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A review of the most important cooling techniques to improve the performance of the photovoltaic cell

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Abstract - *Photovoltaic (PV) units operate in a contradiction; solar radiation is the essential input to produce electricity with Photovoltaic cells, but they drop in performance when the temperature increase by radiation. This work reviews the most important literature related to the research works submitted to achieve improved efficiency via convenient cooling systems. The passive cooling methods reduce the photovoltaic unit temperature in the range of 6-18 °C and enhance electrical efficiency up to 15 % maximum. While active cooling techniques, the performance is better as a reduction in photovoltaic unit temperature achieve to 33 °C. and an enhancement in electrical efficiency up to 22.2%. It can be expected that with the exponential growth of solar photovoltaic electricity worldwide, a compatible cooling system has become mandatory to ensure better harvest and use of energy.*

Keywords - *photovoltaic; efficiency; solar radiation; electricity.*

I. INTRODUCTION

Traditional energy generation threatens the environment and prevents environmental sustainability. In modern energy generation, hothouse gases emitted by fossil fuels are a global concern that must be effectively treated. Solar energy is one of the most important types of renewable energy sources that had attracted researchers around the world to work on it. Two types of energy can be produced from solar energy: electric and thermal energy. Electric power can be produced using photovoltaic cells (PV). Photovoltaic modules most efficient, sustainable, environmentally friendly, which a small portion of solar radiation is converted into electricity. Then the remaining portion of the solar radiation is converted into heat, which causes the increased temperature of the cells and reduces the PV unit [1]. Photovoltaic cell temperature can reach as high as 80 °C, especially in hot, dry regions [2]. The open-circuit voltage, short circuit current, and maximum output power are the main parameters influenced by the temperature variation of the cell's temperature. The maximum output power and open-circuit voltage reduce with the temperature increase, whereas the short circuit current rises slightly [3]. Using solar energy via photovoltaic cells is the futurity and the most reliable renewable energy source. However, during the operating of a solar PV cell, its production and efficiency are affected by different factors along the operating cycle and certainly reduce the cell's permanent electrical performance. The main factor affecting the PV cell's electrical output is the temperature, especially in hot and dry areas, and when the PV cell is addressed for performance and production. The photovoltaic cells' efficiency drops with a temperature rise, and the rate of reduction ranges between (0.40-0.65%) / degree Celsius depending upon the material of the photovoltaic cell used [4].

II. Cooling methods for PV cells

Two types of cooling can be distinguished: active cooling, which consumes power (fans, pumps, etc.), and passive cooling, which uses conduction or natural convection to excrete heat (it does not consume power).

A. Passive cooling methods

It can be divided into two main categories: passive water cooling, passive air cooling. A significant difference is that the mechanism of heat transfer from photovoltaics is conductive. Cuce et al. [5] worked on experimental research to know the effect of passive cooling on poly-crystalline photovoltaic cells' performance. Two photovoltaic cells were used in controlled conditions: one without aluminum fins and aluminum fins as a heat sink. The irradiance varied from 200 to 800 watts / m2. The highest cooling is observed for the intensity solar irradiance of 600 W/m2. An increase in efficiency of 9% was achieved by using this method. Hernandez et al. [6] worked on an experimental study using air as a cooling liquid. Movement is either by free convection or forced convection by a fan. Shown that the depth of the flow duct under Photovoltaic cells has a significant effect on passive cooling, it has been confirmed that, for Aspect Ratio 0.085, the PV panels temperature rise by 5 - 6 °C when compared with a conventional Photovoltaic panel. i.e., passive cooling may have the reverse effect on PV module cooling

Cooling with phase change materials (PCM) is passive cooling because no power is consumed to subtract away the heat- it is dissipated mostly conductively. Hassan et al. [7] shown that, with the right type of phase change material(PCM), a reduction of 15 °C relative to reference Photovoltaic cell can be made, for 5 hours, at insolation of 1000 W/m2. Photovoltaic cells with 65 watts' power, with 50 mm of phase change material (PCM) from the rear, with perpendicular aluminum fins to raise conduction. Power gain was 9.7% higher than that of the photovoltaic reference unit. Maiti et al. [8] Use a reflective panel through-V to get a light intensity concentration. A Photovoltaic panel of 0.133 m2 surface area was used, with 10 W of nominal power. The geometric focus ratio (A/B) for the V-trough was two. Using 5.5 kg of Phase change material mixed with lathing shavings reduced the temperature from 85 °C to 65 °C. efficiency increased was about 55 %.

Passive cooling with water is slightly more effective, mainly due to the water's high thermal capacity. Many studies have been conducted with front and rear cooling. Rosa-Clot et al. [9] cooled the mono-crystalline PV panel by submerging it in water. The influence has finite success: the temperature remained at 30°C, which in turn led to a relative increase in efficiency of 20%, but insolation intensity decrease with deepness. But, at a depth of 40 mm, relative efficiency is raised by 11 %. El-Seesy et al. [10] attempted to cool the photovoltaic panel with a thermosiphon effect.

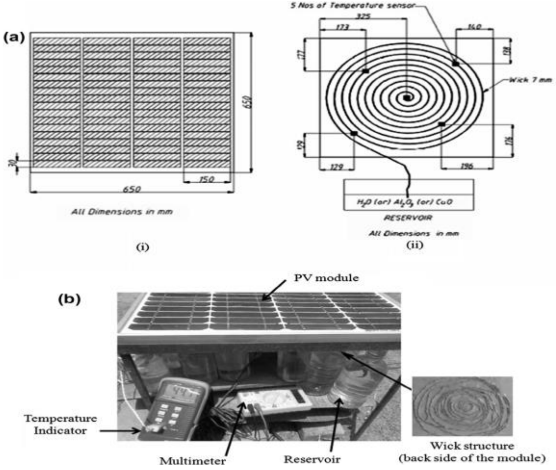
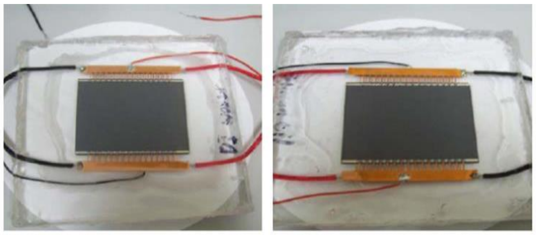


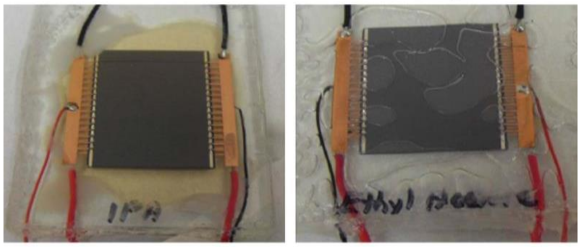
Fig. 1 (a) Schematic of (i) front side of the Photovoltaic unit and (ii) rear side of the Photovoltaic unit with wick structure (b) Photograph of the experimental Photovoltaic unit.

A poly-crystalline photovoltaic panel with a surface area of 0.260 m2 was used, along with copper plate and tubes mounted on the PV unit's back. A thermosiphon has a water capability of 80 liters. The rise of relative efficiency achieved was 19 %. Chandrasekar et al. [11] using the capillary effect to cooling the rear of a mono-crystalline photovoltaic panel, with area 0.36 m2, Fig. 1. The capillarity was created by cotton wool structures covered spirally at the rear of the module and submerged in fluid. Nanofluid capillary cooling was also tested, but it unsuccessful in improving the cooling effect compared to water—the maximum rise inefficiency to 10.4 % comparative to a non-cooled unit. See Fig. 1.

Han et al. [28] compared submersion in various cooling fluids. The submersion occurs in isolation liquid, deionized water, and three various organic fluids (IPA, dimethyl silicone oil, ethyl acetate), as shown in Fig. 2. The irradiance was increased to 10, 20, and 30 suns, where one sun is 1000 W/m2. The relative efficiency rises to 15 %. The most important result is that photovoltaic cells remain unchanged after 180 days of submersion.



(a) Cell#1 in DI water for 170 days (c) Cell#3 in dimethyl silicon oil for 170 days



(b) Cell#2 in IPA for 170 days (d) Cell#4 in ethyl acetate for 99 days

Fig. 2. silicon PV solar mini-units with a 1.5 mm thick liquid layer on top for several months.

Abdulgafar et al. [13] compared several efficiencies of 0.12 Watt, and it has area15 cm2 photovoltaic cell poly-crystalline submerged in various depths of deionized water. The maximum overall energy was obtained at the lowest depth of 1 cm. However, the maximum efficiency of 22 % was obtained at a depth of 6 cm. This was because the solar meter used to observe solar radiation was submerged in water at the same depth. With reduced radiation, relative efficiency increases, although the energy production is much smaller than unsubmerged photovoltaic cells. Because the amount of water used for cooling very massive, the mass of photovoltaic cells can't be compared with large-scale photovoltaic cell systems.

B. Cooling by Heat pipes

Heat Pipes are one of the most efficient ways to move heat, or thermal energy, from one point to another. These two-phase systems are typically used to cool areas or materials. Heat pipes are sealed vacuum vessels partially filled with a working fluid, typically water in electronic cooling, which serves as the heat transfer medium. The heat pipe envelope is made of copper in many shapes, including cylindrical, rectangular, or any other enclosed geometry. As heat is applied to the heat pipe's surface, the working fluid is vaporized Fig. 3. The vapor at the evaporator section is at a slightly higher temperature and pressure than other areas. This creates a pressure gradient that forces the vapor to flow to the heat pipe's cooler regions. As the vapor condenses on the heat pipe walls, the vaporization's latent heat is transferred to the condenser. The capillary wick then transports the condensate back to the evaporator section. This closed-loop process continues as long as heat is applied.

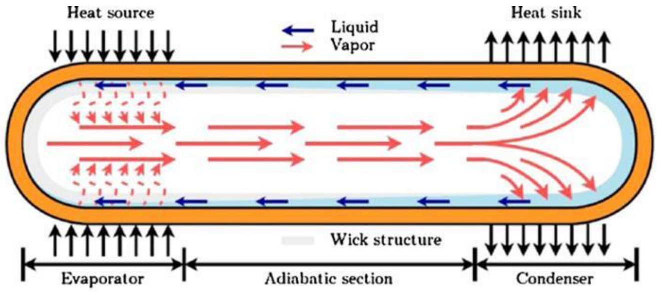


Fig. 3. Schematic diagram of heat pipe [14]

Russell [15] developed a cooling method for concentrated Photovoltaic systems utilizing heat pipes to enable the high-temperature operation and extracted heat for useful use. The systems consist of a row of photovoltaics installed on the outside of a heat pipe, where the heat pipes are arranged next to each other to form a panel, and Fresnel lenses have been used to provide a high density of solar irradiance, Fig. 4.

Anderson et al. [16] Designed a cooling system utilizing a copper/water heat pipe with three wraps of mesh and aluminum fins to improve cell cooling with the assist of natural convection to cool Photo-voltaic concentrator under concentrate the solar intensity from 200 to 1000 suns. A comparison between several working fluids suited with copper heat pipes manifests that copper-water heat pipes could load more than six times the power of other working fluids. Fin size and spacing for subtraction heat by free convection were determined through a series of CFD analyses.

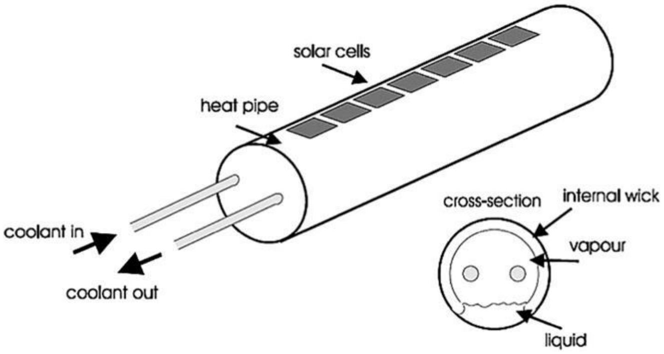
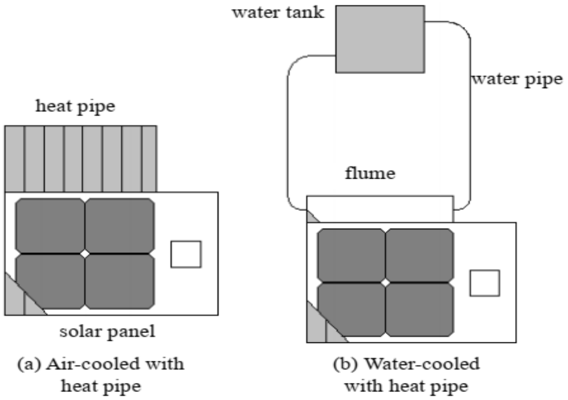


Fig. 4. Heat pipe cooling of PV cells [15]

Heat subtraction to the environment by free convection reached cell to-ambient difference of 43 °C when heat flux was applied 40 W/cm2. Tang et al. [17] utilized a micro heat pipe to cooling photovoltaic cells of 0.0625 m2 PV module, using water and air passive cooling method at the condensing side of the micro heat pipe, Fig. 5. The experimental results of both systems were compared to a normal photovoltaic panel without cooling. When using maximum water difference was in the efficiency of 3% and the average increase of 0.5%, air cooling reached 2.6% and 0.4% respectively compared to the conventional panel without cooling.



(a) Air-cooled with heat pipe

(b) Water-cooled with heat pipe

Fig. 5. Micro heat pipe cooling for conventional Photovoltaic module using air and water[17].

Gang et al. [18] used nine heat pipes(water-copper) attached at the back of the aluminum plate integrated at the rear of a Photovoltaic unit. They proved a relationship between electrical efficiency and the number of heat pipes. Also, they reached a stable temperature of photovoltaic cells with heat pipes cooled with water at maximum solar radiation of nearly 800 W/m2. The panel's surface area is about 1.0 m2; the total amount of water in circulation was about 200 liters. The maximum water temperature has reached 48°C Wu et al. [19] investigated the effect of heat pipe cooling on keeping a regular cooling for Photovoltaic cells by absorbing the excessive heat-accumulating on Photovoltaic cells. Results indicated that heat pipe cooling could aid the uniform temperature of Photovoltaic cells on the absorber plate with a change of Photovoltaic cell temperature less than 2.5 °C. The overall electrical, thermal, and exergy efficiencies of the heat pipe PV/T system reported were 8.45%, 63.65%, and 10.26%, respectively.

C. Active cooling techniques

The active cooling technique can be considered as energy-consuming methods for cooling photovoltaic panels. Most of the techniques used are dependent on water or air cooling. Thus, the main consumption system is the fan or pump needed to keep the fluid circulation. In general, active cooling techniques increase the energy produced and the thermal energy that is more accessible. Still, when energy consumption is considered, there is a question as to whether the cooling system can support itself. The active cooling method can easily be applied when concentrated photovoltaic cells are used, mainly Due to the ratio of fluid mass to cell and the Possibility to use less cooling fluids. So, less energy is needed to preserve the system.

Farhana et al. [20] used a multi-crystal photovoltaic panel of 0.924 m2 to test air cooling influence. Two photovoltaic panels have been compared, one with air cooling and the other without air cooling. The cooling panel has an aluminum envelope on the rear side, acts as a flow channel, as shown in Fig. 6. The research skips info about the mass flow of the cooling air. Only fan specifications are given. Results show a relative efficiency rise of 6.5 % and a reduction in the temperature of a maximum of 12 °C.

Fig. 6. The backside of the photovoltaic panel.

Arcuri et al. [21] cooled a poly-crystalline photovoltaic module of 1 m2. Cooling was provided on the rear side of the photovoltaic module by a specially designed flow channel. The Flow channel consists of aluminum sheets thickness 1 mm at the rear of the plate, with a wooden casing around it. The mass flow rate of air about 0.016 kg/s. Mass flow is created by a helical fan of 3.6 Watt rate energy-consuming. The rise in total efficiency was about 0.6 %, count on the insolation and portion of the year

Du et al. [22] Concentrated mono-crystalline photovoltaic cells of 0.152 m2 are used. The focus was at 8.5 sun intensity. The cooling method used was rear side cooling by two aluminum tubes over aluminum mounting. Peak efficiency was increased by 0.8% for the mass flow rate of water 0.035 kg/s. The peak photovoltaic temperature was about 60 °C.

Bahaidara et al. [23], a 1.24 m2 mono-crystalline photovoltaic panel was cooled from the rear side by a special heat exchanger through which water flowed, Fig. 5. A 0.5 HP power water pump consumes. The mass flow rate is 0.06 kg/s. Compared to a non-cooled panel, efficiency increase is 2.8%, and reduction panel temperature is 10°C.

Dorobantu et al. [24] A photovoltaic cell of about 0.56 m2 on the front side was cooled by washing with 0.03 kg/s of water. An increase in efficiency has not been measured. Instead, a rise in power product was given, up to 4 watts. The drop in temperature was 12.5°C and 8°C on the back and front side. Pump consumption is not given; it is only confirmed that increasing energy productivity is sufficient to cover the cost of pumping.

D. Cooling by Nanofluids

Nanofluids are mixtures of coolant and solid nanoparticles, and most of the particles used are metal oxides, such as Alumina Al2O3 and CuO. The concentration of nanoparticles in the base fluid has a great influence on the nanofluid's thermal performance due to the good heat conductivity these particles possess.

Karami et al. [25] used a nanofluid composed of water and aluminum hydroxide (AlOOH_xH2O) to cool a 0.059 m2 poly-crystalline cell. Cooling was done from the backside of the cell through straight and spiral cooling channels. The results showed that a small concentration of nanofluids in the cooling water enhances cell surface temperature. The researcher found that the concentration of 0.1% of the nanofluids and the fluid flow rate of 0.006 kg /s led to a decrease in temperature to 18.33 °C for the straight channel and 24.2 °C the spiral channel. This resulted in an increase in the electrical efficiency of about 20.57% for the straight channel and 37.67% for the spiral channel, respectively, compared to normal water cooling.

Sardarabadi et al. [26] used copper tubes containing a nanofluid composed of water and silica particles at weight concentrations of 1% and 3% to cool from the backside poly-crystalline PV cells have a nominal power of 40 watts from the backside and surface area of 0.35 m2. The maximum fluid flow was 0.011 kg / s. The researcher indicated that 3.0% of the nanoparticles enhance the efficiency by about 1.5% compared with pure water cooling.

E. Thermoelectric (TE) cooling

Thermoelectric units are solid-state semiconductor devices capable of transforming thermal energy directly into electrical energy and vice versa. The TE consists of thermoelectric elements composed of two dissimilar semiconductors, p-type and n-type junctions electrically connected in series and thermally parallel. The PV/TE system consists of a thermoelectric unit attached at the Photovoltaic unit's backside with a heat sink attached to the other side of the unit to raise the heat transfer process. Najafi and Woodbury [27] modeled a Photovoltaic cell cooling with the Peltier element. It was shown that the operation of thermoelectric cooling could be applicable for high concentration Photovoltaic cells. Only in specific cell working regimes, enough additional energy can be produced to preserve cell cooling.

III. Conclusions

- Photovoltaic temperature rise can seriously degrade photovoltaic performance; hence PV cooling must be an integral part of photovoltaic systems for efficient operation.
- Various technologies can achieve photovoltaic cooling; Passively, actively, or both operate in conjunction with varying degrees of cooling abilities and system complexity.
- Air cooling techniques are applicable and applied in different designs; however, enhancement in the photovoltaic unit performance is limited due to small heat capacity and low density of air.
- Cooling by liquid shows the best alternative to air cooling.

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