American Journal of Mechanical Engineering, 2020, Vol. 8, No. 4, 154-162
Available online at http://pubs.sciepub.com/ajme/8/4/2
Published by Science and Education Publishing
DOI:10.12691/ajme-8-4-2

Performance Evaluation of a Hybrid Photovoltaic Solar Thermal System

Md. Mizanuzzaman, Md. Faisal Kader*

Department of Mechanical Engineering, Faculty of Engineering, Bangladesh Military Academy (BMA), Bhatiary, Chattogram, Bangladesh
*Corresponding author: mfaisaliut@yahoo.com

Received September 23, 2020; Revised October 25, 2020; Accepted November 02, 2020

Abstract Hybrid photovoltaic/thermal (PV/T) system consists of a solar photovoltaic panel and a heat extraction unit, which are mounted together. These systems can simultaneously provide electrical and thermal energy, thus achieving a higher energy conversion rate of the absorbed solar radiation than the conventional photovoltaic systems. In this study a hybrid PV/T system was designed and manufactured, both air and water circulation was considered with modifications in the air channel. First modification was to place a thin flat metallic sheet (TMS) inside the air channel and second one was to use painted black ribbed surfaces at the bottom of the air channel. To observe the variations of heat transmittance with different shape of the ribs four experimental setups with a trapezoidal, saw tooth forward, a saw teeth backward ribbed surfaces and a flat plate were used. Natural convection was applied instead of forced convection to increase the system's net electrical output & thereby the overall system efficiency. All setups were of the same capacity, projected area, average depth and water heat extraction method. The experiment was carried out during the months of February to June, 2018. Significant improvement in the performance was observed with the above stated modifications. In an intense sunny day of March, the maximum temperature of water was found to be 45°C for Trapezoidal, 44°C for Saw teeth forward, 43°C for Saw teeth backward and 41°C for flat plate setup. Maximum temperature of air inside the air channel was found to be 39°C for Trapezoidal, 38°C for Saw teeth forward, 37°C for Saw teeth backward ribbed surfaces and 36°C for flat plate in an intense sunny day of march 2018 with an ambient temperature of 34°C. The average efficiency from all calculated values is found to be 64% for Trapezoidal, 62% for Saw teeth forward, 61% for Saw teeth backward and 58% for flat plate setup.

Keywords: *hybrid photovoltaic/thermal system, solar thermal, solar photovoltaic*

Cite This Article: Md. Mizanuzzaman, and Md. Faisal Kader, "Performance Evaluation of a Hybrid Photovoltaic Solar Thermal System." *American Journal of Mechanical Engineering*, vol. 8, no. 4 (2020): 154-162. doi: 10.12691/ajme-8-4-2.

1. Introduction

Solar energy is an important clean, cheap and abundantly available renewable energy. The earth receives an incredible supply of solar energy. Different Photovoltaic cell converts only 5-15% of the incoming solar radiation into electricity, with the greater percentage converted into heat. The solar radiation converted into heat increases the temperature of the PV modules, resulting in the drop of their electrical efficiency. This undesirable effect can be partially avoided by applying a suitable heat extraction mode with a fluid circulation, keeping the electrical efficiency at a satisfactory level. Furthermore, this extracted heat can be utilized for heating water. For this purpose the concept of Hybrid PV/T solar systems were developed. The PV modules that were combined with thermal units, where circulating water of lower temperature than that of PV modules was heated to constitute the Hybrid PVT solar systems. It provides electrical and thermal energy, increasing therefore the total energy output from PV modules using the same projected area. The objectives of this study are to carry out an experimental investigation to compare the performances of four PV/T collectors having three different ribbed surfaces (Trapezoidal, Saw teeth (tooth) forward, Saw teeth backward rib) and a flat plate opposite to each absorber plate. All collectors were of same capacity, projected area, and average depth.

Many theoretical and experimental works have been carried out for the improvement of hybrid PVT solar systems since its appearance in 1980's. Among the first who provided the main concepts of these systems with results, by the use of water or air as heat removal fluid. Bhargava *et al.* [1] present results regarding the effect of air mass flow rate, air channel depth, length and fraction of absorber plate area covered by solar cells (packing factor, PF) on single pass, Sopian *et al.* [2] on single pass and double pass hybrid PVT system performance. Garg and Adhikari [3] present a variety of results regarding the effect of design and operation parameters on the performance of air type PVT systems.

In the above works the calculated thermal efficiencies of liquid type PVT systems are in the range of 45% to 65%, the higher values derived for systems that include thermal losses suppression by using air gap with glazing. Regarding air type PVT systems, the thermal efficiency depends strongly on air flow rate, air duct depth and collector length. For higher values of air flow rate, small air duct depth and long PVT systems thermal efficiencies up to about 55% are given by the theoretical models. The packing factor is an important parameter in most of the above papers.

Because of their easier construction and operation, hybrid PV/T systems with air heat extraction are more extensively studied, mainly as an alternative and cost effective solution to building integrated PV (BIPV) systems. Following the above referred studies, test results from PVT systems with improved air heat extraction are given by and from roof integrated air-cooled PV modules by present design and performance studies regarding air type building integrated hybrid PVT systems.

The building integrated photovoltaic is going to be a sector of a wider PV module application in future. The works on building integrated air-cooled photovoltaic include the studies on the multi-operational ventilated PVs with solar air collectors, the ventilated building PV facades and the design procedure for cooling air ducts to minimize efficiency loss [4,5].

Despite these improvements, commercial application of PVT/air collectors is still marginal, but it is expected to be wider in the future where many building facades and inclined roofs will be covered with photovoltaic. PVT/water systems are more expensive than PVT/air systems due to additional cost of the thermal unit with the pipes for the water circulation. On the other hand water from mains does not often exceeds 25^0C and ambient air is usually higher during summer in low latitude countries and water heat extraction is of more practical value at these locations as it can be used during all seasons. The liquid type hybrid PVT systems are less studied than air type systems.

Regarding recent works, modeling results [6], the study on domestic PVT systems [7] can be referred. PVT/ water collectors can replace thermal collectors for water heating in the domestic and industrial sectors, but they are not yet cost effective and this is the main reason for their niche market penetration.

An experimental study of facade-integrated photovoltaic/water-heating system has been reported done by Chow *et al.* [8]. This work describes an experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system. Collectors are mounted at vertical facades. Different operating modes were performed with measurements in different seasons. Natural water circulation was found more preferable than forced circulation in this hybrid solar collector system. The thermal efficiency was found 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer of Hong Kong.

In China, the energy performance of PV/water-heating collector systems with natural circulation of water has been examined by the authors Chow *et al.* [9,10] based on the weather conditions of Hong Kong and Hefei. These studies showed that the use of a flat-box type thermal absorber is very effective. In Hong Kong for a stand-alone PVT collector system with mono-crystalline solar cells, the daily thermal efficiency was found 48.3% in winter and 45.4% in summer at zero reduced temperature (i.e. when the initial water temperature in the storage tank is as cold as the mean ambient temperature on the day of measurement). This was for water storage to collector-area ratio (M/Ac) of 96.6 kg/m^2 and at a desirable tilt angle.

Design and performance improvements of hybrid PVT systems with water or air as heat removal fluid have been carried out at the IUT including modifications that contribute to the decrease of PV module temperature and to improve the total energy output (electrical and thermal) of the PVT systems [11]. Two systems (PVT/UNGLAZED and PVT/GLAZED) were tested outdoors, consisted of pc-Si PV modules and heat exchanger of copper sheet with copper pipes. Also, PVT solar water heaters of ICS [12] and of thermosiphonic type have been studied.

Tripanagnostopoulos [13] at the University of Patras, Greece has done an extended research on PVT systems aiming at the study of several modifications for system performance improvement. A new type of PVT collector with dual heat extraction operation, either with water or with air circulation is presented. Experiments with dual type PVT models of alternative arrangement of the water and the air heat exchanging elements were performed. The most effective design was further studied, applying to it low cost modifications for the air heat extraction improvement. The modified dual PVT collectors were combined with booster diffuse reflectors, achieving a significant increase in system thermal and electrical energy output.

The present work was studied for performance evaluation of a Hybrid PV/T dual solar collector using different ribbed surfaces placed opposite to the air channel wall. Tests were carried out in the months of February to June, 2018 at Gazipur, Bangladesh.

2. Experimental Setup

Four experimental setups were fabricated with similar design and dimensions except the shape of the ribs. All works were done in the Mechanical Workshop of Islamic University of Technology (IUT), Gazipur, Bangladesh. The whole setup was constructed in a wooden box. PV panels were set at the top of the box. Thin Metallic Sheet (TMS) was placed at the middle part of the box on top of which pipes were set for water circulation. Air channel of 0.1m height was kept under the water heat exchanger. Different ribbed surfaces (*Trapezoidal, Saw* **teeth** *forward, and Saw* **teeth** *backward) and a Flat plate* of same height and dimension were placed on opposite wall of the air channel. The whole inner portion of the box was insulated. TMS and Ribbed plates were painted black for better heat absorption. The Photograph of the installed experimental setup has been presented in Figure 1. The setup was installed in front of the mechanical workshop of IUT. Details of hybrid collector and test specimens used in this study are shown in Figure 2 and in Figure 3.

Figure 1. Photograph of the installed experimental setup

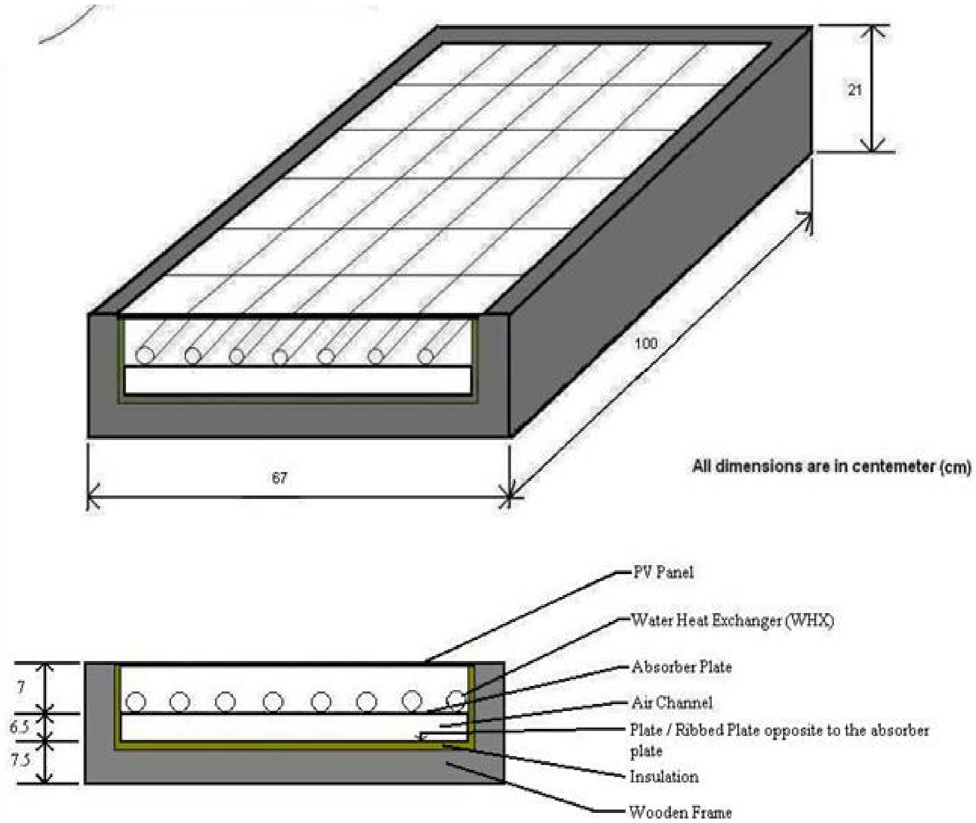

Figure 2. Details of Hybrid Collector (All dimensions are in cm)

2.1. Test Procedures

All the collectors were installed in front of the IUT workshop where there is no obstacle to sunshine and faced towards south with an inclination angle of 23.5^0 which is the best angle to collect as much as available radiation. Photograph of which are shown Figure 1. All storage tanks were filled early in the morning with fresh water. Temperatures were measured for PV panel (T_{PV}) and water heat exchanger (T_{WHX}), by using seven 36 S.W.G. Chromel-Alumel thermocouples. Selector switches were used to switch between the thermocouples. Ambient temperatures (T_{amb}), solar radiation (G) were recorded hourly each day from at 8 AM up to 6 PM. All readings were recorded in specific data sheets.

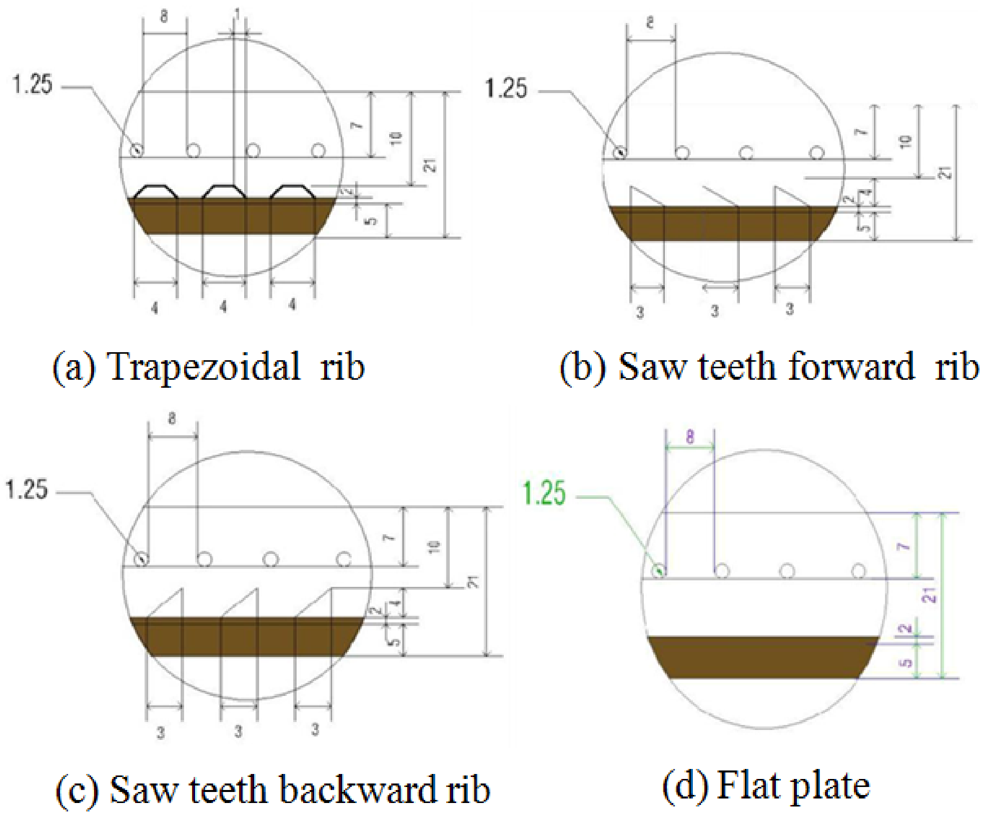

Figure 3. Test specimens. (All dimensions are in mm)

2.2. Equations Used

To calculate the thermal efficiency (η_{th}) of the collector the following equations are used:

Heat energy absorbed at any time for the projected area,

$$Q_{ab} = m \times C_p \times \Delta T_w / A_a \left(Wm^{-2}\right)$$

Here, ΔT_w is the temperature difference between inlet and outlet of water.

Solar radiation received in that time for the projected area, G (Wm^{-2})

So thermal efficiency can be found from, $\eta_{th} = Q_{ab} / G$.

3. Results and Discussions

Performance study of four hybrid PVT systems were carried out in IUT Campus, Gazipur, Bangladesh during the months of February to June 2018. PV panel temperature and water heat exchanger surface temperature were recorded and plotted against time. These are presented from Figure 4 to Figure 13. Thermal efficiency is calculated for all the setups and average plotted in and presented in Figure 14. Thermal output is emphasized more than the electrical output in this study. As no electrical load is used as a part of the setup, output from PV panel is not hampered.

3.1. PV Panel Temperature

Temperature distributions of PV panels of different setups with time are shown in Figure 4 to Figure 8. As the PV panel receives the solar energy directly on top of the setup, panel temperature rises very quickly with time. The figures shows similar patterns of temperature survey with slight difference among four setups. PV panel temperature rises from 8:00 am to 12:00 noon and then decreases after 2:00 pm rapidly. In a sunny day of 15 February 2018, the maximum temperature of PV panel is found 61°C for Flat plate, 57°C for Trapezoidal, 57°C for Saw teeth forward and 59°C for Saw teeth backward plate. In a sunny day of 30th February 2018 the maximum temperature of PV panel is found 60°C for Flat plate, 56°C for Trapezoidal, 57°C for Saw teeth forward and 58°C for Saw teeth backward plate. In an intense sunny day of 15 March 2018, the maximum temperature of PV panel is found 62°C for Flat plate, 56°C for Trapezoidal, 57°C for Saw teeth forward and 59°C for Saw teeth backward plate. In a sunny day of 30 March 2018, the maximum temperature of PV panel is found 62°C for Flat plate, 56°C for Trapezoidal, 57°C for Saw teeth forward and 60°C for Saw teeth backward plate. In a sunny day of 15 April 2018, the maximum temperature of PV panel is found 62°C for Flat plate, 55°C for Trapezoidal, 56°C for Saw teeth forward and 59°C for Saw teeth backward plate. In a sunny day of 30 April 2018, the maximum temperature of PV panel is found 61°C for Flat plate, 54°C for Trapezoidal, 56°C for Saw teeth forward and 59°C for Saw teeth backward plate. In a partly cloudy day of 15 May 2018, the maximum temperature of PV panel is found 40°C for Flat plate, 44°C for Trapezoidal, 43°C for Saw teeth forward and 42°C for Saw teeth backward plate at the time was 02:00 PM. In a Rainy day of 30 May 2018, the maximum temperature of PV panel is found 40°C for Flat plate, 41°C for Trapezoidal, 40°C for Saw teeth forward and 39°C for Saw teeth backward plate. In an intense sunny day of 15 June 2018, the maximum temperature of PV panel is found 64°C for Flat plate, 63°C for Trapezoidal, 62°C for Saw teeth forward and 60°C for Saw teeth backward plate. In a sunny day of 30 June 2018, the maximum temperature of PV panel is found to be 62°C for Flat plate, 61°C for Trapezoidal, 60°C for Saw teeth forward and 59°C for Saw teeth backward plate.

Setup with Saw teeth forward and Saw teeth backward ribs setup gave lower temperature of the panel which shows better cooling of PV. Trapezoidal ribbed plate gave moderate cooling better than that of flat plate setup. In flat plate setup PV temperature is found always high, which shows inadequate heat transfer for PV cooling.

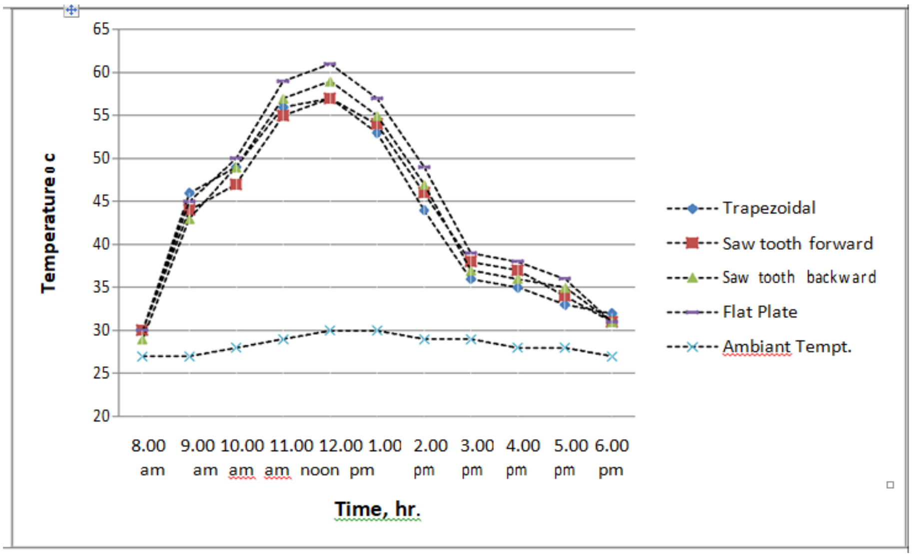

Figure 4. Temperature distribution of PV panel temperature on 15/02/2018

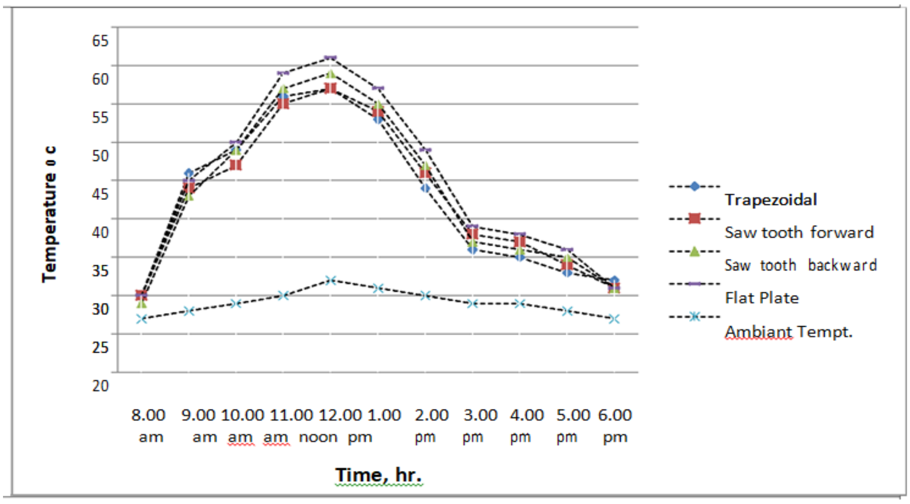

Figure 5. Temperature distribution of PV panel temperature on 15/03/2018

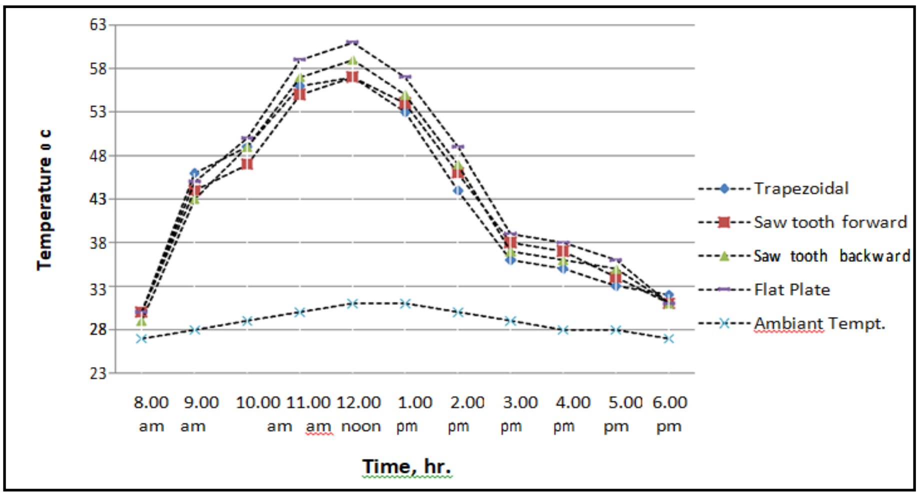

Figure 6. Temperature distribution of PV panel temperature on 15/04/2018

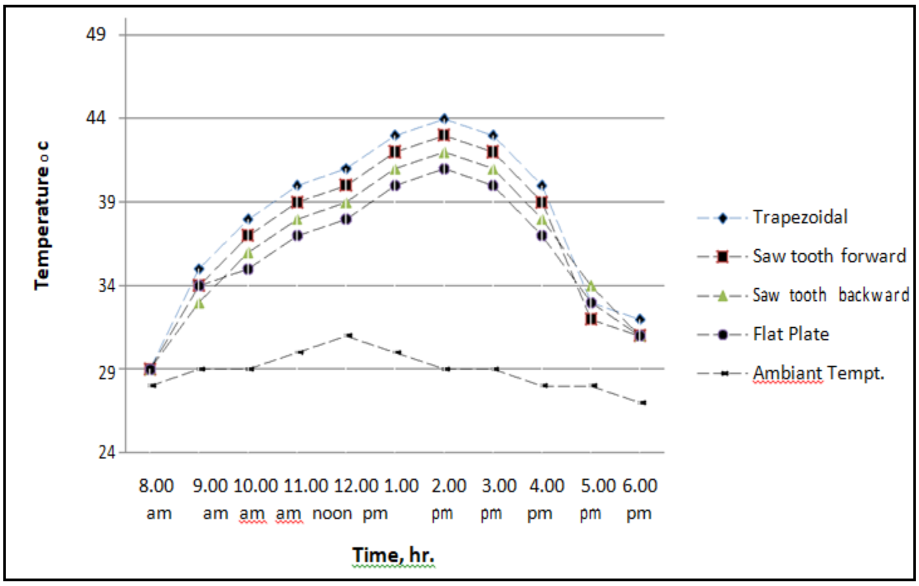

Figure 7. Temperature distribution of PV panel temperature on 15/05/2018.

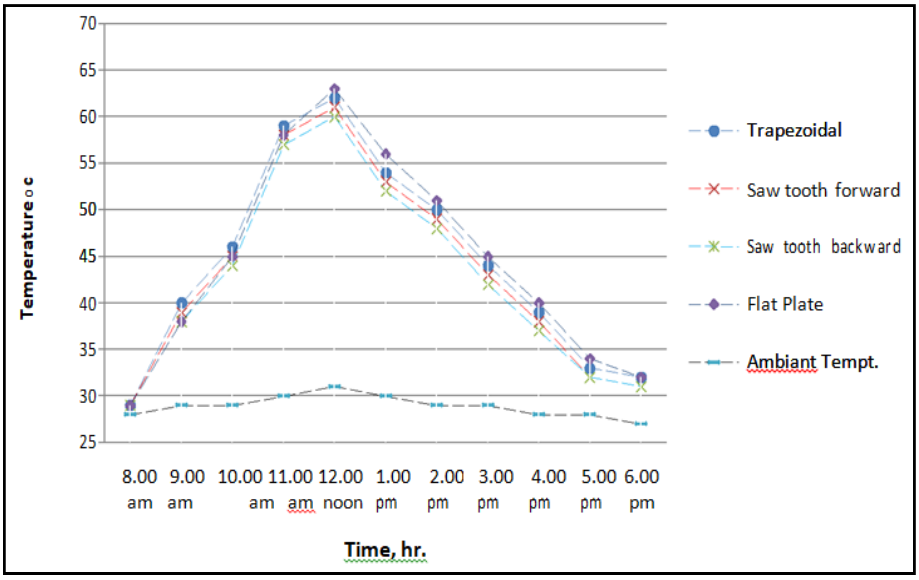

Figure 8. Temperature distribution of PV panel temperature on 15/06/2018

3.2. Water Heat Exchanger Temperature

Water Heat Exchanger (WHE) surface temperature distributions of different setups with time are shown in Figure 9 to Figure 13. Water heat exchanger with TMS is placed below the PV panel at the middle section of the setup. Heat energy is absorbed here from the PV rear surface and water is heated flowing through it. It is evident from these figures that the temperature of this heat exchanger also rises with time from 8:00 am to 12:00 noon and then decreases after 2:00 pm rapidly. In a sunny day of 15 February 2018, the maximum temperature of WHE is found 50°C for Flat plate, 48°C for Trapezoidal, 49°C for Saw teeth forward and 51°C for Saw teeth backward plate. In a sunny day of 30 February 2018 the maximum temperature of WHE is found 49°C for Flat plate, 46°C for Trapezoidal, 50°C for Saw teeth forward and 48°C for Saw teeth backward plate. In an intense sunny day of 15March 2018, the maximum temperature of WHE is found 48°C for Flat plate, 46°C for Trapezoidal, 49°C for Saw teeth forward and 47°C for Saw teeth backward plate. In a sunny day of 30March 2018, the maximum temperature of WHE is found 48°C for Flat plate, 46°C for Trapezoidal, 49°C for Saw teeth forward and 48°C for Saw teeth backward plate. In a sunny day of 15April 2018, the maximum temperature of WHE is found 49°C for Flat plate, 52°C for Trapezoidal, 52°C for Saw teeth forward and 49°C for Saw teeth backward plate. In a sunny day of 30 April 2018, the maximum temperature of WHE is found 49°C for Flat plate, 47°C for Trapezoidal, 51°C for Saw teeth forward and 49°C for Saw teeth backward plate. In a partly cloudy day of 15 May 2018, the maximum temperature of WHE is found 36°C for Flat plate, 38°C for Trapezoidal, 37°C for Saw teeth forward and 36°C for Saw teeth backward plate at the time was 02:00 PM. In a Rainy day of 30 May 2018, the maximum temperature of WHE is found 34°C for Flat plate, 37°C for Trapezoidal, 36°C for Saw teeth forward and 35°C for Saw teeth backward plate. In an intense sunny day of 15 June 2018, the maximum temperature of WHE is found 45°C for Flat plate, 48°C for Trapezoidal, 47°C for Saw teeth forward and 46°C for Saw teeth backward plate. In a sunny day of 30 June 2018, the maximum temperature of WHE is found 45°C for Flat plate, 47°C for Trapezoidal, 48°C for Saw teeth forward and 46°C for Saw teeth backward plate. Average good temperature is found in case of setup with Saw teeth forward rib. Average temperature difference between PV panel and WHE is around 10-12°C.

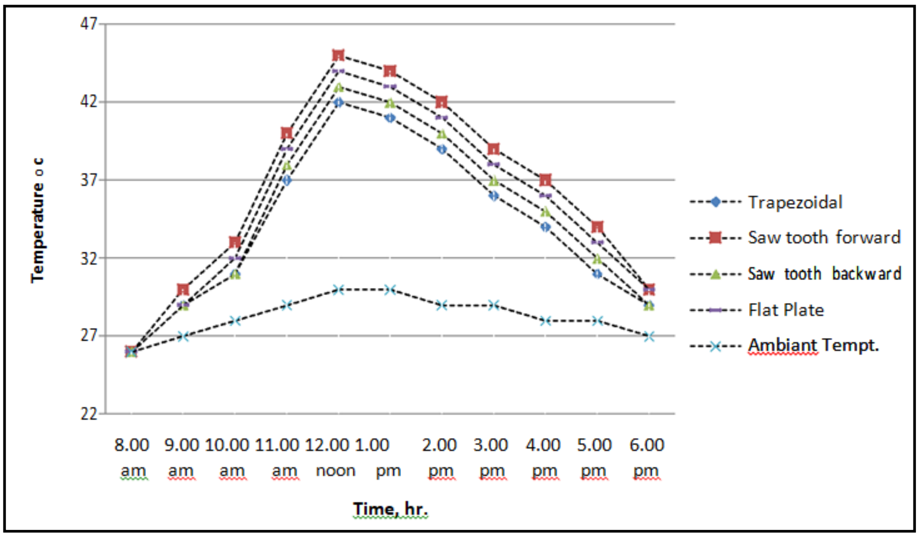

Figure 9. Temperature distribution of water heat exchanger temperature on 15/02/2018

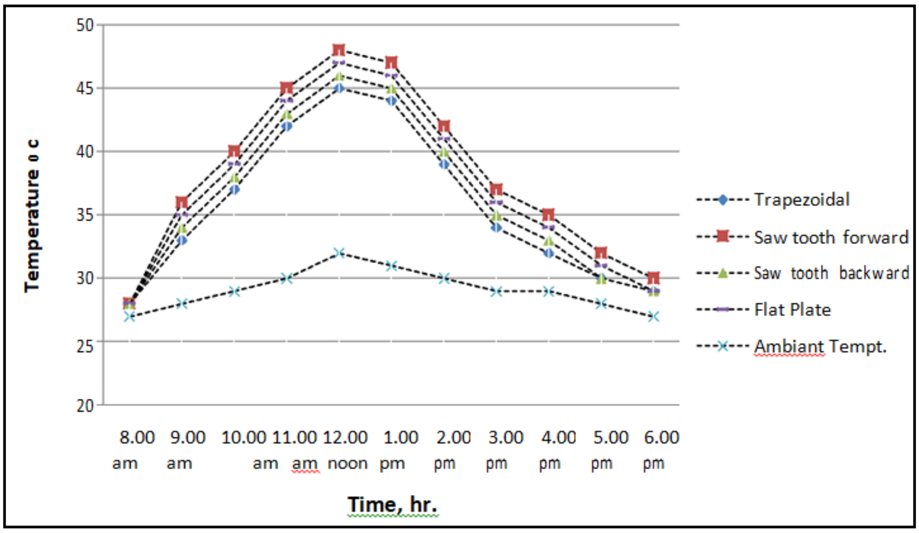

Figure 10. Temperature distribution of water heat exchanger temperature on 15/03/2018

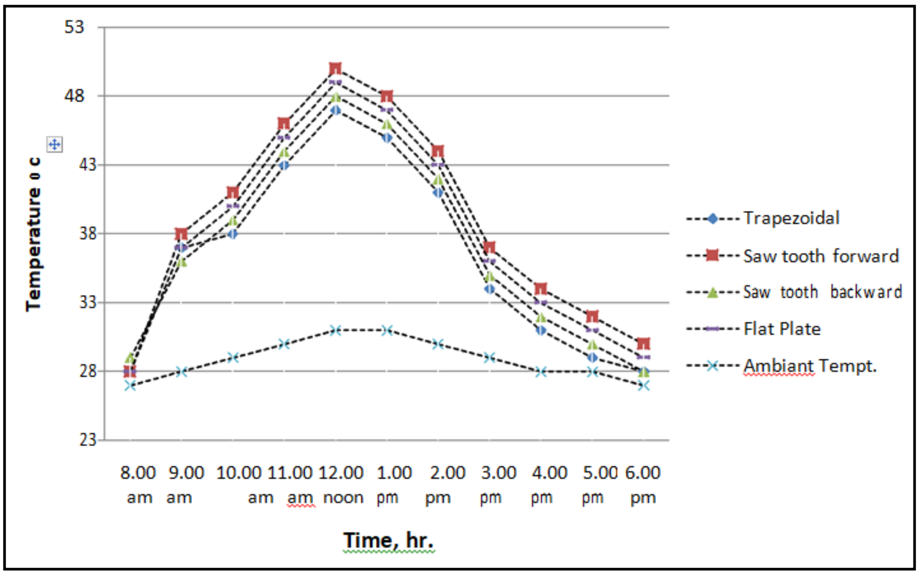

Figure 11. Temperature distribution of water heat exchanger temperature on 15/04/2018

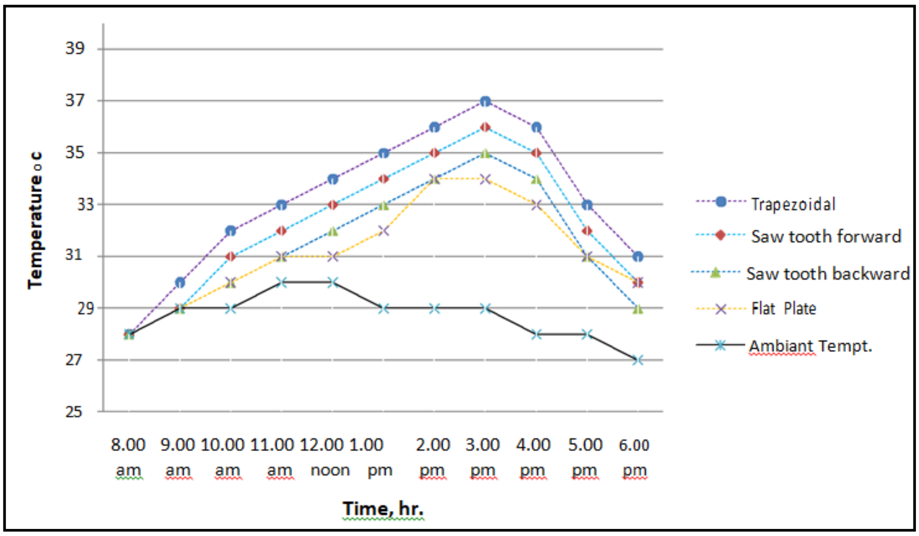

Figure 12. Temperature distribution of water heat exchanger temperature on 15/05/2018

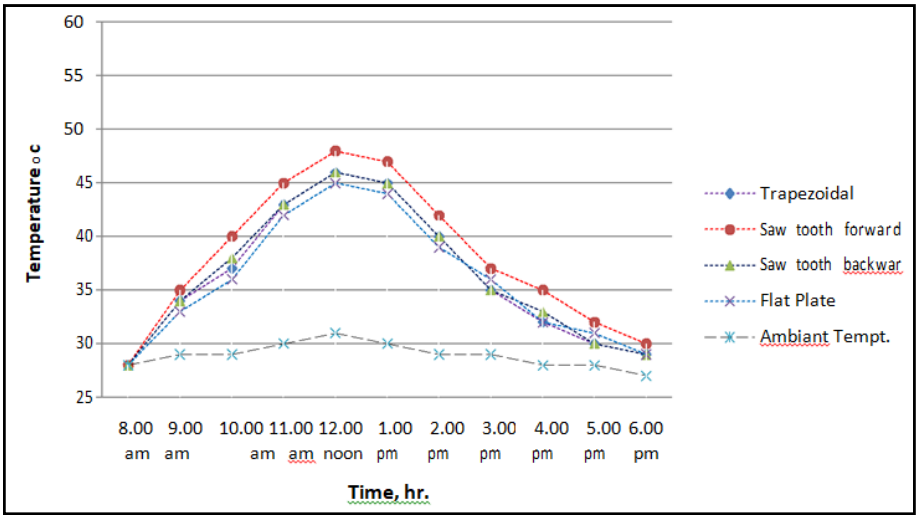

Figure 13. Temperature distribution of water heat exchanger temperature on 15/05/2018

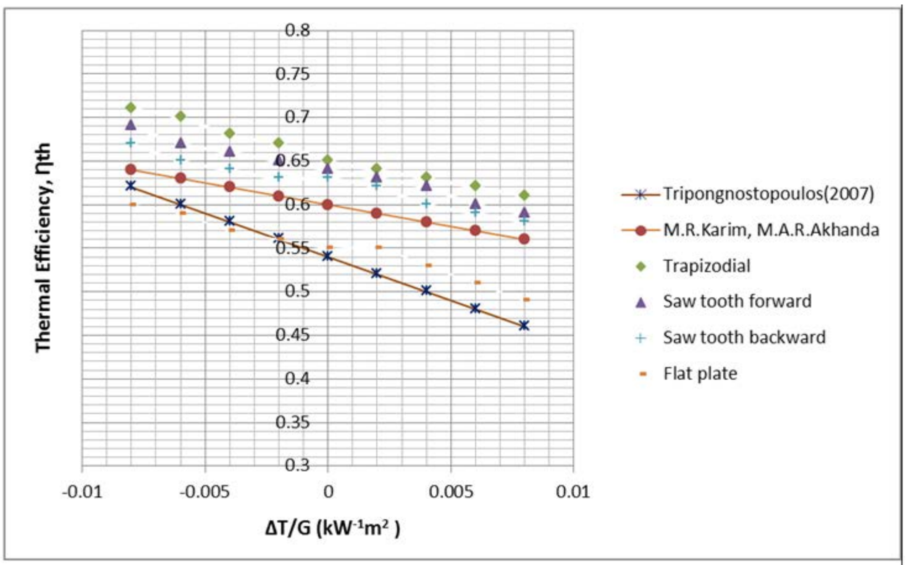

Figure 14. Comparison of thermal efficiencies of all four systems

3.3. Thermal Efficiency Comparison

Thermal efficiency regarding water is compared as a function of ΔT/G ($Kw^{-1}m^2$).ΔT is the temperature difference between input fluid and the ambient temperature. Efficiency of all four setups is compared along with the work of Tripangnostopoulos (2007) and Rezwan (2011) in Figure 14 for comparison. Tripangnostopoulos studied a hybrid PVT/dual system having corrugated rib on opposite air channel with WHE placed just under the PV panel in 2007 at the University of Patras, Greece. Karim and Akhanda (2011) studied a hybrid PV/T solar system using three different rib surfaces (Triangular, Semicircular, and Square) and flat plate in 2011 at IUT.

The present study was carried out using hybrid PV/T solar system using three different ribbed surfaces (Trapezoidal, Saw teeth forward, and Saw teeth backward) and a flat plate in 2018 at IUT, Bangladesh. The efficiency of Trapezoidal is 36% to 73%, Saw teeth forward is 37% to 70%, Saw teeth backward is 36% to 67% and Flat plate is 33% to 59%. Tripangnostopoulos (2007) PVT system is found to vary from 45% to 62% and Rezwan (2011) reported results to vary from 35% to 70%. The average efficiency from all calculated values in the present study is found to be 67% for Trapezoidal, 62% for Saw teeth forward, 61% for Saw teeth backward and 54% for flat plate setup.

The range of efficiency varies with the operating temperature of the system. The thermal efficiency of PVT/dual system for water heat extraction is extended in negative $\Delta T/G$ axis, as some experiments were performed for ambient temperature being higher than the water temperature at system input. Data taken for comparisons of setups are similar with $\Delta T/G$ values, to make the comparison more correct.

4. Conclusions

From this experimental study the following conclusions are drawn;

With the increase of PV panel temperature the water temperature increases and reaches a maximum value around noon. The temperature then decrease slowly with the ambient temperature.

Average water temperature rise is found to be better in Trapezoidal and Saw teeth forward ribbed surface then those of surfaces with Saw teeth backward and Flat plate. Setup with Saw teeth forward ribbed surface shows better performance than that of Flat plate but its average performance is lower than that of setup with Trapezoidal and Saw teeth forward ribs.

Thermal efficiency is found to be the best in the setup with Trapezoidal ribs among all setups, applying similar experimental conditions (T/G). Efficiency of Saw teeth forward, saw teeth backward and flat plate is also found satisfactory within the range of experimental conditions.

PV/T system can be used to heat water depending on the weather conditions and building needs. The water heat extraction part could operate mainly during periods of higher ambient temperature and the air heat extraction part to operate mainly when the ambient temperature is low. In mild weather conditions (like Bangladesh) it is possible to operate both heat extraction modes, if it is considered useful for the application.

References

[1] A. K. Bhargava, H. P. Garg and R. K. Agarwal, “Study of hybrid solar system- Solar air heater combined with solar cells,” *Energy conversion and Management*, vol. 31, pp. 471-479, 1991. (Article)

[2] K. Sopian, H. T. Liu, S. Kakac and T.N. Veziroglu,”Performance analysis of photovoltaic thermal air heaters,” *Energy Conversion and Management,* vol 37, no. 11, pp 1657-1670, 1996. (Article)

[3] H. P. Garg and R. S. Adhikari, “Conventional hybrid photovoltaic /thermal (PV/T) air heating collectors: steady state simulation,” *Renewable Energy*, vol. 11, pp 363-385, 1997. (Article)

[4] B. J. Brinkworth, R. H. Marshall and Z. Ibrahim, “A validated model of naturally ventilated PV cladding,” *Solar Energy*, vol. 69, pp. 67-81, 2000. (Article)

[5] B. J. Brinkworth and M. Sandberg, “Design procedure for cooling Ducts of minimize efficiency loss due to temperature rise in PV arrays,” *Solar Energy*, vol. 80, pp. 89-103, 2006. (Article)

[6] J. Ji , T. T. Chow and W. He, “Dynamic performance of hybrid photovoltaic/thermalcollector wall in Hong Kong,” *Building and Environment*, vol. 38, part 11, pp.1327-1334 2003. (Article)

[7] J. S. Coventry, , Lovegrove. K., 2003. “Performance of a concentrating photovoltaic/thermal solar collector,” *Solar Energy*, vol. 78, pp. 211-222, 2003. (Article)

[8] T. T. Chow, W. He and J. Ji, “Hybrid photovoltaic-thermosyphon water heating system forresidential application,” *Solar Energy*, vol. 80, part 3, pp. 298-306, 2006. (Article)

[9] T. T. Chow, W. He, J. Ji and A. L. S. Chan, “Performance evaluation of photovoltaic-thermosyphon system for subtropical climate application,” *Solar Energy*, vol. 81, part 1, pp. 123-130, 2006. (Article)

[10] T. T. Chow, W. He and J. Ji, “Photovoltaic-thermal collector system for domestic application,” *ASME Journal of Solar Energy Engineering*, vol. 129, pp. 205-209, May 2007. (Article)

[11] M. R. Karim and M. A. R. Akhanda,”Study of a hybrid photovoltaic thermal (PVT) solar systems using different ribbed surfaces opposite to absorber plate,” *Journal of Engineering and Technology (JET)*, vol. 09, no.01, June 2011. (Article)

[12] Y. Tripanagnostopoulos, T. H. Nousia and M. Souliotis, “Hybrid PV ICS systems,” *Proceedings of International Conference, WREC V,* Florence, Italy, pp. 1788-1791. 20-25 September, 1998. (Conference Paper)

[13] Y. Tripanagnostopoulos,”Aspects and improvements of hybrid photovoltaic/thermal Solarenergy systems,”*Solar Energy*, vol. 81, pp 1117–1131, 2007. (Article).