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Experimental investigation of a hybrid setup for distilled water and power production

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ABSTRACT

This work majorly concentrates on the effect of mass flow rate of water (m_{fw}) and phase change material (PCM) in an inclined panel basin solar still (IPBSS).To assess the performance of the proposed technique experiments were carried out using the constant mass of PCM beneath the basin of the IPBSS and m_{fw} is varied on the panel surface. Results show that there is a decrease in freshwater production with an increase in m_{fw} at the time of sunshine hours where as, the production increases at the time of offshine hours with continuous discharge of heat while using PCM material. Comparative analysis shows that the freshwater yield is higher for IPBSS without PCM at the time of sunshine hours, the yield and water temperature (T_w) is higher for IPBSS with PCM at the time of offshine hours. The production from the IPBSS with PCM is enhanced by 50% at minimum water flow in the panel surface while the yield from IPBSS without PCM is found as 5.8 kg/m^2 day. Similarly, the production of electrical power from the panel is lower in addition of PCM material, which increases the panel temperature (T_{pv}). From the results, it is found that the melting temperature and latent heat of fusion plays a significant role in Photovoltaic (PV) power production. The power production of PV panel during the sunshine hours with and without PCM at minimum mass flow is found as 78 and 68 W respectively.

Keywords: Solar energy; PV panel; PCM material; Solar desalination

1. Introduction

The need for fresh water is rapidly increasing in the present century due to rapid global urbanization and industrial developments. With a greater possibility in the industrial sector and its greater utilization of water resources, people living in the urban-rural areas are majorly affected. Several processes were developed to produce freshwater to serve the domestic commodity. Even several process processing units were developed to reduce the industrial pollutants before it is discharged to the atmosphere as these affect the ground and surface water sources. Among various methods, desalination using renewable energy is the most promising methods for producing freshwater as it requires minimum electrical energy, eco-friendly, available in abundant and low cost [1–6]. Kabeel and Abdelgaid [7] used phase change

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material (PCM) for augmenting the freshwater yield from a conventional solar still (CSS) under the climatic conditions of Egypt. It was published that the yield from the CSS with PCM was improved to about 67% as compared with the same type of still without PCM. Also, the daily efficiency of the solar still was improved to about 86.6% than solar still without PCM. Kabeel et al. [8] conducted different experiments on the CSS using different PCM. It was published that there is no significant improvement in the yield over the thickness of PCM, while the organic PCM A48 got less negative impact on the environment. Organic PCM A48 also increased the freshwater yield to about 92% compared to the CSS. Manokar et al. [9,10] analyzed a Photovoltaic (PV) panel integrated inclined solar still for simultaneous production of power and fresh water using three different experimental conditions. Results showed the freshwater yield and efficiency from PV basin solar still improved with bottom and sidewall insulation, while the power production is decreased as there is an increase in the T_{pv}. The overall efficiency of still with complete insulation improved to about 70%. Kabeel et al. [11] augmented the freshwater yield by coating the absorber plate with the black nanoparticles. From the analysis, it was found that the influence of nanoparticle enhances the output to about 16% and 25% with 10% and 40% by weight fraction respectively. Kabeel et al. [12] researched the modified *v*-corrugated pyramid solar still (PSS) with PCM beneath the basin. It was submitted that this system improved the productivity by 87% as compared to PSS with the flat absorber. While comparing the daily efficiency, the modified solar still performed better than about 70% as compared to PSS with a flat absorber. In addition, the cost of fresh water produced is almost similar to modified and conventional PSS. Kabeel et al. [13] also studied the yield of the CSS with PCM and bottom parabolic reflector for improving the freshwater yield. Their result revealed that the total accumulated yield was improving to a maximum of 65% and 45% during summer and winter respectively. The daily yield using dish type concentrator and PCM at the bottom for 1 and 5 cm of water depth maintained inside the basin was found as 7 and 4 kg/m^2, respectively, during summer condition, whereas, in winter it was found as 4.5 and 2.5 kg/m^2. Arunkumar and Kabeel [14] studied concentric tube solar still with PCM for improving the yield. Results showed that the use of concentric parabolic concentrator improved the daily freshwater yield from 5.3 to 5.77 kg/m^2 in addition to PCM layer in the absorber. Kabeel and Abdelgaied [15] enhanced the solar still performance using coaxial pipes inside the basin of the CSS. It was reported that increasing the axial distance (thickness) between the two pipes decreases the productivity. The daily efficiency of present system with 5, 8, 11 and 14.5 mm axial distance was found as 67.6%, 62.6%, 57.4% and 53.4%, respectively. Similarly, the fresh water is improved by 97.82%, 77.3%, 63.5% and 52.7 % for type A, type B, type C and type D, respectively, and higher as compared to the CSS. Kabeel et al. [16] studied a CSS with PCM and integrated with parabolic trough collector using oil as working medium. Their study revealed that increasing the T_w is one of the best methods to enhance the evaporation while excess heat energy will be stored in the form of latent heat at the bottom of the basin. Using the proposed technique a daily yield of 10.6 kg/m^2 was achieved which is 140.36% as higher comparing with the CSS. Sathyamurthy et al. [17,18] improved the freshwater yield in a triangular PSS and studied the effect of water mass and mass of PCM. Experimental results revealed that the use of latent heat energy storage improved the efficiency of solar still up to 53% as compared to solar still without energy storage. Results also revealed that the use of PCM improved the water-glass temperature difference up to 10°C for increased improvement in yield of about 20%. The similar study of Sathyamurthy et al. [19] in effect of water mass revealed that the distillate improved at least water mass kept in the basin. The daily yield was improved from 3.5 to 5.5 kg/m^2 while the efficiency of the still improved up to 35%. The performance of the active solar still with PCM has been investigated by Abu-Arabi et al. [20–22]. Mousa et al. [23–25] introduced a falling film solar still. Zurigat and Abu-Arabi [26,27] enhanced the condensation rate by using double-glass collector with water cooling. From the literature, it is identified that the effect of latent heat energy storage material inside the inclined solar still it not carried out. In the present study, the effect of mass flow rate of water (m_{fw}) and constant mass of PCM on fresh water production is experimentally investigated. Similarly, the effect of m_{fw} over the PV panel power generation, electrical efficiency is investigated while the constant mass of PCM is loaded in the base of the basin.

2. Experimental methodology and setup

The pictorial representation of the inclined panel basin solar still (IPBSS) is shown in Fig. 1. It consists of a 1.6 m^2 area of the solar panel, while the PCM is loaded underneath the photovoltaic panel for a thickness of 0.01m under constant mass. Paraffin wax is used as a PCM for the present study. A glass cover with a thickness of 4 mm and transmissivity of 0.92 is used for the present study. The air gap distance between panel and glass cover with a distance of 0.15 m is maintained. The entire experiment is carried out with an inclination of 13° latitude with a North-South orientation. Water from the storage tank is fed into the basin and thus extracting the heat from the photovoltaic panel for evaporation. By gravity fed method water is flown over the panel and using a flow control valve the water flow is controlled. Specification of the photovoltaic panel is provided in Table 1 and the specifications of PCM is provided in Table 2. Due to the excellent properties of paraffin wax and thermal energy storage, it is used as a PCM. Due to continuous charging and discharging of PCM, the T_{pv} and T_w increases. At the bottom of the PCM material, insulations were provided to avoid heat loss. The evaporated water from the basin by increased temperature condenses on the inner surface of the glass due to the partial pressure developed between panel and glass cover. The condensed water in the inner surface of the glass is collected in the distillate collector and glides through the collector to the calibrated flask. Similarly, hot water from the exit of the IPBSS is collected in the hot water storage tank. For determining the efficiency of the PV panel output, a parameter such as voltage and current were measured using voltmeter and ammeter respectively. Experiments were carried out in between 9 AM to 5 PM in open outdoor condition.

Ambient conditions are the significant parameters for effective condensation. From the previous studies and

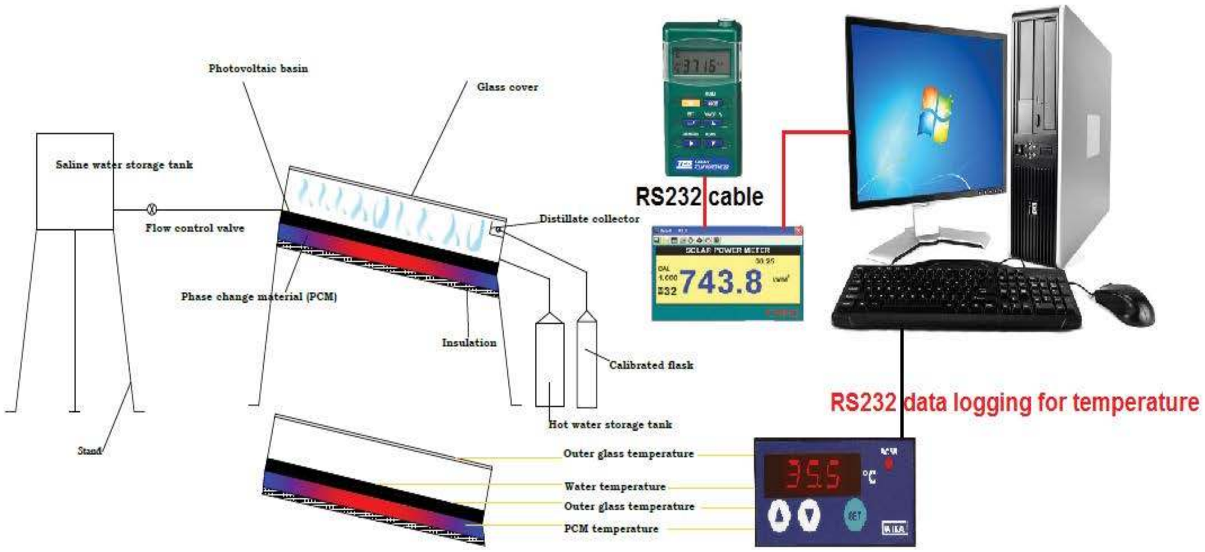


Fig. 1. Graphical representation of IPBSS with PCM.

Table 1
Detailed specification of photovoltaic panel

Electrical parameters	Specifications
Maximum power (P_{max})	90 W
Voltage at P_{max} (V_{mpp})	17.9 V
Current at P_{max} (I_{mpp})	5.03 A
Short circuit current (I_{sc})	5.58 A
Open circuit voltage (V_{oc})	22.2 V
Module efficiency (μ)	13.9%
Tolerance P_{max}	±5%

Table 2
Thermophysical properties of paraffin wax

Property	Value
Melting temperature (°C)	56.2
Density (L/S) (kg/m^3)	834/782
Specific heat capacity (S/L) (kJ/kg K)	2.87/2.45
Thermal conductivity (W/mK)	0.24
Latent heat of fusion (kJ/kg)	223

literature, effective condensation occurs in the solar still with a significant decrease in glass temperature (T_g). Using TES1333R and AM4836-3cup anemometer with RS232 interface the hourly variation in solar intensity and wind velocity was measured respectively and logged in a personal computer. While the parameters such as basin, glass cover (inner and outer), PCM, inlet and the outlet temperature of IPBSS is measured using PT100 RTD sensors. For comparative analysis, similar IPBSS was fabricated without the addition of PCM and the entire testing's conducted in the climatic condition of Chennai.

The detailed experimental uncertainty analysis of instruments used is calculated and provided in Table 3.

The uncertainty of the measuring instruments used in the current study is given in Appendix-1.

3. Results and discussion

3.1. Effect of m_{fw} on inclined PV panel as basin over fresh water yield

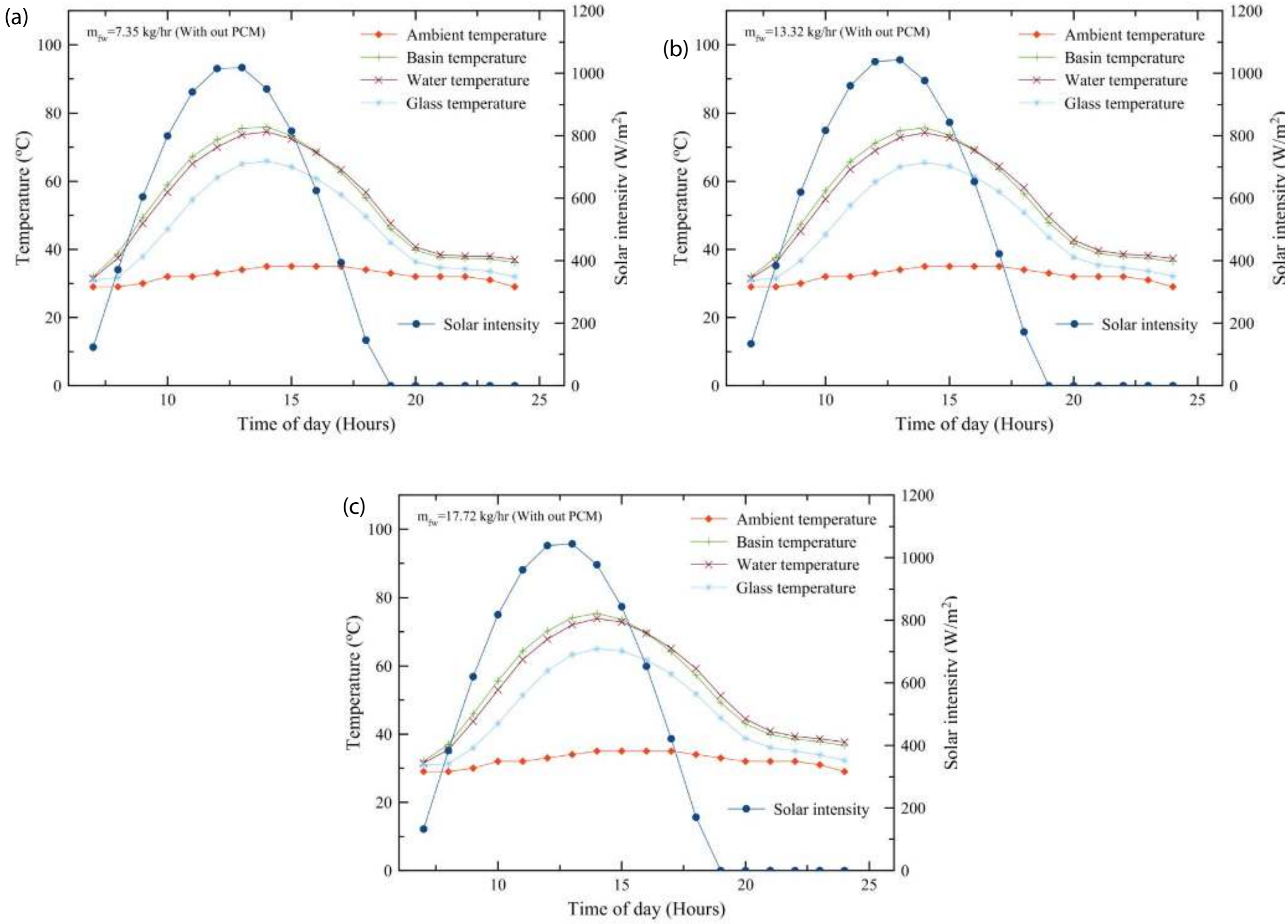
Figs. 2a–c show the hourly variations in water, glass, basin temperature of IPBSS without PCM for different m_{fw} namely 7.35, 13.32, and 17.72 kg/h. It is observed that the maximum solar intensity occurs during the mid-noon (1 PM) and averaged to about 998 W/m^2 while the complete experiments were carried out under clear sky conditions. Similarly, ambient temperature is observed as 39.4°C during the months of February 2018. Throughout the entire experiments, the ambient conditions such as ambient temperature and solar intensities were with a marginal deviation of ±3.2%. This resulted in validating the IPBSS with and without PCM for different test parameter condition.

The maximum hourly T_w of IPBSS without PCM is recorded as 75.94°C whereas, increasing the m_{fw} decreases the T_w to 75°C and 74°C for m_{fw} of 13.32 and 17.72 kg/h respectively. Furthermore, the T_w is lower than the T_{pv} during sunshine hours. The absorbed energy by the panel is liberated during the offshine hours for increased T_w than basin (panel). The average T_w from the IPBSS without PCM for m_{fw} of 7.35, 13.32 and 17.72 kg/h are found to be 53.18°C, 53°C and 53.21°C respectively. Similarly, the differences between T_w and T_g during peak solar intensity for the same m_{fw} are found to be 8.2°C, 7.2°C and 7°C respectively. During the sunshine hours, the T_w is higher at a minimum m_{fw} (7.35 kg/h) whereas, with increased m_{fw}, the temperature is lower during the sunshine hours. This effect is mainly due to the absorption of heat energy in the panel surface. In addition, the continuous extraction of heat at higher m_{fw} resulted in an increased T_w.

The hourly variation in productivity from the IPBSS without PCM is shown in Fig. 3. It can be seen that the decrease in m_{fw} increases the yield to a maximum of

Table 3
Uncertainty, standard uncertainty, error and measuring range of instruments

Instrument	Accuracy	Range	Error (%)	Observed error (%)	Standard uncertainty
Thermocouple (PT100 RTD)	±1°C	0°C–100°C	0.25	1.2	±0.57°C
TES 1333R solar power meter	±1 W/m^2	0–2,500 W/m^2	2.5	3.1	±0.57 W/m^2
AM4836, 3 cup anemometer	±0.1 m/s	0–45 m/s	10	6.8	±0.05 m/s
Calibrated flask	±10 mL	0–1,000 mL	10	8.3	±5.77 mL



Figs. 2. (a) Diurnal variations of different parameters in the IPBSS without PCM, (b) diurnal variations of different parameters in the IPBSS without PCM, and (c) diurnal variations of different parameters in the IPBSS without PCM.

0.8 kg/m^{2}h, and the yield is increased by 10% and 15% for 13.32 and 17.72 kg/h of m_{fw}, respectively with the minimum value (7.35 kg/h). Similarly, for the period of offshine hours, the yield for maximum flow is higher due to the accumulation of vapour liberating its heat through the glass surface and energy stored by the panel as comparing it with minimum m_{fw}. At minimum m_{fw}, the entire heat energy is removed at a lower rate, which simultaneously increases the T_{pv} for reduced power production. Due to the thin layer of water formed in the panel surface, the entire heat is extracted at higher m_{fw}, which simultaneously increase the rate of power production and decreased yield.

3.2. Effect of m_{fw} on inclined PV panel as basin with PCM over fresh water yield

Figs. 4a–c shows the hourly variations in solar intensity, ambient, basin, water, glass and PCM temperature of IPBSS with PCM as energy storage. It can be observed that the maximum temperature recorded at peak intensity at minimum water flow inside the basin with 10 kg of PCM (mpcm = constant) of about 82°C. Similarly, the maximum recorded temperature of 78°C and 65°C are observed with m_{fw} of 13.32 and 17.72 kg/h respectively. The improvement in T_w with PCM energy storage for m_{fw} of 13.32 and

17.72 kg/h is found to be 8% and 3.8% respectively. There is a decrease in the improvement of about 7.1% in T_w with 17.72 kg/h m_{fw} and with PCM which is due to the continuous extraction of heat through the basin surface. This effect reduces the effect of PCM to melt in order to generate the heat through the panel surface. Furthermore, the influence of PCM increases the power production during sunshine hours as the heat is utilized by flowing water and PCM which completely converts into a liquid phase. The use of PCM provided the extended hour to heat the panel surface during off shine hours which improved the productivity for the duration of offshine hours as shown in Fig. 5. The maximum-recorded yield is observed with a m_{fw} of 7.35 kg/h and found as 1.3 kg/m^2 h whereas, the yield of fresh water with 13.32 and 17.72 kg/h were recorded as 0.85 and 0.6 kg/m^2 h, respectively. In addition, of PCM at the bottom, the freshwater yield is improved by 50% during peak intensity for the m_{fw} at 7.35 kg/h. Similarly, the freshwater yield is lower until the sunshine hours whereas, during the offshine hour's yield of fresh water is improved. This is due to the effect of latent heat energy storage stored in PCM to liberate.

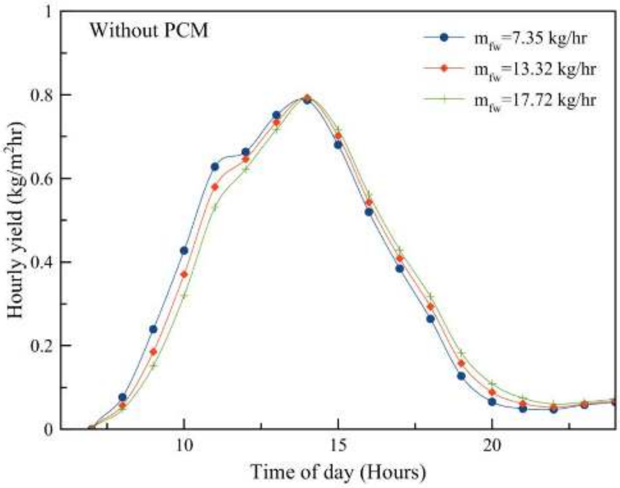


Fig. 3. Variations in yield of fresh from IPBSS without PCM.

3.3. Effect of m_{fw} and PCM in power production of IPBSS

The Figs. 6 and 7 show the effect of m_{fw} and PCM in power production in IPBSS without and with PCM. It is observed that the effect of latent heat energy storage below the photovoltaic panel decreases the temperature than the IPBSS without PCM during the sunshine hours. The effect of storage of energy to complete of phase change from solid to liquid decrease the T_w and T_{pv} for the attainment of melting

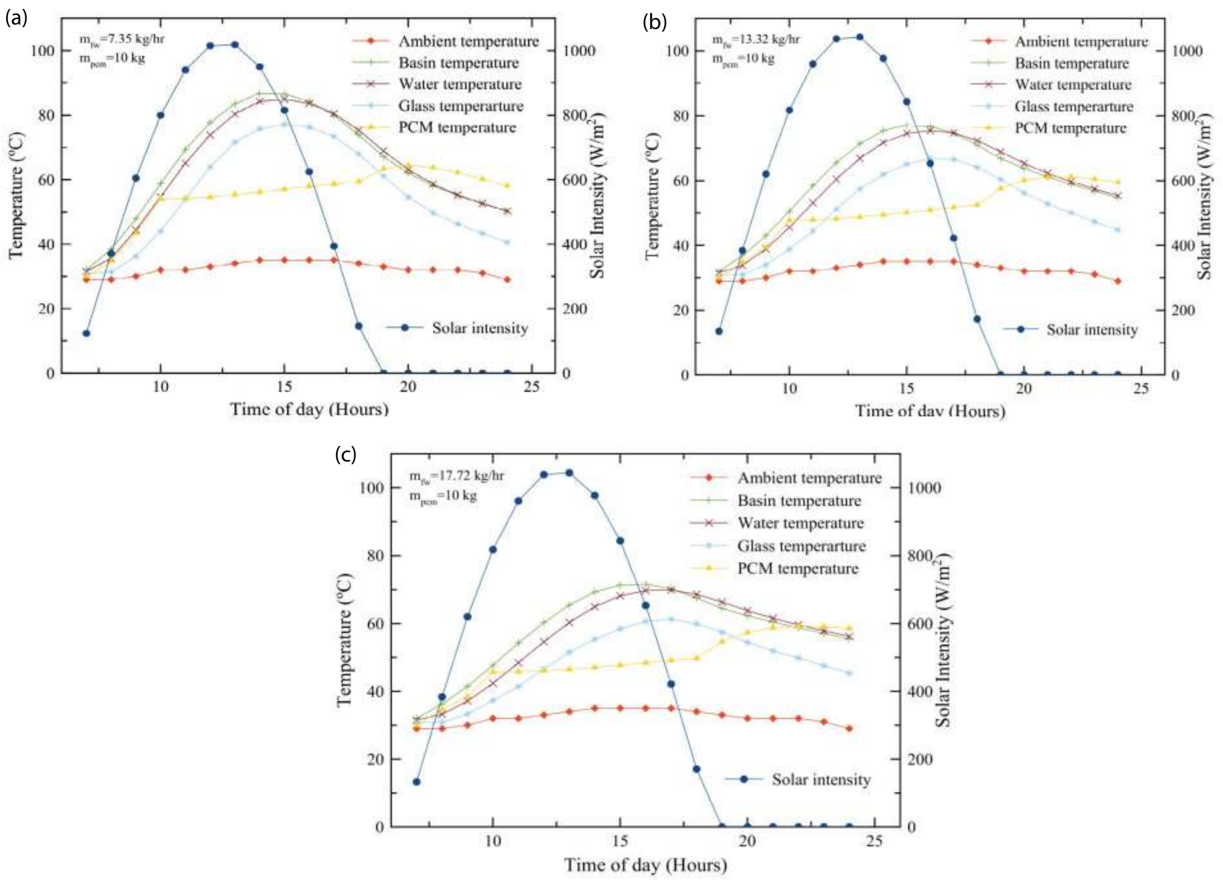


Fig. 4. (a) Diurnal variations of different parameters in the IPBSS with PCM, (b) diurnal variations of different parameters in the IPBSS with PCM, and (c) diurnal variations of different parameters in the IPBSS with PCM.

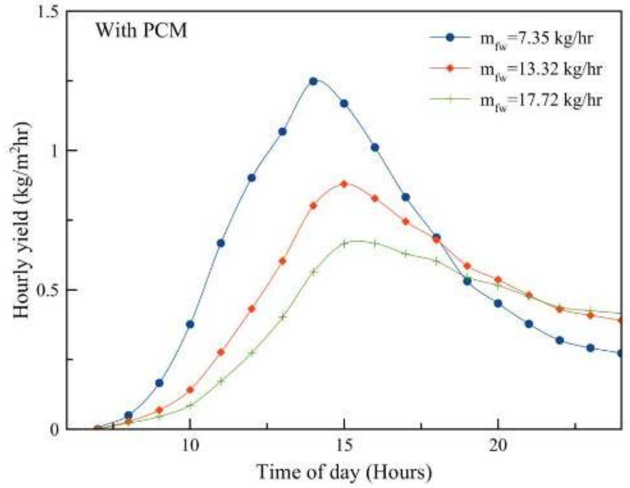


Fig. 5. Variations in yield of fresh from IPBSS with PCM.

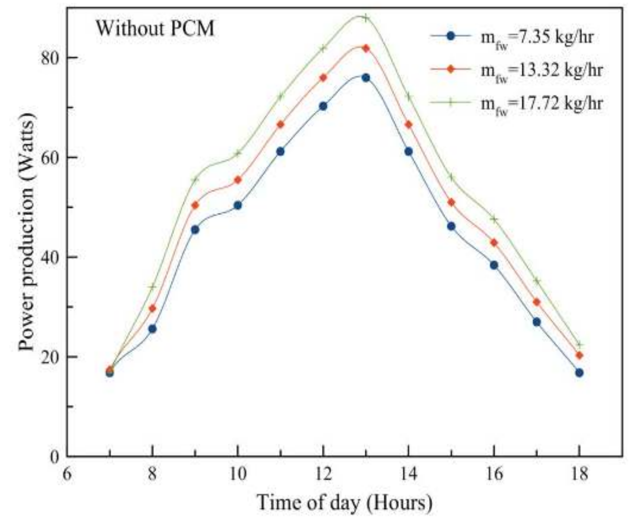


Fig. 6. Hourly variations in power production by IPBSS at different m_{fw} without PCM.

temperature of wax below the panel. This effect has a reverse phenomenon in the power generation during the sunshine hours for an extended increase in the power of the panel as it is depicted in Fig. 7. The internal generation of heat from the bottom of the panel to the material increases the power production of the panel by 10% as compared to IPBSS without PCM. The maximum power production of IPBSS without PCM is found as 78, 80 and 88 W for 7.35, 13.32 and 17.75 kg/h respectively. Similarly, the highest recorded power production for 66, 75 and 82 W for 7.35, 13.32 and 17.75 kg/h respectively for IPBSS with PCM. This decrease in the power production is majorly due to the melting phase of PCM, which reacted through the panel surface for increased temperature. As comparing it with the sunshine hours there is an increase of about 4–5 W until the PCM completely melts to create a discharge of heat by the material to conduct through the absorber surface (Panel).

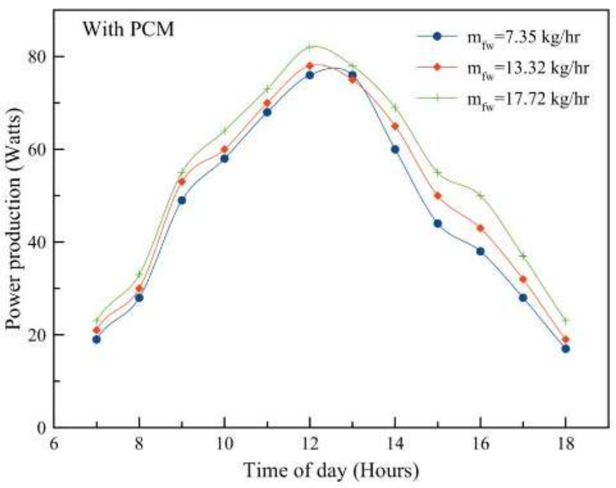


Fig. 7. Hourly variations in power production by IPBSS at different m_{fw} with PCM.

4. Conclusions

The experimental studies on the effect of m_{fw} and PCM on IPBSS were conducted in the humid climatic condition of Chennai, India during the month of February 2018. From the investigational results, it is found that the addition of PCM increases the freshwater yield from 5.4 to 10.8 kg/m^2 for minimum water flow inside the basin which improved the freshwater yield up to 50%. Similarly, the addition of PCM improved the rate of power produced during the sunshine hours. There is an improvement of about 4% and 8% for 7.35 and 13.32 kg/h of m_{fw}. Simultaneously, the electrical power generation improved to about 4 to 5 W by adding PCM. Similarly, the T_w is improved to about 10% with the addition of PCM at lower m_{fw} as it enhanced the evaporation. The maximum recorded T_w of 82°C and 75.4°C for the IPBSS with and without PCM, respectively at a minimum m_{fw}.

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Appendix-I

The uncertainty of the measuring instruments utilized in the present investigationis to measure the solar intensity, temperature, wind speed and yield deliveredin the flask calculated by using Eqs. (1) and (2):

$$u = \frac{a}{\sqrt{3}} \tag{1}$$

where a is the accuracy of the instrument

$$u = \left[\left(\frac{\partial R_1}{Y_1} u_1 \right)^2 + \left(\frac{\partial R_2}{Y_2} u_2 \right)^2 + \left(\frac{\partial R_3}{Y_3} u_3 \right)^2 + \ldots + \left(\frac{\partial R_n}{Y_n} u_n \right)^2 \right]^{0.5} \tag{2}$$

The total uncertainty based on the output is determined based on yield and solar irradiance falling on the slanted surface is obtained by Eq. (3).

$$u(\eta_d) = \left[\left(\frac{\partial \eta_d}{m_w} u_{m_w} \right)^2 + \left(\frac{\partial \eta_d}{I(t)} u_{I(t)} \right)^2 \right]^{0.5} \tag{3}$$

The uncertainty of water collected in the flask is determined based on the mass of water collected and it is written as:

$$u_m = \left[\left(\frac{\partial m}{\partial m_w} u_{m_w} \right)^2 \right]^{0.5} \tag{4}$$

Based on the independent variables, the uncertainty of the set-up is expressed as:

$$u = u_1 + u_2 + u_3 + \ldots u_n \tag{5}$$

where u is the total uncertainty of the set-up. u_1, u_2, u_3, …, u_n is the uncertainty of the individual independent variable.