ANNUAL TRANSIENT SIMULATIONS AND EXPERIMENTAL INVESTIGATION OF A HYBRID FLAT PLATE AND EVACUATED TUBE COLLECTORS ARRAY IN SUBTROPICAL CLIMATE

by

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Non-concentrating solar thermal collectors are being used for various heating and cooling applications. Flat plate collectors and evacuated tube collectors are extensively being used in this regard and their hybrid configuration could be an energy efficient solution. In the current work, model-based transient simulation approach is implemented using TRNSYS to decide the optimal number of flat plate collectors. Detailed experimental analysis of standalone and hybrid configurations of flat plate collectors and evacuated tube collectors is performed under real climate conditions of Taxila, Pakistan. Experimental tests have been conducted to analyze the system performance in terms of energy and exergy efficiencies. Afterwards, annual transient simulations are performed for whole year to determine the overall performance of the hybrid system. The maximum average temperature difference per unit area for flat plate collectors, evacuated tube collectors, and hybrid collector array was found to be 0.95 °C, 1.67 °C, and 0.98 °C, respectively. The maximum energy and exergy efficiency were found 65%, 41% for flat plate collectors, 88.36%, 60 % for evacuated tube collectors, and 62.14%,42% for hybrid collector, while 10% increase in energy efficiency of hybrid collector array is found as compared to the standalone flat plate collectors. Average 9.78% deviation is observed in experimental and model-based efficiency. Finally, annual simulations show that hybrid collector array is 16% more efficient than standalone flat plate collectors throughout the year.

Key words: *flat plate collector, evacuated tube collector, hybrid collector array, solar water heating, annual simulation*

Introduction

The renewable energy resources are attracting considerable attention due to rapid depletion, price fluctuation, uncertain availability of fossil fuels and regional conflicts. Effects of global warming and climate change have also forced the researchers to focus on alternate energy resources. Pakistan receives around 1.0 kW of solar energy per square meter on average for a given solar day, where the number of sunshine hours ranges from 3000-3300 per year and estimated solar energy potential is around 2900000 MW [1]. Solar energy is harnessed through photo-voltaic and thermal technologies [2], in which various types of collectors are used. Flat

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plate collector (FPC) and evacuated tube collector (ETC) are two very popular types of solar collectors. Experimental results have also been reported in literature along with analytical calculations. However, simulation studies are usually carried out to extend the study. Reportedly, simulation is more advantageous and precise compared to analytical calculations, especially for annual analysis [3]. Additionally, a simulation approach, due to modular nature, can play important role to decide system control strategies at initial design stage, validation and commissioning for operational activities of a system. Furthermore, simulation analyses are cost effective and time saving, especially when designing new and pioneering systems [4]. Therefore, it is a handy tool for an overall system performance evaluation.

It has been reported through simulation that ETC is 15% and 30% more efficient in hot and cold climate, respectively than FPC [5]. Comparison of TRNSYS model and experimental data shows that 16.9% and 18.4% mean percentage error has been observed for FPC and ETC [6]. Similarly, a novel FPC with micro heat pipe arrays was evaluated and it was found that average efficiency was 69% at flow rate of 290 m^3/h [7]. A study of FPC array revealed that efficiency of the collectors decreased as the temperature of the water increased [8]. In another study parametric study of ETC shows that inlet parameters strongly effect the energy and exergy performance [9]. Similarly, the comparison of solar water heaters with FPC and ETC showed that the annual average collector efficiencies were 46.1% and 60.7%, while the system efficiencies were 37.9% and 50.3%, respectively [10]. Potential assessment of various solar thermal collectors for solar desiccant cooling system revealed that ETC were more feasible economically and reduced primary energy consumption [11], whereas cost of system increased up to 31% for ETC as compared to conventional system [12].

A few studies have also been found for hybrid configurations. An investigation of hybrid array of FPC and parabolic trough collectors resulted in 5-9% reduction in investment cost [13]. The hybrid FPC can be used to overcome the overheating of photovoltaic system and provides highest exergy efficiency as compared to different types of HC [14]. In another study of solar thermal air collectors found that maximum solar radiation causes maximum irreversibility [15]. Similarly, comparative study shows that combined cooling, heating, and power systems operated by solar energy are more efficient in terms of energy and exergy [16].

Literature review reveals that several studies have been performed for standalone collectors. However, the hybrid arrangement of these collectors is rarely analyzed. Therefore, in the current study, a hybrid configuration is proposed in which FPC are connected in series with heat pipe, ETC. The transient model is developed in TRNSYS by considering two configurations:

– standalone FPC and ETC,
– hybrid collectors (HC) array.

The model is then simulated for selected days of summer and real time analysis is also performed for assessment of energy and exergy efficiencies under a wide range of climate conditions in terms of ambient temperature and solar radiations. The experimental and simulation results are compared, and transient analysis is then performed for whole year.

Model development for transient simulations

In this study TRNSYS is used due to its wide applicability and validated component models in view of advantages highlighted in [3, 4]. Initially, the HC array system model is developed then annual system transient simulations are performed under sub-tropical climate conditions. Figure 1 shows TRNSYS system model incorporating hourly climate data (*e. g.* ambient temperature, radiations, incidence angle) based on Type 15 for the selected climate of

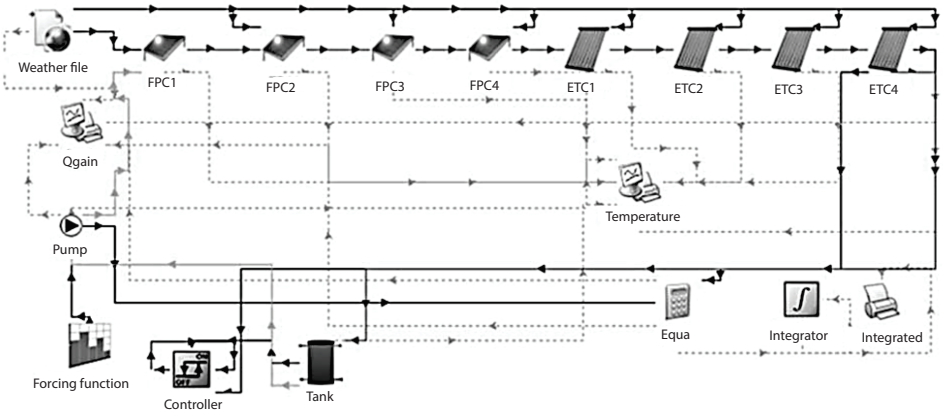

Figure 1. Transient simulation model in TRNSYS for HC array

Taxila, Pakistan. Transient analysis is then performed by applying appropriate control strategies. Cold water from stratified storage tank is drawn through pump at constant flow rate and circulated through the collectors. Firstly, transient simulations are executed for selected days for which real time experiments are performed for model validation. Afterwards, annual simulations are then performed to determine the performance of FPC, ETC, and HC array throughout the year by setting simulation interval of one hour and time schedule is implemented from 9:00 a. m. to 4:00 p. m.

Experimental set-up and measurement procedure

Experimental set-up consists of FPC and ETC connected in series for both standalone and hybrid configuration, fig. 2, and details of measuring instruments are given in tab. 1. The dotted lines show standalone operation of FPC and ETC, respectively and solid lines show operation of hybrid collector array. Physical experimental set-up of hybrid configuration is shown in fig. 3, whereas properties of collectors is presented in tab. 2. The experiments are conducted at Renewable Energy Research and Development Center (RERDC) located in Taxila (latitude 33.7370° N and longitude 72.7994° E). In the current study, various climate, inlet, and outlet parameters are continuously measured with a time interval of 5 minutes from 9:00 a. m. to 4:00 p. m. in each case. The parameters include direct solar radiation, ambient temperature, wind velocity, water temperature.

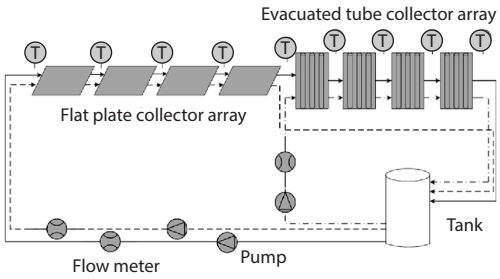

Figure 2. Schematic diagram of experimental set-up

Table 1. Specifications of measuring instruments

Measurement	Instrument	Range	Accuracy
Temperature	KLK 100	–50 to +50	±0.5 °C
Pressure	Manometer	0 to 3″ H_2O	±3%
Water flow	Rota meter	0-2 kg per minute	±5%
Global solar radiations	Pyranometer TBS-2	280-3000	9.876 uv/Wm^{-2}

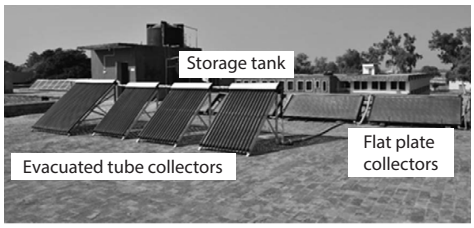

Figure 3. Experimental set-up

Table 2. Design specifications of collectors

Parameter	FPC	ETC
Number of collector in series	4	4
Collector absorber area [m^2]	7.37	4.78
Intercept efficiency	0.75	0.83
First order efficiency coefficient [WK^{-1}m^{-2}]	4.3	1.85
Second order efficiency coefficient [WK^{-1}m^{-2}]	0.0064	0.007
Stagnation temperature [°C]	197	238
Operating pressure [Pa]	$10 \cdot 10^5$	$6 \cdot 10^5$
Collector title angle [°]	45	45
Tested flow rate [kgs^{-1}]	0.125	0.125

Energy and exergy analysis

The energy performance indices include solar energy gain by collectors, incident energy fall on collectors, and collector efficiency [17], which are presented in eqs. (1)-(3) [2, 18, 19], respectively.

$$Q_{\text{gain}} = \dot{m}c_p(T_{\text{o}} - T_{\text{in}}) \tag{1}$$

$$Q_{\text{incident}} = A_c GR \tag{2}$$

$$\eta = \frac{Q_{\text{gain}}}{Q_{\text{incident}}} \tag{3}$$

The actual work produced by the solar collectors can be calculated by exergy analysis as the effect of the environmental temperature on the exergy efficiency cannot be underestimated and the energy efficiency of the system is higher than the corresponding exergy efficiency [20]. Moreover, increase in ambient temperature negatively effects exergy. However it is positively affected by incident solar energy [21]. The useful exergy gain from the solar collector, incident exergy on collectors and exergy efficiency is presented in eqs. (4)-(6) [22]. The Sun temperature in the previous equation is equal to 6000 K. This value is the absolute temperature of the sun's surface [23].

$$E_u = \dot{m}c_p\left[(T_o - T_{\text{in}}) - T_{\text{amb}}\ln\frac{T_o}{T_{\text{in}}}\right] \tag{4}$$

$$E_{\text{solar}} = Q_{\text{solar}}\left[1 - \frac{4}{3}\frac{T_{\text{amb}}}{T_{\text{Sun}}} + \frac{1}{3}\left(\frac{T_{\text{amb}}}{T_{\text{Sun}}}\right)^4\right] \tag{5}$$

$$\eta_{\text{ex}} = \frac{E_{\text{u}}}{E_{\text{solar}}} \tag{6}$$

Results and discussion

The hourly average data of real time incident solar radiations and ambient temperature is shown in fig. 4. The intensity of solar radiations and ambient temperature is minimum during morning and evening time while maximum around 12 p. m. Simulation based solar incident radiations are between 500-934 W/m^2 while real time ranges are between 450-950 W/m^2 with 4% deviation. The ambient temperature ranges from 28-40°C.

Selection of number of FPC

Temperature difference achieved by each FPC is shown in fig. 5. It is evident from simulation results that when inlet temperature reaches near 70 °C, ΔT achieved by each collector starts decreasing. The maximum ΔT achieved by FPC at number five is 1.63 °C and minimum 0.41 °C for selected days so there is no significant achievement in ΔT after FPC at position four. To overcome financial loss and high efficiency of collector, experiments are restricted with four FPC.

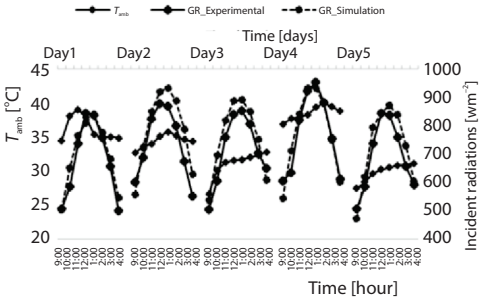

Figure 4. Average solar radiations and ambient temperature

Energy analysis

Experimentation of standalone and hybrid configuration is performed for the month of July to evaluate them in terms of energy and exergy efficiencies. Variation of hourly average water inlet temperature and outlet temperature along with temperature difference is shown in figs, 6(a)-6(c) for FPC, ETC, and HC array. The increase in incident radiations positively effects the outlet temperature of the water. The maximum temperature difference achieved by FPC, ETC, and HC array is 7 °C, 7.71 °C, and 12.07 °C, respectively, which corresponds to higher incident radiations.

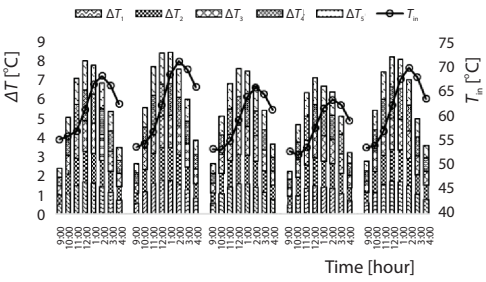

Figure 5. The ΔT variations for each FPC

The instantaneous energy efficiency of FPC, ETC, and HC array is shown in figs. 7(a)-7(c), respectively. Experimental data shows that hourly average energy efficiency,

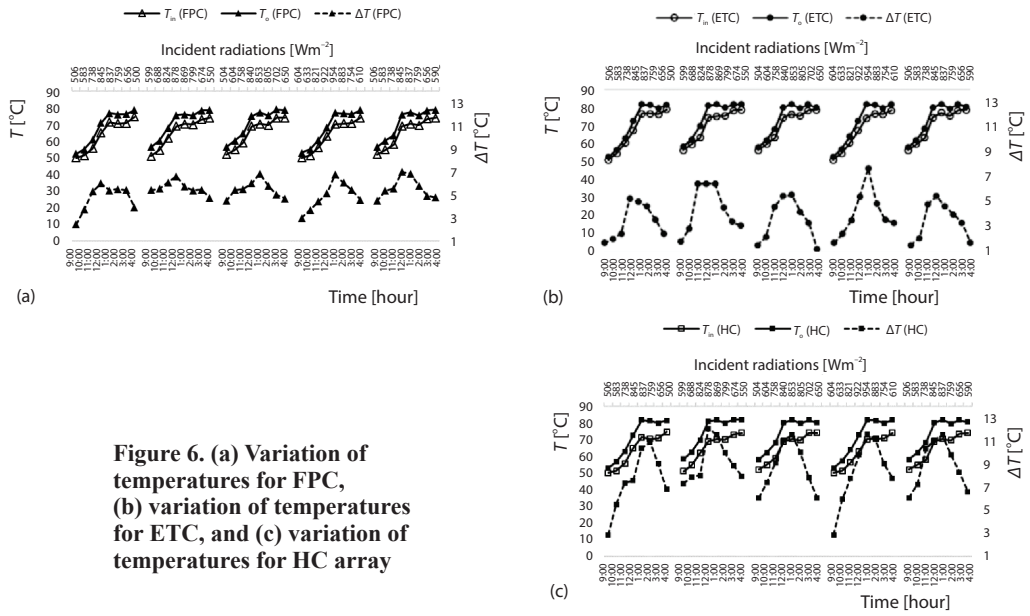

Figure 6. (a) Variation of temperatures for FPC, (b) variation of temperatures for ETC, and (c) variation of temperatures for HC array

η_{energy}, was minimum when intensity of solar radiations was low during the morning and afternoon. The maximum and minimum values of hourly average η_{energy} are about 65.17%, 34.31% for FPC and 88.36%, and 21.05% for, ETC. For HC array, the maximum observed value of η_{energy} is about 62.14% and minimum η_{energy} is about 20.32%.

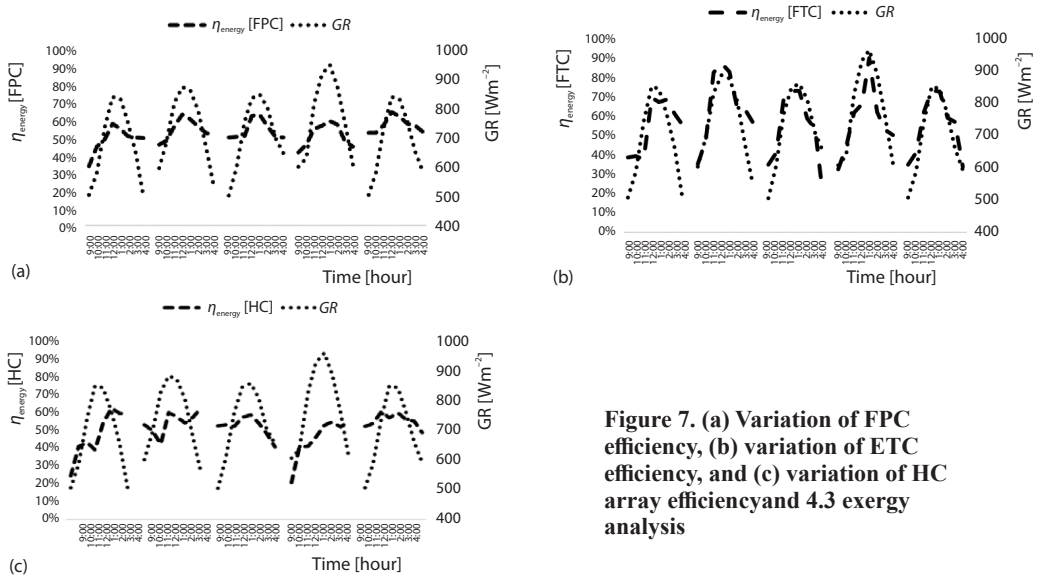

Figure 7. (a) Variation of FPC efficiency, (b) variation of ETC efficiency, and (c) variation of HC array efficiencyand 4.3 exergy analysis

Exergy analysis

The effect of hourly average fluid inlet temperature on exergy efficiency is shown in figs. 8(a)-8(c) for FPC, ETC, and HC array. It is noted that at dead state when inlet temperature increases exergy efficiency also increases. The maximum observed values of exergy efficiency

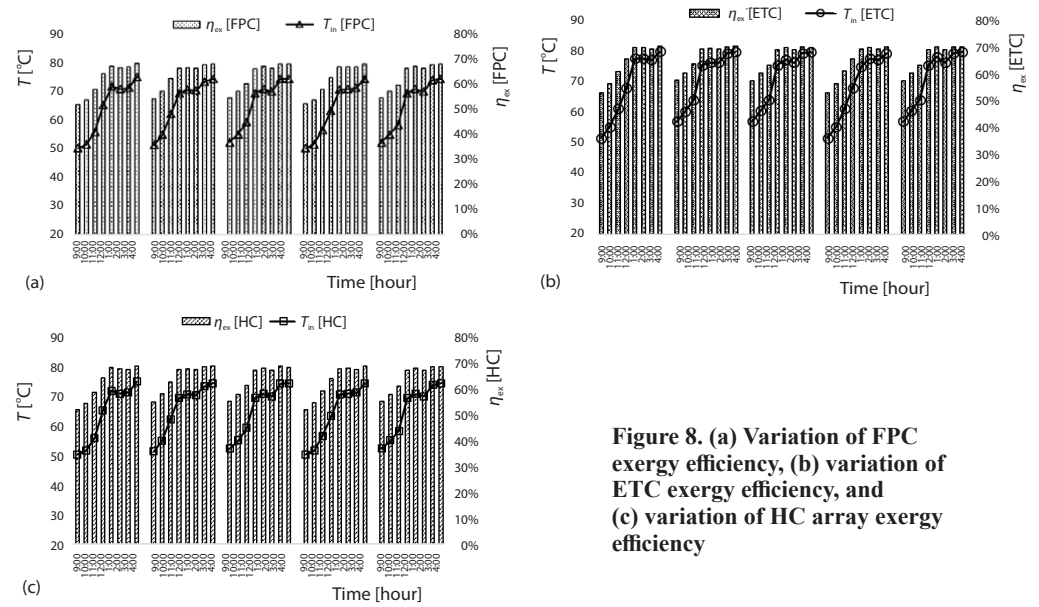

Figure 8. (a) Variation of FPC exergy efficiency, (b) variation of ETC exergy efficiency, and (c) variation of HC array exergy efficiency

for FPC and ETC are around 41 % and 60%, respectively, which corresponds to inlet temperatures of 74 °C and 78 °C, respectively. Similarly, minimum observed values of exergy efficiency for FPC and ETC are 51.47% and 16%, which corresponds to inlet temperatures of 50 °C and 51.09 °C, respectively. The maximum exergy efficiency for HC array is 42% corresponding to inlet temperature of 74 °C and 10.5% minimum at 50 °C.

Comparison of standalone and hybrid configurations

Figures 9(a) and 9(b) present the hourly average exergy and energy efficiency comparison of FPC and HC array. It is evident that energy efficiency of FPC consistently increases up to inlet temperature of 71 °C and drops on further rise in inlet temperature. Efficiency of HC array has increasing trend at same temperature. It can also be seen that about 10% difference occurs in efficiencies at elevated inlet temperature. Similarly, comparison of exergy efficiencies also shows consistent increasing trend as inlet temperature rises above 70 °C.

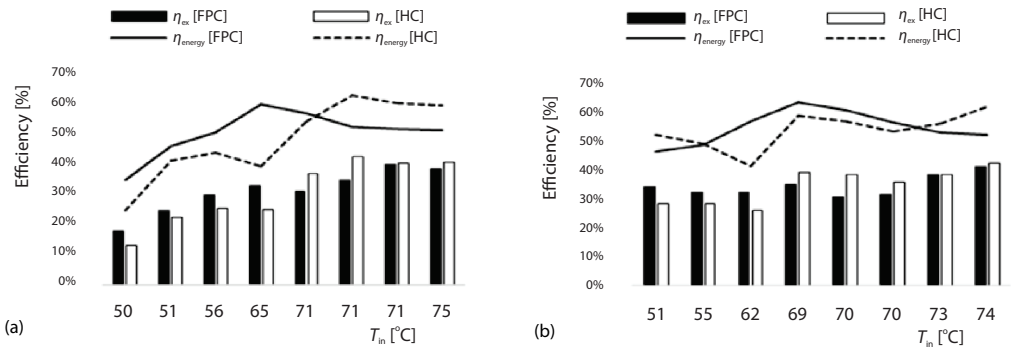

Figure 9. Variations of exergy and energy efficiency of FPC and HC array for (a) day 1, (b) day 2

Experimental results are compared with TRNSYS simulation model. The comparison of ΔT and efficiency of HC array is shown in fig. 10. When experimental data and TRNSYS models are compared for HC arrays, average 13.24% difference is observed in ΔT and 9.7% difference is observed in efficiency.

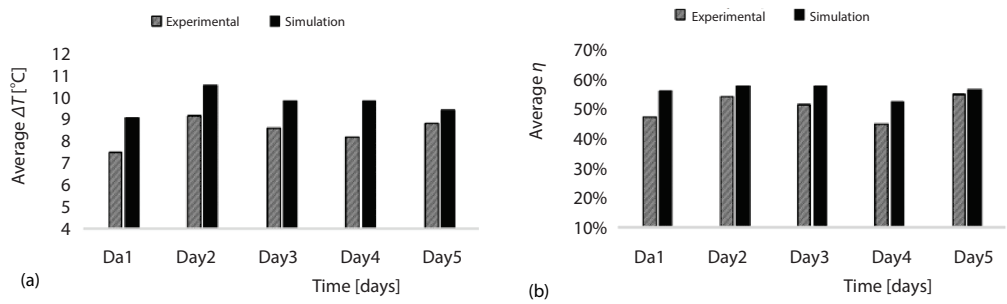

Figure 10. Comparison of (a) average ΔT, (b) average efficiency for HC array

Annual simulations for FPC, ETC, and HC array configurations

It is evident from annual simulations of standalone and hybrid configurations, fig. 11, that HC array achieves 23% more temperature difference per unit area throughout the year than FPC and 9% less than, ETC.

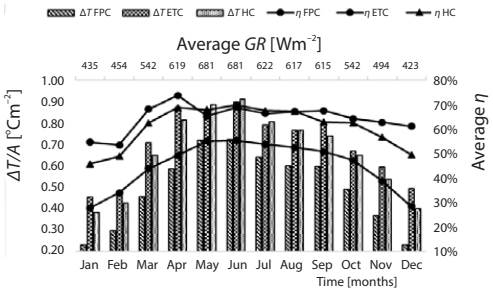

Figure 11. Monthly average Δ*T* and efficiency achieved by FPC, ETC, and HC array

Furthermore, it is observed that HC array efficiency is 15-22% more in winter and 12-19% more in summer than standalone FPC, while its efficiency is 10% less than standalone ETC for winter and almost equal in summer.

Conclusion

This study compares various aspects of FPC, ETC, and HC array, through experimental and simulation studies. Maximum average temperature difference per unit area for FPC, ETC, and HC array was found to be 0.95 °C, 1.67 °C, and 0.98 °C, respectively, corresponding to incident radiations of 954 W/m^2. Maximum energy efficiency and exergy efficiency is found as 52%, 41% for FPC, 88%, 60% for ETC, and 65%, 42% for HC array, respectively. When inlet temperature rises to 75° C exergy efficiency increases and further increase in inlet temperature causes decrease in exergy efficiency. Similarly increase in ambient temperature causes decrease in exergy efficiency. The exergy efficiency is low as compared to energy efficiency as thermal losses takes place during heat transfer. When thermal efficiencies of FPC and HC array are compered, it is found that there is about 10% increase in thermal efficiency of HC array at higher inlet temperature. So, HC array overcomes the disadvantages of FPC at elevated temperatures. Annual simulations show that HC array gives higher average efficiency throughout the year than standalone FPC and comparable to standalone ETC in summer season. This study reveals that HC array can be used for different applications with less auxiliary energy inputs.

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Nomenclature

A – area, [m^2]
c_p – specific heat of fluid, [kJkg^{-1}°C^{-1}]
GR – incident solar radiations, [Wm^{-2}]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
Q – energy rate, [W]
T – temperature, [°C]
ΔT – temperature difference

Greek symbol

η – efficiency, [%]

Subscript

amb – ambient temperature
c – cover area
ex – exergy
in – fluid inlet temperature
o – fluid outlet temperature
u – useful exergy gain

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