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Temperature Control Of Photo-Voltaic Modules: A Review

Avijit Mallik, Md. Arman Arefin

Dept. of Mechanical Engineering, Rajshahi University of Engineering & Technology Kajla, Rajshahi-6204, Bangladesh, PH- +8801777-678831
avijitme13@gmail.com

Dept. of Mechanical Engineering, Rajshahi University of Engineering & Technology Kajla, Rajshahi-6204, Bangladesh, PH- +8801722-668616
dipto70@yahoo.com

Abstract: Renewable Technology is a very common topic for engineering research. Researches on renewable engineering are mainly eyed on Solar Energy Technology which consist photovoltaic cells. Effectiveness and efficiencies of those PV modules are very important to make researches feasible. This paper is based on current advances of the temperature control methods of PV modules. Temperature control is a very important part for solar energy research; it normally inversely changes with respect to electrical efficiency of PV module. Increase in electrical efficiency depends on temperature controlling techniques, type and size of the panel along with geographical position rising about 3-5% of the overall efficiency. A perspective on other temperature controlling methods for PV modules will also be discussed in this paper.

Keywords: PV module, cooling techniques of PV, Photovoltaic, Temperature control methods.

1. Introduction

Renewable energy sources are becoming more and more popular, regarding the pollution and non-sustainability of common energy sources. With increasing human population, a scarcity of fossil based petroleum has been introduced. One of most abundant resources is solar energy, which manifests itself directly, as solar irradiance, or indirectly as wind energy and biomass energy. When it comes to the efficiency of energy transformation, a couple of things need to be distinguished. Those renewable energies are mainly transformed into electrical and thermal energy for various purposes. Electrical energy, mostly because of its easy transformability to work, is effective than thermal energy. The most efficient way to obtain electrical energy is from direct solar irradiance via photovoltaic cells (PV cell). The overall efficiency of PV cells ranges from about 5 % - 20 %, higher than the total indirect efficiency when it comes to wind and biomass efficiency. However, it has been shown that the overall efficiency of photovoltaic cells drops drastically with an increase in temperature. The rate of decrease ranges from 0.25 % to 0.5 % per degree Celsius, depending on the cell material used. [1] Especially for concentrated PV cells, which use concentrated sunlight to produce larger amounts of power, and reduce the cost of generally expensive PV equipment, it has been observed that high temperatures greatly decrease the working life of the whole PV system. Cooling mechanisms have already been proposed [2, 3] and the development of cooling techniques continues. It has been shown that a sizable amount of power can be gained, up to a total of 5 % [4], by utilization of a cooling system. Nevertheless, a large amount of irradiated energy (up to 87 %) converts into heat. More recent developments have been concentrated on harnessing that waste heat into useful thermal energy. Generally, hybrid elements that harness both electrical and thermal solar energy are called photovoltaic-thermal units (PV/T unit). Usually those units have higher overall efficiency but lower specific efficiencies, when compared with stand-alone photovoltaic and solar collectors [5].

2. Different Temperature Controlling Techniques for PV:

Basically temperature controlling for PV modules means cooling of the panel. The advantage of cooling is evident; resulting higher electrical output. This cooling requires a separate system removing total heat to some extent. The construction and maintenance of that system can be expensive and there is a possibility that the cost of system maintenance could outweigh the benefits of the improved electrical yield. Hence, overall electrical gain can be discussed in most of the studies made for example. [2, 6-10] There are mainly two types of distinguished cooling techniques: active cooling, consuming energy from a source (pump, fan etc.) and passive cooling, using natural convection to enable heat extraction.

2.1. Active cooling methods

Active cooling methods can be considered as those methods that continuously consume power in order to cool the PV module. Most of the methods used are based on air or water cooling. Thus, for main system consumption pump or fan is needed for regulating fluid circulation. In general, active cooling methods result in more produced power and more accessible thermal energy, but when power consumption is taken into account, question arises if cooling system can support itself. When concentrated PV cells are used, active cooling system can easily be applied, mainly because of fluid-to-cell mass ratio and the ability to use less cooling fluid. Thus, less power is needed to maintain the system. Teo et al. 2012, [11] cooled four polycrystalline PV modules of 55W nominal power, from back side. The surface of PV module is 0.78 m2. Special flow channel was manufactured and CFD analysis was used to optimize its shape. Total efficiency gain was around 1 %, depending of the irradiation. Optimal air flow beneath the panel is 0.055 kg/s, although no ambient temperature was given. This information is therefore reliable only for this specific case. Nevertheless, this information can be valuable when trying to evaluate the amount of air needed to cool down standard PV module. Farhana et al. 2012, [12] used polycrystalline PV cell of 0.924 m2 to examine air cooling effect. Two cells have been compared, one with and the other without cooling. The cooling cell has aluminum casing on the back side, which acts as flow channel. The work omits information about mass flow of the cooling air. Instead, fan specification was given. From it, mass flow can be approximated to 0.035 kg/s. Results show a maximum relative efficiency increase of 8.9 % and a decrease in temperature of maximum 12 °C. Mazón-Hernández et al. 2013, [13] has showed that, for air mass flow of 0.74 m^3/s, total efficiency can be maintained above 13.5 % at peak insolation of 970 W/m^2, and an overall increase in efficiency is about 2 %, Figure-1. At certain regimes, temperature decrease of 15 °C has been achieved.

Figure-1: *Active air cooling [13]*

Arcuri et al. 2014, cooled a polycrystalline PV panel of 1 m^2. Cooling was provided on back side of panel, through specially constructed flow duct. Flow duct consists of aluminum sheet 1 mm thick at the back of the plate, and wooden casing around it. Mean air mass flow of about 0.016 kg/s was established. Mass flow is established via helical fan of 3.6 W power consumption. Mean increase in total efficiency was about 0.6 %, depending of the insolation and part of the year. [14] As for water cooling, 2 distinct techniques can be applied: front side and back side cooling. Hosseini et al. 2011, [15] introduced a thin fluid film at front side of a mono-crystalline PV panel and gained total efficiency increase of about 1 %. Total area of panel was 0.44 m2 and maximum water flow was around 1 lit/min. The pump used consumes 0.25 hP. A temperature fall of 20^oC was observed. There is no mentioning of amount of heat taken off by evaporation, which should be taken into account when cooling is done from the front side. Du et al. 2012, [16] used concentrated mono-crystalline PV cell of 0.152 m^2. The concentration was at the intensity of 8.5 suns. Cooling technique used was back side cooling via 2 aluminum pipes on aluminum mounting. Peak efficiency gain was 0.8 % for mass flow of 0.035 kg/s of water. Peak PV temperature was around 60 °C. Bahaidarah et al. 2013, cooled a mono-crystalline PV module with an area of 1.24 m2 from back side, [17] via closed casing through which a flow of water is established, Figure-2. Water pump consumes 0.5 hP of power. Maximum mass flow is 0.06 kg/s. Maximum increase in efficiency, when compared with non-cooled module is total of 2.8 %, and decrease of module temperature is 10 °C. Considering the size of the panel, the rise in efficiency is significant.

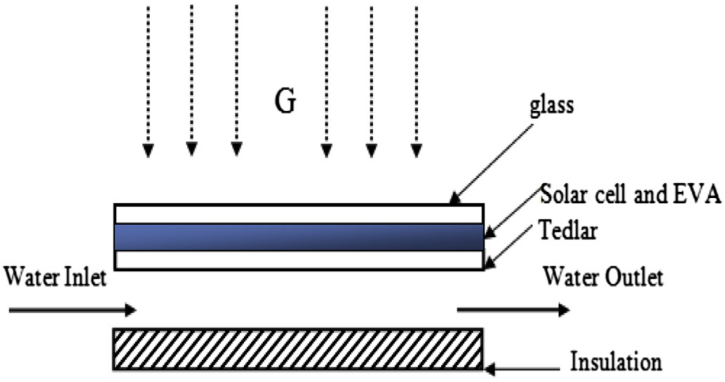

Figure-2: *Water cooling as used in Bahaidarah et al. 2013 [17]*

Dorobantu et al. 2013; cooled a PV cell of about 0.56 m2 on front side by washing it with 0.03 kg/s of water. Increase in efficiency was not measured. Instead, increase in power yield is given, and it reaches up to 4 W. Decrease in temperature was 12.5 °C and 8 °C on back and front side respectively. [18] Pump consumption was not mentioned, it is only emphasized that increased power yield is enough to cover the pumping cost. Moharram et al. 2013 used mono-crystalline PV panel of 1.25 m2 surface, and cooled it with a water flow on the front side of the panel. The pump used consumes around 1 hP of power. Flow of the water is fixed at 0.48 kg/s. The cooling was conducted in intervals of 5 minutes, with 15 minute pauses and it was proven that cooling rate is about 2 °C/min. Total increase in efficiency, as a result of cooling, was about 1.5 %. According to [19], optimal temperature for cooling start should be 45 °C. Also, the mechanism keeps the front of the panel clean, which is important for dusty regions such as Sahara or Middle East. Sun et al. 2014, cooled a concentrated mono-crystalline PV cell array of 0.014 m^2, illuminated by 9.1 suns. Cooling liquid used was dimethyl silicon oil. Mass flow was varied from 0.19 to 0.95 kg/s. Cell temperature was maintained in interval of 20 °C to 32 °C, depending of mass flow. Overall efficiency was kept between 12.5 % and 13.74 %, depending of the time of the year. That efficiency is fairly close to efficiency of non-concentrated cell array, which is 13.94 %.[20] Hence, there was very little drop in efficiency due to higher concentration of sunlight. Also, no significant cell degradation was observed after 270 days of direct immersion. Smith et al. 2014; measured an increase in power yield for concentrated cells by cooling the front side with spraying water. Mono-crystalline PV panels were used, without panel specifications. Another group of panels was also measured as a test group. Concentration factor was omitted. Water flow was at maximum 0.116 kg/s. Net power gain for regular water cooling was 4.6 %,[21] when pump consumption is taken into account. When ice water was used (2.5 °C at the entrance), largest power improvement was 24 %. When light concentration and ice water cooling was combined, power increase was 43 % greater than that of the control group. Tina et al. 2011, cooled the polycrystalline PV panel of 1.27 m2 with water flow at the front of the PV module. The water flow was at maximum 0.0167 kg/s, and depth of closed water box was 25 mm. It was proven that front side cooling is inefficient for small irradiation intensity. Optical losses overcome thermal drift caused by heating effect. In contrast, for high irradiation, front side cooling reduces thermal drift which gives greater power yield regardless of optical losses through water layer. For higher irradiation, shows that efficiency can be raised up to 1.2 % for passive cooling technique. [22] Cooling technique from both front and back side is tried out. Water flow is varied and its maximum value was 0.0625 kg/s. Water is applied in jet form, which enhances the cooling effect, according to Rahimi et al. 2011, results are showing a relative increase in efficiency of 14.8 %, 19.1 %, and 20.4 % for back side, [23] front side and simultaneous back and front cooling. Also, relation of type of flow with heat dissipation is discussed in Røyne et al. 2005, it was shown that high velocity fluid fluxes (jets) have a capability to drastically take away the heat from the PV cell. The downside is the need for high pressures in the system. [24]

2.2. Thermo-electric cooling

The basics of thermoelectric cooling lie in phenomena of Peltier effect. The Peltier Effect occurs at an electrified junction as a heat flow in specific direction. On one side of the junction it produces heating, and on the other, cooling effect. The heating/cooling intensity depends on the temperature difference and voltage/current intensity. Cooling effect consumes electricity. Najafi and Woodbury in 2013 [25] modeled a PV cell cooling with Peltier element. It was shown that implementation of thermoelectric cooling can be viable for high concentration PV cells. Only in specific cell working regimes enough extra power can be produced to maintain cell cooling. Figure-3 presents thermo-electric effect.

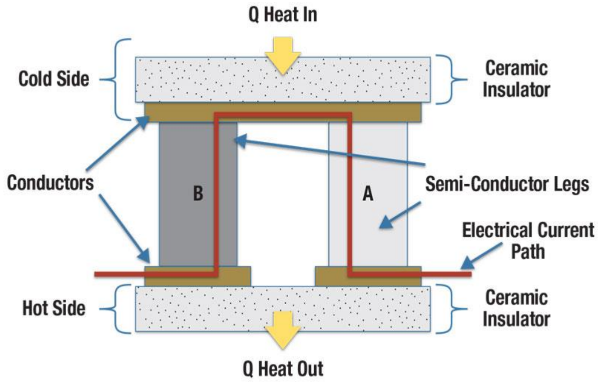

Figure-3: *Thermo-electric effect [26]*

2.3. Nano-fluids cooling

Nano-fluids are considered to be dispersed mixtures of cooling fluid and solid nanoparticles. Most of the particles used are metal oxides, per example Al2O3 or CuO particles. Weight percentage of dispersed particles is around 0.1-2.0 %. The particles have Brownian motion through cooling fluid. Main advantages of Nano fluids are greater thermal conductivity (therefore connectivity) and somewhat greater heat capacity [27]. Main disadvantage is pumping process and overall change in flow regime, i.e. characteristic turbulent flow occurs at different speeds and geometries, when compared with regular fluids. Xu and Kleinstreuer in 2014, made a numerical model for water and Nano fluid cooling of silicon PV cells and showed the cooling potential of Nano fluid to be somewhat greater than that of water. Electrical efficiency seems to maintain higher values even at increased temperatures, when PV panel is cooled with Nano fluids. [28] The efficiency difference between water and Nano-fluid cooling is significant during higher outlet fluid temperatures, and it can be up to 1 % of total efficiency. Karami and Rahimi in their research [29] used Boehmite Nano-fluid to conduct cooling of polycrystalline module of 0.059 m^2. Cooling was made on the back side of the module, via cooling ducts of two different shapes. It was shown that small percentage of Nano-fluid in cooling water enhances temperature difference of module surface. For a concentration of 0.1 % wt. of Nano fluid, and fluid flow of 0.006 kg/s, a decrease in temperature of about 4.5 °C was observed, when compared with water cooling. Strong influence of flow channel shape on cooling intensity was observed. It was proven that Nano-fluid cooling efficiency mainly depends of Nano-fluid content and local flow regime. Figure-4 shows cooling method using nano-fluids.

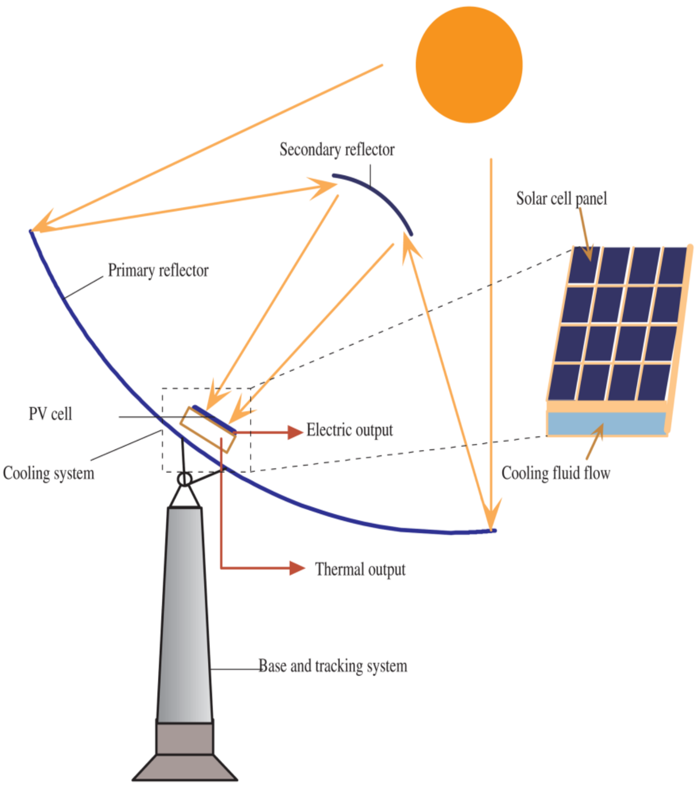

Figure-4: *Nano-fluid cooling method [28]*

2.4. Passive cooling techniques

Passive cooling methods are divided into three main groups: air passive cooling, water passive cooling, and conductive cooling. Conductive cooling mostly ends up with air passive cooling, but an important difference is that the prevailing mechanism of heat transfer from PV cells is conductive in nature. Cuce et al. 2011; had done an experiment on mono-crystalline PV modules in a controlled way. Two modules were used: one was made of aluminum fins with applying thermal grease at heat sink and one without a heat sink. Power varied from 200 to 800 W/m^2. A relative increase in electric efficiency of 9 % has been gained by using passive cooling along with a heat sink. [30] Hernández et al. 2013, [31] has shown that the depth of flow channel beneath PV cells has significant influence on passive cooling, for larger PV surface (1.95 m^2). It has been shown that, for a length-to-depth ratio of 0.085, the PV module heats up by 5-6 °C when compared with a PV module on a regular mount. It has been noted that the temperature difference rises with the increase of insolation. In other words, passive flow channels can have the reverse effect on PV module cooling. A special type of passive cooling method is Phase-change-Material (PCM). In Hassan et al. 2010, authors had showed that, with the right type of PCM, a decrease of 15 °C relative to reference PV cell can be achieved, in 5 hours, insulating at 1000 W/m^2. PV modules with nominal power of 65W were used, with 50 mm of PCM material from the back, with vertical aluminum fins to enhance conduction. The power gain was higher by 9.7 % than that from a reference PV module. Maiti et al. 2011, they used a V-type reflective panel for gaining as much concentration as of two suns, Figure-5. [32] A PV panel of 0.133 m^2 surface was used, with 10 W of nominal power. Using 5.5 kg of PCM material mixed with turning shavings decreased the maximum temperature from 85 °C to 65 °C. The rise in efficiency was about 55 %. However, 5.5 kg of PCM material for 0.133 m2 of surface under 2 suns is significantly higher mass of material than in [33].

Figure-5: *PCM [34]*

Water passive cooling is somewhat more efficient, mainly because of the higher thermal capacity of water. Several studies have been made with front and back cooling. Rosa-Clot et al. 2010; used a submerged technique to cool down the mono-crystalline PV module in water. The effect had limited success: the temperature was maintained at 30 °C which in turn yielded a relative efficiency increase of 20 %, but insolation intensity dropped with depth. However, at a depth of 4 cm, relative efficiency is increased by 11 %. [35]

Figure-6: *Thermo-syphon effect used on PV/T system [36]*

El-Seesy et al. 2012, made an attempt to cool down the PV cell with a thermo-syphon effect, Figure-6. A poly-crystalline silicon module, with a total area of 0.260 m^2 was used, along with a copper sheet and tubing installed on the back of the module, and a thermo-syphon water system with a water capacity of 80 liters. The increase of relative efficiency gained was 19 %.[36] Chandrasekar et al. 2013, used the capillary effect to cool down the back of a mono-crystalline PV module, 0.36 m^2 of surface. The capillary effect was produced via cotton wick structures wrapped spirally at the back of the module, and immersed in fluid. Nano fluid capillary cooling was also tried, but it failed to enhance the cooling effect when compared with water. [37] The maximum increase in efficiency goes up to 10.4 % when compared to a non-cooled module. Han et al. 2013, compared immersion in different cooling fluids. The immersion takes place in isolation liquid, de-ionized water and three different organic liquids. The irradiance was augmented to 10, 20 and 30 suns, where 1 sun is 1000 W/m^2. The relative efficiency increase goes up to 15 %. Several things need to be taken into account. Mainly, the fact that the cell is relatively small when compared to the amount of liquid and its casing. On the other hand, a concentration of 30 suns requires a sizeable amount of cooling, which can obviously be done with passive liquid cooling. For a better understanding, temperature measurements should be conducted, which is omitted in [38]. A more important conclusion states that the PV cell lingers unchanged after 180 days of immersion. Abdulgafar et al. 2014; analyzed different efficiencies of .12W and 15 cm^2 polycrystalline PV cell immersed in different depths of deionized water. Highest overall power was gained at lowest depth of 1 cm. However, highest efficiency of 22 % was gained at depth of 6 cm. This was due to the fact that pyrometer used for detecting solar irradiance was also immersed in water to same depth. [39] With decrease in irradiance, relative efficiency rises, although the output power is much smaller than that of a non-immersed PV cell. Also, the amount of water used for cooling greatly overcomes the mass of PV cell hence it cannot be easily compared with large-scale PV systems.

3. Conclusion

Many works emphasize the utilization of waste heat for domestic hot water. Although hot water (and heat in general) production is important, main purpose of PV cells is electrical energy production. When energy is compared, the energy of electrical energy is significantly greater than energy of produced thermal energy. Produced hot water almost never reaches the temperatures above 65 °C, due to significant decrease in PV electrical efficiency, except in concentrated PV systems. Hybrid PV/T technology is a necessity, mainly because of space optimization and compactness of design. The system should focus on gaining more electrical energy, because of its higher quality. For that reason it is important to define optimal working temperature and to establish a control process by which outlet water temperature can be varied. One serious issue is definitely the mismatch of energy needs - most thermal energy is needed in winter, when there is a lack of it. For that purposes, concentrated PV cells can be used, mainly because of the higher ratio of water-to-cell mass. In summer, large amount of heat needs to be taken away. A PCM can be used to capture additional heat at peak loads. When considering nano-fluid cooling, a separate circulation system needs to be taken into account, if cooling water is to be used for domestic needs. Since nano-fluid cooling can enhance electrical efficiency by up to additional 1 %, it can be considered as a good solution for large PV/T systems, where the introduction of additional circulation system could be economically viable.

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Authors Profile:

Avijit Mallik is currently studying Mechanical Engineering at Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh.

Md. Arman Arefin is currently studying Mechanical Engineering at Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh.