Preparation and selection of a eutectic phase change material for cooling the PV module under Thailand climatic conditions

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Abstract. Several studies have found that incorporating an appropriate melting temperature (Tmelt) of Phase Change Material (PCM) behind the PV module enhances the cooling effect. In this study, PCM is selected for hybrid cooling for summer and winter using six years of meteorological data obtained from NASA. Considering the hybrid cooling method, winter season Tamb is selected to optimize the Tmelt as the selected PCM must reach the latent heat property in an early sunshine. It is found that during winter, 70 % of the period, Tamb lies around 28 ℃ whereas the Tmelt of PCM should be in the range of 31-34 ℃ according to the modified optimization method. In total, twelve combinations of eutectic mixtures are prepared using Lauric Acid (LA), Myristic Acid (MA) and Stearic Acid (SA), and their thermophysical properties are analysed using a differential scanning calorimeter. Only seven eutectic mixtures attain the 31-34 ℃ Tmelt among that LA:MA (70:30) and LA:SA (70:30) show excellent latent heat of fusion of 194 J/g and 190 J/g, respectively. Furthermore, it is recommended that LA:MA (70:30) and LA:SA (70:30) are suitable for Thailand's climatic conditions for PV module cooling.

Keywords: Phase change material, PV module, Cooling, Eutectic, Climate

1 Introduction

An increase in human population adversely increases the consumption of energy in turn of fuel, electricity, and other natural resources. Consumption of fossil fuels mainly increased CO_2 emissions and health issues, according to the IEA world energy outlook 2021, global temperature will rise by 1.5 ℃ every year to 2030 and following that it could reach a maximum of 2.6 ℃ in the following periods. Electricity and heat consumption is the major contributor following that industry and transport holds the second and third positions,

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respectively in global warming and temperature rise [1]. There are several renewable energy-based power and heat generators that are commercialized, among them solar energy gained recent attention in both heat and electricity. The major concern in solar Photovoltaic (PV) systems is their internal loss during power generation. Solar PV systems undergo several losses under real-time operating conditions among that PV module temperature (T_{PV}) loss itself reduces the power generation maximum of 0.65 % per increase in the operating temperature higher than the Standard Test Condition (STC) [2]. Several studies are conducted to cool the excess raise in T_{PV} using sensible and latent heat storage material among these PCM becomes vital in cooling the PV module and extracting the heat energy for thermal applications [3-5]. Generally, PCMs are placed behind the PV module using physical or non-physical contact, as soon as the T_{PV} increases, heat energy transfers to the PCM surface [6, 7]. PCM contains excellent heat storage capacity, and the melting temperature (T_{melt}) should be in an optimized range nonetheless cooling effect adversely reduces the benefit rather than the uncooled PV module. Selecting a low T_{melt} enables the cooling effect in early sunshine hours by utilizing the latent heat of fusion (H_m) completely resulting during the effective sunshine hours PCM stores the heat energy in a liquid state that is ineffective to cool the PV module [8]. Secondly, selecting the T_{melt} equal to the ambient temperature (T_{amb}) failed to cool the PV module as the PCM absorbs thermal energy both from surrounding and PV module on the other hand, PCM struggles to dissipate the energy to surroundings [9]. Increasing the thickness of PCM can remove the complexity in dissipation though it increases the total weight, cooling system cost and reduces the mechanical strength of PV mounting structure. Other than the above mentioned criteria, if the selected PCM has a high T_{melt} will also leads to ineffective cooling as the PCM will start to melt after the peak sunshine hours resulting early period of the solar PV operation will face the cooling issues [10]. Above mentioned all criteria for selecting the PCM are mostly applicable to passive cooling as the PCM is not supported by an auxiliary unit to remove the heat from the PCM. Other than these studies, some researchers recommended to use more than one PCM unit to cool the PV module effectively for an entire year [11]. Especially in tropical location, there is a noticeable variation in T_{amb} and that results the PCM to perform effectively in summer or winter [9]. However, if the PCM is actively cooled during sunshine hours, a single unit of PCM structure is capable to cool the PV module in an entire year. Generally, actively cooled PCM structures are often integrated for hybrid applications where the PCM container is directly attached on the PV module back surface and other surfaces are insulated well to control the heat dissipation or gaining from the surrounding. In such a case, selecting an appropriate T_{melt} based on the experimental location will cool the PV module effectively during the winter and the same PCM will enable the cooling effects in summer with the association of fluid flow inside the PCM. Auxiliary fluid will remove the heat and favors the PCM to sustain the H_m for an entire day of operation. In this study, meteorological data such as solar irradiance, wind speed and T_{amb} are obtained from the NASA to find the appropriate T_{melt} of PCM for Thailand climatic conditions. Based on the meteorological inputs, LA, MA, and SA are selected as these eutectic mixtures are thermally stable and reliable for low temperature applications. From these base mixtures, twelve different combinations are prepared and their thermophysical properties are analyzed using Differential Scanning Calorimeter (DSC). Further, a simplified PCM selection model is developed based on our previous study and suitable eutectic mixtures are selected that are thermally stable according to the input parameters of NASA data.

2 Materials and methods

2.1 NASA meteorological data for PCM selection

In a tropical location, there is a wide variation in T_{amb} as compared to subtropical location more likely subtropical location requires the PCM unit to cool the PV module in summer and during the winter, low T_{amb} with wind can dissipate the heat from the PV module [9]. In a tropical location such as Thailand T_{amb} is moderately high and tends to require an PCM unit to cool unless the winter cooling rate of the PV module is lower than summer. The reason behind this deterioration in annual cooling is that, in most cases, PCM T_{melt} is selected based on the peak sunshine hours which is from the summer. Optimizing a PCM based on the summer climatic conditions will not perform in the same way for winter. However, integrating different PCM units for summer and winter will make the complexity in maintenance and system lifetime and cost effectiveness. Thailand is hot climatic country still the household water heaters are widely used for bathing and washing the clothes. Considering the demand of hot water usage in summer and complexity in using the different PCMs for summer and winter, it is recommended to implement the PCM unit with an auxiliary fluid cooling technique whereas the single unit of PCM can exhibit higher cooling effect for both summer and winter. During the summer, PCM can be cooled using water flow inside the PCM chamber and can be utilized the hot water for domestic or mid-commercial purpose in such a case PCM will be effective for annual power enhancements. Further, in this study last 6 years meteorological data are obtained from open-source NASA power data access in an hourly interval for 16.47, 102.82.

2.2 Preparation of eutectic PCM

In this study, three organic fatty acids were taken to prepare the eutectic mixture namely LA, MA and SA as shown in figure 1 and their properties are listed in Table 1. These fatty acids are thermally stable for longer operation and applicable for low temperature applications such as cooling the PV owing to the excellent thermophysical properties [12]. In total 12 different proportions of mixtures are prepared using probe sonication following that prepared mixtures are examined using DSC with a heating rate of 1 ℃/min. Thermophysical property of the prepared mixture such as T_{melt} and H_m are examined to find the appropriate PCM for Thailand's climatic conditions.

Fig.1. Organic fatty acids for eutectic mixture

Table 1. Thermophysical properties of organic fatty acids [12]

PCM	Melting temperature (℃)	Latent heat of fusion (J/g)
Lauric acid	43.93	178.11
Myristic acid	54.28	191.27
Stearic acid	69.62	217.62

2.3 Criterion for PCM selection

A simplified PCM selection criteria is developed based on our previous study as mentioned in section 3.3. To select the desired range of PCM T_{melt}, six years meteorological data of the selected location such as solar irradiance, wind speed and T_{amb} are taken as input parameters. Solar irradiance and wind speed represent the nature of power generation and thermal stress due to surroundings with respect to the T_{amb}. As mentioned earlier, selecting a single unit of PCM will benefit in summer or winter, considering these complications, a hybrid cooling method is adapted for this study and the PCM is selected based on the winter T_{amb}. With the help of auxiliary fluid, PCM maintains the H_m property for longer time in summer and delivers the higher cooling effect for throughout year.

3 Results and discussions

3.1 Input parameters for PCM selection

Figure 2 shows the annual solar irradiance of the selected location in Thailand. The pattern of solar irradiance throughout the year shows similar trends for all seasons. The highest solar irradiance occurred in summer with an average of 937 W/m^2 (2016-2021) owing to the clear sky and during the winter, it was 833 W/m^2. Beneficially in winter, the effective solar irradiance attained at 10 AM which shows Thailand is rich in solar energy to fulfill the national energy demands. Wind speed of the selected location showed a huge variation according to the seasonal changes, in summer most of the days wind speed sustained at 3 m/s that induced in increasing the T_{PV} higher than other seasons. Beneficially, in winter peak wind speed reached 10 m/s and the higher frequency recorded to be 6 m/s as shown in figure 3. It is noted that, T_{amb} is the main cause in increasing the T_{PV} whereas in summer the peak T_{amb} was 42℃ and during the winter it was 35 ℃. In both seasons, T_{amb} is higher than the STC conditions and PV module suffers to dissipate the heat that has been generated during the photovoltaic effect and absorbed by the sun as shown in figure 4. However, 70% of the days in summer and winter T_{amb} sustained at the peak of 35 ℃ and 28 ℃, respectively. Thus, selecting a PCM by considering the summer period will cause a decrease in cooling effect for winter.

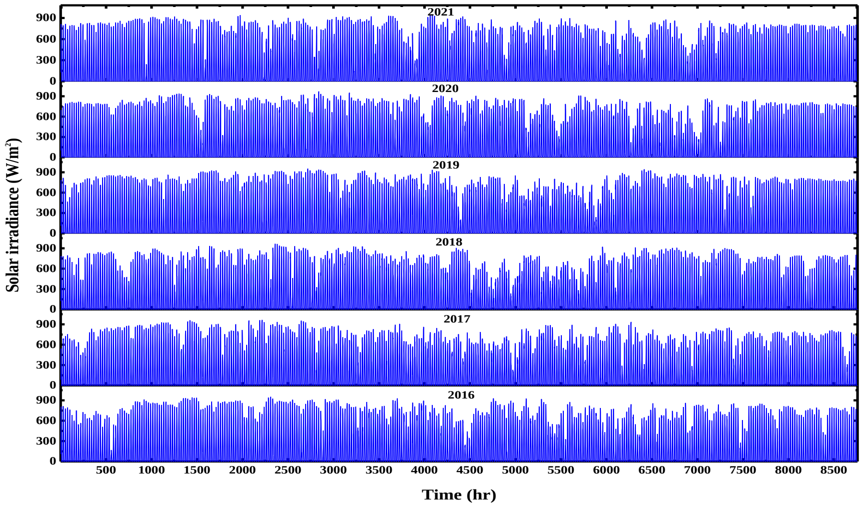

Fig.2. NASA sourced solar irradiance for the period of 2016 – 2021

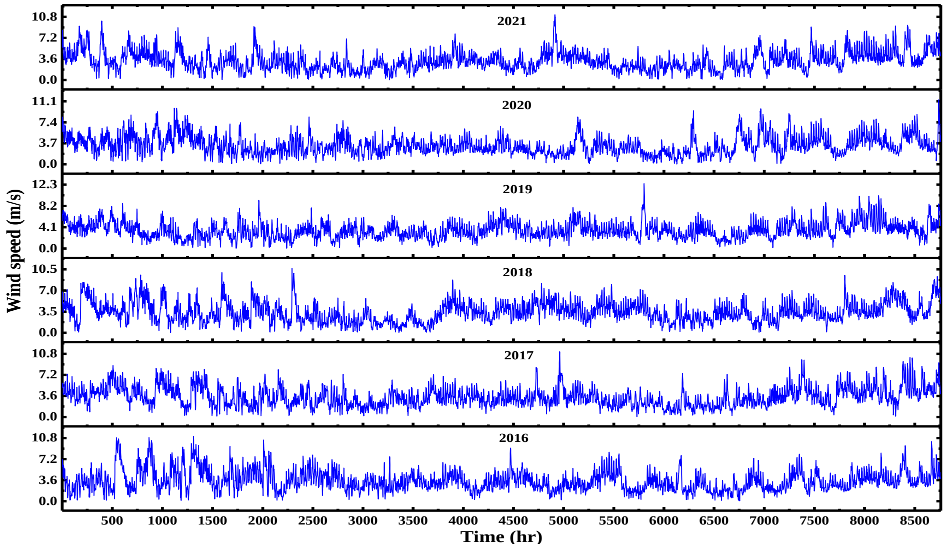

Fig.3. NASA sourced wind speed for the period of 2016 – 2021

As mentioned earlier selecting two PCMs for a single location will increase the complexity in operation. Notably, in this study PCM selection is aimed for hybrid cooling, thus, the PCM is selected based on winter climatic condition which can remove the higher amount of heat from the PV module during summer. During the summer, a low T_{melt} PCM, that is selected based on the winter season, will liquefy in the early sunshine hours. However, with a favor of fluid flow inside the PCM container, it will maintain the H_m for throughout the sunshine hours. The operation of PCM mainly depends on the period of melting state, if the PCM is selected according to the summer climatic conditions. PCM will start to melt at noon and off-sunshine hours in winter and the cooling effect will be delivered in the off-sunshine hours resulting in an ineffective cooling for winter.

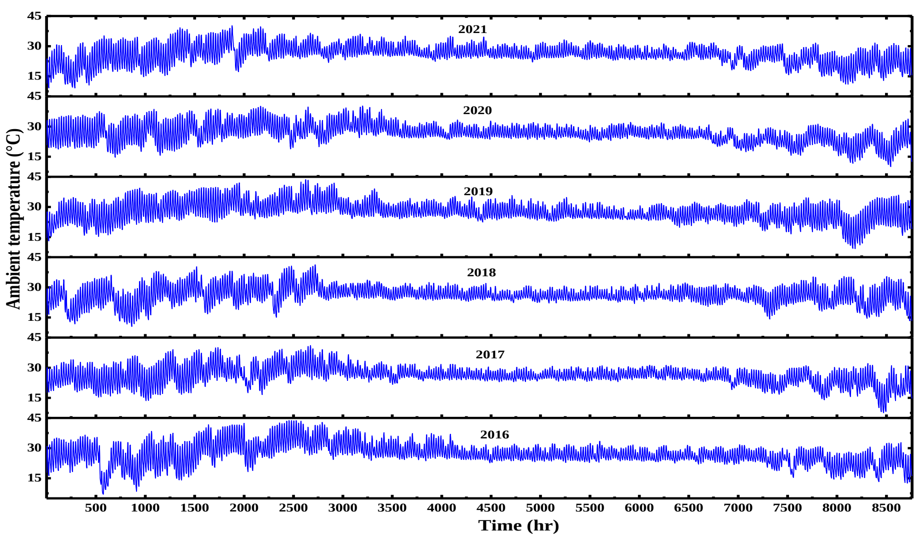

Fig.4. NASA sourced T_{amb} for the period of 2016 – 2021

3.2 Thermophysical properties of prepared eutectic mixture

Figure 5 (a) shows the DSC analysis heating curve of LA and MA based eutectic mixture. MA with a 100 wt% depicts the onset T_{melt} of 50 °C that is the initial state of PCM melting, generally the PCM T_{melt} is widely marked where the latent heat state is activated which means the sharp decline in heat flow. In the melting curve, tangent will be plotted between the sharp decline in heat flow and base integral area of the curve. According to the tangent curve, LA:MA (0:100) attains the T_{melt} of 53 °C with a total integral area of 228 J/g. In this study, LA is used in a high proportion rate as the MA T_{melt} is high, and it could not be appropriate for mixing in a high proportion for PV module cooling. LA with a 90 wt% proportion shows the improper texture in the chemical bonding, and it shows double peak during the heating cycle. First heating curves shows an onset T_{melt} of 31 °C with a tangent of 33.57 °C and a sharp decline in heat flow to the -2800 µW and following that second peak tangent attains at 35.6 °C with an overall integral area of 191 J/g. Notably, integral area of the LA:MA (90:10) is higher than the pure LA as the 10 wt% of MA enhances the heat storing capacity. The second composition of MA is increased to 20 wt% and notably single peak attains during the melting process with an onset T_{melt} of 30.5 °C and an effective latent heat property is activated at 33.4 °C. The peak T_{melt} of the LA:MA (80:20) reaches to 35.56 °C and the heat flow starts retaining to the base line whereas the clear fluctuation is noted at 36 °C during the liquid transformation and overall integral of the sample is 185 J/g that is lower than pure LA and LA:MA (90:10). Following that LA:MA (70:30) and LA:MA (60:40) show onset temperatures of 31 °C and 31.1 °C and the latent heat property attains at 33.6 °C and 33.7 °C, respectively. Beneficially, LA:MA (70:30) shows the sharp decline in heat flow as compared to LA:MA (60:40) and during the liquid state withdrawal of latent heat property is identical to the base material of LA and MA. In overall, LA:MA (70:30) shows the excellent thermophysical properties among the other four different proportions of LA and MA, in particularly the H_m is high that can favour to achieve the cooling effect in higher order for PV module.

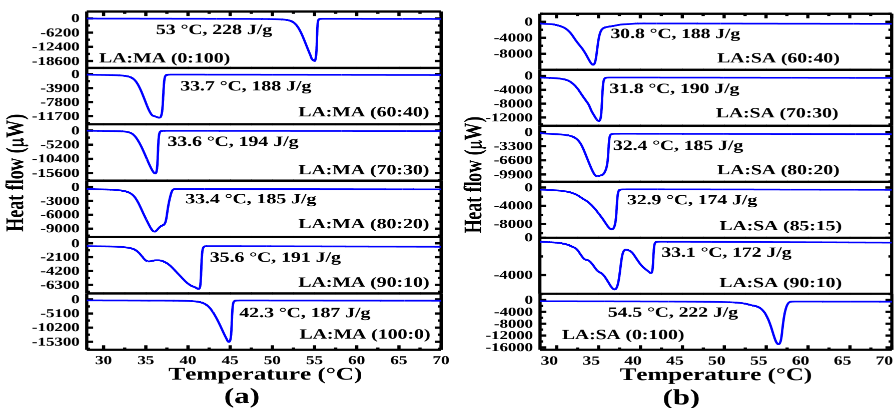

Fig.5. DSC analysis of (a) Lauric acid: Myristic acid and (b) Lauric acid: Stearic acid

Figure 5 (b) shows the eutectic mixture of LA and SA, in this composition SA is considered as a low mixing component as the T_{melt} is higher than LA. SA with 100 wt% proportion shows an excellent latent heat property with an integral area of 222 J/g and the T_{melt} of 54.5 °C. Mixing the 10 wt% of SA into LA attains to two peaks in heating cycle with an integral area of 172 J/g which is lower than the other proportions of LA:MA and LA:SA. The reason behind this massive deterioration in heat storage capacity is that the first heating curve peak T_{melt} is 36.67 °C and following that the mixture attain the second state of semi-

 https://doi.org/10.1051/e3sconf/202337903004

solid specific heat capacity ($C_{p,s}$) rather than performing a single state of $C_{p,s}$, H_m and liquid specific heat capacity ($C_{p,l}$). Following that both peaks attain fluctuations in absorbing the heat energy showing that LA:SA (90:10) is not suitable for any form of thermal applications due to its improper texture. Secondly, increasing the SA proportion of 15 wt% with LA shows a single peak in heating cycle with an onset, and T_{melt} of 28.5 °C and 32.9 °C, respectively. However, the heat storing capacity of LA:SA (85:15) is nearly the same as LA:SA (90:10) due to the wide variation in activating the latent heat property such as the difference between the onset and T_{melt} is 4.4 °C. The third proportion of 20 wt% SA with LA shows a higher H_m of 185 J/g and a sharp decline in heat flow describing that the mixture is stable in texture. However, it attains double peaks T_{melt} in a single heating curve, although sharp liquid state was attained. With a proportion of 30 wt% and 40 wt% SA, they show a single heating peak with onset temperatures of 28.9 °C and 28.2 °C, respectively. These mixtures show a slight fluctuation in latent heat property which is negotiable and latent heat tangent slopes based T_{melt} are 31.8 °C and 30.8 °C, respectively. Comparatively, H_m for both mixtures are 190 J/g and 188 J/g, respectively which are higher than the other proportions of SA with LA.

3.3 PCM selection for Thailand climatic condition

In this study, PCM is selected for hybrid cooling method in such a case, winter season T_{amb} is considered to optimize the PCM T_{melt}. As mentioned earlier, selecting a low T_{melt} of PCM can favour in cooling the PV module during summer with the assistance of auxiliary fluid flow but selecting a high T_{melt} of PCM will not control the raise in T_{PV} during the winter. Because the PCM will be in solid state during the early and peak sunshine hours. Selection of PCM for Thailand climatic condition is adopted from our previous studies [9, 13] with a modification according to the present study. Selected location winter T_{amb} lies around the peak of 28 °C for 70% of the period and that turns to be a key parameter in optimizing the PCM T_{melt}. Based on our previous works and literature, it is necessary to maintain the PCM T_{melt} around 3-6 °C higher than the peak T_{amb}. According to that criterion shown in Figure 6, in this study selected PCM should have a T_{melt} in a range of 31-34°C. Considering this operating temperature, LA, MA, and SA are taken as base materials to prepare the different proportions of eutectic PCMs. From the DSC studies, LA:MA (60:40, 70:30 and 80:20) and LA:SA (70:30, 80:20, 85:15 and 90:10) meet the requirement of suggested T_{melt} for annual PV module cooling. Considering the long-term use of PCM, the LA:MA (70:30) and LA:SA (70:30) are selected as it contains sharp melting point with a higher H_m as compared to other eutectic mixtures. While the LA:MA (60:40) and LA:MA (80:20) show the fluctuation in heat absorption as well as LA:SA (80:20), LA:SA (85:15) and LA:SA (90:10) attain similar complexities in heat absorption, less H_m and double heat absorption peaks.

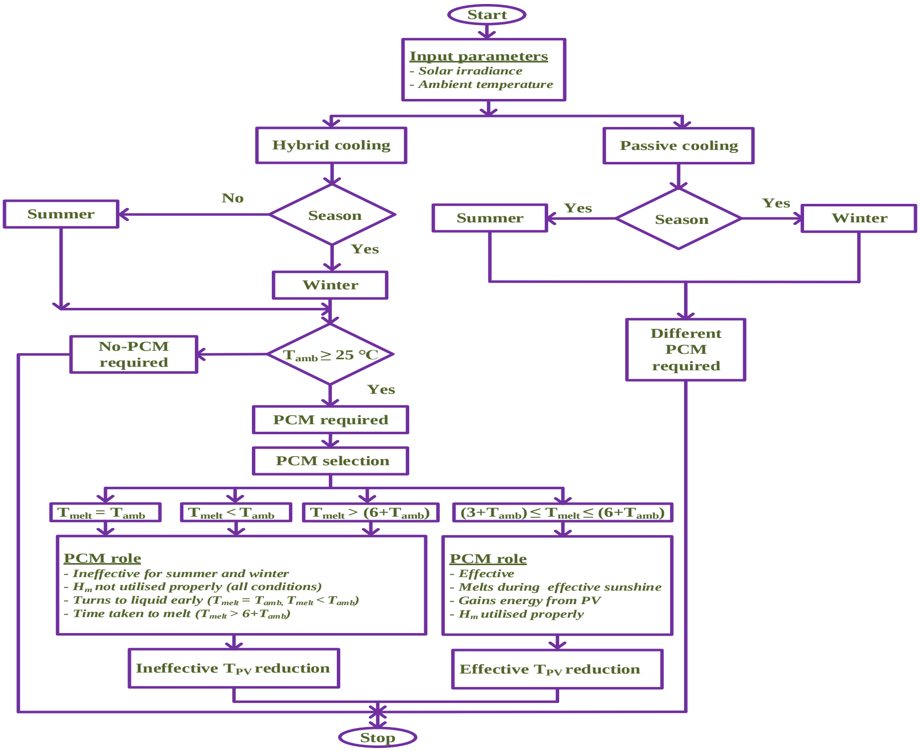

Fig.6. Modified flow chart for PCM selection to cool the hybrid PV module method [9].

4 Conclusion

Eutectic PCM is selected for the Thailand climatic condition using the last six years of meteorological data. Annual solar irradiation of the selected location is identical in summer and winter with minor variations showing that Thailand is rich in solar energy. Following that T_{amb} also shows minor differences in summer and winter that causes to perform the PV modules under severe thermal stress throughout year. In summer and winter, 70% of the day, T_{amb} are 35 ℃ and 28 ℃, respectively. In most cases, PCM T_{melt} is selected based on the summer that leads to reduce the cooling effect in winter due to high T_{melt}. However, in a hybrid cooling system it is necessary to consider the summer T_{amb} unless the PCM will liquefy in the early sunshine hours. In this study, PCM is selected for hybrid cooling method, in such a case, PCM T_{melt} can be selected based on the winter climatic conditions and hybrid system will retain the latent heat property in summer throughout the sunshine hours. Developed PCM optimizing technique shows that T_{melt} should be in the range of 31-34℃. The results obtained from the DSC show that only seven PCMs are passed the criteria of PCM selection among that LA:MA (70:30) and LA:SA (70:30) are chosen as the best material owing to the suitable T_{melt} and high H_m with an excellent endothermic peak. It is recommended to use the LA:MA (70:30) and LA:SA (70:30) for cooling the PV module under Thailand’s climatic conditions.

Acknowledgement

The authors would like to thank the Centre for Alternative Energy Research and Development, Khon Kaen University for providing the generous grant under the postdoctoral fellowship program.

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