JCARME
ISSN: 2228-7922
Journal of Computational and Applied Research in Mechanical Engineering
Vol. 10, No. 1, pp. 1-24
jcarme.sru.ac.ir

A systematic approach for a better thermal management of photovoltaic systems- A review

Akash Pandey, Siddharth Chakrabarti*and Pratik Daghe

Mechanical Engineering Department, OP Jindal University, Raigarh, Chhattisgarh, 496109, India

Article info:

Type:	Research
Received:	10/08/2019
Revised:	02/12/2019
Accepted:	12/12/2019
Online:	14/12/2019

Keywords:
Photovoltaic panel,
Heat pipe,
Immersion cooling,
Phase change material,
Evaporative cooling.

Abstract
Solar energy is a highly recognized energy source, capable of fulfilling the world's future energy demands. The solar photovoltaic technology involves the unmediated transformation of sunlight into electricity. A little fraction is converted into electricity and the remaining gets exhausted as unused heat. This results in an increase in the operating temperature of the PV Panel. The conversion efficiency and the life span of the photovoltaic panels are affected by an increase in working temperature. Hence, an appropriate cooling technique is essentially required for maintaining the operating temperature of the module within the limits prescribed so as to obtain higher electrical yield and an increased lifespan. The objective of this paper is to present a summary of the various cooling techniques used to enhance the performance of PV panels, namely air cooling - free and forced, water spray cooling, cooling by phase change materials, heat pipe cooling, liquid immersion cooling, and forced water circulation. Several research articles are reviewed and classified on the basis of technology used for the thermal management of PV modules. The paper also investigates one of the passive evaporative cooling techniques to control the temperature rise of the PV module and enhancement inefficiency. Around 12^{o}C reduction in PV panel temperature under maximum insolation and a 7.7 % increase in average electric power generation efficiency was observed under this technique.

1. Introduction

Countries across the world rely mainly on coal, oil and natural gas to fulfill their energy needs. These conventional energy resources are depleting at a fast rate and are available in a limited quantity representing a situation of energy crisis for the world. Another major issue associated with the use of conventional energy resources is their adverse effect on the environment – like the continuous increase in CO_2 content which is causing global warming and release of other secondary toxic substances which have become a threat for biological species. Renewable energy is the best alternative to fossil fuels and has the potential to meet the world's current and future energy needs. They are clean and inexhaustible sources of energy, having minimum impact on the earth's environment [1]. Solar energy involves harnessing the energy of the sun to either generate electricity or to complete the tasks that would have otherwise required electricity, like heating and cooling. Earth receives 1.8

*Corresponding author
email address:siddharth.chakrabarti@opju.ac.in

$\times 10^{11}$MW of energy from the sun that is much more than the present energy needs of the world [2].

The solar photovoltaic technology involves the direct conversion of energy possessed by the solar radiation into electricity. The primary component of a photovoltaic system is a PV panel made up of a number of solar cells, which generate electromotive force on the absorption of solar radiations [3]. Owing to their simple design, low maintenance cost and cleanliness, they are used to generate electricity, pump water, and provide power to terrestrial components like communication satellites and space vehicles [2, 3, 4]. As they can be used for various applications, there has been a continuous rise in the demand for photovoltaic panels and a lot of investigation have been done to develop new materials and improve their performance. Still, the efficiency with which solar cells convert the input energy lies well below 30%, with 24.7% being the maximum efficiency recorded under standard test conditions (STC) [4]. The conversion efficiency of PV panel is affected by a number of factors, with the operating temperature of the module being the major one.

1.1. The impact of temperature on performance of PV cells

The performance of a PV panel depends largely on some external and internal factors. Operating temperature of the module, solar radiation intensity, accumulation of dust over the panels, wind speed are some of the external environmental factors which have a direct influence on the power output of the PV panels. The operating temperature has a pronounced impact on the current and output voltage of the module [5]. Out of the total incident energy, less than 20% is transformed into useful electrical energy and the remaining is lost as heat, which substantially increases the effective temperature of the module above the ambient temperature. The effect gets pronounced when the ambient temperatures are high [6, 7]. A large number of correlations are available in the literature that reflect the dependence of electrical conversion efficiency of the module on the working temperature, and most of them have reported a linear relationship. The electrical efficiency drops with an increase in module temperature because with temperature the fill factor and open circuit voltage drop whereas the short circuit current surges by a small value. The overall effect reduces power output, which decreases the electrical efficiency [8].

Radziemska [9] conducted an experimental study to access the influence of temperature and wavelength on the open circuit voltage and output power of the crystalline solar cell. Fig. 1 shows the variation of output power and voltage with temperature. It was observed that both parameters decreased with increasing the temperature. For a rise of 1 K rise in temperature of the output power, fill factor and electrical efficiency were observed to decrease by 0.65 %, 0.2 %, and 0.08 % respectively.

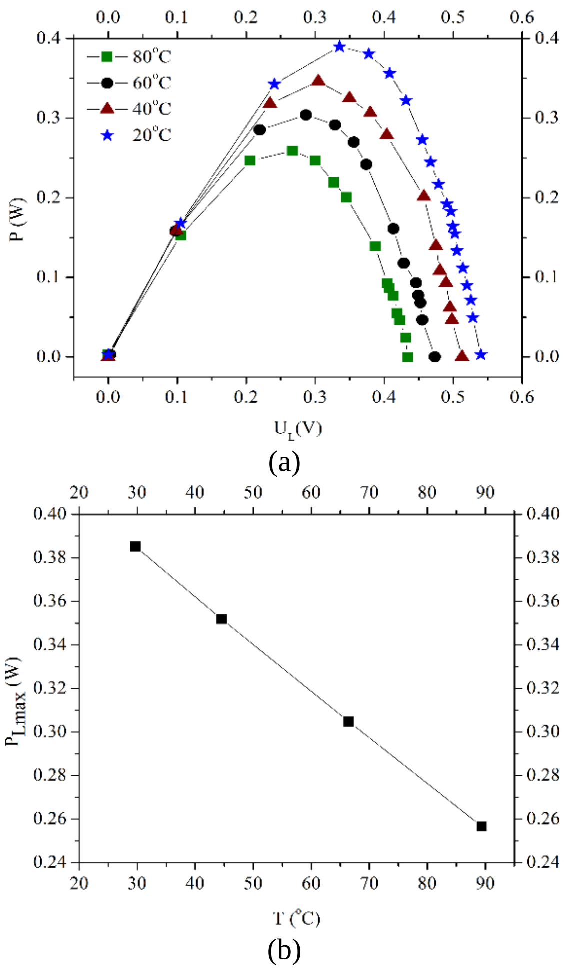


Fig. 1. (a) Variation of output power versus voltage at different temperatures (b) maximum output power versus temperature [9].

They showed that the increase in lattice vibrations and reduction in the mobility of charge carriered with increasing temperature are the basic reasons behind the performance deterioration of PV modules.

Rahman et al. [10] performed an experimental study to understand the impact of solar irradiance and temperature on the performance of PV modules. They selected a mono-crystalline PV unit of 90 W output power for the experimental study. The experimental results revealed that the power output and electrical efficiency of PV module decreased by 0.37 and 0.06 %, 0.33 and 0.06 %, 0.24 and 0.06 %, 0.17 and 0.06 % under intensities of 1000, 800, 600, 400 W/m^2 respectively for an increase of 1^{0}C in the temperature of the module (Fig. 2). They observed that the module temperature increased by 4.93^{0}C for an increase of 100 W/m^2 in the radiation intensity.

Zaini et al. [11] through their experimental investigation showed a decrease in output power and open-circuit voltage of a photovoltaic module with rising operating temperature. A mono-crystalline photovoltaic panel of 50 W rated output power was used for performing the experiment under the constant intensity. They carried out an experiment under the constant intensity of 458.2 W/m^2. During tests, the temperature varied between 25^{0}C to 60^{0}C. The experimental results matched with the simulation results of MATLAB/SIMULINK, and a fair consensus was observed.

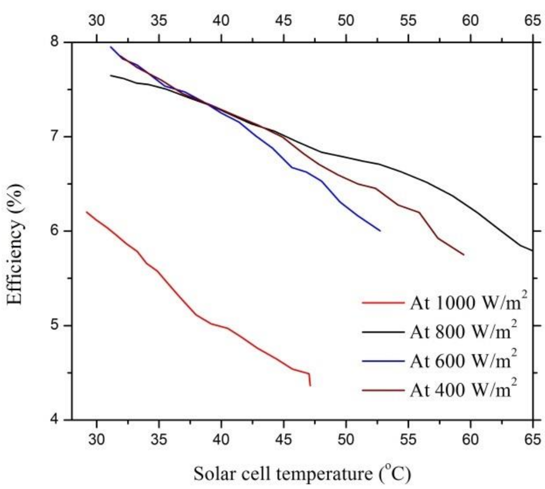


Fig. 2. Variation of efficiency with module temperature at different intensity levels [10].

They suggested that for the same radiation intensity, the modules for achieving better performance should be installed at locations with low ambient temperature. Du et al [12] established a theoretical model to calculate the temperature of PV modules and observed the temperature of the module to be 60^{0}C under a radiation intensity of 1000 W/m^2. They estimated a drop of 2.9-9.0 % in the electrical efficiency of cells having a temperature coefficient of 2.1 - 5.0 %.

In the present work an extensive review of the numerous cooling technologies employed to maintain the operating temperature of modules closer to the specified limit to enhance the PV modules performance is presented and for which an enormous number of research articles are referred to. The cooling technologies used are described under two broad categories: passive cooling techniques and active cooling techniques. An experimental investigation is also carried out to access the effectiveness of evaporative cooling, using a wood wool cooling pad in reducing the temperature and increasing the power output of the PV module.

2. Cooling techniques

2.1. Passive cooling techniques

Passive cooling systems are the least expensive means of cooling which maximize the efficiency of a PV module without using any mechanical device. They rely on natural means: conduction, convection, and radiation for heat dissipation from the PV module without using any external energy. Natural air cooling, heat pipe cooling, cooling by water, cooling by phase change material, and evaporative cooling are different passive cooling technologies employed for the thermal management of PV modules and are discussed in this paper.

2.1.1. Natural air cooling

Cooling by means of natural air circulation is one of the simplest and cheapest methods for thermal regulation of PV panels. However, it is associated with low heat transfer rates owing to low specific heat and low density of air, which results in a very small temperature drop of PV panels. It is easy to integrate and can be implemented by providing fins or by mounting the panels on the roof. It is observed that the solar panels installed on rooftop experience more temperature than the ambient. In rooftop systems, module to sheet-roof gap plays an important role to have convective cooling on lower surface of the module. An optimum air gap is required to be considered and the air gap between the modules and the roof sheet is best at 110mm and beyond this, the benefits are less.

Tonui et al. [13] proposed two low-cost cooling systems to boost the heat transfer rate in the air channel of a PV/T solar air collector. The channel geometry was changed by hanging a thin metal sheet at the center and by attaching fins to the rear surface of the air channel (Fig. 3). The test setup was made by means of a poly-crystalline Si PV module having rated power of 46 W, fitted at the top of a rectangular air duct box, made of an aluminum sheet having channel depth of 0.15 m. Tests were conducted with natural circulation of air. For the GL configuration, a low iron glass of 4 mm thickness was mounted in front of the PV module. FIN system gave better performance in comparison to the TMS system, although both contributed positively to enhance the thermal and electrical energy generation. A reduction of 3°C in temperature was observed for FIN system and unglazed TMS system at 15 cm channel depth. For the same depth glazed TMS and FIN system had a temperature reduction of about 4 and 10°C, respectively when compared with the REF system, presenting an improvement of 4 and 10% in output power, respectively. One of the key outcomes of the tests was that there is an optimal depth of channel which is between 5 to 10 cm at which the thermal efficiency and mass flow rate of air become maximum.

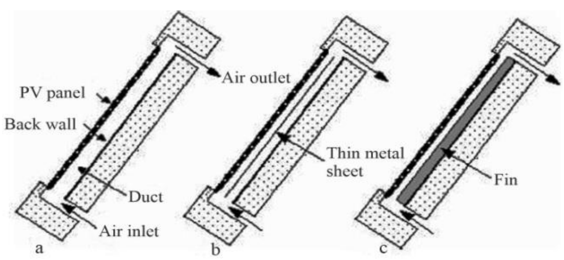


Fig. 3. Diagram displaying the 3 configurations studied (UNGL), (a) REF, (b) TMS, and (c) FIN [13]

Cuce et al. [14] performed an experimental investigation to access the impact of a passive cooling technique on a silicon PV module performance. The aluminum heat sink was used as the heat dissipation device to lower the effective temperature of the module (Fig. 4). Energy, exergy and power conversion efficiency of the PV cell was experimentally determined in the illumination intensity range of 200-800 W/m^2, under different ambient temperature.

Experiments were carried out on a solar simulator consisting of 12 halogens bulbs (tungsten) having maximum illumination power of 12 suns that was placed in a control room equipped with an air conditioning arrangement. Results clearly showed that the modified photovoltaic module provided more power output than the conventional module. An increase of 8, 27, 46 and 65 mW in power output was recorded under an illumination intensity of 200, 400, 600 and 800 W/m^2, respectively. Experimental results clearly dictate that with an increase in radiation intensity, the energy, exergy, and power transformation efficiencies of PV cell rise exponentially. Ambient temperature was observed to have a significant influence on the PV cell performance; power output of both the configurations was observed to increase with reducing the temperature.

Carlos Correa-Betanzo et al. [15] conducted a study to access the impact of wind speed, temperature, and radiation intensity on the electrical energy generation of the photovoltaic system.

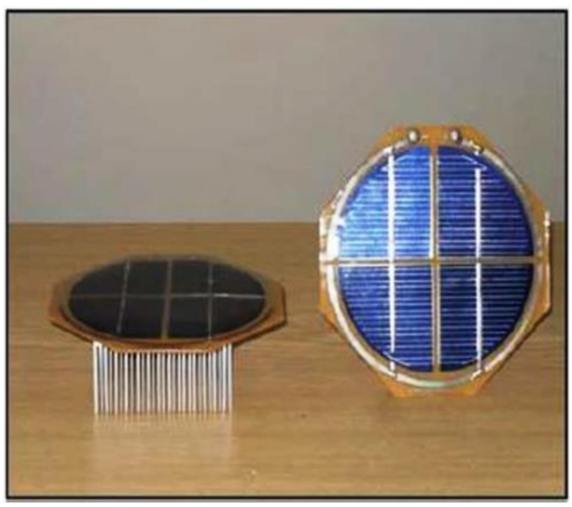


Fig. 4. PV cells without fins and with fins [14]

Four different mathematical models were considered for determining the temperature of the cell, with and without considering the impact of wind speed. It was found that the increase in panel temperature has an adverse impact on the electrical yield of the system and the results clearly indicated that the flow of air current above and below the surface of photovoltaic panel reduces the negative impact of temperature and thus aids in increasing the electrical efficiency.

Filip et al. [16] designed, developed and experimentally verified a novel passive cooling technique to reduce the temperature levels of the photovoltaic module, so as to improve its electrical efficiency. Aluminum fins with epoxy conductive glue were attached to the rear wall of the polycrystalline photovoltaic panel, and two different fin configurations were used. The first configuration comprised of a series of fins positioned in an up-down direction and second consisted of randomly placed perforated fins. During the tests insolation varied between 300 to 900 W/m^2, and mean atmospheric temperature was 12°C. The results clearly indicated that the second fin gave a better performance in comparison to the first fin geometry as the random arrangement of fins reduced the impact of separation of air on the backside. Also, the panel fitted with perforated fins yielded an extra power of 0.6 W in comparison to referent panel under radiation intensity of 750 W/m^2, reflecting a 2% increase in the electrical efficiency. It was stated that the second fin configuration helped in gaining high turbulent flows on the rear side of the panel, resulting in an increased heat dissipation rate.

2.1.2. Water cooling

Han et al. [17] carried out an experimental investigation to predict the performance of Si concentrating photovoltaic solar cells dipped in four different kinds of liquids. The experiments were conducted on a solar cell of 40 mm width, 50 mm length and an aperture area of 19.5 cm^2, made up of mono-crystalline silicon cells with silicon dioxide anti-reflection coating. De-ionized (DI) water, dimethyl silicon oil, isopropyl alcohol (IPA), and ethyl acetate were chosen as immersion liquids. To understand the effect of thickness of the liquid film directly above the cell surface, two separate tests were conducted; one with 1.5 mm and the other with a liquid layer thickness of 9 mm. The 9 mm test was also used to understand the influence of absorption of the incident light by different liquids. The tests were conducted at 30 Sun and 25°C. Results showed that in comparison to I_{sc} and V_{oc} of CPV solar cells in the air, the I_{sc} and V_{oc} of the cells immersed in liquids of 1.5 mm thickness were larger, although the overall variation in V_{oc} was comparatively less than that of the I_{sc}. Maximum change of 15.5% in I_{sc} was recorded for the cell immersed in IPA. The largest change in efficiency was observed to be 15.2% for the cell immersed in IPA with 8.5% being the minimum change for the cell in DI water. The test results clearly demonstrated that with an increase in liquid layer thickness the degree of improvement in cell efficiency decreases due to increased absorption of the incident light.

Xin et.al. [18] observed an improved electrical performance of GaInP/GaInAs/Ge triple-junction solar cell immersed in dimethyl silicon oil. A CFD analysis was also presented to predict the optimum liquid film thickness. For the experimental investigation, a GaInP/GaInAs/Ge solar cell of 99.2 mm^2 aperture area was selected and tests were conducted at 500 suns and 25°C. Oil film thickness of 1.0 – 30.00 mm was selected for performing the tests. Results showed that for silicon oil thickness of 1.0 mm the maximum power output and electrical efficiency of solar cell were 20.083 W and 40.572% in comparison to 19.556 W and 39.567% of solar cell without liquid immersion. Liquid film thicknesses of 1.0, 2.5, 5.0, and 10.0 mm were selected for CFD simulation; and Fig. 5 shows a decreasing trend in the electrical performance of solar cell with increasing thickness. At oil mass flow rate of 5 kg/hr and oil film thickness of 1.0, 2.5, 5.0, and 10.00 mm the average cell temperatures were observed to be 351.92, 344.92, 355.43, and 388.69 K, respectively. For the best performance, the optimum oil thickness was found to be 6.3 mm. The CFD simulation results also predicted that a minimum oil thickness of 2.5 mm and 20 kg/hr mass flow rate is needed to retain a low uniform temperature of the solar cells.

Chandrasekhar et al. [19] proposed a novel passive cooling technique for the thermal management of the photovoltaic module, using cotton wick structures. For the experimental study, a 7 mm diameter cotton wick was mounted at the backside of a panel with its free end dipped in the fluid. Water, Cuo/water nanofluid and Al_2O_3/water nanofluid were chosen as fluids for the cooling system. For panels without cooling system the maximum temperature reached 65°C, which reduced to 45°C, 54°C and 59°C for the photovoltaic panels with cotton wick structures dipped in water, Al_2O_3/water nanofluid and CuO/water nanofluid respectively, which showed a decrease of 30%, 17% and 11% in module temperature, respectively. They specified that the reduction in panel temperature is due to the moist state maintained at the backside of the panel caused by the damped cotton wick. The maximum power output of conventional panel was observed to be 41 W, which increased to 47.5 W and 44.6 W for the panels cooled using cotton wick with water and nanofluid, respectively. The module efficiency was witnessed to be 9% with no cooling system which increased to 10.4%, 9.7% and 9.5% for panels with cotton wick structure combined with water, Al_2O_3/water, and CuO/water nanofluid, respectively.

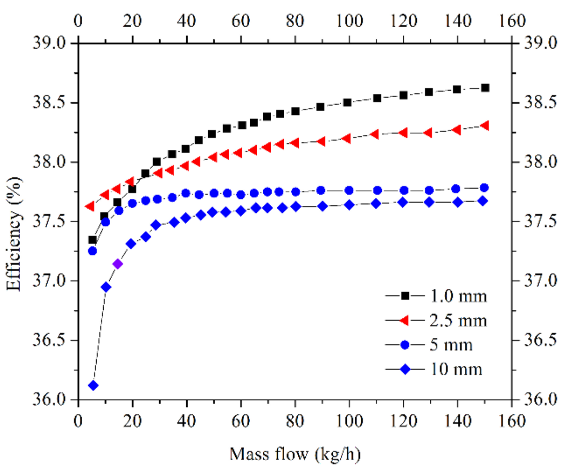


Fig. 5. Variation of efficiency with the mass flow rate at different oil film thickness [18].

2.1.3. Heat pipe cooling

Anderson et al. [20] successfully showed the use of a Copper/Water heat pipe fitted with made up of aluminum to remove heat from a concentrating photovoltaic cell (CPV). The CFD analysis was also carried out to obtain the optimum fin size and fin spacing. An experimental test setup was prepared and the tests were conducted under a heat flux of 40 W/cm^2. Results showed a total cell-to-ambient temperature increase of 40°C owing to the heat rejected by the heat pipe. Gang et al. [21] carried out an experimental investigation on a heat pipe-photovoltaic/thermal system (HP-PV/T). A dynamic model was also established to predict the performance of the system. From the experiments conducted on 4 collectors having total PV cell area of 2.91 m^2, in the month of May, it was observed that the mean temperature of water kept in the storage tank reached to 44.2°C from 28.1°C. Results showed that the average gain in electrical power per unit PV area and average gain in thermal output per unit collecting area were 62.3 and 276.9 W/m^2 respectively; while the thermal and electrical efficiencies were observed to be 41.9% and 9.4%, respectively.

Moradgholi et al. [22] incorporated a heat pipe into a PV/T system with the aim to reduce the temperature of solar panel and to achieve a gain in electrical power generation. Tests were conducted in both spring and summer. The test results showed an average increase of 5.67% in electrical power and 16.35% in the thermal efficiency of PV/T system, during spring. In summer the PV/T system generated 7.7% more electrical power, with a thermal efficiency of 45.14%. A substantial drop of 15°C in temperature of the panel was seen which increased the power generation by 1.1 and 1.26 W during spring and summer, respectively.

Du et al. [23] proposed an innovative hybrid photovoltaic/thermal management system to recover the loss of efficiency instigated by the temperature rise of solar panels. The thermal management device used was a heat pipe plate composed of groups of micro-grooved channels and nano-coated compressed metal foams (Fig. 6).

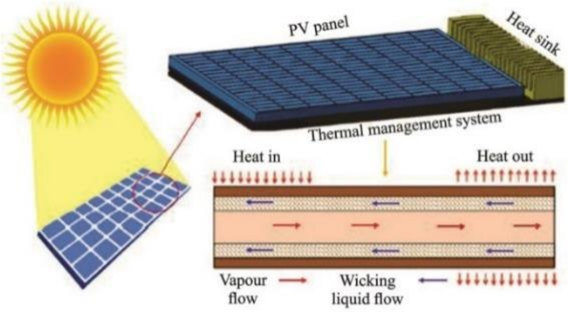


Fig. 6. Representation of the hybrid PV/T system using heat pipe [23].

Heat pipe was used owing to its high rate of heat transfer brought by the phase transformation of the working fluid, DI water. Additional heat sinks were fixed to the condenser section of the heat pipe, to facilitate the removal of a large amount of heat under intense solar radiations.
The energy balance equation proposed for the solar cell was:

$$q_s = q_c + q_r + q_e + q_n \quad (1)$$

where q_s is the illuminated light, q_e is the part of illuminated light converted into electricity, q_c and q_r represent the thermal energy dissipated by means of natural convection and radiation respectively and q_n is the cooling heat flux, i.e. the excess thermal energy to be removed from the solar panel for cooling. And the panel temperature was expressed as in Eq. (2).

$$T_s = \frac{[(1-\beta).\epsilon_0.Q_s - 2.\epsilon_1.\sigma_{sb}.({T_s}^4 - {T_a}^4) - q_n]}{2h_c} + T_a \quad (2)$$

where T_a and T_s are the temperatures of ambient and solar cell respectively, ε_0 is the absorption rate of thermal energy, ε_1 is emissivity of solar cell for thermal radiation, and h_c is the convective heat transfer coefficient.
The evaporative heat flux qn was evaluated using the Rohesenow model [24] which governs the liquid vapor phase transformation

$$\frac{\left(\frac{q_n}{h_{lg}}\right)}{\mu_l} * \left[\frac{\sigma}{g*(\rho_l - \rho_a)}\right]^{\frac{1}{2}} = \left[\frac{J_a}{C_{sf}*Pr_l^n}\right]^3 \quad (3)$$

where, h_{lg} is the liquid vapor latent heat of the working fluid, g and C_{sf} represent acceleration due to gravity and coefficient of surface and working fluid, ρ_l, ρ_v, σ, μ represent the liquid and vapor density, surface tension, dynamic viscosity of the working fluid. Ja and Pr denote the dimensionless Jacob and Prandtl number, respectively.
Jacob number is defined as:

$$Ja = \frac{C_{pl}*(T_s - T_{ev})}{h_{lg}} \quad (4)$$

where Cpl represents the heat capacity of the liquid, T_s is the PV panel temperature and T_{ev} is the temperature of vapor in the evaporator section. The above equation clearly shows that the evaporating temperature of the working fluid (T_{ev}) and PV panel temperature (T_s) affect the cooling heat flux, q_n.
The experiments were conducted under a radiation intensity of 300 - 1000 W/m^2, ambient temperature 25°C and wind velocity 0-1 m/s. Fig. 7 clearly shows that the maximum evaporative heat flux is around 450 W/m^2, allowing the solar cell temperature to be maintained below 40°C, with a temperature reduction of more than 22°C.
Koundniya et al. [25] performed an experimental study to access the role of a finned heat pipe for cooling of a solar PV panel. For the removal of heat from the panel, a copper-water heat pipe was used. Aluminum fins were attached to the heat pipe to intensify the heat removal by means of natural convection.

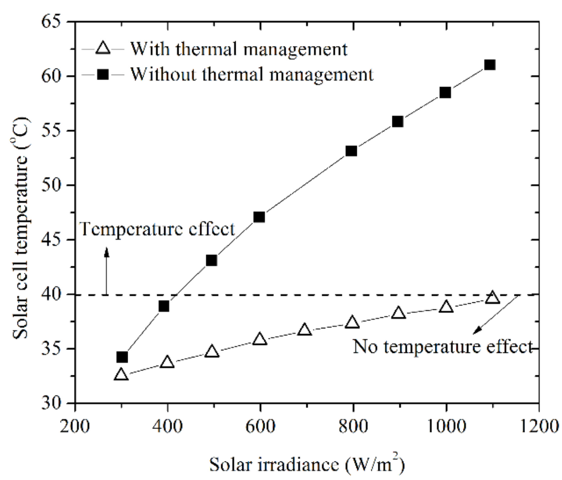


Fig. 7. Effect of heat pipe cooling on solar cell temperature [23].

The experimental results clearly indicated that the extreme temperature of the panel was 73.2°C without using finned heat pipe which reduced to 58.2°C with finned heat pipe, showing an overall decrease of 13.80°C in temperature.

2.1.4. Cooling with phase change material

Park et al. [26] conducted an experimental study to access the effectiveness of a material which changes phase in reducing the operating temperature of a PV panel, mounted on a vertical wall surface. The numerical model is shown in Fig. 8 was used to perform simulation in TRNSYS software to predict the optimum values of thickness and melting temperature of the PCM.

The PCM was inserted in between two plates of 2 mm thickness made up of aluminum and was then attached to the backside of the PV module made up of polycrystalline cells. For parametric study east, southeast, west, southwest, and south were selected as the installation direction and the maximum output was obtained for the panel facing south direction. The test results revealed a reduction of 5 K in the temperature for the PV/PCM system in comparison to the conventional system, resulting in a 3.1% increase in energy generation efficiency. For the PCM, the optimum value of melting temperature was found to be 298 K, irrespective of the direction in which the system was installed. The simulation results revealed that the optimal thickness varied with installation directions. Under optimal conditions, the power output was enhanced by 1.0-1.5% for the PV/PCM system installed along the south direction, in comparison to the conventional module.

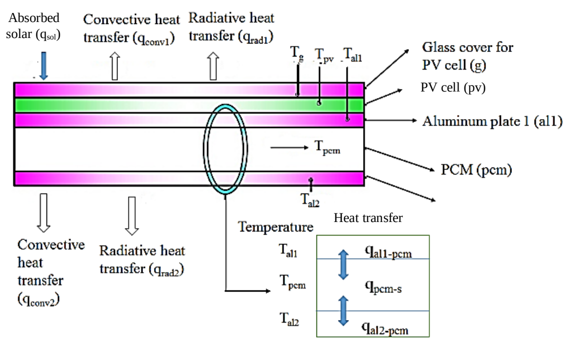


Fig. 8. Numerical model of the pv/pcm system [26].

Indartono et al. [27] proposed a novel cooling technique using yellow petroleum jelly as PCM for the efficiency improvement of building integrated photovoltaic system. Aluminum tube filled with 1 kg of yellow petroleum jelly was fixed to the rear side of a monocrystalline PV panel and its thermal regulation performance was compared with an unmodified PV panel. Two different conditions were considered for conducting the tests-"PV on roof" and "PV on stand". For the "PV on roof" experiment top and back surface temperature for conventional module was observed to be 60°C and 58.8°C, respectively, whereas for the PV/PCM system 54.3°C and 55.7°C was the top and bottom surface temperature respectively, so an average difference of 2.7°C in temperature was observed. For "PV on stand" arrangement top and back surface temperature was 42.2°C and 39.2°C, respectively in comparison to 44.8°C and 41.4°C observed for the conventional module, with 0.4°C being the average temperature difference. An average increase of 22.6% and 21.2% in power and efficiency was listed for "PV on roof" configuration, while the average increase in power and efficiency of "PV on stand" arrangement was 7.3% and 6%, respectively. Experimental results revealed that "PV on roof" arrangement is more suitable for building integrated photovoltaic application, as the performance of "PV on stand" arrangement is deteriorated due to convection cooling of the back surface.

Atkin et al. [28] developed a thermal model and performed an experimental investigation to predict the overall efficiency of a PV panel with Paraffin Wax infused graphite combined with a finned heat sink fixed to its rear surface. Two mono-crystalline solar panels each having 0.052 m^2 surface area were used and halogen lamps of 500 W were used to provide the insolation. Paraffin wax RT40, having a melting temperature of 40°C and 0.25W/mK thermal conductivity was used as PCM and was infused with graphite to increase its overall thermal conductivity. The peak temperature for PV panel attached with PCM infused graphite combined with finned heat sink was 19°C less than the unmodified PV panel and was 5°C less for the panel attached with pure paraffin. A greater reduction in temperature was observed because 16.6 W/mK was the thermal conductivity of infused graphite PCM and it was much higher than the thermal conductivity of pure paraffin; and the addition of heat sink resulted in more heat loss due to increased surface area. An increase of 12.97% in overall efficiency was observed.

Stropnik et al. [29] conducted an experimental investigation on a photovoltaic panel with a paraffinic organic phase change material RT28HC, fixed to its rear surface. Numerical simulation was performed on TRNSYS software to analyze the yearly electric energy generation and efficiency of unmodified and PV-PCM modified panel. Fig. 9 shows the experimental setup fabricated using a PV panel made of mono-crystalline solar cells, modified by attaching RT28HC, enclosed in acrylic glass to its backside. For numerical simulation in TRNSYS software, they used TYPE601, the electrical model of the photovoltaic panel, which includes four modes for calculating the PV performance and the second mode was used for simulation. Maximum PV cell temperature for the modified panel was found to be 44°C, whereas, it reached 75.2°C for the conventional panel. The average increase in electrical power and energy generation efficiency was 9.2% and 1.1%, respectively. Simulation results showed an annual increase of 7.3% and 0.8% in electricity generation and energy generation efficiency, respectively.

Kibra et al. [30] suggested a thermal model for predicting the effectiveness of a PCM in reducing the temperature of the photovoltaic panel.

Fig. 9. Conventional PV panel (left) modified panel (right) [29].

Fully implicit scheme was used for the discretization of heat balance equation; and energy balance equation was discretized by finite difference method. Thermal management performances of three distinct PCM's with distinct melting temperatures were compared. Numerical results showed PCM is quite effective in reducing the temperature of PV panels and an overall rise of 5% in the thermal performance was observed. The obtained numerical results showed a close approximation with prior experimental results.

Klugmann-Radziemska et a.l [31] performed an experimental investigation to show the effectiveness of three dissimilar PCM's – Paraffin 42-44, Rubitherm RT22 and Ceresin for the temperature stabilization of a photovoltaic module. For the thermal stabilization of the module, PCM with three different thicknesses of 2 cm, 3 cm, and 5 cm were applied at the rear surface of the module, with an additional choice of water cooling of the PCM. Tests were conducted in the radiation intensity range of 950 to 1050 W/m^2; and the results of PV/PCM systems matched with those of an unmodified PV module. In the operating temperature range Paraffin 42-44, melting temperature range of 42°C-72°C was observed to give the best performance that was selected for temperature stabilization of the PV module. The electricity production per year for the unmodified PV module was observed to be 1010 kWh, which increased to 1080 kWh for the PV/PCM system fitted with paraffin 42-44, of 2 cm thickness without water cooling, which shows an increase of 7%. A total reduction of 7 K in temperature was observed and the lowered temperature was maintained for more than 5 hours, which resulted in increased output and improved efficiency of the modified module. The use of paraffin as PCM avoids the problem of corrosion of the PV panel which is normally observed with water cooling was one of the key findings of their experimental study.

Luo et al [32] applied a form stable paraffin (ZDJN-28)/EG composite as PCM on the backside of the panel to control its temperature. To determine the optimum density of the PCM material, a numerical simulation on FLUENT software was carried out.

Table 1 provides additional information about the works related to passive cooling technologies mentioned above. The table contains authors' names, publication year, technology adopted, the type of PV cell, and some key findings of the study.

Table 1. Summary of research work on passive cooling of modules

Researcher	Year	Technology	Type of PV cell	Key findings
Tonui et al.	2008	Air-based PVT	Poly-crystalline silicon	Thermal efficiency is maximum at an optimum depth of 5-10 cm.
Cuce et al.	2011	Heat sink	Poly-crystalline silicon	Power output increases by 8, 27, 46 and 65 mW under a solar irradiance of 200, 400, 600 and 800 W/m^2.
Filip et al.	2018	Extended surface (fins)	Poly-crystalline silicon	The proposed system reduced the separation of air on the backside. Average efficiency increased by 2% at peak power.
Han et al.	2011	Liquid immersion cooling	Mono-crystalline silicon CPV cells	A maximum increase of 15.2% in efficiency was observed for cells immersed in Isopropyl alcohol. The efficiency of cell decreases with an increase in liquid thickness.
Xin et al.	2015	Liquid immersion cooling	GaInP/GaInAs/Ge solar cell	Optimum oil thickness was 6.5 mm.
Chandrasekhar et al.	2013	Moist cotton wicks (three types of fluids used)	Mono-crystalline silicon	30% reduction in module temperature and cell efficiency was 10.4%.
Anderson et al.	2008	Heat pipe-based CPV	Mono-crystalline silicon	Cell to ambient temperature difference = 40^0C.
Gang et al.	2011	Heat pipe-based PVT	Mono-crystalline silicon	Average electrical and thermal gain per unit PV area – 62.3 and 276.9 W/m^2.
Moradgholi et al.	2014	Heat pipe-based PVT	Mono-crystalline silicon	A maximum temperature drop of 15^0C was obtained. 0.72% and 0.88% increase in output power during spring and summer.
Yanping Du	2017	Heat pipe-based PVT	___	A temperature reduction of more than 22^0C was obtained. Maximum heat removal capability 390 W/m^2.
Sandeep Koundiya et al.	2017	Heat pipe-based PVT	Mono-crystalline silicon	13.8 ^{0}C decrease in temperature. Increase in output voltage – 1.878 V.
Park et al.	2014	PCM	Poly-crystalline Silicon	Maximum temperature of panel reduced by 5 K. 3.1% increase in energy generation efficiency.
Indartono et al.	2014	PCM (yellow petroleum jelly)	Mono-crystalline silicon	PV on-roof arrangement is more suitable for BIPV application
Atkin et al.	2015	PCM (paraffin wax infused graphite)	Mono-crystalline silicon	Finned heat sink attached to PCM increased heat transfer. Maximum reduction in panel temperature = 19^0C.
Stropnik et al.	2016	PCM (RT28HC)	Mono-crystalline silicon	Maximum reduction in panel temperature = 31.2^0C. Electrical power and generation efficiency increased by 9.2 and 1.1 %.
Kibra et al.	2016	PCM	-	Proposed a thermal model for predicting the effectiveness of PCM.
Klugmann-Radziemska et al.	2017	PCM (3 phase change materials were considered)	-	Paraffin 42-44 gives the best performance in comparison to two other PCM's. Module temperature is reduced by 7K.
Luo et al.	2017	PCM (ZDJN-28)/EG composite)	Poly-crystalline Silicon	Maximum temperature of the modified panel - 57^0C, 4.7^0C below the temperature of the unmodified panel. Average increase of 7.28% in output power.

A new composite PCM was developed by them having a melting temperature of 27.17°C and thermal conductivity of 7.571 W/mK. The temperature of the modified panel was witnessed to be 57.0°C, 4.7°C below the temperature of the conventional panel. Throughout the experiment the PV/PCM panel temperature was maintained below 50°C for 4.07 h which was 1.92 h more than the conventional panel. The maximum output voltage and power of the unmodified panel were 20.48 V and 17.85 W, whereas, for the modified PV panels, it was 20.99 V and 18.30 W, respectively. Numerical simulation results revealed that with an increase in the density of PCM, the thermal management improves and 900 kg/m^3 was found to be the optimum density of PCM considering the weight and cost of PCM. A fair agreement was observed amongst the numerical and experimental results.

2.2. Active cooling method

Active cooling refers to the techniques that depend on an external device to boost the rate of heat transfer. An active cooling method involves forced air or water flow for the thermal management of PV panels. A fan is used when the working fluid is air and the pump is used with water. The external devices like fan and pump increase the rate of fluid flow which in turn increases the convection heat transfer coefficient and thus leads to a high heat transfer rate. In general, active cooling methods result in higher electrical and thermal efficiency but require electrical power which results in higher costs, compared to passive cooling.

2.2.1. Forced airflow cooling

Tiwari et al. [33] established a thermal model to predict the overall efficiency of a hybrid photovoltaic thermal air collector, considering the energy balance for individual components. For the experimental investigations, three modes of convection were chosen- natural, forced with one fan, and forced with two fans. The analytical results were validated with the obtained experimental results, which showed a close approximation. Fig. 10 clearly shows that there is an optimum mass flow rate of 2 m/s, after which the overall efficiency decreases. Optimum depth lied between 0.03-0.06m. An increase of 18% in overall efficiency was reported for the designed system.

Joshi et al. [34] evaluated and made a comparison between the performances of two PV modules- one having glass to glass and other having glass to tedlar configuration. The experimental setup was fabricated by attaching an air duct of the constant cross-sectional area beneath the photovoltaic module, and one DC fan was used for the forced circulation of air. Rear surface, temperature of solar cell and exit air along with overall efficiency were chosen as the parameters for performance comparison of two configurations. Overall thermal efficiency of glass to glass configuration was in the range of 43.4 - 47.4%, whereas for glass to tedlar it lied between 41.6 – 45.4%.

Shahsavar et al. [35] fabricated an experimental test setup to evaluate the electrical and thermal performance of a PV/T air collector under natural and forced convection modes, with and without glass cover on PV panel. The effect of different numbers of fan – two, four and eight on the output of PV/T air collector was also determined. Two poly-crystalline PV panels were attached in parallel and were placed over the air channel. To enhance the heat transfer from panel one thin sheet of aluminum was positioned at the center of the channel. For the forced convection mode DC fans of 6.6 W were used and the experiments were conducted under outdoor situations of Kerman, Iran. An analytical model was established to assess various performance parameters and a fair match was witnessed amongst the analytical and experimental results.

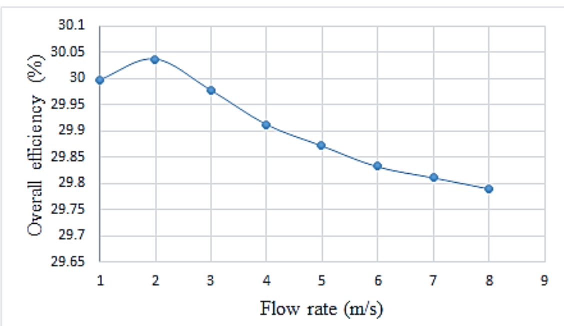


Fig. 10. Overall efficiency v/s mass flow rate [33].

Teo et al. [36] performed an experimental investigation to access the influence of air flow on the temperature and the electrical and thermal performance of a PV/T system. Heat transfer simulation using COMSOL MULTIPHYSICS software was also done to find the temperature of the PV module. An array of air ducts fitted with fins were fixed to the back surface of the PV module to allow the air to pass through and extract heat from the panel. Fig. 11 shows how electrical efficiency reduced with rising module temperature of the module and for the panel without active cooling, the module temperature touched 68°C and electrical efficiency was observed to be 8.6%.

Kim et al. [37] developed an air-based photovoltaic thermal collector and evaluated its performance experimentally. The experimental test setup was fabricated using mono-crystalline PV module having an overall area of 1.6 m^2 and 10 cm diameter exhaust pipe for heat extraction (Fig. 12). Airflow rate of 240 m^3/h was maintained using a fan during the experiments. Under the radiation intensity of 750 W/m^2 the electrical efficiency was observed to be 16%, exactly similar to the value for PV panel under standard test conditions.

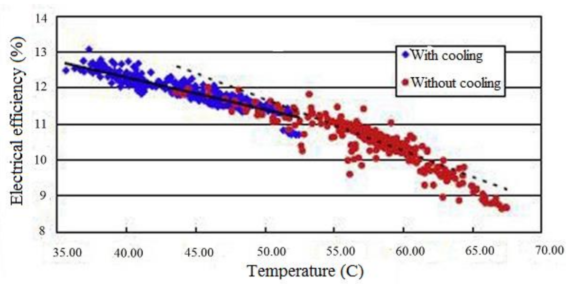


Fig. 11. Electrical efficiency versus module temperature [36].

Fig. 12. Test setup of pv/t system [37].

The average thermal efficiency was 22%. Results clearly showed that the modified system was quite effective in lowering the temperature of PV panel.

Farshchimonfared et al. [38] performed a numerical analysis to predict the optimum depth of channel, air flow rate per unit collector area and the diameter of duct of a PV/T air collector, with an aim to boost the overall performance of the PV/T collector. Different collector areas and different ratios of length to width were considered during the study. The results showed an increase in the optimum depth with increasing L/W ratio, for a PV/T collector of the fixed area. For the system optimal depth varied between 0.09 m to 0.026 m. The air flow rate per unit area had an optimum value of 0.0213 kg/m^2. The diameter of the air distribution duct increases with increasing collector area and the optimum value fluctuates between 0.3 to 0.5 m.

Pauly et al. [39] carried out CFD analysis using ANSYS FLUENT 14.5.0 to determine the overall performance of a PV/T air collector and validated the numerical results against the experimental results of Joshi et al [34].The validated model was used to estimate the optimum depth and mass flow rate. The parametric study showed a decrease in the overall efficiency with increasing duct depth, and they suggested keeping the duct depth on the maximum side to achieve a higher value of overall efficiency. They suggested using a duct with a continuously decreasing cross-sectional area along the length of flow of air, which makes the air velocity to increase and extract more heat leading to better uniform cooling of the panel. With the new design, the exit air temperature was observed to be 322.3 K, in comparison to 320.6 K. Overall efficiency increased by 20% in comparison to the conventional system.

2.2.2. Forced water cooling

Odeh et al. [40] performed an experimental investigation to assess the impact of water cooling on the power output of PV panels used for irrigation purpose. They designed and fabricated an outdoor test facility comprising of a multi-crystalline PV module, a submersible pump, water surge tank, and a water trickling tube (Fig. 13). Water trickling tube of 2.5 cm diameter, having 32 holes was mounted at module's upper edge to maintain the flow of cooling water. During the experimental study, a constant flow rate of 4 l/min of water was maintained over the PV module surface. Fig. 14 shows that under a radiation intensity of 1000 W/m^2 maximum module temperature reduced to 32°C from 58°C, and this reduction of 26°C in temperature was observed due to increased convection heat transfer caused by the flow of water over the surface. The results indicated an increase of 4 – 10% in the PV module power output.

Moharram et al. [41] proposed a cooling arrangement for PV modules that consumed a minimum amount of energy and water and was suited for hot regions like deserts. They developed two mathematical models- heating and cooling rate models.

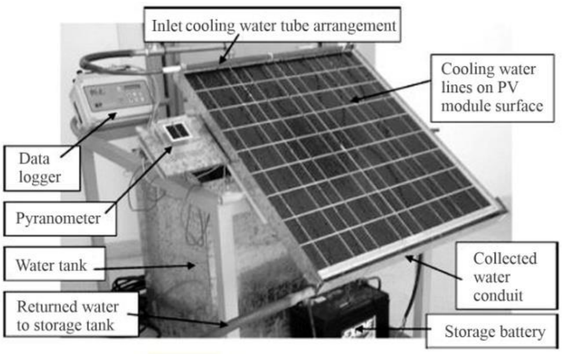


Fig. 13. PV water cooling test rig [40].

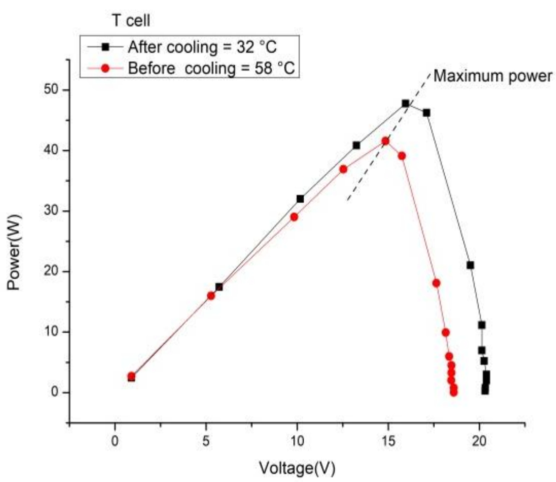


Fig. 14. Water cooling effect on the power and voltage characteristics, radiation intensity 1000 W/m^2 [40].

The heating rate model was utilized to find out the time at which cooling has to be started and the cooling rate model determined the time needed to bring back the model to its initial temperature. They found the heating rate of the cells to be 0.1°C/min and cooling rate to be 2°C/min. An experimental setup consisting of 6 mono-crystalline silicon PV modules, each having 185 W power output and 120 water nozzles fitted at the upper edge of the modules was fabricated to validate the mathematical model and to assess the impact of water cooling on the PV modules performance. During the cooling period, water was sucked from an aluminum water tank and was sprayed over the upper surface of modules, through water nozzles. Experimental results showed an increase of 10°C in temperature of the solar cell that reduces the electrical efficiency from 12% to 10.5%. They observed the experimental cooling rate to be 2.1°C/min, which showed a fair agreement with the value determined by the mathematical model. A reduction of 10°C in operating temperature was seen in 5 min that caused an increase of 12.5% in electrical efficiency. They proposed that for the cooling system to use the minimum amount of energy and water, and yield highest output, cooling of the module should be started when the panel reaches to maximum acceptable temperature (MAT). The optimal value of MAT was found to be 45°C, for the developed system.

Irwan et al. [42] designed and fabricated a solar simulator consisting of 20 halogen lamps and used a DC water pump for spraying water over the front surface of the photovoltaic panel. Tests were conducted under four sets of solar radiation values – 413, 620, 821 and 1016 W/m^2. Results exhibited that the maximum temperature of the photovoltaic panel decreases by spraying water over the surface. In comparison to conventional photovoltaic panel decrement of 5.03°C, 7.78°C, 13.26°C and 23.17°C in temperature was observed under intensities of 413, 620, 821, and 1016 W/m^2, respectively. The maximum power output was observed to be 19.87, 27.97, 33.87 and 40.33 W for water-cooled PV panel under intensities of 413, 620, 821, and 1016 W/m^2, respectively, which showed an increase in power output by 9.76%, 14.87%, 18.19%, and 22.81%

compared to power output of a conventional panel.

Matias et al. [43] performed an experimental study to evaluate the gain in power output of a PV panel cooled by water. Tests were conducted with different flow rates of water – 1, 2, 3 and 4 l/min with solar radiation value fixed at 800 W/m^2. The test results showed 2 l/min as the optimum flow rate resulted in an efficiency gain of 24% compared to the PV panel without cooling arrangement. The power output of conventional panel was found to be 62 W-h, which increased to 77 W-h with water cooling. At a flow rate of 2 l/min, considering the pumping power requirement a total gain of 16.66% in panel efficiency was observed. It was concluded that the front surface water cooling of PV panels improves their performance by reducing the maximum operating temperature.

Tomar et al. [44] presented an analytical model to predict the performance of a PV module with and without surface water cooling. The experimental setup was fabricated using five different commercially available PV modules- mono-crystalline (m-Si), poly-crystalline (p-Si), amorphous silicon thin film (a-Si), cadmium telluride thin film (CdTe) and copper indium gallium selenide (CIGS) and tests were conducted at IIT Delhi to validate the analytical model. To maintain the flow of water over the front surface, a tube of 2.5 mm diameter with 46 holes was mounted on the upper side of each module. A close match was seen between the theoretical and experimental results and for all the modules involving water cooling; the maximum temperature was observed to be 36°C and was maintained throughout the operation. Whereas, without water cooling the maximum temperature was 58°C, 54°C, 53°C 50°C and 49.8°C for CIGS, CdTe, a-Si, p-Si and m-Si modules, respectively. The average value of electrical efficiencies for modules m-Si, p-Si, a-Si, CdTe and CIGS was found to be- 12.30%, 10.98%, 6.08%, 6.60% and 7.71% with top surface water cooling and 11.41%, 10.30%, 5.80%, 6.26% and 6.90% (respectively without water cooling). The daily average thermal efficiency for water cooled case observed to be 18.32, 17, 10.4, 20.43, and 18.52% for m-Si, p-Si, a-Si, CdTe and CIGS PV modules, which was almost doubled in comparison to the case without water flow. It was clearly observed that the proposed top surface cooling of the module enhances the overall performance of the PV module by reducing the operating temperature and cleaning the modules.

Wu et al. [45] carried out a numerical study on PV/T system having a water channel fitted above the PV panel. They developed a 3D physical and mathematical model to access the effect of different parameters like – the height of the channel, cooling water inlet temperature, the mass flow rate of water and intensity of radiation on the performance of PV/T system. The thermal and electrical, energy and exergy efficiency of the system was also calculated. For validation of the mathematical model, results of the numerical analysis were compared with experimental data of Erdil et al. [46] who have built and tested the performance of a system of similar configuration. Results showed that the system's thermal efficiency is greatly affected by the mass flow rate of water and both thermal and electrical efficiency showed an increasing trend with the mass flow rate. The total exergy efficiency had a maximum value of 13.8% at an optimal flow rate of 0.003 kg/s. Any rise in mass flow rate above the optimal value resulted in a reduction in the total exergy efficiency. They found the optimum height of the channel to be 5 mm, from the total exergy efficiency viewpoint. They found that with increasing the radiation intensity exergy efficiency increases. The results also indicated that the panel's electrical efficiency decreases by installing a water channel above the PV panel, but results in improved thermal performance has a higher overall efficiency when compared to a conventional system.

An experimental arrangement was made by Du et al. [47] to analyze the performance of a water-cooled CPV module. They fabricated a CPV module using mono-crystalline silicon cells and 12 mirrors to concentrate the light on the solar cells. A water cooler made up of aluminum, having 10 and 13 mm, internal and external diameter respectively was fixed to the rear side of the module. A continuous flow of water through the water cooler was made using a pump. The concentration ratio of the CPV module was 8.5. The maximum working temperature of the CPV module was higher in comparison to a normal module, with an average difference of 3°C, but it had 4.7 to 5.2 times higher power output than a normal module. Test results showed that the electrical efficiency remained below 09% during the operation. The thermal and electrical efficiency of CPV module; initially, increased with an increase in mass flow rate and became constant above 0.03 kg/s.

Colt et al. [48] attached a heat exchanger having a honeycomb structure, made up of aluminum at the back surface of the PV panel. Water flow was maintained through the heat exchanger using a submersible pump, to continuously dissipate heat from the panel surface. Numerical simulation was carried out on COMSOL Multiphysics software and a close match was observed between numerical and experimental results. A rise of 12.5% in the power output of the PV panel was observed after deducting the energy consumed by the pumping system and other accessories.

Zanlorenzi et al. [49] proposed a novel active cooling technique using water as a coolant for performance enhancement of the PV module. They designed and developed a hybrid PV/T collector that simultaneously converted solar energy into electrical and thermal energies. The initial design and prototype development of the hybrid module was done in Solid Works simulation software. A serpentine tube was fixed to the rear surface of a PV module having 250 W power output and an electric pump which consumed 2.66 W power was used to maintain the circulation of water inside the serpentine. The experimental setup was installed in Panama, Brazil and to know the influence of solar radiation intensity on PV module, the data were recorded in three intervals of time a) 8:00 am to 10:59 am b) 11:00 am to 2:59 pm and c) 3:00 pm to 5:59 pm. The experimental results showed a decrease of 8.83°C in the maximum effective temperature of the hybrid module in relation to the conventional module. The mean electrical efficiency of the hybrid and the original module was observed to be 15.20% and 13.95% respectively, which shows a gain of 1.25% in the electrical efficiency. The hybrid module was found to produce 8.22% more energy than the conventional module. The proposed design improved the thermal performance of the hybrid system with 23.5% maximum thermal efficiency. They concluded that the proposed hybrid module not only increases the electrical power output but also improves the life of the PV module, by decreasing the maximum effective temperature which leads to overheating of the module and reduces their life.

Table 2 provides additional information about the works related to active cooling technologies mentioned in the section 2.2. The table contains authors' names, publication year, technology adopted, the type of PV cell, and some key findings of the study

Table 3. provides a comparison between different cooling techniques discussed in this paper on the basis of certain parameters like their effectiveness in reducing the temperature of PV panel, initial setup cost, operating cost and, maintenance cost. Phase change materials (PCM) are found to be most effective in reducing the temperature of PV panel in comparison to other techniques but they turn out to be costliest and most of them are toxic and corrosive in nature, which reduces the life of the panel. Also, the disposal of PCM creates an additional problem. Auxiliary power requirement is maximum for forced water circulation which increases the overall operational cost; however. it is more efficient than forced-air circulation technique owing to higher thermal conductivity and heat capacity of water.

3. Evaporative cooling

In this section of the paper, evaporative cooling of the photo-voltaic panel has been considered. Evaporative cooling is a latent heat cooling in which the water evaporates into the air. This type of cooling has been applied in many residential and industrial applications. However, the research on using evaporative cooling for thermal management of PV Panels is few. This unique passive cooling method does not take into account any energy input, it is easy to implement and it enhances the overall efficiency of the system. The effectiveness of this type of cooling appears to be very high. This section has been devoted to the variation of the performance of the PV Panel cooled by evaporative cooling with time under the real environmental condition to access the viability of this process.

Table 2. Summary of research work on active cooling of PV modules.

Researcher	Year	Technology	Type of PV cell	Key findings
Tiwari et al.	2006	Forced air circulation	Mono-crystalline silicon CPV cells	An increase of 18% in overall efficiency was observed 2 m/s was obtained as the optimum mass flow rate
Joshi et al.	2009	Forced air circulation	Mono-crystalline silicon	Glass to Glass configuration gives better overall efficiency than glass to tedlar.
Shahsavar et al.	2010	Forced air circulation	Poly-crystalline silicon	Maximum electrical efficiency is obtained at an optimum mass flow rate. Increase in mass flow results in higher thermal efficiency.
Teo et al.	2012	Forced air circulation	Poly-crystalline silicon	Module temperature was maintained at 38^0C Total efficiency was 50-70% for proposed system was
Kim et al.	2014	Forced air circulation	Mono-crystalline silicon	Average electrical efficiency was found to be 15%, near to STC
Farshchimonfared et al.	2015	Forced air circulation	-	Optimum PV/T collector area with aspect ratio was found.
Pauly et al.	2016	Forced air circulation	Mono-crystalline silicon	Duct with decreasing cross-sectional area gave 20% increase in overall efficiency.
Odeh et al.	2009	Forced water circulation (front surface)	Poly-crystalline silicon	Operating temperature was reduced by 26^0C
Moharram et al.	2013	Forced water circulation (front surface)	Mono-crystalline silicon	Operating temperature was reduced by 10^0C. Electrical efficiency was increased by 12.5%
Irwan et al.	2015	Forced water circulation (front surface)	Mono-crystalline silicon	Operating temperature reduced by 5-23^0C Power output increased by 9-22%
Matias et al.	2016	Forced water circulation (front surface)	___	16.66% increase in panel efficiency considering pumping power requirement was observed.
Tomar et al.	2018	Forced water circulation (front surface)	Mono-crystalline silicon	With water cooling maximum temperature of all five modules was not more than 36^0C.
Wu et al.	2018	Forced water circulation (front surface)	-	Higher overall efficiency was observed, but electrical efficiency reduced. Optimum depth of channel was 5 mm.
Du et al.	2012	Forced water circulation (back surface	Mono-crystalline silicon	The output power of CPV cell was observed to be more but had 9% lower electrical efficiency than the fixed cell.
Colt et al.	2016	Forced water circulation (back surface	-	Power output increased by 12.5%.
Zanlorenzi et al.	2018	Forced water circulation (back surface	-	Electrical efficiency increased by 1.25%. Operating temperature was reduced by 8.83^0C

Table 3. Comparative applicability and cost of different cooling technologies.

Cooling technique	PV panel temperature range (^{0}C)	Heat transfer rate	Initial cost	Maintenance cost	Auxiliary power requirement	Life time of PV panel
Natural air cooling	50-70	Low	Zero	Zero	Zero	Longer life
Liquid immersion cooling	30-45	High	Low	Low	Zero	Less due to corrosion of PV panel
Heat pipe	30-96	Low	Low	Low	Zero	Longer life
PCM	25-30	High	High	Zero	Zero	Less as PCM's are corrosive in nature
Forced air circulation	20-30	High	High	High	High	Lower then natural air circulation
Forced water circulation	20-30	High	High	High	High	Lower then forced air circulation due to chances of corrosion

Aiming to fill the research gap in this field, this section of the paper presents an experimental study with a simple, cheap and effective configuration based on this principle. The performance of the panel was investigated for certain days in the summer months.

3.1. Experimental setup for evaporative cooling of solar PV panel

In the experimental setup, the power generating unit consists of two modules, poly-crystalline and having a total power rating of 80 Wp. The maximum load current of power conditioning unit is 2 A with nominal system voltage of 12 V. Two PV modules were tested, one acted as a reference while the back of the second is covered with the wood wool cooling pad as shown in Fig. 15. Both PV modules have been subjected to the same solar insolation, and the characteristics of both have been collated. One of the PV module (Panel 1) is cooled using water flowing inside plastic tubes attached to the rear side of the module, with a total length of 7 feet, that drips water only enough to keep the wood wool saturated, designed as shown in Fig. 16. The experiments were conducted in the month of April, and the relative humidity was found to be nearly constant with an average value of 39%. The water consumption was not precisely quantified during the experimentation. However, it was observed that 0.8 L/h of water was approximately consumed during the experimentation. Water flows by gravity and no pump has been used. This is similar to indirect evaporative cooling, similar to pot-in-pot refrigerators for the evaporation of water from the wet porous clay surface to the ambient dry air stream [50]. A throttling valve was used to control the water flow rate. Moreover, the second PV module (Panel 2) is left under a natural convective environment (ambient Cooling). This evaporative cooling method has the advantage of utilizing wind in the cooling process. The convection mass transfer will increase the evaporation process. However, the wind will lower the temperature of both the panels; the cooled panel (by heat and mass transfer) and the reference one (by heat transfer)

(a)

(b)

Fig. 15. (a) and (b) test setup of photovoltaic cells with evaporative cooling arrangement.

3.2. Results and discussion

The photo-voltaic panel has been examined under different ambient conditions and irradiations, the open-circuit voltage (Voc), and short circuit current (Isc) are measured along with the panel temperature. The experimental values are represented in the form of graphs.
The electrical power of a PV module is given by Eq. (5).

$$P = V_{oc} \times I_{sc} \quad (5)$$

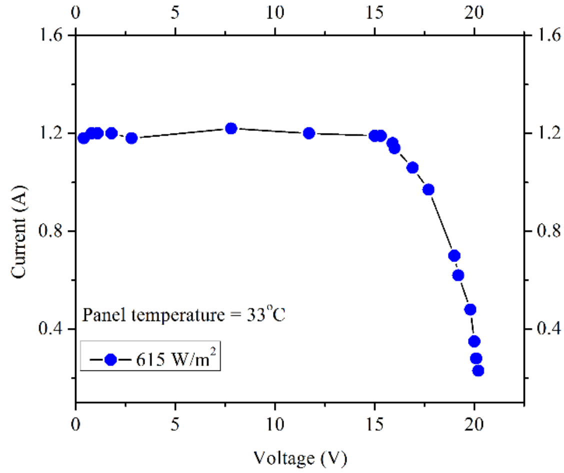
$$I_{pv} = I_i - I_o \left(e^{\frac{q\,(V_{pv} + I_{pv} R_S)}{AKT}} - 1 \right) - \frac{V_{vp} + I_{pv} R_S}{R_{sh}} \quad (6)$$

The relationship of PV module current with temperature can be summarized as mentioned above in the Eq. (6) proposed by Mahmoud et al. [51].

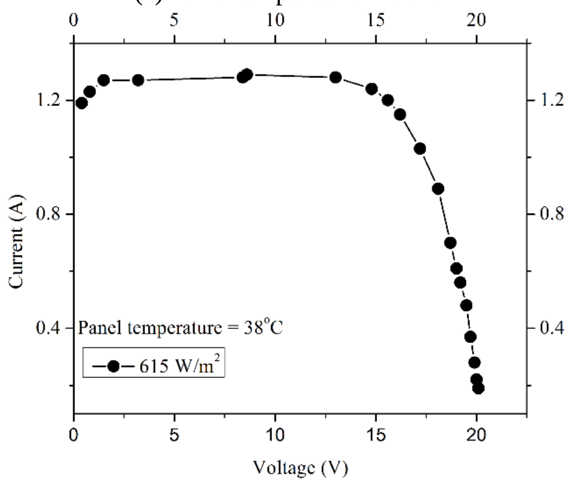
Fig. 16. Arrangement of wood wool cooling pad on the backside of the plate.

Fig. 17(a and b) represents the I-V characteristics at 33ºC and 38ºC for the same value of insolation. I-V Characteristics of the panel have been studied at different insolation and represented in Fig 18. As the solar radiation intensity rises, the short circuit current I_{sc} will increase due to the rise in carrier concentration, and results in an increase of open-circuit voltage. Fig. 19 shows the variation of Power output with the voltage for different insolation. With the increase in solar radiation intensity, the power output also increases so max power output is for max solar radiation intensity The scaling down of bandgap energy results into an increase in short circuit current and it further causes abjection of the open-circuit voltage and available maximum power. The power curve has been plotted for two different panel temperatures and obtained to be more at lower temperature as shown in Fig. 20. The short circuit current and open-circuit voltage have been plotted with respect to time under evaporative cooling and normal ambient cooling as shown in Fig. 21.

Fig. 22 (a) shows that the power curve is at a higher value for the evaporative cooling, at an insolation level of 1000 W/m^2 the power output of modified panel was found to be 45 W, whereas for the conventional panel it was 41 W, which shows an increase of 9.75% in the power output at maximum insolation. Fig. 22 (b) shows the variation of solar radiation and panel temperature with reference to the time for solar panel with ambient and evaporative cooling. Under evaporative cooling from the rear side of the panel, the temperature maintained is less. At a maximum insolation level of 1000 W/m^2 temperature of the conventional panel was observed to be 54^{0}C, whereas the panel with evaporative cooling was maintained at 42^{0}C, so a reduction of 12^{0}C in temperature was observed.



(a) Panel temperature = 33ºC



(b) Panel temperature = 38ºC

Fig. 17. (a) and (b) I-V characteristics for solar cells at two different panel temperatures.

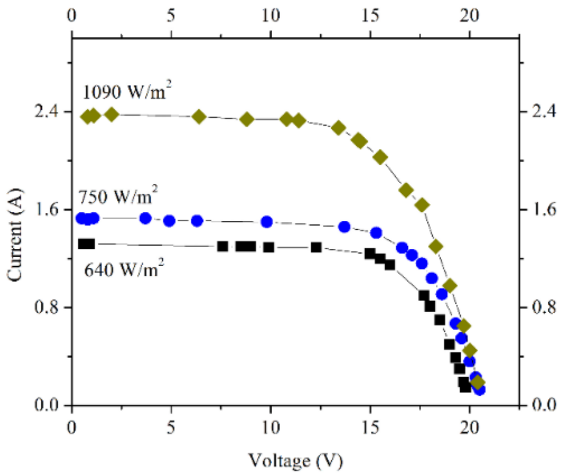


Fig. 18. I-V curve at different solar radiation.

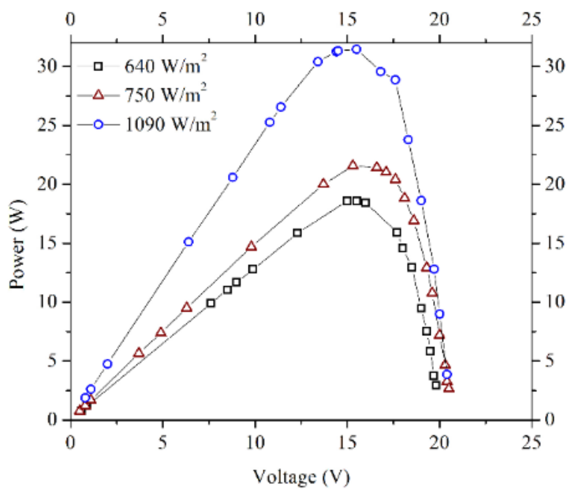


Fig. 19. Power curve at different solar radiations.

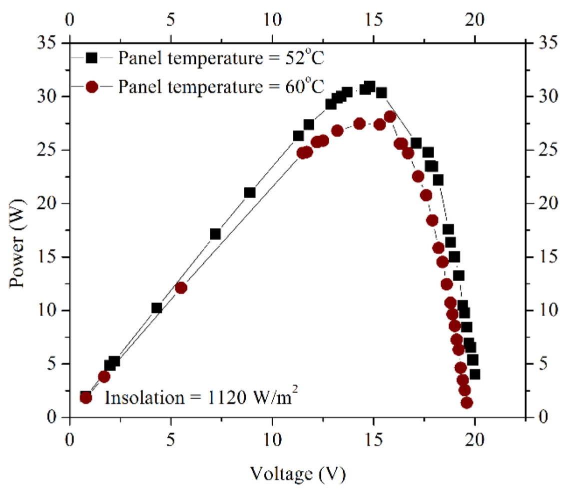
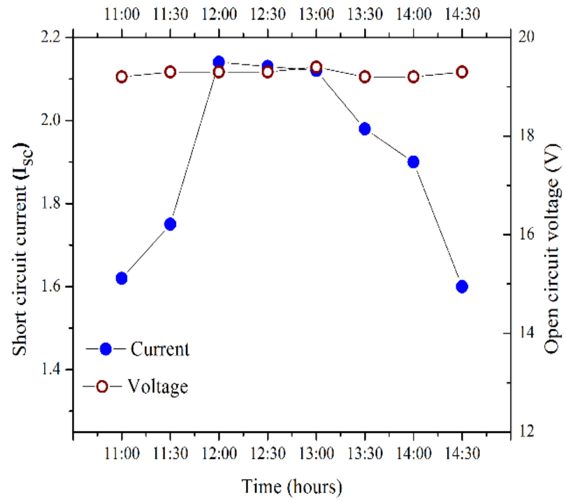
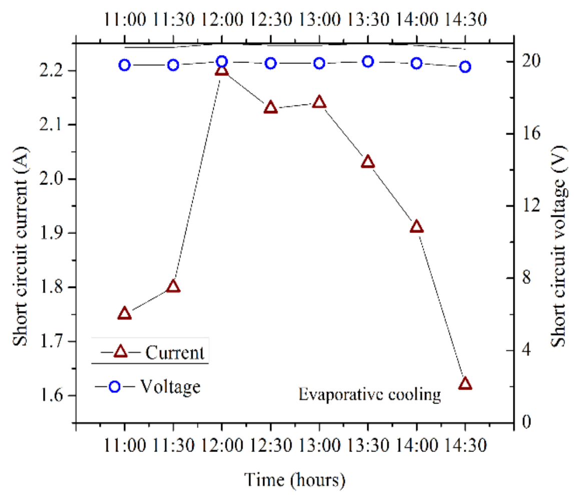


Fig. 20. Power output curve with the panel temperature.



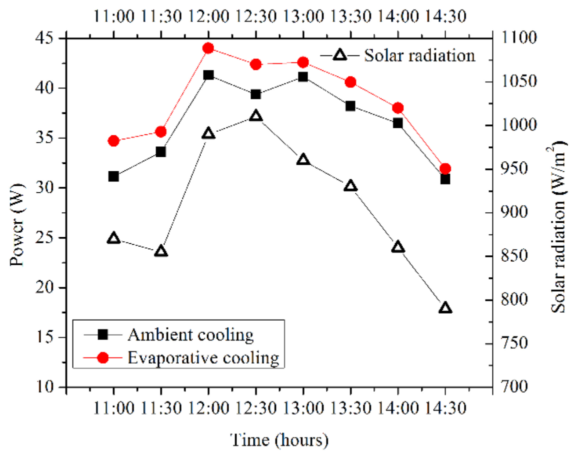
(a) Ambient cooling



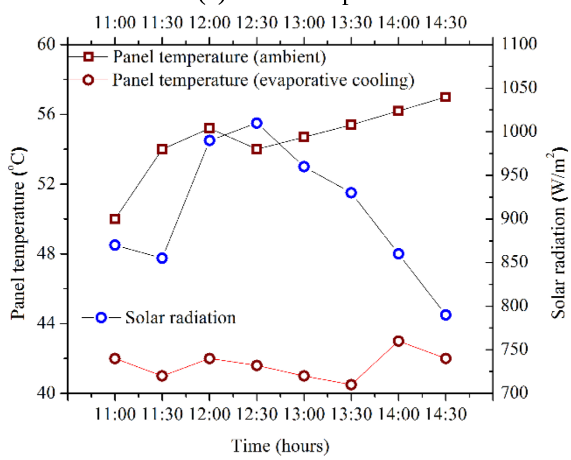
(b) Evaporative cooling

Fig. 21. Variation of short circuit current and open-circuit voltage with time for (a) ambient cooling and (b) evaporative cooling.

Fig. 23 shows the variation of panel efficiency with time, average efficiency of panel cooled using evaporative technique was observed to be 8.4% and was 7.8% for the conventional panel, resulting in an increase of 7.7% in the average efficiency of panel. The results conclude that the cooling of the panel with evaporative mechanism would give higher panel efficiency and also results in a higher value of open-circuit voltage. The method does not involve any energy input and displaces the cooling load.



(a) Power output



(b) Panel temperature

Fig. 22. Variation of (a) power outputand (b) panel temperature with time.

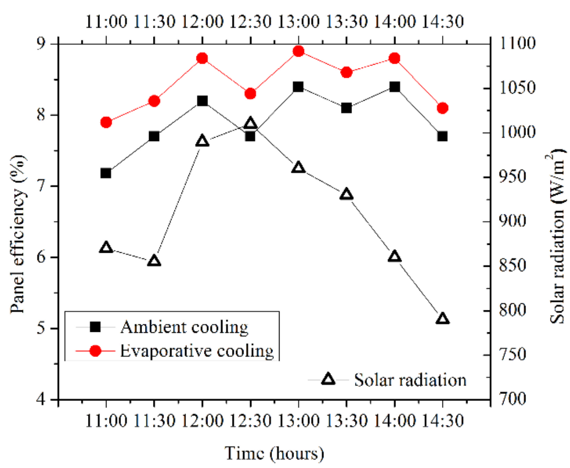


Fig. 23. Variation of panel efficiency and solar radiation with time.

4. Conclusions

This work presents an overview of the different cooling technologies used for the thermal control of PV modules. Further experiments have been performed to represent that the evaporative cooling of the solar panel is quite effective and can increase panel efficiency. From the review, it is clear that a good number of researchers have worked in the progress of cooling systems for enhancing the working of PV modules. Most of the cooling techniques involve the extraction of heat from the PV module surface, and future research should be focused on the effective utilization of this extracted heat and making these techniques economically viable to be used in large systems. Based on the review, below mentioned cooling techniques are found to be encouraging on the basis of their performance:

- The rear sides of the PV module are attached with fins and found to be quite effective in reducing the operating temperature and increasing power output. However, the amount of heat extracted depends on wind speed and ambient temperature. Low heat transfer coefficient and heat capacity of air limit the temperature reduction.
- Cooling of PV modules using liquid immersion technique gives a preeminent performance when the module is immersed at optimum depth. This technique results in a high heat transfer rate, owing to direct contact with the liquid. One of the major drawbacks of this technique is the deposition of salts on the surface, which occurs due to longtime immersion.
- Solar photovoltaic coupled with heat pipe is quite effective in reducing the working temperature of Photo-Voltaic modules. It is relatively simpler, but heat extraction capacity is limited by the wind speed and low heat transfer coefficients of ambient air.
- Cooling of PV modules using phase change materials results in a drastic change in the operating temperature of modules. Latent heat transfer takes place during the melting of material, which leads to a high heat transfer rate and makes this technique most effective in comparison to others. However, the cost of PCM is high, also the rate of heat absorption

decreases as the melting proceeds, and some of the PCM's are toxic in nature also.

- Hybrid solar photovoltaic system cooled by forced air circulation provides better cooling and higher energy conversion efficiency in comparison to natural air circulation. Maximum electrical output and efficiency are obtained at an optimum mass flow rate and duct depth. However, the operating cost increases owing to auxiliary power requirements.
- Solar photovoltaic system cooled by forced circulation of water on the rear surface is more effective in reducing the operating temperature of modules when compared with the forced circulation of air, owing to the high heat capacity of water. Installation and operational costs are high as pumps are required to maintain the continuous flow of water.
- Water spray cooling over the top surface results in higher efficiency along with the cleaning of modules surface. The additional heat is absorbed by water, and the continuous flow of water above the top surface results in a reduction in the reflection losses, which helps in maintaining the temperature of modules near the limits specified under standard test conditions (STC). A major drawback associated with this technique is the wastage of water and evaporation losses; also additional power is required to maintain the water flow.
- Different techniques were discussed to increase the performance of PV Panels by reducing the panel temperature. Using evaporative cooling in a dry climate can be a very effective way to reduce the panel temperature. One of the sections of the paper presented an outdoor experimental study with and without evaporative cooling. The results show a 12^0C reduction in PV panel temperature under maximum insolation and a 7.7 % increase in average electric power generation efficiency.

References

[1] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review", *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 3, pp. 1513–1524, (2011).

[2] Bhubaneshwari Parida, S.Inyan, Ranko Goic, "A review of solar photovoltaic technologies", *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 3, pp. 1625–1636, (2011).

[3] H. P Garg and J. Prakash "*Solar Energy: Fundamentals and Applications*", first revised edition, Tata McGraw-Hill, pp. 370-371, (2000).

[4] L. El Chaar, L. A. Lamont, and N. El Zein, "Review of photovoltaic technologies", *renewableand sustainable energy review*, Vol. 15, No. 5, pp. 2165-2175, (2011).

[5] M. M. Fouad, L. A. Shihata, and E. S. I. Morgan, "An integrated review of factors influencing the performance of photovoltaic panels", *Renewable and Sustainable Energy Reviews*, Vol. 80, pp. 1499-1511, (2017).

[6] K. A. Moharram, M. S. Abd-Elhady, H. A. Kandil, H. El-Sherif, " Enhancing the performance of photovoltaic panels by water cooling", *Ain Shams Engineering Journal*, Vol. 4, No.4, pp. 869-77, (2013).

[7] M. S. Abd-Elhady. M. M. Fouad, T. Khalil, "Improving the efficiency of photovoltaic (PV) panels by oil coating", *Energy Conversion Management*, Vol. 115, pp. 1-7, (2016).

[8] E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations", *Solar Energy*, Vol. 83, No. 5, pp. 614-624, (2009).

[9] E. Radziemska, "The effect of temperature on the power drops in crystalline silicon solar cells", *Renewable Energy*, Vol. 28, pp. 1-12, (2003).

[10] M. M. Rahman, M. Hasanuzzaman, and N. A. Rahim, "Effects of various parameters on PV-module power and efficiency", *Energy Conversion and*

Management, Vol. 103, pp. 348-358, (2015).

[11] N. H. Zaini, M. Z. Ab Kadir, M. Izadi, N. I. Ahmad, M. A. M. Radzi, and N. Aziz, "The effect of temperature on a mono- crystalline solar PV panel", *IEEE Conference on Energy Conversion, CENCON 2015*, pp. 249-253, (2015).

[12] Y. Du, C. J. Fell, B. Duck, D. Chen, K. Liffman, Y. Zhang, M. Gu, and Y. Zhu, "Evaluation of photovoltaic panel temperature in realistic scenarios", *Energy Conversion and Management*, Vol. 108, pp. 60-67, (2016).

[13] J. K. Tonui and Y. Tripanagnostopoulos, "Performance improvement of PV/T solar collectors with natural air flow operation", *Solar Energy*, Vol. 82, No. 1, pp. 1–12, (2008).

[14] E. Cuce, T. Bali, and S. A. Sekucoglu, "Effects of passive cooling on performance of silicon photovoltaic cells", *International Journal of Low Carbon Technology*, Vol. 6, No. 4, pp. 299-308, (2011).

[15] C. Correa-Betanzo, H. Calleza and S. DeLeon-Aldaco, "Module temperature models assessment of photovoltaic seasonal energy yield", *Sustainable Energy Technology & Assessments*, Vol. 27, pp. 9-16, (2018).

[16] F. Grubišić-Čabo, S. Nižetić, D. Čoko, I. MarinićKragić, and A. Papadopoulos, "Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface", *Journal of Cleaner Production*, Vol. 176, pp. 119-129, (2018).

[17] X. Han, Y. Wang and L. Zhu, "Electrical and thermal performance of silicon concentrator solar cells immersed in dielectric liquids", *Applied Energy*, Vol. 88, No. 12, pp. 4481-4489, (2011).

[18] G. Xin, Y. Wang, Y. Sun, Q. Huang and L. Zhu, "Experimental study of liquid-immersion III-V multi- junction solar cells with dimethyl silicon oil under high concentrations", *Energy Conversion and Management*, Vol. 94, pp. 169–177, (2015).

[19] M. Chandrasekar, S. Suresh, T. Senthilkumar and M. Ganesh Karthikeyan, "Passive cooling of standalone flat PV module with cotton wick structures", *Energy Conversion and Management*, Vol. 71, pp. 43–50, (2013).

[20] W. G. Anderson, S. Tamanna, D. B. Sarraf, P. M. Dussinger and R. W. Hoffman, "Heat Pipe Cooling of Concentrating Photovoltaic (CPV) Systems", *Am. Inst. Aeronaut. Astronaut.*, p. 9, (2008).

[21] P. Gang, F. Huide, Z. Tao and J. Jie, "A numerical and experimental study on a heat pipe PV/T system", *Solar Energy*, Vol. 85, No. 5, pp. 911–921, (2011).

[22] M. Moradgholi, S. M. Nowee and I. Abrishamchi, "Application of heat pipe in an experimental investigation on a novel photovoltaic/thermal (PV/T) system", *Solar Energy*, Vol. 107, pp. 82-88, (2014).

[23] Y. Du, "Advanced thermal management of a solar cell by a nano-coated heat pipe plate: A thermal assessment", *Energy Conversion and Management*, Vol. 134, pp. 70-76, (2017).

[24] P. Singh and N. M. Ravindra, "Temperature dependence of solar cell performance an analysis", *Solar Energy Materials and Solar Cells*, Vol. 101, pp. 36-45, (2012).

[25] S. Koundinya, N. Vigneshkumar and A. S. Krishnan, "Experimental Study and Comparison with the Computational Study on Cooling of PV Solar Panel Using Finned Heat Pipe Technology", *Materials Today Proceedings*, Vol. 4, No. 2, pp. 2693– 2700, (2017).

[26] J. Park, T. Kim and S. B. Leigh, "Application of a phase-change material to improve the electrical performance of vertical-building-added photovoltaics considering the annual weather conditions", *Solar Energy*, Vol. 105, pp. 561-574, (2014).

[27] Y. S. Indartono, A. Suwono and F. Y. Pratama, "Improving photovoltaics performance by using yellow petroleum jelly as phase change material", *International Journal of Low- Carbon Technology*, Vol. 11, No. 3, pp. 333-337, (2016).

[28] P. Atkin and M. M. Farid, "Improving the efficiency of photovoltaic cells using PCM infused graphite and aluminium fins", *Solar Energy*, Vol. 114, pp. 217-228, (2015).

[29] R. Stropnik and U. Stritih, "Increasing the efficiency of PV panel with the use of PCM", *RenewableEnergy*, Vol. 97, pp. 671-679, (2016).

[30] M. A. Kibra, R. Saidur, F. A. Al-Sulaiman and M. M. A. Aziz, "Development of a thermal model for a hybrid photovoltaic module and phase change materials storage integrated in buildings", *Solar Energy*, Vol. 124, pp. 114-123, (2016).

[31] E. Klugmann-Radziemska and P. Wcisło-Kucharek, "Photovoltaic module temperature stabilization with the use of phase change materials", *Solar Energy*, Vol. 150, pp. 538–545, (2017).

[32] Z. Luo, Z. Huang, N. Xie, X. Gao, T. Xu, Y. Fang, and Z. Zhang, "Numerical and experimental study on temperature control of solar panels with form-stable paraffin/expanded graphite composite PCM", *Energy Conversion and Management*, Vol. 149, No. May, pp. 416-423, (2017).

[33] A. Tiwari, M. S. Sodha, A. Chandra and J. C. Joshi, "Performance evaluation of photovoltaic thermal solar air collector for composite climate of India", *Solar Energy Materials and Solar Cells*, Vol. 90, No. 2, pp. 175–189, (2006).

[34] A. S. Joshi, A. Tiwari, G. N. Tiwari, I. Dincer and B. V. Reddy, "Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system", *International Journal of Thermal Sciences*, Vol. 48, No. 1, pp. 154-164, (2009).

[35] A. Shahsavar and M. Ameri, "Experimental investigation and modeling of a direct- coupled PV/T air collector", *Solar Energy*, Vol. 84, No. 11, pp. 1938–1958, (2010).

[36] H. G. Teo, P. S. Lee, and M. N. A. Hawlader, "An active cooling system for photovoltaic modules", *Applied Energy*, Vol. 90, No. 1, pp. 309-315, (2012).

[37] J. H. Kim, S. H. Park and J. T. Kim, "Experimental performance of a photovoltaic-thermal air collector", *Energy Procedia*, Vol. 48, pp. 888-894, (2014).

[38] M. Farshchimonfared, J. I. Bilbao and A. B. Sproul, "Channel depth, air mass flow rate and air distribution duct diameter optimization of photovoltaic thermal (PV/T) air collectors linked to residential buildings", *RenewableEnergy*, Vol. 76, pp. 27– 35, (2015).

[39] L. pauly, L. Rekha, C. V. Vazhappilly, and C. R. Melvinraj, "Numerical Simulation for Solar Hybrid Photovoltaic Thermal Air Collector", *Procedia Technol*ogy, Vol. 24, pp. 513–522, (2016).

[40] S. Odeh and M. Behnia, "Improving photovoltaic module efficiency using water cooling", *Heat Transfer Engineering*, Vol. 30, No. 6, pp. 499-505, (2009).

[41] K. A. Moharram, M. S. Abd-Elhady, H. A. Kandil, and H. El-Sherif, "Enhancing the performance of photovoltaic panels by water cooling", *Ain Shams Engineering Journal*, Vol. 4, No. 4, pp. 869-877, (2013).

[42] Y. M. Irwan, W. Z. Leow, M. Irwanto, M. Fareq, A. R. Amelia, N. Gomesh and I. Safwati, "Indoor Test Performance of PV Panel through Water Cooling Method", *Energy Procedia*, Vol. 79, pp. 604– 611, (2015).

[43] C. A. Matias, L. M. Santos, A. J. Alves and W. P. Calixto, "Electrical performance evaluation of PV panel through water cooling technique," *EEEIC 2016 – International Conference*

on Environment and Electrical Engineering, (2016).

[44] V. Tomar, G. N. Tiwari, T. S. Bhatti and B. Norton, "Thermal modeling and experimental evaluation of five different photovoltaic modules integrated on prototype test cells with and without water flow", *Energy Conversion and Management*, Vol. 165, No. February, pp. 219-235, (2018).

[45] S. Y. Wu, C. Chen and L. Xiao, "Heat transfer characteristics and performance evaluation of water- cooled PV/T system with cooling channel above PV panel", *Renewable Energy*, Vol. 125, pp. 936-946, (2018).

[46] E. Erdil, M. Ilkan and F. Egelioglu, "An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system", *Energy*, Vol. 33, No. 8, pp. 1241-1245, (2008).

[47] B. Du, E. Hu and M. Kolhe, "Performance analysis of water-cooled concentrated photovoltaic (CPV) system", *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 9, pp. 6732-6736, (2012).

[48] G. Colţ, "Performance evaluation of a PV panel by rear surface water active cooling", 2016 International Conference on *Applied and Theoretical Electricity ICATE 2016 - Proc*., pp. 1–5, (2016).

[49] G. Zanlorenzi, A. L. Szejka and O. Canciglieri, "Hybrid photovoltaic module for efficiency improvement through an automatic water cooling system: A prototype case study", *Journal of Cleaner Production*, Vol. 196, pp. 535-546, (2018).

[50] S. SChakrabarti and P. K. Das, "Thermal behavior of pot-in-pot refrigerator- Simulation and Experimental approach", *Heat Transfer Research*, Vol. 50, pp. 1081-1103, (2019).

[51] Y. Mahmoud, W. Xiao and H. H. Zeineldin, "A parameterization approach for enhancing PV module accuracy", *IEEE Transactions on Industrial Electronics*, Vol. 60, No. 12, pp. 5708–5716, (2013).

How to cite this paper:

Akash Pandey, Siddharth Chakrabarti and Pratik Daghe, " A systematic approach for a better thermal management of photovoltaic systems- A review*", Journal of Computational and Applied Research in Mechanical Engineering*, Vol. 10, No. 1, pp. 1-24, (2020).

DOI: 10.22061/jcarme.2019.5814.1734

URL: http://jcarme.sru.ac.ir/?_action=showPDF&article=1176