported in their results that efficiency increase with increased in air mass flow rates. The overall efficiency of the collector tested in the present experiment is 20% higher than the solar collectors used in the literature.

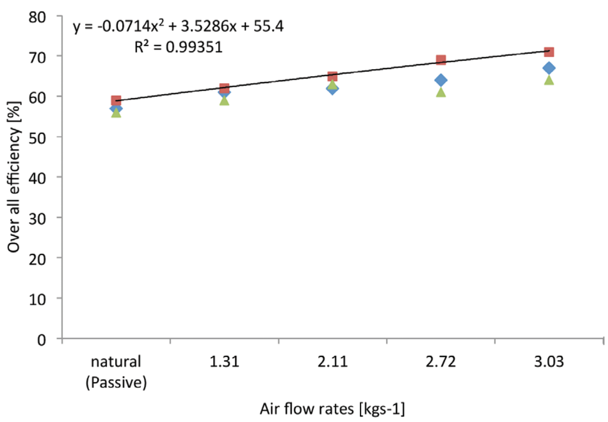

FIGURE 8. Overall efficiencies of the flat plate solar collector as affected by air mass flow rates and tilt at different tilts of the solar collector

CONCLUSION

It was concluded that energy and overall efficiencies of the solar collector increase while exergy efficiency decreased with increasing air mass flow rates inside the collector under a constant tilt angle. In tilting the solar collector gave better results at 35° tilt. Based on the efficiencies, the collector must be operated at high air mass flow rate of 3.03 kgs^{-1} under 35° tilt angle to achieve maximum performance from it as a dryer for drying carrots.

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