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Performance Improvement of Solar PV Cells Using Phase Change Material

Shivam Sharma[1], Deepesh Singh Gehlot[2]

[1,2]Department of Mechanical Engineering, LNCT Indore, Madhya Pradesh, India-452003

Abstract - Solar energy is widely used for electricity generation through photovoltaic (PV) cells. Although PV cells absorb nearly 80% of incident solar radiation, only a small fraction is converted into electricity because of their low conversion efficiency. In hot climatic conditions, the operating temperature of PV panels rises significantly, resulting in reduced performance. This study aims to investigate the factors affecting PV cell temperature and to enhance electrical efficiency using passive cooling techniques based on Phase Change Materials (PCM). Numerical simulations were conducted in ANSYS Fluent 19.2 for three systems: PV only, PV/PCM, and PV/T-PCM (Thermal PCM). The solar panel was installed at an inclination angle of 25° to the horizontal. Annual average solar flux, ambient temperature, and wind speed data for Indore has been obtained from the PVGIS solar database. The SIMPLE algorithm and PRESTO method were applied with a time step of 0.1 s for model solution.

The results indicate that the temperature of the PV-only system reached 118.23°C after 2 hours. This temperature was reduced by 15.60°C and 30.97°C for PV/PCM and PV/T-PCM systems, respectively. The efficiency of the PV cell increased from 6.65% for the conventional PV panel to 8.59% with PV/PCM and 10.23% with PV/T-PCM. These findings demonstrate that PCM-based passive cooling significantly reduces PV temperature and improves overall electrical performance.

Keywords: Phase Change Material, Photovoltaic Cells, Natural Convection, Solar Energy, Ansys Fluent.

1.0 INTRODUCTION

Solar photovoltaic systems are increasingly adopted for clean power generation. However, only a portion of incident solar radiation is converted into electricity, while the remaining energy appears as heat, increasing module temperature. Higher PV temperature reduces voltage output, accelerates material degradation, and lowers overall efficiency. Conventional active cooling methods such as water circulation and forced air improve performance but increase cost, maintenance, and auxiliary power demand. Passive cooling techniques offer a practical alternative. Among them, Phase Change Materials (PCM) absorb excess heat through latent heat storage during melting, limiting PV temperature rise. Further enhancement can be achieved by integrating an air duct that promotes natural convection [1-2]. In this study cooling of PV cell by using Phase change Material is simulated for 2 hours the Solar panel is placed in optimum inclination of 25◦ to the horizontal as per the geographical location of Indore, India as shown in figure 1. Two different configurations are used for this experiment in the first combination PCM is attached to the backside of the PV cell which is represented as PV/PCM and in the second combination additional to PCM air passage is also introduced to remove the heat by natural convection represented as PV/T-PCM. RUBUTHERM 35-HC is selected as PCM and the effects of conventional currents on melting rate are studied. The variation in operating temperatures and the change of PV efficiency is studied for both the systems and results are compared to check the effectiveness of systems.

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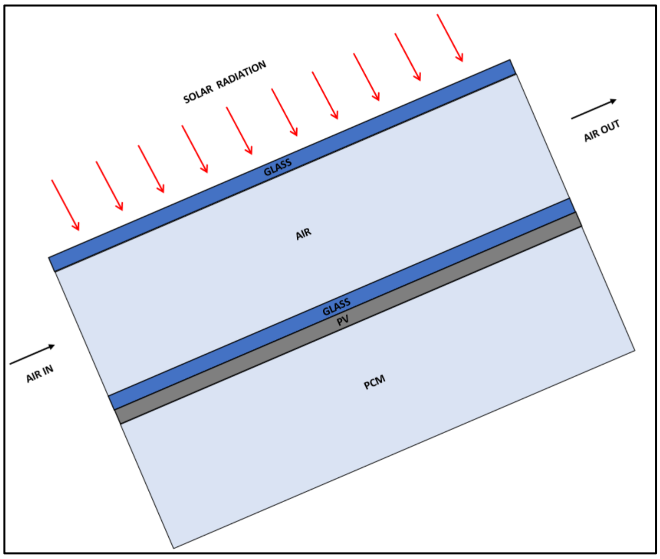

Fig. 1. Schematic Diagram of Natural convection through PV/T-PCM

1.1 Literature Survey

S.Verma et al. has discussed various methods for cooling of the Solar PV Cell concentrating mainly on two reasons that are to enhance the working efficiency of the Solar PV Cell and to increase the life span of the Solar cell. The cooling methods that are briefly discussed in this study are Heat sink, heat pipe, PCM material based, micro channel, thermoelectric (Peltier) [3]. T. Kozak et al. studied the influence of the ambient air on the efficiency of the Solar PV Cell though there are many other methods to cool the Solar PV Cell they require some initial cost or operation costs for working so they investigated the ambient air [4]. Sellami.A et al. has modelled a heat transfer in a PCM and studied the performance of two approaches in the first approach they have considered the conduction mode of heat transfer and in the second approach additional to conduction they also considered the natural convection mode of heat transferred which has occurred during the melting of the PCM [5]. H. Liu et al. has developed a model of metal honeycomb structure which is sandwiched between the fluids and then performed the numerical simulation to prove that honeycomb structure can be used to enhance the heat transfer efficiency [6]. Furkan Dincer et al. studied the different factors that are affecting the efficiency of solar cells such as Cell Temperature, Energy Conversion Efficiency and Maximum power point tracking [7]. Mittleman et al. conducted a scaling and numerical analysis of combined convection and radiation heat transfer in inclined 2D channels with uneven heating and for their application in thermal management of rooftop PV panels. Based on the experiment performed it is said that the cooling rate increases monotonically with an increase in channel spacing [8]. Ilya et al. have experimented on the modelled battery pack whose side walls are fixed with the Phase Change Material (PCM) and the results show that for longer cycles and medium cycles the drop in the peak temperature is 4^0C and 13^0C respectively. The study also suggests that the thermal conductivity of the PCM can also be enhanced by using thermally conductive structures [9].

1.2 Research Objective

By the study of the literature review, it has been observed that most of the research related to the cooling of Solar PV cells is carried either by using different types of PCMs, enhancing thermal conductivity of the PCM by using Nano-particles or by using some external sources (passive cooling) such as fans, water pumps etc. but study done on cooling the Solar PV Cell by modifying the architecture of the solar panel along with the use of PCM is limited. The present work is aimed to bridge the aforesaid gaps. The objectives of the work are as follows:

- Evaluation of operating temperatures of PV cells in different cases of an only PV cell, PV/PCM, Air PV/T-PCM.
- To see the effect of real-time atmospheric conditions like Solar flux, ambient temperature, wind velocity and inclination of the Solar panel.

2.0 Modelling and Methodology

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The numerical methodology was developed to compare thermal behavior and efficiency of three PV cooling configurations under identical operating conditions. A transient CFD approach was selected because solar heating, PCM melting, and natural convection are time-dependent phenomena.

Three systems were modelled:

- Conventional PV module
- PV module with backside PCM layer (PV/PCM)
- PV module with air passage and PCM layer (PV/T-PCM),

The module was inclined at 25° to the horizontal. Standard multilayer PV construction consisting of glass, EVA, silicon cell, Tedlar, and frame was considered.

2.1 PCM Selection

Rubitherm RT35HC was selected because its phase change temperature range is suitable for PV operating conditions. It possesses high latent heat capacity and stable thermal behaviour [10].

2.2 Simulation Conditions

Simulations were conducted in ANSYS Fluent 19.2 using a pressure-based transient solver [11]. SIMPLE pressure-velocity coupling and PRESTO pressure interpolation were employed. Time step size was 0.1 s.

Boundary conditions:

- Solar heat flux: 900 W/m^2
- Ambient temperature: representative summer conditions
- Natural convection from exposed surfaces
- Two-hour simulation period

2.3 Governing Equations

Some of the important governing equations used in this study are shown below:

Mass Conservation Equation:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0 \qquad (1)$$

Momentum Conservation Equation:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla\cdot(\rho\vec{u}\cdot\nabla) = \nabla\cdot(\mu\nabla\vec{u}) - \nabla P + S \qquad (2)$$

Where S is called the Source term which further consists of two terms Boussinesq term

$[\ \rho g\beta(T - T_0)]$ and Darcy term $[-\frac{C(1-v_l)^2}{v_l^3+\epsilon}\vec{u}]$ (3)

Boussinesq model approximation:

$$(\rho - \rho_0)g \sim \rho_0\beta(T - T_0)g \qquad (4)$$

The criteria to use this model is the temperature difference should be low and satisfy

$$\beta(T - T_0) \ll 1 \qquad (5)$$

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$$\rho = \frac{P_{op}}{\frac{R}{M_{\omega}}T} \quad (6)$$

The energy conservation equation that is solved for liquid PCM and air region is:

$$\frac{\partial(\rho C_p T)}{\partial t} + \nabla \cdot \left(\rho C_p \vec{u} T\right) = \nabla \cdot (k\nabla T) - \frac{\partial(\rho v_l h_f)}{\partial t} \quad (7)$$

2.4 Boundary Conditions

At time t = 0, $T = T_\infty$

T_∞ = 300 K

Initially, The Solar Panel And PCM Is Assumed To Be At Ambient Temperature. On The Topmost Surface (Glass) Of The Solar Panel Constant Solar Irradiation Of 900W/M^2 Is Made To Incident.

No-Slip Condition – At The Walls Of Air Duct And PCM

The Sidewalls Of PCM Are Considered To Be Adiabatic Walls (Q" = 0 W/M^2)

The Top Layer And Bottom Are Open To The Atmosphere So Convection Heat Transfer Is Considered As $h = 5.7 + 3.8v_\infty$ W/M^2, Where The Velocity Of Air Becomes Zero Due To The Assumption Of Stagnant-Air Condition.

The Air Inlet Condition Is Stagnation Inlet And The Air Outlet Condition Is Stagnation Outlet Since At Both Interfaces Air Is At Ambient Condition.

To Solve The PV/T-PCM Air Acts As A Medium To Transfer Heat For Which DO Radiation Model With The Coupled Condition Is Used And Other Default Values Are Kept Constant.

The Solar Panel Has Different Layers And The Resistance Between The Layers Is Neglected.

Between The Interfaces Of Different Layers In Solar Panel Heat Transfer Takes Place Through Conduction But For Air And PCM Both Conduction And Convection Take Place. Mushy Constant (C) For Solidification And Melting Model Is Taken As C = 1000000.

For PCM Solidus Temperature = 307 K

Liquidus Temperature = 309 K

Viscosity = 0.0044 Kg/M-S (Constant)

2.5 Mesh Generation

ANSYS Fluent 19.2 Uses The Set Of Governing Equations And Solves The Model Numerically By Using The Finite Volume Method. A Different Number Of Meshes Is Generated By Changing The Different Parameters Like No Of Edges And The Calculations Are Used To Evaluate The Grid Independence Test Which Is Discussed Later In The Same Section. The Mesh Generation For Plane Objects Is Relatively Easy Which Can Be Done By Using The Face Meshing In Face Meshing Quadrilateral Elements Are Formed But Coming To The Assembly Meshing Such As Solar Panel It Is Difficult To Generate The Mesh Because It Has Many Contact Points And Surfaces Which Have To Be Taken Care Of For This Meshing Tools Like Patch Confirming Method, Edging, Refinement, Automatic Method Were Made Use To Get The High-Quality Mesh In Patch Confirmation Method Tetrahedrons Mesh Elements Are Formed Which Give Good Result But It Also Increases The Computing Time It Is Always Necessary To Check The Quality Of The Mesh To Get A Better Result. The Solar Panel Assembly That We Have Modelled Has 160882 Nodes And 71987 Elements (Figure 2).

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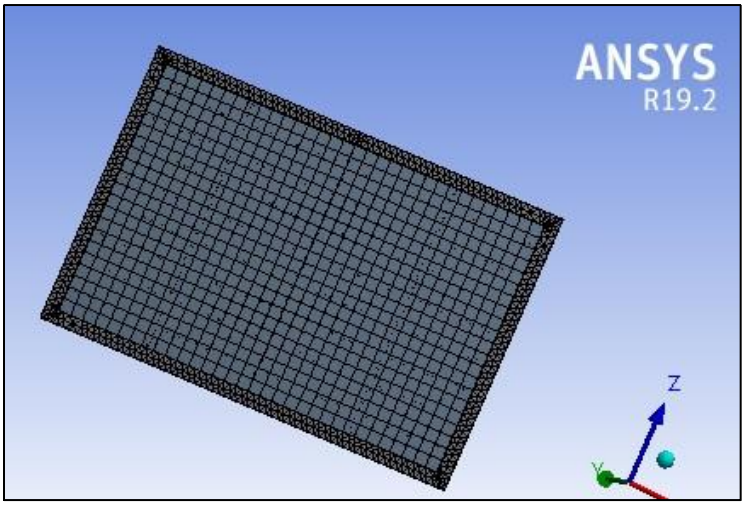

Fig. 2. Meshing of assembled Solar panel

3.0 Results and Discussion

The experimental simulation for Solar Panel using Transient Thermal is validated against the previous results of the W Z Leow et al. [12], where the transient thermal simulation is done on the solar panel assembly by using the ANSYS software. The boundary conditions used in the experimentation are Solar heat flux is taken as 900W/m^2 and is incident on the topmost surface (glass) of the Solar panel and the ambient temperature is taken as 35℃. This simulation is performed for the period of 3600 seconds and the maximum temperature of the surface of the assembled solar panel is taken considering the wind velocity of the ambient atmosphere as 0.43m/s. the maximum temperature of the surface of the Solar panel obtained is 88.239℃.

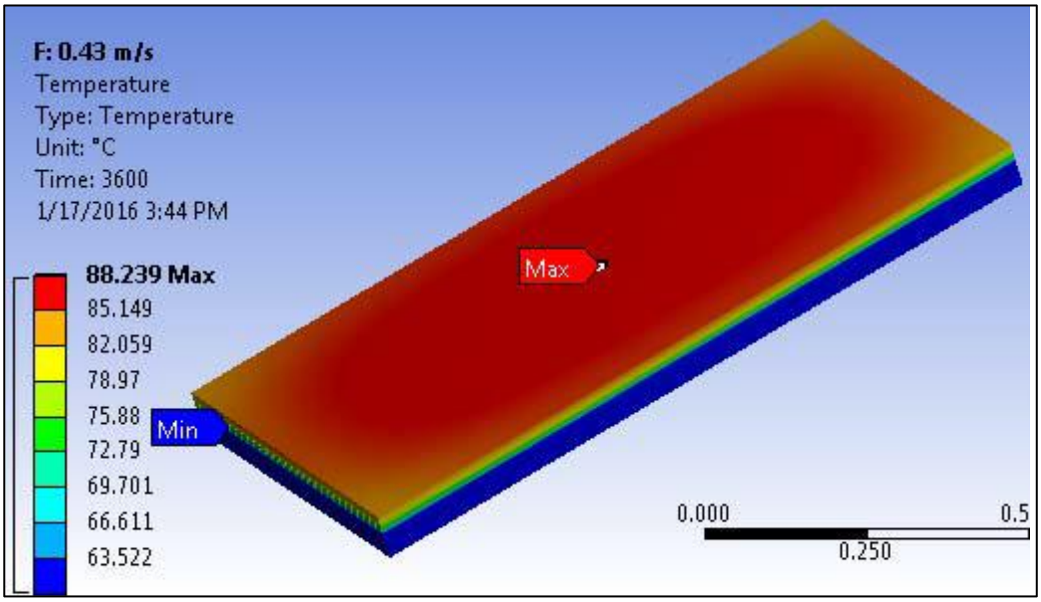

Fig. 3. Temperature distribution of Solar panel model after 3600 seconds

To validate the simulation similar boundary conditions are taken as in W Z Leow et al literature [12] and simulation is performed for 3600 seconds using Transient Thermal simulation and the maximum temperature that has been obtained is 84.94 ℃.

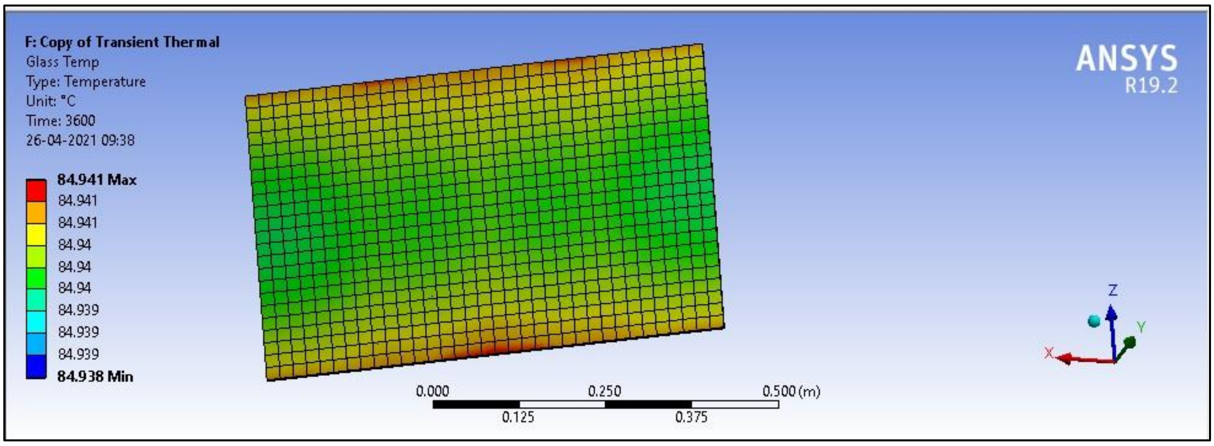

Fig. 4. Temperature contour of Solar Panel after 3600 sec using Transient Thermal condition

$h_c = 12.12 - 1.16V + 11.16V^{0.5}$ h_c = Heat transfer coefficient (W/m^2K)

V = 0.43m/s [12] V = Velocity (m/s)

$h_c = 19.23$ W/m^2K

Validation results of temperature

	Temperature
W Z Leow et al [12]	**88.239^{0}C**
Present Results	**84.941^{0}C**

The magnitude of error obtained between the validation paper and the obtained results is about 3.73%. The reason for the error is slight variation in thermo-physical properties of different layers of the solar panel and the accuracy of the meshing method because the results get vary based on the type and number of meshing elements and by the magnitude of percentage error obtained, we can conclude that the experimental simulation has been conducted in accordance to that of mentioned in the literature paper.

3.1 Simulation of PV/T-PCM system

For this simulation a 2D model consisting of air passage between two glasses, PV cell and PCM is created and constant heat flux of 900W/m^2 is incident on the surface of the top glass for 2 hours and the heat radiation to reach PV cell it has to pass two layers of glass and a layer of air so to solve this model Discrete Ordinate Radiation Model has been considered because gases (air) also produce some radiation because of the high-temperature difference between glass and air. From this simulation Liquid fraction of PCM, Air outlet temperature, PV temperature and mass flow rate of the air at the outlet are obtained and the results are tabulated in Table 1 and this simulation is continued for real-time simulation of 2 hours.

Table 1. Results for simulation of PV/T-PCM

Time (minutes)	**Maximum Air-outlet temperature (^{0}C)**	**liquid-fraction**	**Mass flow rate (kg/s)**	**PV Cell temperature(^{0}C)**
0	27.0000	0.00000	0	27.0000
10	91.8458	0.00001	6.28E-06	33.0183

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20	100.3791	0.02939	1.94E-05	37.6925
30	100.4763	0.08457	3.10E-05	42.0211
40	100.4820	0.15978	4.59E-05	45.2751
50	85.8019	0.23594	2.59E-05	49.7685
60	94.3668	0.31766	1.61E-05	54.2491
70	107.0641	0.40248	1.69E-05	57.5658
80	105.8924	0.48846	1.63E-05	60.2963
90	106.3676	0.57388	1.53E-05	62.6024
100	106.7334	0.65271	1.34E-05	65.0250
110	107.1672	0.72116	1.02E-05	68.0599
120	107.5708	0.77867	6.36E-06	71.7247

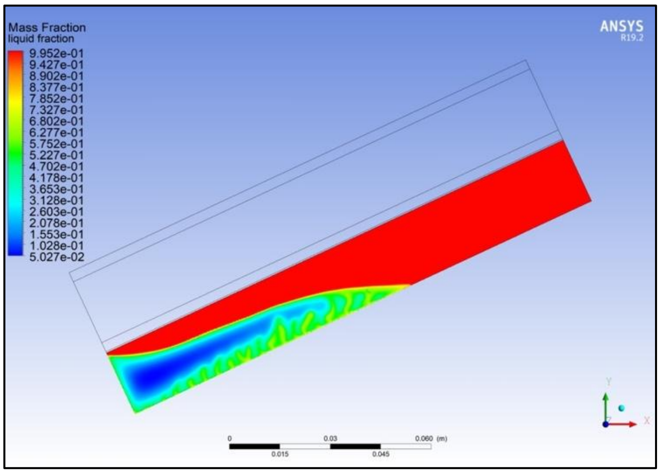

Fig. 5. Liquid fraction contour of PCM in PV/T-PCM system after 2 hours

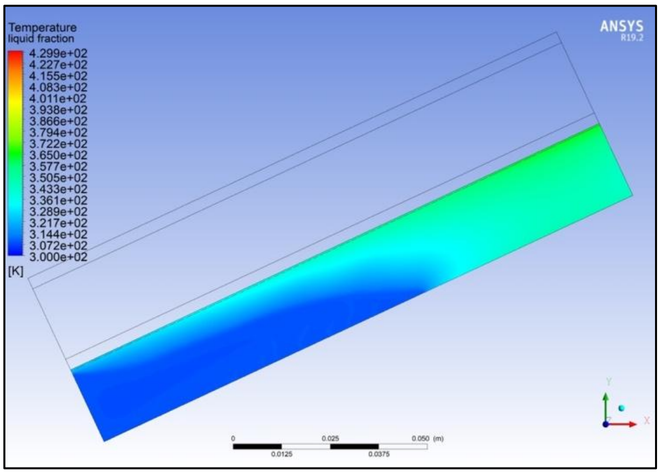

Fig. 6. Temperature contour of PV and PCM in PV/T-PCM system

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At the end of the simulation liquid fraction of PCM is 0.7786 which says that 77.86% of the PCM is in liquid form whereas the maximum air outlet temperature obtained is 107.57 °C and the temperature of the PV panel is 71.72 °C as shown in figures 5 & 6.

3.2 Comparison of Results

3.2.1 PV Cell Temperature

Variation in temperature of PV cell with respect to time for different systems is shown in figure 7. When the constant heat flux of 900W/m^2 is directly incident on the PV cell the temperature of the PV cell rises rapidly as it doesn't have any heat sink so that heat can be removed from it and during this the maximum temperature reached is 118.23℃. When PCM is added to the PV cell which is also called as PV/PCM system the temperature of the PV cell is reduced to 102.39℃ because more amount of heat is absorbed by the PCM which is fixed right beneath the PV cell by adding the PCM there is a temperature drop of 15.84℃. Further adding the Natural convection Air passage, the temperature of PV cell reduces to 71.72℃ because some more amount of heat from the radiation is taken away by the air by the process of Natural convection where the air gets heated and its density decreases with an increase in temperature and due to density difference buoyancy forces are developed in the air passage pushing away the hot air through the outlet zone. By adding the air passage (PV/T-PCM) system the temperature further decreased by 30.97℃. A temperature drops of 13.39% and 29.95% is observed in PV/PCM and PV/T-PCM systems respectively when compared to the only PV cell.

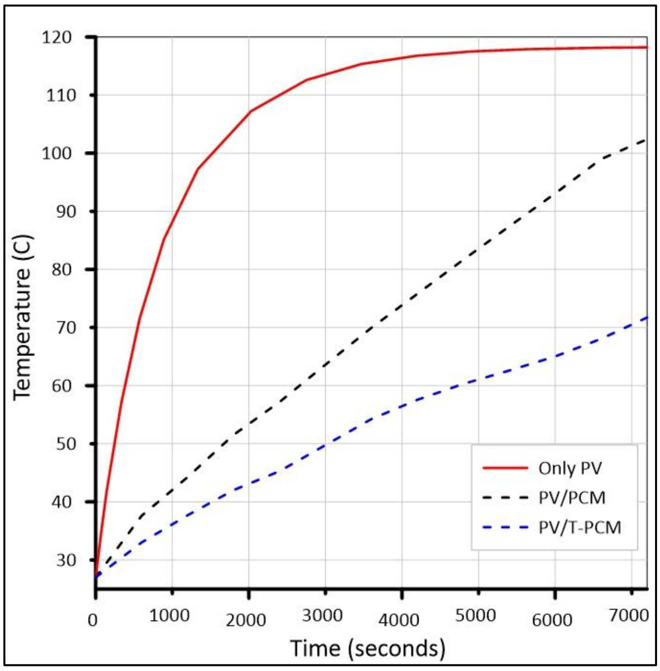

Fig. 7. Temperature variation of PV Cell with time in different systems

3.2.2 Melting Rate of PCM

The melting rate of PCM with respect to time is shown in figure 8. When the only PCM has been incident with a constant heat flux of 900W/m^2 on its surface the liquid fraction obtained after 2 hours is 0.93 after the introduction of the PV/PCM system liquid fraction reduced to 0.83 and there is decrement of 10% in melting of PCM. When the PV/T-PCM system is introduced, the liquid fraction is further decreased to 0.78 which is a further decrement of 5% in melting of PCM because air acts as a partial resistance for heat and extracts the heat in the form of natural convection. There is a total decrement of 10.75% and 6.41% in the melting of PCM after the addition of PV/PCM and PV/T-PCM respectively. The performance of the PV panel is also increased due to a decline in melting rate.

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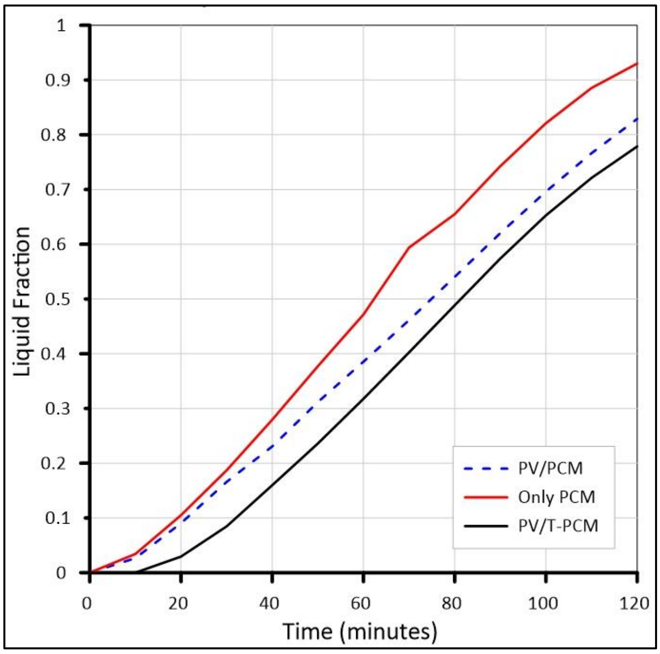

Fig. 8. Liquid Fraction variation of PCM with Time in different systems

3.2.3 PV Cell Efficiency

The efficiency of the PV with respect to time is shown in figure 9. The PV efficiency obtained after an incident of 900W/m^2 constant heat flux after 2 hours is 6.65%. When PV/PCM system is attached the efficiency increases to 8.59% as some amount of heat is absorbed by the PCM and when PV/T-PCM has introduced the efficiency further increases to 10.23% because in this system waste is not only being absorbed by the PCM but some part of the heat is also being removed by Natural convection of air. There is an increment of 29.17% and 19.09% in efficiency of PV cell after addition of PV/PCM and PV/T-PCM respectively.

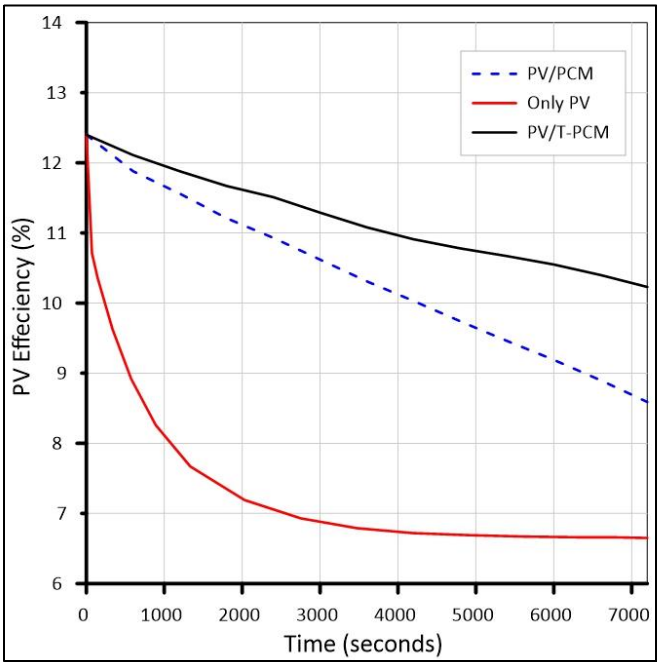

Fig. 9. Variation of PV cell Efficiency with time in different systems

4.0 Conclusions

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In this study, the thermal performance of photovoltaic (PV) cells integrated with Phase Change Material (PCM) was analysed using CFD under real-time atmospheric conditions. The numerical model was validated with previous studies and showed acceptable agreement. Heat transfer in PCM occurred initially through conduction, followed by convection during melting due to buoyancy effects. The results showed that the PV cell operating temperature decreased by 13.39% for the PV/PCM system and by 29.95% for the PV/T-PCM system. The efficiency of the PV also increased as of 29.97% and 19.07% PV cell efficiency when PV/PCM and PV/T-PCM are added respectively. Among all configurations, the PV/T-PCM system exhibited the best thermal and electrical performance due to lower temperature and improved cooling duration. Hence, passive cooling using PCM combined with natural convection is an effective technique for improving the efficiency and performance of photovoltaic systems.

NOMENCLATURE

ρ = Density (kg/m^3)

μ = Viscosity (kg/m-s)

ρ_0 = Constant density (kg/m^3)

β = Thermal Expansion Co-efficient (K^{-1})

g = Gravitational constant (m^2/s)

v_l = Volume liquid fraction

T = Temperature (K)

T_0 = Operating temperature (K)

v_l = Volume liquid fraction

K = Thermal Conductivity (W/m-K)

C_p = Specific heat (KJ/kg-K)

h_f = Latent heat of liquid (KJ/kg)

q'' = Heat flux (W/m^2)

T_{pv} = PV cell temperature (K)

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