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Ali Ghalib Hussein
Energy and Renewable Energies Engineering Department, College of Engineering Al-Musayab, University of Babylon, Hillah, Babil ZIP/Zone 51001, Iraq

Fatimah Adeeb Mousa
Energy and Renewable Energies Engineering Department, College of Engineering Al-Musayab, University of Babylon, Hillah, Babil ZIP/Zone 51001, Iraq

Abeer Sami Joodi
Material Engineering Department, College of Engineering Al-Musayab, University of Babylon, Hillah, Babil ZIP/Zone 51001, Iraq

Corresponding Author:
Ali Ghalib Hussein
Energy and Renewable Energies Engineering Department, College of Engineering Al-Musayab, University of Babylon, Hillah, Babil ZIP/Zone 51001, Iraq

Innovative cooling techniques in photovoltaics: Passive and active approaches

Ali Ghalib Hussein, Fatimah Adeeb Mousa and Abeer Sami Joodi

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Abstract
The efficiency of photovoltaic panels is strongly affected by their operating temperature. Elevated surface and ambient temperatures decrease efficiency and can cause thermal degradation in photovoltaic materials, particularly their semiconductor components. This review explores fundamental cooling techniques to lower photovoltaic panel temperatures and enhance performance. It examines passive and active cooling methods, including water, air, phase change materials, and nanofluids. The findings suggest that water cooling is more effective than air cooling, while phase change materials also present a viable cooling alternative.

Keywords: Cooling PV Panels, Photovoltaic Panels Cooling Techniques.

1. Introduction

The world has recently turned to generating electricity from clean energy sources. Photovoltaic panels were one of these sources to achieve carbon neutrality. It is an effective way to reduce greenhouse and global warming risk [1].

Although environmental factors greatly affect photovoltaic panels, they have advantages in reducing harmful emissions that outweigh the flaws [2]. Photovoltaic panels are a direct current source that converts solar energy into electricity. Photovoltaic panels are connected in series or parallel to achieve high power output [3]. Photovoltaic panels produce electricity using the photoelectric effect, where photons of light from the sun collide with the surface of semiconductor materials, releasing electrons. This movement of electrons is an electric current. As a result of this incident light, an electric voltage is generated on the semiconductor diode, and thus, the current is generated due to the application of the photoelectric effect [4].

Solar energy comes from the sun in the form of heat and light, as the increase in solar radiation and the ambient temperature affects the efficiency of converting solar radiation into electricity in the photovoltaic panel; the issue of the effect of the temperature coming from solar radiation on the efficiency and performance of the photovoltaic panel has been analyzed [5]. The authors tested the efficiency of photovoltaic panels with increasing radiation intensity and observed from their experimental results that the efficiency decreased between 20.1 and 22.8%.

It is affected by temperature because it is made of a semiconductor material, which affects its semiconductor material parameter. The band gap of semiconductors decreases with increasing temperature, thus reducing the efficiency of the panel and the production of electrical energy from it [6]. Figure 1 shows the relationship between the power output (in Watt) and Voltage (in Volt) from photovoltaic modules under different temperature settings [7].

The use of cooling techniques in photovoltaic panels has been resorted to due to the harmful effect of the high temperature of the photovoltaic panel, which consequently reduces its efficiency. In this paper, a review will be presented of the different cooling methods that regulate the temperature distribution and reduce the temperature of the photovoltaic panel.

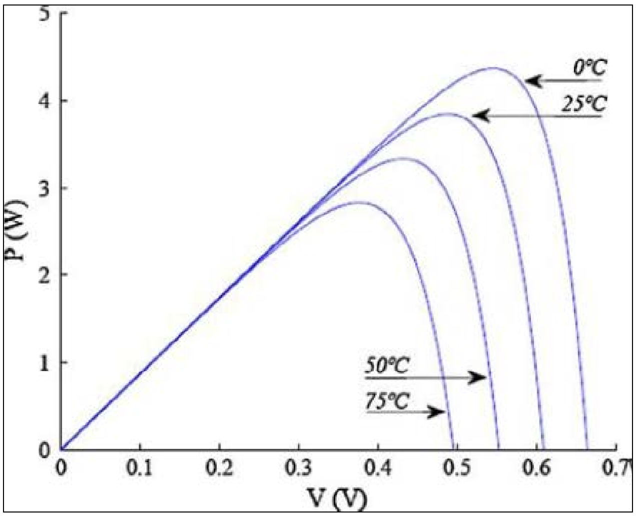

Fig 1: Characteristic Curve of PV Module with Different Temperatures.

2. Classification of Different Photovoltaic Panels Cooling Methods

Cooling methods are used to reduce the factors affecting the photovoltaic panels' efficiency and performance [8]. Cooling methods are divided into two types: active cooling and passive cooling. Active cooling requires a cooling fluid such as air or water, and this requires fans and pumps to move the fluid according to the type of cooling technology used. Water sprinklers or air flow mechanisms [9], the performance of PV panels can be significantly improved, leading to an enhancement in electrical power production. Despite the benefits of active cooling, there are limitations to its use that may increase the costs of its implementation, such as requiring an external power source to operate pumps or fans [10]. Passive cooling methods are effective in reducing the effect of high temperatures on the efficiency of PV panels and power output, such as phase change materials (PCMs) and water as natural flow and by using air as in free convection that helps regulate and distribute PV panel temperatures, thus increasing their efficiency and the panel's lifespan. The temperature of the panel affects the efficiency by -0.47%/ °C. That is, a 1 °C increase in the temperature of the photovoltaic panel reduces its efficiency by 0.47% [11]. Passive cooling of photovoltaic panels (PV panels) is preferred due to its ease of application, low cost, and lack of an electrical power source. In addition, it does not require much periodic maintenance [12]. Despite its benefits and low cost, there are limitations to its use, as it is not sufficient at high temperatures [13].

3. Photovoltaic Panels Cooling Methods

3.1 Passive Cooling Photovoltaic Panels Systems

3.1.1 Floating Photovoltaic Panels Cooling System

Passive cooling PV system on lakes, ponds and water bodies play an important role in cooling the photovoltaic panels and also have a benefit in preventing algae and reducing water evaporation in addition to an economic benefit as they work to solve the problem of exploiting photovoltaic panels for areas that are usually more expensive [14].

The floats are designed using materials made of high-density polyethylene. These are dense and are connected by pins to the corner of the city and the middle of the float. Ventilation holes for this passive cooling are provided. All types are fixed to the floating structure through aluminum rails, as shown in Figure 2. This design takes advantage of the breeze phenomenon (continental) and contributes to reducing the temperature and increasing the efficiency of the photovoltaic panels from 15% to 24% [15].

Fig 2: Floating System (FPV).

3.1.2 Submerged Photovoltaic Panels Cooling System

A cooling technique used in submerged solar panel cooling systems [16] compares an absorber plate with cotton wicks embedded in rectangular aluminum fins (CWIRAFs) submerged in water as passive cooling and copper tubes connected behind the panel as active cooling. Immersion cooling, such as using cotton wicks submerged in water (CWIWs) and cotton wicks submerged in rectangular aluminum fins (CWIRAFs), contributes to evaporative cooling where the moist cotton wicks are exposed to air and thus, the temperature of the dry air decreases and the humidity increases and thus evaporative cooling is obtained which is used to cool the back of the solar panel as shown in Figure 3 where the temperature of the unit was reduced by 22%, and the power output increased by 16.3W.

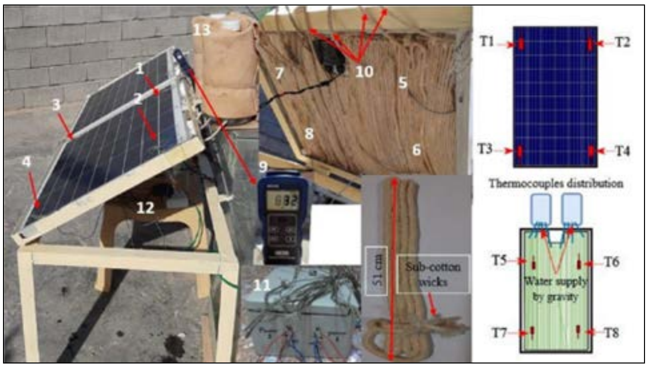

Fig 3: A Sight of the Experimental Setup.

3.1.3 Photovoltaic Panels Cooling Using Heat Sinks

A heat sink, shown in Figure 4, dissipates heat from parts that emit heat and raises the temperature of devices or objects by transferring heat from the hot part to the cold part [17]. Heat is usually transferred from the device to the coolant or air to help dissipate heat efficiently.

A combination of heat sink material and water block cooling was used to reduce the panel temperature, and experiments were chosen away from the environmental conditions that cool the PV panel to obtain accurate results for this system and an increase in power of 43.3% was observed when the system without cooling design was compared with the passive cooling design system [18].

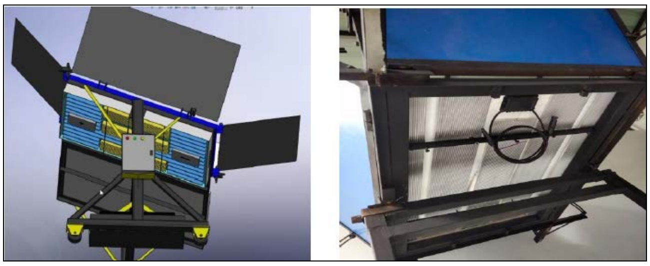

Fig 4: The Mechanical Design of System.

3.1.4 Radiative Cooling for Photovoltaic Panels

Radiant cooling is a method of cooling photovoltaic panels, which enhances the efficiency and life of the panels by reducing their temperature. Radiant cooling is a type of passive cooling and is less expensive, but active cooling distributes heat more efficiently, but is more expensive because it requires an electricity source [19]. Solar radiation heats the photovoltaic panel, which hurts the panel's efficiency and the solar panels' reliability, so radiative cooling dissipates heat passively to the cold part of the panel. Radiative cooling requires materials that emit strong thermal radiation in the transparency window of the atmosphere (wavelengths between 8 and 13 μm) as cooling layers [20]. A radiative cooler using nanoporous anodic aluminum oxide (AAO). It was shown that the cooler emitted infrared radiation (IR) close to ~0.97 units. (Weighted with the IR emission intensity of 298 K blackbody) in the atmosphere window while maintaining an excellent solar transmittance of over 0.94. Radiative cooling cools silicon wafers by 7.5k under solar irradiance of 850 W/m² and at 70% humidity. Commercial cells were compared with a single-junction crystalline silicon (c-Si) cell coated with AAO, and the annual electrical output of a solar cell with AAO was 16.5 kW h/(a·m2) [21].

3.1.5 Photovoltaic Panels Cooling Using PCMs

Phase change materials are used in cooling because they can absorb and release latent heat. In photovoltaic systems, they stabilize the panel's operating temperature [22].

In this type of PV cooling, a combination of aluminum fins with a phase change material (PCMs) as shown in Figure 5 was used on the back side of the PV panel. Paraffin wax was used as the PCM and placed in an aluminum case. The Paraffin wax has a high latent heat capacity and stores large amounts of thermal energy during melting and solidification at 18-30°C [23]. Aluminum fins increase the thermal conductivity of PMC, which speeds up the rate at which it melts or solidifies and increases heat transfer by free convection. This cooling design reduced the temperature by 19.9°C and increased the panel's power output by 23.1% compared to the panel without a cooling system. A wall of aluminum fins and PCM was placed as a coolant, where the PV-Aluminium Finned Wall was created from aluminum fins fixed on the aluminum plate, glued directly to the solar module using heavy-duty epoxy. Nine aluminum fins were fixed on the aluminum plate, and the distance between each pair of fins was 10 cm. As for the phase change material, a PV-Aluminium Finned Wall-PCM was created using the fins and the aluminum container. The fixing used heavy-duty epoxy and materials that prevent the PCM from leaking during its melting. The PCM container consists of 18 aluminum fins distributed inside and on the same dimensions as the first module. The results show the effect of passive cooling on the performance of photovoltaic panels. The two types of passive cooling, the PV-Aluminium Finned Wall-PCM and PV-Aluminium Finned Wall, increased the electrical efficiency by 15.2% and 14.7%, respectively. Also, the PV-Aluminium Finned Wall-PCM and PV-Aluminium Finned Wall reduced the temperature by roughly 27.2% and 9.6%, respectively and the energy production from the panels increased by 23.1% for the PV-Aluminium Finned Wall-PCM and by 16.8% for the PV-Aluminium Finned Wall [24].

Fig 5: PV-Aluminium Finned Wall module structure.

3.1.6 Thermoelectric Cooling Photovoltaic Panels Technique

Thermoelectric cooling devices are used with solar panel technology to cool them, increase their efficiency, and increase the electrical energy output from the photovoltaic panel. Based on the See beck effect, the thermoelectric module is used as a thermoelectric generator (TEG), converting the temperature difference into a direct current output voltage. It can also be used as a thermoelectric cooler (TEC) that is supplied with direct current, creating a temperature difference on the cold and hot sides, as in the Peltier working principle [25].

A solar cell cooling system consisting of two layers of thermoelectric generator as shown in Figure 6 was designed. Several single or double experiments were conducted on these generators, which were connected in series with solar cells and an independent load. Solar energy was tested under a simulation system and in real weather conditions. The results showed a decrease of 10.3 °C and an increase of solar cell output by approximately 30.54% compared to a simple solar cell. The experiments proved that TEGs-PV have better efficiency with the bare solar cell when the solar radiation is reduced through the multi-layer structure. During the period (1600 s), the power output was 27.6% higher than that of a normal solar cell. When using constant artificial light (1000 W/m2), the power output was 3.1% higher than the normal panel.

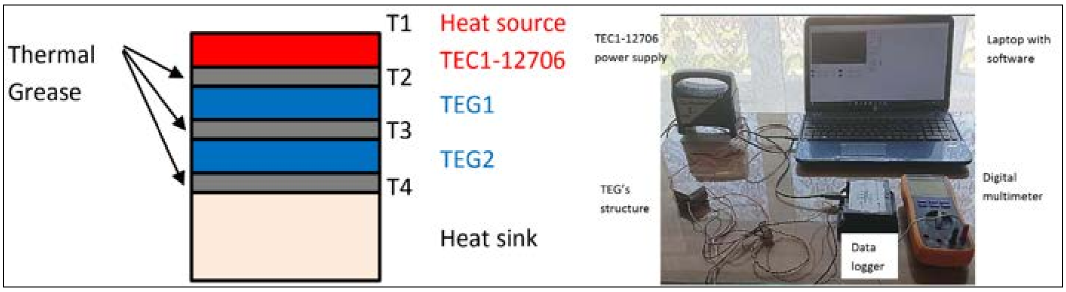

Fig 6: Configuration of Energy Conversion System (TEGs) Layers with Surface Temperature Indicator.

3.2 Active Cooling Photovoltaic Panels Systems

3.2.1 Cooling of Photovoltaic Panels with Water Spray

The forced water spray cooling technique was used, where the system consists of solar panels and a DC pump with a flow rate of 0.022 L/min operating on a separate solar panel. The panels were installed at an inclined angle of 32 degrees to obtain the highest solar energy. Water flows on the surface of the solar panels to improve the panels' efficiency and increase the net energy output. The results showed that the decrease in the temperature of the surface of the photovoltaic panels has a direct relationship with the efficiency of the resulting energy. The system was operated for one day. The temperature decreased by 9.07 degrees Celsius, and the resulting energy increased by 1.73V, i.e., the energy gain increased by 9.27%, and the efficiency increased by 0.71%. The process of cooling the cells by spraying water also leads to cleaning the cells from dust, thus reducing the maintenance cost and extending their life [26].

3.2.2 Circulated Water Cooling of Photovoltaic Panels System

For cooling photovoltaic systems, a forced water cycle enhances the system's efficiency by reducing heat losses. It improves electrical production and facilitates heat management, making it a solution for optimizing photovoltaic systems.

A solar panel cooling system was designed to cool a monocrystalline solar panel by a layer on the back of the panel in which water circulates and reduces the temperature difference along the surface of the solar panel to approximately 3°C and was compared with a system without cooling. The cooling system consists of vinyl tubes that distribute heat uniformly to all tubes, a water tank, and a variable flow pump at the bottom of the tank, as shown in Figure 7. The tank was filled with water, and the system was placed in solar radiation until it reached a constant temperature of 48°C and then the pump was turned on, so the panel temperature decreased to 24°C, and the efficiency increased by 0.046%. The simulation was also used, and the results were a 3°C difference between the measured and simulated ones due to the difference between the conditions, such as the thermal part of the solar spectrum that is converted into heat by the solar panel and the wind speed affecting the surface temperature of the panels [27].

Fig 7: (1) Solarimeter, (2) Control board, (3) Thermal camera, (4) Thermocouple, (5) water pumping system, (6) Computer for recording Data.

3.2.3 Cooling of Photovoltaic Panels with Forced Air System

Cooling solar panels using forced air increases their efficiency, extends their life, and reduces the temperature rise, which reduces energy production, especially in hot areas. Small fans, blowers, or air returned from air conditioning and ventilation systems are used. This method is more effective than the passive method, but it requires energy to operate and additional costs.

Forced convection cooling was used in a photovoltaic module [28] as shown in Figure 8 supported by a 50cm deep insulated duct covered with a 5cm thick polyethylene insulation layer on three sides of the duct. This depth was chosen because it achieves the largest temperature difference, as the temperature difference between the air entering and exiting the duct is 2.6 to 24.6°C. A 12V fan with a variable speed of 1 m/s to 6 m/s was installed at the top of the duct. The system has dimensions of (1.282 x 0.644) m. It is best used inside high-rise buildings' wall systems to ensure the solar panels' best efficiency, thermal performance, and safety. The system tests were conducted by running the light simulator to reach the required heat accumulation for one to two hours, i.e., a temperature of 100 degrees Celsius and an output temperature of 46 degrees Celsius, at a speed increasing by 1 meter per second each time. The results showed that the highest cooling efficiency of 51% of the incident radiation and the highest removal amount of 550W is at speed 4, and the highest improvement in cell efficiency of 17.53 is at speed 6. This shows that the best cooling for the solar panel is at the highest mass flow rate and not at the maximum thermal energy extraction. The fan used is a 12V fan that operates on direct current through a variable speed electrical circuit that operates on part of the solar panel power with a consumption of (0.7W), which increases the production energy by 19W.

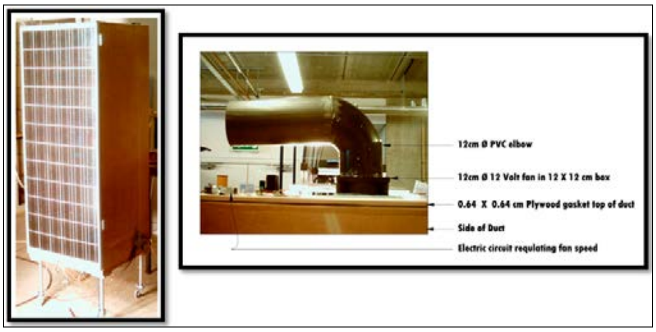

Fig 8: Cooling Photovoltaic by PCM Active.

3.2.4 Cooling of Photovoltaic Panels with Active PCM Technique

Phase change materials (PCMs) are used in solar energy systems as an active cooling technology to improve their performance and thus increase the energy ratio by making the panels ideal operating temperatures, as the phase change of materials greatly improves the efficiency and life of solar panels. It is superior to traditional air and water cooling technologies, especially in high-temperature environments. It stores high amounts of thermal energy relative to its small size, so it is widely used in applications such as buildings to provide electricity or to store ice or in water tanks, or to preserve food, as well as in solar energy applications, but its effectiveness varies according to environmental conditions and the PCM used. There is a problem with its low thermal conductivity, which reduces the effectiveness of cooling and its high cost, so researchers have made improvements by combining PCM with nanofluids and fins to enhance its specific heat capacity and conductivity.

The solar panel cooling system was developed and simulated by combining active and passive cooling systems [29], as shown in Figure 9. The PCM thermal storage and closed-circuit water cooling were used in a special design constructed from multiple CPV cooling layers. Compared with the traditional PCM-PV direct systems and separate water cooling systems, the developed system achieved a temperature reduction of 60%. At a concentration of 10 and a speed of 0.01 m/s HTF, the solar cell temperature remained below 78 °C, and the PCM temperature remained below the maximum temperature drop. When using nanofluid to enhance the HTF, the efficiency increased by 2.7%, the solar panel temperature decreased by 4 °C and the PCM melting time decreased by 12%.

4. Conclusions

Photovoltaic energy systems have emerged as a leading solution to meet the growing global demand for energy. These systems are favored due to their straightforward method of generating electricity, though the initial cost of acquisition and infrastructure setup is significant. Their primary energy source sunlight is abundant and inexhaustible. Photovoltaic systems are easy to install, produce electricity directly, and are emission-free, making them environmentally friendly. However, high operating and ambient temperatures can reduce the efficiency of solar panels. This review explores various cooling techniques to enhance solar panel efficiency, including air, water, and cooling with phase-change materials and nanofluids. Water cooling has proven effective in reducing thermal degradation, extending the lifespan of solar cells, and improving their energy production efficiency. Spray cooling, a subset of water cooling, not only cools but also cleans the panels, further boosting their performance. Despite their benefits, water cooling systems face challenges such as high upfront costs, the need for a constant water supply, and potential issues like algae growth, which can clog pipes. Air cooling, particularly active air cooling, offers a simpler design and easier implementation than active water cooling. However, air cooling efficiency depends on climatic conditions and geographical location, especially for passive systems, making site-specific assessments essential. Phase-change materials and nanofluids present alternative cooling solutions, especially when the water supply is limited or inaccessible or wind impedes air cooling. These innovative methods address key obstacles associated with conventional cooling techniques, offering a promising avenue for future research and application.

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