Experimental Studies on PV Module Cooling With Radiation Source PCM Matrix

KARTHIKEYAN VELMURUGAN1,2,3, VAITHINATHAN KARTHIKEYAN4, TULJA BHAVANI KORUKONDA5, K. MADHAN6, KANCHANOK EMSAENG7, SUKRUEDEE SUKHA1, CHATCHAI SIRISAMPHANWONG8, TANAKORN WONGWUTTANASATIAN2,3, RAJVIKRAM MADURAI ELAVARASAN9, HASSAN HAES ALHELOU10, (Senior Member, IEEE), AND UMASHANKAR SUBRAMANIAM11, (Senior Member, IEEE)

1School of Renewable Energy and Smart Grid Technology, Naresuan University, Phitsanulok 65000, Thailand
2Center for Alternative Energy Research and Development, Khon Kaen University, Khon Kaen 40002, Thailand
3Mechanical Engineering Division, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
4Department of Materials Science and Engineering, City University of Hong Kong, Hong Kong
5Centre for Energy Studies, IIT Delhi, New Delhi 110016, India
6Department of Physics, MIT Campus, Anna University, Chennai 600044, India
7Faculty of Education, Pibulsongkram Rajabhat University, Phitsanulok 65000, Thailand
8Department of Materials Science and Engineering, City University of Hong Kong, Hong Kong
9Department of Physics, MIT Campus, Anna University, Chennai 600044, India
10Renewable Energy Laboratory (REL), Department of Communication and Networks, College of Engineering, Prince Sultan University (PSU), Riyadh 11586, Saudi Arabia

Corresponding author: Chatchai Sirisamphanwong (chatchaisi@nu.ac.th)

This work was supported by the Smart Energy System Integration Research Unit, Department of Physics, Faculty of Science, Naresuan University, Thailand.

ABSTRACT Rise in PV module temperature (T_{PV}) majorly drops the electrical output of the PV system. This research presents a novel cylindrical tube PCM matrix that is not in physical contact with the PV module back surface unlike the existing PCM based PV module cooling techniques. This contactless PCM matrix prevents the PV module from thermal and physical stress, also it blocks thermal energy re-conduction from PCM to PV module. While stored thermal energy from PCM retransferred to the PV module during off-sunshine hours and also when the PCM turns to liquid T_{PV} starts to rise abruptly, this contactless PCM matrix minimizes these issues as PCM matrix receives thermal energy by the mode of radiation and convection; Besides, PCM matrix surface area is not enclosed with the PV module back surface area that reduces the thermal stress and re-conduction. Developed PCM matrix is integrated beneath the PV module at particular distances of 6 mm, 9 mm and 12 mm to optimize the spacing between PV module and PCM matrix. It is found that 6 mm spacing PCM matrix reduced the T_{PV} maximum of 2.5 °C compared to 9 mm and 12 mm spacing. This T_{PV} reduction enhanced the PV module electrical output by 0.2 % than PV without PCM and it is observed that 6 mm is an optimal spacing for the radiation source PCM matrix.

INDEX TERMS PV module cooling, optimal spacing, PCM matrix, radiation heat transfer, temperature corrected power.

NOMENCLATURE

A_{Al} upper surface area of PCM matrix, m^{2}
A_{air} area of critical spacing, m^{2}
A_{PV} back surface area of PV module, m^{2}
A_{PCM} surface area of PCM, m^{2}

C_{pv} PV module specific heat capacity, J kg^{-1} K^{-1}
C_{air} specific heat capacity of air, J kg^{-1} K^{-1}
C_{pcm,s} solid specific heat capacity of PCM, J kg^{-1} K^{-1}
C_{pcm,l} liquid specific heat capacity of PCM, J kg^{-1} K^{-1}
D diameter of the Al cylindrical tube (PCM matrix tube), mm
F_{pv–air} view factor between PV module and PCM matrix

The associate editor coordinating the review of this manuscript and approving it for publication was Manoj Datta.®

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I. INTRODUCTION

The adoption of urbanized and modernized culture forces us to consume excessive power in our daily life and it is predicted that global energy consumption will increase by 50% by 2050 [1]. Global total energy production is about 25721 TWh in 2019, among which coal, gas and nuclear energy sources combined to produce 71.4% [2], [3]. This rapid consumption of fossil and nuclear fuels directly increases global warming. To reduce fossil fuel consumption and eradicate the adverse effects of global warming, renewable energy-based power productions should be widely employed. Among various available renewable sources and systems, the solar PV systems gained popularity owing to their low-cost maintenance and fascinating power conversion efficiencies i.e about 19 % for conventional Silicon based PV system [4], [5]. However, the system undergoes considerable efficiency loss during hot summer as solar irradiance and ambient temperature soar thereby increasing the T_PV abruptly [6]–[10]. Studies reveal that an increase in every 1 °C of T_PV higher than the standard test condition (STC) causes reduction in the electrical output power by 0.3-0.4 % [11], [12].

Earlier T_PV reductions were widely performed using water and air as they are well known thermal remover [13]–[19]. Following that, phase change materials (PCMs) are examined and they yielded an effective T_PV reduction in comparison to water and air [20]–[25]. PCM is a latent heat storage material and that stores thermal energy from PV module by changing a phase change, PCM enables latent heat of fusion (H_f) that stores thermal energy from PV module by changing water and air [20]–[25]. PCM is a latent heat storage material and they yielded an effective T_PV reduction in comparison to water and air as they are well known thermal remover [13]–[19].

Earlier T_PV reductions were widely performed using water and air as they are well known thermal remover [13]–[19]. Following that, phase change materials (PCMs) are examined and they yielded an effective T_PV reduction in comparison to water and air [20]–[25]. PCM is a latent heat storage material and that stores thermal energy from PV module by changing its physical appearance mostly from solid to liquid. During a phase change, PCM enables latent heat of fusion (H_f) to store the high amount of thermal energy (J/g) without increasing the PCM temperature. But other materials store thermal energy in the form of specific heat capacity (J/g.K) and that are temperature dependent, as it starts to increase.
TABLE 1. Literature review of passively cooled PV module and present study.

<table>
<thead>
<tr>
<th>PCM</th>
<th>Description</th>
<th>Integration type</th>
<th>Mass of PCM (g)</th>
<th>T&lt;sub&gt;PV&lt;/sub&gt; reduction (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candle wax</td>
<td>PCM integrated as back sheet and performed under Malaysian hot climatic condition.</td>
<td>Physical contact</td>
<td>30.4</td>
<td>4.41</td>
<td>[46]</td>
</tr>
<tr>
<td>Crude palm oil (CPO) and coconut oil</td>
<td>Coconut oil turns ineffective and not suitable for hot climatic condition where the T&lt;sub&gt;amb&lt;/sub&gt; is higher than 27 °C however COP reduced the T&lt;sub&gt;PV&lt;/sub&gt; effectively.</td>
<td>Physical contact</td>
<td>154.4</td>
<td>14.1</td>
<td>[47]</td>
</tr>
<tr>
<td>RT25</td>
<td>Indoor simulation performed to find the suitable tilt angle for PCM along with the PV module by varying speed and wind azimuth angle.</td>
<td>Physical contact</td>
<td>36.4</td>
<td>10.1</td>
<td>[48]</td>
</tr>
<tr>
<td>RT28</td>
<td>Numerical model developed for different thickness and melting range of PCM, resulting 3.8 cm thickness and 28 °C of PCM T&lt;sub&gt;melt&lt;/sub&gt; was optimized, resulting higher T&lt;sub&gt;PV&lt;/sub&gt; in summer than winter both Ankara and Mersin location.</td>
<td>Physical contact</td>
<td>57.9</td>
<td>13.8</td>
<td>[49]</td>
</tr>
<tr>
<td>Paraffin wax and beeswax</td>
<td>Two different PCM’s were experimented to find the correlation of environmental factor that affects the PCM performance, results showed reducing the T&lt;sub&gt;PV&lt;/sub&gt; in higher order as high solar insolation intensity makes paraffin wax to melt quickly than beeswax.</td>
<td>Physical contact</td>
<td>57.7</td>
<td>10.6</td>
<td>[50]</td>
</tr>
<tr>
<td>RT35</td>
<td>A 2.5 cm thickness of RT35 commercial PCM was filled in a box type container that was attached on the PV module back surface to improve the performance of the PV power output using different tilt and wind speed.</td>
<td>Physical contact</td>
<td>60.8</td>
<td>24.1</td>
<td>[51]</td>
</tr>
<tr>
<td>Paraffin wax 35</td>
<td>A paraffin was pasted on the PV module collector surface with the thickness of 0.5 cm and back sheet was used to cover the PCM resulting, PCM integrated T&lt;sub&gt;PV&lt;/sub&gt; starts to rise after 13:00 due to fall in solar irradiance causes to gain the thermal energy from PCM (re-condensation).</td>
<td>Physical contact</td>
<td>30.4</td>
<td>8</td>
<td>[52]</td>
</tr>
<tr>
<td>Biphenyl and CaCl&lt;sub&gt;2&lt;/sub&gt;6H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>Biphenyl shows minor T&lt;sub&gt;PV&lt;/sub&gt; reduction until 11:00 after that it starts to increase the T&lt;sub&gt;PV&lt;/sub&gt; than reference model as it contains high T&lt;sub&gt;melt&lt;/sub&gt; however CaCl&lt;sub&gt;2&lt;/sub&gt;6H&lt;sub&gt;2&lt;/sub&gt;O performs better than Biphenyl.</td>
<td>Physical contact</td>
<td>83.6</td>
<td>10</td>
<td>[53]</td>
</tr>
<tr>
<td>CaCl&lt;sub&gt;2&lt;/sub&gt;6H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>TRANSYS simulation was validated with experimental result for a 1 cm thickness of calcium chloride hexahydrate that was integrated behind the PV module using glass cover than metal box type container.</td>
<td>Physical contact</td>
<td>36.1</td>
<td>23.4</td>
<td>[54]</td>
</tr>
<tr>
<td>RT35</td>
<td>A L-D thermal resistance model was developed to find the relationship of T&lt;sub&gt;PV&lt;/sub&gt; with different thickness of PCM.</td>
<td>Physical contact</td>
<td>60.8</td>
<td>30.5</td>
<td>[55]</td>
</tr>
<tr>
<td>RT27</td>
<td>A box type PCM container was performed in an indoor condition of controlled solar irradiance, wind speed and T&lt;sub&gt;amb&lt;/sub&gt; of 1000 W/m&lt;sup&gt;2&lt;/sup&gt;, 6 m/s and 28 °C respectively for about 60 minutes.</td>
<td>Physical contact</td>
<td>38</td>
<td>7</td>
<td>[56]</td>
</tr>
<tr>
<td>OM29</td>
<td>A 2.5 cm thickness of organic PCM stuffed on the PV module collector surface and backside of the PCM covered using 0.5 mm thickness of an aluminum sheet to prevent the leakages.</td>
<td>Physical contact</td>
<td>38</td>
<td>2.9</td>
<td>[41]</td>
</tr>
<tr>
<td>Paraffin wax 48</td>
<td>PCM’s are filled in cylindrical tube and developed PCM matrix by arranging the PCM in parallel, spacing between each tube are uniform (1 – 2 SD). Further developed PCM matrix installed at 6mm, 9mm and 12mm spacing behind the PV module without physical contact to reduce the T&lt;sub&gt;PV&lt;/sub&gt;. In this experiment, radiation is considered as dominant mode of heat transfer that makes this system has novel.</td>
<td>Non-physical contact or contactless</td>
<td>3.4</td>
<td>5</td>
<td>Present study</td>
</tr>
</tbody>
</table>
• PCM reconduction rise the $T_{PV}$ than conventional PV module during afternoon period of the experiment-ation [42].
• Integrating PCM container on the back surface of the PV module using physical contact could lead to the physical damage of the fragile PV module.
• Conduction source PCM increases the $T_{PV}$ when the PCM turns to be ineffective due to phase change [41].
• Increase in thickness of PCM container enhances the $T_{PV}$ reduction but also it increases the total weight of the system and requires additional mounting structure, that could increase the investment cost [43].
• It is necessary to optimize the thickness of PCM when it is in conduction mode because low thickness of PCM could turn to ineffective in the early period of experimentation. Further it creates the thermal resistant that directly increase the $T_{PV}$ higher than PV without PCM [41].
• PCM volume expansion can cause damage in the structure of PCM container and the PV module back surface.

To overcome these issues, PCM matrix are decided to be integrated beneath the PV module with non-physical contact.
• This contactless PCM matrix restricts the metal-based potential induced degradation (PID) [44] and indirectly reduces the $T_{PV}$ based PID loss [45].
• Integrating PCM matrix behind the PV module without physical contact allows the environment air to circulate around the PV module and PCM matrix that enhance the heat transfer.
• Cylindrical tube PCM matrix consumes less amount of PCM compared to box type PCM.
• Developed PCM matrix are clamped to the frame of PV module without using separate mounting structure.

The main objective of this research is to minimize or neutralize the $T_{PV}$ using the PCM matrix without increasing the thermal resistance like conduction source PCM. Existing PCM based cooling techniques are discussed and compared with the present radiation source PCM matrix. Developed radiation source PCM matrix installed at 6 mm, 9 mm and 12 mm spacing behind the PV module to find the effect of the radiation to optimize the spacing. It was found that considerable $T_{PV}$ reduction was achieved for 6 mm spacing.

II. MATERIALS AND METHODS
A. PCM SELECTION AND DSC CHARACTERIZATION
PCM is the most efficient materials to reduce the $T_{PV}$. As mentioned earlier, during phase transformation, heat from PV module is removed effectively with the help of $H_m$ without increasing the PCM temperature compared to sensible heat storage material. In the recent decade, PCM employed PV module cooling technique gains attention in turns of its fascinating $T_{PV}$ reduction compared to conventional methods of water, air and other techniques. Organic PCMs are widely experimented to cool the PV module as it contains high $H_m$, non-corrosive to metal, congruent, and thermally stable for after several thousand thermal cycling [57]–[63]. But inorganic PCMs are less likely experimented due to their corrosiveness to metal and incongruent after several hundred thermal cycling [64], [65]. The eutectic mixture is thermally stable like organic PCM [65], [66]. Yet, eutectic PCMs are less explored as they are rare in local market. It requires special skill to prepare the eutectic mixture using probe sonication that makes this material unpopular for PV module cooling. In precise, paraffin wax and commercial PCMs are widely used rather than fatty acids [20], [21], [67]–[70].

Current relaying on the existing technique, paraffin wax selected as PCM to reduce the $T_{PV}$ in this study. Paraffin wax is purchased from the SQI Group, Bangkok, without further processing the PCM is analyzed to find the $T_{melt}$ and $H_m$ using Digital Scanning Calorimeter (DSC). A 5.4 mg of the material is placed in the aluminum sample holder and heated up by 5 K/min under nitrogen as a working fluid. The obtained DSC curve and PCM thermal properties are shown in Fig. 1 and Table 2, respectively.

![DSC characterization of paraffin wax.](image)

**FIGURE 1.** DSC characterization of paraffin wax.

**TABLE 2.** Thermo-physical properties of paraffin wax.

<table>
<thead>
<tr>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM name</td>
<td>Paraffin wax</td>
</tr>
<tr>
<td>$T_{melt}$ (°C)</td>
<td>48</td>
</tr>
<tr>
<td>$\Delta H_m$(kJ/g)</td>
<td>180</td>
</tr>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>0.88</td>
</tr>
<tr>
<td>$K_{PCM}$ (W/m.K)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

B. EXPERIMENTAL SETUP
PCM matrix is made up of an aluminum cylindrical tubes that are filled by 95 % of liquid PCM and rest are left for PCM volume expansion. In total 36 tubes are placed in parallel with uniform spacing between each tube ($S = 2.5D$), as shown in Fig. 2 (a). From our previous study, it was clear that selective absorber enhances the heat absorption rate, following that in this research also selective absorber is coated on the front surface of the 36 PCM matrix cylindrical tubes [71].

Further, the developed PCM matrix is installed at 6 mm, 9 mm and 12 mm spacing behind the 310 Wp of the
Polycrystalline PV module (properties are listed in Table 3) to optimize the critical spacing as this experiment performs with contactless PCM integration unit. In this study, 6 mm spacing is selected as the least spacing distance because, decrease in spacing below 6 mm induces PCM matrix re-radiation effect and low convection which reduces the performance of the system compared to 6 mm spacing. Fig. 2 shows the overview of contactless PCM matrix and the experimentation process. The temperature profile of the PCM matrix and the PV module with and without PCM are measured across nine equidistance points using T-type thermocouples to get an even temperature following that solar analyzer is used to measure the electrical output of the PV modules as shown in schematic diagram of Figure 2 (b) and Figure 2 (c). Solar irradiance data collected from SGtech Meteorological office, Naresuan University, Thailand. This experiment is conducted in School of Renewable Energy and Smart Grid Technology, Naresuan University during the March 2018 which is usually the hottest month of the year. The experiment is deliberately chosen to be conducted in this month to access the consistence of the PCM and the random set of unbiased data are analyzed. All the experimental equipment’s are calibrated before starting the experiment and they are in high accuracy up to 99.5%.

### III. THERMAL HEAT TRANSFER NETWORK

The development of heat transfer network for PV module cooling using radiation source (contactless) PCM matrix comprises of different form of heat transfer mode, as shown in Fig. 3. First stage depicts the thermal interaction of the PV module front and backside. Thermal energy from PV module glass surface transferred to sky (R1) and the ambient (R2) by radiation and convection, respectively. Following that, PV module tedlar surface transfers thermal energy by radiation (R3) and convection (R4) to the surrounding or ambient without using any auxiliary source. In this experiment PCM matrix is integrated at a particular distance to remove the energy from surrounding exactly beneath the PV module.

The second stage represents the thermal absorption of PCM matrix, PV module dissipates some of the thermal energy absorbed by PCM matrix front surface (R5) and rest is left to the surroundings. As PCM matrix surface area is not enclosed with the PV module tedlar surface, that makes thermal energy from PV module transfers to the surrounding without restricting them to store in the PCM unlike existing PCM based PV module cooling technique. PCM matrix absorbed thermal energy is further transferred to the inner wall (R6) where the PCM is present by conduction. Following that, PCM stores thermal energy by changing its phase from solid-liquid (R7) that helps to reduce the $T_{PV}$. 

### TABLE 3. Properties of the PV module and PCM matrix.

<table>
<thead>
<tr>
<th>Items</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shinsung PV module</td>
<td>310 W</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>45.3 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>8.99 A</td>
</tr>
<tr>
<td>PV module efficiency</td>
<td>16.17 %</td>
</tr>
<tr>
<td>PV module temperature co-efficient</td>
<td>0.42 C(^{-1})</td>
</tr>
<tr>
<td>Specific heat capacity of PV module</td>
<td>900 J kg(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>PV module back surface area</td>
<td>1.9 m(^2)</td>
</tr>
<tr>
<td>PV module tedlar emissivity</td>
<td>0.93</td>
</tr>
<tr>
<td>PV module front glass transmittance</td>
<td>0.9</td>
</tr>
<tr>
<td>PV front glass absorptivity</td>
<td>0.89</td>
</tr>
<tr>
<td>PCM matrix absorptivity</td>
<td>0.9</td>
</tr>
<tr>
<td>PV module packing factor</td>
<td>0.89</td>
</tr>
<tr>
<td>PCM matrix tube gauge</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>PCM matrix tube diameter</td>
<td>11.5 mm</td>
</tr>
</tbody>
</table>
Stage three represents the thermal dissipation from PCM matrix to surrounding or ambient. During sunshine and off sunshine thermal energy from PCM is transferred to the PCM matrix’s lower surface by conduction ($R_8$), further it is transferred to the surrounding or ambient by radiation ($R_9$) and convection ($R_{10}$) to perform the next day operation. Above mentioned three stages are expressed by energy balancing equations by modifying our previous work from rectangular tube PCM matrix to cylindrical tube PCM matrix in the following subsections [39].

### A. PV MODULE FRONT AND BACK SIDE

Physical appearance of the PV module front and back side heat transfers are expressed in the form of mathematical representation as expressed in equation (1). Thermal energy from PV module glass surface is transferred to the sky ($h_{PV\rightarrow sky}$) and ambient ($h_{PV\rightarrow amb}$) with the help of PV module glass emissivity and wind. Further, PV module tedlar surface transfers the thermal energy to the PCM matrix by radiation and natural convection ($h_{PV\rightarrow Al}$) as PCM matrix is not in physical contact that helps to enhance electrical efficiency ($\eta_{PV}$).

\[
\frac{m_{PV}}{C_{PV}} \frac{dT_{PV}}{dt} = [\alpha_{PV} \tau_g I(t) - h_{PV\rightarrow air} (T_{PV} - T_{air}) - h_{PV\rightarrow sky} (T_{PV} - T_{sky}) - h_{PV\rightarrow amb} (T_{PV} - T_{amb}) - h_{PV\rightarrow Al} (T_{PV} - T_{Al}) - \eta_{PV} I(t)] \beta A_{PV} \quad (1)
\]

From equation (1), $h_{PV\rightarrow air}$ represents the convection and radiation mode of heat transfer from PV module tedlar surface to PCM matrix, that are expressed in equation (2).

\[
h_{PV\rightarrow air} = \left( \frac{K_{PV\rightarrow air} N_{up PV\rightarrow air}}{L_{PV}} \right) + \varepsilon_{PV} \alpha (T_{PV} + T_{air}) (T_{PV} + T_{air})^2 \quad (2)
\]

Nusselt number for various spacing of 6 mm, 9 mm and 12 mm is expressed in equation (3).

\[
N_{up PV\rightarrow air} = \left( 0.825 + \frac{0.387 R_{ap PV\rightarrow air}^{1/6}}{1 + (0.492 / Pr_{PV\rightarrow air})^{9/6}} \right)^2 \quad (3)
\]

View factor for various spacing of 6 mm, 9 mm and 12 mm is expressed in equation (4).

\[
F_{PV\rightarrow air} = 1 - \left[ 1 - \left( \frac{D}{S} \right)^2 \right]^{0.5} + \frac{D}{S} \tan^{-1} \left( \frac{S^2 - D^2}{2S} \right)^{0.5} \quad (4)
\]

From equation (1), $h_{PV\rightarrow sky}$ represents the PV module glass surface radiation to the sky as expressed in equation (5), this radiation is truly based on the $T_{amb}$ as expressed in equation (6) [20].

\[
h_{PV\rightarrow sky} = \varepsilon_{PV} \sigma (T_{PV} + T_{sky}) (T_{PV} + T_{sky})^2 \quad (5)
\]

\[
T_{sky} = 0.0522 T_{amb}^{1.5} \quad (6)
\]

From equation (1), $h_{PV\rightarrow amb}$ represents the PV module glass surface convection to ambient with the help of wind as expressed in equation (7) [72].

\[
h_{PV\rightarrow amb} = 2.8 + 3V, \quad 0 < V < 7 \text{ m/s} \quad (7)
\]

### B. SPACING BETWEEN PV MODULE AND PCM MATRIX

Considering our previous study [71], selective absorber is coated on the PCM matrix top surface to absorb the thermal energy effectively that are transferred by PV module tedlar surface. PCM matrix front surface at particular distance absorbs the thermal energy by radiation and convection ($h_{PV\rightarrow air} = h_{PV\rightarrow Al}$) as it does not have physical contact with the PV module tedlar surface that are expressed in

**FIGURE 3.** Thermal heat transfer network for PV and PCM matrix.
equation (8). Further, PCM matrix absorbed thermal energy transferred to PCM matrix inner wall \( (h_{\text{air} \rightarrow \text{Al}}) \) and then transferred to PCM by conduction \((h_{\text{PCM}})\).

\[
\alpha_{\text{Al}} I(t) A_{\text{Al}} = \left[ -h_{\text{PV} \rightarrow \text{Al}} (T_{\text{Al}} - T_{\text{PV}}) - h_{\text{air} \rightarrow \text{Al}} (T_{\text{Al}} - T_{\text{air}}) - h_{\text{Al} \rightarrow \text{PCM}} (T_{\text{Al}} - T_{\text{PCM}}) \right] A_{\text{Al}} \tag{8}
\]

where,

\[
h_{\text{air} \rightarrow \text{Al}} = h_{\text{PV} \rightarrow \text{Al}} + \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}}
\]

\[
h_{\text{Al} \rightarrow \text{PCM}} = \frac{K_{\text{PCM}}}{\Delta X_{\text{PCM}}}
\]

Equation (9) represents the amount of thermal energy that has been transferred to the critical spacing.

\[
m_{\text{air}} C_{\text{air}} \frac{dT_{\text{air}}}{dt} = \left[ -h_{\text{PV} \rightarrow \text{air}} (T_{\text{air}} - T_{\text{PV}}) - h_{\text{air} \rightarrow \text{Al}} (T_{\text{air}} - T_{\text{Al}}) \right] A_{\text{air}} \tag{9}
\]

C. RADIATION SOURCE PCM MATRIX

Equation (10) represents the amount of thermal energy that has absorbed at particular distance and it is stored in the form of solid-phase, melting phase and liquid phase concerning the \( T_{\text{PCM}} \) as expressed in equation (11). As mentioned earlier, thermal energy from PCM matrix transferred to surrounding or ambient by radiation and natural convection, to enhance the heat transfer from PV module tedlar surface during sunshine hours and also to perform the consecutive day operation as expressed in equation (12).

\[
m_{\text{PV}} C_{\text{PV}} \frac{dT_{\text{PV}}}{dt} = \left[ -h_{\text{PV} \rightarrow \text{PV}} (T_{\text{PV}} - T_{\text{PV}}) - h_{\text{PV} \rightarrow \text{air}} (T_{\text{air}} - T_{\text{PV}}) - h_{\text{PV} \rightarrow \text{Amb}} (T_{\text{Amb}} - T_{\text{PV}}) \right] A_{\text{PV}} \tag{10}
\]

\[
C = \begin{cases} 
C_{\text{PCMs}}, & T_{\text{PCM}} < T_{\text{melt}} \\
L_{\text{PCM}}, & T_{\text{PCM}} = T_{\text{melt}} \\
C_{\text{PCM}}, & T_{\text{PCM}} > T_{\text{melt}}
\end{cases} \tag{11}
\]

\[
h_{\text{PV} \rightarrow \text{Amb}} = \left( \frac{N_{\text{air}1} \times K_{\text{Al}}}{\Delta X_{\text{Al}}} + \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}} \right)
\]

\[
+ \left( \epsilon_{\text{Al}} \sigma (T_{\text{Al}} + T_{\text{Amb}}) (T_{\text{Al}} + T_{\text{Amb}})^2 \right)
\]

\[
+ \left( \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}} \right) \tag{12}
\]

Further, equation (1), (8), (9) and (10) are solved analytical to find the unknown variables of \( T_{\text{PV}}, T_{\text{Al}}, T_{\text{air}} \) and \( T_{\text{PCM}} \), (13)–(16), as shown at the bottom of the page, where,

\[
X_1 = \alpha_{\text{PV}} T_{g} I(t) + h_{\text{PV} \rightarrow \text{air}} T_{\text{air}} + h_{\text{PV} \rightarrow \text{sky}} T_{\text{sky}}
\]

\[
+ h_{\text{PV} \rightarrow \text{Amb}} T_{\text{Amb}}
\]

\[
+ h_{\text{PV} \rightarrow \text{Al}} T_{\text{Al}} - \eta_{\text{PV}} I(t)
\]

\[
X_2 = h_{\text{PV} \rightarrow \text{air}} + h_{\text{PV} \rightarrow \text{sky}} + h_{\text{PV} \rightarrow \text{Amb}} + h_{\text{PV} \rightarrow \text{Al}}
\]

Equation (13), (14), (15) and (16) can not solve directly as unknown variables are present in each, to mitigate this issue Newton Raphson method is applied. At the end of these process, electrical efficiency of the PV module is greatly enhanced as expressed in equation (17).

\[
\eta_{\text{PV}} = \eta_{\text{STC}} \left[ 1 - \beta_{\text{STC}} (T_{\text{PV}} - T_{\text{STC}}) \right] \tag{17}
\]

IV. RESULTS AND DISCUSSION

A. RADIATION SOURCE PCM MATRIX AT 6 mm SPACING

In general, PCM containers are integrated on the PV module tedlar surface using physical contact to achieve the effective heat transfer. In this experiment, developed PCM matrix installed at 6 mm spacing, considering the least possible spacing between the PV module tedlar surface and PCM matrix served the purpose. This contactless PCM matrix.
does not restrict the airflow to the PV module back surface that makes this system unique and free from thermal resistance, as an increase in resistivity could create a negative impact on the PV module cooling process. Fig. 4 shows an experimental result of PCM matrix at 6mm spacing, during experimentation, \( T_{\text{amb}} \) reached a maximum of 33 \(^\circ\)C due to low wind speed and high humidity (not shown). Also, solar irradiance started to rise from 11:00 to 13:00, following this \( T_{\text{PV}} \) raised to a maximum of 60 \(^\circ\)C that causes to drop the system performance by 15 \%. For PV system with PCM matrix integrated, \( T_{\text{PV}} \) is reduced until 15:00 with a maximum of 2.5 \(^\circ\)C. After 15:00, PCM turns to liquid, but this novel PCM matrix did not increase the \( T_{\text{PV}} \) as PV module back surface transmits thermal energy to surrounding and ambient without any disturbance with the influence of Tedlar emissivity factor and wind speed. In general, conduction based PCM had its disadvantage in PV module cooling [32], [73]–[75].

As mentioned earlier, this radiation source PCM matrix did not increase the \( T_{\text{PV}} \) at the time of solar irradiance drop that makes this system has novel performance than conduction source PCM [42].

**B. RADIATION SOURCE PCM MATRIX AT 9 mm SPACING**

In order to optimize the critical spacing, a PCM matrix is integrated at 9 mm spacing to observe the thermal distribution of the PV module. An increase in spacing shows that thermal absorption of PCM matrix is ineffective, where the 6 mm spacing plays a vital role in \( T_{\text{PV}} \) reduction. However, it did not increase the \( T_{\text{PV}} \) until 11:00 as shown in Fig. 5, but after 11:00 slightly, \( T_{\text{PV}} \) started to increase than PV without PCM. As PCM matrix at an inappropriate distance causes to increase the thermal resistance and it affects the rise in \( T_{\text{PV}} \). Even though this thermal resistance could not bear and sustain the rise in \( T_{\text{PV}} \) for a longer time like conduction source PCM, at the time of 16:30 both \( T_{\text{PV}} \) remains the same.

**C. RADIATION SOURCE PCM MATRIX AT 12 mm SPACING**

Further, the PCM matrix is integrated at 12 mm, resulting minor \( T_{\text{PV}} \) reduction noticed until 10:30 however, this reduction is lower than 6 mm spacing as shown in Fig. 6. An increase in spacing reduces the radiation effect but convection dominates with the help of wind better than 9 mm spacing. As mentioned earlier, increase in spacing beyond 6 mm causes to increase the \( T_{\text{PV}} \) at the time of peak sunshine, but in this 12 mm spacing also both \( T_{\text{PV}} \) remains constant after 16:00. Comparatively, 6mm spacing yields higher \( T_{\text{PV}} \) reduction than other spacing; also, it did not increase the \( T_{\text{PV}} \) like 9 mm and 12 mm spacing that makes 6 mm is an optimal spacing for developed radiation source PCM matrix. To confirm the stability of the PCM matrix performance, consecutive one day optimized PCM matrix experimental results shown in Fig. 7 and another selective two days experimental results are shown in Table 4.

However, this novel radiation source PCM matrix reduced less \( T_{\text{PV}} \) than most of the conduction source PCM...
but it should be noted that this cylindrical tube PCM matrix consumes less amount of PCM (3.4 kg) than any other existing PCM based PV module cooling technique. Fig. 8 depicts existing method consumes minimum and maximum of 30.4 kg and 154.5 kg of PCM that reduces the $T_{PV}$ of 4.43 % and 14.4 % when it compared to the present model it supposed to enhance the $T_{PV}$ reduction of 40.27 % and 227.1 %, respectively, higher than the obtained results. Following that, several researchers obtained and expected $T_{PV}$ reductions also projected based on the present study to make the effective comparison. All the existing conduction-based method records higher $T_{PV}$ reduction, but linearity fails compared to present study at the same time performance is better than the existing model that makes this system is the replacement for conduction based PCM container. Integrating high amount of PCM enhances the higher electrical efficiency but payback period will be questionable and higher than the loss obtained by $T_{PV}$ [76]. In such way our proposed method will favor in attractive payback period as this method consumes 45.4 % of less PCM compared the existing methods. Also, this radiation type did not increase the thermal resistance, controls PID, avoids physical damage and easy in installation and maintenance.

### D. ELECTRICAL PARAMETERS FOR OPTIMIZED PCM MATRIX

A solar cell is a semiconductor that converts incident photon into electrical energy during this process solar cell gains heat from sun. Increase in every 1 °C of $T_{PV}$ higher than STC causes to reduce the open-circuit voltage ($V_{oc}$) by

![FIGURE 8. Comparative analysis of radiation and conduction source PCM (15/03/2018).](image)

![FIGURE 9. Comparison of temperature-corrected $V_{max}$ using optimized spacing and PV without PCM (15/03/2018).](image)
FIGURE 10. Comparison of temperature-corrected $P_{\text{max}}$ using optimized spacing and PV without PCM (15/03/2018).

FIGURE 11. Comparison of power loss using optimized spacing and PV without PCM (15/03/2018).

FIGURE 12. Comparison of temperature-corrected electrical efficiency using optimized spacing and PV without PCM (15/03/2018).

0.30 - 0.48%. Fig. 9 shows a reduction in $T_{\text{PV}}$ increases the $V_{\text{max}}$ until 15:00 further $V_{\text{max}}$ is neutralized for PCM matrix at 6 mm as $T_{\text{PV}}$ for both systems is neutralized after 15:00.

PV module voltage profile is temperature-dependent; at the same time PV module current profile has less effect as an increase in $T_{\text{PV}}$ because solar cell is a current generator that is highly correlated with solar irradiance. Experimental data reveals that the temperature coefficient of $I_{\text{sc}}$ is 0.049%/°C from STC that makes minor fluctuation in current profile (not shown here) because less $T_{\text{PV}}$ reduction is obtained in the present study. However, clear variation is noticed in power curve with a maximum enhancement of 10 Wp as depicted in Fig. 10. An increase in solar irradiance increases the $I_{\text{max}}$ and it contributes to generate high power. However, PCM matrix integrated system is not close to the nominal power as it is difficult to achieve in real time condition also in this experiment less amount of PCM is performed to cool the PV module. In precise, Fig. 11 shows the power loss of both experimented PV modules compared to the nominal power but there is a noticeable difference between PV with and without PCM matrix.

E. ELECTRICAL EFFICIENCY FOR OPTIMIZED PCM MATRIX

Manufacturer rated electrical efficiency (%) is highly impossible to achieve, at the field level PV system undergoes various losses like soil loss, AC and DC cable loss, inverter loss, shading loss and $T_{\text{PV}}$ loss. Among other losses, $T_{\text{PV}}$ loss takes a bigger number. Since PV module electrical efficiency is sensitive to $T_{\text{PV}}$ and it becomes imperative to reduce it or to run the $T_{\text{PV}}$ close to ambient temperature, especially in a hot region like Thailand. In this experiment, PV module electrical efficiency enhanced maximum of 0.2 % using PCM matrix. Once the PCM matrix stopped its performance, PV module electrical efficiency closely remains the same as with the PV without PCM as shown in Fig.12.

F. PERFORMANCE RATIO FOR OPTIMIZED PCM MATRIX

In general, the performance ratio (PR) is used to find the loss obtained in the actual power production compared to the predicted power. In this study, PR is calculated for PV with and without PCM matrix to evaluate the performance enhancement of the proposed novel PCM matrix. Fig. 13 depicts until 15:00 PR of PCM matrix integrated PV module greatly enhanced 3 % than PV without PCM, however an increase in solar irradiance drops the PR profile against current and power as $T_{\text{PV}}$ majorly affects the PR and efficiency of the PV module.

G. ENVIRONMENTAL IMPACT ON PV MODULE EFFICIENCY

Fig. 14 depicts Pearson’s correlation heat map of PV without PCM and PV with optimized PCM matrix to find the thermal correlation. In this study Pearson’s correlation is used to find the association and direction of relationship between the environmental data (solar irradiance, $T_{\text{amb}}$, wind)
and output of the PV module as it is a well-known and effective method to measure the co-variance relationship. This heat map shows PV without PCM matrix $T_{PV}$ has a strong positive correlation with solar irradiance, moderate positive correlation with $T_{amb}$, and has no correlation with the wind. As mentioned earlier, increase in solar irradiance raises the $T_{PV}$ with the help of $T_{amb}$. This rise in $T_{PV}$ has a high negative correlation with the PV module electrical efficiency, such as increase in $T_{PV}$ drops the PV module electrical efficiency. Also, PCM matrix integrated PV module shows a similar strength of direction compared to PV without PCM matrix but it has noticeable variation in the correlation chart that makes the necessity of $T_{PV}$ reduction using PCM matrix.

V. CONCLUSION

Developed radiation source PCM matrix was integrated beneath the PV module at three different spacings to investigate the thermal distribution between the PV module teflon surface and the PCM matrix upper surface. In this study, experimental results are compared with the developed numerical model and also with existing PCM based passively cooled PV module. It has been proved that beyond 6 mm spacing heat transfer is not occurring effectively and it leads to increase thermal resistance. This increase in thermal resistance shows the necessity of finding the optimal spacing, the experimental result reveals that beyond 6mm spacing $T_{PV}$ reduction is not effective that makes 6mm is an optimal spacing for radiation-source PCM matrix.

- Optimized PCM matrix reduced the $T_{PV}$ maximum of 2.5 °C compared to other spacing, reportedly this optimized PCM matrix did not increase the $T_{PV}$ like existing conduction based PCM at the time of solar irradiance drop.
- This optimized PCM matrix enhanced the electrical output power and efficiency maximum of 10 Wp and 0.2 %, respectively.
- Following output power and efficiency, PR also enhanced maximum of 3 % compared to PV without PCM.
- Further, it is recommended to prepare the eutectic PCM that can have high latent heat of fusion with the enhanced $K_{PCM}$. In such case, optimized PCM matrix can reduce the $T_{PV}$ for longer time.

ACKNOWLEDGMENT

This work was supported in part by the Smart Energy System Integration Research Unit, Department of Physics, Faculty of Science, Naresuan University, in part by the Department of Electrical Power Engineering, Faculty of Mechanical and Electrical Engineering, Tishreen University, Latakia, Syria, and in part by the Renewable Energy Laboratory, Faculty of Engineering, Prince Sultan University, Riyadh, Saudi Arabia. The authors would also like to thank K. Sunilkumar from the SB Energy-SoftBank Group, Renewable and Environment, New Delhi, India, for his contributions in this article.

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KARTHIKEYAN VELMURUGAN received the bachelor’s degree in electronics and communication engineering from the IITF College of Engineering, Anna University, Chennai, the master’s degree in green energy technology from Pondicherry University, Puducherry, and the Ph.D. degree in renewable energy from Naresuan University, Thailand. He currently works as a Post-doctoral Researcher with Khon Kaen University, Khon Kaen. He has published papers in international journals and conferences. His research interests include solar PV and thermal systems, smart grid, and energy storage.

VAITHINATHAN KARTHIKEYAN received the bachelor’s degree in electronics and communication engineering and the master’s degree in green energy technology from Pondicherry University, Puducherry, and the Ph.D. degree in materials science and engineering from the City University of Hong Kong. He has published papers in international journals and conferences. His research interests include solar photovoltaics and thermoelectric materials.

TULIA BHAVANI KORUKONDA received the bachelor’s degree in electrical and electronics engineering from the College of Engineering, GITAM, and the master’s degree in green energy technology from Pondicherry University, Puducherry. She currently works as a Research Scholar with the Center for Energy Studies, IIT Delhi, New Delhi. She has published papers in international journals and conferences. Her research interest includes the development of third generation solar cell devices via spray coating.
K. Madhan received the bachelor’s degree in physics from Thiruvalluvar University, the master’s degree in material science and technology and the M.Phil. degree in physics (material science and technology) from Pondicherry University, Puducherry, and the Ph.D. degree in physics (material science and technology) from Anna University, Chennai. He has published papers in international journals and conferences. His research interests include multifunctional materials, graphene–metal oxide, nano materials, semiconducting thin films for photonic applications, solar cell, solar thermal systems, and energy storage.

Kanchanok Emsaeng received the bachelor’s and master’s degrees in English from Naresuan University, Thailand. From 2018 to 2019, she was a Lecturer with Thesapri Rajabhat University. Since 2019, she has been working as a Lecturer with Pibulsongkram Rajabhat University. She has published papers in international journals and conferences. Her research interests include science and academic English.

Sukruedee Sukchai received the B.Sc. degree in physics from Srinakharinwirot University, Thailand, in 1988, the M.Sc. degree in energy technology from the King Mongkut’s University of Technology Thonburi, Thailand, in 2002, and the Ph.D. degree in renewable energy from Naresuan University, Thailand, in 2006. Since 2014, she has been with Naresuan University, where she is currently the Director of the School of Renewable Energy Technology. She has authored various papers in academic journals and international conferences. Her current research interests include smart grid systems, renewable energy technology, and energy management systems.

Chatchai Sirisamphanwong received the B.Sc. degree in physics-energy and the M.Sc. and Ph.D. degrees in renewable energy from Naresuan University, Thailand, in 2000, 2004, and 2013, respectively. Since 2004, he has been with Naresuan University. He has authored various papers in academic journals and international conferences. His research interests include photovoltaic systems, smart grid systems, wind energy, and hydrogen technology.

Tanakorn Wongwuttanasatian received the bachelor’s degree from Khon Kaen University, Thailand, and the Ph.D. degree from the University of Leeds, U.K. Since 2000, he has been working with Khon Kaen University as an Associate Professor. He has published numerous research papers in journals and conference. His research interests include biodiesel, biogas, thermal management, solar photovoltaic, and thermal application development.

Rajivkram Madurai Elavarasan received the B.E. degree in electrical and electronics engineering from Anna University, Chennai, and the M.E. degree (Hons.) in power system engineering from the Thiagarajar College of Engineering, Madurai. He worked as an Associate Technical Operator with the IBM Global Technology Services Division. He worked as an Assistant Professor with the Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering. He is currently working as a Design Engineer with the Electrical and Automotive Parts Manufacturing Unit, AA Industries, Chennai, India. He has published papers in international journals and international and national conferences. His research interests include renewable energy and smart grid, wind energy research, power system operation and control, and artificial intelligence control techniques. He is a member of the IEEE Power and Energy Society. He received the Gold Medal for his master’s degree.

Hassan Haes Alhelou (Senior Member, IEEE) received the B.Sc. degree (Hons.) from Tishreen University, Latakia, Syria, in 2011, the M.Sc. degree (Hons.) from the Isfahan University of Technology (IUT), Isfahan, Iran, in 2016, all in electrical power engineering, power systems, where he is currently pursuing the Ph.D. degree. He is also a Faculty Member with Tishreen University. He is included in the 2018 Publons’ list of the top 1% best reviewer and researchers in the field of engineering in the world. He has published more than 30 research papers in the high-quality peer-reviewed journals and international conferences. He has also performed more than 160 reviews for high-prestigious journals, including the IEEE Transactions on Industrial Informatics, the IEEE Transactions on Industrial Electronics, Energy Conversion and Management, Applied Energy, and the International Journal of Electrical Power and Energy Systems. He has participated in more than 15 industrial projects. His major research interests include power systems, power system dynamics, power system operation and control, dynamic state estimation, frequency control, smart grids, micro-grids, demand response, and load shedding. He was a recipient of the Outstanding Reviewer Award from many journals, such as Energy Conversion and Management (ECM), JSA Transactions, and Applied Energy. He was also a recipient of the Best Young Researcher in the Arab Student Forum Creative among 61 researchers from 16 countries at Alexandria University, Egypt, in 2011.

Umashankar Subramaniam (Senior Member, IEEE) worked as an Associate Professor, the Head, and a Senior Research and Development Engineer, and a Senior Application Engineer in the fields of power electronics, renewable energy, and electrical drives with the Vellore Institute of Technology (VIT), Vellore. He is currently with the Renewable Energy Laboratory, College of Engineering, Prince Sultan University, Saudi Arabia, and has more than 15 years of teaching, research, and industrial research and development experience. Under his guidance, 24 master’s degree students and more than 25 bachelor’s degree students completed the senior design project work. Also, six Ph.D. scholars completed the doctoral thesis as a Research Associate. He has published more than 250 research papers in national and international journals and conferences. He is also involved in collaborative research projects with various international and national level organizations and research institutions. He has also authored/coauthored/contributed 12 books/chapters and 12 technical articles on power electronics applications in renewable energy and allied areas. He is a member of IACSIT, IDES, and ISTE. He was an Executive Member, from 2014 to 2016. He received the Danfoss Innovator Award-Mentor, from 2014 to 2015 and from 2017 to 2018, and the Research Award from VIT, from 2013 to 2018. He also received the INAE Summer Research Fellowship, in 2014. He has taken charge as the Vice-Chair of the IEEE Madras Section and the Chair of IEEE Student Activities, from 2010 to 2019. He was the Vice-Chair of the IEEE MAS Young Professional and the IEEE Madras Section, from 2017 to 2019. He is an Editor of Helix (Elsevier) journal.