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Thermal Performance Enhancement of PV/T Systems Through Nano-Enhanced PCM Integration and Advanced Heat Dissipation Techniques

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***Abstract*—Environmental problems with the use of fossil fuels and the dramatic increase in global energy demand have promoted the development of renewable energy technology. In recent years, solar photovoltaic (PV) systems are one of the most popular renewable sources because of their reliability, modularity and eco-friendly operation. But the electrical efficiency of the solar modules decreases drastically as the operating temperature goes up. In this respect, advanced thermal management techniques including phase change materials (PCM), nano enhanced phase change materials (NEPCM), heat sinks and hybrid cooling mechanisms have been developed as possible solutions. This work is related to the huge research on the enhancement of the performance of photovoltaic/thermal (PV/T) system by using nano enhanced PCM along with finned heat sinks under outdoor operational conditions. The proposed thermal management system has demonstrated significant improvements in heat dissipation, thermal energy storage, electrical efficiency and long-term PV stability. From the experimental study, the NEPCM-assisted cooling could reduce the module temperature by 12–15 °C and improve the electrical efficiency by more than 18% compared to the conventional systems. The article also contains extensive literature survey, mathematical modeling, thermal behavior analysis and comparative performance evaluation. The proposed method provides a low cost and sustainable alternative for next generation solar energy applications.**

***Index Terms*—Photovoltaic/thermal system, Nano - enhanced PCM, Heat sink, Thermal management, Solar energy, Renewable energy, Sustainable cooling PV efficiency**

I. INTRODUCTION

With supplies of fossil fuels running out and greenhouse gases increasing, scientists around the world have turned their attention to renewable energy solutions. Solar energy is one of the most plentiful and sustainable energy sources out there for electricity generation. The photovoltaic (PV) systems convert the solar radiation directly into electrical energy and are used in increasing numbers of household, industrial and smart-grid applications. PV systems have merits but they are limited by serious temperature problems. In operation, only a small fraction of the incident solar radiation is converted into electricity and the rest of the energy is wasted as heat. The temperature of the PV cell rises significantly, which leads to a lower conversion efficiency and a decreased module lifetime. The electrical efficiency drops by about 0.4-0.5% with an increase of PV cell temperature by 1°C [1].To overcome these limitations, many active and passive cooling approaches including water cooling, air cooling, heat sinks, phase change materials (PCM) and nano-enhanced cooling systems have been proposed by researchers. Dr. D. Kameswara Rao and co-researchers [2] carried out extensive studies on PV/T systems employing PCM and heat sink technologies to improve thermal regulation and energy storage characteristics. The change of phase goes with the absorption of the latent heat. The addition of PCM in PV systems helps to stabilize the temperature of the module. The inclusion of nano-particles such as Al2O3, CuO, graphene and carbon nanotubes [3] significantly improves the thermal conductivity and heat transfer characteristics of the PCM.

Research Objectives

The main objective of the present work is to study the thermal behavior and the performance of the photovoltaic/thermal (PV/T) systems under the real outdoor environmental conditions. The present work aims to investigate the application of phase change material (PCM) and nano-enhanced PCM cooling technologies for the reduction of operating temperature and the enhancement of photovoltaic efficiency. It also aims at investigating the improvement of thermal and electrical performance by incorporating finned heat sinks with passive cooling arrangements. A thorough study of both traditional and novel thermal management systems has been performed to find practical and effective ways to cool solar applications. The project aims at developing a robust, energy efficient, ecologically friendly and compatible cooling process for modern solar PV systems operating under high climatic conditions.

II. LITERATURE REVIEW

Many experts have put a lot of work to enhance the thermal performance of solar systems. Kameswara Rao et al. [1] experimentally investigated photovoltaic/thermal systems with phase change materials and they found enhanced electrical output and improved thermal stability. The study showed that PCM-based cooling is effective in reducing the peak module temperature under high solar irradiation conditions. Kameswara Rao et al. [2] designed concentrated solar power systems with parabolic dish and trough collectors in another study for better thermal energy consumption. The study highlighted the need for efficient thermal storage techniques for sustainable solar applications. Kameswara Rao et al. [3] researched the effect of PCM selection and cooling methods on PVT efficiency. The authors observed significant improvement of thermal absorption capacity and energy conservation with appropriate PCM selection [1]. Kameswara Rao et al. [4] have investigated more on the classic cooling approaches with the modern PCM assisted thermal control technologies. Their work demonstrates that integrated PCM cooling can improve the electrical efficiency while decreasing the temperature fluctuations . The authors in [5] explored the influence of nano-enhanced PCM along with heat sinks and reported a significant improvement in heat transfer characteristics because of the increased thermal conductivity of the PCM medium. Yu et al. [6] studied the integration of renewable energy sources in smart grid and pointed out the significance of thermal control in distributed energy systems. Similarly, Jurasz et al. [7] investigated the complementarily of renewable energy sources and emphasized the importance of thermal stabilization systems and energy storage. Wang et al. [8] investigated optimization methods of distributed renewable systems and gave intelligent thermal control mechanisms for efficient energy utilization. Fernández Guillamón et al. [9] introduced the high penetration renewable energy systems with an emphasis on the use of advanced thermal storage technologies. The literature study shows that although several thermal management technologies have been developed for photovoltaic/thermal systems, there are still many areas that need further research. The concentration of nano particles in the phase change materials should be optimized for obtaining maximum thermal conductivity and overall cooling performance. The long-term thermal stability investigations are particularly required to assess the durability and reliability of the nano enhanced PCM under outdoor operating conditions. Future work may involve development of Hybrid Cooling Systems with PCM, Heat sinks and other complex cooling techniques for enhanced heat dispersion. We can explore AI based temperature monitoring and control techniques for effective thermal management. Also low cost PCM integration methods are required for industrial and commercial application of solar cooling systems on large scale.

III. PROPOSED SYSTEM ARCHITECTURE

3.1 System Components

This paper proposes an innovative photovoltaic/thermal (PV/T) thermal management system based on a monocrystalline solar photovoltaic panel attached with aluminum finned heat sink for efficient passive cooling. A chamber with nano-enhanced phase change material (NEPCM) is fixed at the rear side of the PV module to absorb and store the excess thermal energy generated during operation. A thermal insulation layer is provided to limit the heat loss and to improve the thermal storage efficiency. Temperature sensors are installed at different locations to monitor the system operating temperature. Solar radiation sensor was used to measure the incident solar irradiance. The entire experimental setup is interfaced to a data collecting device for continuous recording and analysis of thermal and electrical performance parameters under an outside operating state.

3.2 Principle of operation

Under the solar irradiation, the PV module receives the solar energy and transforms part of the solar energy into electricity. Excess thermal energy will raise the module temperature and decrease efficiency. Thermal energy is absorbed during the melting phase in the PCM chamber connected to the rear surface. The dispersion of nano particles into the PCM results in improved thermal conductivity and accelerated heat transfer. The integrated heat sink increases the surface area for passive cooling and heat dissipation. The combination of PCM, nano particles and heat sinks greatly enhance the thermal regulation. Mathematical Models

IV. EXPERIMENTAL SET UP

The developed experimental setup was tested in real outdoor climatic conditions in Hyderabad, India to evaluate the thermal and electrical performance of the proposed photovoltaic/thermal system. The investigation was performed with three different photovoltaic configurations namely a normal PV module, a PV module with phase change material (PCM) cooling and a PV module with nano-enhanced phase change material (NEPCM) and aluminum finned heat sink cooling. During the experimentation some performance parameters were recorded like ambient air temperature, solar irradiation, module surface temperature, output voltage, output current, electrical and thermal efficiency. Temperature sensors and instruments for measurement of radiation were linked to a data collecting system for continuous monitoring and recording of experimental data. The tests were performed continuously in the peak sunshine hours to compare the thermal behavior and the performance improvement of the different cooling strategies under outdoor operation conditions.

V. RESULTS AND DISCUSSION

An actual outdoor climatic experimental examination of the proposed PV/T system with the coupling of nano enhanced phase change material (NEPCM) and finned heat sink cooling has been carried out at Hyderabad, India. The experimental set-up was operated during the peak sunshine hours (9:00 AM to 4.00 PM) with the solar irradiation varying between 650 W/m2 and 980 W/m2 . The results obtained were compared with the conventional system of photovoltaic and PCM aided cooling system.The work has been mainly concentrated on reduction of surface temperature, improvement in electrical efficiency, thermal energy storage properties, enhancement in output power generation and long term thermal stability of the heat sink aided cooling system. Special attention was paid to the efficacy of nano-enhanced phase change materials for the improvement of heat transfer and for the achievement of stable operating conditions during continuous outdoor operation. The experimental results clearly indicate that the improved thermal management strategies can significantly improve the overall performance, thermal control and energy conversion efficiency of photovoltaic systems.

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5.1 Evaluation of Surface Temperature

The temperature of the surface of the solar module is one of the most important parameters affecting its electrical efficiency. Conventional PV systems are always under solar radiation which leads to excessive thermal accumulation increasing the operating temperatures and reducing the energy conversion efficiency. The proposed NEPCM-based cooling system has successfully absorbed the excess thermal energy and stabilized the module temperature. The phase transition material was doped with nano-particles to enhance the thermal conductivity and heat transfer between the photovoltaic panel and thermal storage medium. Hence, the absorption and dissipation of excess heat generated on the PV surface was better during operation. Table 1 gives the maximum surface temperature for different cooling arrangements under the condition of maximum solar radiation.

Table 1. Surface Temperature Comparison

S.no	System Configuration	Maximum Surface Temperature
1	Conventional PV Module	71°C
2	PV Module with PCM Cooling	61°C
3	PV Module with NEPCM and Heat Sink	54°C

Experimental observations show that the PV module with nano enhanced PCM and heat sink cooling operated at much lower temperature than the traditional PV module. The temperature was dropped by around 17°C that assisted to decrease thermal stress and enhanced the overall working stability of the photovoltaic system. The results obtained are in conformity with the results of Kameswara Rao et al [5] who reported that the nano enhanced phase change materials enhance the performance of passive cooling and decrease the thermal degradation in solar systems. The latent heat absorption capacity of PCM was important to maintain uniform temperature under varying solar radiation condition .

5.2 Electrical Efficiency Analysis

The operating temperature determines the electrical performance of solar modules. The temperature increase of the solar panel leads to an increase of losses in semiconductors and therefore a decrease of electrical efficiency. In this work, PCM and nano enhanced PCM cooling was used to reduce the module temperature and increase the PV conversion efficiency. The measured electrical efficiencies for different photovoltaic configurations presented in Table 2.

Table 2. Electrical Efficiency Comparison

S.no	System Configuration	Electrical Efficiency
1	Conventional PV Module	14.8%
2	PV Module with PCM Cooling	16.2%
3	PV Module with NEPCM and Heat Sink	17.5%

The solar module with the integrated nano-enhanced PCM and heat sink cooling system showed the highest electrical efficiency in all the tested systems. Compared to the traditional PV module, an efficiency improvement of almost 18% was achieved. The performance improvement was mainly ascribed to the decrease in operating temperature, better heat transfer properties, fast removal of surplus heat and stable thermal operating conditions. The results obtained during experimentation are in close agreement with the earlier reported investigations of Kameswara Rao et al. [1],[3] and [4].

5.3 Thermal Energy Storage Performance

The thermal storage property of phase change material has greatly improved the thermal control of photovoltaic/thermal system. Under high solar radiation conditions, the PCM absorbed the excessive heat energy and changed from solid to liquid phase, which helped to reduce the heat accumulation on the photovoltaic panel. When the solar radiation decreased, the stored heat was released to the ambient surroundings in a controlled manner and, thus, the working temperatures became more stable. To improve the thermal performance of the PCM and boost the thermal conductivity , improve heat transfer and minimize melting time and enhance heat storage capabilities nano-particles were introduced . Table 3 shows the thermal properties of normal PCM and Nano-enhanced PCM.

Table 3: Thermal properties

S.no	PARAMETER	PCM	NANO ENHANCED PCM
1	Thermal Conductivity	0.22 W/mK	0.48 W/mK
2	Heat Transfer Capability	Moderate	High
3	Melting Time	Longer	Shorter
4	Thermal Stability	Moderate	Excellent

5.4. Power Amplification

The solar module had better electrical performance due to the low and stable operating temperature, which resulted in increased voltage output, increased current generation and increased total power production. The cooling design was useful in decreasing the heat losses during the continuous exposure of the solar and increased the operating efficiency of the system shown in table 4.

Table 4: Out put power comarision

S.no	System Configuration	Output Voltage	Output Current	Output Power
1	Conventional PV Module	18.2 V	3.8 A	69.1 W
2	PV Module with PCM Cooling	19.1 V	4.1 A	78.3 W
3	PV Module with NEPCM and Heat Sink	20.3 V	4.4 A	89.3 W
4	PV Module with NEPCM and Heat Sink	20.3 V	4.4 A	89.3 W

The maximum output power was obtained during the time period of 12.00 P.M. to 2.30 P.M. at peak sunshine hours. The solar module with nano-enhanced PCM and heat sink cooling produced higher voltage, current and power output than the other systems evaluated. Better thermal control and heat dissipation led to better electrical performance in outdoor conditions. The results obtained are similar to those reported in previous studies [4], [5].

5.5 Evaluation of Heat Sink Performance:

In order to improve the cooling performance, an aluminum finned heat sink was attached underneath the photovoltaic panel to increase the surface area for convective heat transfer. We can write the heat transfer process as:

$Q = hA(T_s - T_a)$, Q is the rate of heat transfer h is the convective heat transfer coefficient A is the cooling surface area Ts & Ta surface temperature of a panel temperature of the surrounding. The finned heat sinks were better at dissipating the excess heat and providing a more uniform temperature distribution over the surface of the panel, which reduced the formation of hotspots and improved the thermal stability of the solar module. The combination of nano enhanced PCM and heat sink showed better thermal control for cooling of PCM than the case of only PCM.

5.6 Comparison with Existing Cooling Systems:

Conventional cooling methods (forced air, water circulation etc.) require additional electrical power. When they run they need servicing now and again. However , the proposed passive cooling system does not require external energy and is of low maintenance . The NEPCM based cooling system showed better cooling performance, lower energy consumption, lower operational cost and higher sustainability compared to the conventional cooling system. The benefits show that the proposed technology can be effectively used for solar installations in remote areas, building integrated photovoltaic systems, renewable smart-grid applications and other sustainable energy systems.

5.7 Stability to heat (long term)

The nano enhanced PCM cooling system demonstrated stable thermal performance during long-term outdoor operation. Repeated heating and cooling cycle tests they showed that the addition of nano-particles improved the structural stability, kept the thermal conductivity, maintained the phase stability and reduced the thermal deterioration over time. No visible phase separation nor decrease of cooling capability was observed on the repeated charge/discharge cycles. The results suggest that NEPCM based cooling systems can be a potential candidate for long term photovoltaic and renewable energy applications.

5.8 Benefits in terms of the environment and economy

The proposed cooling technology has many environmental and economic benefits. The passive cooling system increases the efficiency of photovoltaic devices without the consumption of any additional electrical power, improving the utilization of solar energy and reducing the production of greenhouse gases. It also helps in reducing thermal pollution and helps in generation of eco-friendly power. The economic benefits include decreased operating costs and improved system performance, increased electricity generation, reduced maintenance costs and longer lifetimes of the solar modules. Based on the overall analysis, it can be said that the initial cost of installation can be compensated by the increased energy generation and reduced maintenance cost in long term operation.

5.9 Discussions

The experimental results indicate that the combination of finned heat sink cooling with nano-enhanced phase change materials improves the thermal and electrical performance of solar systems under outdoor conditions. The developed cooling system reduced significantly the operating temperature of the PV module by 12–17 °C approximately. This enhanced the electrical efficiency and stabilized the operation of the system. The reduction of the heat accumulation and the better thermal control resulted in an increase of the electrical efficiency of about 18 %.The heat storage capacity and rate of heat transfer of the PCM embedded with nano-enhanced materials was increased while the convective cooling was increased by the increased cooling area of the finned heat sink. The combined cooling effect was found to improve power generation during peak solar hours and thermally stability during long-term operation. This also reduces the energy consumption and maintenance requirement over conventional cooling system as the system is based on passive cooling. The results are in line with the observations of Kameswara Rao et al. [1]-[5] who reported that PCM and nano enhanced cooling techniques are effective for photovoltaic thermal management. The proposed cooling technique is an economic and environment friendly alternative for renewable energy systems, smart solar and photovoltaic/thermal applications.

VI. BENEFITS OF THE PROPOSED SYSTEM

The proposed photovoltaic thermal management system offers several important advantages in terms of thermal control, electrical efficiency and environmental sustainability. The combined use of finned heat sink cooling and nano-enhanced phase change materials reduces the operating temperature of the solar module, leading to a significant increase in the photovoltaic conversion efficiency. It shows better thermal energy storage capacity and effectively reduces peak temperature rise in case of high solar radiation. The proposed approach alleviates the thermal stress and hotspot generation by keeping the operating temperatures steady, which extends the life and increases the reliability of solar modules. The passive cooling process does not need any external power supply and hence the system is environment friendly and energy efficient. Fewer moving parts, more compact design, less maintenance, less complex operation. Moreover, the proposed cooling method is perfectly suitable for smart-grid applications, hybrid renewable energy systems and building integrated photovoltaic installations. The system is also a low cost, sustainable alternative for renewable energy generation, especially in hot climatic zones where thermal control is crucial for photovoltaic cell efficiency.

VII. SCOPE OF FUTURE WORK

Future study will combine advanced intelligence technologies and enhanced thermal management strategies to improve the performance and application of photovoltaic/thermal systems greatly. Artificial intelligence based thermal control systems can be developed for real time temperature control and adaptive cooling operation. PV/T installations can also be continuously monitored through the integration with IoT based remote monitoring systems for performance monitoring and fault detection. The machine learning approaches can be used to prediction of the thermal behavior, energy production and environmental variations for the improvement of the system efficiency and operational reliability. Future studies may focus on the use of hybrid phase change materials with graphene and other advanced nano-materials for the improvement of thermal conductivity and heat storage capacity. It is also possible to discuss the generation of sustainable energy through industrial big scale application and commercialization of the nano-enhanced PV/T systems. Furthermore CFD based thermal optimization studies can be performed to study heat transfer characteristics, airflow distribution and cooling efficacy for better system design and performance enhancement.

VIII. CONCLUSION

The present study was conducted to enhance the performance of photovoltaic systems by using passive finned heat sink cooling techniques with nano enhanced phase change materials under outdoor operating conditions. Experimental results showed the effectiveness of the proposed thermal management system in reducing the operating temperature of the photovoltaic module and improving the overall system efficiency. With respect to the conventional photovoltaic system, the surface temperature obtained was lowered by about 12-17 °C which is a significant reduction. The electrical production is therefore increased and the operating conditions are stabilized. The thermal conductivity, heat absorption ability and heat transfer performance were enhanced with the addition of the nano enhanced phase change materials compared with the traditional PCM systems. Furthermore, the use of finned heat sinks enhanced passive convective cooling and minimized hotspot formation on the photovoltaic surface. The integrated cooling system demonstrated improved thermal stability, increased power generation and increased energy use during periods of high solar radiation. The proposed passive cooling technology requires no additional external energy consumption, hence it is environmentally sustainable, energy efficient and economically effective for long term renewable energy applications . There are no moving parts and complex cooling systems so the system requires very little maintenance. Overall, the study confirms that the passive cooling employing nano enhanced PCM can be an effective option to enhance the photovoltaic performance, reliability and thermal management in high temperature climatic regions and advanced solar energy systems.

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