Thermal Management of Photovoltaic Systems - case studies

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Abstract: The output of the photovoltaic (PV) system reduces when the operating temperature of the solar cell increases. For the better performance of the PV systems, it is necessary to maintain the lower operating temperature of the photovoltaic modules. Several attempts are being made for the thermal management of the solar photovoltaic modules. In the present work, various techniques of the thermal management of the photovoltaic modules have been explored. These techniques mainly include, the module cooling by using fins, wind catchers, circulating liquids and spectrum filters. Exhaustive experimental studies have been conducted using these thermal management techniques at Solar Energy Laboratory, RCOEM, Nagpur (21.10 N, 79.09 E). The details of experimental work and significant findings have been discussed in this article. Use of Liquid spectrum filters is recommended as a future thermal management technique for photovoltaic thermal system.

1. Introduction

The terrestrial solar radiations are not monochromatic; they are in the wavelength range of 250 to 2500 nm [1]. The commercially available single junction solar photovoltaic systems can not convert this complete solar spectrum into electricity. Only the radiations corresponding to the response range of the solar cell material are used by the solar cell to generate the electricity. The unused radiations will dissipate its energy as heat in the solar cell. The operating temperature of the solar cell is one of the most important performance affecting parameters of the solar cell [2]. In the terrestrial applications in the tropical region like India, the solar PV modules are exposed to 15 °C to 50 °C even sometimes more than that. Several studies in the literature [2-5] have pointed out that the performance of solar cells degrades with increase in temperature. It is reported that the output of the photovoltaic cells reduces when the operating temperature of the solar cell increases. The output voltage of the C-Si solar cell reduces by 2.3mV/°C temperature rise of the solar cell [2]. For the better performance of the solar cells, it is therefore required to maintain the lower operating temperature of the solar cells in PV modules.

Several attempts are being made for the thermal management of the solar photovoltaic modules. Use of various module cooling techniques has been explored in the past. Mostly explored methods are cooling of photovoltaic modules by circulating liquids and circulating air. These techniques are popularly known as Photovoltaic Thermal Systems (PVT). In these systems, the photovoltaic module and conventional solar thermal collectors are integrated in a single unit. The PVT systems are useful where electrical and thermal demands are simultaneous. Since the inception of PVT systems, there are several new configurations of such systems have been reported in the literature. The different configurations include, use of different working medium, use of concentrated and non concentrated...
optics, use of different heat transfer enhancement techniques, use of different PV technologies and PV materials, different flow arrangements etc. Different PVT systems have been invented in the last three decades. The significant work is carried out on water and air type of PVT systems.

In water type PVT systems, PV module heat is extracted by using water. The literature on the water type PVT system includes, PVT systems with glazing [6], without glazing [7], water channels [8], fully and partially covered collectors [9], surface covering arrangement [10], semitransparent PV modules [11], selective coating [12], multi fluid [13], PCM [14] etc.

In other systems, air is used to remove the heat from the PV modules. The literature in the air type PVT system discusses PVT without glazing [15], air channels [16], natural, forced air circulation [17], use of inserts [18,19]. The details of all the PVT systems explored till year 2018 are reported in the form of review paper by Sandeep. S. Joshi et al. [20].

In the present work, various techniques have been used for the thermal management of the photovoltaic modules. These techniques mainly include, the module cooling by using fins, wind catchers, circulating liquids and spectrum filters. Exhaustive experimental studies have been conducted using these thermal management techniques at Solar Energy Laboratory, RCOEM, Nagpur (21.10 N, 79.09 E). The details of experimental work and significant findings have been discussed in this article.

2. Experimental work (Case studies)

The experimental work is divided into following main categories.

**Category-A:** Heat Transfer enhancement using extended surfaces and forced convection (Air cooling)

**Category-B:** PV module cooling using water circulation (Water cooling)

**Category-C:** Submerged Photovoltaics

**Category-D:** Use of liquid spectrum filters

In all the experimental studies, the electrical performance of the system has been analysed using the current –voltage characteristic (I-V curves using Fluke 107 Digital Meters and suitable loads) for the period of one month for the entire time of the day. Irradiations are measured using a class-I pyranometer (Kipp Zonen/PM-10). Temperatures are measured using an infrared temperature Gun (Fluke 59-Mini IR) and PT100- type thermocouples (Creative, DTI-306). The system performances have been calculated on the basis of average parameters. All the experimental studies have been carried out at Solar Energy Laboratory RCOEM Nagpur (India). The experimental work is presented as case studies in the subsequent text.

**Category A: Heat Transfer enhancement using extended surfaces and forced convection**

**System-A-1: Aluminum strip fins and wind catcher for PV cooling [21]**

**System Description (Fig.1):** L-shaped strip fins (675 mm length, 35 thicknesses) of Aluminium material are attached to the rare surface of a 40 W C-Si PV module. In addition, a suitably designed wind catcher is attached to leeward side of the PV module to enhance the wind flow over the PV module. To simulate the performance of the system a CFD analysis is carried out. Also, the performance of the modified system is compared with the reference PV module (without any attachment) experimentally in the sunlight.

**Significant outcomes (Fig.2):**

- Use of windcatcher is suggested for PV module cooling for the first time.
- From the study, it is evident that fin height is directly proportional to drop in average PV module temperature.
- Around 18 % improvement in the electrical efficiency of the system using fins and windcatcher is recorded.
From simulation result it was clear that 21° wind catcher mechanism gives the best velocity boundary layer formation over PV module for Nagpur location.

Fig. 1: PV cooling by fins and wind catcher

Fig. 2: System performance (Case-I: Reference Module, Case-II: Only fins, Case-III: Windcatcher and fins)

System A-2: Aluminum conical fins and miniature fans for PV cooling [22]

System Description (Fig. 3): Conical fins (40 mm length, 10 mm base diameter) of Aluminium material are attached to the rare surface of a 40 W C-Si PV module. In addition, an array of miniature fans is attached to rare surface of the PV module to enhance the wind flow over the PV module. The performance of the modified system is compared with the reference PV module (without any attachment) experimentally in the sunlight.

Significant outcomes (Fig. 4):

- Temperature measurements revealed that the PV module temperature as high as 62 °C for an uncooled system (Reference module) for April and May month at Nagpur.
- By applying the cooling system (combination of aluminium conical fins and array of miniature rotating fans), the average PV module temperature was reduced to 51 °C. Around 17% increment in the electrical efficiency of PV module has been recorded

Category B: PV module cooling using water circulation (Water cooling)

Fig. 3: PV cooling by fins and fan array

Fig. 4: System performance
Category-B: PV module cooling using water circulation (Water cooling)

System B-1: Non concentrated system, PV module with attached cooling channel [23]

System Description (Fig.5): An Aluminium channel of corrugated sheet is attached to the rare surface of a 40 W C-Si PV module. Water channel is attached to the module to extract heat from its surface. The performance of the modified system is compared with the reference PV module (without any attachment) experimentally in the sunlight.

Significant outcomes (Fig.6):
- Maximum PV module surface temperature is found to be 52.35°C in condition-I, as no cooling is provided. While in condition-II i.e when cooling is provided maximum temperature is found to be 38.5°C (at atmospheric temperature of 30°C)
- The significant improvement in the electrical efficiency of PV module has been recorded after cooling. The Maximum average electrical efficiency found to be around 16.83% after cooling. Whereas, it was around 12.36% for the reference case.

System B-2: Concentrated system, PV module with attached cooling channel [24]

System Description (Fig.7): An inverted trapezoidal flume shaped PVT system is developed in this work. In this system, the flat mirror reflectors are used to enhance the incoming solar radiations on the PV modules. The top and side surfaces of the PVT trapezoidal system are used as both PV and thermal systems combined and independently. The Aluminium channel is attached to the rare surface of 40 W C-Si PV modules (fixed on top surface) and 10 W C-Si PV modules (fixed on lateral surfaces). Water channel is attached to the module to extract heat from its surface.

Significant outcomes (Fig.8):
- The thermal and electrical efficiencies of 78% and 13.05% were obtained respectively.
- About 520 kJ/m²/day heat gain was achieved.
- The PVT system is trapezoidal in shape, it requires less footprint area as compared with the flat system of same capacity.
- The system is tracking free and thus requires less maintenance.
Category C: Submerged Photovoltaics [25]

System Description (Fig.9): A 10 W C-Si PV module is submerged in the liquid bath. Various liquids such as water, silicone oil, liquid paraffin, Glycerin, Ethylene Glycol etc. have been used in the liquid bath. The heat from the liquid bath is extracted by secondary heat exchanger submerged in the bath by forced circulating water. The performance of the modified system is compared with the reference PV module (without any attachment) experimentally in the sunlight.

Significant outcomes (Fig.10):
- Maximum increase in average electrical efficiency of the system using Distilled water was 11.25 %, by using Liquid Paraffin it was 16.02 % and for Coconut oil it was 7.098 % as compared to the reference module.
- Average heat gain by water is found to be highest as 0.1102 kW and for Polyethylene Glycol (PEG) 400 it was 0.0963 kW.
- Maximum PV module surface temperature is found to be 43.8°C in condition-I, when immersion cooling is not provided. While in condition-II maximum temperature is found to be 37.2°C when immersion cooling is provided at average ambient temperature of 43°C.
Category D: Use of liquid spectrum filters [26-30]

**System Description (Fig.11):** Various clear liquids such as Coconut oil, silicone oil, Glycerin, Ethylene Glycol etc. have been used as liquid spectrum filters for PV. These liquid spectrum filters are mounted on a 10 W C-Si PV module, thermally separated from the module. The filters trap the undesired part of solar spectrum and transmit only the desired spectrum on the PV modules. The detailed spectroscopic analysis, simulation studies, analytical studies and experimental studies are discussed in our previous published work [26-30].

**Significant outcomes (Fig.12):**
- Beam Split Photovoltaic Thermal System (BSPVT) systems with liquid spectrum filters are explored. Simulation and experimental studies conclude that the liquids can be used as spectrum filters. Details are discussed in our another published work [27,28]
- The average overall efficiencies of, and 59%, 33% and 54% were obtained for, coconut oil, water and silicone oil spectrum filter, respectively. The average electrical efficiency of 12.53% and average thermal efficiency of 47% was obtained for coconut oil spectrum filter. Details are discussed in our another published work [29,30]

![Fig. 11: Spectrum filters for PV](image1)
![Fig. 12: System performance](image2)

(In fig. 11, A: Schematic diagram showing position of filter, B: Actual photograph showing filter mounted on PV module, C: Actual photograph showing display unit, D: Pyranometer)

3. Discussions and Conclusions

In the present work, various techniques have been used for the thermal management of the photovoltaic modules. These techniques mainly include, the module cooling by using fins, wind catchers, circulating liquids, submerged PV and spectrum filters. These thermal management techniques for PV have been explored by experimental studies at Solar Energy Laboratory, RCOEM, Nagpur (21.10 N, 79.09 E). After experimental work, it has been observed that, the thermal management of the photovoltaic system using natural air current is an easiest way; however, this technique has limited cooling scope. In the water cooling arrangement, water is required to flow in the system continuously; it requires additional pumping power and the systems are bulky. In these systems, water circulation can be carried out using DC pumps powered by solar PV modules. The
water cooling techniques are more suitable for the places where hot water and electricity demands are concurrent. Some of the potential applications of these systems are hotels, motels, hostels, hospitals, banquet halls etc. The use of liquid spectrum filters is a modern thermal management technique. There is a huge scope for further research in the area of liquid spectrum filters for photovoltaics. In our other published work [26-30] a most recently developed Beam split Photovoltaic Thermal System, (BSPVT) is explored in details.

The Photovoltaic systems are being used extensively in all corners of the world. Significant research work is also being carried out to improve the efficiency of the solar cells in various laboratories. Nevertheless, it is essential to carry out more research for the field applications of the PVT systems discussed in this article.

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References
[1] C. S. Solanki, ‘Solar photovoltaics Fundamentals, technologies and applications’, Second edition, PHI learning, New Delhi, 2013
[2] S. M. Sze, ‘Physics of Semiconductor Devices’, John Wiley & Sons, New York, 1981, p.264 (Chapter14).
[3] P. Singh, N. M. Ravindra, ‘Temperature dependence of solar cell performance an analysis’ Solar Energy Materials & Solar Cells, 101 (2012)36–45
[4] Swapnil Dubey, ‘Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World A Review’ Energy Procedia 33 (2013) 311 – 321
[5] E. Skoplaki, J.A. Palyvos, ‘On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations’ Solar Energy 83 (2009) 614–624 615
[6] R. Santbergen, C. C. M. Rindt, H. A. Zondag, and R. J. C. Van Zolingen, ‘Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors,’ Solar Energy, vol. 84, no. 5, pp. 867–878, 2010
[7] C. Huang, H. Sung, and K. Yen, ‘Experimental Study of Photovoltaic / Thermal ( PV / T ) Hybrid System,’ International Journal of Smart Grid and Clean Energy, vol. 2, no. 2, May 2013 pp 148–151 2012.
[8] B. J. Huang, ‘Performance Evaluation of Solar Photovoltaic/Thermal Systems’, Solar Energy, Vol. 70, No. 5, pp. 443–448, 2001
[9] N. Aste, C. Del Pero, F. Leonforte, and M. Manfren, ‘Performance monitoring and modeling of an uncovered photovoltaic-thermal ( PVT ) water collector,’ vol. 135, pp. 551–568, 2016.
[10] R. K. Mishra and G. N. Tiwari, ‘Energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode,’ Sol. Energy, vol. 90, pp. 58–67, 2013.
[11] G. Li, G. Pei, M. Yang, and J. Ji, ‘Experiment Investigation on Electrical and Thermal Performances of a Semitransparent Photovoltaic / Thermal System with Water Cooling,’ International Journal of Photoenergy Volume 2014, Hindawi Publishing Corporation, http://dx.doi.org/10.1155/2014/360235
[12] M. La, T. Kroyer, S. Fortuin, M. Wiese, and M. Hermann, ‘Development and modeling of highly-efficient PVT collectors with low-emissivity coatings,’ Sol. Energy, vol. 130, pp. 161–173, 2016.
[13] M. Y. Othman, S. A. Hamid, M. A. S. Tabook, K. Sopian, M. H. Roslan, and Z. Ibrahiim, ‘Performance analysis of PV / T Combi with water and air heating system : An experimental study,’ Renew. Energy, vol. 86, pp. 716–722, 2016.
[14] S. M. Bambrook and A. B. Sproul, ‘Maximising the energy output of a PVT air system,’ Sol. Energy, vol. 86, no. 6, pp. 1857–1871, 2012.
[15] Poorya Ooshaksaraei, K. Sopian, S. H. Zaidi, and R. Zulkifli, ‘PT,’ Renewable Energy (2016), doi: 10.1016/j.renene.2016.10.043
[16] J. K. Tonui and Y. Tripanagnostopoulos, ‘Performance improvement of PV / T solar collectors with natural air flow operation,’ Solar Energy, vol. 82, pp. 1–12, 2008
[17] V. V Tyagi, S. C. Kaushik, and S. K. Tyagi, ‘Advancement in solar photovoltaic / thermal ( PV / T ) hybrid collector technology,’ Renewable and Sustainable Energy Reviews 16 (2012) 1383–1398
[18] Tonui JK, Tripanagnostopoulos Y, ‘Air-cooled PV/T solar collectors with low cost performance improvements.’ Sol. Energy. 81: 498–511, 2007.

[19] M. Farschimonfared, J. I. Bilbao, and A. B. Sproul, ‘Full optimisation and sensitivity analysis of a photovoltaic – thermal (PV/T) air system linked to a typical residential building’, Sol. Energy, vol. 136, pp. 15–22, 2016.

[20] Sanjeev S. Joshi, Ashwinkumar S. Dhoble, ‘Photovoltaic –Thermal systems (PVT): Technology review and future trends, Renewable and Sustainable Energy Reviews, Volume 92, September 2018, Pages 848–882, [DOI: 10.1016/j.rser.2018.04.067]

[21] Apurva Raut, Sanjeev S. Joshi. ‘Design Of Windcatcher Mechanism For Cooling Of Solar Photovoltaic Module’, thesis submitted at Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, June 2017

[22] Swati Mor, Sanjeev S. Joshi, ‘Performance analysis of photovoltaic module attached with aluminium conical fins and array of miniature horizontal-axis rotating fans’ thesis submitted at Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, June 2018

[23] Ashish Jha, Sanjeev S. Joshi et al. ‘Experimental analysis of solar photovoltaic thermal system’ thesis submitted at Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, May 2017

[24] Sanjeev. S. Joshi et al. ‘Performance Analysis of An Inverted Trapezoidal Flume Shaped Photovoltaic-Thermal System, Appl. Sol. Energy -Springer , Vol. 54, Issue 6, 2018 (Paper in press)

[25] Vishal Gajbhiye, Sanjeev S. Joshi, ‘Performance Analysis Of Solar Photovoltaic Module Immersed In Liquid Bath’ thesis submitted at Department of Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, June 2017

[26] Sanjeev. S. Joshi, A.S. Dhoble, P.R. Jiwanapurkar, ‘Investigations of different liquid based spectrum beam splitters for combined solar photovoltaic thermal systems. Journal of Solar Energy Engineering: Including Wind Energy and Building Energy Conservation, Vol.138, April 2016, pp 021003-1-7 ASME trans. [DOI: 10.1115/1.4032352]
Sanjeev. S. Joshi, Ashwinkumar S. Dhoble, ‘Use of Silicone Oil and Coconut Oil as Liquid Spectrum Filters for Beam Split Photovoltaic Thermal Systems: With Emphasis on Degradation of Liquids by Sunlight’, Journal of Solar Energy Engineering: Including Wind Energy and Building Energy Conservation, Vol.140, Feb. 2018, pp – 014502-1-9, ASME Trans. [DOI: 10.1115/1.4038052]

[27] Sanjeev. S. Joshi, Ashwinkumar S. Dhoble, ‘Experimental Investigation of solar photovoltaic thermal system using water, coconut oil and silicone oil as spectrum filters’ Journal of the Brazilian Society of Mechanical Sciences and Engineering, Springer, August 2017, Volume 39, Issue 8, pp 3227–3236 [DOI 10.1007/s40430-017-0802-0]

[28] Sanjeev. S. Joshi, Ashwinkumar S. Dhoble et al. ‘Performance Analysis of Photovoltaic Thermal System Using Silicone Oil Spectrum Filter, Appl. Sol. Energy -Springer , Vol. 54, Issue-01, 2018, pp 4-9 [DOI:https://doi.org/10.3103/S0003701X18010061]

[29] Sanjeev. S. Joshi, Ashwinkumar S.Dhoble, ‘Analytical Approach for Performance Estimation of BSPVT System with liquid spectrum filters, ‘Energy’, Volume 157, 2018, Pages 778-791, [DOI: 10.1016/j.energy.2018.05.204]