Experimental Studies on PV Module Cooling With Radiation Source PCM Matrix

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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.

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h_1 \quad \text{heat transfer coefficient between the PV module and the different spacing by radiation and natural convection, W m}^{-2} K^{-1}

h_2 \quad \text{heat transfer coefficient between PV module glass and the sky by radiation, W m}^{-2} K^{-1}

h_3 \quad \text{heat transfer coefficient between PV module glass and the ambient by convection, W m}^{-2} K^{-1}

h_4 \quad \text{heat transfer coefficient between the PV module and the PCM matrix by radiation and natural convection, m}^{-2} K^{-1}

h_5 \quad \text{heat transfer between the PCM matrix upper wall and inner wall by conduction, W m}^{-2} K^{-1}

h_6 \quad \text{heat transfer in PCM by conduction, W m}^{-2} K^{-1}

h_7 \quad \text{heat transfer coefficient between lower surface of the PCM matrix and the ambient by radiation and convection, W m}^{-2} K^{-1}

I \quad \text{solar irradiance, W m}^{-2}

K_{air} \quad \text{thermal conductivity of air, W m}^{-1} K^{-1}

K_{PCMC} \quad \text{thermal conductivity of PCM, W m}^{-1} K^{-1}

K_{Al} \quad \text{thermal conductivity of PCM matrix (Al cylindrical tube), W m}^{-1} K^{-1}

L_{PCM} \quad \text{PCM latent heat of fusion, J kg}^{-1}

L_{PV} \quad \text{length of PV module, m}

m_{air} \quad \text{mass of the air, kg}

m_{PV} \quad \text{mass of the PV module, kg}

m_{PCM} \quad \text{mass of the PCM, kg}

N_{U_{air}} \quad \text{Nusselt number between the PV module and the PCM matrix}

R_{air} \quad \text{Rayleigh number between the PV module and the PCM matrix}

Pr_{PV} \quad \text{Prandtl number between the PV module and the PCM matrix}

R_1 \quad \text{thermal resistance between the PV module glass and the sky}

R_2 \quad \text{thermal resistance between the PV module glass and the ambient}

R_3, R_4 \quad \text{thermal resistance between the PV module and the PCM matrix spacing}

R_5 \quad \text{thermal resistance between the PV module and the PCM matrix upper surface (selectively coated absorber)}

R_6 \quad \text{thermal resistance between the PCM matrix upper wall and the inner wall}

R_7 \quad \text{thermal resistance in the PCM}

R_8 \quad \text{thermal resistance between the PCM and down wall of the PCM matrix}

R_9, R_{10} \quad \text{thermal resistance between the down wall of the PCM matrix and ambient}

t \quad \text{time, min}

T_{Al} \quad \text{PCM matrix upper wall temperature, °C}

T_{Al1} \quad \text{PCM matrix lower wall temperature, °C}

T_{air} \quad \text{air temperature, °C}

T_{amb} \quad \text{ambient temperature, °C}

T_{melt} \quad \text{PCM melting temperature, °C}

T_{PV} \quad \text{PV module temperature, °C}

T_{PCMC} \quad \text{PCM temperature, °C}

T_{sky} \quad \text{sky temperature, °C}

T_{STC} \quad \text{PV module operating standard test condition, °C}

V \quad \text{wind speed, m/s}

\varepsilon_{pv,b} \quad \text{PV module tedlar emissivity}

\varepsilon_{pv,t} \quad \text{PV module glass emissivity}

\sigma \quad \text{Stefan Boltzmann constant, W m}^{-2} K^{-4}

\Delta X_{PCM} \quad \text{thickness of PCM, m}

\Delta X_{Al} \quad \text{thickness of PCM matrix upper wall, m}

\eta_{PV} \quad \text{obtained PV module efficiency (％)}

\eta_{STC} \quad \text{PV module efficiency at STC (％)}

\alpha_{PV} \quad \text{PV module glass absorptivity}

\alpha_{Al} \quad \text{Selective coated thermal absorber on PCM matrix upper surface}

\beta \quad \text{PV module packing factor}

\beta_{STC} \quad \text{PV module temperature coefficient}

\tau_{g} \quad \text{PV module glass transmittance}

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 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_m) 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 Type</th>
<th>Description</th>
<th>Integration type</th>
<th>Mass of PCM (g)</th>
<th>T_{PV} reduction (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candel 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_{melt} is higher than 27 °C however, coconut oil reduced the T_{PV}</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>30.4</td>
<td>10.1</td>
<td>[48]</td>
</tr>
<tr>
<td>RT28</td>
<td>Numerical model developed for analysing different thickness and melting range of PCM, resulting 3.8 cm thickness and 28 °C of PCM T_{melt}. Optimal, resulting higher T_{PV} in summer than in winter both Ankara and Mersin location.</td>
<td>Physical contact</td>
<td>57.7</td>
<td>13.8</td>
<td>[49]</td>
</tr>
<tr>
<td>Paraffin wax and boeexwax</td>
<td>Two different PCM's were experimented to find the correlation of environmental factor that affects the PCM performance, resulted beans reduced the T_{PV}. In higher order as high solar intensity makes paraffin wax to melt quickly than beans.</td>
<td>Physical contact</td>
<td>60.8</td>
<td>24.1</td>
<td>[51]</td>
</tr>
<tr>
<td>RT35</td>
<td>A 2.7 cm thickness of RT55 commercial PCM was filled into 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>30.4</td>
<td>8</td>
<td>[52]</td>
</tr>
<tr>
<td>Paraffin wax 35</td>
<td>A paraffin was poured on the PV module tilt surface with the thickness of 5.5 cm and back sheet was used to cover the PCM. PCM integrated T_{PV} started to rise after 13:00 due to fall in solar irradiance causes to gain the thermal energy from PCM (re-conduction).</td>
<td>Physical contact</td>
<td>83.6</td>
<td>10</td>
<td>[42]</td>
</tr>
<tr>
<td>Biphenyl and CaCl_{2}·6H_{2}O</td>
<td>Biphenyl shows minor T_{PV} reduction until 11:00 after that it starts to increase the T_{PV} than reference model as it contains high T_{melt}, however CaCl_{2}·6H_{2}O performs better than Biphenyl.</td>
<td>Physical contact</td>
<td>30.4</td>
<td>11.1</td>
<td>[53]</td>
</tr>
<tr>
<td>CaCl_{2}·6H_{2}O</td>
<td>TRNSYS simulation was validated with experimental result for 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 1-D thermal resistance model was developed to find the relationship of T_{PV} 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>Box type PCM container was performed in an indoor condition of controlled solar irradiance, wind speed and T_{amb} of 1600 W/m², 6 ms 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 tilt surface and backside of the PCM covered using 0.5 mm thickness of an aluminium 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 tubes in parallel, spacing between each tube are uniform (5 – 2.5D). Further developed PCM matrix installed at 6mm, 9mm and 12mm spacing behind the PV module without physical contact to reduce the T_{PV}. 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>

The temperature of the storage material [26], [27]. Moreover, PCM is a stationary unit that extracts the thermal energy effectively from PV module without fluid motion and it does not require an external source.

Conventionally, PCMs are stuffed in a box type container that are made up of high thermal conducting metal to avoid the conduction barrier between PV module back surface and PCM as containers in physical contact with the module [28]. Initially, researchers focused on selecting the appropriate melting temperature of PCM as it is the physical property that dictates the temperature at which heat storage should be carried out in the material [29]–[31]. To optimize the PCM T_{melt}, Waqas and Jie [30] performed the simulation for hot climatic condition using different T_{melt} of PCM (30 °C, 35 °C, 40 °C and 44 °C). Among these 44 °C T_{melt} of RT44 PCM reduced the T_{PV} maximum of 28 °C. Secondly, several researchers worked on establishing the effect of thickness of PCM employed, general thumb rule that increase in PCM thickness enhances the mass heat transfer between PV module back surface and PCM and it favors reducing the T_{PV} in higher-order and for longer time [32]. Further, it is observed that beyond 2 cm thickness of PCM the T_{PV} reduction is poor [30].

Mahamudul et al. [33], [34] figured out that filling PCM in the metal container creates the conduction barrier as it is difficult to attain the perfect physical contact with the PV module back surface. Also, PCM has a low thermal conductivity (K_{PCM}) that induces the thermal conduction barrier at the time of charging and discharging. Further, to minimize this contact loss PCM is stuffed directly on the PV module back surface and plexiglass is used to seal the backside of the PCM. In such a case, PCM receive thermal energy directly from the back surface of the PV module without any transitional layer [35], [36]. This technique resulted in better T_{PV} reduction. However, still conduction barrier occurred in PCM due to its low K_{PCM} is not addressed [37]. Several studies are performed to minimize this PCM conduction barrier by incorporating thermal distribution heat sink projecting inside the PCM that helps to increase heat transfer. Following that, expandable graphite (EG) [38], [39], metal scrap, copper powder and metal foams [40] are also composited with PCM to enhance the PCM thermal conductivity (K_{PCM}).

It is noted in above literature and Table 1 most of the research groups focused on finding the suitable PCM and the ways to enhance the K_{PCM}, none of them were considering the PCM re-conduction during the afternoon other than our previous study [39] and also very few of them discussed the disadvantage of the PCM especially the period when phase changes to liquid during this high sunshine hours. Elavarasan et al. [41] examined OM29 organic PCM to cool the PV module under hot climatic conditions, resulting in PCM integrated T_{PV} starts to rise compared to PV without PCM. With a drastic rise in T_{PV} due the extreme outdoor condition such as high ambient temperature (T_{amb}) and solar irradiance, the entire PCM melted within an hour of experimentation period. As mentioned earlier PCM liquid state is ineffective in extracting the heat from PV module back surface, even though the same PCM achieved effective T_{PV} reduction in winter. PCM performance differs based on the outdoor condition, which is unpredictable and unstable for every day and every month. Under this circumstance, integrating PCM containers with the PV module using physical contact could be effective for some days and exacerbate for some days also it creates the thermal and physical stress on the PV module.

Major problems finding in conduction-based PV module cooling techniques are summarized below.
• PCM reconduction rise the $T_{PV}$ than conventional PV module during afternoon period of the experimenta-
tion [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 turns 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 struc-
ture 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 $H_m$ with-
out 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 meth-
ods 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 son-
ication 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].
Currently 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>$ΔH_m(\text{J/g})$</td>
<td>180</td>
</tr>
<tr>
<td>$\rho$ (g/cm³)</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 ($S = 2.5\text{D}$), as shown
in Fig. 2 (a). From our previous study, it was clear that selec-
tive 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 polycrystalline 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 auxilary 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>Shingung 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°</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 m²</td>
</tr>
<tr>
<td>PV module tedlar emissivity</td>
<td>0.03</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 ($\eta_{PV}$).

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

\[
h_{PV\rightarrow air} = \left( \frac{K_{PV\rightarrow air} N_{up_{PV\rightarrow air}}}{L_{PV}} + \varepsilon_{PV, h} \sigma F_{PV\rightarrow air} (T_{PV} + T_{air}) (T_{PV} + T_{air}) \right)^2
\] (2)

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

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

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

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

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

\[
T_{sky} = 0.0522T_{amb}^{1.5}
\] (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].

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

\[
\alpha_{\text{AI}} I(t) A_{\text{AI}} = [-h_{\text{PV} \rightarrow \text{AI}} (T_{\text{AI}} - T_{\text{PV}}) \]
\[-h_{\text{air} \rightarrow \text{AI}} (T_{\text{AI}} - T_{\text{air}}) - h_{\text{AI} \rightarrow \text{PCM}} (T_{\text{AI}} - T_{\text{PCM}})] A_{\text{AI}}
\]

(8)

where,

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

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

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

\[
m_{\text{air}} C_{\text{air}} \frac{dT_{\text{air}}}{dt} = [-h_{\text{PV} \rightarrow \text{air}} (T_{\text{air}} - T_{\text{PV}}) \]
\[-h_{\text{air} \rightarrow \text{AI}} (T_{\text{air}} - T_{\text{AI}})] A_{\text{air}}
\]

(9)

C. RADIATION SOURCE PCM MATRIX

Equation (10) represents the amount of thermal energy that has absorbed at particular distance and 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).

\[
\frac{dT_{\text{PCM}}}{dt} = [-h_{\text{AI} \rightarrow \text{PCM}} (T_{\text{AI}} - T_{\text{PCM}}) \]
\[-h_{\text{PCM} \rightarrow \text{amb}} (T_{\text{PCM}} - T_{\text{amb}})] A_{\text{PCM}}
\]

(10)

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

(11)

\[
h_{\text{PCM} \rightarrow \text{amb}} = \left( N_{\text{air}} A_{\text{l}} \times \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}} + \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}} \right) + (\varepsilon_{\text{Al}} \sigma (T_{\text{Al}}^4 + T_{\text{amb}}^4) (T_{\text{Al}}^4 + T_{\text{amb}}^4)^2 + \frac{K_{\text{Al}}}{\Delta X_{\text{Al}}} \right)
\]

(12)

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

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

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

\[
X_2 = h_{\text{PV} \rightarrow \text{air}} + h_{\text{PV} \rightarrow \text{sky}} + h_{\text{PV} \rightarrow \text{amb}} + h_{\text{PV} \rightarrow \text{AI}}
\]

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).

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

(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

\[
\frac{dT_{\text{PV}}}{dt} = \frac{\beta_{\text{PV}} (\eta_{\text{PV}} C_{\text{PV}} (dT_{\text{PV}^0}/dt)}{\beta_{\text{PV}} (\eta_{\text{PV}} C_{\text{PV}} + X_2 \beta_{\text{PV}})}
\]

(13)

\[
T_{\text{AI}} = \frac{h_{\text{PV} \rightarrow \text{AI}} T_{\text{PV}} + h_{\text{air} \rightarrow \text{AI}} T_{\text{air}} + h_{\text{AI} \rightarrow \text{PCM}} T_{\text{AI}} - \alpha_{\text{AI}} I(t)}{h_{\text{PV} \rightarrow \text{AI}} + h_{\text{air} \rightarrow \text{AI}} + h_{\text{AI} \rightarrow \text{PCM}}}
\]

(14)

\[
\frac{dT_{\text{air}}}{dt} = \frac{(h_{\text{PV} \rightarrow \text{air}} T_{\text{PV}} + h_{\text{air} \rightarrow \text{AI}} T_{\text{AI}} + m_{\text{air}} C_{\text{air}}) A_{\text{air}}}{(h_{\text{PV} \rightarrow \text{air}} + h_{\text{air} \rightarrow \text{AI}}) A_{\text{air}} + m_{\text{air}} C_{\text{air}}}
\]

(15)

\[
\frac{dT_{\text{PCM}}}{dt} = \frac{-h_{\text{AI} \rightarrow \text{PCM}} T_{\text{AI}} + h_{\text{PCM} \rightarrow \text{amb}} T_{\text{amb}} + m_{\text{PCM}} C_{\text{PCM}} (dT_{\text{PCM}^0}/dt)}{m_{\text{PCM}} C_{\text{PCM}} - (h_{\text{AI} \rightarrow \text{PCM}} + h_{\text{PCM} \rightarrow \text{amb}}) A_{\text{PCM}}}
\]

(16)
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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 6 mm spacing, during experimentation, $T_{amb}$ reached a maximum of 33 °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 $T_{PV}$ raised to a maximum of 60 °C that causes to drop the system performance by 15%. For PV system with PCM matrix integrated, $T_{PV}$ is reduced until 15:00 with a maximum of 2.5 °C. After 15:00, PCM turns to liquid, but this novel PCM matrix did not increase the $T_{PV}$ 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 $T_{PV}$ 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 $T_{PV}$ reduction. However, it did not increase the $T_{PV}$ until 11:00 as shown in Fig. 5, but after 11:00 slightly, $T_{PV}$ 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 $T_{PV}$. Even though this thermal resistance could not bear and sustain the rise in $T_{PV}$ for a longer time like conduction source PCM, at the time of 16:30 both $T_{PV}$ remains the same.

C. RADIATION SOURCE PCM MATRIX AT 12 mm SPACING

Further, the PCM matrix is integrated at 12 mm, resulting minor $T_{PV}$ 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 $T_{PV}$ at the time of peak sunshine, but in this 12 mm spacing also both $T_{PV}$ remains constant after 16:00. Comparatively, 6mm spacing yields higher $T_{PV}$ reduction than other spacing; also, it did not increase the $T_{PV}$ 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 $T_{PV}$ 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

#### TABLE 4. Consecutive optimized PCM matrix experimental day 3 (19/03/2018) and day 4 (20/03/2018) solar irradiance, $T_{amb}$ and $T_{PV}$ for both PV with and without PCM matrix.

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Solar Irr (W/m²)</th>
<th>$T_{amb}$ (°C)</th>
<th>$T_{PV}$ without PCM (°C)</th>
<th>$T_{PV}$ with PCM (°C)</th>
<th>Solar Irr (W/m²)</th>
<th>$T_{amb}$ (°C)</th>
<th>$T_{PV}$ without PCM (°C)</th>
<th>$T_{PV}$ with PCM (°C)</th>
</tr>
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<tbody>
<tr>
<td>9:00</td>
<td>419</td>
<td>25.1</td>
<td>39.8</td>
<td>39.7</td>
<td>407</td>
<td>24.5</td>
<td>37.8</td>
<td>37.7</td>
</tr>
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<td>10:00</td>
<td>606</td>
<td>27.5</td>
<td>46.4</td>
<td>45.4</td>
<td>588</td>
<td>26.9</td>
<td>44.1</td>
<td>43.1</td>
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<tr>
<td>10:30</td>
<td>684</td>
<td>28.8</td>
<td>50.0</td>
<td>48.5</td>
<td>664</td>
<td>28.2</td>
<td>47.5</td>
<td>46.1</td>
</tr>
<tr>
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<td>782</td>
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<td>54.4</td>
<td>53.0</td>
<td>759</td>
<td>29.2</td>
<td>51.7</td>
<td>50.3</td>
</tr>
<tr>
<td>11:30</td>
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<td>30.2</td>
<td>55.8</td>
<td>53.9</td>
<td>744</td>
<td>29.6</td>
<td>53.0</td>
<td>51.2</td>
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<tr>
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<td>805</td>
<td>30.6</td>
<td>58.3</td>
<td>57.0</td>
<td>781</td>
<td>30.0</td>
<td>55.4</td>
<td>54.1</td>
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<td>30.5</td>
<td>59.7</td>
<td>58.5</td>
<td>723</td>
<td>29.9</td>
<td>56.7</td>
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<td>59.9</td>
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<td>30.5</td>
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<td>56.4</td>
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<td>30.9</td>
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<td>55.7</td>
<td>590</td>
<td>31.6</td>
<td>52.9</td>
<td>52.9</td>
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<td>31.3</td>
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<td>50.1</td>
<td>50.0</td>
<td>411</td>
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<td>47.5</td>
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<td>47.5</td>
<td>313</td>
<td>31.5</td>
<td>45.3</td>
<td>45.2</td>
</tr>
<tr>
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<td>189</td>
<td>31.5</td>
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<td>42.8</td>
<td>183</td>
<td>30.8</td>
<td>40.1</td>
<td>40.6</td>
</tr>
</tbody>
</table>

**FIGURE 8.** Comparative analysis of radiation and conduction source PCM (15/03/2018).

**FIGURE 9.** Comparison of temperature-corrected $V_{max}$ using optimized spacing and PV without PCM (15/03/2018).
0.30 - 0.48%. Fig. 9 shows a reduction in $T_{PV}$ increases the $V_{max}$ until 15:00 further $V_{max}$ is neutralized for PCM matrix at 6 mm as $T_{PV}$ 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 $T_{PV}$ because solar cell is a current generator that is highly correlated with solar irradiance. Experimental data reveals that the temperature coefficient of $I_{sc}$ is 0.049%/°C from STC that makes minor fluctuation in current profile (not shown here) because less $T_{PV}$ 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 $I_{max}$ 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 $T_{PV}$ loss. Among other losses, $T_{PV}$ loss takes a bigger number. Since PV module electrical efficiency is sensitive to $T_{PV}$ and it becomes imperative to reduce it or to run the $T_{PV}$ 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 $T_{PV}$ 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, $T_{amb}$, 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 tedlar 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.

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REFERENCES


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