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Impact of integrated photovoltaic-phase change material system on building energy efficiency in hot climate

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ABSTRACT

A photovoltaic phase change material (PV-PCM) system is investigated as a building element for enhanced energy efficiency by PV cooling and reduced heat transmission indoors. The PV-PCM system is developed by adding a PCM layer behind PV and an insulated chamber behind PV-PCM to mimic a scaled down indoor space. The impact of the added PCM layer is experimentally studied on electrical and thermal energy efficiency of the PV and indoor space, respectively in the warmer climate. A drop in PV transient temperature, indoor transient temperature, and delay in peak indoor temperature in observed by the use of PCM. Consequently, an increase in PV power output by 7.2% at peak and 5% on average along with enhanced indoors cooling effect of 9.5% at peak and 7% on daytime average is observed.

1. Introduction

Previous studies observed that phase change materials (PCMs) applied to building skin can effectively reduce energy consumption by reducing cooling load [1] as well as heating load [2]. PCMs have been applied to building being a layer in walls [3], layer with cavities [4], impregnated into wall boards [5] and coupled with air conditioning system as thermal energy storage unit [6]. The PCM cooling/heating performance heavily depends on its melting and solidification characteristics and climatic conditions [7]. Variable weather conditions render the choice of PCM with suitable melting and congealing points crucially important [8]. In extremely hot weather conditions, PCM integration in walls and roof can reduce cooling load [9] however finds it difficult to self-regenerate to solid at night-time. In such cases passive heat release to warmer ambient would be insufficient and would require an active ventilation system for enhanced heat transfer [10].

Thermally enhanced insulations employing paraffin can reduce the peak and total daily heat flow up to 9.2% and 1.2% respectively [11]. Employing salt hydrates into the insulation as well reduces heat flow [12] however the salt degrade in opposed to paraffin over time [11,13]. Structural insulated panel (SIP) employing PCM by weight ratios of 10–20% can save peak cooling demand by 37–62% and average cooling load by 33–38% [14]. The cooling load reduction is mainly achieved by the time shift of peak load by up to 2 h [15,16]. The delay is caused by increased thermal mass due to heat absorbed in melting PCM [2] during day time which can be released to cooler ambient at night-time [17].

Building integrated photovoltaics (BIPV) are increasingly replacing conventional building envelop [18]. BIPV are predicted to reach up to 22% (840 TWh) share of electricity consumed in the European Union by 2030 [19]. BIPV experiences substantially higher temperatures compared to rack-mounted free back PV [20] thereby resulting in considerable drop in PV cell efficiency [21]. In order to mitigate overheating of BIPV and prevent resulting power loss, naturally ventilated [22] as well as forced ventilated [23] PV claddings are studied. Natural ventilation is limited in heat removal due to lower airflow rates while the forced ventilation is expensive due to additional system and power requirement. Forced water cooling reduced cell temperature by 7 °C [24] and increased PV module efficiency by 3% however is not considered practical due to additional pumping power needs. Alternatively, PCMs are employed at the rare of PV as passive temperature regulators resulting in effective cooling and increased PV efficiency [25,26]. Although the PCMs are effective in cooling PV and increasing power output [27,28,29], still they are not economical considering only electrical power enhancement [30] unless the resulting cooling/heating impact is determined. Based on the previous research, the current paper investigates the effect of PCM inclusion in PV as building element

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Nomenclature

Abbreviations

BIPV	Building integrated photovoltaic
DSC	Differential scanning calorimetry
EVA	Ethylene vinyl acetate
FF	PV fill factor
PCM	Phase change material
PV	Photovoltaic
PV-PCM	Photovoltaic- phase change material
SD	Population standard deviation

Symbols

ϕ	Absorptance of clear glass (%)
ρ	Density of the material (kg/m^3)
A	Area of the surface (m^2)
d	Thickness of the material (m)
G	Global solar radiation intensity (W/m^2)
h	Convective heat transfer coefficient (W/m^{2}K)
H	Latent heat of fusion (kJ/kg)
I_{SC}	Short-circuit current (A)
P	Power output (W)
Q	Energy (Wh/day)
T	Temperature (°C)
V	Volume (m^3)
V_{OC}	Open-circuit voltage (V)
v_w	Wind speed (ms^{-1})
W_P	Watt peak (W)

Subscripts

α	Photovoltaic reference
β	Photovoltaic- phase change material
amb	Ambient
b	Back surface
e	Electrical energy
f	Front surface
i	Indoor air
in	Incident solar energy
l	Energy losses
PCM	Inside the PCM
S	Stored energy

on PV power output as well as on heat gain to indoors in high heat load climate of UAE.

2. Experimental set up & procedures

The research starts with PCM thermo-physical characterization through differential scanning calorimetry (DSC), inclusion of PCM at the PV back to obtain a small-scale PV-PCM. The PV-PCM is employed to conduct outdoor experiments measuring their thermal and electrical performance. Two polycrystalline ethylene vinyl acetate (EVA) encapsulated 40 W_P Microsol PV panels (Model # PV Module –MM0025) with dimensions 53 cm × 63 cm were studied in the experiments. Prior to the start of the experiments, the PV integrity was inspected and performance was measured for three days under stable outdoor conditions in Al Ain, UAE. The PV output of open circuit voltage (V_{OC}) and short circuit current (I_{SC}) were measured. The measured data showed the consistent performance of the panels with variation below 1% which falls within instruments errors. One PV panel served as a reference while the other panel was attached to PCM container. The container was internally fitted with straight vertical back-to-back fins with 7 cm horizontal inter-fin spacing. The container was fabricated from a 4 mm thick sheet of aluminum alloy (1050A), fixed to PV by the epoxy resin and settled under pressure to form a strong bond. A tray like a test chamber with dimensions 53 × 63 × 73 cm was constructed to mimic a test room. The PV and PV-PCM were affixed at the front of the test chamber as a building integrated PV shown in Fig. 1. The test chamber walls and top cover were fabricated from 20 cm thick polystyrene sheets. The arrangement realized nearly adiabatic system boundaries allowing heat transfer only from PV to the test space. The commercial PCM RT42 was characterized through DSC to verify its thermo-physical properties. The PCM was filled melted in the containers at 80 °C and subsequently cooled down to 25 °C to get it completely solidified in the container. Upon PCM solidification, a 7 cm free space was left from the top of PV-PCM container. The free space was meant to accommodate volume changes and release trapped air during successive melting and solidification cycles. The fabrication materials and their thermo-physical properties are given in Table 1.

T-type copper–constantan thermocouples calibrated in ice-bath with a measurement error of ±0.3 °C were attached to both PV and PV-PCM systems at the front surface, inside PCM, the back surface and inside the test chamber as shown in Fig. 1. A self-powered Apogee pyranometer (model # SP-110) with 0.2 mV per Wm^{-2} sensitivity and ±5% calibration uncertainty) [31] was installed at the angle of the site (latitude: 24.21°N, longitude: 55.74°E) to measure G. A weather station (Starmeter-WS1041) having temperature resolution and accuracy of 0.1 °C and ±1 °C respectively and wind speed range and resolution of 0–50 ms^{-1} and 0.1 ms^{-1} respectively was installed to measure ambient temperature (T_{amb}) and wind speed (v_w). The PV, PV-PCM, and pyranometer were connected to an NI compact Rio (NI cRIO-9073) data acquisition system. The system had an integrated 266 MHz real-time controller with accuracy of 200 ppm to 35 ppm at room temperature [32]. The parameter of temperature (T), open circuit voltage (V_{oc}), short-circuit current (I_{sc}) and global solar radiation intensity (G) were recorded.

The reference PV and the PV–PCM systems were deployed outdoors facing south at the latitude angle of Al Ain (24.21°N, 55.74°E). The experiments were conducted for 14 consecutive days from 23/09/2015 to 07/10/2015 to evaluate PCM cooling performance over repeated thermal (melt-freeze) cycles. The temperature was measured at front surfaces of PV ($T\alpha_f$) and PV-PCM ($T\beta_f$), at back surfaces of PV ($T\alpha_b$) and PV-PCM ($T\beta_b$), inside the PCM (T_{PCM}) and in the middle of the test chamber for reference PV ($T\alpha_i$) and the PV-PCM ($T\beta_i$). All temperatures were measured at three locations and the average was calculated apart from T_{PCM}. T_{PCM} was measured only at one location due to the concern of PCM leakage if multiple thermocouples were to be inserted. The thermocouples were fixed at the front and back surface with strong white tape, were shielded from direct irradiation. Thermocouples were monitored continuously to assure the fixation. The V_{OC} and I_{SC} were measured for both panels with a five seconds delay considered being simultaneous. Every measurement was conducted with 5 min time step since the weather was stable and no reasonable variation was expected with lesser time step.

3. Experimental results

The experimental results of weather data, PV temperature reduction achieved through the inclusion of PCM, associated power enhancement and the reduced heat flow due to enhanced thermal mass are presented in the following section. The results are discussed for one day from 07:00 on 30/09/2015 to 07:00 on 01/10/2015 for more resolved illustrations (day 8 as shown in Table 4). For remaining days, the data is summarized in Table 4 as peak and average values for 14 days, their mean and standard devi-