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COMPARISON OF THERMAL ENERGY STORAGE WITH PHASE CHANGE MATERIALS IN PHOTOVOLTAIC PANELS AND PV/T SYSTEMS

FOTOVOLTAİK PANELLERDE VE PV/T SİSTEMLERDE FAZ DEĞİŞTİREN MADDE KULLANILARAK ENERJİ DEPOLANMASININ KARŞILAŞTIRILMASI

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Ecem Şen[1], Melih Soner Çeliktaş[2,*]

Abstract
Solar energy has advantages such as accessibility, applicability, and predictability compared to other renewable energy sources. This energy source is used for many purposes in the world. Photovoltaic panels provide applications such as generating electricity from solar energy or heating and cooling. Their performance changes depending on the PV panel material, the amount of solar radiation, and the operating temperature factors. In the electrical energy conversion of PV systems, overheating of the PV module leads to a decrease in power generation and causes a decrease in efficiency. Therefore, there are cooling methods, divided into two categories as passive and active for cooling of PV panels. In this study, the properties of the phase change material (PCM) used in the cooling of PV panels are given. Furthermore, experimental and numerical studies of PCM in PV cooling and PV/T systems are reviewed in order to improve PV panel efficiency. PCM is reported to reduce the temperature of PV panels and increase the efficiency and power output data obtained.

Özet
Güneş enerjisi, diğer yenilenebilir enerji kaynaklarına kıyasla erişilebilirlik, uygulanabilirlik ve öngörülebilirlik gibi avantajlara sahiptir. Bu enerji kaynağı dünyada birçok amaç için kullanılmaktadır. Örneğin, fotovoltaik (FV) paneller ile güneş enerjisinden elektrik üretimi ısıtma veya soğutma gibi uygulamalar sağlanmaktadır. FV panel malzemesine, güneş ışınım miktarına ve çalışma sıcaklığı faktörlerine bağlı olarak panel performansları değişmektedir ve FV sistemlerde elektrik enerjisi dönüşümünde FV modülünün aşırı ısınması, güç üretiminin azalmasına ve verimin düşmesine neden olur. Bu nedenle FV panellerin soğutulması için soğutma yöntemleri kullanılmakta olup, bunlar pasif ve aktif olarak ikiye ayrılmaktadır. Bu çalışmada FV panellerin soğutulmasında kullanılan faz değiştiren malzemelerin (FDM) özellikleri verilmiştir. Ayrıca, FV panellerin sıcaklığını düşürmek için FDM kullanan çalışmalar ve termal enerjiden faydalanırken FDM kullanarak sistem verimliliği artıran deneysel ve sayısal çalışmalar verilmiştir. Yapılan çalışmalarda, FDM kullanıldığında FV panelin sıcaklığının düşürüldüğü ve buna bağlı olarak sistemin veriminin ve güç çıkışının arttırıldığı görülmüştür.

Keywords: Phase Change Materials, PV Cooling, PV/T, Solar Energy, Thermal Energy Storage

Anahtar Kelimeler: Faz Değiştiren Madde, FV Soğutma, PV/T, Güneş Enerjisi, Termal Enerji Depolama

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[1] Ege University Solar Energy Institute, Evka 3,119/1. St. No:2, 35100 Bornova, İzmir, Turkey, ecemsen@gmail.com, orcid.org/0000-0001-9852-9348

[2,*] Corresponding author: Ege University Solar Energy Institute, Evka 3,119/1. St. No:2, 35100 Bornova, İzmir, Turkey, soner.celiktas@ege.edu.tr, orcid.org/0000-0003-0597-5133

1. INTRODUCTION

Energy is one of the basic needs for people to survive. Due to the increasing population in the world, energy consumption and the need for energy are increasing day by day. Along with the increasing demand, the use of new sources has become mandatory due to the fact that fossil fuels are non-renewable energy sources, and the concerns about global warming have increased. As a result of this situation, renewable energy, which is a cleaner and more sustainable source, has started to be preferred. Solar energy, which is one of these energy sources, has great potential in terms of use in the world. Conversion of sunlight into usable energy forms, which are electrical and thermal energy, is carried out with a photovoltaic (PV) system. The use of photovoltaic systems has become widespread as they can be used both connected to the grid and independent from the grid (Shukla et al., 2017). The majority of solar energy is transformed to heat and lost to the environment via radiation and convection (Haidar et al., 2018). However, using this heat is possible by photovoltaic thermal (PV/T). In these systems, both electrical and thermal energy become available. Efficiency of photovoltaic cells decreases depending on the increase in temperature, and PV cells can be cooled with the use of these systems (Yıldız & Gürel, 2020). The heat transfer in the panel is depicted in Figure 1. Climate variables such as wind velocity, ambient temperature, relative humidity, dust, and radiation cause the temperature of the panel to increase (Elbreki et al., 2016). Therefore, panel cooling techniques are an important factor in increasing the electrical efficiency, reducing the rate of cell deterioration and, accordingly, increasing the lifetime of the panel (Siecker et al., 2017).

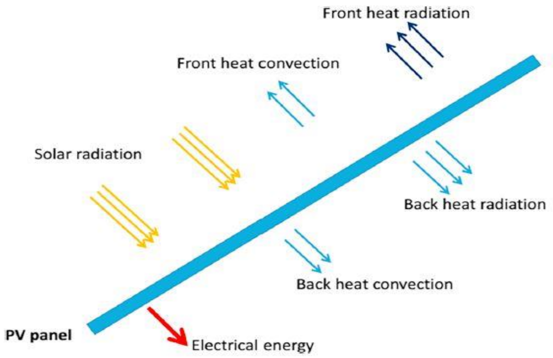


Figure 1: Radiations affecting the PV panel (Haidar et al., 2018).

The amount of heat transfer and the thermal conductivity of the working fluid change depending on the working fluid used, which is one of the most critical parameters in cooling systems (Özerinç et al., 2010). Today, some cooling techniques are used to keep the panel temperature at the desired level. These techniques are divided into active and passive cooling techniques. Passive cooling methods are mostly air, liquid (water, nanofluid, etc.), phase change materials and radiator based (Nižetić et al., 2017), and it is used to lower the surface temperature of solar panels through conduction or natural convection (Tan et al., 2017). In active cooling techniques, air, water or nanofluids as coolants provide cooling of the panel by using an extra energy, and it is more effective but more costly than passive cooling (Ma et al., 2018). The cooling used in active cooling systems is water-based and for photovoltaic/thermal (PV/T) configurations that reduce the high temperature in the PV panel (Nižetić et al., 2018). The use of PV/T systems by using different fluids is a trendy topic in recent years (Joshi & Dhoble, 2018; Sultan & Ervina Efzan, 2018). Apart from generating electricity, the installation of photovoltaic energy systems on building facades or roofs have become widespread for heating of water and various spaces.

Phase change materials, which have large latent heat capacity, are materials that can act as heat sinks and absorb the heat transferred from the PV cells (Atkin & Farid, 2015; Kakaç et al., 2012). There are types of phase change materials that solidify or melt at different temperatures, allowing the usage in different energy storage methods (Sharma et al., 2009). Detailed studies have recently been carried out on PCMs that have the ability to store latent heat (Sharma et al., 2009; Velmurugan et al., 2021). When phase change materials are used as a passive cooling method, no extra electricity or fluid is required, so less costly or less maintenance may be required compared to the cooling techniques used in PV/T systems (Ma et al., 2019). Moreover, research has been done to increase efficiency and performance of thermal systems, phase change materials are preferred as a good option as thermal storage batteries (Joshi & Dhoble, 2018). The most important role in PCM applications in order to increase the thermal performance in photovoltaic systems is the selection of the PCM. In the article, working principle of PCMs, advantages and disadvantages of PCMs according to their categories, the classification of PCMs and PCM selection criteria investigation are shown in the first section (Part 2). In part 3, PCM applications provided to decrease the temperature of PV panel and PCM applications used in heat (thermal) energy storage are discussed.

2. PROPERTIES AND WORKING PRINCIPLE OF PHASE CHANGE MATERIALS

PCMs are compounds that can absorb and store heat energy during phase change. This heat is called “latent heat”. PCMs can absorb heat energy from the environment and release this energy by changing phase from liquid to solid. Thus, thermal energy is conserved and stored. A solid-liquid phase change process by melting or solidification in PCMs can store large amounts of heat if a suitable material is selected (Yang et al., 2021). PCMs are divided into four according to the phase change which are solid-solid, liquid-gas, solid-liquid, and solid-gas respectively. Solid-liquid PCMs are generally used in thermal energy storage systems due to their high latent heat and small volumetric changes. Moreover, solid-liquid PCMs are classified as organic, inorganic, and eutectics. Organic materials are generally divided into two as paraffin and non-paraffin (Ma et al., 2019). Inorganic materials consist of metallic and hydrated salts while eutectic materials consist of a mixture of two or more PCMs to reach the desired melting temperature (Veerakumar & Sreekumar, 2016). The advantages of the materials are: Organic PCMs have high heat storage capacity, no supercooling, and show good chemical stability over time without decomposition. Inorganic PCMs have almost twice the thermal storage capacity and higher thermal conductivity compared to organic PCMs. Eutectic PCMs combine and solidify harmoniously without causing segregation and allow the phase change temperature to be brought to the desired level with the mixture of different materials. Disadvantages are as follows: Organic PCMs have low thermal conductivity, are flammable, and may show instability at high temperatures. Inorganic salts may show incompatible fusion and precipitation (Cárdenas-Ramírez et al., 2020). Eutectic PCMs show similar properties to organic and inorganic PCMs. The classification of PCMs is presented in Figure 2. PCM phase transition is illustrated in Figure 3.

In PCM applications, the material in the liquid phase can leak out from where it is and can be retained by encapsulation and shape stabilization, as this can cause losses and yield reduction (Cárdenas-Ramírez et al., 2020). Encapsulation is a preferred method as it provides better heat transfer while preventing possible reactions between the phase transition. Thermal stability and heat transfer efficiency vary according to the particle size used (Ghalambaz et al., 2021). Different encapsulation methods and types have been reported in the literature. For instance, Khadiran et al. (2015) compiled encapsulation techniques for organic PCMs and thermal properties of encapsulated organic PCMs. Huang et al. (2019) valuated the advantages and disadvantages of porous materials (metal foams, graphite, carbon nanotubes, porous silica, etc.) used in shape-stabilized PCMs and their effects on the phase change behavior of PCMs. Milián et al. (2017) classified the methods of core-shell and shape-stabilized encapsulated inorganic PCMs and analyzed the effect on their thermophysical properties, and Kirilovs (2021) integrated the microencapsulated phase change material into the board used in the building indoor wallboard, and the calorific value of the boards increased by 28% when 5% microencapsulated PCM was mixed into the sheet. This showed that the need for cooling in summer can be reduced.

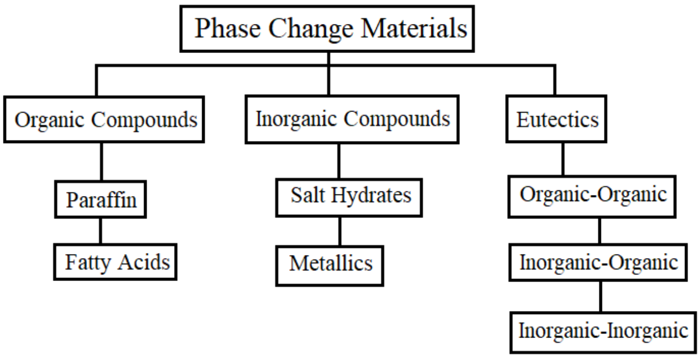


Figure 2: Classification of the PCMs (Cabeza et al., 2011).

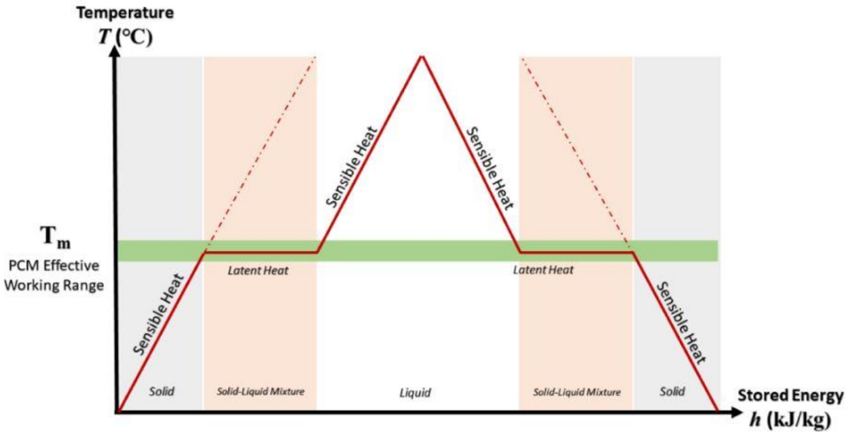


Figure 3: Graph of phase change of PCM (Faraj et al., 2021). (Permission obtained from the publisher).

2.1. Organic Phase Change Materials

Organic PCMs which are carbon-based compounds are the most widely used materials in PV-PCM systems (Ma et al., 2018; Veerakumar & Sreekumar, 2016). These materials can be open chain saturated alkanes, fatty acids, and paraffins, which are vegetable oils (Chandel & Agarwal, 2017). Wide temperature range for phase transition, high latent heat fusion, no subcooling process, chemical stability within 500°C and recyclability, and excellent compatibility with other materials are all advantages of organic PCMs. However, it has lower thermal conductivity (0.2 W/m K) and a wide surface area is required to increase the heat transmission rate. There are two types of organic PCMs: paraffin and non-paraffin materials (Zhou et al., 2012).

2.1.1. Paraffin

Paraffin is widely used in thermal and solar energy storage systems due to its large latent heat, non-corrosive and non-toxicity features. However, the limited thermal conductivity of paraffin can be a disadvantage for larger storage applications (Sahan & Paksoy, 2014). Paraffin consists of a mixture of straight chain alkanes (CH_3–CH_2–CH_3). The latent heat is released during the phase change, and it occurs as a result of the crystallization of the CH_3 chain. Since the melting point and latent heat of fusion may rise with the change of chain length, it may be utilized in a wide range of temperatures. Paraffin is inert, stable and forms low vapor pressure in the liquid state below 500°C (Sharma et al., 2009).

2.1.2. Non-paraffin

Fatty acids, esters, and alcohols from non-paraffin materials are also used in photovoltaic systems. However, they are more unstable in comparison to paraffin. Fatty acids are among the most extensively used organic molecules that have been investigated in recent years, and fatty acids have many promising properties for thermal energy storage. They are reasonably affordable and widely employed in a variety of applications (Ma et al., 2019). Fatty acids, which are more preferred than others, are relatively inexpensive, preferred for wide phase change temperature range and large-scale thermal energy storage systems, and the melting points of fatty acids are between 7 and 71°C (Kenisarin, 2014). The properties of some organic materials are given in Table 1 below.

Table 1: Comparison of organic materials (Sharma et al., 2015).

Material	Melting Temperature (°C)	Heat of fusion (kJ/kg)
Paraffin		
Paraffin wax	64	173.6
Napthelene	80	147.7
Biphenyl	71	119.2
Eicosane	36.6	247
Paraffin C21-C50	66-68	189
Propionamide	79	168.2
Non-paraffin		
Dimethyl sabacate	21	120-135
Elaidic	47	218
Myristic	54	187
Nonadecylic	67	192
Vinyl stearate	27-29	122

2.2. Non-Organic Phase Change Materials

Inorganic PCMs are generally divided into two as hydrate salts and metals. These materials are denser, cheaper and more energy efficient than organics. On the other hand, they are highly corrosive and do not have crystalline structures, when they reach the solid phase; large volume changes and corrosion effect are disadvantages (Khadiran et al., 2015; Sharma et al., 2009).

2.2.1 Hydrated salts

Salt hydrates are one of the inorganic salts containing one or more water molecules. It is one of the cheapest PCMs with a cost of 0.13-0.46 $/kg. It is widely preferred in storage systems with its high thermal conductivity and good latent heat capacity. Moreover, they have wide melting temperature range which is 5-130°C, and they are not flammable and can be recycled. However, there is a large volume change during the phase change, and this can be corrosive to the metals it comes into contact with. In hydrated salts, the latent heat is released before it reaches the melting temperature, and this causes excessive cooling. These problems are controlled by studies (Casini, 2016; Kenisarin, 2014).

2.2.2. Metallics

Metals are materials that do not need fillers and conductivity-enhancing materials and have higher thermal conductivity compared to other phase change materials. Thus, they do not require much weight and cost. However, it is generally not preferred to be used due to its low transition heat (fusion) per unit weight. Despite this disadvantage, it does not have problems such as supercooling large volume changes during phase change and corrosion in inorganic materials, so it can be an alternative in energy storage applications (Cabeza et al., 2011; Faraj et al., 2021).

2.2.3. Eutectics

Eutectic phase change materials are mixtures of two or more organic phase change materials. These materials are obtained to have the desired properties. Generally, mixtures of eutectic fatty acids have a lower melting temperature and higher heat storage density than their constituent organic materials. Moreover, the high melting temperature of organic materials creates problems in some energy storage applications, and it is preferred by researchers in terms of mixing organic materials into eutectic materials, obtaining the desired melting and freezing temperature and high latent heat energy storage properties (Mohamed et al., 2017; Singh et al., 2021).

2.3. The Properties of PCMs as a Thermal Energy Storage Material

Selection of the appropriate PCM plays a major role in latent heat energy storage applications. There are many various properties, and certain criteria must be considered when deciding the most suitable material. One of the basic criteria is that the melting point of the material is expected to be higher than ambient temperature and smaller than heat temperature. Having a melting temperature suitable for the conditions of the installed system is efficient in increasing the thermal performance. There are certain criteria in the selection of the suitable phase change material. These criteria are used when choosing the appropriate PCM. The amount of latent heat storage and phase change situation are effective in evaluating the performance of PCMs. These are shown below (Magendran et al., 2019).

2.3.1. Thermal properties

Suitable phase transition temperature: The temperature of the cooling or heating area should be suitable with the phase change temperature of the chosen PCM.

The amount of latent heat and specific heat: The large latent heat storage capacity of the PCM during phase change and the possibility to store sensible heat for the same temperature difference indicates that the thermal storage density is high. This allows physical size of heat storage to be reduced.

High thermal conductivity: High thermal conductivity allows good heat transfer, rapid storage or release of heat energy in the relatively lower temperature range. This feature can increase the efficiency of storage.

Compatible melting: PCMs should have a stable chemical structure in phase states, thus avoiding phase separation where density differences between solid or liquid phases are problematic (Wei et al., 2018).

2.3.2. Physical properties

Favorable phase balance: Phase change stability should depend only on temperature.

Low vapor pressure: The low vapor pressure during the phase change temperature means that the material has no possibility of evaporation or degradation.

High density: The high density of PCMs indicates that the amount of heat storage per unit volume is high and allows a smaller storage container size.

Little volume changes in phase change: While little volume changes reduce the problem of storage of the material, it shows that heat transfer can be achieved with smaller volume changes (Wei et al., 2018).

2.3.3. Kinetic properties

No supercooling: Supercooling has been particularly problematic for hydrated salt. Supercooling or supersaturation of more than a few degrees inhibits heat transfer during phase change (Wei et al., 2018).

Crystallization rate: The reaction of the storage medium to the material can increase the thermal performance of the PCMs (Wei et al., 2018).

2.3.4. Chemical properties

Long term chemically stable: There should be no chemical degradation as a result of phase changes. This increases the long-term reliability of the storage capacity.

Low corrosiveness and anti-oxidation: It indicates that the PCM is compatible with the containers in which it is located and makes it less costly to select the containers.

No toxicity and fire hazard: PCM should not be flammable, explosive or toxic to the environment and safe to use (Wei et al., 2018).

2.3.5. Economics properties

The low cost and large-scale availability of PCMs are economically important (Wei et al., 2018).

2.3.6. Technical properties

It is expected that the selected phase change material will be technically reliable, applicable, and efficient. However, it is difficult to reach a material that will meet all the given criteria. The fact that the phase change temperature of the material is compatible with the temperature of the working environment greatly increases the function of the material as well as the latent heat capacity, leading to low costs. Moreover, PCMs' heat transmission characteristics can be improved via encapsulation method (Wei et al., 2018). Also, the summary of specifications required to use PCMs are shown in Table 2.

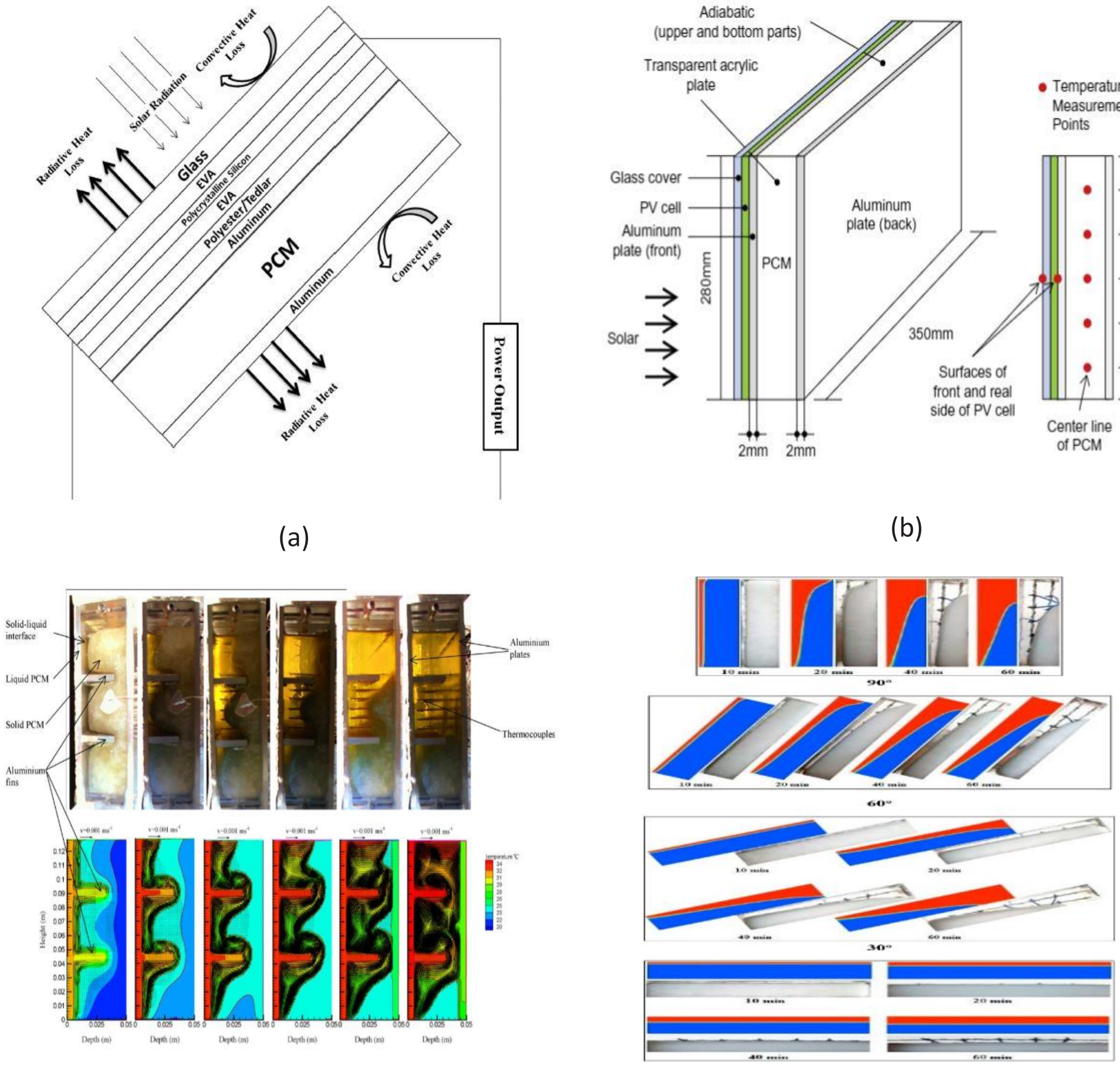
Table 2: Summary of the properties of PCMs (Leong et al., 2019).

Thermal	Physical	Kinetic	Chemical	Technical	Economics
Phase transition	Stability	Supercooling	Chemical stability	Applicable	Cost
Latent/Specific heat	Vapor pressure	Crystallization	Corrosiveness	Efficient	Availability
Thermal conductivity	Density	-	Toxicity	-	-
Melting	Volume changes	-	-	-	-

3. PHASE CHANGE MATERIALS IN PV COOLING APPLICATIONS

While some of the solar radiation amount reaching on a typical PV panel can be converted into electricity, the remaining amount is converted into heat, and this heat causes the cell temperature to increase in the PV panels. Depending on this temperature increase, a decrease in power generation and efficiency is observed. Temperatures higher than the panel's standard operating temperature (25°C) diminish its efficiency. The PCM integrated into the PV panel allows to increase the thermal performance by keeping the panel temperature at a lower level. Numerous studies have been carried out examining the thermal properties of PV panels combined with PCM. Stropnik and Stritih (Stropnik & Stritih, 2016) wanted to increase the efficiency and power output of solar panels by PCM RT28HC which has 27-29°C melting temperature range and high thermal energy storage capacity. PCM was located to the back of the module which used monocrystalline silicon solar cell. Two panels with and without PCM were simulated in TRNSYS software according to the cell temperatures, and the outcomes of the simulation were compared with the experimental data. According to the experimental studies carried out under certain climatic conditions in Ljubljana, Slovenia in October 2013, the temperature of the panel with PCM was 35.6°C, which was lower than the temperature of the panel without PCM. In addition, the annual increase in electrical energy production was 7.3%, and energy production efficiency was 0.8% compared to the panel without PCM.

Hasan et al. (2014) aim to increase the efficiency and life of the panel by keeping the temperature of the photovoltaic panel at a low level. PCM is integrated into the PV panels in order to absorb excess heat. Experiments were conducted in Ireland and Pakistan, which have two different climates. The results obtained in Pakistan were determined to be less costly. Hasan et al. (2014) investigated the relationship between the phase transition properties of the material consisting of five different (paraffin waxes, salt hydrates, and mixtures of fatty acids) PCM mixtures and the electrical efficiency of the PV panel. Differential scanning calorimetry and temperature history technique were used to measure the phase transition properties. Kant et al. (2016) have done the research of heat transmission of the panel combined with PCM. It is understood from the results that the convection effect in the molten PCM, the angle of inclination of the PV panel, and the wind velocity are important factors in the heat and mass transfer calculations of the PV panel. The heat transfer scheme is shown in Figure 4a. It has been observed that it is reached when wind velocity is 4 m/s and tilt angle of the panel is 30°.



(a)

(b)

(c)

(d)

Figure 4. (a) View of PV panel and heat transfer flow diagram (Kant et al., 2016), (b) Schematic diagram of PV/PCM layers (Park et al., 2014),(c) Melting process and predicted isotherms PV/PCM system with fins (Huang et al., 2004), (d) Different melting stages according to 4 tilt angles (Abdulmunem et al., 2021). (Permission obtained from the publisher).

Park et al. (2014) analyzed the impact of changing the PV-PCM module's installation direction, and annual electrical energy generation according to the melting temperature and thickness of the PCM were analyzed in simulation. Layers of the PV module are shown in Figure 4b. With the addition of PCM, the annual electrical power output increased by 3%, and the effect of PCM on the panel decreased due to weather conditions in winter.

Huang et al. (2004) investigated experimental and numerical simulations of PCM to reduce the temperature rise of a building integrated photovoltaic panel. They designed three different systems: a single flat aluminum plate system, a PV/PCM system without an inner fin, and a PV/PCM system without an inner fin. The PCM melting process and the predicted isotherms are shown in Figure 4c. According to the results, the metal fins ensured homogeneous temperature distribution in the PCM container, but the increased number of fins may restrict the movement of the molten PCM.

Abdulmunem et al. (2021) researched the effect of the solar radiation amount reaching the panel surfaces which have different tilt angles on the melting performance of the PCM. Four different tilt angles (0°, 30°, 60°, and 90°) were considered in numerical modeling and experiments. According to the results, it was seen that the melting process time of PCM decreased as the angle of tilt increased. The time-varying solid-liquid transition according to different tilt angles is shown in Figure 4d. As a result, the PV cell temperature decreased between 0.4%-12%. It was understood that the cooling performance decreased at lower tilt angle.

Abdelrahman et al. (2019) experimentally studied the effect of PCM (RT35HC) and PCM mixed with nanoparticles (Al_2O_3) on the temperature attitude of the PV panel front surface in order to develop the performance of photovoltaic cells. Three different configurations (11, 18, 22 fins) of heat sink and thermal conductivity enhancing cylindrical fins placed inside the PCM tank were made. The results revealed that cylindrical fins with PCM caused 20-46.3% temperature drop in front surface temperature.

Bayrak et al. (2020) conducted an experimental investigation to determine the system performance effects of PCM, thermoelectric and aluminum fins, which are cooling techniques. It was seen that as aluminum fin number and thermoelectric components on the back-side of the panel increased, the panel's surface temperature decreased. The output power of the panel was increased 2.14% by using the cooling system with fins and 7.72% by using thermoelectric modules. Senthil Kumar et al. (2021) designed a cooling system to see the effects of temperature drop in PV panel on the efficiency of the panel according to Indian climatic conditions. The thermal conductivity of PCM was increased by mixing with copper and silicon carbide powders. Two prototypes were created to evaluate the effect of the prototypes. With the use of integrated PCM, the average temperature of the PV panels was decreased by 4°C- 5.4°C, and the electrical efficiency was increased by 3% on average.

Lu et al. (2018) numerically and experimentally discussed the heat transfer property of a concentrated PV system using PCM. In the experimental study, a solar radiation intensity of 670 W/m^2 was employed with a solar simulator. Since the standard operation temperature of the PV cells is 25°C and the melting temperature of the phase change material is around this temperature, R27, a type of paraffin, was chosen as the suitable PCM. It has 25-28 °C melting temperature range, 870 kg/m^3 density value and when solid and liquid, specific heat capacity is 1.8 and 2.4 kJ/kg K respectively. As a result of the experimental measurements, it was shown that when the PCM system is integrated, it can decrease the solar-based temperature rise above 20°C, resulting in an increase of approximately 10% in the solar to electricity efficiency. Numerical simulations were made by attaching horizontal and vertical aluminum fins of different thicknesses to increase the heat transfer inside the PCM. These fins have been observed to improve the thermal performance of the PCM system, and the vertical fin system has been shown to reduce the temperature of the PV system by 25°C compared to the PV without PCM.

Hasan et al. (2017) evaluated the year-round energy-saving capacity of a PV/PCM system in the United Arab Emirates with an extreme hot environment. The use of paraffin based RT40 phase change material was deemed appropriate. PCM's performance has varied over the months. Using PCM, the PV temperature decreased by 13°C in April and 8°C in June. Due to the high temperature during the night in the summer, the PCM could not fully solidify. It did not get enough heat energy to melt entirely in the winter, which hampered its performance. The best performance was achieved in the milder months which are spring and autumn months. The maximum average and maximum temperature drop on the front-side of the PV with PCM are seen in October and April. Accordingly, it is seen that there is less temperature drop in winter and summer than in other warmer months. As a result, the average PV temperature at peak time dropped by 10.5°C, resulting in a 5.9% annual increase in PV power output.

Ma et al. (2018) stated that there are some unresolved problems or uncertainties in the use of PCM in PV panels and difficulties in modeling the effect of PCM. In order to examine these problems, they developed a thermal resistance model using the developed conductivity method, and as a result of the numerical simulation, it was seen that ignoring the PCM radiative and convective heat transfer would cause problems. According to the simulation of more than 300 events and the bivariate analysis, each increase in solar radiation of 100 W/m^2 results in a 5°C rise in temperature. The best performance can be attained when PCM melting temperature is higher than ambient temperature.

Atkin and Farid (2015) analyzed the thermal response of the PV-PCM system under 960 W/m^2 daylight. The experimental setup of the system is shown in Figure 5. To evaluate the system's efficiency, they made four different assumptions: case A, case B, case C, and case D. Case A is PV panel without thermal regulation, case B is PV panel with PCM which is 30 mm thick graphite on the back, case C is case PV with finned heat sink located to the back, and case D is PV panel case with a pair of PCM infused graphite and finned heat sink. The schematic illustration of the cases is shown in Figure 5. Case D was the most efficient at increasing the overall efficiency of the PV panel, with the largest efficiency increase of 12.97%. Analyses to improve efficiency show that PCM-based thermal regulation needs to be used with heat sinks if it is to be an effective method to become viable.

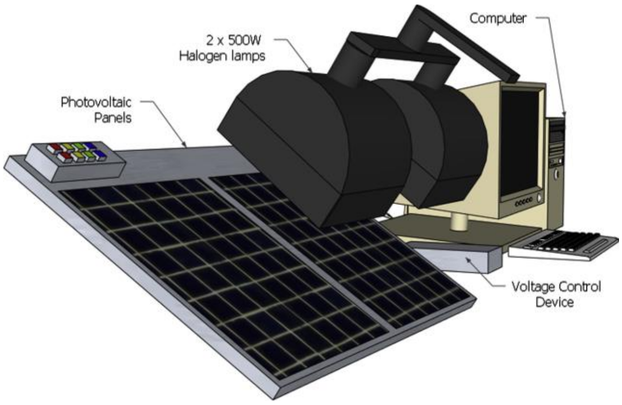


Figure 5: Experimental setup of PV system (Atkin & Farid, 2015). (Permission obtained from the publisher).

Tan et al. (2017) showed the effect of fins inside the PCM on efficiency and power output by examining finless, 3, 6, and 12 fin configurations in a PV/PCM system under unreal environment conditions.

The PCM used in the study is paraffin wax (RT27) which has a melting temperature of 27°C, is non-corrosive, has a high latent heat storage capacity (184 kJ/kg) and is suitable for use in this system. Since the thermal expansion of the PCM in liquid state at 40°C was approximately 16%, to permit for thermal expansion during heat removal, paraffin wax was charged to 80% of the enclosure capacity. According to the experimental results, the highest panel temperature was seen in the PV panel without PCM, that is, naturally cooling, while the lowest temperature was noticed in the 12 fins PV/PCM system. Compared with the inherently cooled PV system, the maximum temperature was 15, 13, 10, and 5°C for the 12, 6, 3 fins, and finless PV/PCM system, respectively. Increasing the number of fins resulted in a rise in the heat transfer area, which accelerate the melting of PCM. Thus, rising the number of metallic fins has a consistent effect on reducing the panel temperature.

4. APPLICATIONS OF PHASE CHANGE MATERIALS IN PV/T SYSTEMS

Photovoltaic panels are frequently preferred today due to their work under diffuse radiation ability. In practice, 15-20% of solar radiation is converted into electricity, and the remaining radiation acts as heat. In hot climate regions, PV temperature can go up to 80°C. Depending on the increase in temperature, panel efficiency decreases. With the use of photovoltaic/thermal (PV/T) systems, heat is used while the PV module generates electricity (Brahim & Jemni, 2017). Heat is transferred to the used fluid (air, water, oil) and is used in many useful applications after being transported (Yang et al., 2018). One of them is the use of hot water. Hot water is used for heating or cooling in domestic or industrial places. In air-based PV/T systems, the use of heat is provided by air. It is then used in applications such as space heating or crop drying (Laghari et al., 2020). In hybrid-based systems, solar energy is used both to generate electricity and as hot air and hot water. Its advantage is that it can be used in two different fluids and can be used in two different applications at the same time (Jarimi et al., 2016). However, the storage of this heat causes some problems. Therefore, PCMs with latent heat storage technology are used in PV/T systems. The temperature of the fluid decreases more slowly thanks to the PCM, and the fluid temperature is kept at the desired level. Thus, the efficiency of the solar thermal system increases (Islam et al., 2016).

4.1. Air Cooled PV/T-PCM Systems

Air cooling techniques are divided into two categories: Active and passive cooling. In the active method, the air is circulated behind the panel by using fans. In passive cooling, natural air flow is used without the need for extra power (Laghari et al., 2020). The thermophysical properties of air are less than that of water. However, air-based systems come to the forefront due to the use of less material and lower operating costs compared to water-based cooling (Su et al., 2017). Figure 6 shows the PCM integrated PV/T collector.

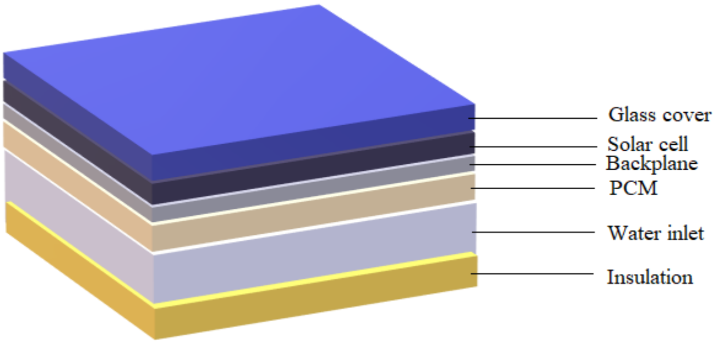


Figure 6: Layers of PCM integrated PV/T collector.

Akshayveer et al. (2021) investigated the natural air integrated PV/T-PCM system to use the heat in the PV panel. They developed numerical modeling for this system and approved it with experimental data. In addition, numerical studies have been carried out to compare the thermal and electrical behavior of PV, PCM integrated PV, and PV/T-PCM systems. The results showed that when using PCM in PV, a 25% decrease was observed in cell temperature, and 35% decrease was observed when air and PCM were integrated. The electrical efficiency of the cells was 14.12% and 19.75% for PV/PCM and PV/T-PCM systems, respectively, as a result of the temperature fall.

Lin et al. (2021) designed a laboratory-scale experiment and developed an optimization strategy under Australian climatic conditions to investigate the PVT/PCM system's electrical and thermal behavior. Analyses were made with changes in slope, air flow rate, orientation. The aim is to determine the most suitable design and test the control method. The collector has the ability to rotate 360° and adjustable inclination of 0°-35°. The air channels through which the air is used as the working fluid passes with the help of fans. The heated air was used for indoor heating. The S21 PCM material, consisting of twelve PCM bricks, was used for thermal energy storage. The efficiency of the PV/T-PCM system increased when the slope of the PV/T collector was increased and its direction was turned 0° north. The energy efficiency of the system increased from 37.6% to 40.2% compared to the non-optimized system when the optimization was made, and the daily usage rate of the thermal energy storage capacity increased from 13.3% to 79.5%.

Tariq et al. (2020) utilized suitable PCM for climatic conditions and analyzed the PV/T system based on multidimensional data, where the most suitable PCM was selected based on its environmental and economic effects. RT35HC was used for tropical savanna climate, RT28HC for hot semi-arid climate, and RT25HC PCM for highland climate regions. When using the ideal PCM, there was an increase of about 20%-24% compared to the PV/T system without PCM. The highest performance increase was in the savanna climate with regular climate changes (Tariq et al., 2020).

4.2. Water Cooled PV/T-PCM Systems

Yang et al. (2018) investigated the use of PCM in an experimental study to increase the energy production potential in a PV/T-PCM system under the influence of solar radiation. For comparison, the PV/T system was used. Firstly, power output, panel temperature, and tank water temperatures were measured to calculate the energy efficiency of the two systems. It was observed that the heat loss was reduced in the PCM integrated system. By using PCM with 800 W/m^2 radiation and 0.15 m^3/h water velocity, energy efficiency increased by 14%.

The power output increased by 7.4 W. Thermal efficiencies were 58.35% in the PV/T system, whereas 70.34% in the PCM integrated system, which indicated that the efficiency was increased by cooling the back of the panel.

Bakır et al. (2021) investigated the effect of different shading conditions on collector power and hot water output by comparing PV/T systems with and without PCM. Experiments were carried out in Turkey on days when the weather was not cloudy in July. PCM was used for hot water storage and Calcium Chloride Hexahydrate was selected. Shading conditions were compared according to three different inclination angles (25°, 30°, and 35°) According to the outcomes of the experiments, the hot water outlet temperature in the PV/T collector with PCM is 7°C higher than the one without PCM. Moreover, energy efficiencies for 25°, 30°, and 35° inclination angles were found to be 73.26%, 84.70%, and 68.96%, respectively.

Carmona et al. (2021) used a conventional PV module and a PV/T-PCM module for experimental comparison. Organic paraffin wax RT35 phase change material with a fusion temperature of 29-36°C is used because it helps the PV cells maintain a low operating temperature while achieving beneficial results. Often the charged heat is greater than the discharged heat, indicating that there is thermal energy that can be used at night. Moreover, when the heat discharged is greater than the heat charged, this is due to the temperature difference in the PCM between sunrise and sunset. As a result of the experiments, the daily electrical efficiency of the PV/T-PCM system increased by 7.43% compared to the PV module.

Browne et al. (2016) designed a PV/T-PCM system that generates electricity, stores heat and preheats water in Dublin, Ireland. In the system, a PV module is combined with a thermal collector-system, and heat is transferred from a heat exchanger linked in the PCM to the tank via a thermosiphon flow. Performance of four different systems are compared: System 1: PCM with thermal collector and thermosiphon, System 2: Without PCM, System 3: container with heat sink, and System 4: PV panel only. The results showed that the PV/T-PCM system had a greater impact on thermal performance and PCM increased the thermal energy removal from the PV up to seven times compared to a system without PCM. Moreover, it was seen that the temperature of the water in the PV/T with combined PCM system was 5.5°C higher than the system without PCM. This proved to be an influential way of storing heat for later use using PCM.

Preet et al. (2017) performed an experimental study to analyze the electrical efficiency change caused by the cooling of the PV panel. The uncooled temperature of the PV module reached 85°C, and the maximum temperature was reduced by 47% in the system without PCM, which is in the water-cooled system only, and 53% in the PV/T-PCM system. Fayaz et al. (2019) included PCM in the system to increase the thermal performance of the PV/T system. Five different PCMs were examined, and safety was determined as the most important selection criterion. Among the tested PCMs, A44 paraffin wax was preferred because of its reliability and suitable temperature range. The low thermal conductivity efficiency was ignored. In the results, PV, PV/T, and PV/T-PCM systems were compared. The maximum temperature of the PV panel was 75.6°C and 75.1°C while it was 67 and 69.3°C for PV/T, and 63°C and 64.8°C for the photovoltaic-thermal system with PCM numerically and experimentally, respectively. The maximum temperature drop was 8.3°C and 8.1°C for the PV/T system and 12.8°C and 12°C for the PV/T-PCM system numerically and experimentally. The highest efficiency was 89.9% and 88.84% for PV/T, 85.88% and 82.87% for PV/T-PCM numerically and experimentally, respectively.

Hossain et al. (2019) approved the energy, exergy, and economic performance of the system by integrating PCM into the PV/T system, and comparisons have been made according to the reference PV. The lauric acid selected PCM was placed around the flow channel. Investigation was made according to different volumetric water flow rates. According to the results, the maximum electrical output power and efficiency were achieved at a flow rate of 4 L/min. Moreover, the PV/T system efficiency was 4.72% higher when compared to the reference PV. Each 1°C decrease in cell temperature increased the output power by 8.76W and the electrical efficiency by 0.37%. The maximum thermal efficiency was 87.72% when the flow rate was 2 L/min, and the highest temperature increase was 26.40°C when the flow rate was 0.5 L/min. While the maximum exergy output of 134.10 W was obtained at 0.5 L/min, a maximum average exergy efficiency of 12.19% was seen at a flow rate of 1 L/min.

5. CONCLUSION

In this paper, the advantages and disadvantages of PCMs, the factors that are important when choosing a PCM, and the studies that enable PCMs to cool PV panels and store thermal energy in air and water-based PV/T systems are presented. From this study, it is concluded that applications that provide cooling by using heat are necessary in order to benefit from the best efficiency in photovoltaic cells and to control the increasing cell temperature. Phase change materials are one of the effective cooling techniques today. However, it is necessary to evaluate with cost management techniques whether the cost of PCM implementations exceeds the amount of savings achieved.

Carbon containing PCMs are the most often utilized photo-thermal PCMs. Introducing metal particle effects to boost light absorption or change the heat transfer mode of carbon containing PCMs is a very sensible way to solving their low efficiency. Despite its importance as a research area, however, there are comperatively less studies on this topic. This is also a promising area for discovering novel photothermal fillers.

In addition, the full compatibility of PCMs with PV systems, as well as their applicability and environmental consequences, should be evaluated.

From a cost perspective, PCM is expected to have a longer payback period as additional costs can be inquired to the established systems. On the other hand, if the energy obtained from PV panels is to be used for hot water, ventilation, heating or electricity generation, economic benefits are expected to increase. Thus, the additional costs of PCM can be ignored. Therefore, life cycle analysis and economic evaluations of PV systems should be made. Research into the creation of multifunctional energy conversion PCMs is still popular and important. More work should be done to improve the properties and efficiencies of energy conversion PCMs, as well as to increase their use.

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