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EXPERIMENTAL ANALYSIS ON THE PHOTOVOLTAIC-THERMAL SOLAR COLLECTOR WITH COMPOUND PARABOLIC CONCENTRATOR USING PHASE CHANGE MATERIAL-TOWARDS SOLAR ENERGY UTILIZATION

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Abstract

In this study, the performance of a photovoltaic-thermal solar collector with compound parabolic collector for clear day in winter and summer season was investigated. Phase change material storage unit, compound parabolic collector unit, photovoltaic thermal unit were integrated into one piece to reduce the area to get higher performance and better concentration ratio. The performance of water flow rate, heat removal factor, amount of energy storage of the collector in winter season and comparison of temperature variation, total generated energy, performance factor in summer season by varying different parameters were evaluated. Water flow rate increases up to 0.004 kg/s corresponding to the thermal efficiency of around 42%. Heat removal factor for thermal collector was in the range of 0.94-0.96, which indicates better energy gain of the system and effective outlet water temperature was found 55 ^{0}C in winter season. The total generated thermal energy 1500W and maximum performance factor of a collector was 0.0135 kW^{-1}m^2 in summer season. Finally total efficiency of a collector varies from 58% -68% in summer season.

Keywords: Compound parabolic concentrator, Energy storage, Phase change material, Solar energy, Water heating.

1. Introduction

Last few decades, tremendous research works have done on the Photovoltaic Thermal (PVT) solar collector and this system has been the subject of intensive experimental investigations [1]. But the broad application of hybrid photovoltaic thermal solar energy system is now limited because the initial investment is costly. For better performance, the photovoltaic-thermal compound parabolic concentration is developed. Moreover, a comparative cost analysis is also conducted [2-5]. Ji et al.[3] developed a wall mounted photovoltaic thermal solar collector system.

This study found that better cooling performance is improved; when the mass flow rate of the working fluid for this system has increased. This system has many advantages for domestic users [3]. Energy storage from solar radiation is an important issue and this energy may be stored as latent heat, sensible heat or combination all of them. Economic viability, storage period required, efficient operating condition are an important parameter for storage selection method [4, 5]. Florschuetz [6] has analysed the performance of combined photovoltaic thermal flat plate collector using modified Hottel-Whillier model. He studied the effect of temperature on cell array efficiency. It is observed that efficiency decreases with the increase in temperature. Kern et al. [7]. have investigated the water and air-cooled PVT system that was performing on a simple photovoltaic collector system with force or natural cooling process. Experimentally evaluated different designs of integrated and various phase change material solar collector was proposed. Effective thermal conductivity is used for the solidification and melting process of phase change material in a vertical cylinder [8].

The result of experimental data from a prototype PVT collector with modified Hottel-Whillier models, where theoretical results were verified. The various design parameter effect is determined such as thermal conductivity between the PV cells, fin efficiency, thermal and electrical efficiency of PVT solar collector [9]. PVT water collector with glass cover generally used as a transparent cover system to reduce the conduction heat loss from this collector. The polycrystalline cell is more effective for electrical production and the result give lower in term of solar thermal fraction [10]. Both the thermal and electrical efficiencies of a PVT were determined by design parameter effects such as thermal conductivity, fin efficiency. The result show efficiency does not decrease when PVT may be made by low-cost materials.

From the view of efficiency and economic point, PVT system is advantageous for monocrystalline silicon PVT system for higher energy to limited space for mounting [11]. According to Arvind et al. [12], the thermal performance of the system is improving when operation at the optimum mass flow rate. The comparison of experimental data for a simulation model of a PVT and water heating system shows the result of electrical performance with on-site shading with the experimental investigation [13]. For higher energy demand and mounting for limited space, mono-crystalline silicon PVT systems are suitable for applications [14-16]. Electrical and thermal efficiency were investigated for the combined effects of water mass flow rate and solar cell packing factor that reported in increasing mass flow rate. The performance of a PVT collector was investigated for effective flow distribution on collector performance and reported to affect the flow distribution [17-20]. An analytical investigation of a thermal system using phase change material is carried out at Ireland's climate condition. A stainless steel container of phase change material was integrated with a photovoltaic panel used in this system. This method conveys to assess the performance of a photovoltaic thermal system with integrated phase change material for useful heat energy gain by the water [21]. The PV-T prototype, as well as the entire domestic hot water system and the complete TRNSYS model present variation of performance using measurements taken under real condition. The study in this work is to assess the exergetic and energetic performance of systems integrating this new photovoltaic-thermal module [22]. PCM base domestic types of a 304 stainless steel chromium flat plate solar water collector is connected to the pressurized city water line system. The result shown the thermal efficiency of the collector for fluid stored is 12.5% and for fluid flow is 62% [23]. Photovoltaic- thermal solar collector incorporating PCM layer with a lower melting point has better electrical properties of the collector, while the heat stored is more difficult to utilize. This result showed that the maximum energy output is obtained by incorporating a 3.4 cm thick PCM layer at 40 ^{0}C melting point [24]. We have used paraffin wax as a phase change material because of its availability, low cost, non-corrosive, and other thermal properties. Phase change materials have many applications for a different area, which includes a solar collector, greenhouses, as well as building heating.

The finding of this study is an improvement of collector performance by the modification of thermal storage collector design. This study experimentally investigated the performance of a solar thermal collector, where the phase change material container, compound parabolic collector and photovoltaic thermal unit are integrated as a single unit. Performance of the solar collector is measured and compared for winter and summer season in terms of energy storage, heat removal factor and total efficiency. This paper is aimed to experimentally analyse the effects of paraffin wax used as a phase change material into the collector of a conventional solar water heating system. The analysis includes a set of day-long experiments performing the different investigational application. The expose storage system into the collector is simple and can be easily used without expensive modifications. Phase change material acts as latent heat storage media in which, energy is stored from solar radiation during the sunshine hours and delivers the heat to the system during the hours when solar radiation intensity is lower or even absent. Therefore, the main of this study is to investigate the influence of phase change material on the thermal performance of a compound parabolic collector. Furthermore, the effect of the efficiency of the photovoltaic-thermal collector was analysed.

2. Experimental Setup

2.1. Structure and operation

In this study, total solar collector system consists of a solar absorber, a single glass cover, compound parabolic concentrator, photovoltaic thermal and a phase change material storage is one unit. The solar collector outer frame construct by GI sheet with welded in which, final dimension of 1 m by 0.81 m and 4 cm space between absorber plate and single glass cover. Construction of absorber plate, which includes copper pipe and copper plate act as a fin are joint by gas welding. 2.54 cm diameter copper pipe and 0.6 cm thick copper plate was used to construct the collector. The distances between the centres of the pipes were 7.55 cm. Heat retention from solar collector used to corkwood and for measurement, temperature thermocouple was used. Solar collector tilted at three different angles 25°, 35° and 45°, because the angle is varied by ≈ +0 to 20^0 with the latitude of the experiment location (Rajshahi, Bangladesh). The latitude of the location is 24^0 North. However, the experimental setup is installed on roof top in south direction as shown in Fig. 1.

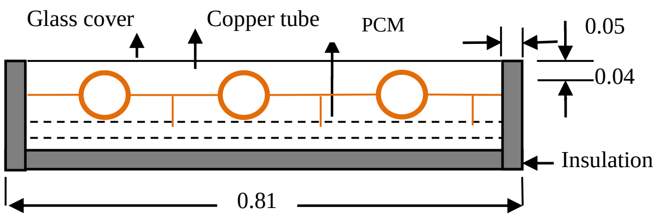

Fig. 1. Configuration details of the cross section of a photovoltaic-thermal system (dimensions in meter).

2.2. System description

Used phase change material filled into a storage tank in which, lateral side contract with absorber plate through the suitable inlet. Phase change material act as a thermal energy storage media in which, the solar collector was made with a back layer of phase change material. This type of phase change material storage heat within sunshine hours. The melting point of used phase change material is 56°C and latent heat of fusion is 256 kJ/kg. The thermocouples were used to measure absorber plate temperature and phase change material temperature. Less use space cover with solar panel that produces heat use for external energy source. The water flow rate from the water source to the entrance of the solar collector was controlled by ball valve.

Reflected and direct solar radiation fall on compound parabolic concentrator in which, incident radiation heated the absorber plate and storage heat in phase change material. The walls of the reflectors were in parabolic shape and surface wall made of reflected glass. The dimension of the compound parabolic concentrator has 1.66 m and 1.89 m head to head reflector distance and height respectively as shown in Fig. 2. Outdoor experiment was performed and the position was considered suitable for geographical location of Rajshahi (RUET), Bangladesh. This experiment was performed from December 2015 to May 2016 and experiment data collection started at 11 a.m. and ended at 4 p.m.

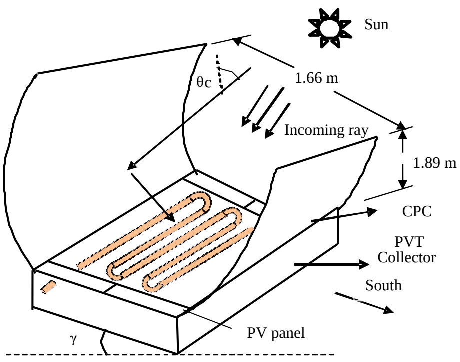

Fig. 2. Photovoltaic- thermal solar collector system used in this study.

2.3. Measuring equipment

Figure 3 shows the schematic diagram of the system to determine the electrical and thermal characteristics of PVT collector. Water is brought to the circulation tube by water control valve and pump. For measuring the surface temperature along the flow direction, five thermocouples were distributed at various positions on the surface of the solar collector and for measuring temperature of PCM another five thermocouples were distributed at different position in the PCM tank. Digital thermometers were used for determining input and output water temperature from the solar collector. Water flow meter was used for measurement of mass flow rate to the collector. All measuring data has been continuously monitored every one hour. Electric multi meter was used to measurement voltage and current from the collector during the day.

Thermocouple data from collector, which have been measured and recorded every thirty minutes. To determinate the total generated energy, these data was used and stored in the data storage unit. Solar radiation intensity has been measured by photovoltaic trainer calibrated with pyranometer and performed by half an hour. The temperature of the glass cover was measured by a heat sensor in which, laser fall on the glass cover and get a direct reading. The thermocouple that measured the ambient temperature was kept in a shelter to protect it from direct sunlight.

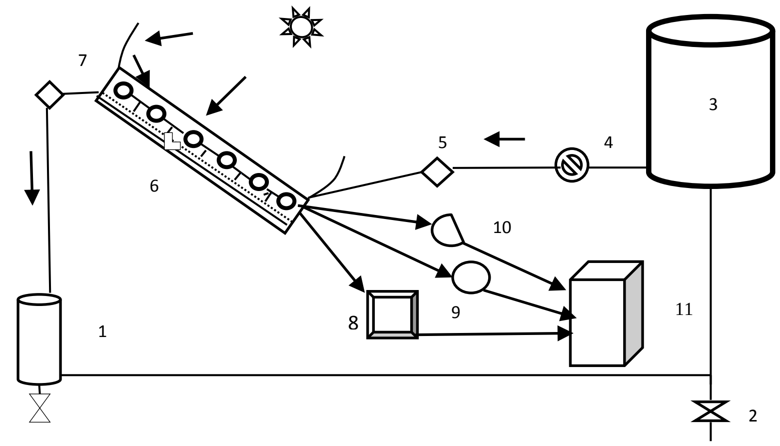

Fig. 3. Schematic diagram of the system of PVT collector: (1) Hot water storage, (2) Valve, (3) Pump, (4) Flow meter, (5) Inlet thermometer, (6) Collector with sun, (7) Outlet thermometer, (8) Pyranometer, (9) Thermocouple, (10) Voltage-current meter, (11) Data storage unit.

2.4. Mathematical analysis

The performance of the solar collector is analysed by measuring various factors with some modification of the basic Hottel-Bliss-Whillier equation [25]. Single glass covers thermal network system with phase change material use in this study shown in Fig. 4. The overall loss coefficient (U_L) is express by:

$$U_L=U_t+U_b+U_e \tag{1}$$

where, U_t *s* heat loss coefficient from top side, U_b is heat loss coefficient from back side and U_e is heat loss coefficient from edge side.

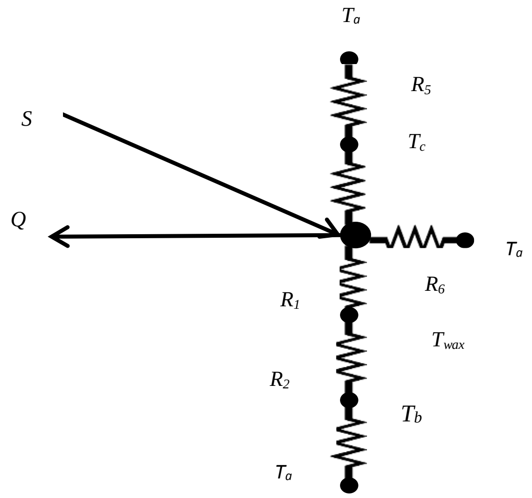

Fig. 4. Thermal network for collector system.

Five series of resistance from top to bottom, which express most energy loss from the collector. Edge heat loss coefficient may be small for better insulation. [26]. Back heat loss coefficient (U_b) is given by:

$$U_b = U_e = \frac{K}{x} \tag{2}$$

where, k represents the insulation thermal conductivity and x is the thickness of insulation on the collector.

The heat loss on top surface is calculated from radiation and convection energy for plate surface [27]. Top heat loss coefficient (U_t) of this system is given by:

$$U_t = \left[\frac{1}{(h_{p-c}+h_{r,p-c})} + \frac{1}{(h_w+h_{r,c-s})}\right]^{-1} \tag{3}$$

where, h_{p-c} is convection heat transfer coefficient pipe and cover, $h_{r,p-c}$ is coefficient of radiation between pipe and cover, $h_{r,c-s}$ is radiation heat transfer coefficient cover and sky and h_w is wind velocity coefficient of convection.

At steady state, the solar collector performance may be described by using the useful energy, thermal and optical loss. The solar radiation absorbed by the collector in which, difference between incident solar radiation on the collector and the optical losses. The loss of thermal energy from the collector to the surrounding are due to the radiation, conduction and convection. Therefore, the useful energy gain may be calculated for a collector of aperture area as

$$Q_u = F_R A_C [S - U_L (T_i - T_a)] \tag{4}$$

where, F_R represents heat removal factor from collector, A_c represents frontal area solar collector, T_i represents inlet temperature of water, S represents total absorbed energy by solar collector and T_a represents temperature of ambient in the environment.

The heat removal factor of the system is given by:

$$F_R=\frac{mC_P}{AcU_L}[1\text{-}exp(-\frac{AcU_LF}{mCp})] \quad (5)$$

where, m is a mass flow rate of water from collector, C_p is specific heat of working water and F is collector efficiency factor.

Electrical output is calculated from:

$$P=V\times I \quad (6)$$

where, V and I are the voltage and maximum current.

The thermal efficiency of this system is calculated from:

$$\eta_t=\frac{Qu}{HA_C\eta_0 CR} \quad (7)$$

where, H is total radiation of solar on the collector, CR is Concentration Ratio and η_0 is the optical efficiency and its value is 0.75 [28].

3. Results and discussion

To determine photovoltaic thermal solar collector performance, technical equation has been used to measure different data such as phase change material temperature (T_{PCM}), plate temperature (T_p), Outlet water temperature (T_0), Inlet water temperature (T_i), Ambient temperature (T_a). The performance also depends on top heat loss coefficient in which, its perfect result gives arrangement of solar collector construction. The solar collector considers various design variables like collector tilted angle (γ), space distance between the glass cover and absorber plate. Different types of tests were performed on photovoltaic-thermal storage solar collector with compound parabolic concentrator during December, January and February in winter season and March, April and May in the summer season. Experiments were conducted 10 clear days in each month and the results of one clear day of each month are presented here. Phase change material and plate temperature was increased sharply up to 1 p.m. after that it becomes slower and the phase change material temperature was found to be greater than that of the plate temperature, which denotes the expected storage capacity. Similar trends of both plate and PCM temperatures before and after 1 p.m. were noticed for the clear day of December, January, and February. Sometimes phase change material temperature value was high around 4 p.m. for a clear day as shown in Fig. 5 and indicating phase change material used as a heat source, which works on off sunshine hour. Photovoltaic thermal solar collector use as a water base is able to achieve a higher overall energy output from per unit collector area.

For daily operation towards the end of the day the thermal performance of the photovoltaic thermal system will drop considerably. When water temperature finally reaches the desired temperature for a specific application, it can be supplied to meet the hot water requirement. In addition, if the phase change material is used as a heat storage media then higher performance can be achieved at low sunshine hours as the phase change material will release the stored energy. Direct solar energy and storage capacity of energy use in a same unit is very promising concept and it may be able to eliminate many problems of using solar system [29, 30]. In this work, the plate temperature is normally higher than PCM temperature because of heat transfer resistance between absorbing plate and PCM.

The Inlet temperature was gradually increased up to 1 p.m. and then decreased gradually. However, after decreasing at 3 p.m. temperature difference showed an increasing trend due to storage phase change material. This graph showed maximum outlet temperature around 55 ºC for clears day in winter season as shown in Fig. 6 because plate temperature was properly heated up. Phase change material may store a large amount of heat and change its phase from solid stay to liquid stay in clear day times.

Eicker [31] commented that this storage heat may be back up to the system as the phase change material change phase again from liquid to solid. The main advantage of storage method the temperature fluctuation in a solar thermal system is reducing by extra heat absorbed at peak radiation hours and it release when solar radiation is low or absent. The use of a different feature in the storage tanks of the solar collector system and different phase change material has been experimentally investigated with a different condition.

Figure 7 explains the effect of reflector position on plate temperature at different times of a clear day in December, January and February. Plate temperature was investigated at three different positions of the upper and bottom reflector, which were denoted by $\gamma 1$, $\gamma 2$ and $\gamma 3$. According to the location and season of the experiment, it was assumed that 45^0 ($\gamma 2$) is the optimum reflector position. In order to justify this assumption, the plate temperature was measured at two other reflector positions, i.e., 35^0 ($\gamma 1$) and 55^0 ($\gamma 3$).

Plate temperature increased up to 1 p.m. for all reflector position because ray fall on the plate increased the plate temperature and decreased after 1 p.m. due to the lower radiation. It is observed that plate temperature at 1 p.m. varies from 64 ºC to 87 ºC for different tilt angles and months. Moreover, it can be seen from the figure that maximum plate temperature in December, January and February were 81 ºC, 82 ºC and 87 ºC respectively at 45^0 ($\gamma 2$) tilt angle. Therefore, 45^0 ($\gamma 2$) is the perfect reflectors position as the maximum solar radiation is concentrated at this angle. At this reflector position, the plane of the sun's position is normal to the surface plate.

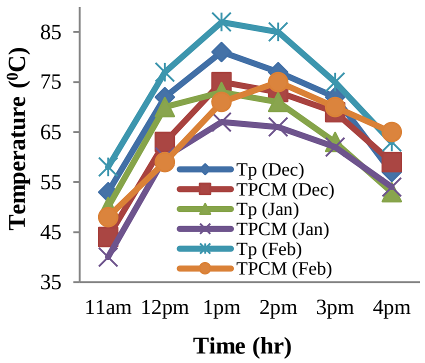

Fig. 5. Variation of phase change material and plate temperature with time.

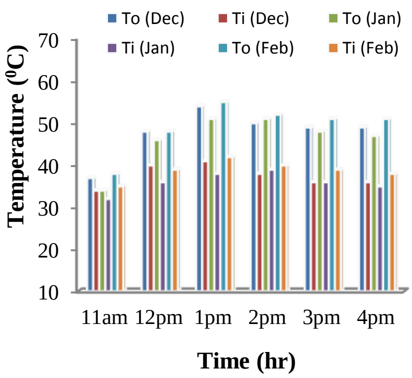

Fig. 6. Variation of inlet and outlet water temperature with time.

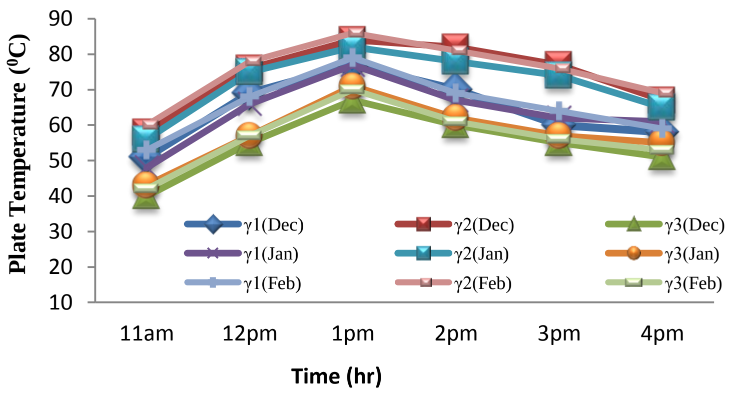

Fig. 7. Variation of plate temperature with time.

Thermal efficiency increases gradually with the water flow rate for three months is shown in Fig. 8, which was due to the reason that, as more water passed through the solar collector system and more thermal energy was extracted. The highest thermal efficiency was observed the month of February, which exhibited an increase from 41% to 44% when the mass flow rate increase from 0.002 kg/s to 0.004 kg/s.

Thermal efficiency for December and January months shows marginal variation, but it varies significantly in the month of February. Elevation of the efficiency is attributed to the rise in solar radiation intensity in February as compared to December and January. The effective performance of a solar collector may be determined by getting the thermal efficiency of the contribution of inlet temperature, ambient temperature and incident solar radiation.

The rate of energy added to the transfer water as it passes through the collector and storage phase change material when the rate of the incident solar falls on the solar collector. Theoretically, actual useful energy gain of a collector to the useful gain act as heat removal factor. Heat removal factor from the collector decrease with the increase of water output temperature and lastly heat removal factor from the collector increase when the water temperature decreases as shown in Fig. 9. For a local made flat plate collector heat removal factor varies from 0.52 to 0.58 but these factors can be considered constants for a given design [32]. In this study, its value will start from around 0.96 then decrease with increased solar radiation and minimum value indicate around 0.94 at time 1 p.m. Lastly heat removal factor increase when the temperature decreases up to 4 p.m. The heat removal factor for the thermal storage collector was found to be in the range 0.94-0.96 compared to 0.52-0.58 for the conventional one.

In Fig. 10, the outlet water temperature decreases with the increase of water flow rate. Water outlet temperature varies from 50 °C to 60 °C in clear day where corresponding mass flow rate was 0.008 kg/s to 0.004 kg/s. Water flow rate measure three different times and three months of the year that compares with output water temperature was decreased due to thermal capacity.

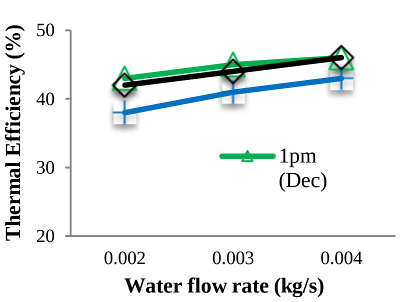

Fig. 8. Variation of thermal efficiency with water flow rate.

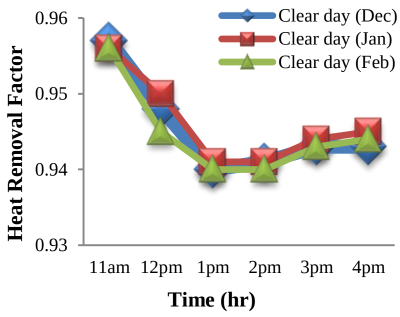

Fig. 9. Variation of heat removal factor with time.

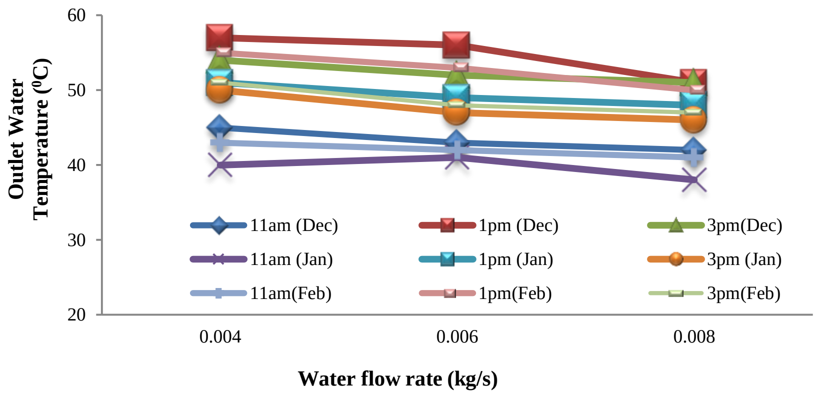

Fig. 10. Variation of outlet temperature with water flow rate.

Total efficiency sum of thermal energy and photovoltaic efficiency were calculated from the ratio of energy gain and solar radiation fall on the system. Graph shows total efficiency slightly decreased with the increase of solar radiation gradually in summer season and total efficiency was comparatively high found at 11:00 a.m. and these result was varied from 58%-68%. In this Fig. 11, compare variation of total efficiency among three months with time and comparable better result in the month of April and May.

Comparison of the inlet, outlet, ambient and plate temperature with time of the day under same solar radiation in summer season is shown in the graph. The distribution of temperature from thermal collector was nearly uniform, that is important for applications in domestic hot water and industrial uses. The value of solar radiation and temperature for different hours are investigated and compared. It can be seen as shown in Fig. 12 that at the beginning of the collect data, the solar radiation in a clear day increase at a faster rate and after 1 p.m. it also decreases gradually. Nearly similar trends for all month to be noticed for a clear day of May. The effect of heat storage of thus days on climate condition is depending on phase change material. For all figures, five data were carried and the averaged value is used for each data point. The hourly test results for the month of May at 1 p.m. for solar radiation and temperature for a selected day are presented in Table 1.

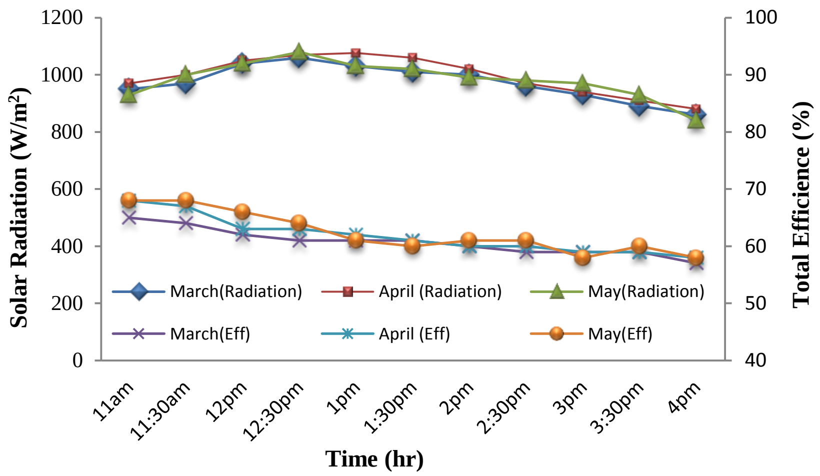

Fig. 11. Variation of total efficiency with time.

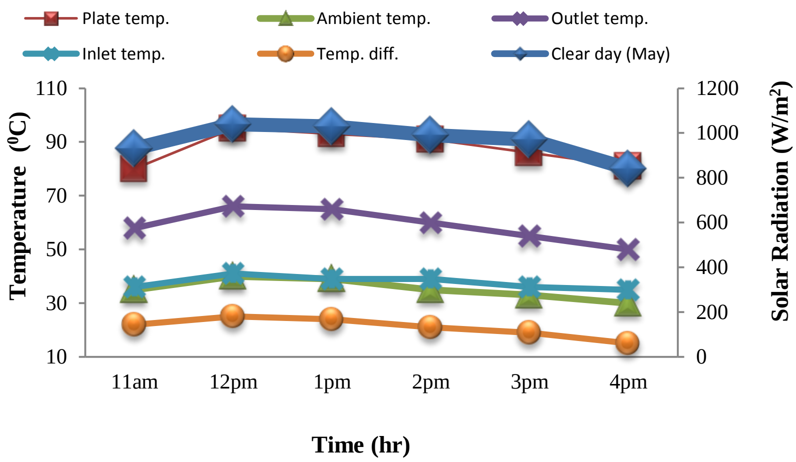

Fig. 12. Variation of temperature and solar radiation with time.

Table 1. Hourly average test results for the month of May at 1 p.m.

Data no.	Plate temperature (^{0}C)	Ambient temperature (^{0}C)	Outlet temperature (^{0}C)	Inlet temperature (^{0}C)	Solar radiation (W/m^2)
1	93.5	40	66	39	1035
2	93.5	40	65.5	39	1032
3	93.5	40	65.5	39	1031
4	92.5	40	64.5	39	1028
5	92.5	40	64	39	1024
Average value	93.1	40	65.1	39	1030

The total generated thermal and electric energy by PVT collector during the summer season was gradually increased. At 4 p.m. its maximum value of thermal energy around 1500 W and electric energy around 120 W. As shown in Fig. 13 the thermal and electrical power against time shows that, as the time of the day increase, the thermal and electrical power output increased exponentially.

The thermal and electrical energy increases up to 4 p.m. for a clear day with the increase of daytime. Thermal and electrical energy was high in May compared to others month for a clear day. The flat plate collector partially covered by the photovoltaic panel and it was observed that combined the production of electricity generation and hot water, the collector partially covered by the photovoltaic panel and there are benefits for the users whose main demand was hot water production [3, 33].

The performance factor determination of thermal collector is depending on the function ratio of temperature difference divided by solar radiation. At 1 p.m. maximum performance factor value denoted 0.0135 $kW^{-1}m^2$. The change of water output and input temperature during the day in thermal collector compare between three months in given Fig. 14. The outlet and inlet temperature during the day month of May were higher than water outlet and inlet temperature compare other two months.

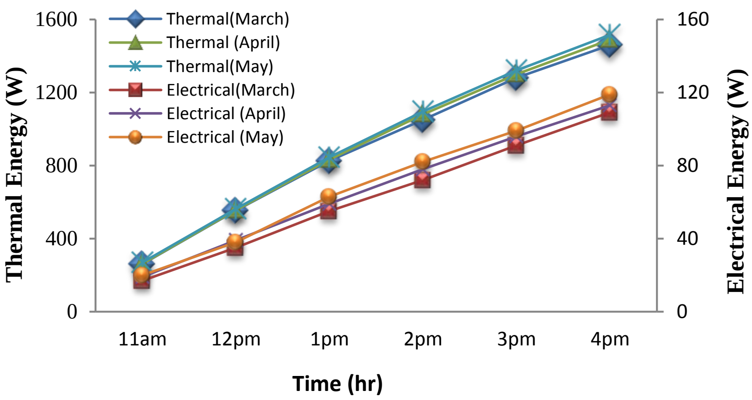

Fig. 13. Variation of total generated energy with time.

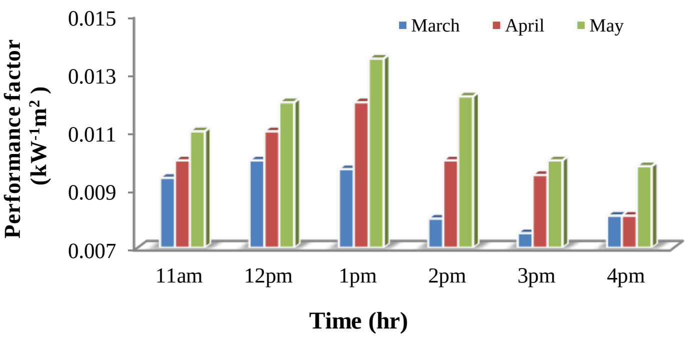

Fig. 14. Variation of performance factor with time.

4. Conclusion

Experimental investigations on the photovoltaic-thermal solar collector with compound parabolic concentrator were found in winter and summer season. Phase change material was more useful in solar system for better heat storage capacity in which, phase change material temperature was found to be higher than the plate temperature meaning heat storage capacity of the phase change material. Maximum outlet temperature obtains around 55 ^{o}C for clears day and gradually increasing temperature difference denoted expected power gain of water in winter season. Change of reflector position to obtain maximum concentration as a result highest plate temperature indicates at 1 p.m., which varies from 64 ^{o}C to 87 ^{o}C. For thermal efficiency increase from 41% to 44% when the mass flow rate increase from 0.002 kg/s to 0.004 kg/s. Heat removal factors value will start from around 0.96 then decrease with increase solar radiation and minimum value indicate around 0.94 at time 1 p.m. Water output temperature varies from 50 ^{o}C to 60 ^{o}C in clear day where corresponding mass flow rate was 0.008 kg/s to 0.004 kg/s and total efficiency of the collector was varied from 58%-68% in summer season.

Maximum value of thermal energy around 1500 W and maximum performance factor value for collector was denoted 0.0135 kW^{-1}m^{2}. Determine experimental data in order to obtain the maximum concentration of solar radiation, collector fixed at optimum positions during among those three months in winter season. Satisfactory concentration of reflector refer maximum reflected ray fall on the absorber plate denote maximum plate temperature. This study can be further extended to design better reflector to increase the thermal efficiency of the photovoltaic thermal collector, which may reduce the initial capital expenditure. In addition to this, the collector can be designed and installed locally as an integrated system with a building to supply hot water for both domestic and industrial applications.

Nomenclatures

A_c	Frontal area solar collector, m^2
C_p	Specific heat of working water, J/kg k
F	Collector efficiency factor
F_R	Heat removal factor from collector
H	Total radiation of solar on the collector, W/m^2
h_{p-c}	Convection heat transfer coefficient pipe and cover, W/m^{2}K
$h_{r,c-s}$	Radiation heat transfer coefficient cover and sky, W/m^{2}K
$h_{r,p-c}$	Coefficient of radiation between pipe and cover, W/m^{2}K
h_w	Wind velocity coefficient of convection, W/m^{2}K
k	Insulation thermal conductivity, W/m K
m	Mass flow rate of water from collector, kg/s
P	Electrical power, W
Q_u	Useful energy of the solar collector system, W
R_1	Plate to phase change material thermal resistance, m^{2}k/W
R_2	Back insulation thermal resistance, m^{2}k/W
R_3	Edge of the collector to ambient thermal resistance, m^{2}k/W
R_4	Plate surface and glass thermal resistance, m^{2}k/W
R_5	Glass to ambient thermal resistance, m^{2}k/W
R_6	Collector side and ambient thermal resistance, m^{2}k/W

S	Total absorbed energy by solar collector, W/m^2
T_a	Temperature of ambient in the environment, k
T_b	Collector bottom temperature on the collector, k
T_c	Glass cover temperature on the collector, k
T_i	Inlet temperature of water, k
T_p	Temperature of surface plate on the collector, k
U_b	Heat loss coefficient from back side, W/m^{2}K
U_e	Heat loss coefficient from edge side, W/m^{2}K
U_L	Overall heat transfer coefficient, W/m^{2}K
U_t	Heat loss coefficient from top side, W/m^{2}K
x	Thickness of insulation on the collector, m

Abbreviations

CR	Concentration Ratio

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