

# A Feasibility of Applying Phase Change Materials Derived from Polymer/VO<sub>2</sub> Composites to Enhance Performance of PV Modules

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## Abstract

This study investigates the feasibility of using vanadium dioxide (VO<sub>2</sub>), a thermochromic and phase change material, to enhance the performance of photovoltaic (PV) modules. By coating a polymer film loaded with VO<sub>2</sub> onto the modules, it was hypothesized that the module temperature can be reduced due to the endothermic latent heat associated with the phase transition of VO<sub>2</sub>. As a result, an improvement in power conversion efficiency (PCE) is expected. Firstly, VO<sub>2</sub> particles were synthesized via a hydrothermal method and subsequently mixed with an acrylic binder at various concentrations (0.1-1.5 wt%) prior to film casting. Crystalline structure and morphology of the polymer composite films were characterized by X-ray diffraction and scanning electron microscopy techniques. Transition temperatures and optical properties of the composite films were determined by differential scanning calorimetry and UV/Vis spectroscopy. Heat shielding properties of the films were evaluated by monitoring temperature change inside a model house installed with the polymer composite films. The system exhibited remarkable temperature reduction with higher particle loading resulting in a more temperature drop. Additionally, the feasibility of applying these films to enhance the efficiency of PV modules was explored. Compared to reference PV modules without coating, the efficiency of the devices coated with polymer/VO<sub>2</sub> film increased by approximately 1.74 %. The results were discussed in relation to phase transition, latent heat of VO<sub>2</sub>.

**Keywords:** Polymer composites; Vanadium dioxides; NIR shielding films; PV cooling

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## 1. Introduction

Temperature regulation plays a crucial role in energy-related applications, such as enhancing energy efficiency in buildings and improving power conversion efficiency (PCE) of photovoltaic (PV) modules. In the latter case, PV module performance is related to temperature regulation, as approximately 20 % of the solar radiation captured by PV modules is converted into heat, which is then absorbed by the module's surface [1]. This leads to an increase in the operating temperature of the modules, which negatively impacts their performance. It has been estimated that PCE decrease by approximately 0.45 – 0.65 % for every 1 °C increase in temperature [2 – 4]. Additionally, the operating temperature of PV modules is influenced by the heat generated during the power conversion process [2, 5, 6].

In this context, various techniques have been developed and implemented for cooling PV modules. Broadly, PV cooling techniques can be categorized into 2 main groups: active cooling techniques, passive cooling techniques [7]. Each technique presents distinct advantages and limitations. For instance, active cooling methods, which rely on mechanical devices to circulate air or water through the systems, provide high heat transfer rates but are associated with drawbacks such as high-power consumption, increased cost, and limited lifespans. In contrast, passive cooling techniques such as natural convection, and heat pipes, require no external energy input but generally offer lower cooling efficiency and are highly dependent on

ambient conditions. Cooling techniques that utilize phase change materials (PCM) also operate without external power and provide additional benefits, including chemical stability, cost-effectiveness, ease of use, and the ability to store heat and regulate temperature over time. PCM materials typically include the organic substances (such as paraffin and paraffin wax) and inorganic substances (such as calcium chloride hexahydrate). The cooling effectiveness PCM is largely influenced by factors such as heat capacity, latent heat, and thermal conductivity. Seto *et al.* [4] reported that using PCM reduced the operating temperature of PV modules from 59.40 – 52.60 °C, which corresponded to 3.08 % improvement in PCE. Hasan *et al.* [8] claimed that utilizing PCM achieved a temperature reduction of up to 35 °C, leading to PCE increase of up to 16 %. Noteworthy, thermal conductivity values of organic-based PCMs are intrinsically low. For example, the thermal conductivity of paraffins ranged from 0.18 – 0.20 (W mK<sup>-1</sup>) [2], which is significantly lower while inorganic materials like ZnO and Al<sub>2</sub>O<sub>3</sub> have the conductivity values of 13 W/mK and 40 W mK<sup>-1</sup>, respectively [4]. To enhance the cooling performance of paraffins, therefore, efforts were made by the incorporating metal oxides and/or nanoparticles with paraffins based PCM [4, 9 – 12]. For examples, Nada *et al.* [9] compared the cooling efficacy of PCM alone and PCM loaded with Al<sub>2</sub>O<sub>3</sub> nanoparticles, finding that temperature of the PV modules decreased by 8.10 °C and 10.60 °C, respectively. This corresponded to an increase in device efficiency by 5.70% and 13.20%, respectively. Similarly, Seto *et al.* [4] demonstrated that incorporating ZnO into paraffin-based PCM increase the PCE of PV panels from 11.16 % (with PCM alone) to 13.19 %. This improvement was accompanied by a temperature reduction from 55.40 – 52.62 °C.

Vanadium dioxide is recognized as a thermochromic material that exhibits a reversible phase transition from a monoclinic crystalline phase [VO<sub>2</sub>(m)] to a rutile phase when the temperature exceeds its critical transition point ( $T_c = 68$  °C) [13]. The transition is accompanied by a reduction in near infrared (NIR) transmittance, making VO<sub>2</sub> (m) an exceptional NIR shielding materials. In addition, to minimizes the gap between the ambient temperature and the transition temperature of VO<sub>2</sub> (m), the  $T_c$  of VO<sub>2</sub> can be reduced by doping with compounds such as fluorine (F), molybdenum (Mo), and tungsten (W) [14 – 17]. Various polymer/VO<sub>2</sub> composite films including PVC/VO<sub>2</sub> [18], PET/VO<sub>2</sub> [19], and EVA/VO<sub>2</sub> [20] have also been developed for use as window films to enhance energy efficiency in buildings.

Despite the notable NIR shielding performance of VO<sub>2</sub>, their use as coating to enhance the performance of PV modules has not been widely explored. Therefore, this study aims to investigate the effects of concentration of VO<sub>2</sub> particles on temperature regulation properties of the polymer composite films. Additionally, the feasibility of using the polymer/VO<sub>2</sub> films to improve efficiency of PV modules was also examined.

## 2. Materials and Methods

### 2.1 Chemicals

VO<sub>2</sub>(m) was synthesized via hydrothermal and calcination techniques, using vanadium pentaoxide (V<sub>2</sub>O<sub>5</sub>) and citric acid (C<sub>6</sub>H<sub>8</sub>O<sub>7</sub>) as a raw material and a reducing agent, respectively. First, a suspension of V<sub>2</sub>O<sub>5</sub> (1.82 g in 25 mL of deionized (DI) water) was prepared. An aqueous solution of citric acid (6.30 g in 25 mL DI water) was then gradually added, and the mixture was stirred at 80 °C for 3 h. The resulting mixture was transferred to a 100 mL Teflon-lined autoclave and subjected to a hydrothermal process in a hot-air oven at 200 °C for 24 h. Afterward, the product was filtered and washed sequentially with DI water and ethanol. The product was then dried in a vacuum oven at 80 °C for 3 h, followed by calcination in a tube furnace at 700 °C for 1 hour, under nitrogen (99.99%) atmosphere.

Next, to reduce the polarity of functional groups on the surface of VO<sub>2</sub>, the synthesized metal oxide was treated with a silane coupling agent, aminopropyl triethoxysilane (APTES). In the experiment, 6.50 g of synthesized VO<sub>2</sub> particles were dispersed in 50 mL of toluene and stirred for 10 min. The suspension was then ultrasonicated at 80 °C for 30 min. After that, 19.50 g of APTES (corresponding to 1/3 weight ratio of VO<sub>2</sub>/APTES) was added under constant stirring. The reaction was carried out at 80°C for 24 h under nitrogen atmosphere with vigorous mechanical stirring. Finally, the modified product was recovered by centrifugation, washed three times with ethanol, and dried in a vacuum oven at 80 °C for 3 h.

The polymer binder (Pliotec HDT12 from Synthomer) used was obtained from the RPSC Chemicals Co., Ltd. According to the datasheet from the supplier, it is a copolymer, colloidal dispersion of styrene-acrylic, with a solid content of 50% [21].

## 2.2 Preparation of NIR Shielding Films

The synthesized VO<sub>2</sub> (m) powder were mixed with 15 g of an acrylic-based binder. The concentration of VO<sub>2</sub> in the mixtures was varied at 0.10, 0.50, 1 and 1.5 wt%). Each mixture was placed in an ultrasonic bath and stirred continuously for 150 min. Subsequently, 5 mL of each mixture was transferred into a glass petri dish and left to dry at room temperature for two days. The resulting dried films, with an average thickness of approximately 0.290 ( $\pm$  0.04) mm, were then analyzed by SEM, DSC, FTIR, and XRD techniques. In addition, to prepare the polymer/VO<sub>2</sub> window films for heat shielding performance test, the above mixtures were coated onto a glass substrate (10  $\times$  10 cm<sup>2</sup>) by using a bar coater. The final film thickness was controlled by selecting an appropriate rod bar, which had a specified gap of 80  $\mu$ m between the rod and the substrate. The coating was left to dry completely overnight.

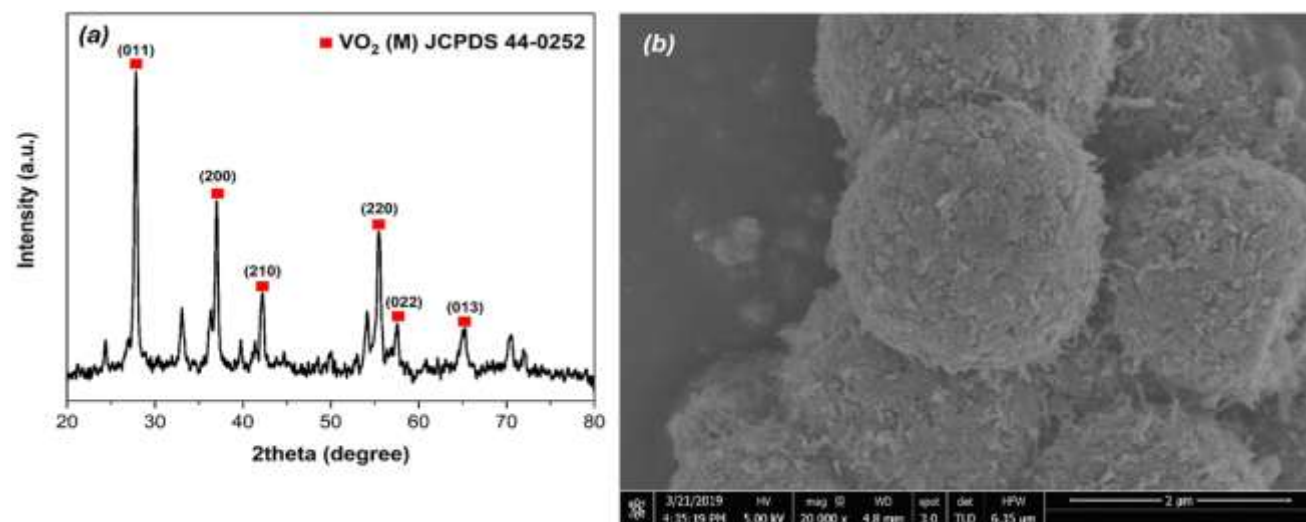
## 2.3 Characterizations

Crystalline structure of the VO<sub>2</sub> particles was characterized by XRD technique and presented in Fig. 1a. The XRD pattern revealed diffraction peaks at  $2\theta$  of 27.86°, 37.05°, 42.23°, 55.53°, 57.53°, and 65.00°, corresponding to the (011), (200), (210), (220), (022), and (013) crystal planes of the monoclinic VO<sub>2</sub> (JCPDS No. 44-0252), respectively. The crystallite sizes of VO<sub>2</sub> particles were also determined, using Scherrer's equation (equation 1) using the main peak at (011) and the results were 23.18 ( $\pm$ 2.24) nm.

$$D = \frac{0.89\lambda}{B \cos \theta} \quad (1)$$

Where, D = The mean crystalline size  
 $\lambda$  = X-Ray wavelength (Cu = 0.15406 nanometer)  
 B = The line broadening at half the maximum intensity (FWHM)  
 $\theta$  = The Bragg's angle

The morphology of VO<sub>2</sub> particles and the polymer composite films were examined by using a scanning electron microscope (SEM) technique using JEOL JSM-6610 LV instrument, equipped with energy dispersive X-Ray spectroscopy. The polymer/VO<sub>2</sub> specimens were prepared by cryogenic fracturing under liquid nitrogen atmosphere. The specimens were then coated with gold via a sputtering technique. The SEM experiment was performed with an acceleration voltage of 20 kV.



**Fig. 1** XRD pattern (a) and SEM image (b) of VO<sub>2</sub> particles.

UV/Vis spectra of the polymer composite films were recorded with a Shimadzu UV-3100 UV-Vis-NIR spectrophotometer. Percentage transmittance and reflectance were measured both in the visible light region (380 – 780 nm) and the near-infrared region (780 – 2500 nm), in accordance with ASTM E891. The critical transition temperature ( $T_c$ ) of the

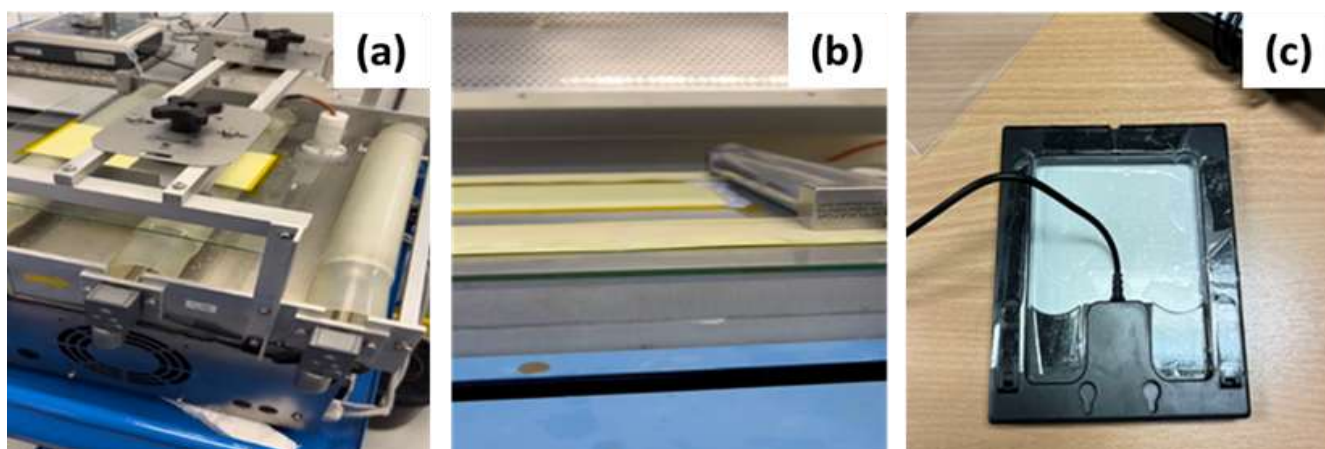
synthesized  $\text{VO}_2$  particles, representing the temperature at which  $\text{VO}_2$  undergoes a crystalline phase transition from the monoclinic phase [ $\text{VO}_2$  (m)] to the rutile phase, and the glass transition temperature ( $T_g$ ) of polymer composite films were determined by a differential scanning calorimetry (DSC) technique, using a NETZSCH (DSC 3500 Sirius) instrument. The DSC specimens were scanned over the temperature ranged between  $(-40)^\circ\text{C}$  and  $120^\circ\text{C}$  at the heating rate of  $10^\circ\text{C min}^{-1}$ , under the nitrogen gas atmosphere. To remove the thermal history of a specimen, the second heating DSC scan was run and the obtained thermogram was analyzed and presented.

#### 2.4 Heat Shielding Test

Heat shielding performance of polymer/ $\text{VO}_2$  films, coated on glass substrate, was tested by using a model house, installed with glass windows. An infrared lamp (BONGBADA Infrared light bulb 259 W) was used as a heating source to generate heat waves for the system. The temperature change inside the model house was recorded for every 1 min for up to 30 min, using a thermocouple placed inside the model house. Additionally, an infrared camera (SEEK thermal/Compact) was employed to monitor changes in temperature on the front side of the window substrates.

#### 2.5 Film Coating and Performance Test of PV Modules

A mixture of acrylic binder and of  $\text{VO}_2$  powder (0.1 wt%) was prepared. After sonication, the mixture was coated onto a PVC film. Prior to coating, the surface of the PVC plastic film was treated using a corona discharge process to improve adhesion properties (Fig. 2 (a)). The treatment was carried out with a corona discharge device operating at 300 W, with the discharge head positioned 5 cm above the film surface. This surface activation process introduced polar functional groups onto the film, thereby enhancing the wettability and adhesion of the subsequently applied polymer/ $\text{VO}_2$  suspension coating. The coating process was performed using a doctor blade bar coating technique (Fig. 2(b)), with the film thickness controlled to approximately  $25\ \mu\text{m}$  by adjusting the gap between the blade and the substrate. Finally, the coated films were applied to the rear side of the PV devices (Fig.2(c)) before testing their power conversion efficiency outdoor.



**Fig. 2** (a) Surface treatment of a PVC film by corona discharge, (b) coating of polymer/ $\text{VO}_2$  mixture onto the PVC film, (c) PV modules coated with PVC/polymer/ $\text{VO}_2$  films.

The experimental setup for measuring the temperature of solar cell module is illustrated in Fig. 3. A 1.50 m high aluminum rack was constructed to securely hold the solar cell modules at a fixed tilt angle of  $15^\circ$ , ensuring optimal sunlight exposure and stable alignment. Each solar cell module was connected to electrical and thermocouple wires, allowing simultaneous measurement of electrical performance and temperature variations. These wires were routed through a weatherproof junction box mounted on the aluminum frame and connected to measurement and data acquisition devices located inside a nearby building. This setup enable precise, continuous monitoring while protecting sensitive electronics from external environmental conditions.

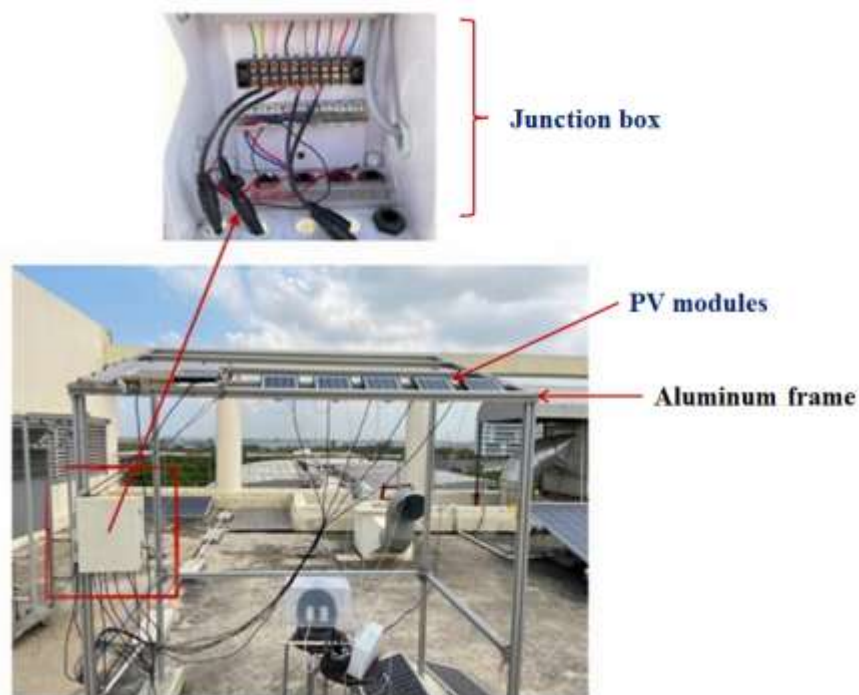
The power conversion efficiency (PCE) of each solar cell module, mounted on the 1.50-meter-tall aluminum rack with a  $15^\circ$  tilt angle, was evaluated under natural sunlight conditions. Electrical wires and thermocouple wires connected to each

module were routed to measurement devices located inside the adjacent building to enable real-time data acquisition. Current-voltage (I–V) characteristics were measured using a calibrated source measurement unit (PXI-4130, National Instruments Inc.), while a pyranometer (Kipp & Zonen SMP3) was employed to monitor the incident solar irradiance concurrently. The PCE values were determined from the measured short-circuit current ( $I_{sc}$ ), open-circuit voltage ( $V_{oc}$ ), fill factor (FF), and incident light power, following standard photovoltaic characterization protocols. Performance of the PV modules, with and without coating with polymer/ $VO_2$  films was recorded from 28 February until 4 March 2024. Single point data of ambient temperature and efficiency were measure at every time stamp. To ensure data reliability and minimize the impact of irradiance fluctuations, all PCE values were normalized against real-time irradiance readings, and multiple measurements were performed at different time intervals during the testing period.

### 3. Results and Discussions

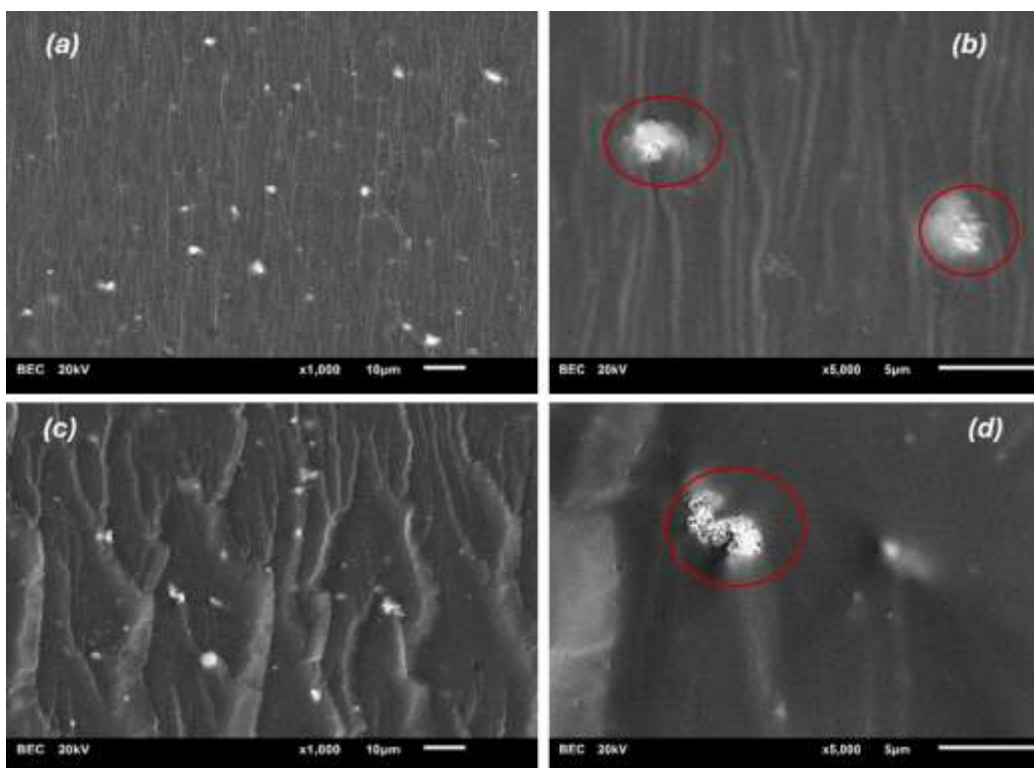
#### 3.1 Morphology and Thermal Properties of Polymer Composite Films

SEM image of  $VO_2$  particles is presented in Fig. 1(b). From the image analysis, the size of  $VO_2$  particles (before mixing with polymer) were approximately 2.61 nm. Fig. 4 displays SEM images of the polymer composite films containing 1 wt% and 1.50 wt% of  $VO_2$  particles. Bright domains observed in the images indicate the presence of metal oxides particles as confirmed by the EDX dot maps of  $V(K_{\alpha 1})$ , representing  $VO_2$ , particles. From the SEM images and EDX dot maps (see Figure S1 and S2 in SI), the metal oxide particles are evenly distributed throughout the polymer matrix phase, with particle sizes ranging between 2.10 and 3.70  $\mu m$ . SEM images of the composite films at the higher magnifications reveal that particles were agglomerated. This is likely due to the interaction of polar groups on the surface of metal oxides particles [17, 22]. Dispersion of particles could be improved by treating the surface of  $VO_2$  particles with silane coupling agents, as demonstrated in the case of poly(vinyl chloride) films reinforced with antimony doped tin oxide particles (PVC/ATO) [23]. As a result, better optical properties, particularly lower NIR transmittance, were achieved.

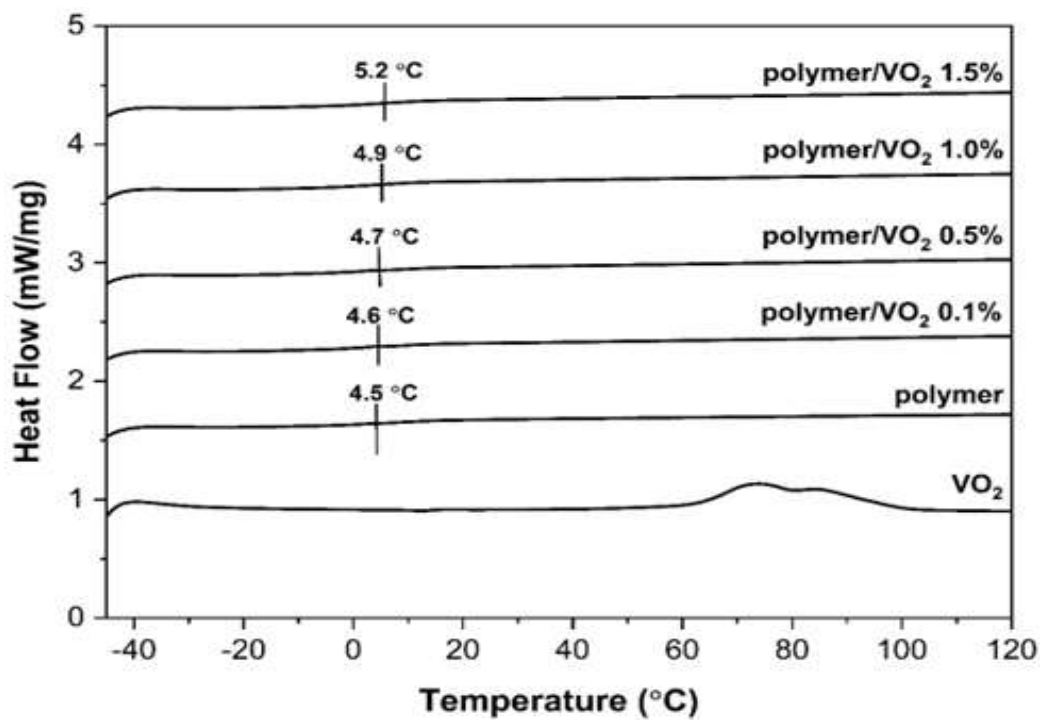


**Fig. 3** Photograph illustrating the experimental setup, which consist of PV module (5 W), for outdoor testing on performance of PV modules on the rooftop of the conference center building, National Nanotechnology Center, NSTDA, Thailand. The measurement wires from each solar module were routed through a waterproof junction box (inset) attached directly to the aluminum frame. From the waterproof box, the wires were connected to the measuring cables of the PCE tester, which was located inside the building. This arrangement facilitated precise, continuous monitoring while protecting sensitive electronics from external environmental conditions.





**Fig. 4** SEM (back-scattering electron images) of polymer films containing 1.0 wt% (a,b) and 1.5 wt % (c, d) of VO<sub>2</sub> particles. Red circles indicate the agglomerate particles

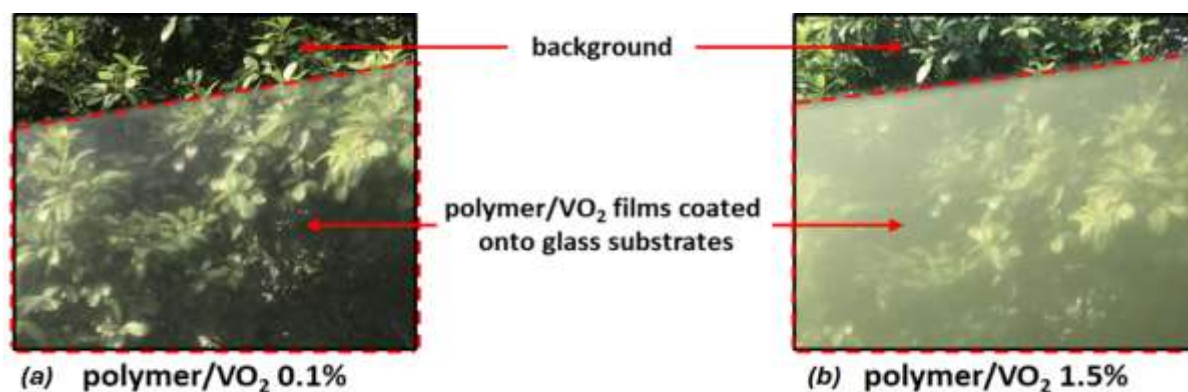


**Fig. 5** DSC thermogram of VO<sub>2</sub>, and the polymer composite films.

Fig. 5 presents DSC thermograms of VO<sub>2</sub> particles and polymer/VO<sub>2</sub> composite films. The DSC thermogram of VO<sub>2</sub> particles displays an endothermic peak at the onset temperature of approximately 74.60 °C, indicating the critical transition temperature of VO<sub>2</sub>. The area under the peak corresponds to the latent heat of VO<sub>2</sub> during its phase transition, with a value of 18.10 J g<sup>-1</sup>, which closely aligns with the report value of 17.90 J g<sup>-1</sup> in the literature [24]. A thermogram of the neat polymer film (without VO<sub>2</sub>) shows an endothermic baseline change at 4.50 °C, indicating the glass transition temperature (T<sub>g</sub>) of the acrylic polymer binder. Upon loading the metal oxides particles, the peak corresponding to phase transition of VO<sub>2</sub> particles was not observed due to the low particle content of 1.50 wt%. However, the endothermic baseline change representing the T<sub>g</sub> of the acrylic binder was clearly noticeable. The T<sub>g</sub> values of polymer/VO<sub>2</sub> films was 5.20 °C, which is higher than that of the neat polymer, suggesting good compatibility between the metal oxide particles and the polymer matrix. The T<sub>g</sub> values of polymer/VO<sub>2</sub> films are well below room temperature, indicating that the polymer composite films remain flexible and rubbery. This is a crucial consideration as polymer films may experience temperature fluctuations during the outdoor use across different climates and seasons. A significant amount of heat absorbed by VO<sub>2</sub> particles might be transferred to the polymer matrix phase and if the polymer lacks flexibility, distortion of the films and delamination from the substrate may occur.

### 3.2 Optical Properties of Polymer/VO<sub>2</sub> Composite Films

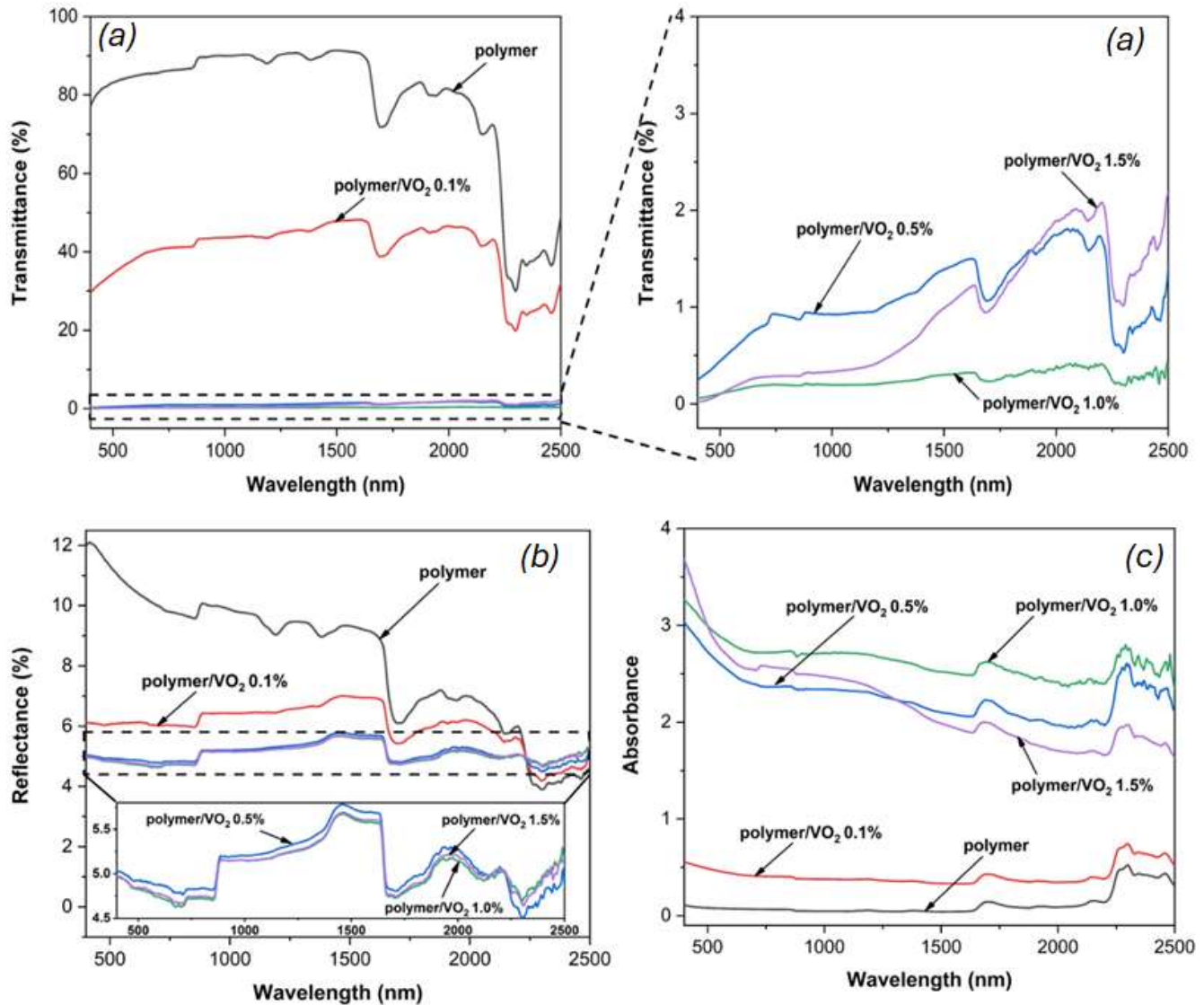
To assess the appearance and transparency of the polymer/VO<sub>2</sub> films, photographs of the composites films coated onto glass substrates are displayed in Fig. 6. Colorimetric parameters of the polymer/VO<sub>2</sub> composite films were also determined and summarized in Table S1 in the Supplementary Information (SI) Section. It is noteworthy that as the percentage loading of VO<sub>2</sub> particles increases the polymer films darken. This phenomenon is attributed to the intrinsic properties of VO<sub>2</sub> particles which exhibit higher absorbance in the visible light region, compared with other types of metal oxide particles such as antimony doped tin oxide (ATO) and cesium tungstate CsWO<sub>3</sub> (refer to Fig. S3 in SI).



**Fig. 6** Photographs of polymer/VO<sub>2</sub> films, (a) 0.10 wt%, (b) 1.50 wt%

Fig. 7 shows the UV/VIS/NIR spectra of composite films loaded with 0.10 wt% and 1.50 wt% of VO<sub>2</sub> particles. Percentage transmittance, reflectance, and absorbance of the polymer composite films containing different concentration of VO<sub>2</sub> particles were determined, and the results are summarized in Table 1. Percentage transmittance in the NIR region (T<sub>NIR</sub>) of the polymer films decreased rapidly with the concentration of VO<sub>2</sub>, while the percentage absorbance (A<sub>NIR</sub>) of the systems increased accordingly. This suggests that the suppression of NIR transmittance through the polymer/VO<sub>2</sub> composite films were counterbalanced with the NIR absorbance by VO<sub>2</sub>. In this regard, a decrease in NIR transmittance is expected to enhance the PCE of PV modules. Li *et al.*, [25] demonstrated that coating silicon-based solar cells with antimony tin oxide (ATO) thin film, resulted in decreased near-infrared (NIR) transmittance as the thickness or number of ATO layers increased. This led to a temperature reduction of 2.70 °C in the solar cells after applying 1 – 4 layers of ATO. The antimony (Sb) doping level also influences performance i.e., when the ATO film contained 10 mol% Sb, the power conversion efficiency (PCE) of the solar cell increased by 0.43%, representing the highest improvement reported in that study. Likewise, Gao *et al.* [26] found that the optical properties and cooling effectiveness ATO films were strongly dependent on both film thickness and Sb doping concentration. An increase in Sb doping level leads to a greater concentration of free electrons, which enhances NIR absorption. Using the optimized film, comprising seven coated layers of ATO with 7 mol% Sb, the temperature of the Si-based solar cell

was reduced by 1 °C, compared with the uncoated control. Additionally, the PCE of solar cells changed with time. Initially, the solar cell coated with the ATO film exhibited lower PCE than the control device, due to reduced transmittance in both the visible and NIR regions. However, after 30 min, the normalized PCE of the ATO-coated solar cell was 97.21 %, whereas that of the control device declined to 91.56 %.



**Fig. 7** UV/Vis/NIR spectra; (a) transmittance, (b) reflectance, and (c) absorbance; of polymer films containing different concentration of VO<sub>2</sub> particles.

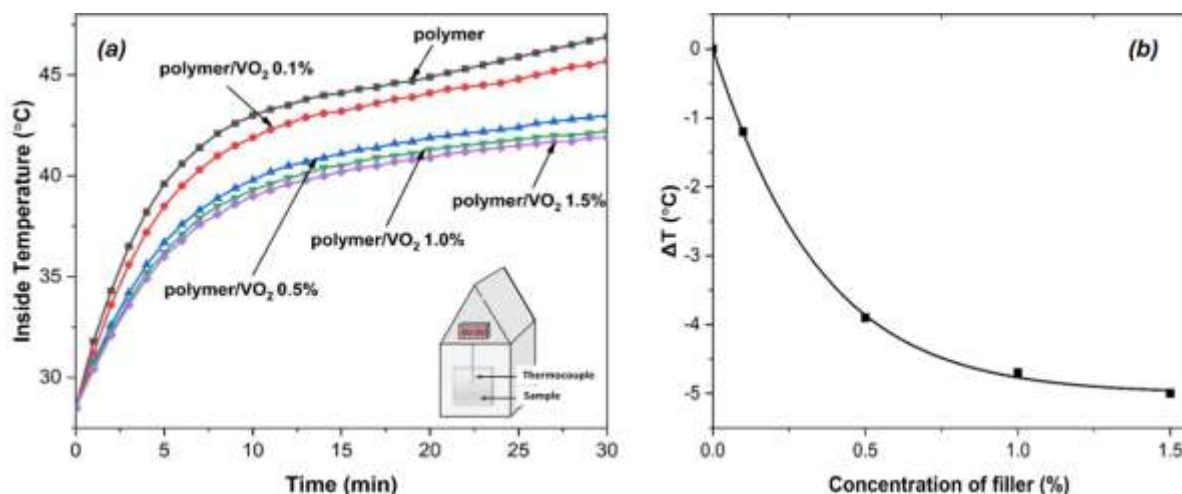
**Table 1** Optical properties of various polymer composite films.

VO <sub>2</sub> Loading (%)	Transmittance (%)		Reflectance (%)		Absorbance (%)	
	T <sub>Vis</sub>	T <sub>NIR</sub>	R <sub>Vis</sub>	R <sub>NIR</sub>	A <sub>Vis</sub>	A <sub>NIR</sub>
0	83.72 (±0.919)	85.94 (±0.493)	10.92 (±0.375)	9.19 (±0.131)	5.36 (±0.251)	4.87 (±0.148)
0.10	36.37 (±3.396)	42.66 (±3.213)	6.09 (±0.066)	6.23 (±0.065)	57.54 (±0.468)	51.11 (±0.364)
0.50	0.56 (±0.469)	1.02 (±0.778)	4.90 (±0.013)	5.11 (±0.005)	94.54 (±2.126)	93.87 (±1.655)
1.00	0.13 (±0.024)	0.22 (±0.038)	4.78 (±0.017)	5.03 (±0.012)	95.09 (±6.095)	94.75 (±5.569)
1.50	0.0013 (±0.001)	0.0033 (±0.001)	4.80 (±0.028)	5.04 (±0.018)	95.19 (±3.691)	94.95 (±3.278)



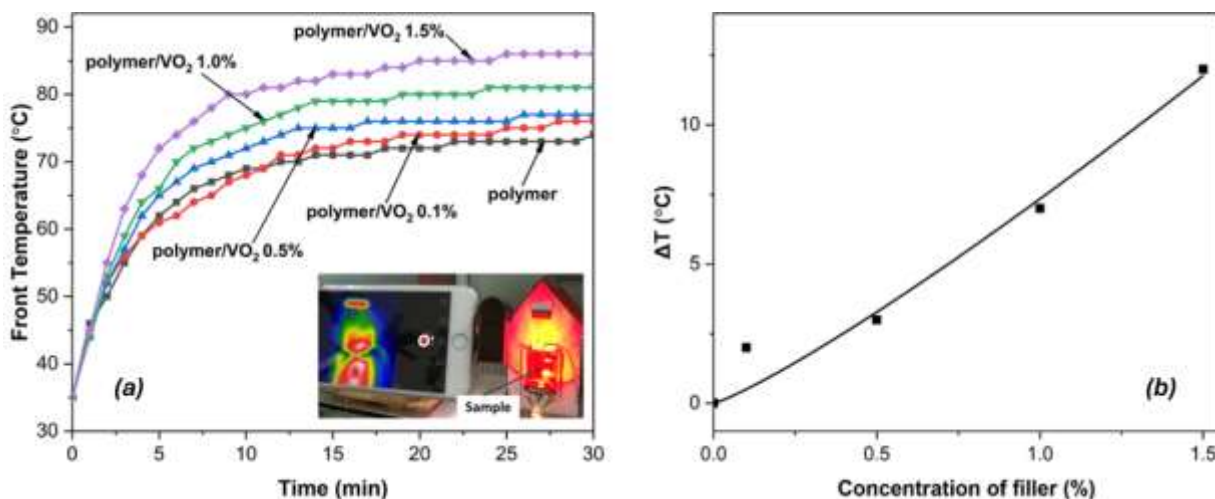
### 3.4 Heat Shielding Ability of Polymer Composite Films

Changes in temperatures inside the model house, installed with the polymer composite films are illustrated in Fig. 8(a). The temperature increased with the testing time until reaching a plateau after 30 min. The final temperature inside the model house, installed with the polymer composite film (1.50% VO<sub>2</sub> loading), was 42 °C. This is lower than the temperature of the system coated with the neat polymer film. Fig. 8(b) shows the effect of concentration of VO<sub>2</sub> particles on the magnitude of temperature drop ( $\Delta T$ ). The higher the percentage loading of VO<sub>2</sub>, the greater the magnitude of temperature reduction. It is worth mentioning that the actual temperature generated by the infrared lamp was 86 °C, which exceeds the critical transition temperature of VO<sub>2</sub>(m) (74.60 °C). Therefore, it was possible that VO<sub>2</sub> underwent a phase change from a monoclinic to a rutile phase. Consequently, greater NIR shielding efficacy of VO<sub>2</sub> can be expected.



**Fig. 8** Changes in temperature *inside* the model house as a (a) function of time and (b) the effects of concentration of VO<sub>2</sub> particles on the magnitude of temperature drop ( $\Delta T$ ) of the systems.

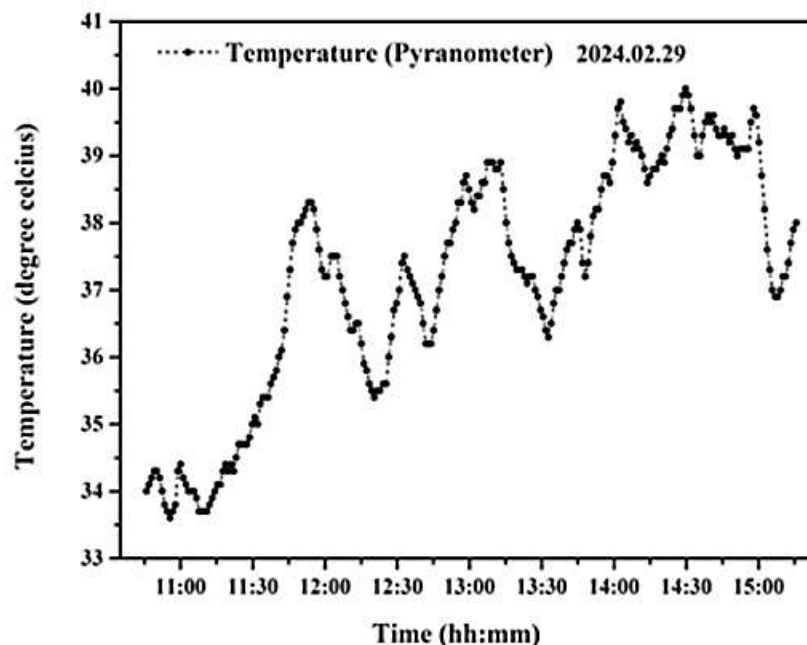
By contrast, the temperature at the front of the window films equipped with polymer/VO<sub>2</sub> window film was higher than that of which installed with the neat polymer film (without VO<sub>2</sub> loading) (Fig. 9(a)). It was also noticed that the higher the percentage loading of VO<sub>2</sub>, the greater the temperature rises (Fig. 9(b)). This effect implies that a significant amount of heat has been accumulated on the surface of the polymer films, probably due to a combination of absorption and reflection of NIR wave by the VO<sub>2</sub>.



**Fig. 9** Changes in temperature at *frontside* of the model (a) house installed with window films, as a function of time, and the effects of concentration of VO<sub>2</sub> particles on the (b) magnitude of temperature drop ( $\Delta T$ ) of the systems.

### 3.5 Performance of PV Modules

Finally, the performance of the PV modules, both with and without the polymer/VO<sub>2</sub> film coating, was evaluated. Notably, in this section, the polymer film containing 0.10 wt% of VO<sub>2</sub> particles was for coating the PV modules, aiming to balance optical transparency with cooling performance. As shown in Fig. 10, the ambient temperature during the test varied between 33.50 and 40 °C, depending on sky conditions. The actual temperature of the PV module could be higher due to the additional heat generated during the power conversion process [27]. For instance, during sunny days, temperature of PV modules can be increased by 35 °C above the ambient temperature [2].



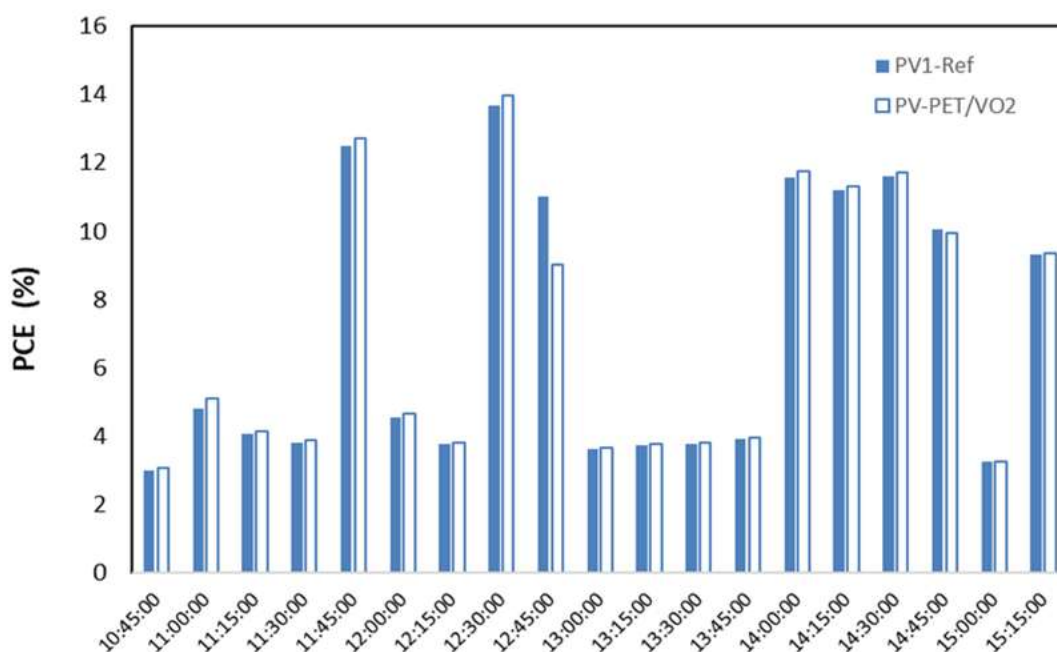
**Fig. 10** The ambient temperature during the outdoor test (day 1).

Fig. 11 shows that the power conversion efficiency (PCE) values of PV modules coated with polymer/VO<sub>2</sub> films increased, compared to the control module without the composite films. Similar trends were observed (Fig. S4 and S5 in the SI) when the tests were conducted on different days (Day 2 and Day 3), during which the recorded ambient temperature ranged from 35.8 – 42.7 °C and 38.6 – 42.8 °C, respectively). The values fluctuated over time due to variation in solar intensity and sky conditions. The improvement in PCE of the PV modules can be ascribed to the enhanced heat dissipation from the backside of the modules, where the polymer/VO<sub>2</sub> composite films were applied. In this study, it was possible that the actual temperature of PV modules exceeded the transition temperature of VO<sub>2</sub>. As a result, the VO<sub>2</sub> particles may have undergone phase transition, allowing them to store heat from the PV modules. A significant amount of heat from the PV modules was also likely absorbed by the polymer/VO<sub>2</sub> films, due to the high percentage NIR absorbance of these materials (Fig. 7). These factors contributed to the cooling of PV modules and so an increase of PCE values can be expected.

Lastly, for a comparison purpose, the efficacies of various materials used to improve the performance of PV modules are summarized in Table 2. Waqas *et al.* [28] demonstrated that applying a commercially available organic based PCM resulted in a 1.87% increase in power conversion efficiency of PV modules. Indartono *et al.* [29] used petroleum jelly, derived from vaselinum flavum, as a phase change material for passive cooling of PV modules, finding an increase in efficiency from 8.32 – 8.82 %. However, the melting point of petroleum jelly (around 42 – 55 °C) may not be sufficiently high for certain conditions, such as in hot and dry regions where surface temperatures of PV modules can reach up to 75 °C [5]. Seto *et al.* [4] used paraffin, both with and without ZnO loading, as a phase change material, and found that PCE of PV modules increased from 11.16 – 13.19 % after applying the PCM. Aldawood *et al.* [30] used myristic acid as a PCM, which were applied to the rear side of PV modules. Their study showed a PCE increase of 5.54 %, corresponding to a temperature reduction of 17 °C.

From the above review, the efficacy of PCM in enhancing the efficiency of PV modules varies significantly, which can be attributed to factors such as material properties, experimental duration, solar radiation and PCM incorporation techniques.

In this study, only 0.10 wt % of VO<sub>2</sub> particles were incorporated into the polymer binder, with the polymer serving as the main component of the films applied to the PV modules. The polymer lacks phase change properties, and its specific heat capacity, in the range of 0.90 – 1.14 (J gK<sup>-1</sup>) [31, 32], is lower than that of paraffins based PCM (2.52 – 2.95 (J gK<sup>-1</sup>) [33]. As a result, the enhancement in PV performance observed in this study was less, compared to those reported in the literature. However, higher concentration of VO<sub>2</sub> particles can be incorporated into the polymer films, particularly when optical transparency is not a critical factor, such as when coating on the rear side of PV modules. In this context, the cooling efficacy of the polymer/VO<sub>2</sub> composite films could be further improved by optimizing the particles loading percentage and film thickness. This would likely lead to a greater enhancement of PV modules efficiency. These aspects are the focus of ongoing research in our study.



**Fig. 11** Power conversion efficiency of PV modules during the outdoor test (day 1).

**Table 2** Power conversion efficiency values of PV modules coated with different types of materials.

Phase change materials (PCM)	Efficiency (PCE, %) of PV modules*		Enhancement of PCE	References
	Without PCM	With PCM		
<b>Paraffin PCM</b>	10.11	11.16	10.38 %	Seto <i>et al.</i> [4]
<b>Paraffin PCM + ZnO</b>	10.11	13.19	20.57 %	
<i>Day 1 (7.00 – 16.00)</i>	15.00	15.20	1.33 %	Waqas <i>et al.</i> [28]
<i>Day 2 (7.00 – 16.00)</i>	14.92	15.20	1.87 %	
<b>Petroleum jelly</b>	8.32	8.82	6 %	Indartono <i>et al.</i> [29]
<b>Myristic acid</b>	<i>no report</i>	<i>no report</i>	5.54 %	Aldawood <i>et al.</i> [30]
<b>Polymer + VO<sub>2</sub> (0.1 %)</b>				
<i>Day 1 (29/02/2024)</i>	13.65	13.96	2.13 %	<i>This study</i>
<i>Day 2 (04/03/2024)</i>	12.50	12.88		
<i>Day 3 (06/03/2024)</i>	12.96	13.08		

\* Refers to the maximum PCE of PV modules in this study

## 4. Conclusion

This study has demonstrated the potential usage of polymer/VO<sub>2</sub> composite films to enhance the performance of PV modules. The near infrared (NIR) shielding and thermal cooling efficacies of these polymer composite films were strongly dependent on the concentrations of VO<sub>2</sub> particles. When coated on glass substrates and exposed to an infrared lamp, the temperature reduction efficacy of polymer/VO<sub>2</sub> films was significant and remarkable. Additionally, when the polymer composite films were applied to the rear side of PV modules and exposed to sunlight, performance of PV modules improved, compared to the control device. Further work is needed to enhance the cooling performance of this polymer composite system. This includes optimizing the VO<sub>2</sub> particle loading and evaluating the performance of the PV modules coated with polymer/VO<sub>2</sub> films under various climatic and environmental conditions.

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