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Performance Analysis of a Natural Phase Change Material-Based Solar Collector with Compound Parabolic Concentrator at Different Flow Rates

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Abstract: The impact of a natural phase change material (PCM) based thermal solar collector, with a compound parabolic concentrator (CPC), was investigated during summer. This paper introduces a natural PCM (beeswax) instead of commercial phase change material, which was used as an energy storage media to improve the performance parameter of the solar collector. In this study, the natural phase change material was used within the solar collector, as it was easily available in nature. The outdoor experiments were carried out where compound parabolic concentrator, made of glass, was mounted on thermal collector during the day time. The data of consecutive three months have been collected and analyzed in this paper. The system performance, such as, thermal efficiency, operating value and collected energy of the collector were tested at a set different flow rate. The date was measured and compared between the systems with and without phase change material. Based on the measured collected energy and thermal efficiency, all parameter for the collectors as functions of water flow rate was obtained. This result shows that the maximum outlet water temperature of 50ºC and the maximum thermal efficiency of 35-40% were achieved at a water flow rate of 0.004 kg/s. The system with PCM was illustrated to have much better performances. Phase change material was more effective to improve thermal efficiency in low solar radiation. The system reaches maximum plate temperature more quickly in June than in July and August. The highest absorber plate temperature reading found in June was 90ºC and it took the system 3.5 hours to reach the point. ΔT/H operating value was inversely proportional to thermal efficiency. Water flow rate was proportional to collected energy and maximum collected energy was 456 W. It can be highlighted that the best water flow rate was 0.004 kg/s because it gives the maximum thermal efficiency and collected energy.

Keywords: Acceptance angle; Compound parabolic concentrator; Efficiency; Thermal collector; Water flow rate.

1. INTRODUCTION

In the last decades, the application of solar technology has become very popular for the increasing demand of energy consumption, environmental issues and the rise of fuel prices all around the world. Direct solar radiation is the most prospective source of energy in Bangladesh for geographic location. All over the world, scientists are searching for renewable energy sources. However, the development of an efficient thermal energy storage device has been one of the major challenges. One of the important developing new energy sources is an energy storage device. Nowadays, a challenge to the technologists is the storage of energy in a suitable form that can be converted to the required form. Efficient energy storage gives us improved performance and reliability of the energy system and reduces the mismatch between the supply and the demand. The storage system helps supply the energy when required. At present, one of the important technologies for storing thermal energy is the application of phase change material (PCM). This technology solves many problems for the researchers. Beeswax is naturally available in Bangladesh and it is cheap. It is a sustainable product for the collector because the rate of degradation of the beeswax is very low. Moreover it does not produce any toxic byproduct in its production process. When it is used as a phase change material, it does not change its volume much. It shows almost similar performance for long term chemical stability compare to other conventional phase change material. The three categories of solar collectors are generally used such as concentrating, evacuated tube and flat plate. The geometrical shape, size and types of the reflector are most important part of the solar collector [1-3]. A solar collector is used for increasing heat from solar radiation and then the heat is carried to the working fluid and PCM.

For industrial work the range of low and medium temperature water can be achieved from the compound parabolic concentrator (CPC). As the axes are inclined to each other, it is non-imaging concentrator because after reflection from the reflector the rays are focused on a line and it is collected on an absorber plate. The CPC fabrication cost is less and easy compared to other concentrating collectors. A CPC collects available solar radiation during the day without the need of tracking the position and it also achieves some diffused radiation. The medium temperature level of water has different fields of application such as in food and beverages, textile and chemical industries. For the short term period, solar thermal energy was stored using paraffin as a PCM and the thermal efficiency increased due to well insulated hot water tank [4].The useful heat energy gained by the water and stored by the PCM was due to photovoltaic thermal system with integrated PCM [5]. Different PCM mixtures were tested for better thermal performance to enhance the supply of domestic hot water [6]. In solar collector, radiant energy flows to water and remains as latent heat energy in PCM [7]. The incident radiation value was different and its best value was about 1100 W/m^2. The solar collector has low and variable radiation problem. For a flat plate system, the moderate temperature was gained [8]. Hot water was used in domestic applications and industrial processes. The heat came from the transformation of solar energy and the system used various conventional collectors with a glass cover and metal absorber plate [9]. The main negative factor was that the temperature of hot water quickly decreased during night [10].

Previously, some researchers used reflector and or concentrator to harness the solar energy; but none of them used CPC effectively in this latitude (latitude: 24º22′N, longitude: 88º36′E). No significant use of a single unit consisting of CPC, PCM container and absorber plate was found; and so, the results of experimental studies were rarely found. This study may provide comparison experiment results of different flow rate; that may be analyzed for effective use of solar power. This study aims to investigate the thermal performance of a compound parabolic concentrator-cum storage system at different flow rates. Furthermore, the thermal efficiency of the system for heating application was also compared by using PCM and not using PCM in the solar collector.

2. MATERIALS AND METHODS

The complete setup has a tilt angle of 35° to 45º. The south-directed solar collector was placed on the rooftop of the Heat Engine Lab of Rajshahi University of Engineering & Technology. Most of the incident solar radiation falls directly and the rest is reflected by the reflector and eventually drop on the collector plate of compound parabolic concentrator to heat it up as shown in Figure 1.

2.1 Methods

The data were collected from outdoors, where the atmospheric temperature and solar radiation levels were different during the day. The data collection started from 11 a.m. and finished at 5 p.m. on clear days. The experiment has been conducted in Rajshahi, Bangladesh. The testing procedure was used to measure the performance of the natural PCM based solar collector. Thermal performance of the natural PCM based solar collector obtained efficiencies of various levels due to the combinations of inlet water temperature, outlet water temperature, solar intensity and ambient temperature. The solar collector was exposed to different solar radiation during the day. During the testing period, the water flow rates were set at 0.002 kg/s, 0.003 kg/s and 0.004 kg/s. Any changes in the output temperature due to these mass flow rates were recorded. The data were collected every hour during a clear day. The collected data were used to calculate the thermal efficiency of the solar collector. In this study, we used non-paraffin beeswax as a natural phase change material. The melting point of this natural PCM was 61.8ºC and the latent heat of fusion was 177 kJ/kg [11-14]. The non-paraffin organic material is a phase change material with high properties of heat fusion. It has some features, such as high heat fusion, inflammability, low thermal conductivity, low flash points, different level of toxicity and high temperature instability. A layer of phase change material contained was placed on the back of the compound parabolic concentrator solar collector system. This phase change material, placed under the absorber plate was direct contract with it. A schematic diagram of a compound parabolic concentrator is shown in Figure 2.

2.2 Design and Fabrication Process

The design processes have three different stages such as product definition, conceptual design and detailed design. In the first stage, identification and collection of data were required, followed by the conceptual design which includes the functional analysis of the diagram to complete the process. The design of the area of the absorber plate, intensity of the ray collector depends on the area of the absorber plate, intensity of the rays, and the total volume of the PCM. The distance of the pipe and its zigzag pattern and the volume of the collector box enable longer duration of heat transfer. 25.4 mm diameter copper pipe was used. To create zigzag pattern, copper joints were used and the pipes were welded. Copper absorber plate performs the highest absorption of heat among available metals. A copper plate was attached with copper pipe to enhance the heat transfer such as convection and conduction during the melting and solidification stages. 0.6 mm plate was used and welded onto copper pipe. The fins were cut from copper sheet to the desired dimension and welded with copper plate. To contain the maximum amount of PCM, the container was carefully design. The collector box was made of GI sheet with 1 m long by 0.81 m wide and 0.03 m depth, which was suitable for the containment of PCM. Materials used in the system must have suitable conductivity to be able to melt due to heat during the day. The collector box was internally leak-proof and reduces heat loss through radiation and reflection. For minimizing heat loss, a good collector design must include good insulation.

A cheap and readily available glass wool with corkwood was used for insulation in this experiment. The glass cover acts as transparent insulation that allows the passage of solar radiation through it. Direct and reflected solar radiations pass through the glass cover to the absorber plate and reduce the transmission of the thermal radiation from the absorber plate. The glass cover used was low cost and durable. In this work the thickness of the glass cover was 3 mm and ordinary black paint was used on the absorber plate. The reflector must have the highest reflectance rate for gathering more heat. The reflector had a line focus which heats the receiver. The high reflectivity glass was used as the reflector. The solar collector with compound parabolic concentrator consists of two reflectors positioned in a special angular way to concentrate the rays. In this work, we used aa stationary concentrator define by the equation, Concentration ratio,

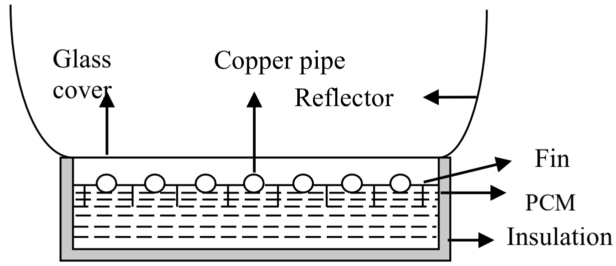

Figure 1. The sectional views of a CPC solar collector with PCM

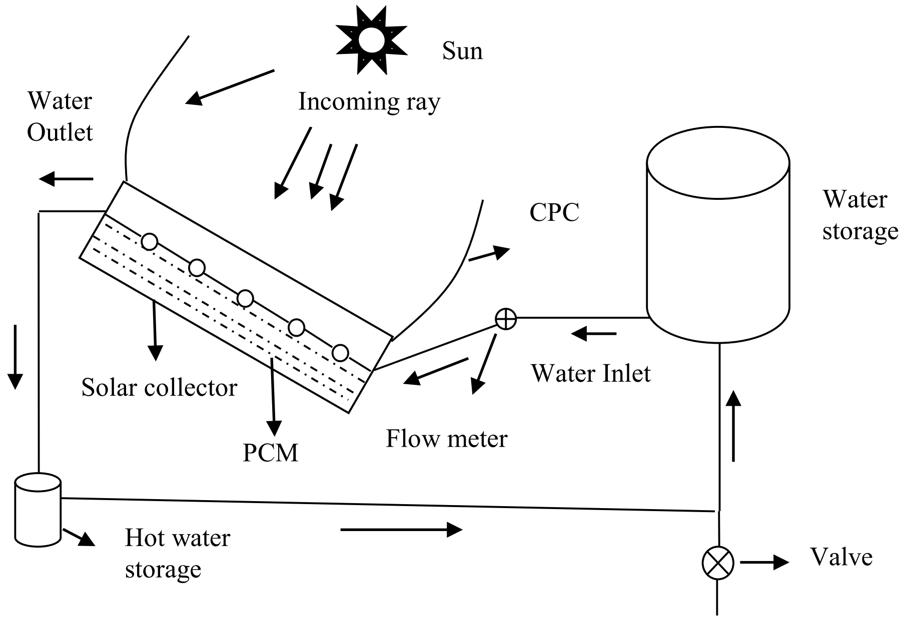

Figure 2. Schematic presentation of a thermal solar collector

$$CR = \frac{1}{sin\theta_C} \tag{1}$$

where θ_C is the acceptance angle [15]. The position of the sun relative to the rotation of earth depends on the value of acceptance angle for a stationary compound parabolic concentrator. In the northern hemisphere, a CPC system that has its axis in a north-south direction and can be tilted can collect a lot of solar energy during the day time. The receiver of a CPC will only absorb incident solar radiation if the angle of incidence of the beam and diffuse radiation is within the acceptance angle of the CPC. In this experiment, sunshine collection time was five hours and sun travelled fifteen degrees per hour. In this condition, concentration ratio was 2. The geometry of a compound parabolic concentrator is shown in Figure 3.

3. EXPERIMENT

The experiment had been conducted during hottest months of the year and the values had been collected for further processing in the experimental process. The absorber plate of the collector was painted black and was covered with a transparent glass to absorb the maximum amount of incident radiation.

The collector was set up in such a way that it could face toward the sun and changed its position with the rotation or the position of the sun. The system experimented different times a day. As radiation of the sun always fall on the system surface perpendicularly, the loss of energy or the amount of reflected energy remained minimum, and the efficiency of the system remained maximum. The outdoor experiment was performed during summer season in the month of June, July and August 2017. The estimated errors in the assessments of solar intensity, mass flow rate and different temperature were obtained. The estimated errors in the calculated parameter are given in Table 1.The repeatability of data was ensured during the experimental investigation. For that reason, every experiment was conducted five times and selected parameters were kept the same. From the measuring instruments of the collector we got the accuracy or typical error value [16-19].

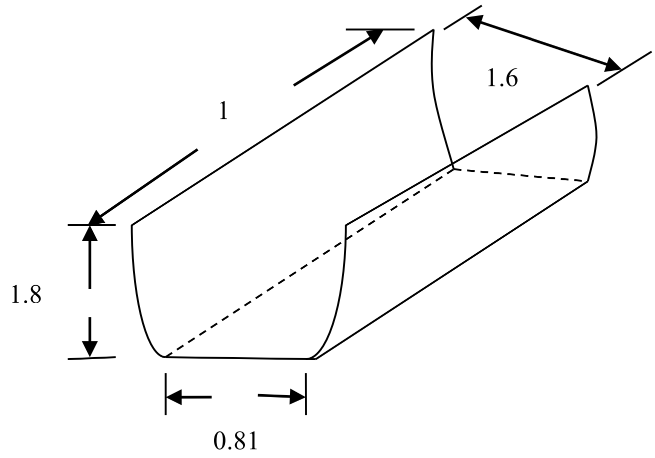

Figure 3. The geometry of a compound parabolic concentrator. (All dimensions are in meter)

Table 1. Estimated error and derived parameters

Parameter	Typical error	Remarks
Solar radiation intensity	±10W/m^2	Measured by Pyranometer
Absorber plate temperature	±0.5^{0}C	Measured by Thermocouple
Outlet and inlet water temperature	±0.5^{0}C	Measured by Digital Thermometer
Mass flow rate	±4%	Measured by Flow meter
Temperature of glass	±0.5^{0}C	Measured by Heat sensor
Phase change material temperature	±0.5^{0}C	Measured by Thermocouple

3.1 Calculation Methods

The collected heat depended on the average mass flow rate of water, the specific heat of the water, inlet water temperature and outlet water temperature. The thermal collector heat absorbs and heat transfer to the working fluid was determined and calculated by parameter depend on Hottlel-Whillier equation [20]. Data obtained from the experiment will be used in the equations by [21-23]. That will ensure to determine the performance of the collector. The useful energy of water which converted heat energy to thermal energy denoted by the equation:

$$Q_w = \dot{m} c_p (T_0 - T_i) \tag{2}$$

where $\dot{m}$ is water mass flow rate, c_p is water specific heat, T_i is water inlet temperature and T_0 is water outlet temperature. The thermal efficiency is calculated by:

$$\eta = \frac{Q_w}{H A_c \eta_0 CR} \tag{3}$$

where H is the solar radiation, η_0 is the optical efficiency, CR is the concentration ratio and A_c is the area of collector plate [24].

4. RESULT AND DISCUSSION

The solar collector, filled with natural phase change material and compound parabolic concentrator, placed on the collector made a combined unit resulting in a compact design. Data such as inlet temperature, outlet temperature, ambient temperature and incident solar radiation were collected from the installed system. The performance of the collector was determined by different performance factors. Different measured data have been used with a technical equation to determine the performance of the solar collector. The different temperature and thermal efficiency of different flow rates during the month of June, operating value and comparison of PCM value of different flow rates during the month of July and collected energy of different flow rates during the month of August were represented. The natural phase change material, has been used here, is having a higher melting temperature. This is why CPC has been used on solar collector. The CPC helped in increasing the value of incident solar radiation in this way the natural PCM has stored energy easily by phase change procedure. Solar rays directly fall on absorber plate through CPC, and as a result, the temperature increased very fast. Here the heat partially goes to the water of the copper tube while partially goes to PCM. In both high and low solar radiation the natural PCM-based-thermal storage system can reduce the thermal-performance fluctuations. The incident solar radiation increased with the use of CPC.

As a result, the difference in temperature of outlet and inlet had increased. The value of thermal efficiency had been increased by increasing temperature difference and mass flow rate of water.

In Figure 4, the variation of plate temperature, ambient temperature, outlet and inlet water temperature was shown during the local day time from 11 a.m. to 5 p.m. when water flow rate was 0.004 kg/s. The figure shows that plate temperature was at maximum value of 90^0C at 1 p.m. After 3 p.m.; the average outlet water temperature was almost constant, although the amount of the available solar radiation decreases towards evening. This is owing to the latent heat released by the PCM storage to the working fluid. When the system cools down, natural PCM transfers heat to the circulating water. The graph represents that the maximum outlet water temperature varied from 44^0C to 50^0C. As the maximum amount of heat needs to be transferred to the working liquid, if the heat loss to the side of environment can be decreased, then the value of heat transfer coefficient in the heat exchange process will be maximum. The way of decreasing conduction heat loss from the absorber plate was using glass wool insulation on the back side and surrounding of the cover box. It will ensure the decrease in the difference of the outlet and inlet water temperature. The ways of improving the efficiency of a collector were: Increase of the amount of energy which was transferred from collector to the fluid. This is why a transparent cover plate was used to improve the transmittance, compound parabolic concentrator was used to increase solar radiation and painted black copper materials were used so that the incident solar radiation can hold by the absorber plate in a massive way. The value of heat transfer coefficient had been increased at the time of heat transfer from the absorbing surface to the working fluid through a pipe.

Figure 4 shows data of three consecutive days of the month of June. The water flow rate of the first day was 0.004 kg/s, second day was 0.003 kg/s, and the third day was 0.002 kg/s. In these three days, in that specific local day, the values of solar radiation were almost the same. The thermal efficiency of mass flow rates shows marginal variation and this fluctuation varies with the fluctuation of climate condition. Among three thermal efficiency results at different flow rates throughout the day time is shown in Figure 5. When the flow rate was 0.004 kg/s, the thermal efficiency varied from 35 to 40%. When the constant water flow rate was 0.003 kg/s, the corresponding thermal efficiency varied from 32 to 39%. Lastly, when the constant water flow rate was 0.002 kg/s, the thermal efficiency varied from 31 to 37%.

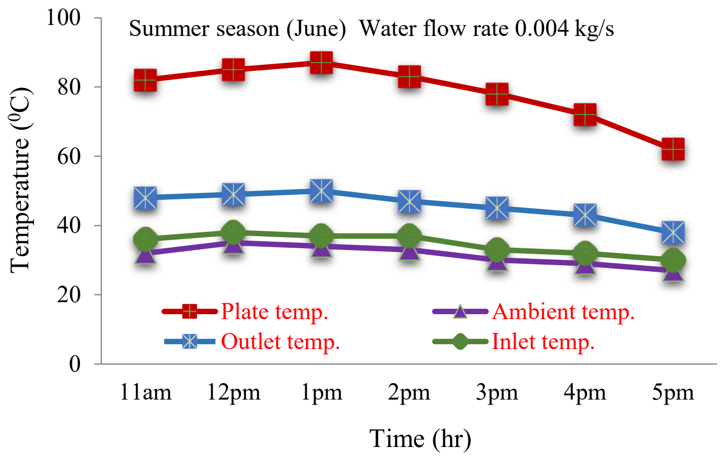

Figure 4. Variation of temperature during day time from 11a.m to 5 p.m.

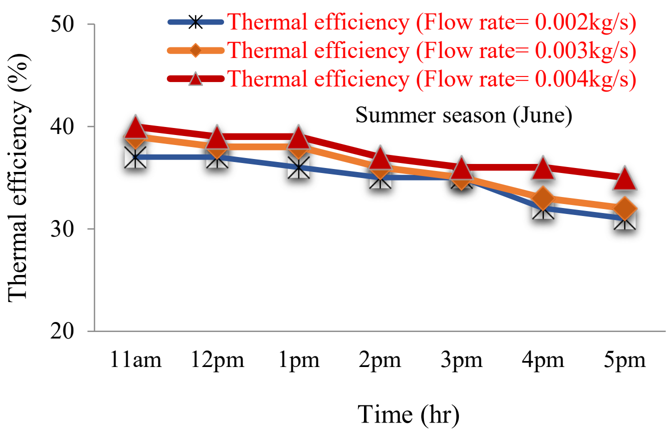

Figure 5. Variation of thermal efficiency at different water-flow rates at different times

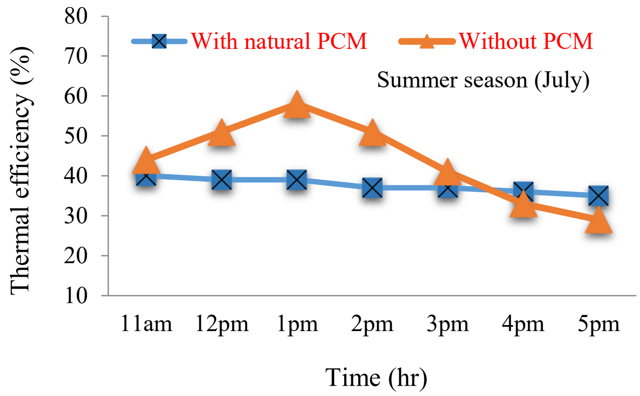

Figure 6. Variation of thermal efficiency with PCM and without PCM condition in July

The variation of thermal efficiency was because of more thermal energy was eliminated due to more water passed through the solar collector. The thermal efficiency of water collector at flow rate 0.004 kg/s was higher as compared to different flow rate because the rise in temperature of water was higher as compare to another flow rate at almost same solar radiation. The effect of heat storage can be found depending on the climate condition of that day, which depends on the phase change of phase change material. The outlet water temperature of the collector decreases with the increase in mass flow rate. Comparing the effects of the three different flow rates (0.002 kg/s, 0.003 kg/s and 0.004 kg/s) at local day time, it was observed that the maximum outlet temperature was obtained at 0.002 kg/s because at lower flow rate water gets more time to collect heat. A rectangular or square channel of an aluminium alloy flat box was design and fabricated. They managed to achieve higher efficiency. For improvement thermal efficiency using suitable insulation for the photovoltaic thermal design and the test result showed the thermal efficiency 38% [25]. Another investigation was provided using aluminium alloy flat box and ploy crystalline silicone cells, which take advance of water. The result was shown when the initial temperature in the system matched the daily mean ambient temperature and they reached the thermal efficiency around 40% [26].

Figure 6 shows the data of two consecutive selected days of the month of July. At a specific time, the value of solar radiation of these two days was almost same from 11 a.m to 5 p.m. Data of the first day were taken without PCM condition while the second day's data were taken natural PCM condition. PCM helps to reduce the fluctuation of thermal efficiency. Because the PCM can store the thermal energy at the time of phase transformation process and at that time, the values of solar radiation remain higher. This energy was released when the value of solar radiation remain lower. In the same way with the PCM system instantly overcome the solar radiation fluctuation. When the values of solar radiation remain lower, the PCM increases the value of thermal efficiency. When the value of solar radiation higher, the values of thermal efficiency of without-PCM remain somewhat higher.

The deviation of thermal efficiency with natural PCM was around 40% less than that of without PCM, because PCM can successfully minimize thermal efficiency fluctuation. As the solar intensity starts to decline after 1 p.m., the thermal efficiency of the system without PCM also starts to go down because nothing was used to retain the heat of the sun. But, with a natural PCM-based system, thermal efficiency exhibited slightly decreasing trend up to 5 p.m., because PCM absorbed intense heat of the sun and delivers back to the water when the solar intensity started to fall. At 5 p.m. PCM delivered its best output. At 5 p.m., the thermal efficiency of PCM-based system was 38% and without PCM based system was only 30%. Thus the thermal efficiency was improved by 8%. So we can say that the natural PCM is very effective for the improvement of the value of thermal efficiency. At the time of lower solar radiation, natural PCM was very effective to increase the value of thermal efficiency because PCM acted as a heat source.

Figure 6 shows the data of consecutive three days in month of July at different flow rates. The efficiency test results of thermal collector were similar to typical solar thermal collector. The thermal efficiency result varied with total incoming solar radiation, ambient temperature and water inlet temperature, which was evaluated by as a function of the ratio ΔT/H, where $\Delta T = T_i - T_a$ and H is the incoming solar radiation. The function of ΔT/H operating values and the thermal efficiency values were of the same day. In this result showed that thermal efficiency depended on solar radiation and ambient temperature. Figure 7 showed that ΔT/H operating values increase with the decrease of thermal efficiency; and the flow rate of 0.004 kg/s results in the higher thermal efficiency compared with other flow rates. Different water flow rates have different thermal efficiency and thus have different operating value. Tripanagnostopoulos et al. [27] show his work as a comparative study of steady-state outdoor test result for photovoltaic air and photovoltaic water collector using si modules, a-Si modules and pc-Si, used as an absorber, having a thin copper sheet with copper pipes in thermal contact with it. The test results trend of thermal efficiency for photovoltaic thermal air UNGL and photovoltaic thermal air GL collector, with pc-Si and a- Si PV modules, were same with our experiment result. The corresponding cost increase of hybrid system is relatively higher because a Si PV modules are less expensive than pc-Si PV modules although the cost of the thermal unit was the same. The difference of this result with a numerical result was mainly due to the lack of proper insulation to prevent convective losses and manufacturing error [28].

In Figure 8, the dissimilar trends for plate temperature, PCM temperature and outlet temperatures may be noticed for comparison of clear day and semi-cloudy day. Sometime PCM temperature was greater than the absorber plate temperature showing the desired storage receptivity. The maximum PCM temperature up to 83^0C for clear day was notice compare to the maximum 70^0C for semi-cloudy day. In this graph, the data of selected five days of the month of August were shown. At 11 a.m and 1 p.m, the mass flow rate was increasing gradually. It showed that increasing the mass flow rate causes a rise in the amount of collected energy. The variation of energy collected with natural phase change material was proportional to mass flow rate. In Figure 9 showed that when the water flow rate was 0.002 kg/s, the corresponding output power was 252 W, and when the water flow rate was 0.004 kg/s; the corresponding maximum output power was 456 W at local day 1p.m. The system operates at medium intensity (11 a.m.) and high intensity (1 p.m) sunshine hours. This has an impact on the quantity of energy collected. Low collection of energy was noticed at the beginning of the day. Afterwards, as more radiation was absorbed, more energy was collected through the system.

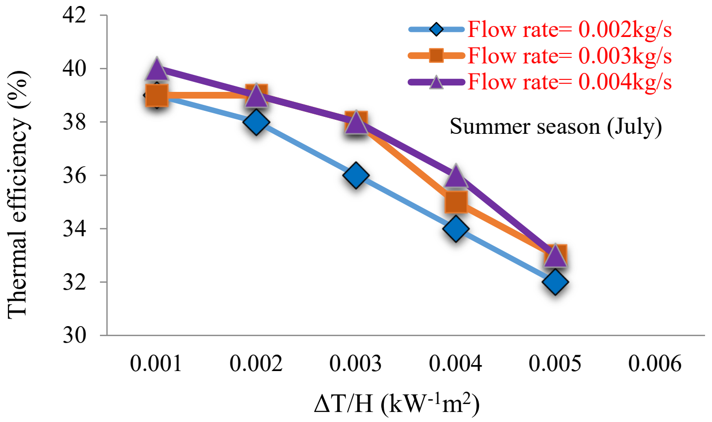

Figure 7. Thermal efficiency of thermal solar collector system for the corresponding ΔT/H operating values

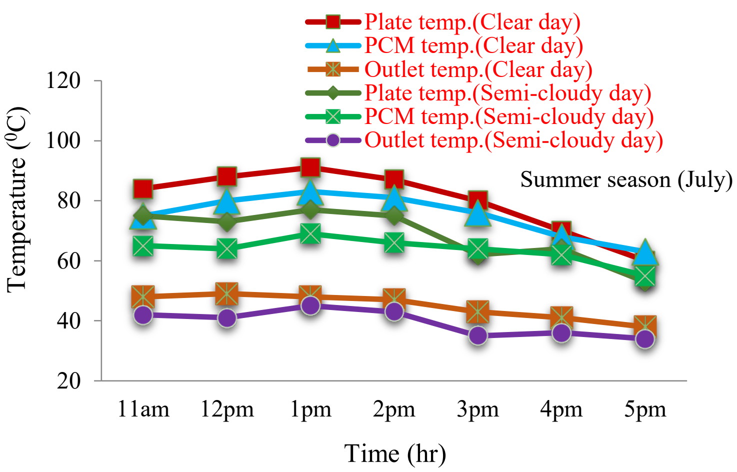

Figure 8. Comparison of the effects of variation in temperature at different local day times on a clear day and semi-cloudy day in July

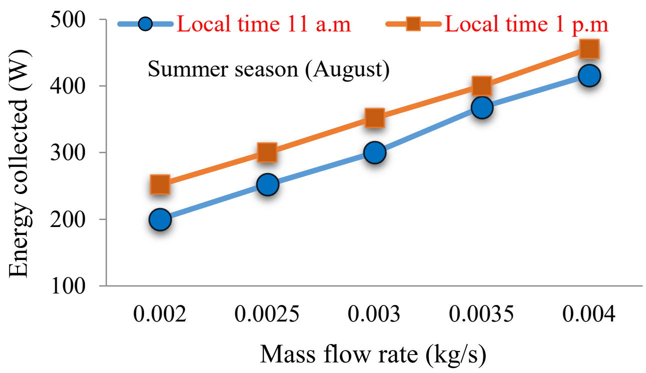

Figure 9. The variation of energy collected with mass flow rate of water

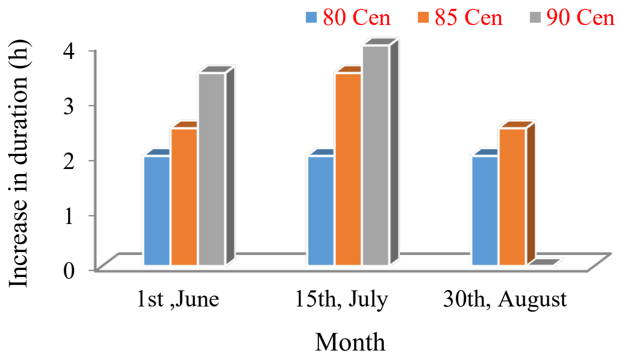

Figure 10. Variation of monthly temperature with the increase in duration.

Figure 10 shows data of three different days of the consecutive month of June, July and August were shown. In June, the compound parabolic concentrator was more effective. Absorber plate temperature increased to 90^0C after 3.5 hours and maximum PCM temperature was archived 83^0C. In July, temperature rose to 85^0C after 3.5 hours and maximum PCM temperature was archived 80 because of semi-cloudy weather. In August, a 90ºC temperature could not be achieved because the sky was almost always semi-cloudy; and the highest temperature achieved was after 2.5 hours and the maximum PCM temperature was 72ºC. Hamood and Khalifa [29] conducted a similar test in August, November and January. A comparison between the results of August and the results of in June was shown, the output temperature varied because of the intensity difference of solar radiation. It was observed that the values of solar radiation used in the experimental study were different from those reported by the theoretical study; therefore, it is necessary to relate the comparison between the results of the two studies to a single parameter that takes into account such differences.

5. CONCLUSION

We have tremendous scope to use solar energy in Bangladesh. So, it can be used to supply low-cost hot water. The PCM effectively reduces the fluctuation of thermal efficiency at the time of higher and lower solar radiation. This is why there was a slowly decreasing trend of thermal efficiency with local day time. It can be concluded that when water mass flow rate was 0.004 kg/s, maximum thermal efficiency 40% was achieved and the maximum collected energy 456 W and the maximum outlet water temperature was 50ºC. This system supplied with uniform temperature hot water from 11 a.m. to 5 p.m.; which is useful for a high and low sunshine hour. The highest temperature reading found in June was 90^0C and it took the system 3.5 h to touch the value. ΔT/H operating value is inversely proportional to thermal efficiency. It has been observed from analysis that the natural PCM base solar collector provides a better solution for thermal efficiency system. The design of compound parabolic concentrator cum storage system in one unit is effective to occupy small space and towards solar energy utilization. Maximum storage and uniformly distributed heat energy produced by utilizing minimum solar energy, which will fulfill the demand and viability of hot water for domestic and industrial application.

REFERENCES

[1] A. H. Jaaz, H. A. Hasan, K. Sopian, M. H. B. H. Ruslan and S.H. Zaidi, Design and development of compound parabolic concentrating for photovoltaic solar collector: Review, *Renewable and Sustainable Energy Reviews,* 76, 2017, 1108–1121.

[2] C-W. Kuoa, P-S. Yana,and W-C. Changa, The design and optical analysis of compound parabolic collector, *Procedia Engineering*, 79, 2014, 258–262.

[3] I. S. Gonzáleza, M. S. Reyesa, O. G. Vallaresb, N. Ortegab and V. H. Gómez, Design and evaluation of a compound parabolic concentrator for heat generation of thermal processes, *Energy Procedia*, 57, 2014, 2956–2965.

[4] T. Koyuncua and F. Lüle, Thermal performance of a domestic chromium solar water collector with phase change material, *Procedia - Social and Behavioral Sciences,* 195, 2015, 2430–2442.

[5] M. C. Browne, D. Quigley, H. R. Hard, S. Gilligan, N. C. C. Ribeiro, N. Almeida and S. J. McCormack, Assessing the thermal performance of phase change material in a photovoltaic/thermal system, *Energy Procedia,* 91, 2016,113–121.

[6] M. Mazmana, L. F. Cabeza, H. Mehling, M. Nogues, H. Evliya and H. O. Paksoy, Utilization of phase change materials in solar domestic hot water systems, *Renewable Energy*, 34, 2009, 1639–1643.

[7] A. Shukla, D. Buddhi and R. L. Sawhney, Solar water heaters with phase change material thermal energy storage medium: A review, *Renewable and Sustainable Energy Reviews*, 13, 2009, 2119–2125.

[8] S. O. Enibe, Thermal analysis of a natural circulation solar air heater with phase change material energy storage, *Renewable Energy*, 28, 2003, 2269–2299.

[9] N. M. Nahar, Year round performance and potential of a natural circulation type of solar water heater in India, *Energy and Buildings*, 35, 2003, 239-247.

[10] H. M. S. Hussein, H. H. El-Ghetany and S. A. Nada, Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit*, Energy Conversion and Management*, 49, 2008, 2237–2246.

[11] R. Ramnanan-Singh, *Formulation and thermophysical analysis of a beeswax microemulsion and the experimental calculation of its heat transfer coefficient*, Thesis, City University of New York, New York, USA, 2012.

[12] W. Su, J. Darkwa, G. Kokogiannakis, Review of solid-liquid phase change materials and their encapsulation technologies, *Renewable and Sustainable Energy Reviews*, 48, 2015, 373–391.

[13] A. Dinker, M. Agarwal and G. D. Agarwal, Experimental assessment on thermal storage performance of beeswax in a helical tube embedded storage unit, *Applied Thermal Engineering*, 111, 2017, 358–368.

[14] N. Putra, E. Prawiro and M. Amin, Thermal properties of beeswax/cuo nano phase-change material used for thermal energy storage, *International Journal of Technology*, 2, 2016, 244-253.

[15] H. P. Garg and J. Prakash, *Solar Energy Fundamentals and Applications*. New Delhi, India: Tata McGraw-Hill Publishing Company, 2009.

[16] Kipp & Zonen: Solar Radiation Measurement. http://www.kippzonen.com (accessed 10.02.2017).

[17] Secon Controls. http://www.seconcontrols.com (accessed 22.02.2017).

[18] Z-6000 series – Flutrol, Nitto Instruments Co., Ltd Japan. http://www.flutrol.co.th (accessed 04.03.2017).

[19] Digital Thermometer at Thomas Scientific. http:// www.thomassci.com (accessed 15.03.2017).

[20] J. A. Duffie and W. A. Beckman, *Solar Energy of Thermal Processes*. New York, USA: John Wiley and Sons Inc., 2006.

[21] S. P. Sukhatme and J. K. Nayak, *Solar Energy, Principles of Thermal Collection and Storage*. New Delhi, India: Tata McGraw-Hill Publishing Company, 2008.

[22] P. Sivakumar, W. Christraj, M. Sridharan and N. Jayamalathi, Performance improvements study of solar water heating system, *ARPN Journal of Engineering and Applied Sciences*, 7(1), 2012, 45-49.

[23] G. D. Rai, *Solar Energy Utilization*. India: Khanna Publishers, 2005.

[24] S. A. Kalogirou, Solar thermal collectors and applications, *Progress in Energy and Combustion Science*, 30, 2004, 131-295.

[25] T. T. Chow, J. Ji and W. He, Photovoltaic thermal collector system for domestic application, *Proceedings of Solar Word Congress ISEC2005,* Orlando, USA, 2005, 471-476.

[26] B. J. Huang, T. H. Lin, W. C. Hung and F. S. Sun, Performance evaluation of solar photovoltaic/thermal systems, *Solar Energy*, 70(5), 2001, 443–448.

[27] Y. Tripanagnostopoulos, T. Nousia, M. Souliotis, and P.Yianoulis, Hybrid photovoltaic/thermal solar systems, *Solar Energy*, 72, 2002, 217-234.

[28] I. Santos-Gonzáleza, M. Sandoval-Reyesa, O. García-Valladaresb, N. Ortegab and V. H. Gómezb, Design and evaluation of a compound parabolic concentrator for heat generation of thermal processes, *Energy Procedia*, 57, 2014, 2956 – 2965.

[29] A. M. Hamood and A. J. N. Khalifa, Experimental study on the performance of a prism-shaped integrated collector-storage solar water heater, *International Journal of Engineering and Environment*, 3(3), 2012, 347-358.